BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

Report WD/OS/87/1

Estimation of aquifer recharge using geochemical techniques

Final report of the Lower Atbara River Basin Project: BGS component
Collaborative project with the National Administration for Water (NAW), Khartoum, and the Arab Centre for Semi-Arid Zones and Dry Lands (ACSAD), Damascus

W. M. Edmunds, W. G. Darling and D. G. Kinniburgh

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Cover photograph

Traditional dug well (Bir Kharbana) at Abu Delaig, some 15 years old and reaching a depth of some 23 m. Research results show that direct recharge by rainfall through landscape such as this only amounts to just under 1 mm a year on long-term average. Replenishment of water levels in these wells occurs by lateral movement of water from the Wadi esh Shelka some 500 m away.

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LOWER ATBARA RIVER PROJECT

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PREFACE

The Lower Atbara River Basin Project has been carried out by BGS staff in collaboration with ACSAD (Arab Centre for Semi Arid Zones and Dry Lands), Damascus and the National Administration for Water (NAW), Khartoum. This report contains the results of one part of this project devoted to the use of geochemical techniques as a means of estimating current recharge to the shallow groundwater system and, more generally, in providing an understanding of the recharge history of the area. Other reports, being prepared by ACSAD and NAW staff include those on hydrogeology, geophysics, hydrology, climatology and development schemes. A summary report will be prepared in English and Arabic with an overview of the main conclusions relevant to development and conservation.

The Overseas Development Administration (ODA) are thanked for providing financial support for this project and staff of the British Embassy, Khartoum are thanked also for providing considerable local support. A research grant was also received from IAEA, Vienna to support some of the isotope studies.

We wish to thank Dr D Harkness of SURRC, East Kilbride for radiocarbon analysis and Mr D Otlet and staff at AERE, Harwell for tritium analyses. Mr D L Miles, Miss J M Cook, Miss J Trafford and Miss R Andrews of BGS Wallingford assisted with the chemical analyses and Mr A Brunsdon (IH, Wallingford) with the stable isotope analyses. We are also grateful to Mrs C Cordery for typing and help with compiling the text.

Finally we wish to thank the people of Abu Delaig for their hospitality and help.

SUMMARY

The Sahel droughts of the past two decades have focussed attention on the scarce water resources in northern Africa and other arid regions where rainfall is less than 400, often less than 200 mm/annum. Groundwater represents the only realistic resource in such areas, since with a few notable exceptions such as the Nile or the Niger rivers, perennial or even seasonal surface water is usually absent. Much of the population in these areas is pastoral and nomadic, relying on shallow wells in wadis or on traditional dug wells, maybe as deep as 100 m. The water balance is delicately poised and sensitive to short and long term climatic changes.

In the Lower Atbara River Basin (Wadi el Hawad) the mean annual rainfall is less than 200 mm/annum. In the four years 1982-85 when this study was carried out, the mean annual rainfall was only 85 mm at Abu Delaig, the largest town in the area. Water is taken from shallow dug wells in the town and from a few deeper traditional wells in the surrounding area; in recent years deep boreholes have been drilled in places, north of Abu Delaig to abstract groundwater from the Nubian Sandstone aquifer.

The main purpose of the present study and specifically the geochemical component was to answer the following questions:

(1) Does rainfall infiltrate directly into the soil and rock over the area, and if so, how much?

(2) During wadi floods, how much infiltration takes place via the wadi bed?

(3) What is the role of the River Nile? Does this provide a sustainable recharge source and if so where is recharge occurring?

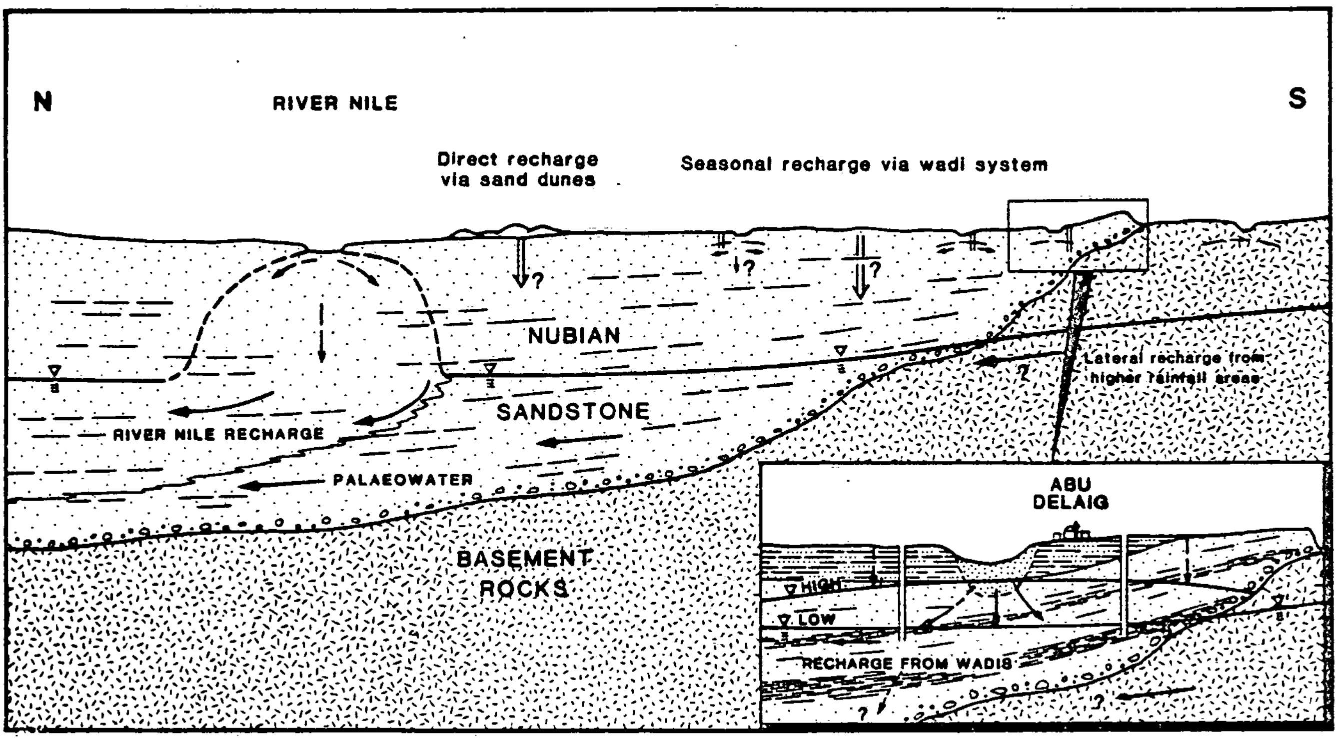
(4) What is the origin of the groundwater now tapped by boreholes in the Nubian Sandstone; is it being replenished in any way or is it being mined?

The groundwater contains clues or fingerprints which may enable the origin of the water (H_2O) or of its dissolved constituents to be identified. Thus the stable isotopic composition of the water itself ($\delta^{18}O$, δ^2H) may indicate whether the groundwater has originated from present day rain storms or from wetter periods thousands of years ago, or, whether a significant amount of evaporation has occurred. The solution composition (e.g. content of sulphate, magnesium to calcium ratio, content of fluoride or strontium etc.) may indicate whether the water has reacted with these rocks and if so what rock types are involved. Radiocarbon derived from the atmosphere (cosmic ray bombardment of CO_2), entering the soil as bicarbonate (HCO_3), acts as a clock, due to radioactive decay over a period of some 50000 years, and enables the water to be dated approximately. As well as these techniques, it has been necessary in this study to examine the historical and archaeological records for indirect evidence of wetter or drier periods during the past.

Samples were collected of rain (1982-85) and of wadi floods; this was possible since NAW staff were in the field throughout the summer and were able to sample the wadi flow on the very few days when this occurred. Samples were also collected of the shallow well water at Abu Delaig and the deeper wells and boreholes in the region. Most of the chemical and isotopic analysis was carried out in UK.

The main research effort was concentrated on obtaining profiles of water contained in the top 30 m of the unsaturated zone. Unsaturated zone profiles had been shown, from earlier work in Cyprus, to contain a record of the recharge history over several decades and could be used to calculate the amount of recharge. Samples were collected by auger drilling and from dug wells; the latter samples were taken by the local NAW well digging team at the end of each day's shift.

The main conclusions of the research may be summarised with reference to the schematic cross-section. The main aquifer is the Nubian Sandstone which thickens northwards, overlying relatively impermeable crystalline rocks. Locally, as at Abu Delaig clays or impure sandy deposits of alluvial or colluvial origin overlie the Sandstone.



The chemistry of water in the unsaturated zone at Abu Delaig is rather saline (1000-4000 mg l^{-1} chloride), and a uniform (steady-state) composition is established below 2 m. This suggests that there is a net downward movement of water. Using the concentration of chloride in the rainfall (between 6-10 mg l^{-1} chloride) and knowing the average rainfall amount it has been possible to calculate a recharge value for the direct recharge to the aquifer via the interfluve areas. The calculated amount of recharge ranges from 0.3 to 3.45 mm/annum with an average of around 1 mm. Thus it is unlikely that the general land surface can provide a route for significant recharge in these areas with around 200 mm annual rainfall, except perhaps where sand dunes can provide more rapid infiltration. The column of water stored in the unsaturated zone represents several hundred years storage. In some areas it is possible that the profiles represent discharge as well as recharge phenomena, with considerable areas enabling groundwater to be lost by evaporation from deep water tables (e.g. up to 20 m). This question is highlighted by the present study and requires further research.

In contrast to the interfluve areas, the wadi bed acts as an important route for recharge to the shallow aquifer and it is this water that provides the replenishment upon which the local population has traditionally relied. Isotopic tracers, in this case tritium (^3H), in minute amounts, derived from nuclear weapons testing in the 50's and 60's, provide evidence that very recent water has moved laterally up to 1 km from the wadi bed. This water is chemically very pure, and some of its chemical characteristics indicate mixing with water in the unsaturated zone as the water table fluctuates seasonally. The absence of any significant recharge from the surface implies an effective barrier against pollution, providing of course, that the wells are properly constructed.

Groundwater from the deeper Nubian aquifer, north of Abu Delaig is quite distinct from the recent recharge, both chemically and isotopically. Most probably it was replenished during a wetter climatic period between 6000-8000 years ago. There is so far no evidence that the present-day wadi recharge is also replenishing the Nubian system. Thus, from a resources viewpoint the deep groundwater is being mined and cannot be viewed as a secure source in the longer term.

It was found using chemical and isotopic tracers that the River Nile is locally recharging the Nubian Sandstone via the river sediments. Thus the deep groundwater resources in this area are being sustained continuously and river recharge induced by pumping is also likely to be filtered of impurities on passing through the sediments. The recharge from the Nile probably extends some 10 km on either side of the river, and then drains naturally to the north in response to regional gradients.

The only renewable water resources in this region are therefore the groundwater adjacent to the Nile valley and the much smaller resources to be found within and close to the wadi systems. Any development or conservation schemes must concentrate on these resources and not rely upon any regional estimates of groundwater recharge. A quantitative appraisal of these resources will be made in conjunction with the results from other aspects of the study.

مشروع حوض نهر عطبرة السفلي (وادي الهود)

السودان

خلاصة

كان لفترات الجفاف التي تعرضت لها سواحل افريقيا الشرقية خلال العقدين المنصرمين اثرها البالغ في تركيز الانتباه على شحة المصادر المائية في شمال افريقيا والمناطق القاحلة الأخرى التي تقل فيها مناسيب هطول الامطار السنوية عن ٤٠٠ ملم بالسنة ، وغالبا ماتكون هذه المناسيب اقل من ٢٠٠ ملم بالسنة ٠ وتمثل المياه الجوفية المصدر الحقيقي الوحيد للمياه في تلك المناطق ، لأن المياه السطحية الدائمية أوحتى المياه السطحية الموسمية على حد السواء تكاد تنعدم ، باستثناء بعض المصادر القليلة الجديرة بالذكر مثل نهري النيل والنيجر ٠ لذلك تتألف نسبة كبيرة من السكان القاطنين في هذه المناطق من الرعاة والبدو الرحّل الذين يعتمدون على الآبار الضحلة في الوديان او على الآبار التقليدية المحفورة الى اعماق تصل الى ١٠٠ متر حيث يكون منسوب الماء مرهفا في توازنه وحساسا للتغيرات الطقسية القصيرة أو الطويلة الأمد ٠

وفي حوض نهر عطبره السفلي (وادي الهود) يقل متوسط منسوب سقوط الأمطار السنوية عن ٢٠٠ ملم بالسنة ٠ وفي فترة السنوات الأربع من ١٩٨٢ – ١٩٨٥ التي أجريت فيها هذه الدراسة ، كان المتوسط السنوي لسقوط الأمطار فقط ٨٥ ملم في ابودليق وهي اكبر مدينة في المنطقة ٠ وفي المدينة يستخرج الماء من آبار ضحلة ، أمّا في المناطق المحيطة بها فتستخرج المياه من بضع آبار تقليدية أعمق منها ٠ وخلال السنوات الأخيرة تم حفر ثقوب عميقة في موافع تقع الى الشمال من مدينة أبودليق لغرض سحب المياه الجوفية من طبقة الحجر الرملي الخازنة للماء في النوبة ٠

أن الغرض الرئيسي من الدراسة الحالية وعلى الأخص القسم الجيوكيميائي منها يستهدف الاجابة على الاسئلة آلاتية :

(١) هل تتسرب مياه الامطار مباشرة بعد هطولها الى داخل التربة والصخور الموجودة في هذه المنطقة ، واذا كان ذلك صحيحا ، فماهي كمية الامطار المتسربة ؟؟ ٠

(٢) خلال موسم فيضان الوادي ، ماهي كمية المياه المتسربة عن طريق قاع الوادي ؟

(٣) ماهو دور نهر النيل ؟ هل يقدّم هذا النهر مصدر دائم التجدد واذا صح ذلك ، أين تحدث عملية التجدد ؟؟

(٤) ماهو منشأ المياه الجوفية التي تفرغ حاليا بواسطة الثقوب المحفورة في الحجر الرملي النوبي . وهل يتم تجديدها بأية طريقة كانت أو هل هي مختزنة تحت الأرض ؟؟.

تحتوي المياه الحوفية على ادلة قاطعة اوبصمات تمكّن من تشخيص منشأ الماء (H_2O) او مقوماته المذابة . وبهذه الطريقة سيبين التركيب النظائري الثابت للماء (d^2H d^{18}) هل أن المياه الجوفية نشأت أصلا من عواصف مطرية حدثت في وقتنا الحاضر أو في فترات سقطت فيها الامطار بغزارة قبل آلاف السنين ، او هل حدثت كمية كبيرة من التبخر . وكذلك سيبين تركيب المحلول المائي (مثل ، محتوى الكبريت نسبة المغنيسيوم الى الكالسيوم ، محتوى الفلوريد أو السترونتيوم..الخ) هل أن الماء قد تفاعل مع هذه الصخور ، واذا تفاعل ، فماهي انواع هذه الصخور ؟؟. حيث أن الكربون المشع المشتق من المحيط الجوي (تفجير غاز ثاني اكسيد الكربون بالاشعة الكونية) والذي يدخل الى التربة على هيئة بيكربونات (HCO_3) يقوم بدور الساعة في تحديد الزمن يسبب الانحلال الاشعاعي عبر فترة تبلغ ٥٠٠٠٠ سنة يمكن من تحديد تاريخ نشوء الماء بصورة تقريبية بالاضافة الى جميع هذه الأساليب التقنية ، كان من الضروري في هذه الدراسة ، القيام بفحص السجلات التاريخية والأثرية لغرض العثور على دلائل غير مباشرة تبين تعرض هذه المنطقة لفترات أشد من الجفاف او من غزارة الأمطار في العصور الماضية .

وقد اخذت عينات من مياه الأمطار (١٩٨٢ – ١٩٨٥) ومن مياه فيضانات الوادي وبما أن افراد (NAW) كانوا متواجدين في ميدان العمل خلال موسم الصيف فقد تمكنوا من اخذ عينات من مياه فيضان الوادي في نفس فترة الأيام القليلة التي تحدث فيها . وكذلك اخذت عينات من مياه الأبار الضحلة في ابودليق ومن الأبار العميقة وثقوب الماء المحفورة في المنطقة . وقد تم اجراء اغلب التحاليل الكيماوية والنظائرية في المملكة المتحدة .

ان الجهود الرئيسية المبذولة في البحث ركزت على العثور على قطاعات جانبية من المياه الموجودة ضمن مسافة ٣٠ مترا العليا من المنطقة غير المشبعة . وقد بينت المقاطع الجانبية للمنطقة غير المشبعة المأخوذة من اعمال سابقة في قبرص احتوائها على سجل بتاريخ التجديد عبر عدة عقود من الزمن ويمكن استعمالها لحساب الكمية المتجددة . وقد تمّ الحصول

على عينات من اعمال الحفر بالمثقاب ومن الآبار المحفورة ، حيث كان الحصول على العينات الأخيرة بواسطة جهود فريق حفر الآبار لـ (NAW) المحلي في نهاية كل نوبة عمل يوميا .

ويمكن ايجاز الاستنتاجات الرئيسية للبحث بالرجوع الى المقطع العرضي التخطيطي . فالطبقة الرئيسية الخازنة للماء هي الطبقة النوبية المتكونة من الحجر الرملي والتي تزداد سماكة كلما اتجهنا نحو الشمال حيث تغطي نسبيا صخورا بلورية كتيمة لاينفذ منها الماء . اما المنطقة المحلية فهي تماما مثل منطقة ابودليق حيث تقع فيها الطبقة المتكونة من الحجر الرملي تحت طبقة من الطفل او الترسبات الرملية المخلوطة بالشوائب والتي نشأت اصلا من ترسبات الغرين او رسوبات الجاذبية .

اما التركيب الكيماوي للماء في المنطقة غير المشبعة في ابودليق فهو ملحي نوعا ما (١٠٠٠ - ٤٠٠٠ مليجرام ل$^{-1}$كلوريد) ويتكون تركيب منتظم (حالة ثابتة) تحت ٢ م . وهذا يوحي بوجود حركة واضحة للماء الى الأسفل . وعن طريق استعمال تركيز الكلوريد في مياه الأمطار (بين ٦ - ١٠ مليجرام ل$^{-1}$ كلوريد) ومعرفة معدل كمية مياه الأمطار الساقطة فقد اصبح في الامكان احتساب قيمة الإمداد الخاصة بالامداد المباشر الى الطبقة الخازنة للماء عن طريق المناطق الواقعة بين مجاري المياه . وتتراوح الكمية المحتسبة لاعادة الامداد من ٠ر٣ الى ٣ر٤٥ مم/ السنة ومع معدل يبلغ حوالي ١ مم . وهكذا فان الطبقة السطحية العامة للارض لايحتمل أن توفر مسلكا كبيرا للامداد في هذه المناطق مع سقوط الامطار بنسبة ٢٠٠ مم في السنة تقريبا ، باستثناء مناطق الكثبان الرملية التي توفر تسربا سريعا للمياه . ويمثل عمود المياه المختزنة في المنطقة غير المشبعة كمية المياه المختزنة لعدة مئات من السنين . كما أنه من المحتمل في بعض المناطق ان تمثل المقاطع الجانبية كل من الظاهرتين الطبيعيتين ، التصريف والامداد على حد سواء مع امكانية فقدان المياه الجوفية في بعض المناطق الكبيرة عن طريق التبخر من سطوح المياه الباطنية (لحد ٢٠ م مثلا) . وقد نوهت الدراسة الحالية بهذا الموضوع الذي يتطلب اجراء بحث اضافي .

وبعكس المناطق الواقعة بين مجاري المياه ، يعمل قاع الوادي بمثابة مسلك مهم في عملية الامداد الى المنطقة الفحلة الخازنة للمياه حيث أن هذه المياه هي التي تقوم بالتجديد الذي يعتمد عليه السكان المحليون بشكل تقليدي . وتقوم الكاشفات النظائرية ، وفي هذه الحالة التريتيوم (^{3}H) بكميات قليلة جدا مشتقة من تجارب الاسلحة النووية في العقدين الخامس والسادس من هذا القرن ، بتقديم الدليل على أن المياه الحالية قد تحركت جانبيا لحد كيلومتر واحد من قاع الوادي . وان هذه المياه نقية جدا كيماويا ، اضافة الى أن بعض خواصها الكيماوية تبين

اختلاطها بالمياه الموجودة في المنطقة غير المشبعة عندما يتغير سطح المياه الباطنية بغير انتظام موسميا . وأن انعدام الامداد بكميات كبيرة من السطح يقدم حاجزا فعالا مضادا للتلوث ، على شرط أن يتم انشاء الأبار بصورة جيدة .

وتكون المياه الجوفية من الطبقة النوبية العميقة الخازنة للماء والواقعة الى الشمال من ابودليق مختلفة تماما عن مياه الامداد الحالية كيماويا ونظائريا . ومن المحتمل جدا أن يكون تجديد هذه المياه قد حصل خلال فترة مناخية اكثر رطوبة قبل ٦٠٠٠ – ٧٠٠٠ سنة من الآن . والى حد ما ، لايوجد الدليل القاطع على أن الامداد الحالي بواسطة الوادي يقوم بتجديد النظام النوبي للماء . وهكذا ، فمن وجهة النظر الخاصة بالمصادر المائية فان المياه الجوفية العميقة التي يجري استخراجها حاليا لايمكن اعتبارها مصدرا مأمونا على المدى الطويل .

لقد تم التوصل عن طريق استعمال الكاشفات الكيماوية والنظائرية الى أن نهر النيل هو مصدر امداد الطبقة النوبية المحلية المتكونة من الحجر الرملي عن طريق الترسبات النهرية . وبهذه الطريقة يتم تعزيز مصادر المياه الجوفية العميقة في هذه المنطقة بصورة منتظمة . كما أن الامداد الذي يحفزه الضخ من المحتمل جدا ان يترشح من الشوائب خلال مروره بالطبقات الرسوبية . ولربما يمتد الامداد من نهر النيل الى مسافة تصل لغاية ١٠ كم على كلتا الضفتين ، ثم يجري تصريفه طبيعيا نحو الشمال بسبب المنحدرات الموجودة في هذا الاقليم .

لذلك فالمصادر المائية الوحيدة القابلة للتجديد في هذه المنطقة هي المياه الجوفية المجاورة من وادي النيل والمصادر المائية الأصغر حجما التي يمكن العثور عليها ضمن انظمة الوادي او بالقرب منها . وعلى هذا الأساس فأية خطط للتطوير او المحافظة يجب أن تركز الاهتمام على هذه المصادر ولاتعتمد على أي امداد اقليمي للمياه الجوفية . حيث سيتم اجراء تقدير كمي لهذه المصادر فيما يتعلق بالنتائج المتحققة من النواحي الأخرى لهذه الدراسة .

LOWER ATBARA RIVER RECHARGE PROJECT

1. INTRODUCTION

The availability and security of groundwater resources in semi-arid regions of the world are areas of major concern. Properly managed, groundwater can offer a reliable long-term source of supply which can be invaluable during a prolonged period of drought such as is being experienced in the Sahel in recent decades.

Estimation of aquifer recharge is one of the main uncertainties in many water resource investigations. Many groundwater development schemes are proceeding even though there is uncertainty as to how much natural replenishment, if any, is taking place; other schemes are being developed which rely on the concept of 'groundwater mining'. This is probably the only safe assumption in the absence of reliable recharge figures to the contrary.

Natural replenishment of groundwater in semi-arid regions can take place by two mechanisms:

(1) direct infiltration of rainfall via the soil and unsaturated zone;

(2) local recharge of surface runoff via permeable wadi beds or drainage systems.

The flashy and unpredictable nature of precipitation in semi-arid and arid zones makes the accurate determination of rainfall amounts and of surface runoff very difficult. The problem of determining aquifer recharge by conventional means is further compounded by the difficulty in obtaining reliable climatic data and in measuring evapotranspiration. Add to this the great variety of soils, topography, geology and land use and the problems of recharge estimation are placed in perspective.

Conventional methods used in temperate regions (Penman, 1948 and later modifications) are often inappropriate when applied to semi-arid regions. Where rainfall and evaporation are of the same order, the difference between the two figures, both with appreciable errors, leads to a considerable uncertainty in the final recharge estimate.

The present project follows logically from an earlier geochemical study carried out with British ODA (Overseas Development Administration) support at Akrotiri, Cyprus, entitled 'Geochemical estimation of aquifer recharge ' (Edmunds et al., 1981). This project set out to examine whether simple, inexpensive chemical techniques, using unsaturated zone profiles, could be used to estimate the direct component of recharge. A reliable methodology was developed and tested on eight unsaturated sand profiles to depths of 30 m. The results were calibrated against a tritium profile method and direct estimate of recharge using a lysimeter. Excellent agreement was obtained demonstrating the effectiveness of using solute profiles for recharge estimation, albeit under relatively ideal conditions (Edmunds and Walton, 1980; Kitching et al., 1980; Edmunds, 1982a).

The results of the Cyprus study clearly could have widespread application and in order to test the methods in an environment more typical of semi-arid regions the present project was set up in Sudan. Following discussions in Khartoum and

Damascus, the Lower Atbara River Recharge Project was initiated with participants from NAW (National Administration for Water) Khartoum, ACSAD (Arab Centre for Semi-arid Zones and Dry Lands) Damascus, and BGS (Wallingford) with ODA support. This project, a regional water resource assessment, provided the framework for the geochemical research programme aimed at assessing the extent of groundwater recharge. The present report contains details only of the geochemical investigations. Other reports are being prepared on hydrogeology, geophysical studies, climatology, hydrology and proposed development projects. Executive summaries are being prepared in English and in Arabic with overall conclusions of the project.

2. SCOPE OF THE PROJECT

The overall water resources proposal was formulated by ACSAD (ACSAD, 1981). The main objectives were to determine the surface and groundwater resources in the Lower Atbara River basin area (Figure 1), but specifically in the Wadi Hawad drainage basin. Small scale water resources development here is the cornerstone to any future socio-economic development in relation to (1) agricultural development with emphasis on pastoral and dry land farming, (2) improvement of the quality of livestock in the disease-free zone of the project and the management of pastoral zones, (3) raising the living standards of nomads by better health, education and other public services.

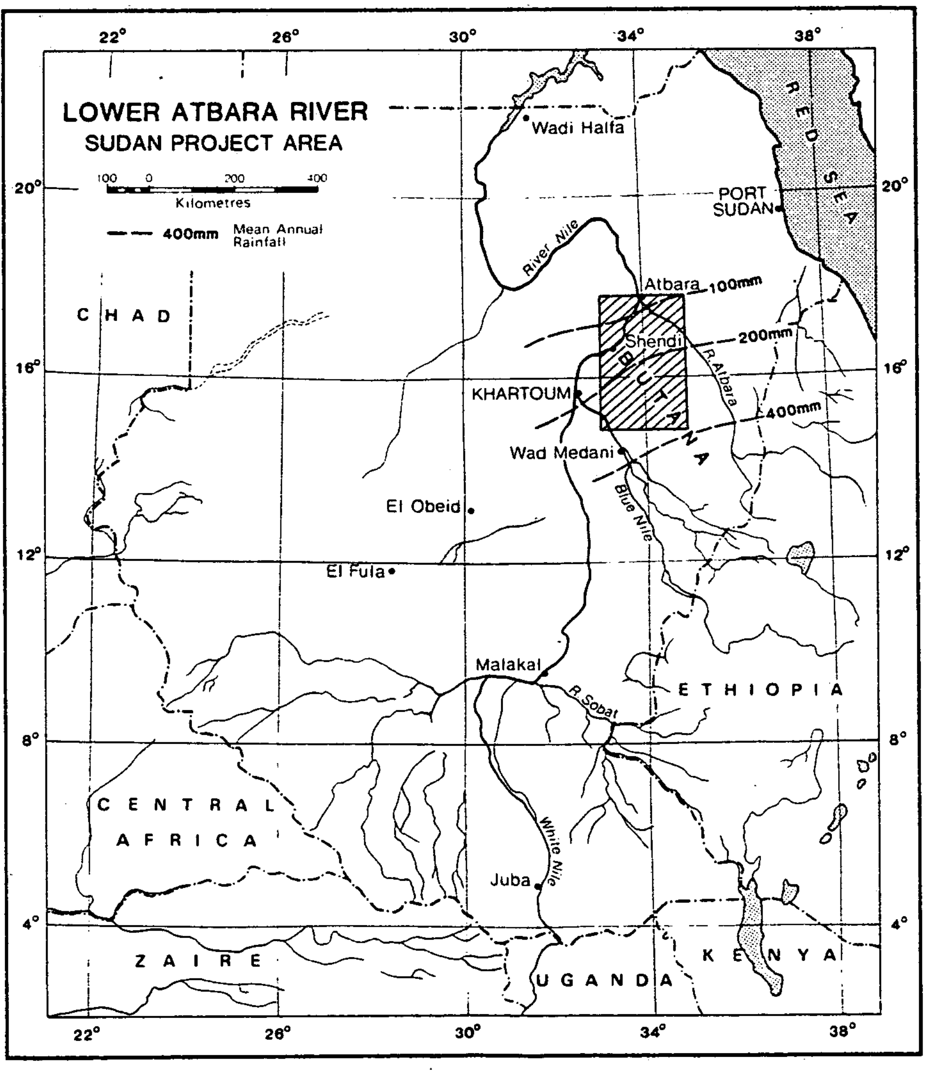


Figure 1. Location of project area (Lower Atbara River Basin).

The water resources survey required that meteorological data and wadi flood data would be collected; a full meteorological station was established at Abu Delaig and three flood measuring stations installed in the catchment. The groundwater studies were to include geological, geophysical and geochemical investigations of the Nubian sandstone aquifer and its relation to groundwater contained in the surrounding geological formations.

The geochemical studies which are the subject of this report were, therefore, set up in the context of a broader water resources study which was principally the responsibility of the NAW and ACSAD. The principal objectives of the geochemical studies were:

(1) Estimation of direct recharge in the unsaturated zones of interfluve areas using geochemical methods based on one or more of the following sampling techniques: shallow dug wells, dry percussion drilling or auger drilling. Samples of interstitial water would be extracted mainly for solute analysis following determination of soil moisture content, bulk density and SEC (specific electrical conductivity) in the field. Some control samples for tritium and stable isotope analysis would be taken.

(2) The characterisation of shallow groundwater and the geochemical estimation of wadi recharge relative to direct recharge.

(3) Investigation of deep Nubian groundwaters to estimate whether they are predominantly palaeowaters and whether they contain a component of modern recharge. Also examine the connection between the shallow wadi system and the Nubian as well as any lateral flow from the basement to the Nubian aquifer using isotopic and conventional geochemical techniques.

(4) Investigation of the Nile and Atbara river valleys to determine the extent of water flow between the rivers and contiguous groundwater systems.

3. PREVIOUS STUDIES AND REGIONAL CONTEXT

3.1 Geological Setting.

The location of the Wadi Hawad basin is shown in Figure 1 in relation to the Nile/Atbara rivers and in relation to the geology of NE Africa. Little has been written in detail about the geology of this area; the solid geology is extensively masked by colluvial deposits and no detailed geological map exists, the best summary being the 1:2,000,000 Scale Map of the country. The basin lies at the southern margin of the extensive Nubian sandstone aquifer which covers much of the Sahel and the unconformable contact between the Nubian Sandstone and the Basement Complex lies within the project area. The basal sandstone is rather heterogeneous, comprising pebble beds, thin clay layers and feldspathic sands. The Basement Complex is mainly granodiorite with a lesser amount of metasediments; later intrusive bodies (Jebel Qeli, Sabaloka Complex) form distinct topographic features to the south and west of the area respectively. The geology of the area is described together with the hydrogeology in a separate project report by ACSAD. A high feature in the Basement Complex, the Sabaloka Ridge (Figure 6) marks the probable western boundary of the Wadi Hawad Basin.

3.2 Palaeoclimate, Palaeohydrology and Climatic Variation.

As a basis for understanding the recharge history of this area and the current recharge patterns, some idea of the palaeoenvironmental changes is needed. The climatic history of the late Quaternary and Holocene has been built up from studies in a number of disciplines - archaeology, palynology, geomorphology, sedimentology and geochemistry. Relatively little of this evidence comes from Sudan however, and it is necessary to construct the most likely chronology of climatic variation in this region from studies in adjacent areas.

Perhaps the best records of environmental changes in the Sahel region come from lake level, diatom and sediment studies in the Chad basin (Maley, 1973; Servant and Servant-Vildary, 1980), the results of which are summarised in Figure 2 and which may be used as a reference for other areas of Africa, including the

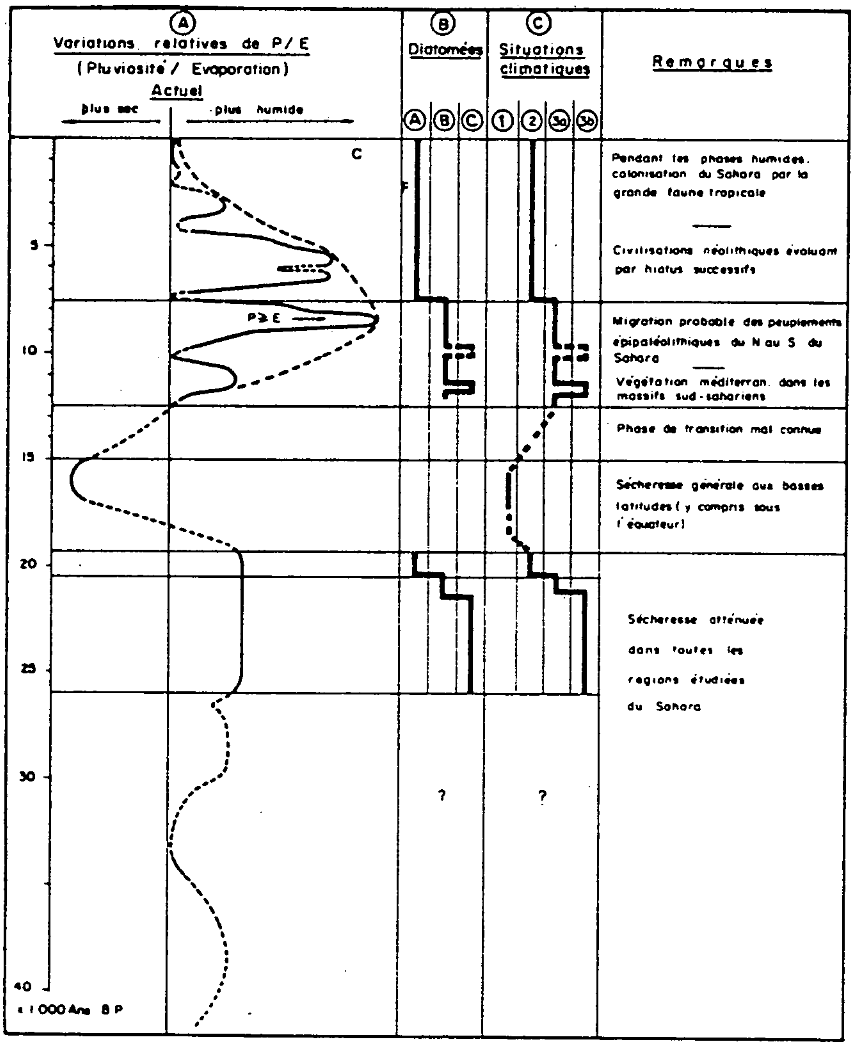


Figure 2. Palaeoevolution of the Chad basin since 40000 yr BP (after Servant and Servant-Vildary, 1980).

(A) variation of P/E towards 14°N

(B) evolution of diatom associations: A-tropical species, B-rare cold water species and C-non-tropical species

(C) atmosphere circulation hypothesis

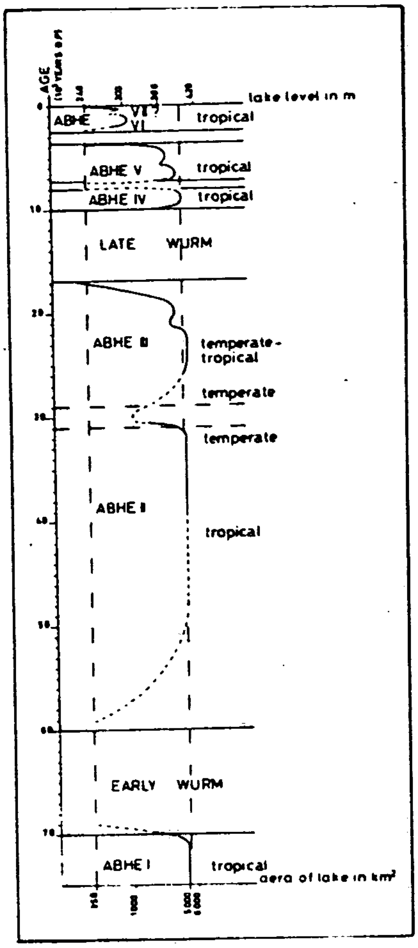


Figure 3. Variations of Lake Chad water level during the last millenium, after Maley (1973).

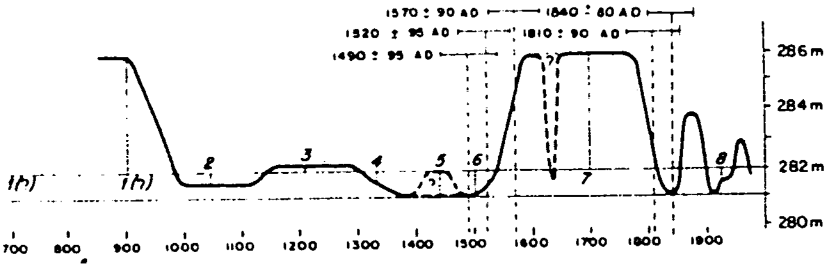


Figure 4. Late Quaternary lake-level fluctuations of L. Abhé (Central Afar) (from Gasse, 1977a).

present study area. During the late Quaternary, a sequence of humid phases with different ratios of precipitation (P) to evaporation (E) can be identified from lake level changes. In order of decreasing importance, the wettest phases were: 9000-8000 (P > E), 6000 (P < E), 3000-3500, 11000 (P < E) and from 40000 to 20000 BP. Driest times were 20000 to 13000, about 10000, 7500, 4000-4500 BP and during historical times (since 3000 BP). During historic times (Maley, 1973), climatic fluctuations have been reconstructed from palynological evidence and show that higher than average humidity was a feature of the 16th to 18th centuries (Figure 3) and that the present day climate is relatively arid. This is also borne out from the historic record for the Lake Chad area and much of Africa (Nicholson, 1980).

In neighbouring countries, including Sudan, there are also records of humid episodes especially during the Holocene. This follows an almost universally accepted arid period between 20000-12000 BP (corresponding to the Wurm glaciation in northern latitudes). The widespread increased lake levels and humidity between 8000-9000 BP resulted from an increase in rainfall in direct response to increasing ocean temperatures (Street and Grove, 1976). In central and southern Libya, there is evidence of lake formation in present desert areas and humid episodes between 13000-7700 BP and also around 5000 until as late as 3500 BP (Pachur, 1975, 1980); Pachur and Roper, 1984) during which time a precipitation of around 200-400 mm/yr is inferred, allowing savannah vegetation to develop with grazing of cattle and the establishment of conditions favourable for large mammals.

In Ethiopia and Djibouti, the Late Pleistocene and Holocene environment has also been dated from lake sediments, especially L. Abhe in Central Afar (Gasse et al., 1980) (Figure 4). Four periods of high lake levels can be recognised between 70000-3000 BP with temperate, drier interludes. A major dry interlude is recorded between 11000-17000 BP corresponding to the late Wurm glacial. Wetter conditions are found in two main phases, 10000-8400 BP, 7000-6500 BP, with the present semi-arid to subtropical climate extending to the present day from 4500 BP but with less humidity than the early Holocene.

The evidence from Sudan itself is generally not as detailed, extensive or unequivocal as in those areas with a detailed lake sediment chronology. Palynological studies of lake sediments from Lake Oyo (NW Sudan) however indicate that a humid tropical climate with annual monsoonal rainfall of at least 400 mm/yr existed in the early Holocene, decreasing to 300 mm/yr at 6000 BP and <100 mm at 4500 BP (Ritchie et al., 1985).

Evidence for late Quaternary and Holocene environmental changes in the Nile sediments of Central Sudan has been reviewed by Williams and Adamson (1980). The White Nile shows high levels around 12500-11400 BP, 8400-8100 BP, 7000 BP, 5500 BP 3000 BP, 3000 BP, 2700 BP and 2000-1500 BP. High Blue Nile flood levels are considered to have occurred at 12000-11000 BP, 7500 BP, 6900 BP and 5500 BP. These flood periods may not always reflect local conditions and therefore the evidence from small Holocene lakes west of the White Nile (Wad Mansurab) and only some 200 km west of our study area, is important. These lakes are some 20-40 m above the highest Holocene flood level of the White Nile and carbon-14 dates of mollusc shells indicate that the lakes were full between 8400-6990 BP; the conclusion that a more humid local climate existed at this time is also supported from sporadic samples elsewhere in Kordofan.

There is also evidence in the historic record of the climatic and environmental conditions pertaining at the time. The evidence from Egyptian civilisations has been reviewed by Hassan (1980) and Shinnie (1967) has described the evidence from the former Meroitic civilisation based within the project area. The present project area is in fact the island of Meroe. It is surrounded by three rivers and supported a flourishing civilisation from c. 590 BC to 300 AD (Figure 5). It is referred to as 'Ethiopia' in the Bible (Acts VIII) and was ruled at

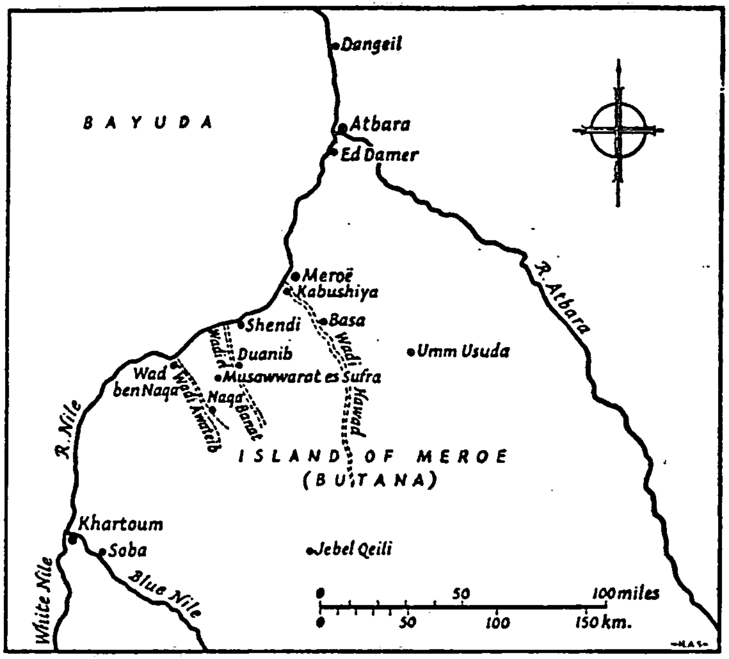


Figure 5. The ancient 'Island of Meroe'.

the time of Christ by Queen Candace. Meroe was referred to by Strabo (7 BC) who stated: 'there is no rain at Meroe'. He said that the people lived on millet from which they made a drink (marisa). Most of the people then were poor nomads. There were no fruit trees, only date palms. Pliny (Natural History, Vol. 35) describes an expedition sent by Nero in c. AD 61 to find the source of the White Nile. Troops reported that around Meroe itself, greener vegetation began, some forest came into view and tracks of rhino and elephant were to be seen. Elephants were also trained during Roman times at Naga in the north-west of the Project area, within Wadi Awatabe in the foothills of the Sabaloka complex (Figure 5). Reviewing the evidence for the extent of the Sudd swamps, Mawson and Williams (1984) suggest that at the time of Nero's expedition the edge of the Sudd was 200 km north of its present day margin. They also find evidence of freshwater molluscs at Erkowit in the Red Sea Hills with dates in the range 1710-1900 BP and believe that this represents a small humid interlude within historic times which may have extended over similar latitudes in Sudan.

There is evidence not only of changes in overall humidity, but also in the climatic patterns and nature of rainfall in the tropical parts of north Africa during the Holocene. Sedimentological and other evidence (Maley, 1977; 1982) suggests that up until 7000 BP rivers deposited mainly silt but that after this time there was a major hydrological change with deposition mainly of sand. This change is linked, it is suggested, with a shift from fine rains to the predominance of thunderstorm rains, which is in turn linked to a transition from tropical depressions in the early Holocene to the mainly monsoon rains typical of the present. During the early Holocene, the Saharan anticyclone belt was shifted further to the north which allowed monsoon rains to migrate across the Sahara (Rognon, 1976). Ptolemy also records rare summer rains from the south suggesting that the Inter-Tropical Convergence Zone on occasion reached further north than it does today (Mawson and Williams, 1984). The strongly convective nature of these rains has been proposed by Edmunds and Wright (1979) to explain the enrichment in ^{18}O of some Holocene recharge in Libya.

4. REGIONAL HYDROGEOCHEMISTRY OF THE HAWAD BASIN

4.1 Overview.

The extent of the area studied is shown in Figures 1 and 6. Within this area water samples were collected from the following sources:

Rainfall from summer storms	}	RAINFALL INPUTS
River Nile Wadi Flood Waters (Wadi Hawad)	}	SURFACE WATERS
Deep Groundwaters Shallowgroundwaters	}	GROUNDWATERS

Deep groundwaters, generally found at depths of at least 50 m, are derived mainly from the Nubian sandstone aquifer by pumping, although several deep wells were also sampled by traditional methods using animal skins. Shallow groundwater refers to samples from shallow wells, again sampled mainly by traditional methods; in most cases, these wells have been excavated in alluvial or colluvial sediments, usually to depths of 5-30 m. They may not be in hydrological continuity with the underlying Nubian sandstone aquifer. Each group of waters is now discussed separately.

4.2 Rainfall.

4.2.1 Collection

Meteorological stations of the Sudanese Meteorological Department exist at Abu Delaig, Shendi and Khartoum. Long term rainfall records are available for Khartoum and Shendi, and records for Abu Delaig exist since 1938 (Table 1). Over the 29 year period 1938-1967 the mean annual rainfall was 224.8 whilst over

Table 1. Monthly Rainfall in mm. Station: ABU DELAIG

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
1971	x	x	x	x	TR	x	45.0	59.0	16.0	x	x	x	120.0
1972	x	x	x	TR	11.0	TR	28.0	134.0	3.0	x	x	x	176.0
1973	x	x	x	x	10.0	TR	69.0	20.0	29.0	7.0	x	x	135.0
1974	x	x	x	x	1.0	59.0	97.0	99.0	TR	x	x	x	256.0
1975	x	x	x	x	TR	x	1.0	190.0	37.0	x	x	x	228.0
1976	x	x	x	TR	TR	TR	34.0	TR	67.0	3.0	x	x	104.0
1977	x	x	x	x	27.0	1.0	55.0	88.0	TR	4.0	x	x	175.0
1978	x	x	x	x	x	TR	45.0	85.0	68.0	TR	x	x	198.0
1979	x	x	x	1.0	TR	91.0	60.0	63.0	40.0	TR	x	x	255.0
1980	x	x	x	x	10.0	38.0	53.0	8.0	x	3.0	x	x	112.0
1981	x	x	x	TR	1.0	15.0	TR	0.1	24.0	TR	x	x	40.1
1982	x	x	x	x	2.0	x	TR	23.0	92.0	75.0	x	x	192.0
1983	x	x	x	x	x	1.8	3.5	9.2	0.9	x	x	x	15.5
1984	x	x	x	x	x	x	3.0	x	9.4	2.0			14.4
1985	Not Available												118.0

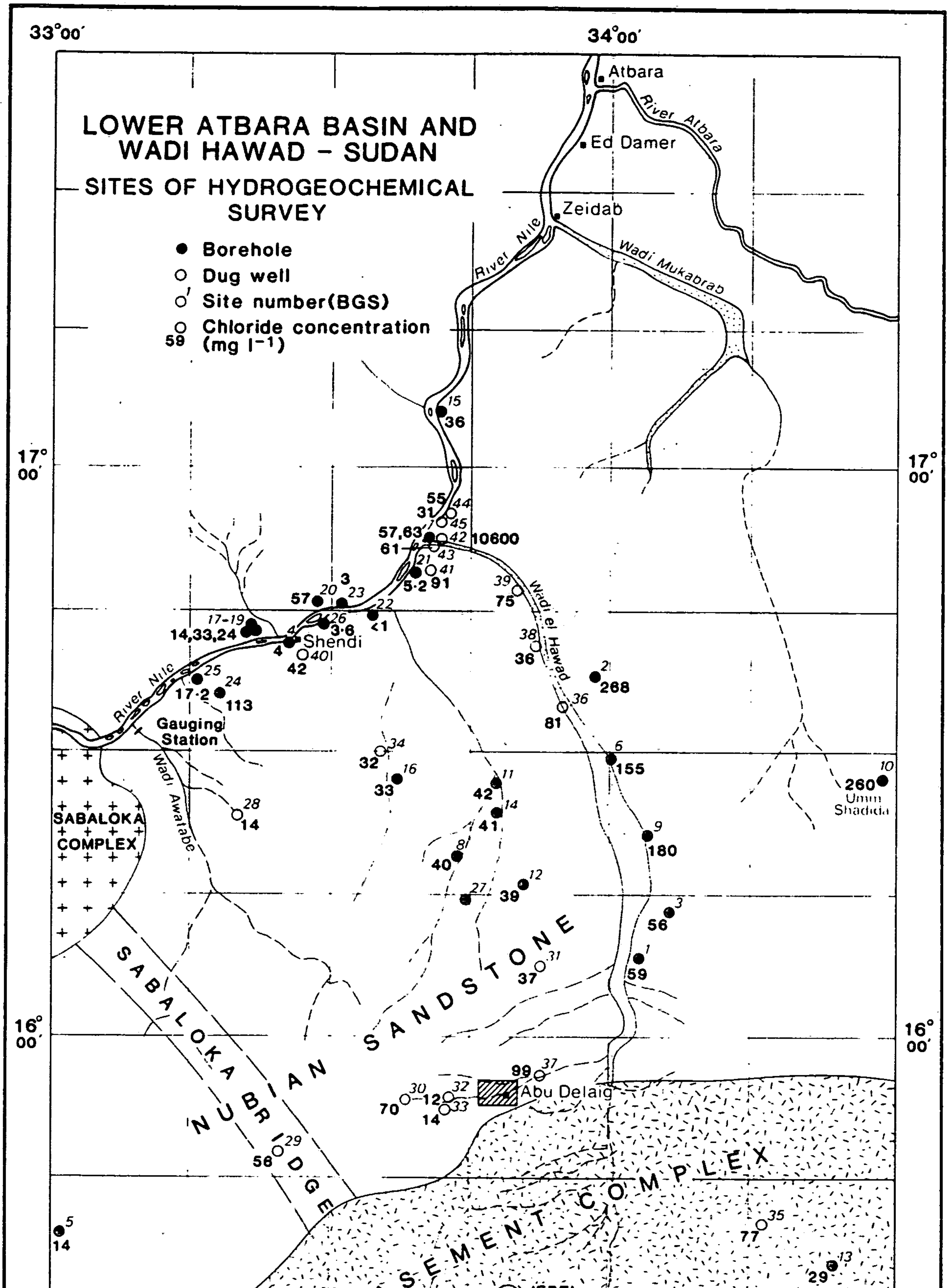


Figure 6. The Wadi el Hawad Basin, the Nile Valley and location map of samples taken for hydrochemical survey with chloride concentration.

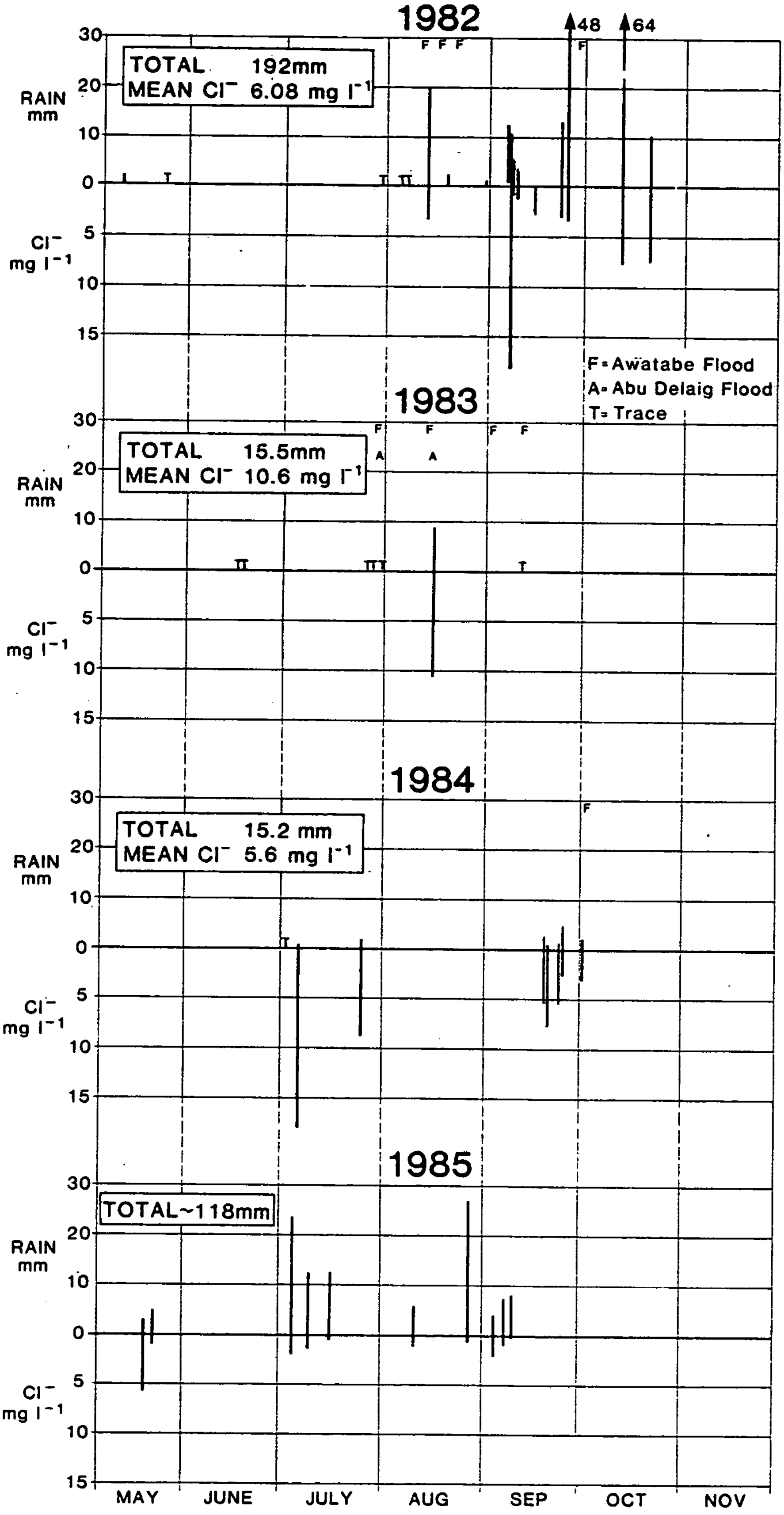


Figure 7. Rainfall distribution at Abu Delaig (1982-1985) and chloride concentrations of rain.

the 14-year period (1971-1985) the mean annual rainfall was 154.3 mm. A full climatological station was established at Abu Delaig for the duration of the project and a separate report by ACSAD describes the meteorological conditions during this interval. Samples of rainfall were collected by Sudanese staff at Abu Delaig field station during the period 1982-85. These were subsequently analysed chemically. The results are described in the present report.

The period 1981-85 was an exceptionally dry period and corresponded with a widespread period of Sahelian drought. Total rainfall in each of the years 1981-85 was, respectively, 40.1, 192, 15.5, 15.2 and 118 mm (Figure 7). During periods of rainfall, rainfall was collected daily by local people from Abu Delaig and stored in clean polyethylene bottles. Samples represent total deposition and the bulked samples all contained atmospheric dust (dry deposition) to a varying extent. At the end of each season, all samples were shipped by air to UK for analysis of major ions and stable isotopes ($\delta^{18}O$, δD). The rainfall data are of special relevance to the present study (a) in their own right because of the virtual absence of rainfall chemistry information from this region; (b) as an input to the geochemical mass balance studies of the regional groundwaters; and (c) as the essential input to the recharge estimation study.

4.2.2 Rainfall chemistry and stable isotope composition

The chemical and isotopic analyses of rainfall carried out during the period 1982-85 are presented in Table 2 (see Appendix). The principal data set comes from Abu Delaig with a few scattered rainfall samples from Omdurman, Khartoum, Shendi and Awatabe. The Khartoum samples are generally high in solutes and probably indicate contamination (either evaporation after collection, or perhaps more likely, the dry deposition of dust on the collecting funnel before the rain). From the isotopic data, evaporation is suspected for two of the samples, 83/882 and 83/883. These data will not be used further in the discussion.

The most significant feature of the rain chemistry is the relatively high total mineralisation for a continental site (Abu Delaig is about 700 km from theRed Sea and over 2000 km from the Indian Ocean. Rainfall at Abu Delaig has chloride concentrations in the range 0.9-18.4 mg l^{-1} (Figure 7) with a weighted mean value of 7.4 mg l^{-1} over the three year period 1982-84. In general, the lightest rains (i.e. the smallest storms) have the highest chlorinity and there is a tendency for the chloride to decrease with time during a rainy period (e.g. 6-10 September 1982). Atmospheric dust therefore may be a major source of chloride in the total rainfall.

It is considered that the rainfall analyses closely reflect the total annual deposition for most parts of the area. There is considerable cycling of dust throughout much of the dry season although this is thought to be a close-to steady-state process with little or no net deposition in the very open landscape of the Wadi Hawad basin. Much of this dust, it is thought, will be in transit over large distances. During rain storms, however, the situation is different and rainout of soluble and insoluble material takes place and thus has the opportunity for recharging the soil.

Sulphate is often the dominant anion in the rainfall (Table 2) indicating that gypsum is also a component of the dust. Most of the heavier rains (shown by larger symbols) have compositions relatively high in Na and with higher Mg/Ca ratios (Figure 8), the latter demonstrating that gypsum contributes more to the chemistry of the lighter rains. The chemistry of the heavier rains is more important in determining the character of runoff and recharge; the volume weighted mean composition is also plotted in this diagram.

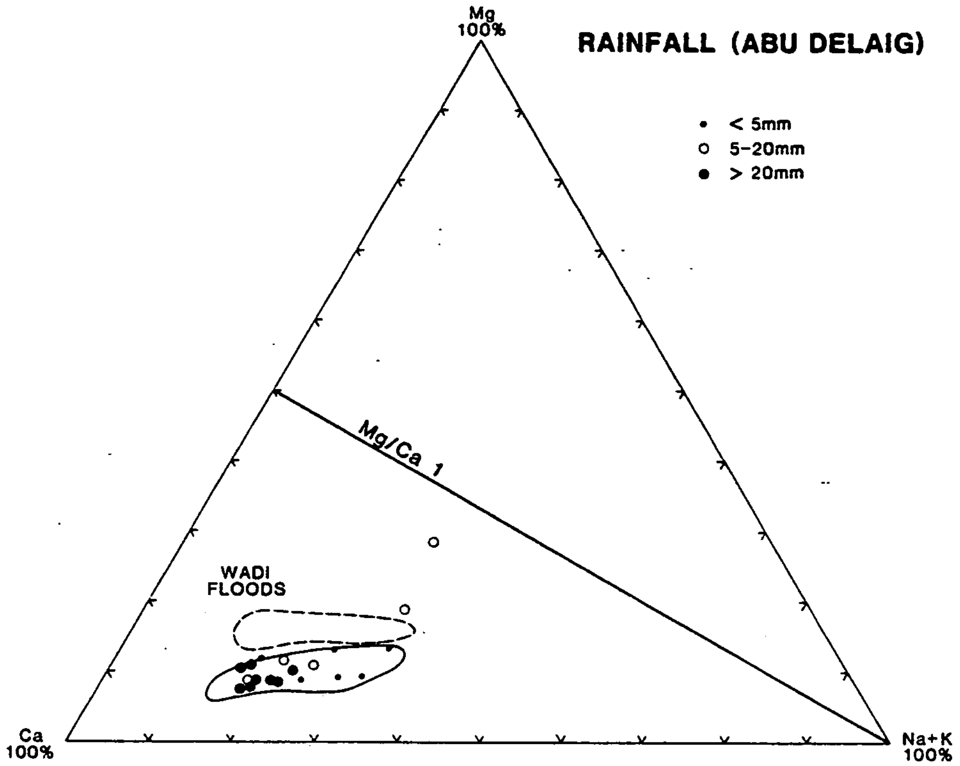


Figure 8. Cation composition of rainfall at Abu Delaig (1982-1985) classified according to rainfall intensity.

Stable isotopic data are available for rain collected during the period 1982-85 and these data are plotted in Figure 9, relative to the world meteoric line and the regression line for Khartoum rainfall (9 years between 1962-1977). Distinction is made between rain storms of different intensity and it can be seen that the heaviest rainfall usually has the lightest isotopic composition.

There is no correlation between ^{2}H and Cl which suggests that there is no evaporative control on Cl concentrations (Figure 10).

4.3 River Nile and Wadi Flood Chemistry.

The River Nile at Shendi was sampled at intervals between April 1982 and July 1984. The chemical and isotopic results are listed in Table 3. At Shendi the Nile is the combined flow of the White and Blue Niles. The flow of the White Nile remains fairly constant throughout the year during its flow from Lake Victoria and Lake Mobutu; the Sobat river adds a little summer rain to it from Ethiopia. The Blue Nile floods during summer and its effect on the White Nile baseflow below Khartoum (Tamaniat) is shown in Figure 11a, this data being the average hydrograph over the period 1912-1973 (Shahin, 1985); no data were available for the years in the study period.

The total mineralisation of the White Nile baseflow, as indicated by its specific electrical conductance in April 1982 is higher than that of the Blue Nile (Table 3). The composition of the flood waters is not entirely clear from the data. It seems likely that the main flood peak is more mineralised than the later flow; this probably reflects the washing out of accumulated salts with the early floods. The Blue Nile has a Ca-rich composition and during the recession in September and October a change is seen to the Na-rich water of the White Nile, with a higher Mg/Ca ratio (Figure 11b).

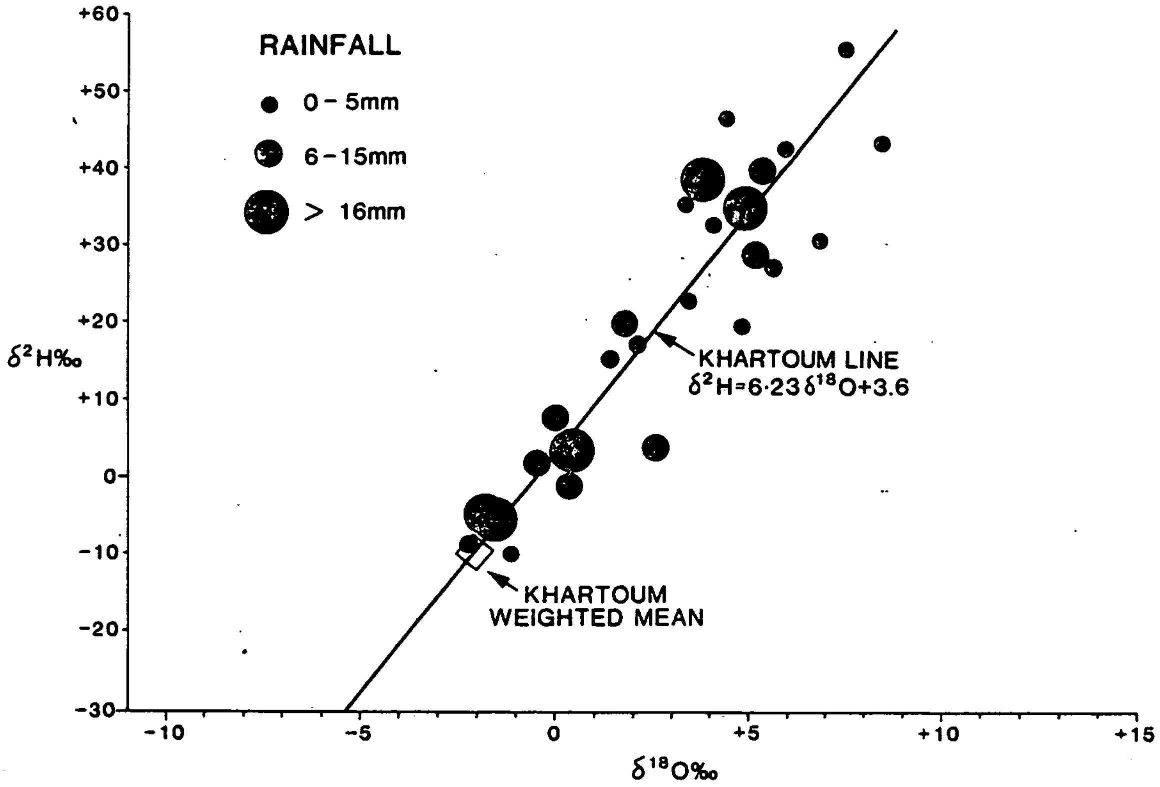


Figure 9. Isotopic composition of Abu Delaig rainfall (1982-1985) classified according to rainfall intensity.

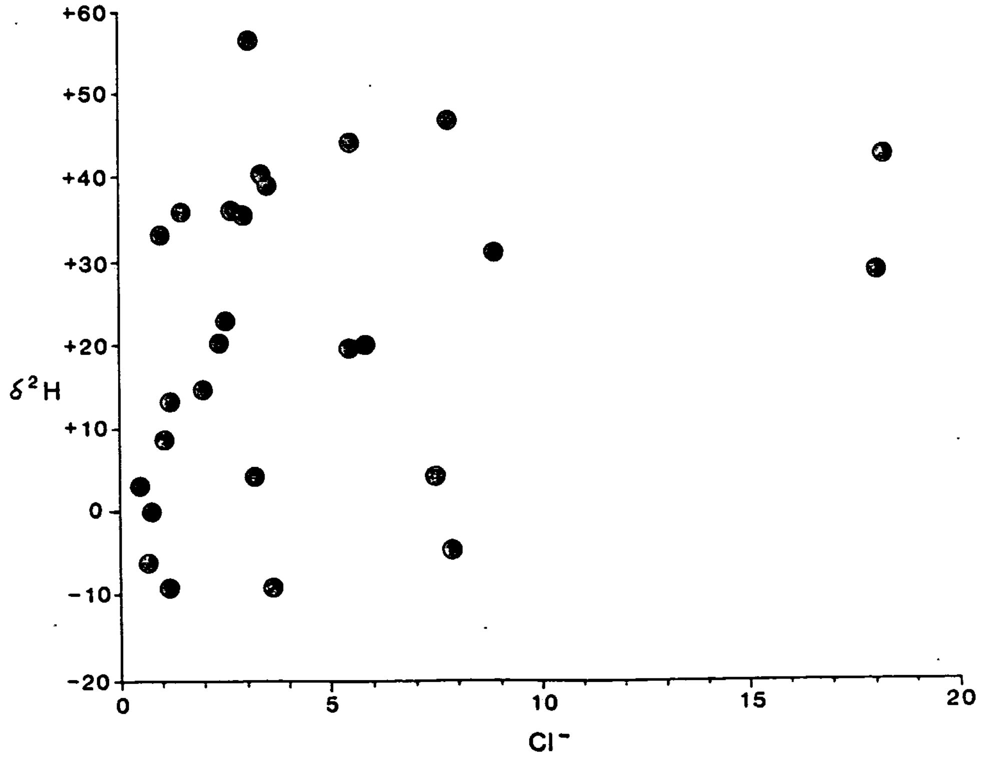


Figure 10. Plot of δ^2H vs Cl for Abu Delaig rains.

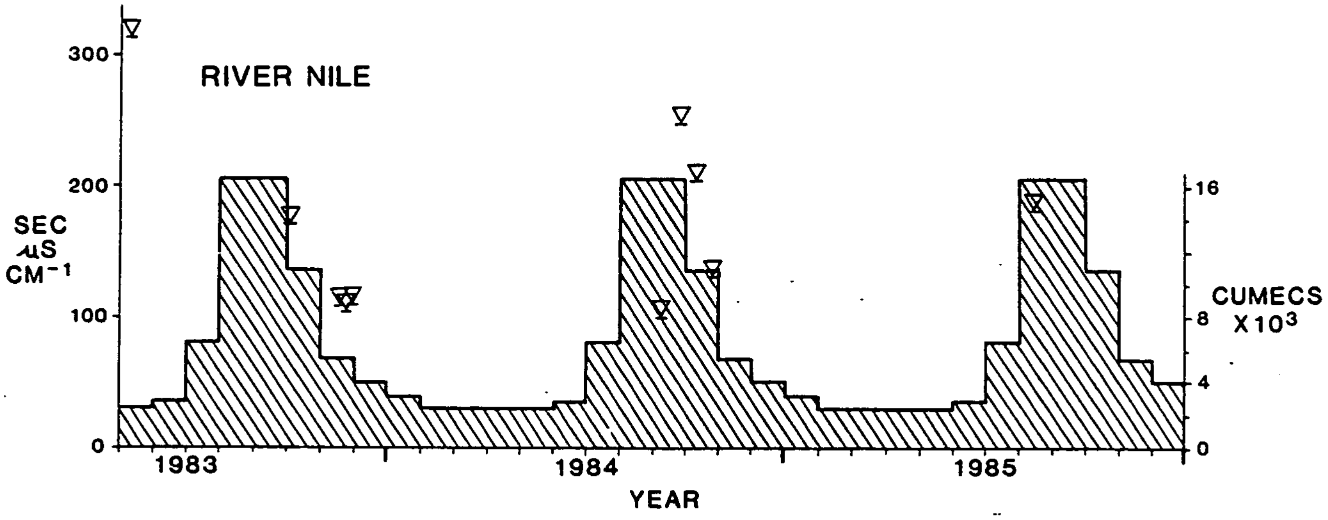


Figure 11a. Hydrograph of the River Nile (1983-1985) and specific electrical conductance (SEC) of river samples.

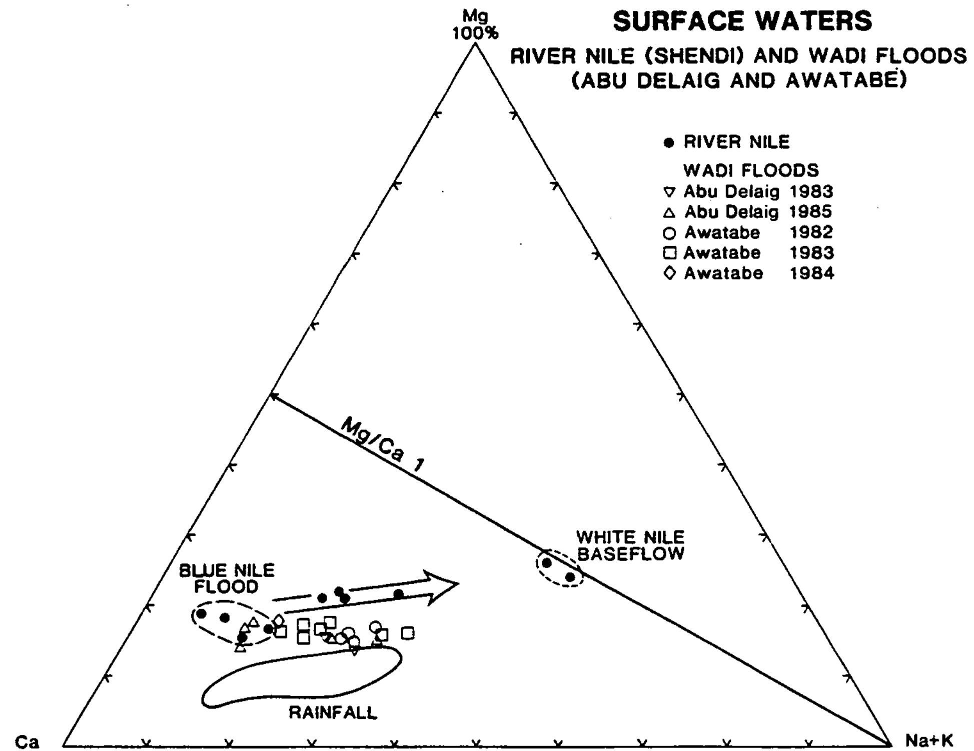


Figure 11b. Cation composition of the River Nile and other surface waters in the Wadi el Hawad Basin. Rainfall envelope shown for comparison.

The seasonal changes in the River Nile are also evident in its stable isotopic composition (Figure 12). The White Nile has a much heavier composition up to +5.4 $^0/oo$ $\delta^{18}O$, compared with the flood waters of the Blue Nile which have minimum values of about -5.7 $^0/oo$ $\delta^{18}O$. The composition of the White Nile reflects evaporation during its flow northwards but both Niles are derived from rains which have a different meteoric line (deuterium enriched) compared with local rains (Figure 12). The meteoric line for Addis Ababa is given for reference.

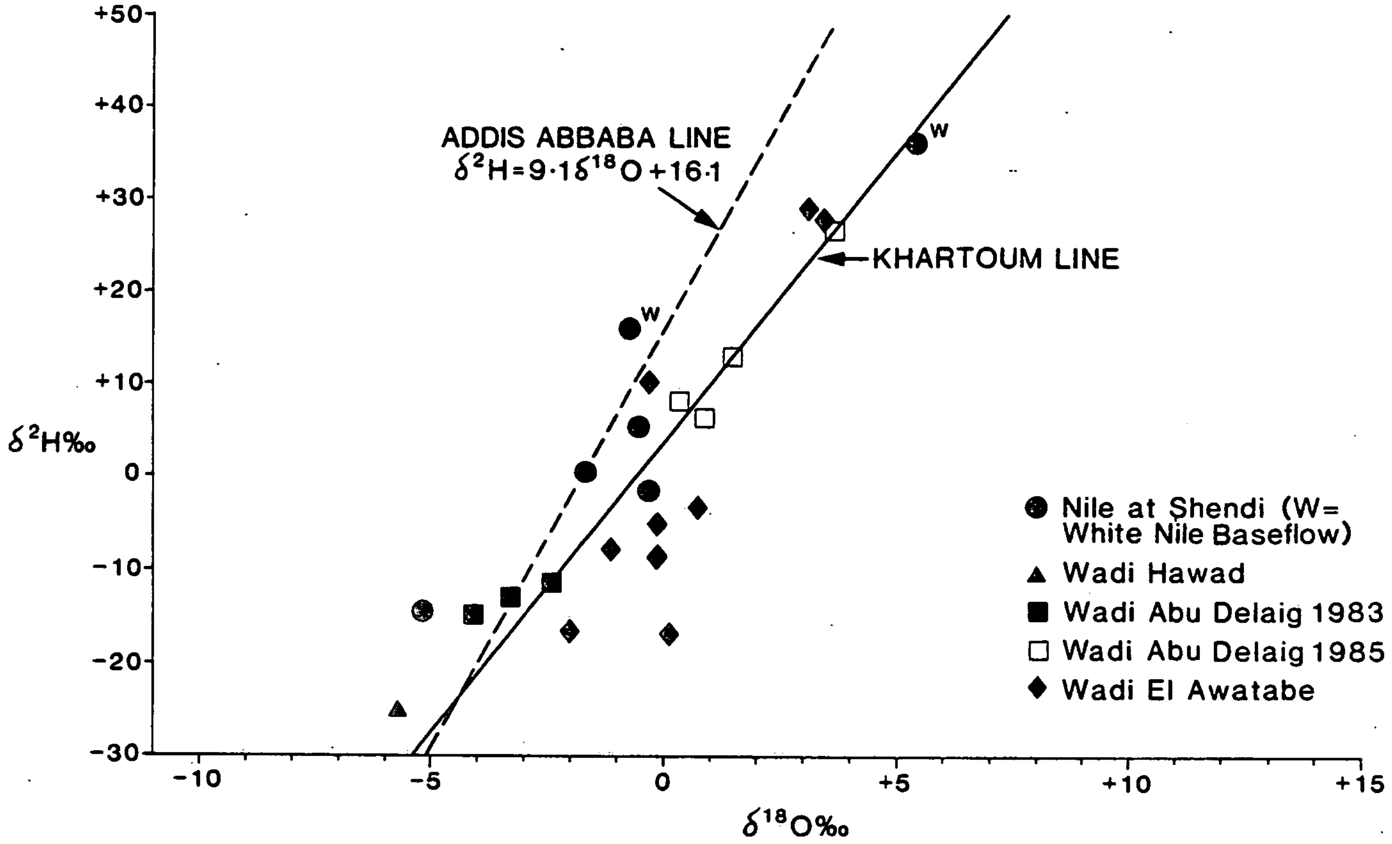


Figure 12. Isotopic composition ($\delta^{18}O$ vs δD of the River Nile and related surface waters.

The tributaries of the Nile in Sudan, with the exception of the Atbara river (for which no data were obtained), are dry except for a few days of flash flood each year. Flows generated by storms in one area may often dissipate by evaporation and recharge over short distances. It is extremely rare for a continuous flow of the Wadi Hawad to be recorded along its whole length. Obtaining samples of the flood requires being in the right place at the right time and this has not been possible for most of the project. Overland travel is particularly difficult during periods of flash flooding. However, flood samples were obtained by NAW staff at two places: (1) Wadi Awatabe in the north-west of the area at the gauging station near the road bridge close to the confluence of the wadi with the Nile, and (2) at Abu Delaig. Samples were obtained from the Awatabe in 1983/84 and at Abu Delaig (Wadi Jugjugi) in 1982/84-85. Wadi flow was more frequent on the Awatabe in both seasons, despite its more northerly position. This probably reflects the influence of the more hilly catchment region of the Sabaloka Hills.

Chloride concentrations in the wadi flows are similar to or slightly lower than the weighted mean rainfall values. The reason for these lower values is not entirely clear but it is well within the uncertainty of the measurements. Possibly the dust content is not uniform over the whole area. Isotope evidence suggests that no significant evaporation of rainfall has occurred.

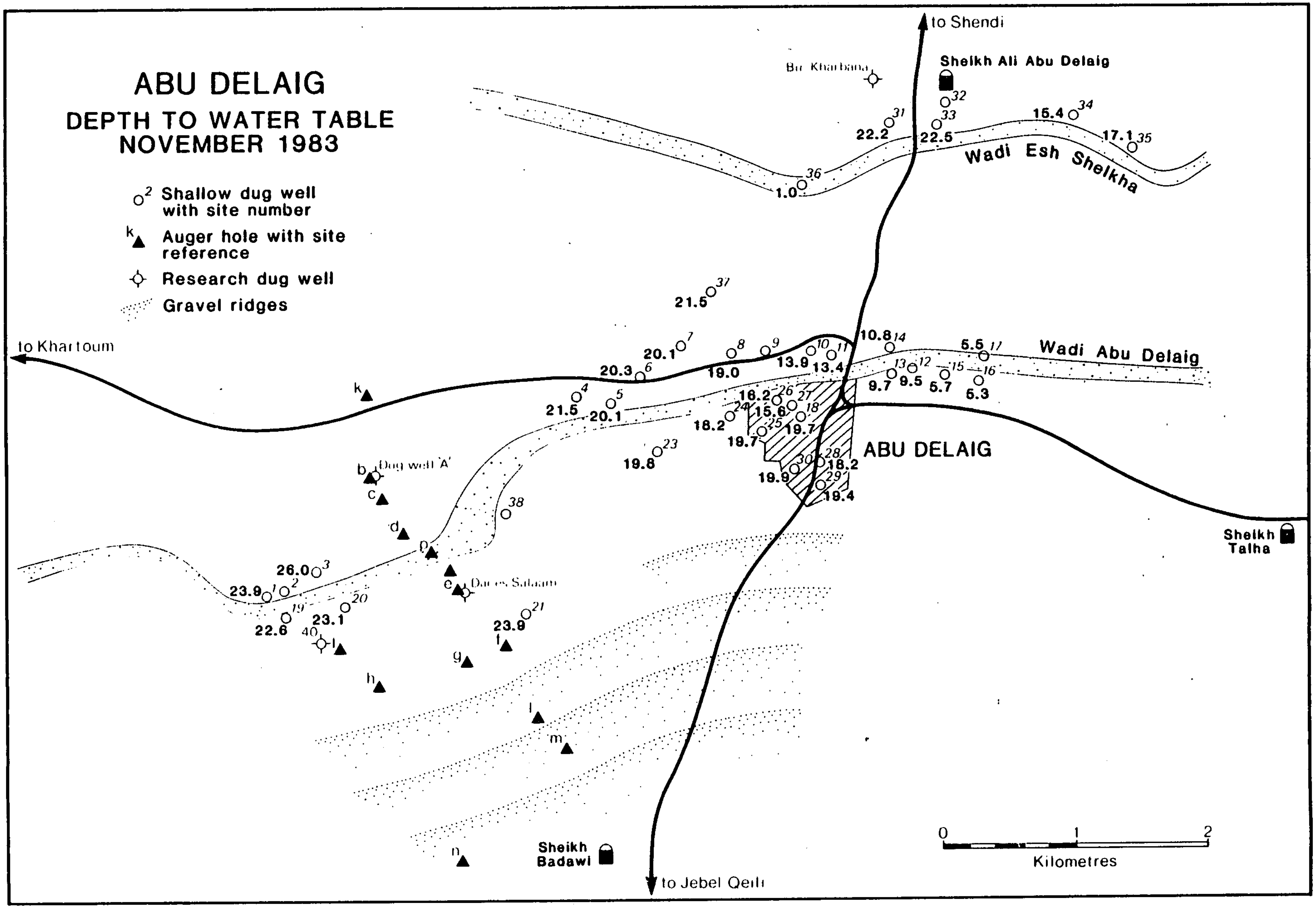


Figure 13. Abu Delaig and surrounding area showing sample locations - village dug wells, new dug wells constructed during the project, auger hole sites and depth to the water table (November 1982) in metres.

The chemical composition of the flood waters is rather similar to that of rainfall (Figure 11) although a slightly higher Mg/Ca and higher SO_4 ratio may indicate some reaction with the soil or rock in the case of Wadi Awatabe but not Wadi Abu Delaig.

4.4 Shallow Groundwater System at Abu Delaig.

All of the 36 shallow dug wells in the vicinity of Abu Delaig were sampled for chemical and isotopic analysis. The location of these wells is shown in Figure 13 with their depths to the water table. Levelling was carried out during the project and a water level map prepared by NAW. The location of "research" dug wells and auger holes made for the recharge studies are also shown in relation to the position of the existing dug wells.

Topographically, Abu Delaig is situated on gently rising ground to the south of a major wadi, Wadi Abu Delaig; a second wadi, Wadi Shelkha occurs a little north of the town. Behind the town, and to the south west in particular, gravel ridges extend ENE-WSW forming a surface expression of the basal coarse-grained facies of the Nubian sandstone. The basement outcrop is only a few km south of the village. Fragments of green (unweathered) foliated basement rocks were recovered from a dug well (now dry) about 500 m east of site 'm' at a depth of about 30 m. Village dug wells have been sited mainly on the interfluves or occasionally within the course of the two wadis. The wadis generally contain coarse sand deposits and the wadi bed is topographically between two and five metres below the interfluves.

The wells are open and typically 2 m in diameter and depth to the water table varied from 5 to 26 m (November) decreasing from west to east in the direction of wadi flow. Most water was drawn by hand or animals (sites 1, 2) except for site 14 which had a submersible pump and shelter and which was used for the local hospital.

Tritium was measured on 10 samples in the Abu Delaig area (Table 4). All waters contained significant tritium in the range 24-73 TU. This indicates that recent (post 1950's) rainfall must be recharging the aquifer to a distance of at least 1 km from the wadi both to the north and the south (Figure 14).

The oxygen stable isotope relationship between the shallow wells can be seen in Figure 15. They all group near to the meteoric line for Sudan and show no evidence of evaporation when compared to local rainfall. The small variations observed between some local wells (Figure 16) can probably be attributed to recharge from different storms and/or small evaporation effects; the greatest evaporation is found in a sample taken from the wadi (AD 36). Many well waters are in fact slightly lighter isotopically than any of the rainfall measured and it is possible that representative rains were not sampled because of the unusually dry period of years.

Despite the lack of significant evaporation indicated by the stable isotope data, the salinity of the dug well samples is much higher than in rainfall with SEC between 300-1700 μScm^{-1}. The distribution of chloride and sulphate (Figures 17 and 18) indicates that higher values generally occur further from the wadis. SO_4/Cl ratios are generally in excess of 2.75 in the shallow groundwaters, compared with around 1 in the rainfall, indicating the net addition of sulphate to the groundwater subsequent to recharge (Figure 19).

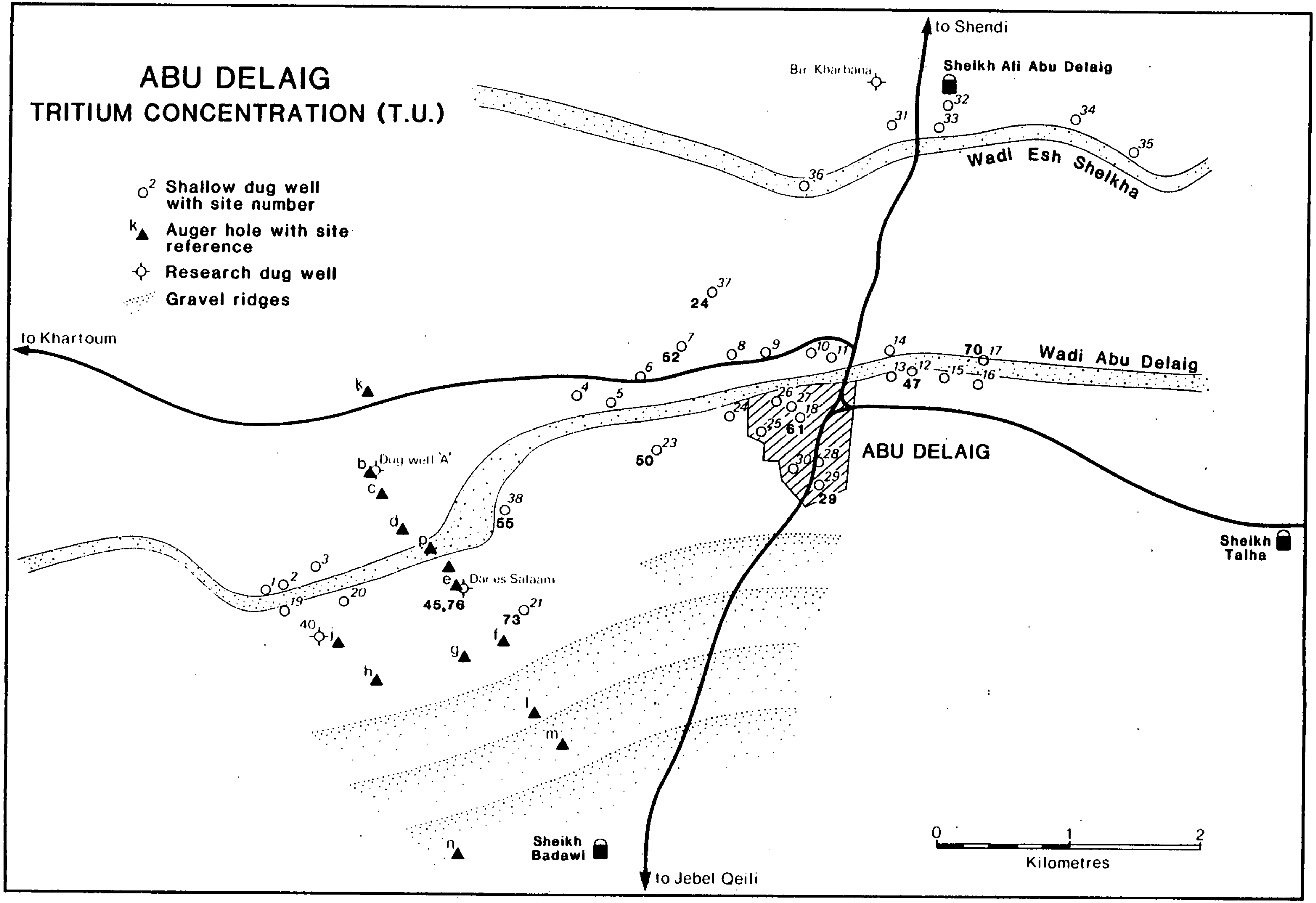


Figure 14. Tritium values (in T.U.) of shallow groundwaters (1 TU = 1 in 10 atoms of hydrogen.

Table 4. Tritium concentrations in shallow and deep groundwaters at Abu Delaig (AD) and Wadi Hawad area.

BGS Reference No.	Site No.	Tritium (T.U)
82/437	3	9±2
82/440	6	4±2
82/441	AD (Dar es Salaam)	76±3 (6.4.82)
82/443	7	26±2
82/643	AD (Dar es Salaam)	45±3 (6.7.82)
83/502	AD 23	50
83/501	AD 21	73
83/516	AD 38	55
83/488	AD 7	52
83/515	AD 37	24
83/492	AD 12	47
83/508	AD 29	29
83/498	AD 18	61
83/491	AD 17	70

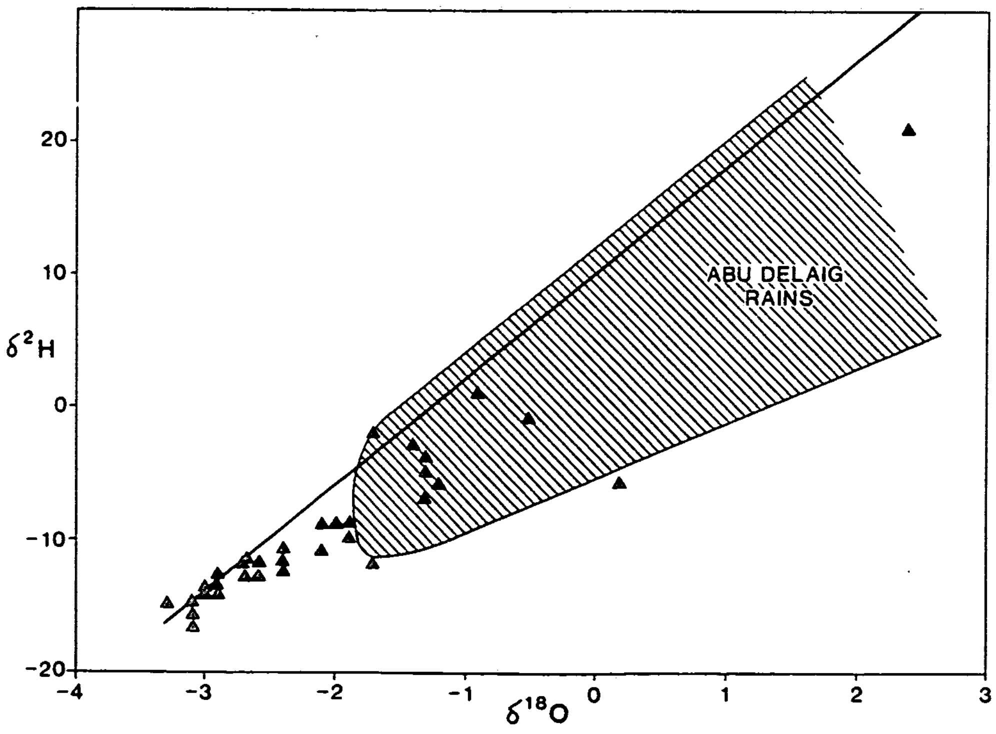


Figure 15. Oxygen ($\delta^{18}O$) and hydrogen (δ^2H) stable isotope ratios in shallow groundwaters at Abu Delaig, in relation to the range of composition of rain (see also Figure 9).

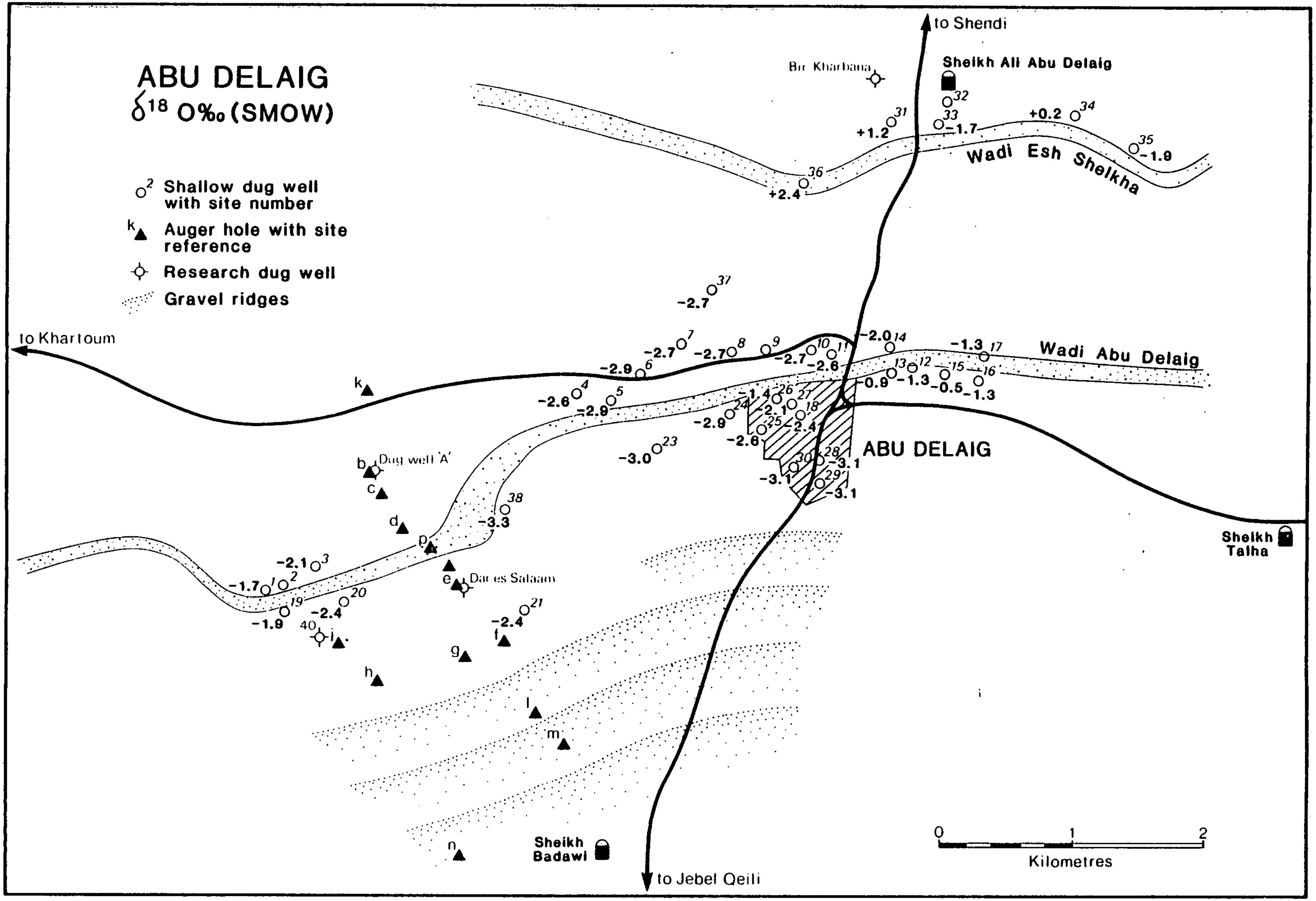


Figure 16. Oxygen isotope ($\delta^{18}O$) ratios for shallow groundwaters in the Abu Delaig area.

Figure 17. Distribution of chloride in shallow groundwaters at Abu Delaig.

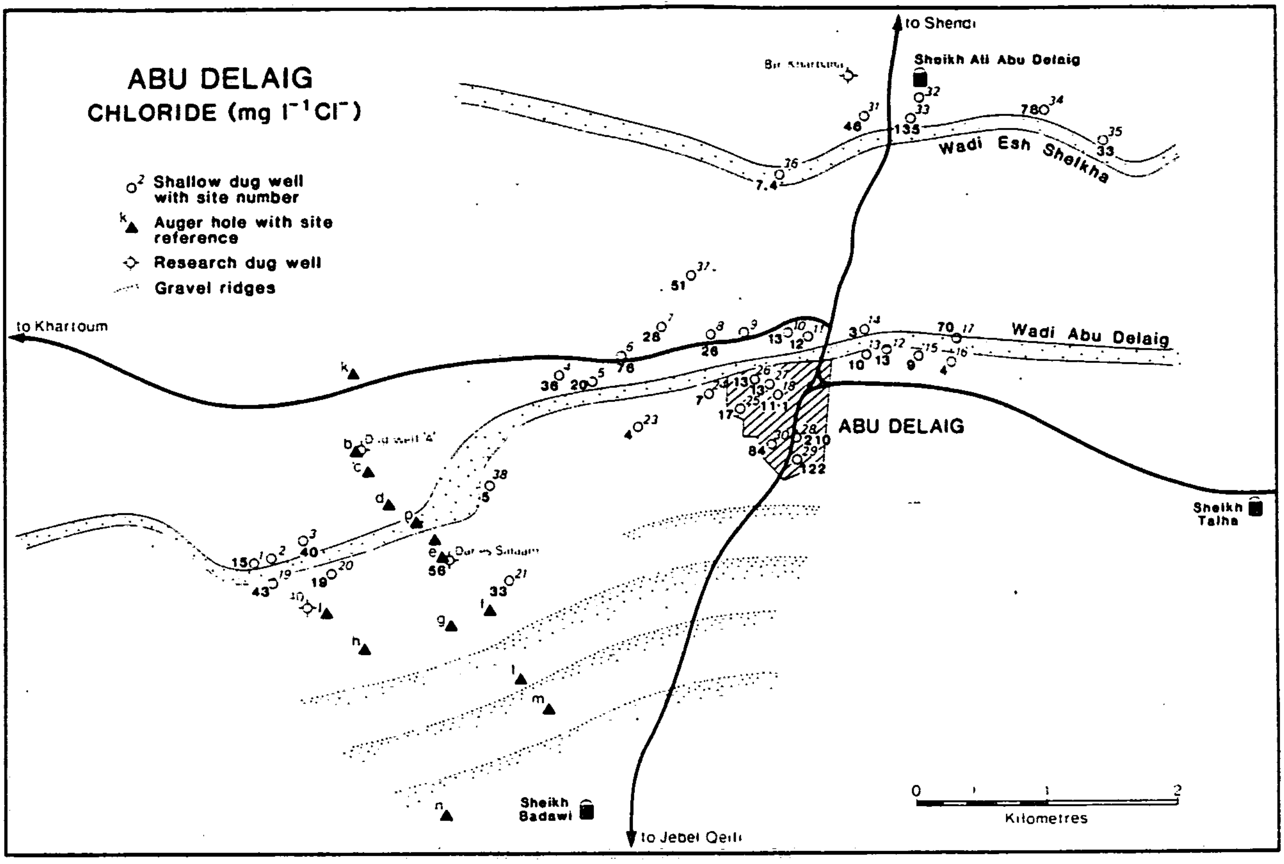
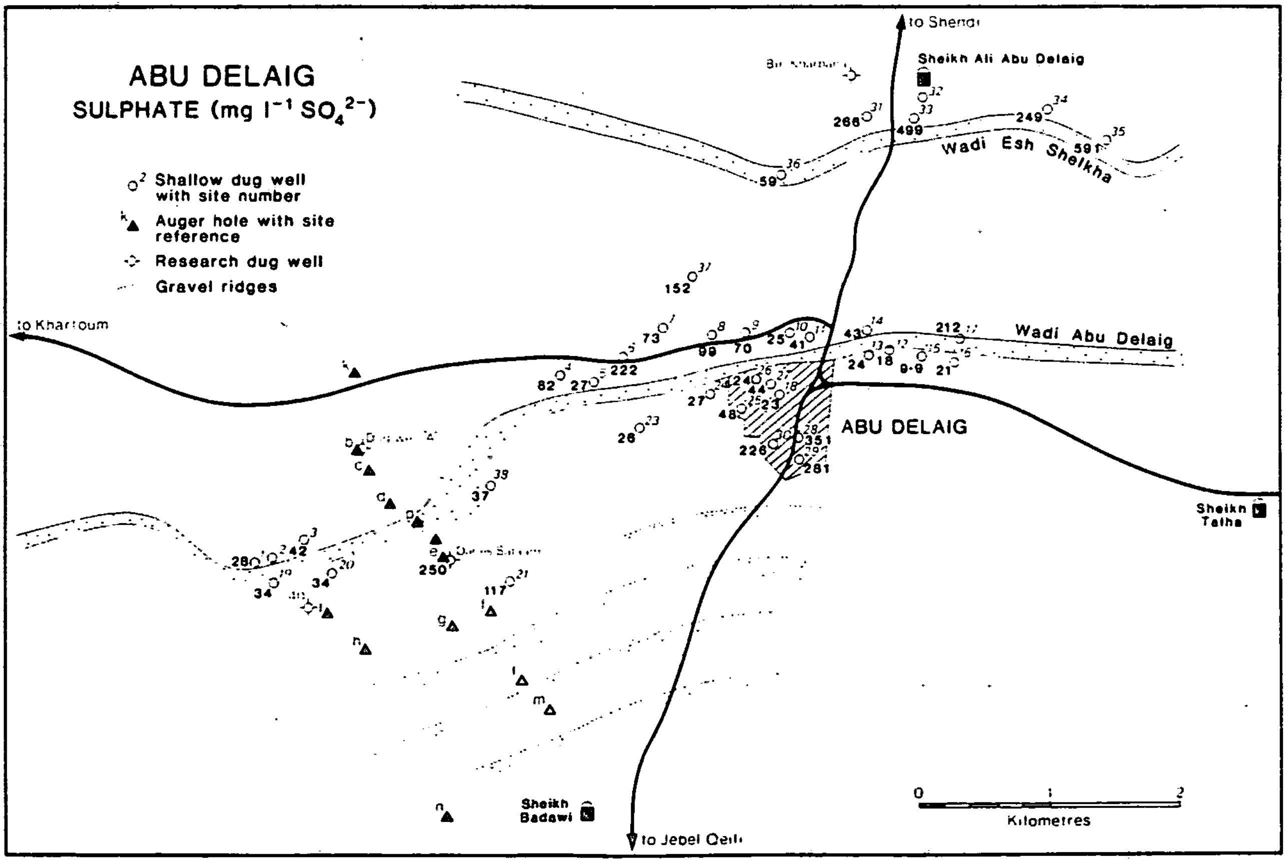


Figure 18. Distribution of sulphate in shallow groundwaters at Abu Delaig.



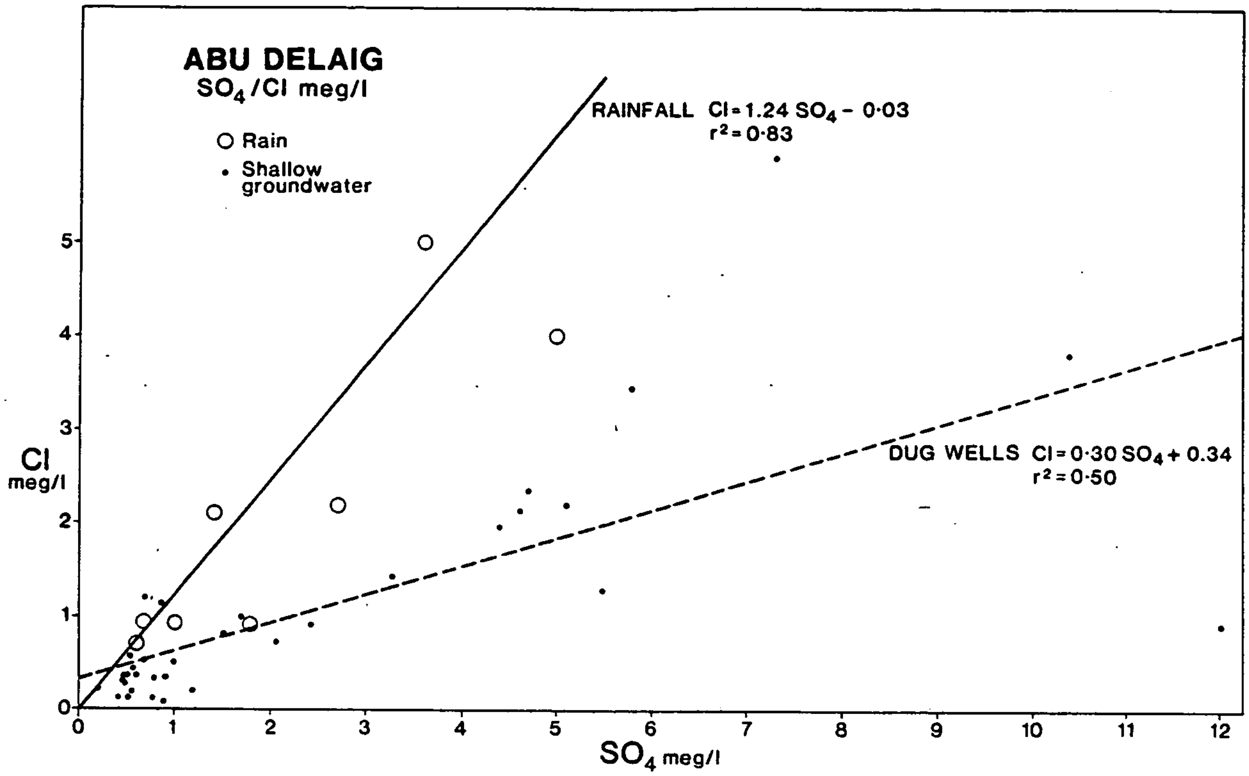


Figure 19. SO_4/Cl (milliequivalent/litre) distribution in rainfall and shallow groundwaters from Abu Delaig.

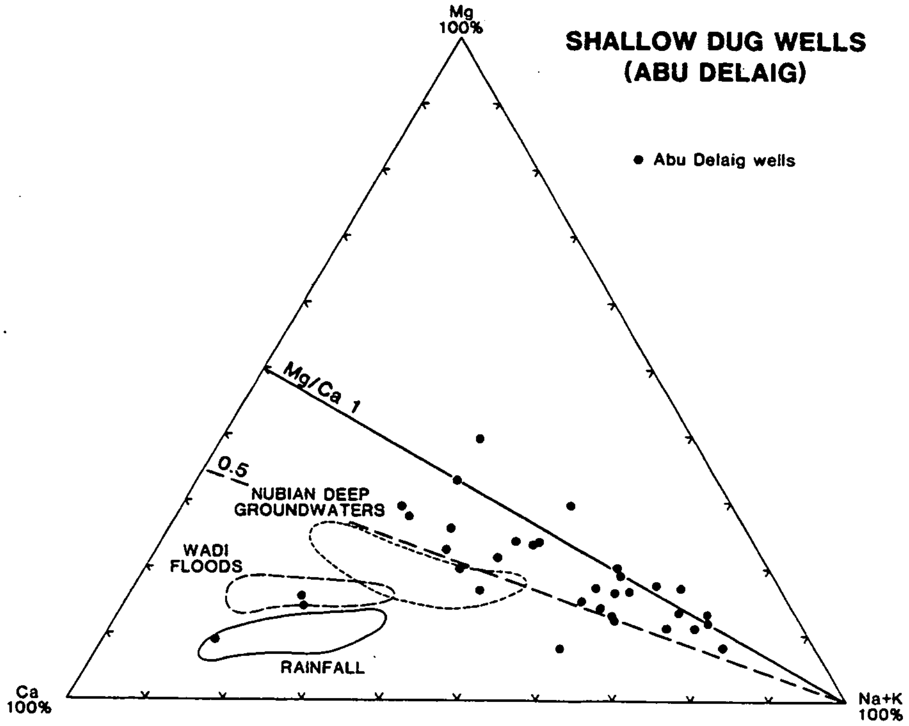


Figure 20. Trilinear plot of cations (Ca, Mg, Na+K) in shallow groundwaters from Abu Delaig.

The cation distribution is highly variable in the water from the shallow wells compared, for example, with water from the deeper Nubian aquifer described below. Although the ionic ratio of the rainfall is preserved in three wells close to the wadi, the trend is for an increase in the Mg and Na relative to Ca so that most of the wells contain Mg/Ca ratios near to 1 and with sodium the dominant cation (Figure 20). Calculations using WATEQF show that all the Abu Delaig groundwaters are saturated or slightly supersaturated with respect to calcite and indicate that carbonates must be present in the lithology and reacting with the groundwater over a relatively short period of time.

The evolution of the shallow waters and the chloride balance of the area will be discussed in more detail in the light of the results obtained from soil moisture profiles.

4.5 Deep Groundwater System (Nubian Sandstone Aquifer).

4.5.1 The deep well system

Groundwater is exploited from boreholes in the Nubian sandstone aquifer at the localities shown in Figure 6. Groundwater is developed using submersible or reciprocating pumps. With this group may also be considered six deep (up to 100 m) dug wells. These are ancient wells which may date in some cases from Meroitic times and which have been deepened during the Roman and Christian civilisations and up to the present day. They are up to 4 m in diameter and are constructed with a system of wooden pulleys made from acacia branches; water is drawn by traditional methods using animal skins raised by camel or donkey. Several deep wells have become redundant as new boreholes have been drilled alongside (e.g. Bir el Geheid). In the Nile valley the water table in the Nubian Sandstone is relatively shallow but declines to the north and south away from the river. The piezometric data for the Nubian aquifer is described in the report by ACSAD. The virtual absence of topographic data for the Nubian wells limits interpretation of regional groundwater flow.

4.5.2 Major element chemistry

The major element chemistry of the Nubian groundwaters well away from the Nile is relatively uniform (Table 6, Figures 21a and 21b). The wells to the west of Wadi Hawad are more uniform in their chemistry relative to those to the east. All groundwaters have rather constant Mg/Ca ratios of 0.5-0.3 and the only significant difference in their cation composition is the variable Na/(Ca + Mg) ratio which indicates a variable salinity. The borehole at Tomeid haj el Tair is relatively high in SO_4^{2-}. Umm Shadida also has an anomalous composition being of relatively high salinity and with high sulphate and Mg/Ca. Several samples have high nitrate concentrations which may indicate some local pollution (e.g. Umm Ruweshied in the basement) especially when accompanied by high K^+ concentrations.

It is concluded therefore that the main Nubian aquifer west of Wadi Hawad is homogeneous and likely to be hydraulically continuous, but to the east the relationship to the main aquifer is not clear.

Groundwaters from the Nile valley have a chemistry quite distinct from that of the Nubian aquifer away from the river and do not appear to be genetically related. The main difference is the higher Mg/Cl ratio (0.5-1.0), the higher K/Na ratio and the absence of nitrate in many samples (Table 6). The overall chemistry of the Nile groundwaters is very similar to the river water and lies

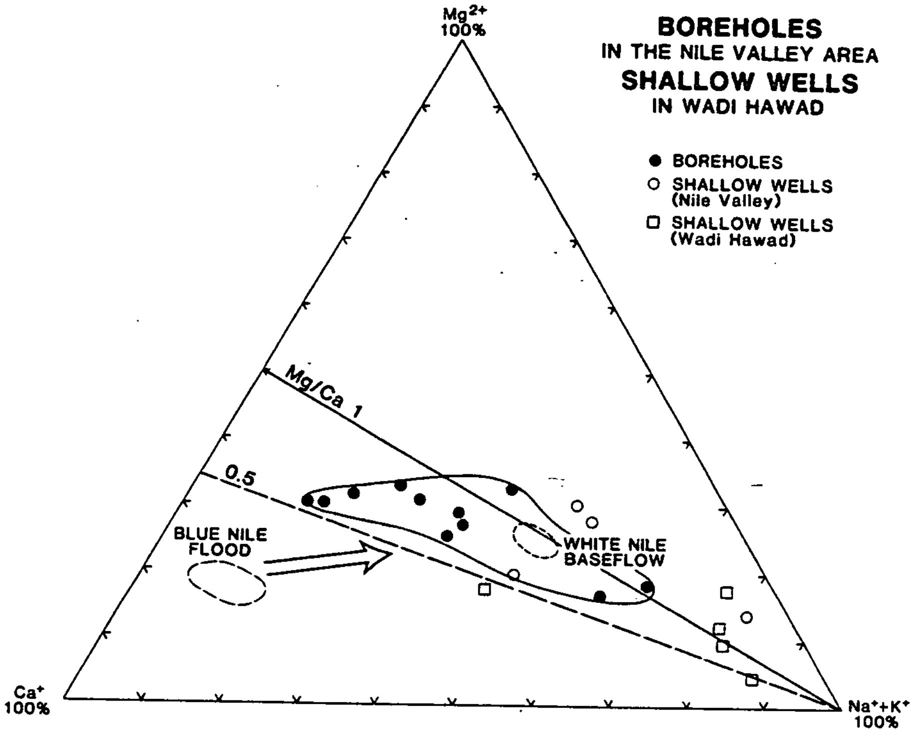
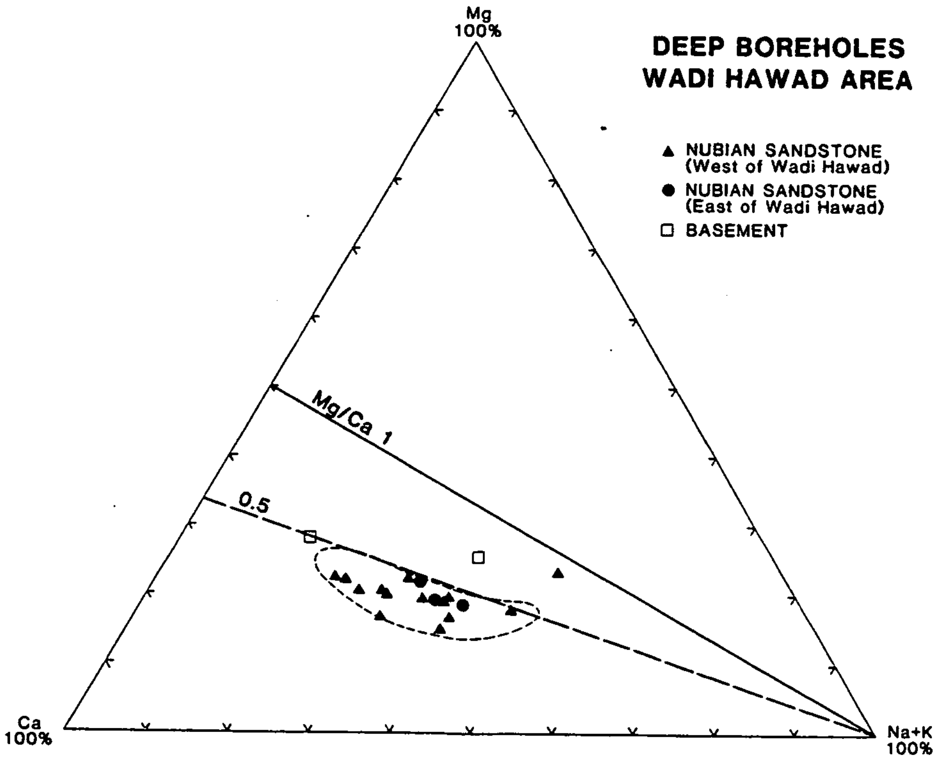


Figure 21. Trilinear plots of (a) groundwater from the regional (Nubian) aquifer plus two samples from the crystalline basement aquifer; (b) groundwater from the Nile Valley boreholes relative to the River Nile and local shallow boreholes.



closer to the baseflow chemistry of the White Nile; the river serves as an excellent tracer of the movement of recharge. The low nitrate concentrations found in the river are also preserved in the groundwater chemistry. There are certain anomalies in the Nile valley groundwaters, notably at Kaboushir (Table 6) where there is high sulphate, also seen in shallow groundwaters (see below). There are insufficient samples away from the Nile to be able to delineate the progress of Nile recharge. On the evidence of Abu Domat (Table 5) it seems likely that this distance is at least 8 km.

4.5.3 Stable isotope chemistry

The distinction between groundwaters in the regional Nubian aquifer and the Nile valley is shown very clearly by their oxygen and hydrogen stable isotope composition. The Nile valley samples all group near the Nile regression line with a cluster of sites near to $\delta^{18}O = -1.5$ ‰, $\delta^{2}H = -3$ ‰ (Figure 22). This value is intermediate between White Nile baseflow and typical flood water compositions and so suggests a contribution of water from both sources.

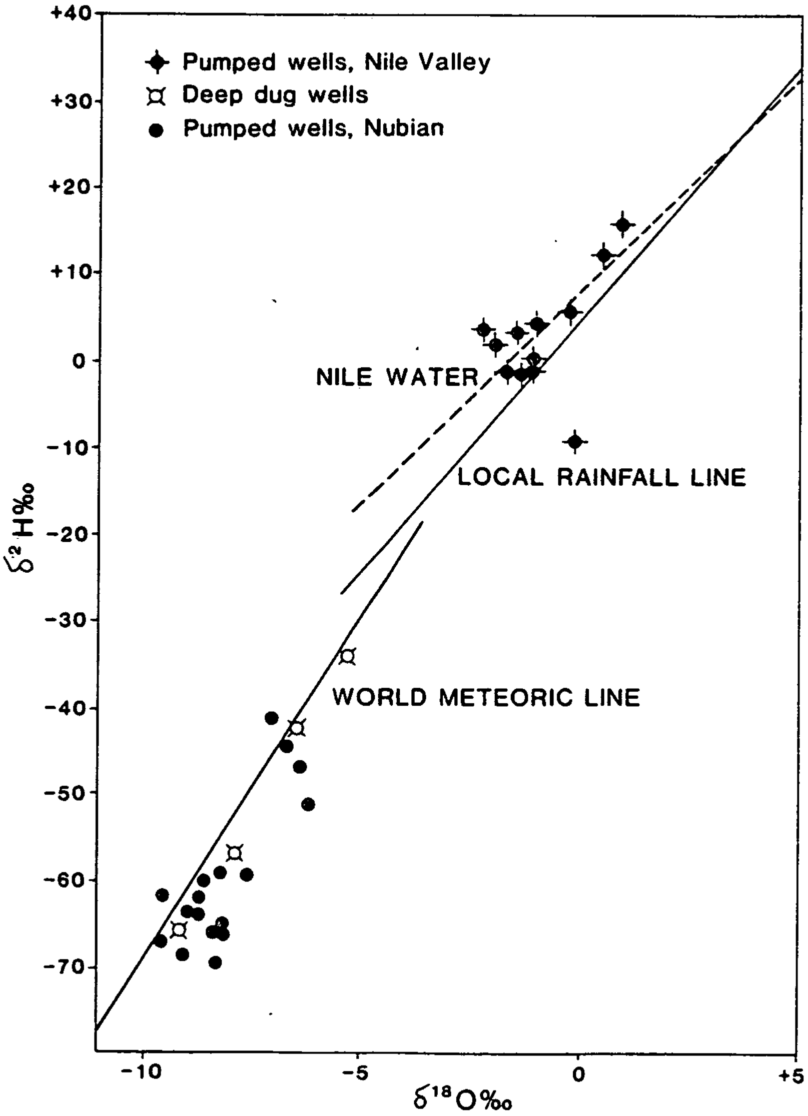


Figure 22. $\delta^{18}O$ vs $\delta^{2}H$ relationship in the Nubian and Nile Valley groundwaters.

The regional aquifer south of the Nile has a much lighter and distinct isotopic composition. Many of the pumped wells cluster around -8.5 ‰ $\delta^{18}O$, -63 ‰ $\delta^{2}H$. In addition the deep dug wells of El Geheid and Bir Ben Nagar also fall in this field. These compositions are quite distinct from present day rainfall and shallow wells (see below), as well as from the Nile, and must represent recharge from an earlier climatic regime. This is discussed in more detail below. The results do however point to homogeneity of the aquifer in the main Wadi Hawad basin and suggest that there is little or no connection with the overlying shallow groundwater.

Exceptions are found to this pattern, especially with sites lying to the east of Wadi Hawad (Figure 23). Values of $\delta^{18}O$ are still below -5 ‰ and are separate from the other sources of heavier groundwater in the region. Thus Timeid Haj el Tair (two samples), Umm Shadida (situated well to the east of the area) and Ambesa (large dug well) have distinct isotopic chemistry, suggesting that the aquifer to the east may be separated from that to the west of Wadi Hawad.

4.5.4 Radiocarbon and Stable Carbon Isotope Results

Samples for radiocarbon (^{14}C) analysis were obtained from representative pumped boreholes in the Wadi Hawad area and the Nile Valley (Figure 23); analysis of $\delta^{13}C$ was also carried out on $BaCO_3$ precipitates. In order to interpret the radiocarbon analyses it was also necessary to use the geochemical data on the carbonate system for computer modelling of the results. Samples of carbonates were obtained at two locations to establish control over input conditions and sources of bicarbonate. One set of samples came from a dug well profile at Abu Delaig and the other from caliche at Abu Domat (dug well material) just south of the Nile. The results are given in Table 7. The carbonate material in each case is an interstitial cement derived from the soil zone rather than a discrete limestone; limestone is absent from any known rocks in this area. The $\delta^{13}C$ stable isotopic composition ranges from (-4.9 ‰ to -7.3 ‰) and is consistent with a freshwater origin. A value of -6.8 ‰ was selected for use in subsequent modelling.

Table 7. Analyses of $\delta^{13}C$ on carbonate material from Wadi Hawad basin.

Site		$\delta^{13}C_{PDB}$
Abu Domat (nr. Shendi) material from Dug Well		-6.8% (average of two measurements)
Abu Delaig. Dug well site AD 40. Interstitial carbonate material		
Depth	1 m	-5.1%
	4 m	-4.9%
	17 m	-7.3%

The radiocarbon results are summarised in Table 8 in terms of % modern activity and uncorrected ages are also given derived on the basis of radioactive decay from a homogeneous carbon source. This assumption is unlikely to be true for most groundwaters since the total dissolved inorganic carbon (TDIC), sampled as bicarbonate, is derived from more than one source by a complex geochemical pathway. The stable carbon isotope values plus the hydrochemical data are the only means available to narrow down the possible carbon origins.

Table 8. Radiocarbon and stable carbon isotope ratios for Nubian groundwaters of the Hawad basin area.

Site	Site No.	SRRC No.	14C Activity % Modern	$\delta^{13}C_{TDIC}$ ‰ PDB	Uncorrected ^{14}C	Modelled 14C Ages* (WATEQ-ISOTOP) pH_I 5	pH_I 8
WAD HASSUNA		2460	41.1	- 9.2	7400± 80	-1618	+1591
SHERISHEH		2457	22.5	-10.3	12240± 80	4680	7680
UMM SHADIDA*		2458	45.8	- 7.1	6570± 70	NEGATIVE	
		2713		- 7.5	6310± 70	NEGATIVE	
EL GEHEID		2322	47.2	-11.3	6250± 70	- 607	2444
SURIBA		2324	28.3	-11.5	10370± 70	32810	6914
UMM DURWA		2323	42.6	-11.5	7080± 70	320	3456
EL SHEIN		2321	42.5	-11.8	7090± 70	415	3880
TOMEID H. EL TAIR		2320	7.6	- 9.7	20940±170	12980	16048
EL DELAIG		2325	37.5	-11.7	8090± 60	1462	4676
WAD EL HAMAD		2319	51.7	- 8.3	5580± 70	NEGATIVE	
AWADAB		2708	1.1	- 9.9	>35840	29188	32500
METEMMA		2710	89.4	- 9.2	1160± 50	NEGATIVE	
KUMEIR		2706	83.0	-10.7	1730± 70	NEGATIVE	
ZAKIAP		2711	83.2	-11.0	1710± 50	NEGATIVE	
TONDOB		2707	72.4	-11.4	2810± 70	NEGATIVE	
HAMORIBA				-11.7	7950± 70	NOT MODELLED	
EL ABAKA				-10.1	1120± 70	NOT MODELLED	
QADAH				-11.0	8620± 70	NOT MODELLED	
DIEM EL GRAY				- 9.3	4520± 70	NOT MODELLED	
EL NAHOND				- 9.4	13220±110	NOT MODELLED	

* Modelled radiocarbon ages (in addition to uncorrected ages) were derived from WATEQF-ISOTOP assuming rock $\delta^{13}C = 0$, initial δ^{13} $CO_2 = -25$‰, and initial activity = 100‰.

At its simplest the acquisition of bicarbonate may be represented by:

$$CaCO_3(s) + CO_2 + H_2O \quad Ca^{2+} + 2HCO_3^-$$

In this case one mole of carbonate carbon reacts with one mole of carbon dioxide carbon to give two moles of bicarbonate. In general, the calcium carbonate must be considered as 'dead' carbon, and the CO_2 which is derived from the atmosphere or the soil zone is likely to be 100% active carbon at the time of infiltration. Thus there is the likelihood that dilution of the radiocarbon by about 50% occurs in most groundwaters, especially in temperate latitudes. If marine limestone ($\delta^{13}C \approx 0$ ^{o}/oo) reacts with biogenic CO_2 from most temperate vegetation in the range -12 to -17 ^{o}/oo (Mook, 1980) due to plants with Hatch Slack as opposed to Calvin photosynthetic cycles.

Corrected ^{14}C results have been obtained using the WATEQF-ISOTOP model (Reardon and Fritz, 1978). This model simulates the chemical evolutionary path of the groundwater by stipulating a variety of initial open system pH, PCO_2 and water chemistry conditions that would subsequently evolve under closed system conditions to the actual water's pH, PCO_2 and chemistry values. This model uses a hypothetical $\delta^{13}C$ of the gas phase in equilibrium with the modelled water which is then compared to the actual value. The main assumptions in the model are that (1) all carbon input is derived from dissolution of rock carbonate (2) no carbonate has been lost (3) no carbonate has been added from external sources (4) water-rock isotopic equilibrium has not been achieved.

In Table 8, the corrected ^{14}C ages are listed for the range of initial conditions: pH 5 and pH 8 with other values intermediate between these, with a rock $\delta^{13}C$ chosen as 0 (marine limestone), initial $\delta^{13}C$ CO_2 = 25 ^{o}/oo and initial atmospheric ^{14}C activity = 100%. The ages so obtained are all substantially younger than the uncorrected ages and suggest that some waters, e.g. those in the Nile valley, might be contemporaneous. In order to investigate the effect of other starting conditions, the WATEQF-ISOTOP model was rerun with different parameters for two waters (Suriba and El Shein) (Table 9).

For Suriba with an uncorrected age of 10370 BP, the corrected age in Table 8 (0 ^{o}/oo, -25 ^{o}/oo, 100 ^{o}/oo for $\delta^{13}C_{carb}$, $\delta^{13}C_{gas}$ and $^{14}C_{imit}$, respectively) is 3280 BP. If, instead of marine limestone, freshwater carbonate with $\delta^{13}C$, -6.8 ^{o}/oo is substituted, the effect is to make even more negative and even a present day age is possible. If the gas phase $\delta^{13}C$ CO_2 were to be heavier (15 ^{o}/oo) then the model produces ages of 5230 and 2906 BP respectively assuming a freshwater limestone $\delta^{13}C_{carb}$ starting composition of -6.8 ^{o}/oo and 100% initial atmospheric ^{14}C activity.

A further complication may arise. It is possible that the solid carbonate fraction, e.g. soil carbonates or 'caliche' may contain active carbon. This possibility has been discussed in the case of groundwaters in Libya (Edmunds and Wright, 1979). Instead of the 1:1 reaction between dead and active carbon described above, the reaction will be at least partially between a gas phase and solid phase <u>both</u> containing active radiocarbon. This will have the effect of producing older ages, closer to the measured uncorrected ages. This possibiity would arise in arid or semi arid regions such as the present area, where there are prolonged dry periods during which there will be net accumulation of

Table 9. The effect of changing the initial conditions, source rock and gas phase of $\delta^{13}C$ on the estimated age of two groundwater samples.

Site	$\delta^{13}C_{carb}$	$\delta^{13}C_{gas}$	$14C_{init}$	Corrected Age
SURIBA (pH 5)	0‰	-25‰	100‰	3280
	-6.8‰	-20‰	100‰	1560
	-6.8‰	-25‰	85‰	-2585
	-6.8‰	-15‰	100‰	5230
EL SHEIN	0‰	-25‰	100‰	415
	-6.8‰	-20‰	100‰	- 800
	-6.8‰	-25‰	85‰	-2483
	-6.8‰	-15‰	100‰	2906

carbonate in the soil/unsaturated zone, with very little associated recharge. During evaporation cycles the salinity of soil solutions will increase significantly and the calcite saturation index will reach zero and deposition of calcite will tend to occur. With the onset of less arid climatic conditions the recharge will redissolve this carbonate. This pattern probably occurred during much of the Holocene up until the present (Section 3.2).

There is no unique solution therefore to the age of the Nubian groundwaters. It is most probable that their true ages are slightly less than the uncorrected ages. Although the non-marine composition of the $\delta^{13}C$ solid phase is fairly certain, further information on the soil CO_2 in this region (both past and present) would be needed to narrow down possibilities for groundwater age.

The uncorrected age results have been plotted on the map (Figure 23) together with $\delta^{13}C$ values. The important point is that it is the relative differences between the uncorrected ages that are likely to be significant and less certainty can be placed on absolute ages. The following points emerge:

(1) Groundwaters to the west of the Wadi Hawad all group in an apparent age range 7080-8620 BP.

(2) Slightly younger ages are found in two nearby wells to the south of the main group, sites 3 and 1 (5580, 6250 BP).

(3) Three wells close to Wadi Hawad on the eastern bank have significantly older groundwater (10370-20940 BP).

(4) Most wells along the Nile valley have apparent uncorrected ages, 1160-4520 BP and one in the Atbara valley 1120 BP. An exception is the well at Awadab in the north of the region and adjacent to the Nile which has the oldest age in the region (>35840 BP), suggesting a lack of hydraulic connection in this area.

The following conclusions may be drawn from the radiocarbon data:

(1) The Nile valley contains modern groundwater probably mixed in one instance (site 21) with a proportion of older groundwater.

(2) The Nubian Sandstone regional aquifer contains groundwater which is older than in the Nile valley. The groundwater beneath Wadi Hawad is of at least two age groups with younger water to the west and south. This probably represents a geological control, e.g. a confined unconfined boundary or a major lithofacies change between permeable and impermeable strata. It may also indicate that lateral flow is occurring from the SE to the NW.

(3) The recharge of the main Nubian aquifer probably occurred during a pluvial period since 8000 BP but before 6000 BP.

Further interpretation cannot be made on the basis of the radiocarbon results alone but taken in conjunction with the $\delta^{18}O$, $\delta^{2}H$ isotope and chemical results it is clear that the deep Nubian groundwater is chemically and isotopically distinct both from the Nile groundwater and from shallow modern groundwaters in the Wadi Hawad. The Nubian sources with older radiocarbon ages also have distinctly different isotopic signatures, maybe indicating some hydraulic boundary at depth between the two sides of the wadi. It is not possible to

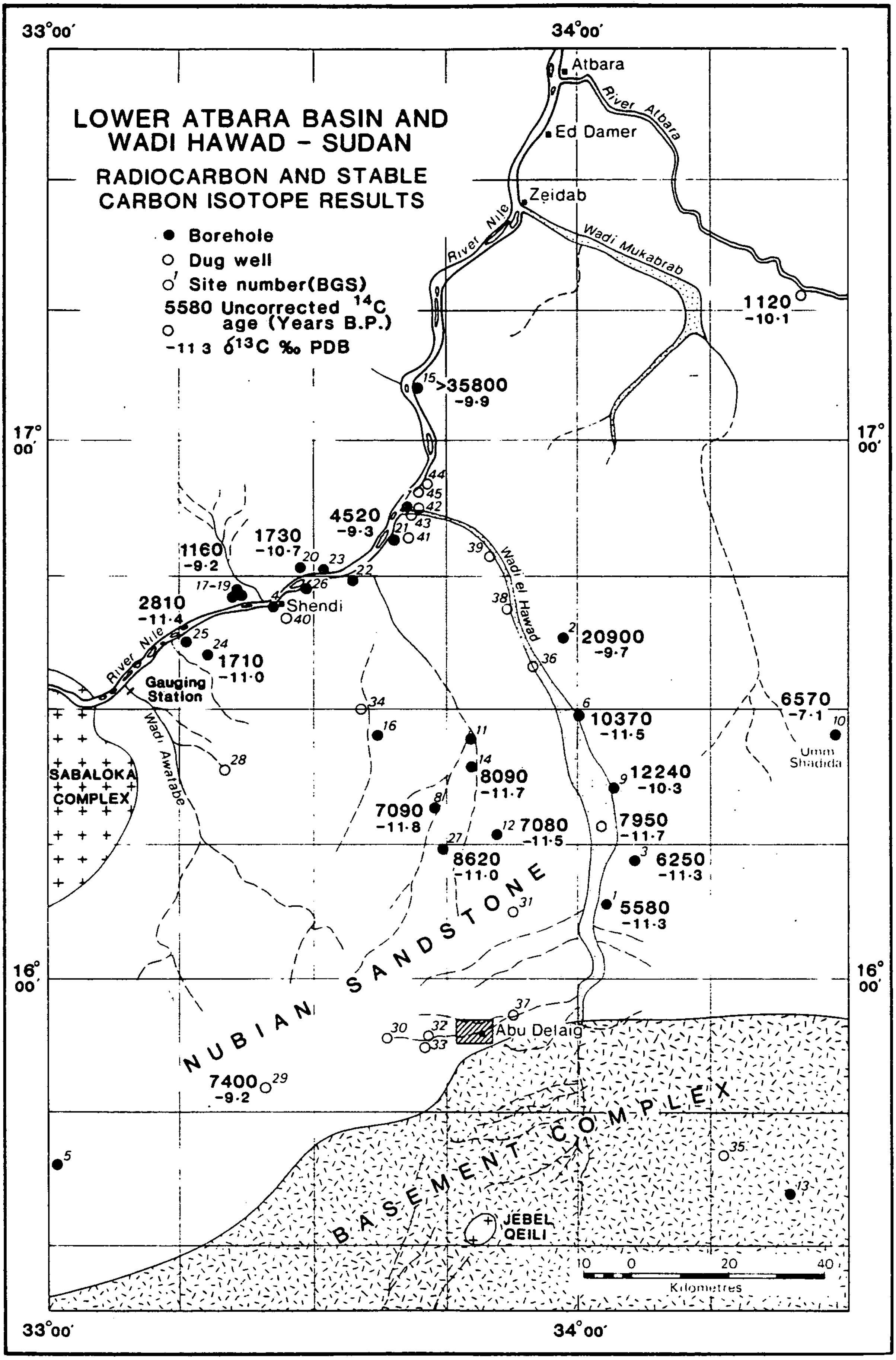


Figure 23. Radiocarbon and stable carbon isotope results for Nubian and Nile Valley deep groundwaters and uncorrected groundwater ages.

analyse these differences further without data on the hydraulic gradients, well construction data and additional geological information.

4.6 Minor and Trace Elements in the Shallow and Deep Aquifer Systems.

The minor and trace element concentrations may be used to provide additional information on groundwater identity and origin as well as important data relating to pollution and potability. The following elements are considered: NO_3, Sr, Ba, F, Br, B, Fe, Mn.

NITRATE - The presence of nitrate in palaeogroundwaters must indicate that oxygen is also present, although the absence of nitrate does not necessarily indicate anaerobic conditions. Quite high nitrate levels have been reported from Saharan and Kalahari groundwaters (Edmunds and Wright, 1969; Edmunds et al., 1985; Vogel et al., 1980; Heaton, 1984). Traces of nitrate (around 1.5 NO_3-N) in most of the Wadi Hawad deep Nubian sandstone groundwater probably indicates oxygen to be present and the absence of very high levels in this region signifies the absence of pollution (Table 6). Contrast this with the basement well at Umm Ruwesheid (21.0 mgl^{-1} NO_3-N), which denotes pollution.

In the Nile valley, the majority of groundwaters (Table 6) contain <1.0 mgl^{-1} NO_3-N and this strongly suggests that anaerobic (reducing) conditions exist in the aquifer adjacent to the Nile (with exceptions at Metemma and Kaboushir).

In the shallow groundwater system, nitrate concentrations are relatively high. At Abu Delaig (Table 5) the values range up to 52.4 mgl^{-1} NO_3-N. The distribution of nitrate is irregular, and high values do not correspond with the area of Abu Delaig town. In other areas, e.g. shallow wells in the Wadi Hawad such as Tomeid, Umm Ushara, Qaid, high nitrate is common and almost certainly relates to the nearby presence of watering holes for livestock.

STRONTIUM - Strontium behaves geochemically in a similar manner to magnesium although strontium can often be used as an indicator of diagenetic changes in the aquifer or to give an indication of groundwater residence time (Edmunds, 1980). The relatively low strontium (generally below 1 mgl^{-1}) is characteristic of continental sandstones as found for example in Libya. The strontium concentration in the Wadi Hawad basin (Figure 24a) increases with salinity in the older Nubian sandstone waters. In the shallow aquifers there is a relative enrichment in strontium over a very short time scale which probably indicates an uptake from clays or incongruent reaction of carbonate or sulphate minerals both of which contain traces of strontium and which will be present in the soil during arid cycles, redissolved during recharge episodes.

BARIUM - Barium is found at concentrations in the range 8-720 $\mu g\ l^{-1}$ and the concentration shows no relationship to the groundwater type (Tables 5 and 6). The main control over barium occurrence is the solubility of barite. The majority of groundwaters (Table 10) are at or just below saturation with respect to barite (± 0.2). Thus the highest levels of barium in the region occur where sulphate concentrations are lowest (e.g. Taragma, El Guweir); lowest barium concentrations occur where high sulphate is found (e.g. AD33, 34, 35). There is ample supply of barium in the rocks therefore and the concentrations are solubility limited, not indicative of pollution or source.

FLUORIDE - Fluoride has been determined on selected groundwaters from the Nubian aquifer as well as the shallow aquifer at Abu Delaig. Rather low concentrations

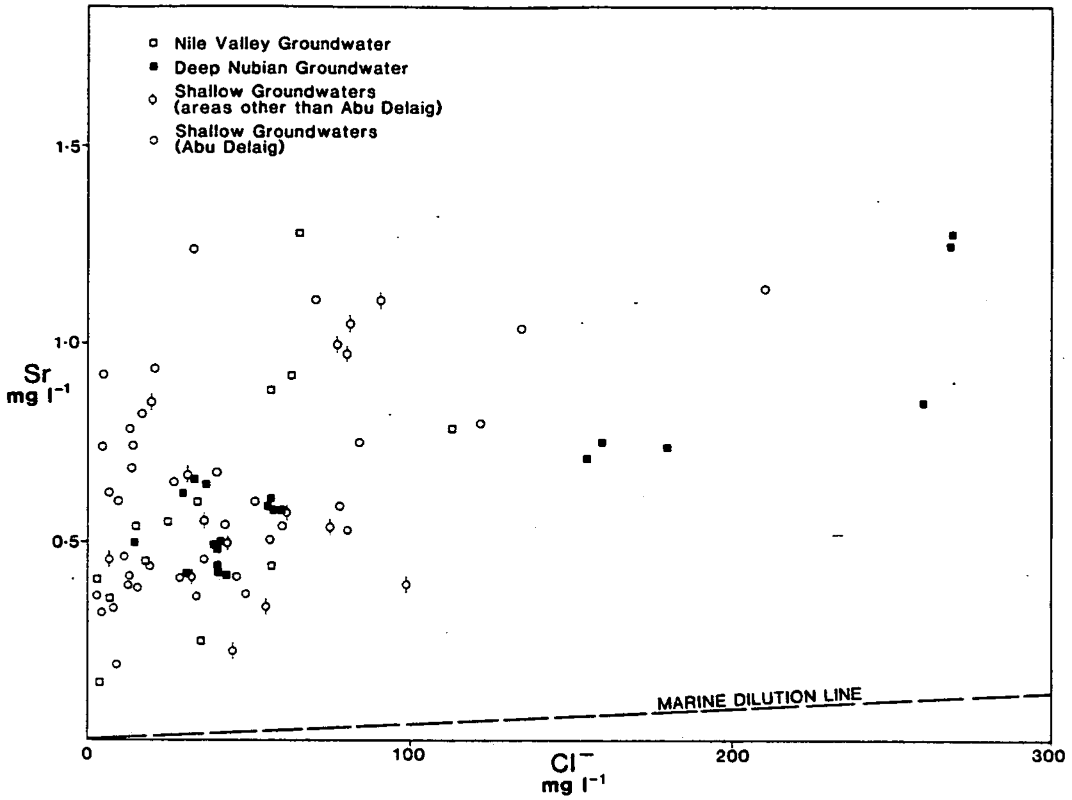


Figure 24a. Plot of strontium vs. chloride for the different surface and groundwaters in Wadi el Hawad and Nile valley.

TABLE 10. Selected saturation indices derived from WATEQF (Plummer et al., 1976) for groundwaters in the Nubian sandstone and shallow aquifer.

	SI CALCITE	SI BARITE	SI FLUORITE
NUBIAN SANDSTONE			
82 522	-0.20	-0.44	-1.90
83 517	0.36	-0.11	-1.71
83 521	-0.16	-0.28	-1.84
83 523	-0.22	-0.20	-0.81
SHALLOW AQUIFER (ABU DELAIG)			
83 483	0.18	-0.31	-0.63
83 485	0.13	-0.18	0.27
83 486	0.31	-0.14	-0.02
83 500	0.13	-0.20	-1.12
83 502	0.36	-0.13	-0.12

are found in the older groundwaters and these values are well below saturation with respect to fluorite. This must indicate a very low fluorine abundance in the sandstone as well as in the area of original recharge. In contrast, the fluoride concentrations are about one order of magnitude higher in the shallow aquifer system with the highest value at 6.20 mgl^{-1} F^{-}. The highest values represent saturation with respect to fluorite and thus depend also on the amount of Ca^{2+} in solution. The fluoride concentrations in many wells are large enough to promote dental problems. The source of fluorine is uncertain, especially since the deep groundwaters in the Nubian aquifer are so low, but must represent some concentration process during the 'recent' sedimentary cycle.

BROMINE - Concentrations of bromine are considerably above those expected from dilution of a marine source, which would have a ratio of Cl/Br = 314 (Figure 24b). The ratio for the R. Nile at Shendi is 64 and many shallow groundwaters including some Nile recharge maintain this low Cl/Br around 85. By contrast, the deep Nubian groundwaters tend to have slightly higher ratios (168). Although the data is sparse, there is evidence for 'continental' enrichment in bromine, possibly more at the present day than during the earlier climatic regime which recharged the Nubian Sandstone.

BORON - In the regional Nubian sandstone aquifer the concentration of boron hardly exceeds 100 µgl^{-1} and there is little if any enrichment (in contrast to strontium for example) with increasing salinity (Figure 24c). The Nile contains a low boron concentration (up to 64 µgl^{-1} B) and groundwaters recharged from the Nile also contain low boron with little or no increase with salinity. Very large increases however are found in B and in B/Cl in the shallow aquifer system, demonstrating like Sr that a source must occur in the near-surface alluvial/colluvial sediments. High boron (above 120 mgl^{-1}) can therefore be used to characterise shallow groundwaters associated with wadi recharge.

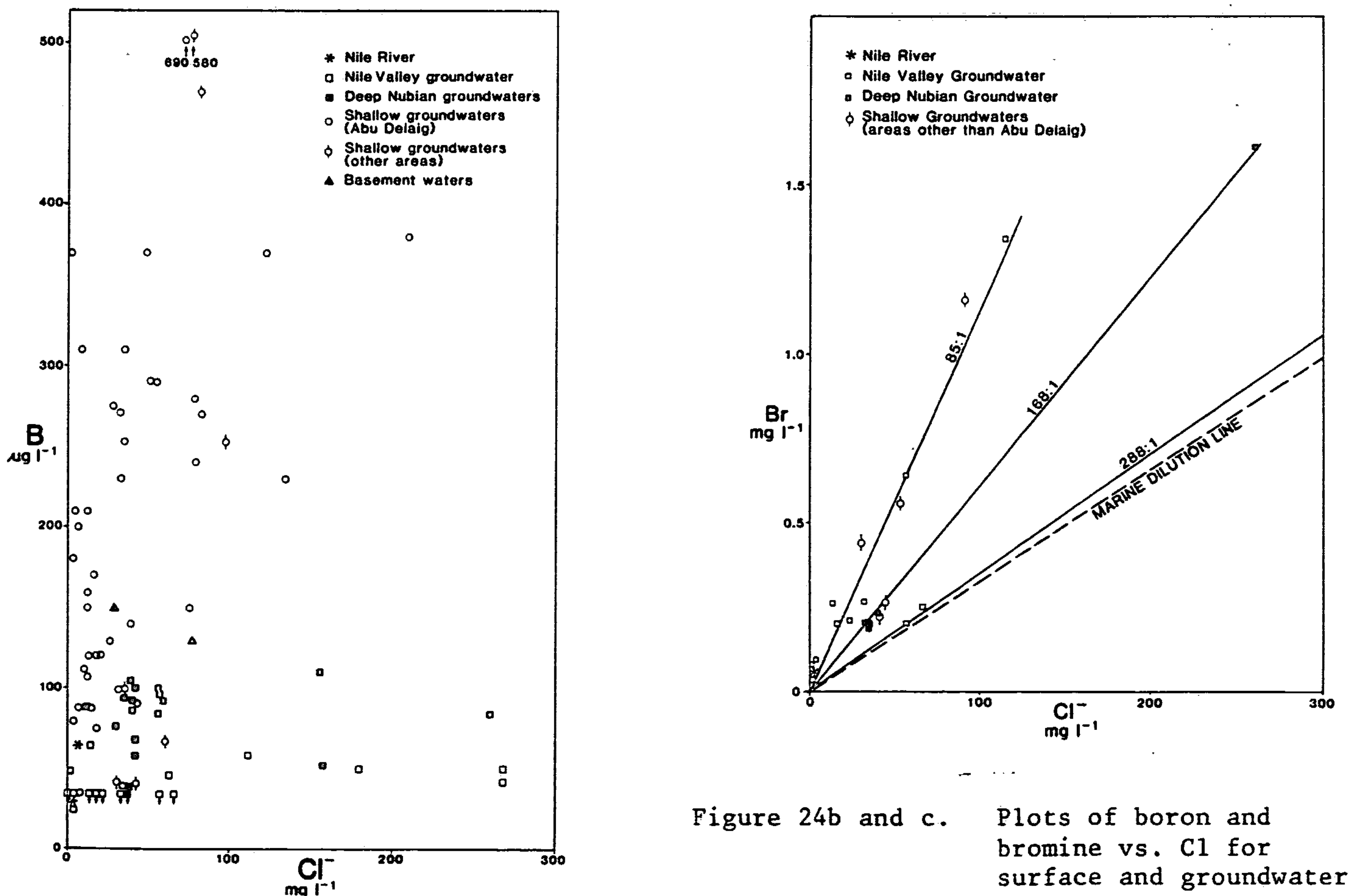


Figure 24b and c. Plots of boron and bromine vs. Cl for surface and groundwaters in the Nile valley.

IRON - Since all samples were filtered through 0.45μ filters the analysis for total iron (Fe_T) should largely represent iron in solution. It can also be used to indicate the presence of reducing groundwaters since high iron concentrations, e.g. above 0.200 mgl^{-1} Fe should be due to Fe^{2+} in solution; if oxidising conditions prevail the Fe_T should reflect Fe^{3+} solubility and concentrations of Fe_T should remain well below 0.100 mgl^{-1}. Similarly if high iron is present and reducing conditions prevail then nitrate should be absent (or at a very low level). The three boreholes at Metemma (sites 17-19) illustrate this (Table 6a).

Using these criteria it is apparent that some wells in the regional Nubian aquifer, e.g. sites 8 and 2 may not contain oxygen and that Syeidab b/h (site 5) well to the west of Abu Delaig must certainly be anaerobic. A patchy distribution is however apparent which suggests that there may be stratification within the aquifer. Most wells in the Nile valley despite their low NO_3 also contain low iron, but Kaboushir contains two wells, one of which is apparently anaerobic (Fe_T 1.74 mg/l) and some stratification here is also likely.

The majority of shallow groundwaters at Abu Delaig contain low Fe_T and therefore also contain oxygen - exceptions include AD17, 15, 11, 26. From the viewpoint of potability and use any groundwater with Fe above 0.200 mgl^{-1} Fe_T is likely to lead to iron staining and above 0.500 mgl^{-1} Fe_T to bad taste.

MANGANESE - In the shallow groundwater dissolved manganese is generally below 0.100 mgl^{-1}; there is no correlation between high iron and high manganese. This is true also of the regional Nubian aquifer. In the latter, manganese concentrations are generally well below 0.100 mgl^{-1} Mn. Higher manganese occurs in the Nile valley aquifer where several wells contain Mn in the range 0.200-0.260 mgl^{-1} Mn.

5. SOLUTE PROFILES AND RECHARGE ESTIMATION

5.1 Background

The present research in Sudan is a development of that carried out in Cyprus (1977-80). The possibility of using solute profiles to estimate recharge was investigated in Cyprus following earlier work using the environmental tritium profile found in the unsaturated zone. 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 successfuly 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). 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) limits the long term usefulness of the method;

(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).

Therefore alternative techniques are desirable which can be used to overcome these difficulties. Solute profiles offer one possible approach. At the same time as the research in Cyprus, chloride and tritium profiles of the unsaturated zone were investigated in Australia by Allison and Hughes (1978) to determine recharge. In Australia, also, investigations of solute profiles to depths of 20-30 m have been carried out to see whether land use changes, notably deforestation, could lead to secondary salinity problems (Peck et al., 1981). A study of the groundwater recharge in southern Africa (Botswana) using profiles has also been carried out by Foster et al. (1981).

5.2 A Model for Solute Movement in Relation to Recharge Studies.

A working hypothesis justifying the use of solute profiles to evaluate direct recharge is illustrated with reference to Figure 25, representing an aquifer with a moderately thick unsaturated zone.

The input of solutes to the aquifer depends initially on the total atmospheric fallout per unit time, made up of rainfall (F_p) and dry deposition (F_d) fluxes. Both the rainfall amount (P) and the 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 varying rates depending on rainfall intensity. These solutes will undergo concentration as a result of evapotranspiration (E). Certain solutes may be removed from solution by plant uptake or by mineral precipitation, if solubility products are exceeded, or by adsorption. Similarly solutes may be released by decay of dead plant material, dissolution or desorption. This places a possible limitation on the use of solutes for recharge studies since only those constitutents for which there is no net release or storage by the soil or rock matrix may be used. Normally chloride is the solute that most conveniently meets these requirements.

Nutrient cycling by plants may affect solute movement on an annual basis but over the long timescales (decades) of interest here, it will be assumed that the amounts removed annually by plant uptake are balanced by the amounts released by plant decomposition, i.e. that a steady state has been achieved. This assumes that there are no additions of the solute in fertilisers and that the permanent removal of solute by crop removal (including the export of grazing animals) is not significant.

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 depends upon the prevailing water potential gradients. A 'zero flux plane' (ZFP) exists (Wellings and Bell, 1980) which under conditions of regular seasonal recharge effectively separates moisture and solutes moving upwards (evapotranspiration) from downward movement (drainage). The position of the ZFP will shift seasonally between the surface and a depth of several metres; 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 to the drainage 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

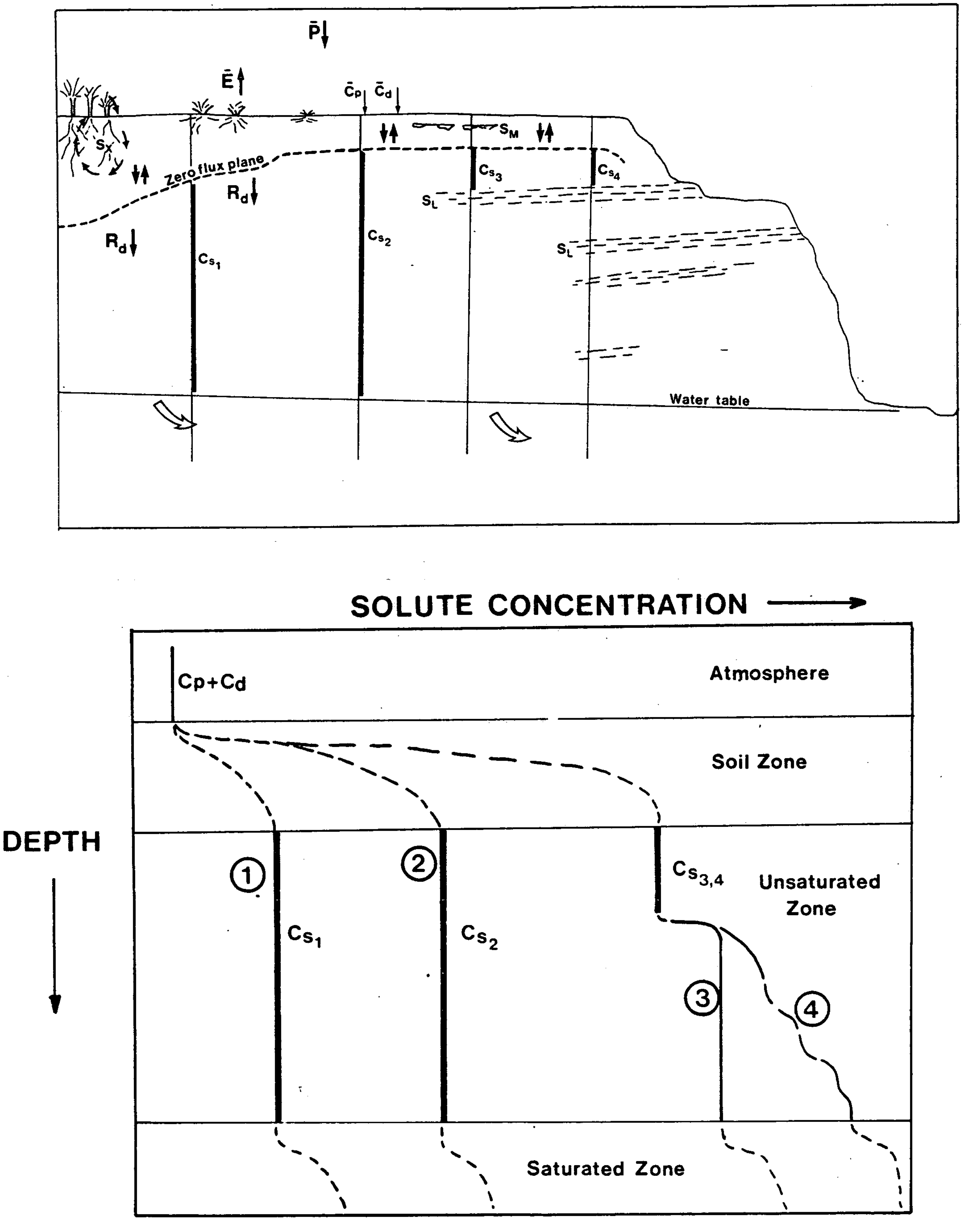


Figure 25. (a) Schematic representation of solute movement and recharge via the unsaturated zone. Section of the profile beneath the zero flux plane that can be used for recharge estimation are shown by solid line. Elsewhere solutes may be added during percolation. (b) Idealised solute profiles developed during percolation in the profiles of 25a.

take place towards the water table. The amount of solute crossing the ZFP would be expected to vary in relation to antecedent rainfall conditions 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 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.

The water balance equation (1) can therefore be given as:

$$\bar{R}_d = \bar{P} - \bar{E}, \qquad \bar{S} = 0 \tag{1}$$

where R_d is the amount of direct recharge, S is the net amount of water storage in the profile in units of depth, and the bars indicate time-averaged and space-averaged quantities. Providing surface runoff is negligible this leads to

$$R_d = P \frac{(C_p + C_d)}{C_s} \tag{2}$$

where C represents a concentration term and the subscripts p, d and s refer to the precipitation, dry deposition and interstitial water components, respectively. C_d is an equivalent concentration of dry deposition given by F_d/P.

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 (i.e. no change in inputs) has occurred over this period;

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

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

In principle, it may be possible to use as 'tracer' any solute that is not released by weathering or removed by precipitation; even interacting solutes, e.g. cations on clays could, in theory, be used since the quantity of any exchangeable ions will be effectively constant and need not lead to a net change in storage. In practice the most inert solutes are likely to prove the best 'tracers' and for this reason chloride has been used here for the recharge calculation although SO_4, NO_3 and SEC have also been considered. It is possible that only a restricted portion of the unsaturated zone profile may be usable in recharge estimation (Figure 25). For example, the presence of certain lithologies, e.g. residual marine bands, may contribute chloride from storage during moisture drainage. The possible development of solute profiles are summarised in Figure 25. 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 3 or 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 immediate water table. However the composition of the saturated flow will have been modified by the incoming lateral flow as well as the inputs from each profile along the flow path.

Therefore, in general water table samples taken from shallow wells or during drilling are unlikely to be reliable for accurate recharge estimates, although in homogeneous terrains they may be quite reliable. However, since chloride is unlikely to be lost during drainage and saturated flow, the shallow groundwater chemistry, or river baseflow, can always be used in areas of current recharge to derive a minimum figure for total recharge. This approach has been used, for example, by Ericsson (1976) in India and could be more widely used in regional water balance studies.

5.3 Principal Conclusions from the Cyprus Study.

Eight profiles were successfully recovered to depths of 15-29 m in unconsolidated deposits of Recent age at Akrotiri. The chloride concentration in the interstitial water was estimated by extracting all of the chloride with distilled water, measuring its concentration in the elutriate and back-calculating the initial interstitial water concentration using the moisture content of the rock sample. (This indirect method of estimating the interstitial water concentration assumes that there is no interaction of the solute with the solid phase and is another good reason for choosing chloride as the indicator solute). The results for chloride are shown in Figure 26 and the main characteristics may be summarised.

(1) Below a certain depth chloride concentrations reach a relatively constant value. This depth (generally 2-3 m) is interpreted as the effective zero flux plane for solutes.

(2) At depth a nearly constant chloride concentration is developed in all profiles, with the possible exception of AK 7. These mean values (C_s) are used in the recharge calculation. The mean chloride concentrations vary and are interpreted to indicate different recharge from place to place. The amount of variation of this mean (steady state) value gives a guide to the reliability to be placed on the recharge estimate.

(3) Steady state conditions are found to persist to the water table (e.g. AK 5) or to the maximum depth drilled (AK 8, 2, 9). In other boreholes there is an indication of chloride addition from the aquifer; in AK 3 there is an abrupt increase in chloride which coincides with a marine horizon (shelly gravels) and the profile below this cannot be used. In AK 4 there is a suggestion of continuous uptake of chloride through the succession, and only a limited portion of the profile has been used.

(4) Distinct peaks are apparent within the steay state sections of some profiles (e.g. AK 2), which indicate that homogenisation by dispersion does not take place. The peaks of AK 2 and possibly other profiles have an apparent periodicity of less than 1 m and are considered to represent cyclic, mainly annual, inputs of solutes from the soil zone (see Edmunds and Walton, 1980).

Those sections of the solute (chloride) profiles that were used in recharge calculations are indicated in Figure 26. They represent an integrated record of recharge over a period of time ranging from 1978 back to the late 1940s.

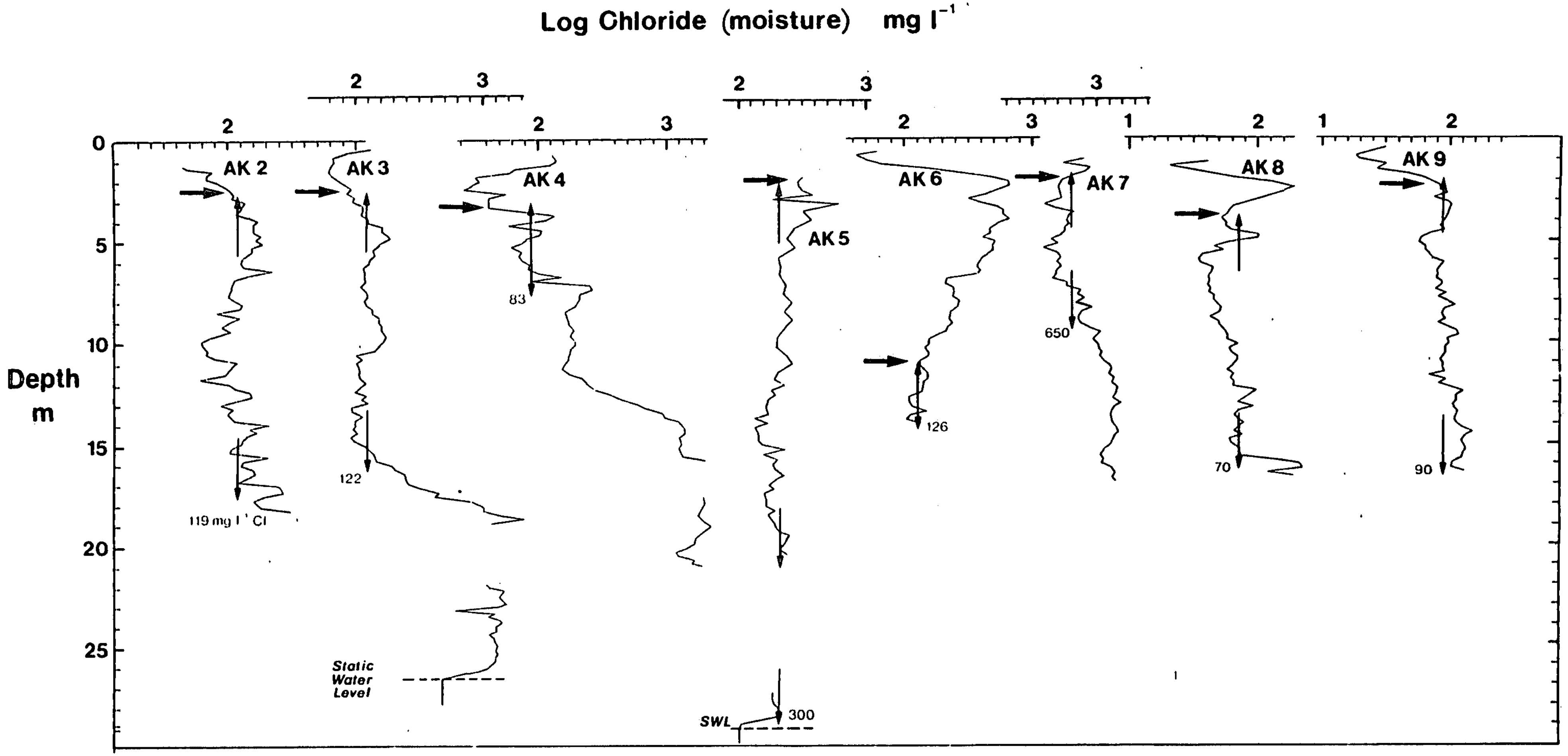


Figure 26. Chloride profiles (log Cl) from eight boreholes drilled at Akrotiri, Cyprus. Vertical arrows indicate the profile length over which steady state conditions are considered to exist. Horizontal arrows indicate the likely depth of the ZFP (Zero Flux Plane) at the time of sampling. Mean Cl values for the intervals are given in mg l^{-1}. Data from Edmunds (1982).

The 25 yr mean rainfall value for Akrotiri (406 mm) was used for calculation and the rainfall chemistry, including dry deposition, measured over a 3-year period is also shown in Table 11. The 3 yr mean chloride concentration was used in conjunction with the 25 yr rainfall value in the recharge calculations. There is some fluctuation in the rain chemistry both over the period of investigation and between the two stations. This is reflected in the total rainfall figures. The use of long term means in this technique is advantageous where the profile itself represents the average input over a number of years. Values for the soil moisture chloride concentrations (C_s) have been derived from the mean value for soil moisture and the elutriate composition. The recharge estimates for the eight boreholes are given in Table 12.

At all eight locations current recharge can be identified in the range 10-94 mm/yr. The variability is consistent with changes in vegetation cover between the sites with highest values occurring in areas of sparse vegetation and low recharge (∿10 mm) taking place where bush vegetation exists. The results compare well with independent recharge estimates obtained from tritium peak analysis.

5.4 Sampling Programme and Methodology (Sudan).

5.4.1 Drilling

In Cyprus samples of the unsaturated zone were obtained by dry percussion drilling using a wireline. In addition a dry rotary drilling method was also successfully carried out using the Pilcon Wayfarer 1500 rig. As a result of this experience in Cyprus, the Pilcon rig was refurbished and sent to Khartoum. The rig was handed over to the drilling section of NAW to be used in the project in July 1982 (Edmunds, 1982). Testing of the rig was carried out rather late in the project (December 1982) due to problems of mobilising the drilling crew. In the event, the dry percussion technique proved to be unsuitable for the rather indurated terrain of the interfluve area and it was not further used for profile sampling but was used elsewhere in the programme to construct observation wells. Sampling was achieved from dug wells, auger profiles and shallow trenches (isotopes only). In general, interfluve areas were selected for drilling since this is where surface runoff is minimal and so these sites were most likely to give the best estimates of direct recharge.

5.4.2 Dug well sampling

In order to adapt the recharge estimation method to local conditions and traditions it was decided to base the field work on a dug well programme supported by augered holes. The NAW Khartoum agreed initially to pay for the construction of two dug wells in the Abu Delaig area (Bir Kharbana, Dar es Salaam) and subsequently three more, two at Abu Delaig and one at Tomeid Haj El Tair.

The initial sampling routine (March 1982) involved side wall sampling of a freshly dug well section (Edmunds, 1982a). The wells had been covered since completion and sampling was carried out by one of the well digging team suspended on a rope cradle. Samples were collected every 20 cm using an adze, excavating cavities in the borehole wall once the outer 2-3 cm had been removed. 250 g samples were collected in polythene bags, transported to Khartoum for elutriation, filtration and moisture content determination the following day. Rock exposed at the depth of excavation (8 m) in Dar es Salaam well was sampled for stable isotope and moisture content analysis. This procedure had the advantage of precise control over the sampling interval but ran the risk of prior loss of moisture by evaporation from the side walls. There could also be migration of solutes by capillary movement induced by the drying out of the well wall. Although this was considered minimal in the present study, it presents a drawback to the method if it were to be used on a routine basis.

Table 11. Mean rainfall values (3 yr and 25 yr) for stations at Akrotiri with average chloride deposition ($C_p + C_d$) over the three year period 1977-80, used in calculations.

Year	Rainfall (mm)	Weighted Mean Cl ($C_p + C_d$) (mg/l)
AKROTIRI (RAF)		
1977/78	455	12.1
1978/79	246	17.3
1979/80	506	15.3
AKROTIRI VILLAGE		
1977/78	426	15.4
1978/79	235	24.1
1979/80	564	17.1
MEAN VALUE	405 (25 yr)	16.4 (3 yr)

Table 12. Data used in Figure 25 for recharge estimation (R_d) at Akrotiri. Comparative results from tritium profiles R_d (^3H) are given for reference.

Borehole	AK 2	AK 3	AK 4	AK 5	AK 6	AK 7	AK 8	AK 9
Profile Interval (m)	2.4-17.3	2.4-16.1	3.2-6.9	2.0-28.3	10.9-14.0	1.7-9.4	3.7-16.0	2.0-16.5
Profile Length (m)	14.8	13.7	3.7	26.3	3.1	7.7	12.3	14.3
Log Cl^- (mg/l)	2.076	2.086	1.920	2.301	2.100	2.813	1.845	1.954
C_s (mg/l)	119	122	83	200	126	650	70	90
R_d (Cl) (mm/yr)	56	55	80	33	53	10	94	74
R_d (^3H) (mm/yr)	52	53	N/A	22	N/A	N/A	62	75

It was decided to try dug well sampling using a side wall coring auger drill and this was attempted during the next field programme (November-December 1982). This technique would have made it possible to sample side walls in relatively recently completed dug wells elsewhere in the area. In the event the drill used (Hilti TE42) proved to be too heavy to be used in the traditional rope sling and the method was abandoned for the remainder of the project.

During 1982 and for the remainder of the project, reliance on 'low technology' methods proved most reliable. Samples from one dug well (at the camp) were processed on site during the field season as digging progressed. Subsequently, samples were collected in 500 ml glass Kilner jars and were taken by the well digging teams at agreed intervals of 0.5 m or similar, usually at the end of each day's shift. Samples were labelled, stored, transported and shipped to UK for analysis. The geochemical consistency of the results demonstrated that this technique was successful.

As a result of a delay in delivery of airfreight in November 1982, Kilner jars did not arrive in Sudan in time for commencement of the project. Thick walled polyethylene jars with rather crude lids were bought locally and firmly sealed with tape. These samples were shipped back and analysed in the UK within 6 weeks also gave reproducible and consistent results. As a precaution they were weighed before and ater shipping to check for possible moisture loss; in every case this was negligible. The Kilner jars are preferred for this method of sampling and if properly sealed, samples should have a shelf life of at least several months. Three shallow (up to 2 m) pits were also hand dug for stable isotope sampling.

5.4.3 Auger samples

It was important that a more rapid and cheaper sampling technique was also available so that a greater density of recharge data could be obtained to supplement the controlled results obtained from frehsly dug wells. To this end, a land rover mounted, petrol-driven, lightweight auger was purchased for the project (JKS Winkie GW15 Auger Drill). This was able to sample to depths of up to 10 m. An additional 12 profiles were obtained by this method.

The sampling method adopted involved collection of sandy material delivered in sequence at the surface. Every metre of material was then subdivided into four or five equal portions and subsamples bagged so as to represent 25 or 20 cm intervals. The augering technique caused a slight temperature rise (about 10^{o}C) and there is a risk of some loss of water vapour, although this was insignificant for the purpose of recharge studies since samples were bagged immediately at the surface. As the augering progressed deeper there was a cumulative error of about 10% in the sample depth due to storage in the auger. Contamination from the side wall appeared to be negligible in the formations studied.

It was necessary to change the auger bits at intervals of 10-15 m and only limited profiles could be obtained in some instances due to worn bits. In conclusion, it is considered that the auger method generally can be a useful technique for proving samples rapidly (e.g. 2 x 10 m per day). The rig used was more adapted to hard rock drilling and a more versatile auger with variable speeds, would be preferable. A powered hollow stem auger would be ideal for this purpose; in sandy formations it would be necessary to case with pvc pipe to about 2 m prior to drilling deeper. In the interfluve region in Sudan the holes stood up well even at the surface.

5.5 Field Laboratory Analysis.

5.5.1 Scope

One of the main objectives of the project was to simplify the analytical techniques as far as possible so that they might be used routinely in the field and by national groups, once the project closed. For the main phase of field work, a tented field camp was established by NAW staff at Abu Delaig. A laboratory was established, equipped with generators, a refrigerator, electronic balance, conductivity meter and equipment for elutriation and filtration of soil samples. Samples were allowed to dry in the heat of the midday sun.

5.5.2 Elutriation.

Samples were obtained at 20-25 cm intervals in polythene bags. Representative 50.0 g samples were transferred to clean preweighed plastic beakers using a plastic scoop. Distilled and deionised water (brought from the UK) with SEC <1 µS cm^{-1} at 25°C was dispersed in 30.0 ml aliquots to each beaker using a precalibrated Oxford automatic pipettor. The slurry was stirred for 30 seconds with a glass rod, left to digest at ambient temperature for 30 minutes, stirred again and then left for a further 30 minutes for the suspension to settle. The solutions were kept covered during this period to minimise evaporative loss. The supernatant water and fines were decanted after one hour into clean numbered tubes and allowed to sediment at least overnight. The aqueous layer was then taken up with a 20 ml plastic syringe and filtered through a 0.45 µm cellulose acetate membrane filter (Millipore Ltd) and transferred to 30 ml polycarbonate 'Sterilin' bottle.

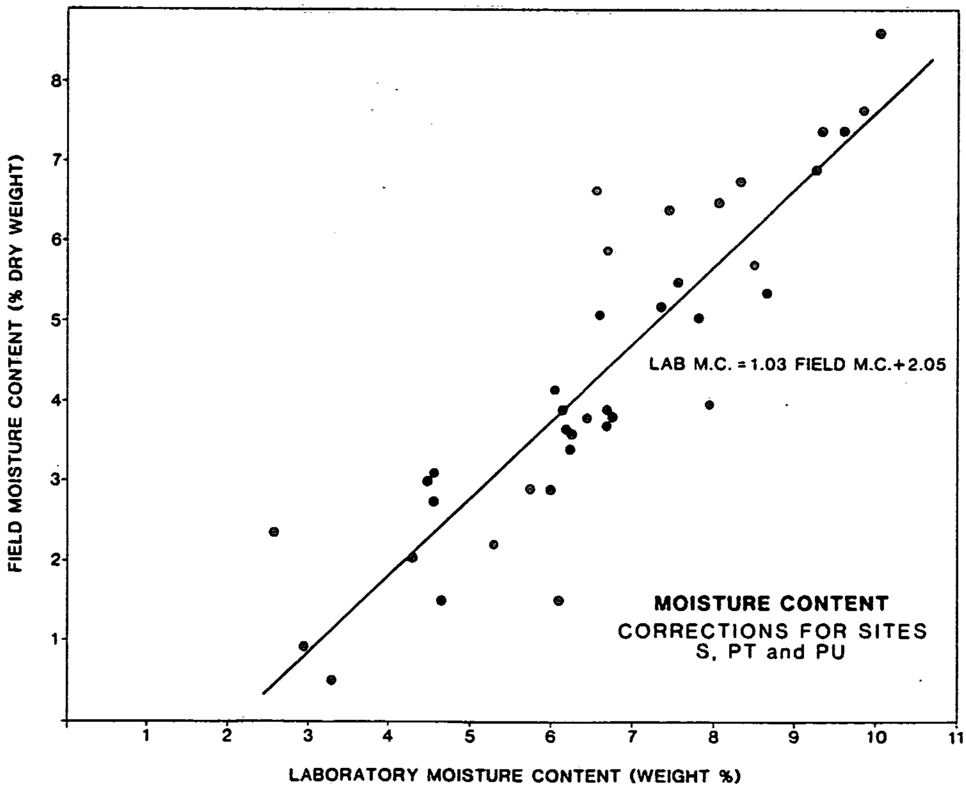


Figure 27. Plot of soil moisture estimation by drying in the sun (field moisture content) and laboratory drying.

The Specific Electrical Conductance (SEC) of each filtrate was then measured using a Mullard 1 cm platinum in glass cell (Type E-7591/A) connected to a Wayne-Kerr (M101) conductivity bridge (precision ± 2%).

Moisture content was determined on ca. 100 gm samples weighed into plastic dishes and allowed to dry in the sun for at least 4 hours before reweighing. It was found that readsorption of water vapour occurred as the air temperature fell in the afternoon and so all weighing was carried out within two hours of midday. Subsequent tests in the UK showed that this drying method consistently underestimated moisture content by about 2 wt% (Figure 27) and results were corrected accordingly.

5.6 Laboratory Analysis.

5.6.1 Inorganic constituents

The 30 ml samples were all shipped to the UK for anion analysis, since at the time of the project no reliable means for chemical analysis of these small samples existed in Sudan. Automated colorimetry (Technicon AA-II) was used for analysis of chloride and nitrate (Cook and Miles, 1980). Sulphate and several major and minor elements were analysed directly on samples from selected profiles by ICP-OES.

5.6.2 Stable isotopes of water

Soil samples collected in thin-walled polyethylene jars (5.4.2) were shipped to the UK for isotopic analysis. All jars were weighed before leaving the Sudan and reweighed in the UK to test for moisture loss; no sample had been significantly affected. Samples from an earlier phase of the project were collected in Kilner jars.

Moisture was extracted from the samples by azeotropic distillation with toluene. Moisture content measurements were used to calculate the amount of sample required to yield about 6 ml of water. Duplicates of each sample were placed in round-bottomed flasks and a slurry made by the addition of toluene. After boiling and refluxing of this mixture for 60 minutes moisture could be recovered from a collecting vessel situated beneath the reflux condenser. In nearly all instances agreement between duplicates was within ±2 $^{o}/oo$ for $\delta^{2}H$ and ±0.2 $^{o}/oo$ for $\delta^{18}O$; duplicates falling outside this range were repeated until satisfactory. Some samples were also recovered by the more traditional method of vacuum distillation as a check.

Isotopic analysis was carried out on a VG 602E mass spectrometer following standard preparation techniques, namely the reaction of 10 µl water with heated zinc shot $\delta^{2}H$ and equilibration of 5 ml water with CO_2 of known isotopic composition $\delta^{18}O$.

5.7 Profile Results.

5.7.1 Solute profiles, 1982 survey

The first solute profiles in this project were obtained in 1982 from two specially dug wells at Bir Kharbana (1 km north of Abu Delaig) and Dar es Salaam (3 km west of Abu Delaig). They were visited in March 1982 when excavation had reached 7.5 m depth. In this exercise the objectives were to examine the formation in the interfluve regions, test the sampling procedures and provide preliminary estimates of recharge rates.

The formation at Dar es Salaam was essentially coarse grits and sandstones, poorly sorted, with a matrix of grey/green clay. The sandstones (Nubian formation) were highly coloured by oxidation products of iron with alternate zones of leaching. Digging progress using one well team of 8 people was about 0.5 m/day.

Side wall samples were collected at 20 cm intervals as described earlier (5.4.2). Due to the relative hardness of the formation it was not possible to excavate by hand more than a few cm into the wall. At the working depth, samples of sand were collected for moisture determination, but above this, some moisture loss could have occurred.

Solute profiles for samples elutriated in the field but analysed in UK are given in Figure 28 for SEC, Cl and NO_3. These raw data are uncorrected for moisture content, but it is apparent that solute values oscillate about a mean value and that there is no salt accumulation at the top of the profile. This demonstrates that current recharge is occurring. A preliminary estimate of the rate of recharge was made using the mean soil moisture content from each borehole at 7.5 m (28 mg/g dry sand and 52 mg/g dry sand respectively) and assuming this is close to the steady state value:

$$R_d = P.C_p/C_s$$

Substituting a value of 200 mm for Abu Delaig mean annual rainfall and 1 mg l^{-1} Cl for the mean composition of rainfall, a preliminary estimate of recharge could be calculated. C_s values were derived from the elutriate results

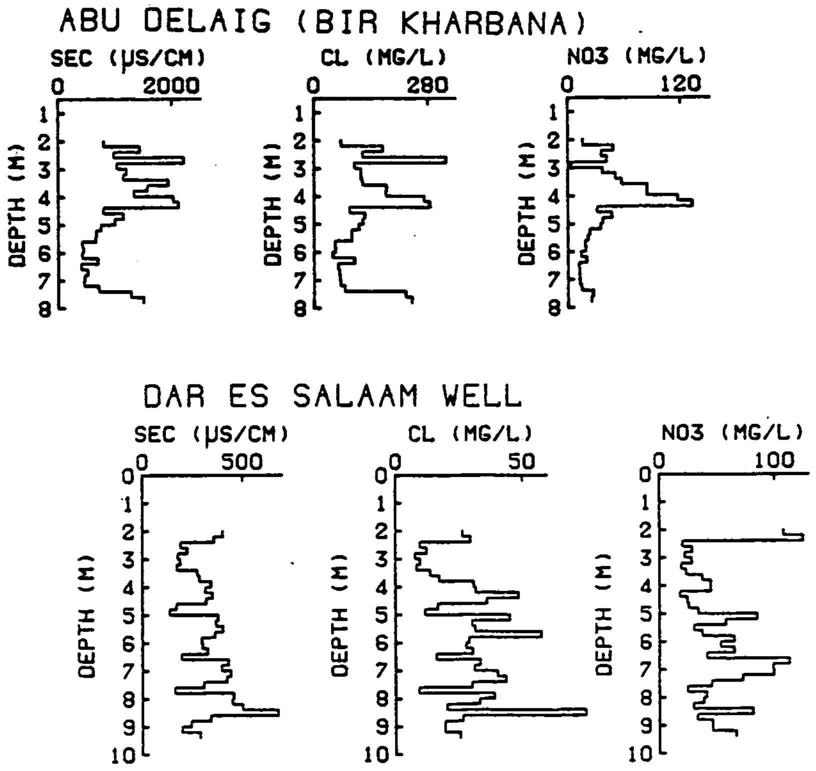


Figure 28. Solute profiles for two dug wells at Abu Delaig (Bir Kharbana and Dar es Salaam).

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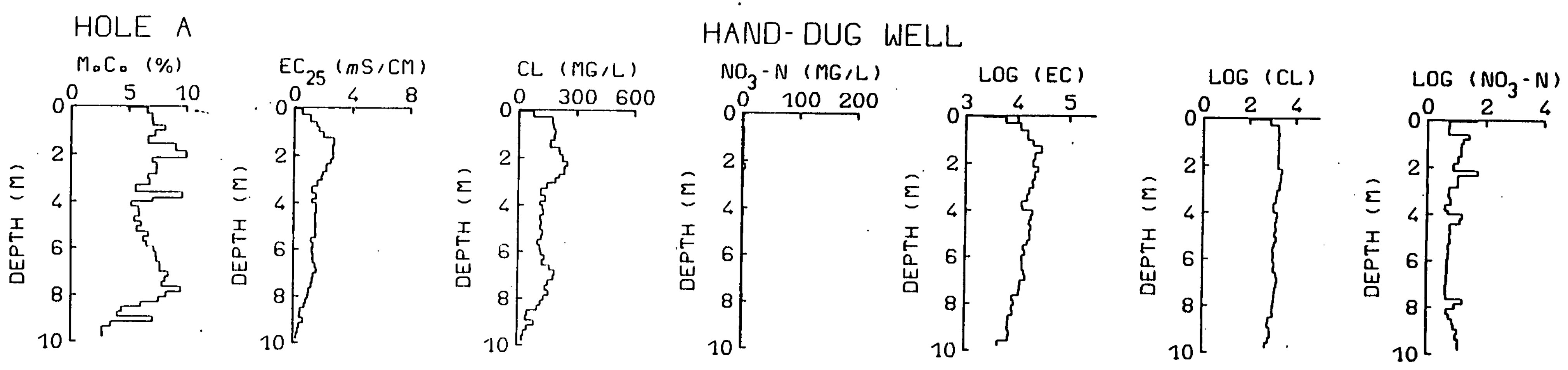
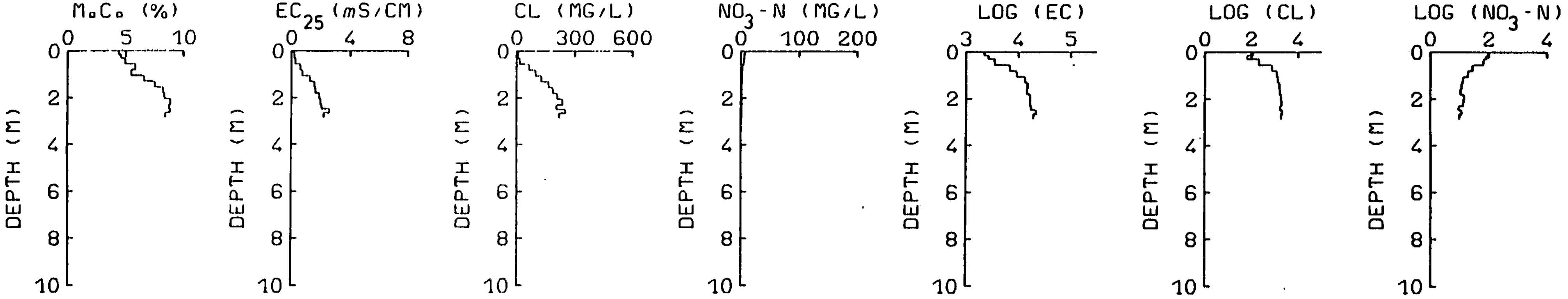


Figures 31-46. Moisture and solute profile results for hand-dug wells and auger holes from Abu Delaig. Data shown are: moisture content M_oC_o in per cent (dry weight basis); specific electrical conductance (EC_{25}) of the elutriate; chloride concentration of the Elutriate (Cl); nitrate concentration for the elutriate (NO_3-N); log of specific electrical conductance of soil moisture after correction for moisture content (LOG EC); log chloride concentration of the soil moisture after correction for moisture content (LOG CL); log concentration of nitrate in soil moisture after correction for moisture content (LOG NO3).

32

HOLE B



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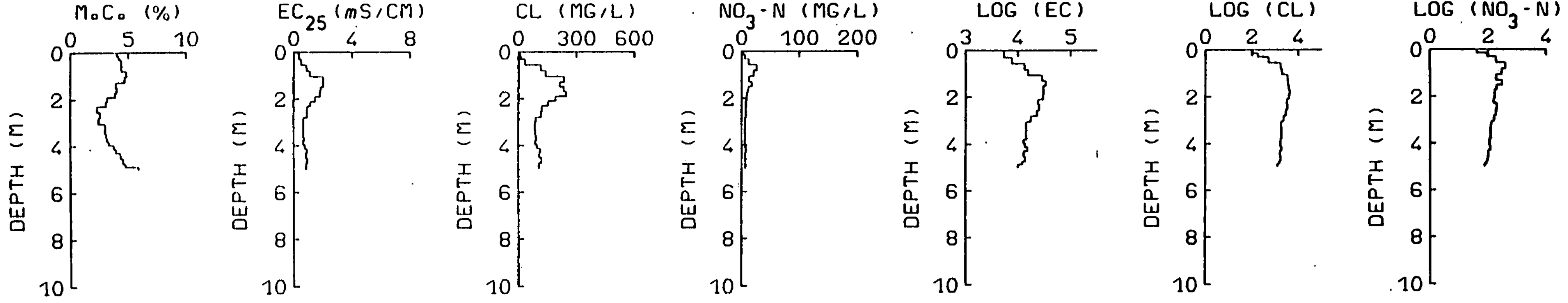
HOLE C



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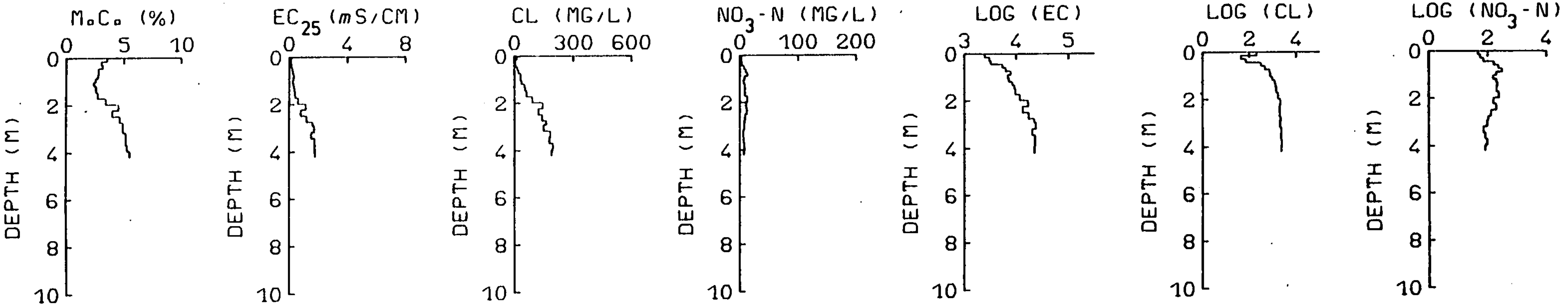
HOLE D



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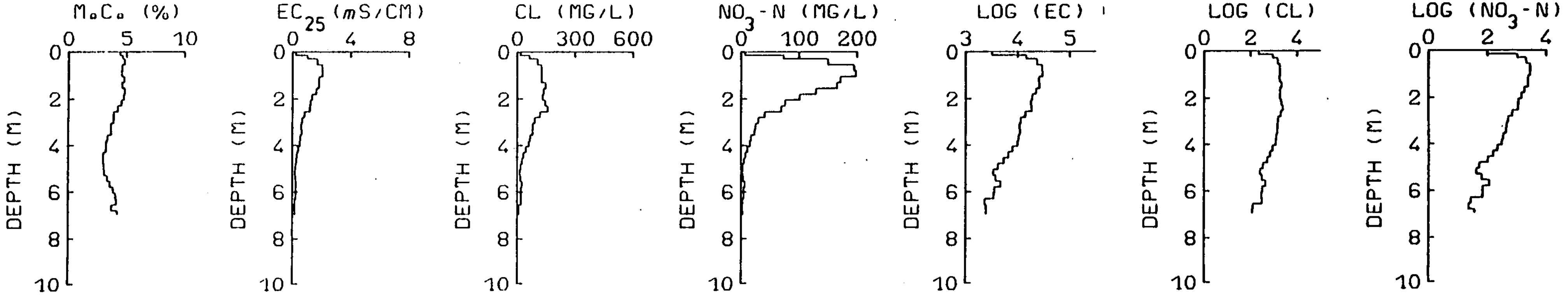
HOLE E



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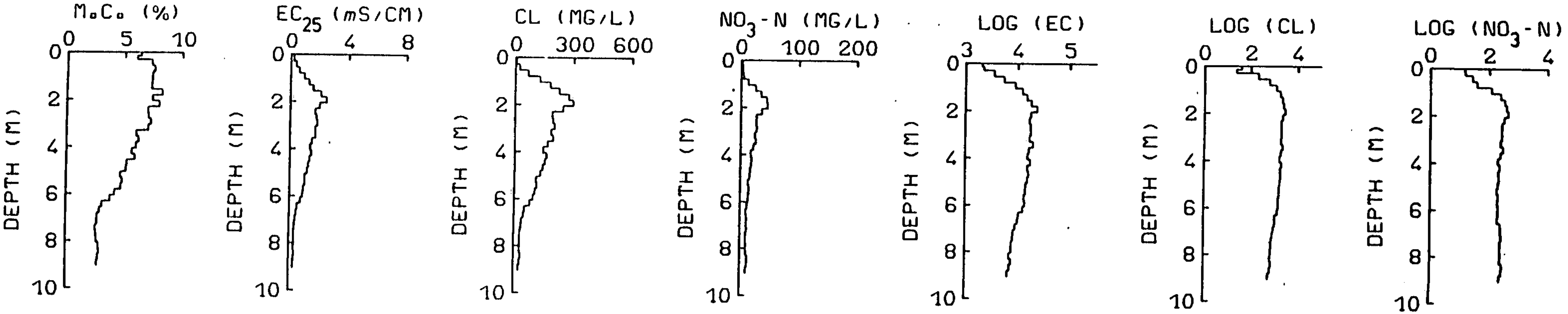
HOLE G



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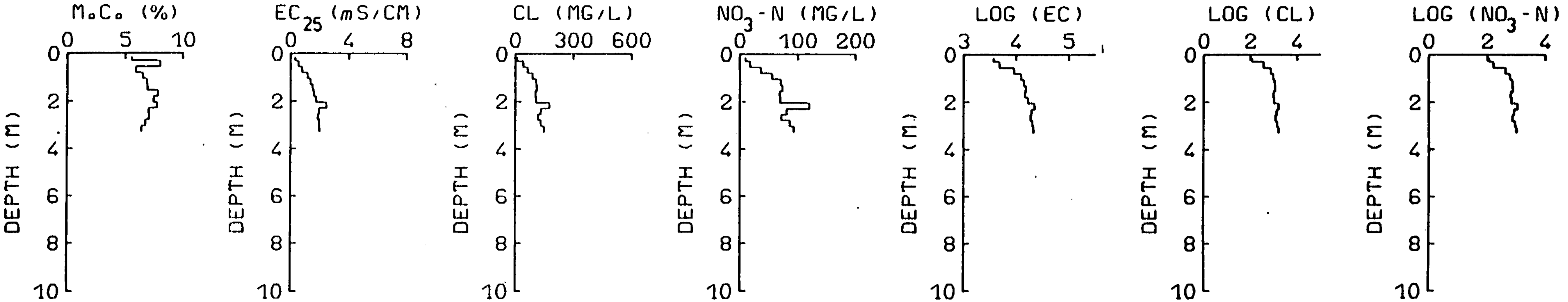
HOLE H



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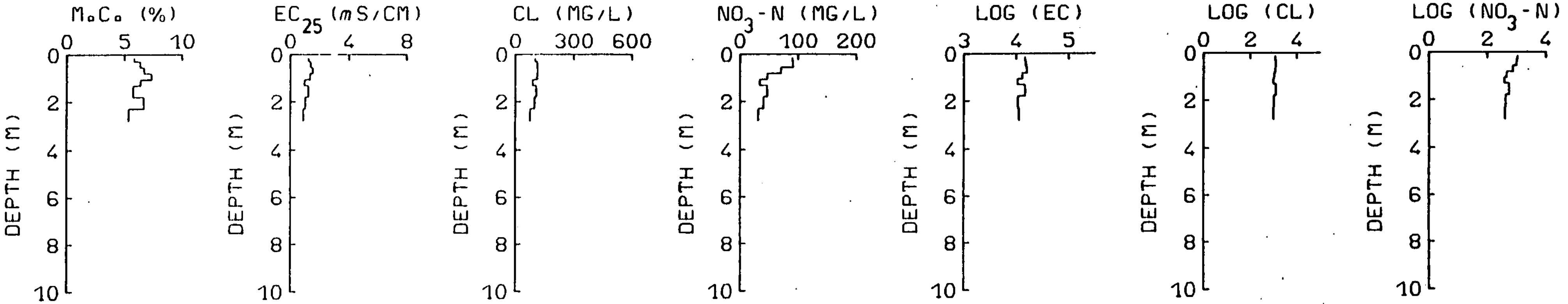
HOLE J



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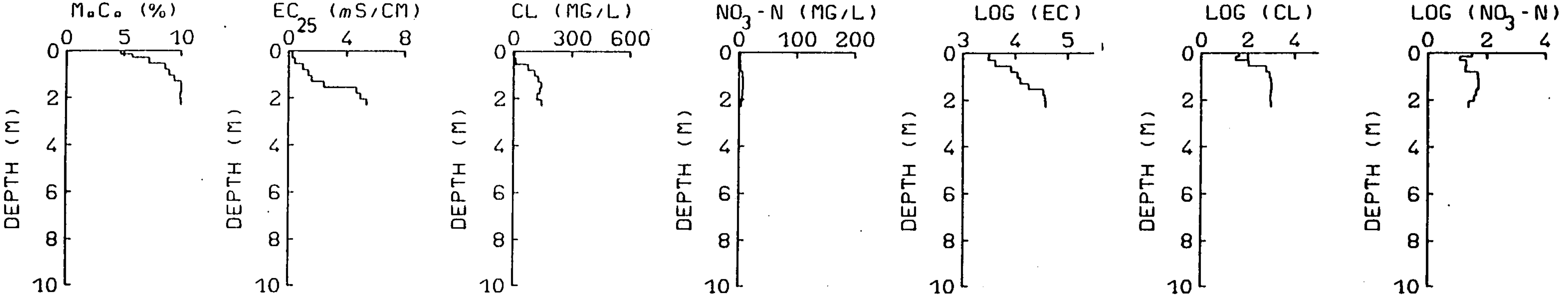
HOLE K



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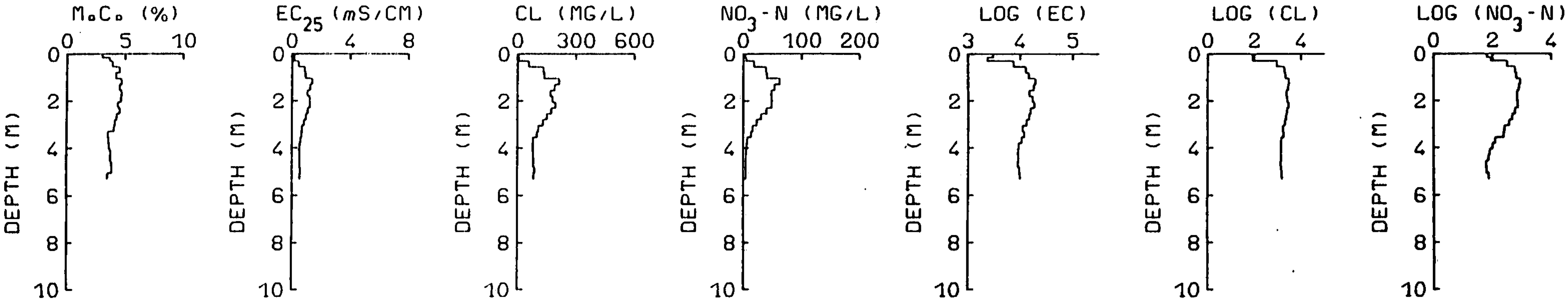
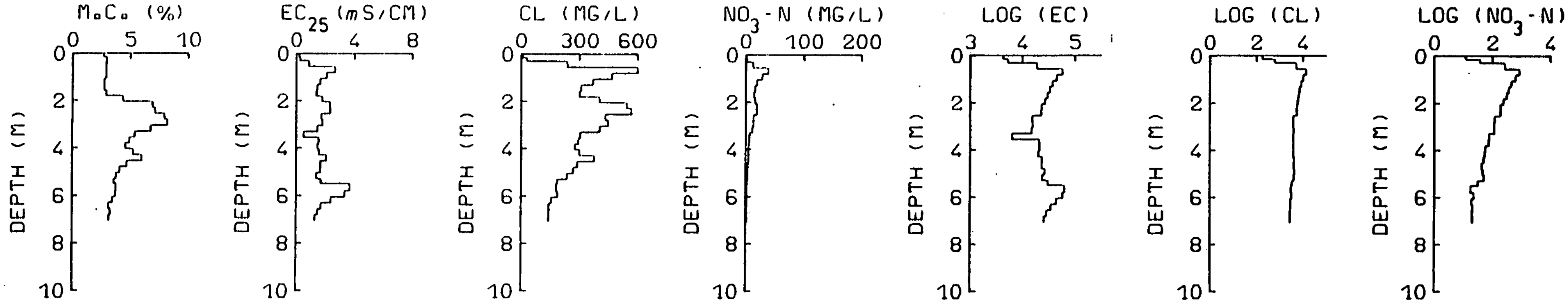
HOLE M



41

HOLE N



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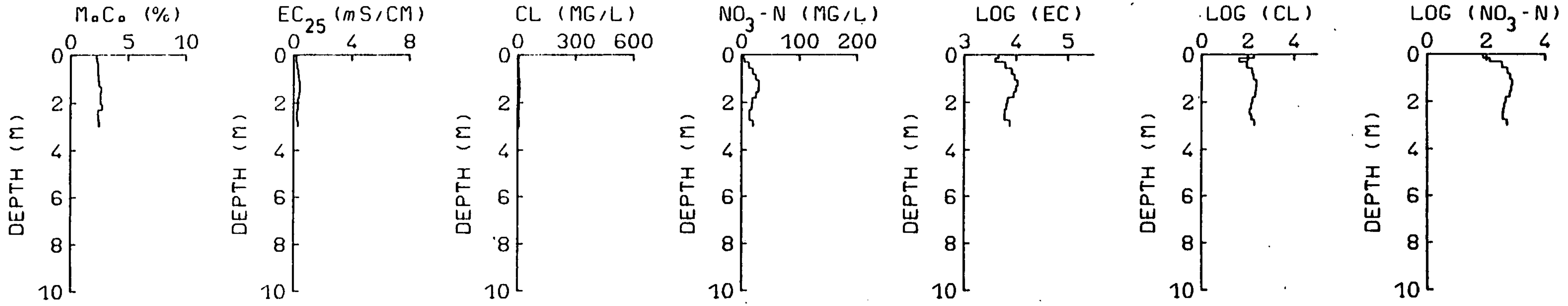
HOLE P



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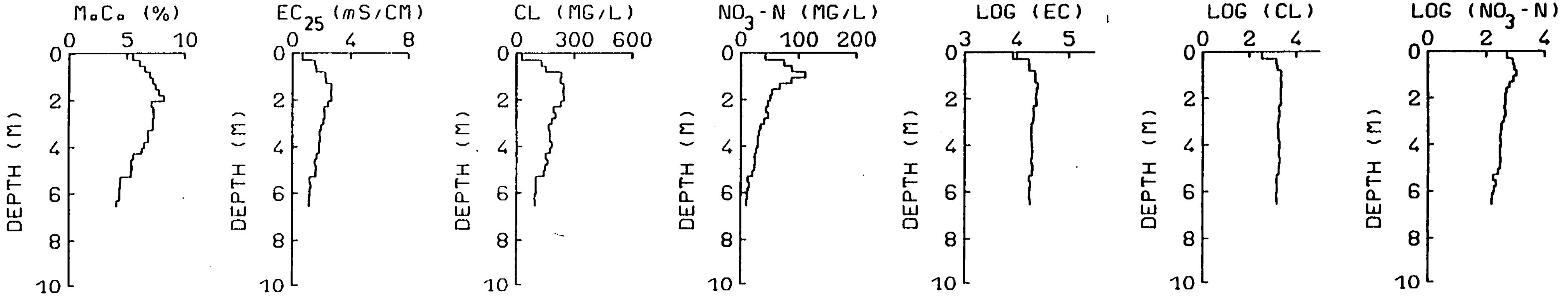
HOLE Q



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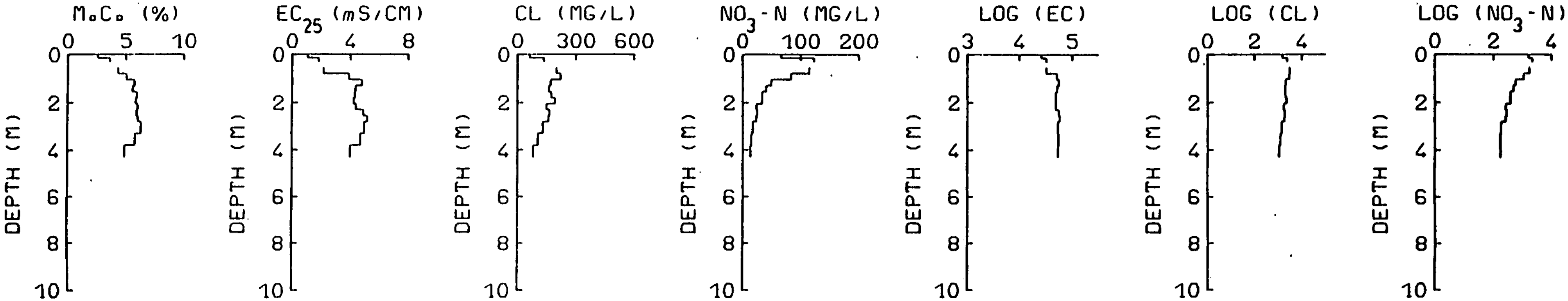
HOLE S



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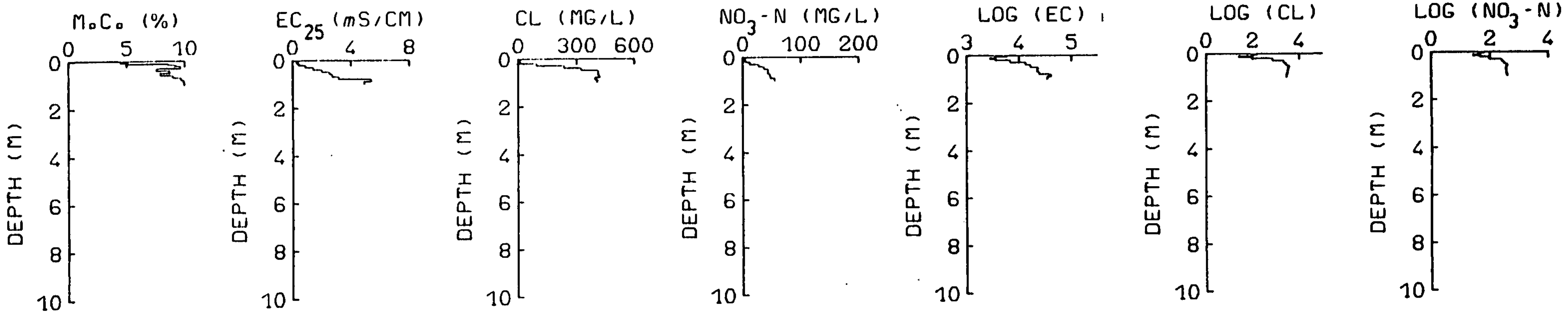
HOLE T



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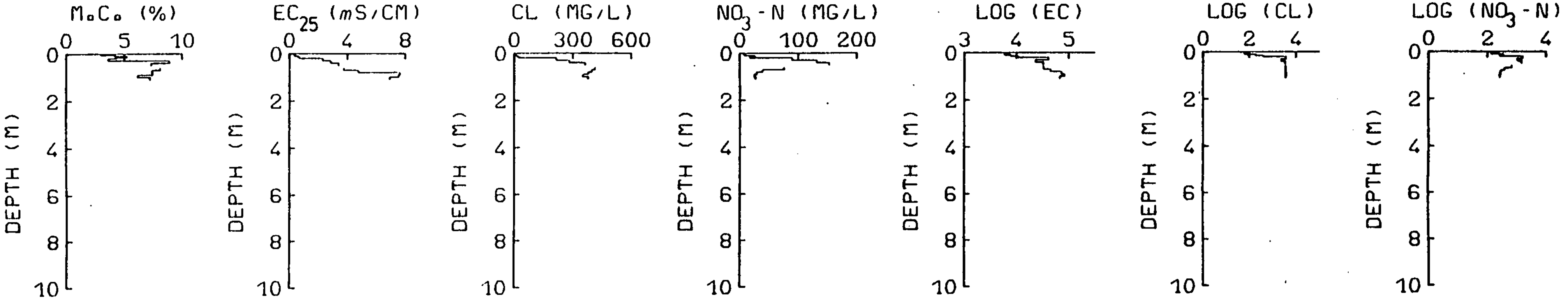
HOLE U


M.C. (%)
0
5
10
EC$_{25}$ (mS/CM)
0
4
8
CL (MG/L)
0
300
600
NO$_3$-N (MG/L)
0
100
200
LOG (EC)
3
4
5
LOG (CL)
0
2
4
LOG (NO$_3$-N)
0
2
4
DEPTH (M)
0
2
4
6
8
10

and gave 68 mg l^{-1} Cl (Dar es Salaam) and 850 mg l^{-1} (Bir Kharbana). Mean direct recharge values of 3 mm/yr and 0.25 mm/yr respectively for these two sites were obtained. If 3 mm/yr proved to be generally applicable, this represents a regional estimate of recharge of 3000 m^3/km^2/yr.

The results from this preliminary drilling demonstrated that using simple techniques recharge estimates could be obtained in this rather difficult terrain having low summer rainfall. However, it was clear that the recharge rates were very low.

5.7.2 Solute profiles, 1983 survey

Results were obtained from two sources - a hand dug well at the site of the base camp at Abu Delaig and from fifteen auger drill holes located within a 3 km radius of Abu Delaig and sited in interfluve areas.

Results from the field work included moisture content and specific electrical conductance for each profile. These were plotted as the project progressed enabling an approximate estimate of recharge to be made on site (assuming a constant ratio between SEC and Cl). Examples of field diagrams are shown in Figures 29 and 30 (Appendix).

The final results for each well or hole including Cl, NO_3 data measured in UK and corrected for moisture content are given in Figures 31 to 46; raw data are included in Table 13 (Appendix 2). Results are quoted both as elutriate concentrations in mg/l (NO_3 and Cl) or µS cm^{-1} (in the case of SEC), and as log concentrations in the interstitial water after correction for the dilution incurred during elutriation.

The moisture contents (plotted on a dry weight basis) range from 2% to nearly 11% depending upon lithology. The highest values occur in clay rich horizons, e.g. hand dug well A and borehole K, lowest values are found in some gravels and grits. The top metre of profile is usually of similar moisture content to the remainder of the profile. Sampling took place within three months of the end of the rainy season and so the uppermost zone which is above the zero flux plane will have changing moisture content according to season. Lower moisture contents are observed (hole P) in the pure sands (within the wadi section).

The SEC profiles are a reflection of the total mineralisation of the interstitial waters (or elutriates) in the profile. After correction for moisture content it is found that moisture SEC's range from 2190 to 79430 µS cm^{-1}, equivalent to a total mineralisation from about 1300 mg/l to values somewhat above those of sea water.

Chloride generally mirrors the profiles for SEC suggesting that Cl is a major constituent of the interstitial water. However there are likely to be other anions, especially SO_4 and NO_3 contributing to the specific electrical conductance value. The chloride concentrations range from 56-14310 mg/l.

Nitrate is present in significant amounts in borehole cores drilled south of the main wadi (Figure 47) but in holes to the north, e.g. A, B, C, D, K, background values of around 10 mg l^{-1} NO_3-N are found. The highest concentrations are around 2800 mg/l NO_3-N in interstitial solutions, for example in borehole E. The reasons for the very high nitrate must lie in the past or present vegetation and land use. North of the wadi there is grazing land with acacia trees and in the area drilled there was no trace of recent or historical settlement. South

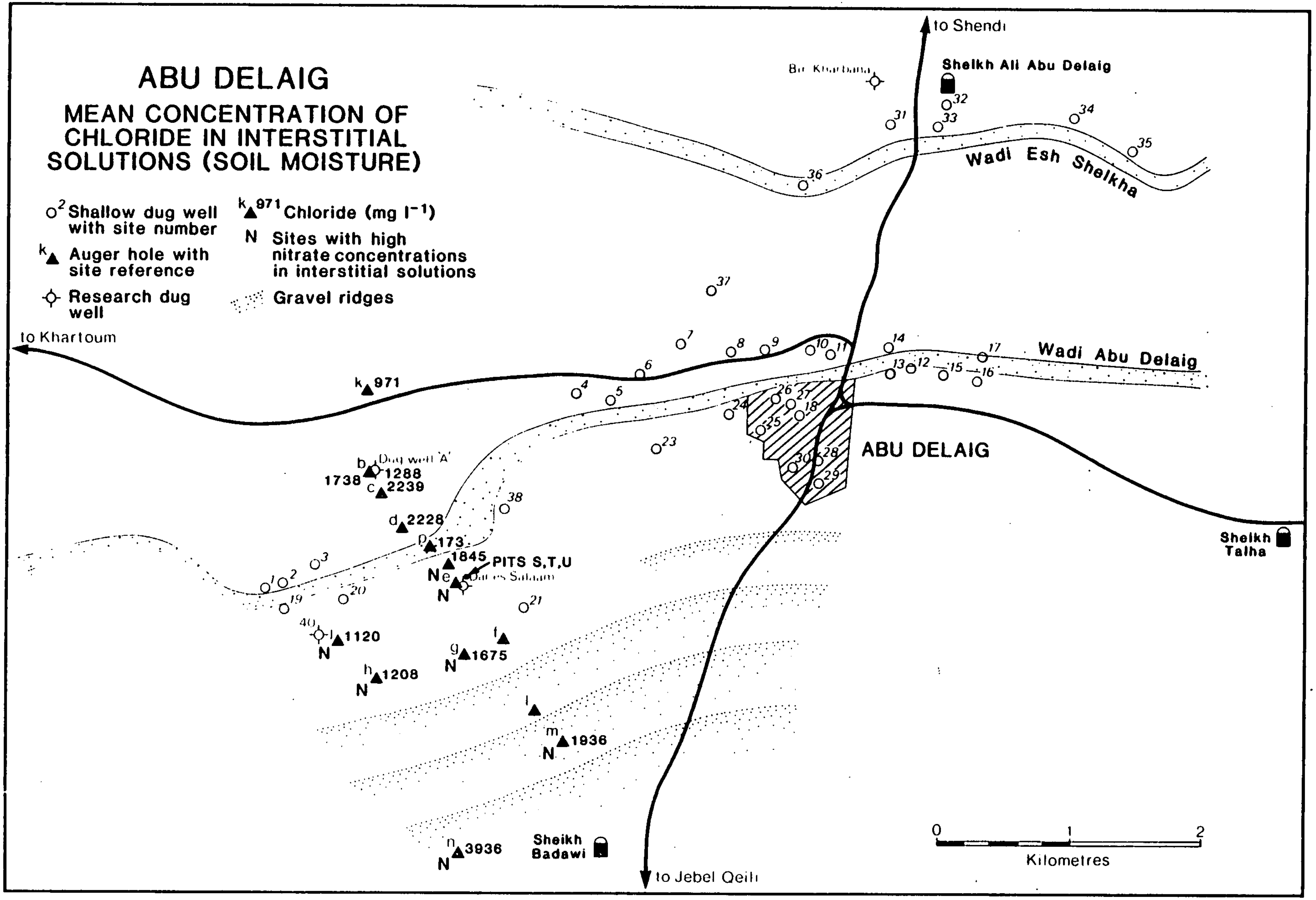


Figure 47. Mean concentration of chloride in interstitial solution of unsaturated zone profiles. Also shown are sites with high nitrate in soil moisture.

of the wadi, the land chosen for drilling was flat grassland but within a few hundred metres of settlements. The most likely causes of the different nitrate concentrations are therefore (a) a net removal of NO_3 by plant uptake and harvesting to the north of the wadi or (b) a net input of NO_3 to the south of the wadi from domestic/agricultural products. This will be further discussed below.

Chloride concentrations increase from the surface downwards but reach near constant, steady-state values within the top two metres although often within the top metre of the profile. Invariably the chloride concentrations (and SEC) at the top of the profiles are considerably lower than those at depth. One explanation for this is that any salt accumulation at the top of the profile is leached downward during periods of intense rainfall (the rainfall has a low chloride concentration). Subsequently, the top metre or so of the profile dries out first of all by upward capillary movement of water (and salts) but later by the upward movement of water vapour only.

Table 14. Mean chloride concentrations in interstitial waters for profiles at Abu Delaig and estimates of direct recharge. Mean chloride values are obtained after correction for dilution resulting from the elutriation method.

Borehole	Interval (m)	Mean Chloride Concentration		No. of Meas.	R_D (mm)
		log (mg/l)	mg/l		
Hand-dug well 'A'	1.0 -9.80	3.110	1288	39	0.88
B	1.05-2.85	3.240	1738	8	0.66
C	1.05-5.00	3.350	2239	20	0.51
D	2.24-4.20	3.348	2228	8	0.51
E	0.80-4.05	3.239	1734	13	0.66
	4.05-6.95	2.520	331	12	3.45
	0.80-6.95	2.894	783	25	1.46
G	2.05-8.80	3.224	1675	27	0.68
H	0.80-3.30	3.082	1208	10	0.94
J	0.15-2.80	3.049	1120	8	1.02
K	0.80-2.30	2.987	971	6	1.17
M	0.80-5.30	3.287	1936	18	0.59
N	1.55-1.80	3.595	3936	22	0.29
P	0.55-3.00	2.238	173	10	0.
Q	0.80-6.55	3.266	1845	23	0.62
S	1.30-4.30	3.221	1663	9	0.69
(T)	0.50-1.00	3.451	2825	5	0.40
(U)	0.60-1.10	3.572	3732	5	0.31

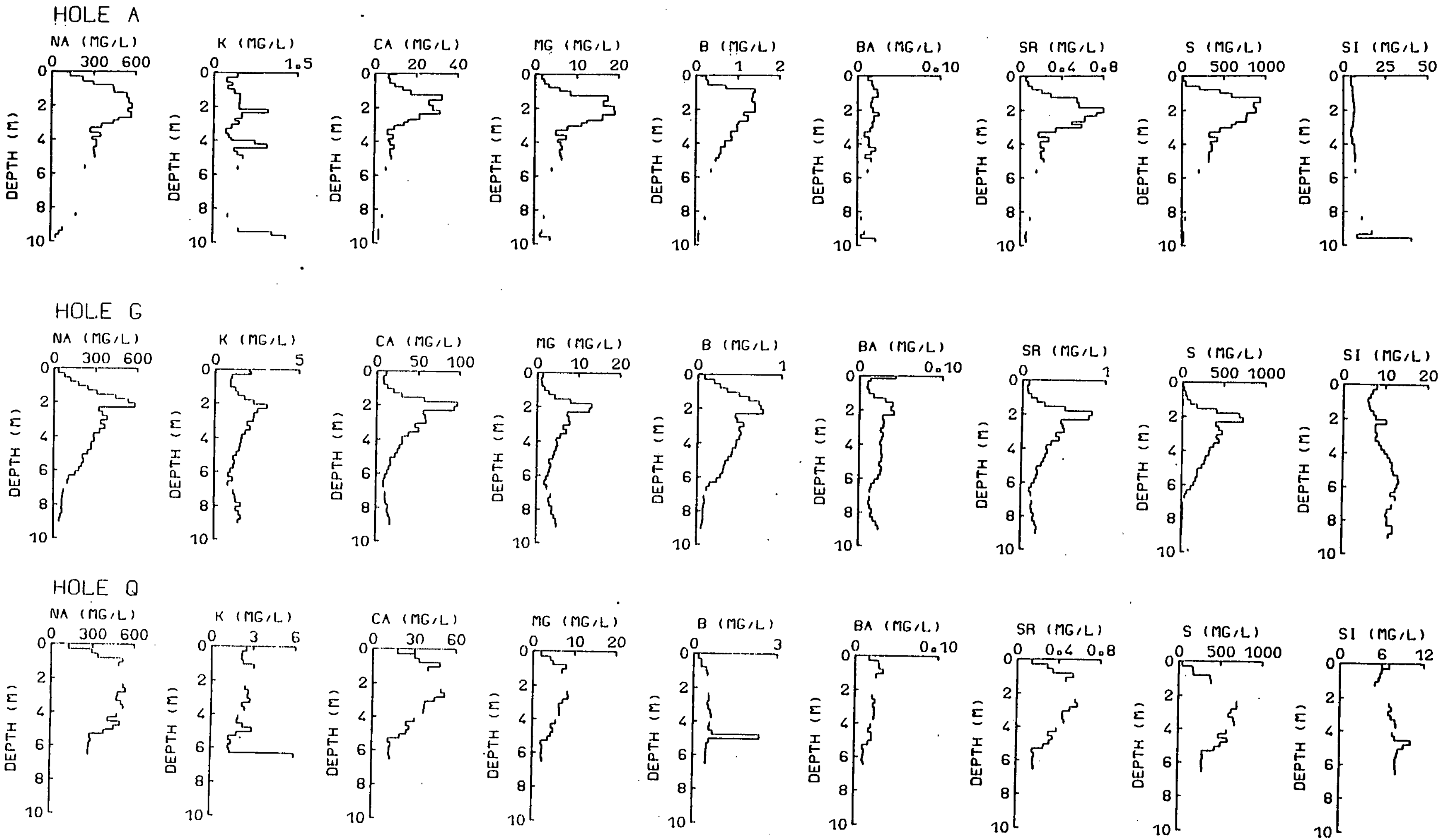


Figure 48. Solute profiles for major and minor elements carried out on elutriates from hols A, G, Q.

In some profiles (D, H, Q) the chloride remains constant with depth, in others, (e.g. E, G, S) there is a tendency for slight chloride decrease with depth; in hole E the decrease with depth is more marked than in the other two.

The mean chloride concentrations and recharge estimates have been calculated for the steady-state sections of the profiles (Table 14). The intervals used range from 0.50 to 9.80 m below ground level. Chloride concentrations in the unsaturated zone are high and range from 1000 to nearly 4000 mg/l. The highest value (profile N) occurs at the top of a sandstone ridge above the wadi where surface runoff is expected to be highest; site M, also on the ridge has slightly higher chloride. Nearly all other sites (Figure 44) on the plain have lower chloride concentrations implying higher recharge. North of the wadi the lowest chloride value (971 mg/l) is found (hole K) in a relatively clay-rich profile and the highest (2239 mg/l) nearest the river. Within the wadi channel itself much lower values (borehole P - 173 mg/l) are found indicating an added input of fresh water from surface runoff.

These chloride values indicate a direct recharge component in the range 0.29-3.45 mm/yr.

5.7.2.1 Minor element concentrations in elutriates

Elutriate samples from three profiles (A, G, Q) were analysed by ICPOES (inductively coupled plasma) for Na, K, Ca, Mg, B, Ba, Sr, S_T and Si. The results (Figure 48) are included here for completeness but their interpretation can only be tentative since they may be compared with the chloride profiles in Figures 31, 36 and 43 respectively. The chloride profile shape in hole G, for example, compares quite well with that of Na, K, Ca, Mg, B, Sr and SO_4 (5) suggesting that the concentrations for these elements may be close to those of interstitial solutions. Silica and barium on the other hand are more constant in their composition indicating a likely buffering mechanism. Further interpretation of this data would for example need comparison with (centrifuge) extracted fluid compositions and this will form part of future studies.

5.7.3 <u>Solute profiles, 1984 season</u>

Two research dug wells were constructed by NAW staff during early 1984, the first at Abu Delaig (AD 40), the second at Tomeid Haj el Tair. Samples were collected in Kilner jars at approximately 1 m depth intervals during digging and

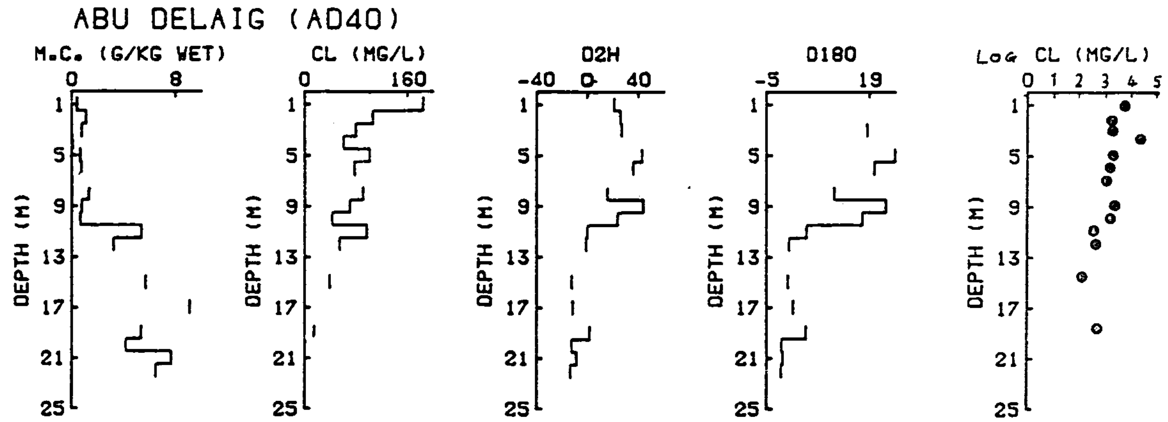


Figure 49. Chloride soil moisture and stable isotope profiles of unsaturated zone moisture from a dug well at Abu Delaig (AD 40).

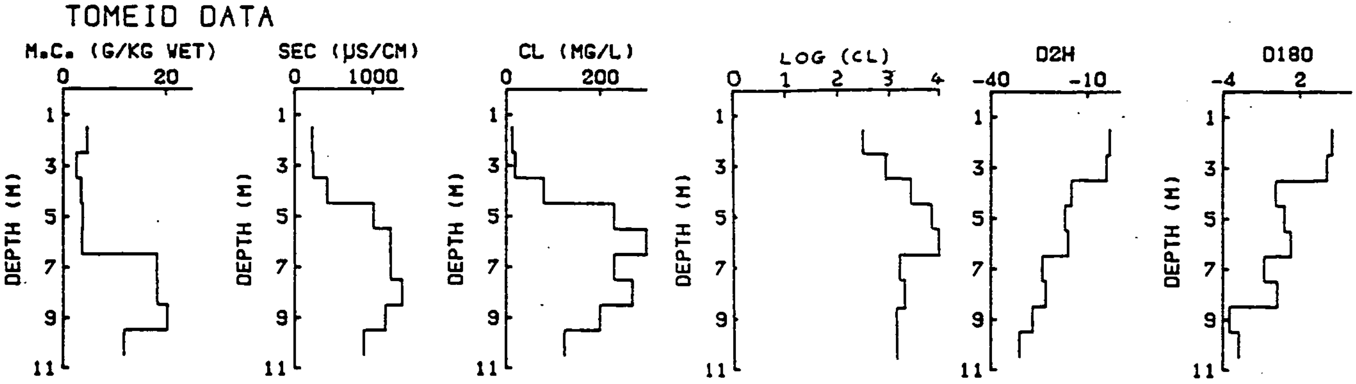


Figure 50. Chloride, SEC, soil moisture and stable isotope profiles of unsaturated zone moisture at Tomeid Haj el Tair dug well, Wadi el Hawad.

shipped to UK for analysis. These samples arrived safely (except two broken bottles) and were then analysed for elutriate chemistry, moisture content and stable isotope moisture composition. The results are given for all these parameters in Figures 49 and 50.

AD 40. This profile was obtained from a dug well to the west of the Abu Delaig area (Figure 13) and was completed to the water table. Despite the rather incomplete data from some intervals it nevertheless is the only profile from the area with complete data, including isotopes, on account of the coarse grain-size of the sands but this is offset by higher chloride concentrations in the elutriates. The corrected profile for chloride is linear across the moisture gradient to 10 m with a mean value of 1580 mg l^{-1} Cl^{-}. Below this depth, the salinity decreases and there is also a shift in the $\delta^{18}O$, $\delta^{2}H$ isotope

Table 15. Oxygen and hydrogen stable isotope results for interstitial waters distilled from moisture profile of AD40.

1 m	+21 % ^{2}H	- % ^{18}O
2	+26	-
3	+27	+18.5
4	-3	-
5	+43	+24.9
6	+36	+20.1
7	-	-
8	+16	+10.7
9	+44	+22.8
10	+24	+17.3
11	0	+ 4.2
12	-1	+ 0.2
13	-	-
14	-	-
15	-12	- 0.1
16	-	-
17	-11	+ 1.1
18	-	-
19	+2	+ 4.0
20	-12	- 1.6
21	-8	- 1.3
22	-13	- 1.7

compositions towards lighter values at around the same depth. The interrelationships are discussed further below. However, the results may be interpreted in two ways: (1) there is recharge similar to the other boreholes in the Abu Delaig area of about 1 mm/yr but the deeper part of the profile is a record of higher recharge sometime in the past, (2) there is a component of upward movement of water from the water table accounting for the isotopic similarity of the shallow groundwater and that in the lower part of the profile.

Tomeid Haj el Tair (Site 2). This profile up to 11 m was completed by NAW staff in 1984. The exact site details are unknown and so also is the total depth in relation to the water table. However, it is likely that this dug well did not reach the water table. The interpretation of data is therefore tentative. There appears to be a steady state value of chloride which is reached below 7 m of about 1500 mg l^{-1} Cl^{-}, although there is higher salinity above this depth. The stable isotope profiles also show a change towards lighter values with depth and the significance of this is also discussed below.

5.7.4 Stable isotopes in the unsaturated zone moisture, 1983 survey

5.7.4.1 Objectives

Unsaturated zone moisture was obtained from soil and rock material sampled at various depths, chiefly in the Abu Delaig area but also near Tomeid Haj el Tair. Water was extracted from this material by distillation (see 5.6.2). The object of this was twofold:

(i) to examine the relationship, if any, between soil moisture and perched water bodies beneath wadis and/or the deeper regional aquifer

(ii) to determine whether stable isotope techniques developed by workers such as Allison & Barnes (1983), Allison et al. (1983), Barnes and Allison (1983) and Sonntag et al. (1985) could be used to obtain estimates of infiltration or evaporation rates.

5.7.4.2 Dug well samples

Two isotope profiles were obtained down to a depth of 22 m at Abu Delaig (AD 40), Table 14 (Figure 49), and 10 m near Tomeid Haj el Tahir (B) (Figure 50). When both δ^2H and $\delta^{18}O$ results are plotted on a conventional δ-diagram (Figure 51), it is apparent that they lie on lines of similar slope, though with different intercepts. This results in the two regression lines reaching the meteoric line at different points and therefore suggests that the evolution of each profile has been somewhat different. Dugwell AD 40 at Abu Delaig has a slope which intercepts the local meteoric line at about -15 % δ^2H and -3.6 % $\delta^{18}O$. This corresponds almost exactly to the composition of water sampled from shallow dugwells in Abu Delaig, which are themselves recharged predominantly from wadi flow. A 'steady state' isotopic composition is only reached at 15 m below surface, while the water table was at about 25 m. The shape of the isotope profile, coupled with chloride evidence (i.e. slightly decreasing salinity with depth) suggest that this may be the result of discharge rather than recharge. This is also believed to occur for example in parts of Algeria (Fontes et al., in press), albeit from somewhat shallower depths; however given the right temperature and humidity gradients upward vapour movement might be possible from this order of depth. Using expressions developed by Allison and Barnes (1983) a tentative discharge figure of 0.8 mm yr^{-1} has been calculated.

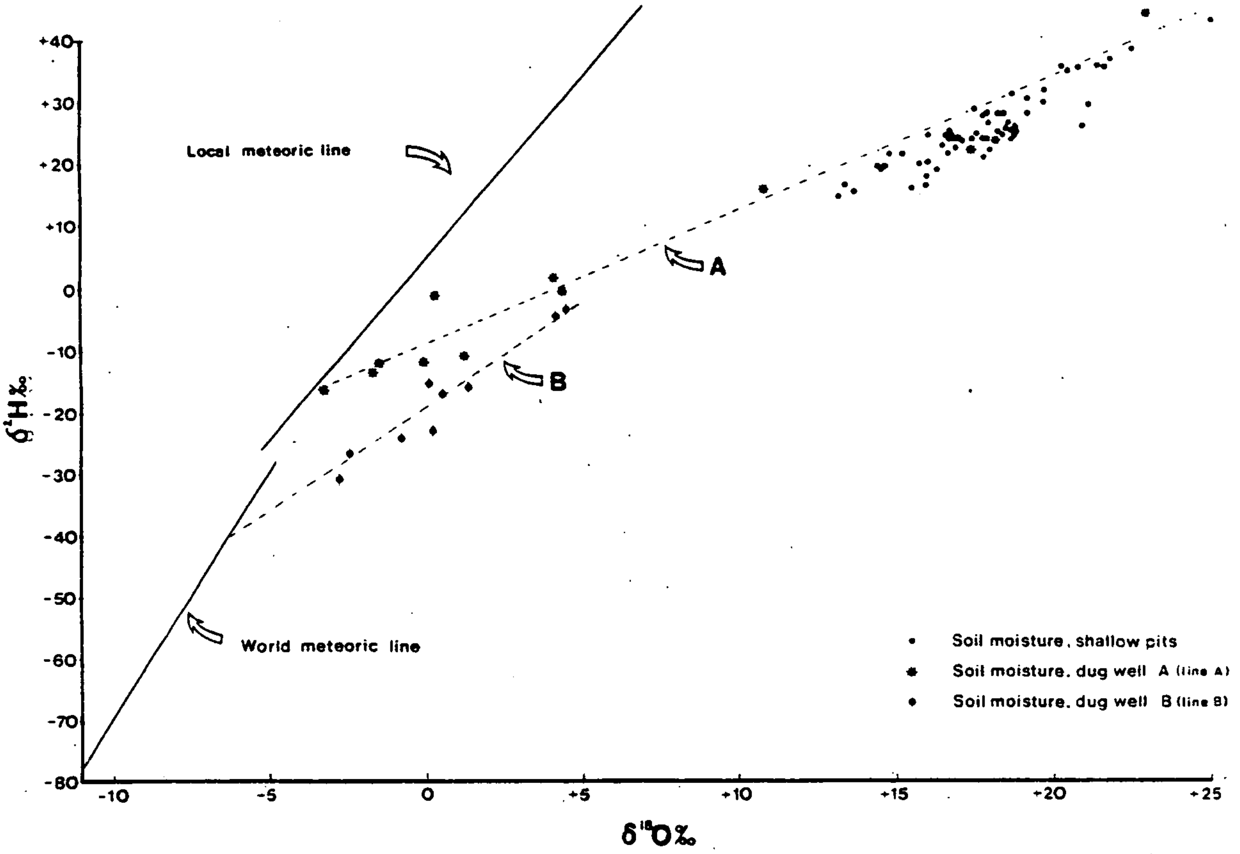


Figure 51. Isotopic plot (δ^2H vs δ^{18}O) of soil moisture in profiles AD 40 (profile A) and Tomeid (profile B) and also shallow pit samples.

The profile of dugwell B lies on a regression which cuts the meteoric line at about -40 ^{o}/oo δ^2H and -6.5 ^{o}/oo δ^{18}O near to the composition of palaeogroundwaters (Figure 51). Its slope of 3.4 is again indicative of evaporation, though less so than for profile A. Local pumped groundwater has a similar isotopic composition and it is considered that this profile could also be the product of evaporative modification. Although it does not become as enriched as profile A (even with a thinner unsaturated zone) it is almost impossible that present day recharge could result in such isotopically light recharge. It is possible however that it represents a basically discharging profile modified by infrequent recharge events. If there is discharge then it is occurring at a very low rate, well below the 0.8 mm calculated for profile A. The only other explanation for this profile is the possibility of extremely slow recharge to the aquifer, such that the lower parts of the profile represent palaeorecharge rather than present day infiltration. Assuming an unsaturated zone of 10 m, a porosity of 30% and a time of 5000 years, infiltration would have to be occurring at a rate of 0.2 mm yr^{-1}.

5.7.4.3 Shallow pit samples

Three shallow pits (maximum depth 2 m) were dug in the Abu Delaig area. These were sampled over 5 cm intervals to 20 cm below surface, and over 10 cm intervals thereafter. Results are given in Table 15 and values (δ^2H only) are plotted against depth in Figure 52. These plots reach a peak just below surface and are typical of arid and semi-arid zone isotope profiles, though the size of

Borehole S

No	Depth (cm)	Field m.c. (% dry wt)	Lab m.c. (% dry wt)	δ^2H	$\delta^{18}O$
S 1	0-15	0.49	3.28	+29	+21.0
S 2	15-30	1.50	4.65	+26	+20.3
S 3	30-55	-	4.93	+30	+19.6
S 4	55-80	2.92	5.75	+28	+19.1
S 5	80-105	2.92	5.98	+25	+17.5
S 6	105-130	3.59	6.26	+25	+18.3
S 7	130-155	3.43	6.27	+25	+18.6
S 8	155-180	3.80	6.74	+22	+17.9
S 9	180-205	3.70	6.71	+21	+17.7
S 10	205-230	3.86	6.72	+24	+17.6
S 11	230-255	3.77	6.47	+22	+17.2
S 12	255-280	3.91	6.14	+24	+16.8
S 13	280-330	4.14	6.05	+16	+15.3
S 14	330-380	3.64	6.22	+24	+16.9
S 15	380-430	2.76	4.57	+28	+17.8

Pit S

No	Depth (cm)	Field m.c. (% dry wt)	Lab m.c. (% dry wt)	δ^2H	$\delta^{18}O$
PS 1	0-5	-	2.81	+29	+17.8
PS 2	5-10	-	4.30	+38	+22.3
PS 3	10-15	-	5.19	+37	+21.7
PS 4	15-20	-	5.49	+36	+21.5
PS 5	20-30	-	6.05	+32	+19.6
PS 6	30-40	-	6.18	+26	+18.4
PS 7	40-50	-	6.24	+28	+18.3
PS 8	50-60	-	6.29	+26	+18.7
PS 9	60-70	-	7.17	+24	+18.5
PS 10	70-80	-	6.92	+26	+18.5
PS 11	80-90	-	7.18	+24	+17.8
PS 12	90-100	-	7.69	+27	+17.8

Pit T

No	Depth (cm)	Field m.c. (% dry wt)	Lab m.c. (% dry wt)	δ^2H	$\delta^{18}O$
PT 1	0-5	2.36	2.62	+26	+16.6
PT 2	5-10	2.98	4.53	+35	+20.3
PT 3	10-15	6.38	7.43	+32	+18.6
PT 4	15-20	6.93	9.27	+25	+15.9
PT 5	20-30	7.40	9.58	+22	+15.1
PT 6	30-40	5.37	8.66	+20	+14.3
PT 7	40-50	6.51	8.05	+16	+13.6
PT 8	50-60	5.71	8.51	+24	+16.6
PT 9	60-70	6.77	8.33	+22	+14.7
PT 10	70-80	7.42	9.36	+19	+14.4
PT 11	80-90	7.65	9.86	+17	+13.3
PT 12	90-100	8.65	10.06	+15	+13.1

Pit U

No	Depth (cm)	Field m.c. (% dry wt)	Lab m.c. (% dry wt)	δ^2H	$\delta^{18}O$
PU 1	0-5	0.90	2.96	+29	+17.4
PU 2	5-10	2.07	4.35	+36	+20.7
PU 3	10-15	3.10	4.54	+36	+21.4
PU 4	15-20	2.19	5.31	+36	+21.4
PU 5	20-30	1.49	6.10	+31	+19.1
PU 6	30-40	6.67	6.56	+26	+18.7
PU 7	40-50	5.12	6.64	+28	+18.2
PU 8	50-60	-	6.54	+26	+18.1
PU 9	60-70	5.88	6.68	+28	+17.7
PU 10	70-80	5.20	7.33	+24	+17.9
PU 11	80-90	5.52	7.57	+24	+17.0
PU 12	90-100	3.96	7.96	+23	+16.8
PU 13	100-110	5.04	7.78	+19	+15.2
PU 14	110-120	-	7.55	+23	+16.3
PU 15	120-130	-	7.91	+20	+15.6
PU 16	130-140	-	8.28	+22	+16.6
PU 17	140-150	-	8.40	+20	+14.5
PU 18	150-160	-	8.57	+21	+15.9
PU 19	160-170	-	8.09	+17	+15.8
PU 20	170-180	-	7.81	+18	+15.9
PU 21	180-190	-	5.11	+25	+16.5
PU 22	190-200	-	3.79	+25	+16.6
Camp dug well	11.60 m		9.94	-29	-2.1

Table 16. Isotopic and soil moisture results for shallow pits samples (s, t, u) and for borehole S.

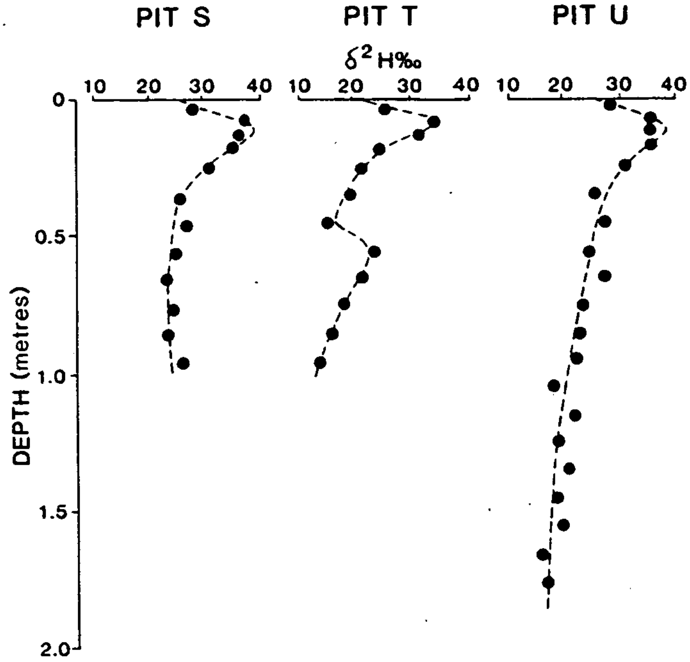


Figure 52. Plot of δ^2H with depth - shallow pits (s, t, u) drilled south of Wadi Abu Delaig.

the peak and its depth below surface can vary greatly according to local conditions. If the peak represents a drying front developing after the previous wet season it may be expected to move steadily downwards during the course of the dry season. The magnitude of the peak would be related to the amount of evaporation undergone by the near-surface soil moisture, which is governed principally by the average soil temperature and by the relative humidity of the overlying air.

A delta plot of all samples (Figure 51) shows that they fall along a line of slope of about 2.5; such a low slope is additional confirmation of extreme evaporative effects. This slope would intercept the local meteoric line in the general vicinity of local shallow dug well composition, but is difficult to relate to weighted mean local precipitation (1982-1985) at +14 ^{0}/oo δ^2H and +1.6 ^{0}/oo δ^{18}O. It would however be quite similar to the long-term weighted average recorded for Khartoum, which is about 100 km away.

As mentioned above, the characteristic shape of isotope vs. depth profiles in arid areas can in principle be used to estimate evaporation. The difficulty in this case is that in contrast to the chloride profiles no apparent steady state condition is reached and the porewater composition is greatly enriched in heavy isotopes compared to local rain or groundwater. It is also not clear how recently and to what depth, the profiles have been wetted. There is also the possibility (already mentioned) that such profiles can be developed not only by intermittent recharge and evaporative loss, but also by a process of vapour phase movement from deep groundwater. However, using the expressions developed by Allison and Barnes (1983) a tentative average evaporation figure of 76 mm has been calculated to have taken place since the last wetting of the shallow profile in September-October by about 175 mm of rain. This, plus any transpirational (i.e. non-fractionating) effects must therefore have occurred in less than two months and accordingly represents a high rate of evaporation.

Presumably the downward movement of the drying front and lessening amounts of transpiration would cause a marked decline in soil water loss during the course of the dry season. Ideally isotope vs. depth profiles would be most useful if collected at the end of the dry season, at which time the calculated amount of evaporation could be compared with the previous season's rainfall input.

5.7.4.4 Summary of stable isotope results

Porewater isotope profiles in the unsaturated zone are developed on two scales and may be the product of complex interactions between processes of recharge and discharge. Even in a profile believed to be discharging, such as is represented by dugwell A at Abu Delaig, the very top of this profile is bound to be modified by at least the previous wet season's infiltration. Therefore two rates of evaporation may be calculated from isotopic values: one for the deep profile as a whole, and the other for the near-surface section. The former represents a very long-term average, while the latter is on a much shorter scale. The possibility of a general discharge from deep groundwater punctuated by infrequent recharge events may be responsible for the shape of the isotope profile. On the other hand, there is the possibility that very low rates of recharge could lead to a situation where the isotope profile represents a record of changing climatic conditions modified only slightly by diffusion. The problem with the latter interpretation is that to calculate the possible age of a profile it is necessary to know the infiltration rate independently.

It is clear therefore that while the stable isotopic composition of unsaturated zone water can be used for estimating discharge, it must be considered in conjunction with other data such as chloride in order to constrain the number of different interpretations.

6. DISCUSSION: RECHARGE HISTORY AND HYDROGEOCHEMICAL EVOLUTION OF THE AREA

Various lines of evidence from this study may be used to examine the recharge history, including active (present day) recharge. The palaeoclimatic history of the region shows that during the early Holocene much higher rainfall (at least 400 mm/yr) occurred in the vicinity but that by 4500 BP the rainfall was as low as 100 mm or even lower than at the present. Throughout the Holocene the Nile Valley has been the main reliable source of freshwater in the region which has also replenished groundwaters both north and south of the river throughout this period. Uncertainty exists as to the amount of recharge that might have occurred regionally during the Holocene, particularly whether this recharge was continuous (even to the present day) and whether the recharge was extensive throughout the area. Permanent settlement and/or nomadic grazing must have occurred in the Wadi Hawad basin for at least 2000 years before the present. Deep dug wells, some with Roman markings, are found at strategic points in the area. It should be possible with further archaeological studies to plot the decline of the regional water table over this period; certainly the past 2-4000 years has been a period of declining water levels. Different lines of geochemical evidence presented in this study shed some further light on the recharge history. The overall picture is summarised in three diagrams - major cations, stable isotopes ($\delta^{18}O$, δD, Figures 53 and 54) and a conceptual cross section through the area (Figure 55).

The deep groundwater in the Wadi Hawad basin (with the exception of three sites east of the valley) has a uniform geochemistry (major ions, minor elements, carbon and oxygen isotopes) which suggests that it is part of one aquifer system. The radiocarbon results indicate that the water must be younger than 8000 yrs and stable carbon isotope ratios indicate a common recharge evolution

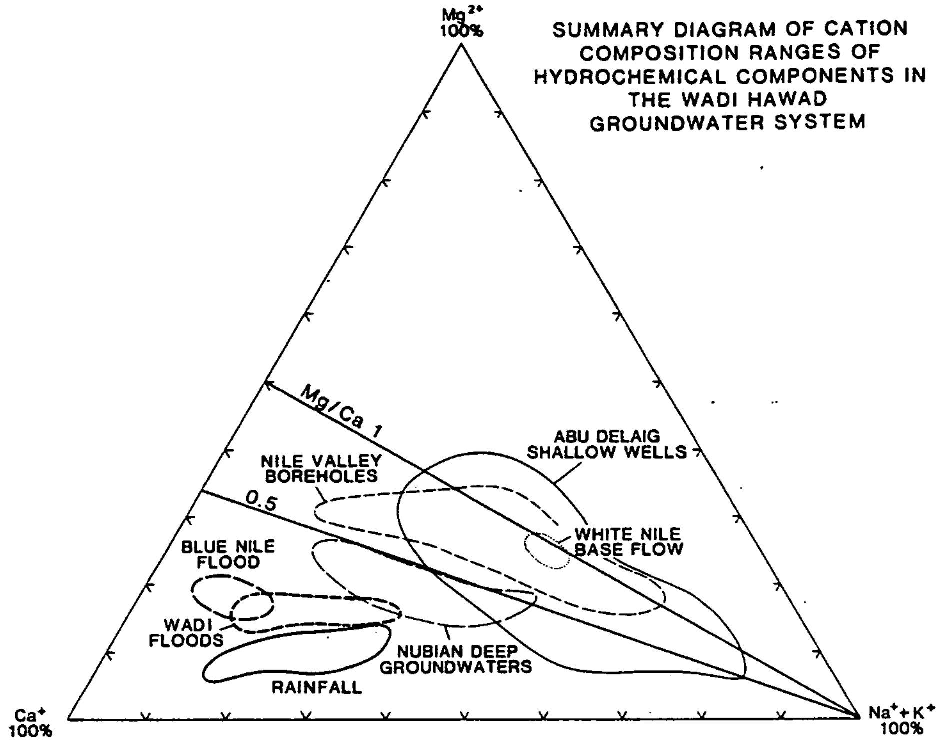


Figure 53. Summary hydrochemical diagram of principal water types in the Wadi Hawad area.

for all waters. The enrichment in lighter oxygen and hydrogen isotopes show clearly that the recharge regime during the mid-Holocene differed from that of the present day. To the east of the Wadi Hawad the groundwater is geochemically different (isotopic and inorganic parameters) and implies a different reservoir (although still palaeogroundwater) to that in the west. It seems reasonable to conclude that the regional Nubian aquifer in the Wadi Hawad area was recharged until the mid-Holocene and that the water contained therein is essentially a fossil system.

There is no evidence for recharge of the deeper regional aquifer by the present day rains or shallow groundwaters except in the Nile Valley. In the Nile Valley the adjacent groundwaters have a distinctive chemistry which bears resemblance to the river itself. The range in radiocarbon results suggests that the abstracted groundwater could be a mixture of relatively recent Nile recharge of different ages and from different depths. It is isotopically distinct from the regional Nubian groundwater and there is no evidence of any mixing of these two sources. The evidence available indicates that the river Nile has only recharged the aquifer some 10 km south of the river. It is possible that this has been or could be induced further by pumping.

Superimposed upon the deeper groundwater body in Wadi Hawad and adjacent areas, there exists a shallow aquifer system which on the basis of isotopic evidence is being replenished at the present day. This aquifer system is that which sustains vegetation, the traditional nomadic life in some areas and shallow wells in towns like Abu Delaig. The development of deep wells in the Nubian has forced a more recent reliance on the fossil system which is being mined at the expense possibly of the shallow aquifer system.

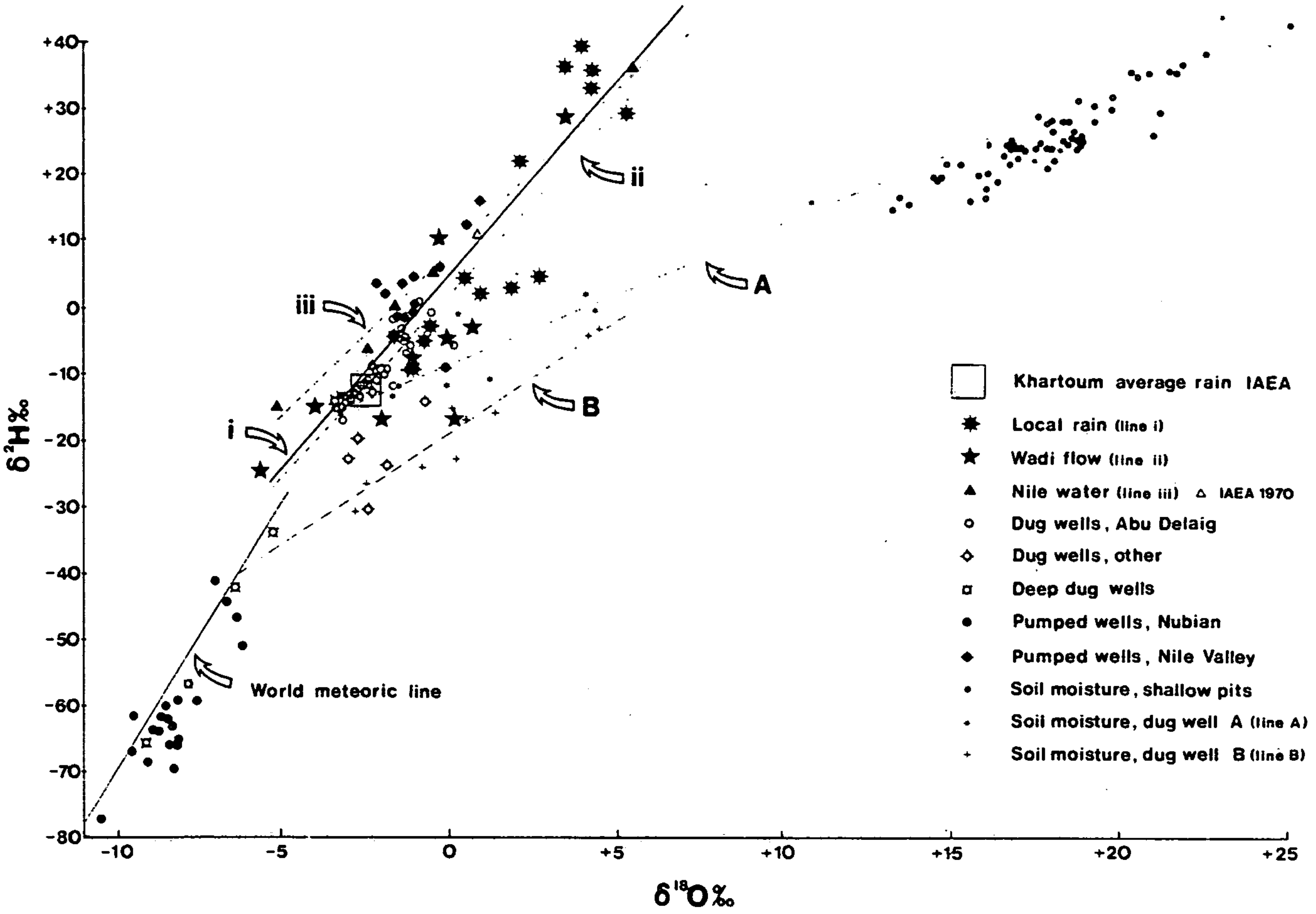


Figure 54. Summary diagram of all isotopic data - rains, surface and groundwaters including soil moisture from pits and dug wells.

Recharge studies show that one mm or less water is entering the shallow system via the interfluve areas where clay soils predominate. Even where sandstone ridges outcrop and on sloping ground, the same situation exists and recharge is negligible mainly due to the clay matrix of the sandstone regolith. Direct recharge may occur more extensively if blown or loose sand forms the main surface deposit, for example east of Kaboushir, and also along former and present wadi channels.

The only certain replenishable resource in the area away from the Nile therefore is that recharged via the wadi system during floods. Chemical and isotopic evidence show that water can rapidly recharge the shallow aquifer, e.g. at Abu Delaig and that water must flow laterally from the wadi up to a distance of a few kilometers in some cases demonstrated by the high tritium values found in this water up to 1 km from the wadi. This water is of good quality (inorganically) and appears to be little contaminated by the urban settlement (at Abu Delaig) as indicated by low K^+ and NO_3- concentrations. Individually some wells may be slightly contaminated due to the open well construction, and it has not been possible in this study to check for microbiological pollution. Risks of local pollution would be reduced greatly by improved well construction.

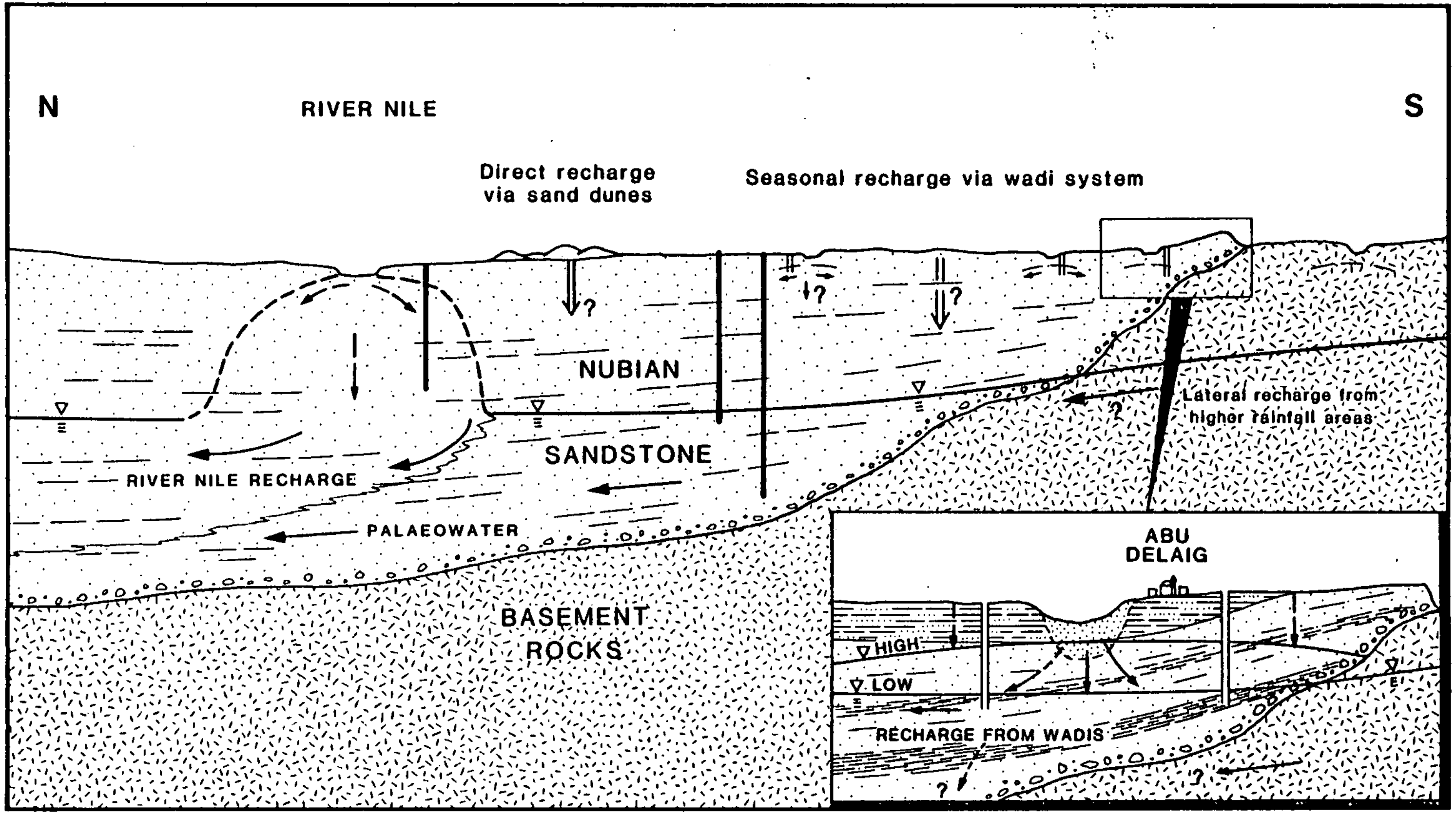


Figure 55. Schematic cross section of the Wadi Hawad showing groundwater resources and likely recharge sources. The only significant active recharge sources are the River Nile and the wadi system. The situation at Abu Delaig is shown in more detail: direct recharge via the predominantly clay interfluve surfaces is negligible but recharge from wadi bed extends laterally beneath interfluves and during seasonal fluctuations gains some geochemical characteristics from the capillary fringe. It is uncertain whether water from these 'freshwater lenses' actually recharges the deeper groundwater systems due to presence of aquicludes in the Nubian series.

On the basis of available evidence there appears to be little interconnection between the shallow and the deep aquifer systems. The reasons for this are not yet clear, but it is likely that stratification in the basal facies of the Nubin sandstone create a perched aquifer of unknown lateral extent. This shallow aquifer is also continuous longitudinally along the lines of wadis which may provide an active hydrogeological system with high transmissivity and the resources available can be estimated by taking the Abu Delaig area as a type cross-section area and multiplying this by the length of hydaulically effective wadi lines. Assuming a saturated thickness of 10 m, a porosity of 30% and a lateral extent of 1 km from the wadis, a resource of 300 Ml is available per 1 km length of wadi. Further estimation of available resources in the shallow aquifer system will be made in the hydrogeological and summary reports.

It is also possible that there could be lateral recharge from the basement to the south, where higher rainfall occurs across the 'feather edge' of the Nubian sandstone. Shallow groundwater is exploited in the basement in much the same manner as in the Nubian, along wadis and also in certain other areas such as Jebel Qeili. There is however no geochemical evidence which shows one way or the other whether such lateral recharge is occurring.

The only evidence of possible connection between deep and shallow groundwaters is to be found in the few dug wells of intermediate depth for example near to Abu Delaig. These probably exploit the intersection of the Nubian shallow system overlying the granite basement with the deeper aquifer. Further careful work, involving geochemical sampling beneath wadi systems would be needed to confirm this possibility.

There are therefore three distinct types of groundwater water in this region of Sudan - Nile valley groundwaters, deep Nubian palaeowaters, shallow aquifer of the Wadi system. The recharge to the first of these systems comes from the Nile, and to the third via wadi floods. A little, effectively negligible recharge may be taking place by direct regional recharge in favoured areas as well as some lateral flow from the basement sustained by higher rainfall belts to the south.

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APPENDICES

Appendix 1	Chemical analyses of rain, surface and groundwaters (Tables 2, 3, 5, 6)
Appendix 2	Chemical analyses of elutriated samples (Table 13)
Appendix 3	Field data sheets for holes D, G (Figures 29, 30)

Seq No	Locality	Date	Well type	Rainfall mm	Temp C	pH	SEC uS/cm	Na	K	Ca	Mg	HCO3	SO4	Cl	NO3-N
								mg/l							
82 819	OMDURMAN	080982	19				27	2.1	1.4	4.3	0.5		2.5	1.1	0.4
82 820	ELAWATABE	060982	19				58	2.7	1.8	13.2	0.9		3.4	1.6	<0.0
82 825	ABU DELAIG	130882	19	20.0			97	7.8	5.2	15.8	2.4		8.8	3.2	1.9
82 826	ABU DELAIG	070982	19	11.0			180	13.9	18.9	26.6	2.8		17.6	18.0	4.9
82 827	ABU DELAIG	080982	19	5.0			33	1.2	1.2	6.9	0.6		2.3	1.0	<0.0
82 828	ABU DELAIG	090982	19	3.0			48	1.9	3.1	9.8	0.9		2.8	1.5	1.0
82 829	ABU DELAIG	230982	19	13.0			33	0.9	1.6	6.6	0.5		3.7	3.3	<0.0
82 830	ABU DELAIG	250982	19	48.0			47	3.7	2.1	8.2	0.8		4.9	3.4	<0.0
82 831	ABU DELAIG	111082	19	64.0			137	12.1	2.7	22.1	4.5		13.0	7.9	3.5
82 832	ABU DELAIG	201082	19	11.0			76	4.2	5.0	13.7	1.2		7.0	7.5	0.3
83 881	ABU DELAIG	140883	19	9.2			175	18.0	3.5	27.5	6.2		17.0	10.7	2.2
85 102	ABU DELAIG	050785	19	0.6										18.2	
85 103	ABU DELAIG	240784	19	2.2										8.9	
85 104	ABU DELAIG	200984	19	0.4										7.9	
85 105	ABU DELAIG	170984	19	2.8				5.8	3.9	23.9	1.7		15.9	5.4	
85 106	ABU DELAIG	230984	19	4.8				4.9	2.9	24.2	1.4		11.3	5.4	
85 107	ABU DELAIG	220984	19	1.4				1.6	1.3	11.8	0.6		3.1	2.5	
85 108	ABU DELAIG	011084	19	2.0				2.8	2.0	13.4	1.0		6.8	3.1	
85 109	SHENDI		19					4.3	2.6	9.1	1.0		3.7	3.2	
851786	ABU DELAIG M	190585	19	2.9				4.7	4.3	25.3	2.6		16.8	6.7	6.7
851787	ABU DELAIG M	220585	19	4.9				3.2	2.0	9.3	1.3		4.8	2.3	2.2
851788	ABU DELAIG M	030785	19	23.7				3.5	1.9	13.1	1.0		7.6	4.1	3.1
851789	ABU DELAIG M	080785	19	12.4				2.7	1.1	9.3	1.0		3.8	3.2	2.1
851790	ABU DELAIG M	150785	19					1.6	1.3	5.1	0.6		2.0	1.5	0.7
851791	ABU DELAIG M	160785	19	12.4				0.9	0.6	5.5	0.5		2.2	1.4	1.7
851792	ABU DELAIG M	110885	19	6.0				1.1	1.5	9.8	0.9		5.3	2.7	3.0
851793	ABU DELAIG M	270885	19	28.0				0.8	0.5	3.5	0.3		1.6	1.4	0.5
851794	ABU DELAIG M	040985	19	3.5				4.0	1.0	11.2	0.9		7.6	4.1	2.7
851795	ABU DELAIG M	070985	19	7.0				1.4	0.5	9.1	1.3		3.1	2.1	1.1
851796	ABU DELAIG M	100985	19	7.6				1.2	0.4	5.0	0.4		2.4	0.9	1.2
851797	SHENDI	080785	19					4.3	2.6	15.5	1.8		8.7	4.2	1.3
851798	SHENDI	100885	19					2.9	3.1	20.5	1.9		12.5	4.5	3.3

TABLE 2. Rainfall chemistry and stable isotope results for samples from Abu Delaig, Omdurman, Shendi 1982-1985.

Seq No	Locality	Si	Sr	Ba	F	Br	Li	B	Fe	Mn	180	2H
							mg/l					
82 819	OMDURMAN											
82 820	ELAWATABE										2.00	22.0
82 825	ABU DELAIG										0.40	4.0
82 826	ABU DELAIG										5.20	29.0
82 827	ABU DELAIG										4.00	33.0
82 828	ABU DELAIG										3.40	36.0
82 829	ABU DELAIG										5.40	41.0
82 830	ABU DELAIG										3.80	39.0
82 831	ABU DELAIG										-1.70	-4.0
82 832	ABU DELAIG										2.60	3.0
83 881	ABU DELAIG										-1.10	-9.0
85 102	ABU DELAIG										6.00	43.0
85 103	ABU DELAIG										6.90	31.0
85 104	ABU DELAIG										4.50	47.0
85 105	ABU DELAIG		0.154								4.80	20.0
85 106	ABU DELAIG		0.147								8.50	44.0
85 107	ABU DELAIG		0.067								3.40	23.0
85 108	ABU DELAIG		0.080								7.50	56.0
85 109	SHENDI		0.068								5.60	44.0
851786	ABU DELAIG M											
851787	ABU DELAIG M											
851788	ABU DELAIG M											
851789	ABU DELAIG M											
851790	ABU DELAIG M											
851791	ABU DELAIG M											
851792	ABU DELAIG M											
851793	ABU DELAIG M											
851794	ABU DELAIG M											
851795	ABU DELAIG M											
851796	ABU DELAIG M											
851797	SHENDI											
851798	SHENDI											

*

Seq No	Locality	Date	Well type	Well depth	Temp C	pH	SEC uS/cm	Na	K	Ca	Mg	HCO3	SO4	Cl	NO3-N
								mg/1							
82 436	R.NILESHENDI	070482	04			7.97*	321	27.0	9.0	15.0	8.3	157*	4.4	7.0	1.2
82 813	R.NILE SHEND	090982	04				170	9.4	3.9	41.4	6.2		13.1	1.7	<0.0
82 814	R.NILE SHEND	161082	04				107	8.1	3.6	20.9	4.9		5.7	1.4	<0.0
82 815	R.NILE SHEND	231082	04				105	7.4	3.4	20.5	5.0		5.5	1.2	<0.0
82 816	R.NILE SHEND	301082	04				107	9.6	4.1	17.3	4.7		4.6	1.6	<0.0
82 821	ELAWATABE	090882	04				199	17.2	5.4	37.2	6.0		13.7	1.4	0.6
82 822	ELAWATABE	200882	04				202	16.9	5.4	38.5	6.5		12.0	1.4	1.4
82 823	ELAWATABE	150882	04				192	15.7	4.8	36.5	5.7		12.0	1.1	0.7
82 824	ELAWATABE	290982	04				65	5.1	3.5	11.2	2.1		3.6	<0.5	<0.0
83 884	WADI HAWAD		04				55	2.2	3.4	9.8	1.6		1.2	0.6	0.7
83 885	EL AWATABE	280783	04				166	22.0	6.6	40.0	7.2		37.0	1.6	4.7
83 887	EL AWATABE	130883	04				144	6.4	4.9	30.0	4.5		11.3	0.8	1.8
83 888	EL AWATABE	010983	04				63	2.5	3.4	12.0	2.0		1.5	0.6	1.0
83 889	EL AWATABE	120983	04				52	2.4	3.3	10.1	1.7		1.4	0.8	0.7
83 890	ABU DELAIG	310783	04				76	4.7	2.9	14.4	2.3		3.2	0.9	<0.5
83 891	ABU DELAIG	140883	04				130	11.7	2.7	24.0	3.5		10.2	1.4	0.8
83 892	R NILESHENDI	070883	04				100	5.0	3.0	30.0	4.1		11.0	1.5	<0.5
83 893	R NILESHENDI	240883	04				250	5.3	3.1	61.0	9.3		10.0	1.5	<0.5
83 894	R NILESHENDI	090983	04				206	6.2	2.9	48.0	7.5		13.0	1.8	<0.5
83 895	R NILLSHENDI	240983	04				133	7.8	3.4	24.0	5.3		11.3	2.4	<0.5
84 150	ELAWATABE 1	010983	04				693	19.0	2.4	1.4	0.1		2.7	1.3	<0.5
84 151	ELAWATABE 2	010983	04				67	5.7	3.5	10.2	2.0		2.6	2.6	<0.5
84 152	ELAWATABE 3	010983	04				1010	2.6	4.5	21.8	4.1		0.8	3.8	<0.5
84 153	ELAWATABE 1	120983	04				739	17.3	1.7	3.7	0.3		12.7	7.1	0.6
84 154	ELAWATABE 2	120983	04				109	17.0	3.6	17.0	2.3		9.8	0.7	<0.5
84 155	ELAWATABE 3	120983	04				200	17.0	5.3	44.0	8.5		10.5	1.1	<0.5
84 396	RNILE SHENDI	130784	04			8.20*	178	14.5	6.5	10.0	5.6	98*	11.6	3.2	<1.0
85 110	EL AWATABE	011084	04					2.0	6.4	19.3	3.2		3.2	2.0	0.
851799	ABU DELAIG K	220585	04					7.9	6.1	47.0	7.3		3.4	2.8	0.5
851800	ABU DELAIG K	030785	04					3.9	2.3	10.5	1.6		5.3	2.7	2.8
851801	ABU DELAIG K	080785	04					7.0	4.3	38.0	5.5		5.9	2.6	0.8
851802	ABU DELAIG K	270885	04					9.7	3.2	50.0	5.9		5.3	1.8	2.2
851803	ABU DELAIG K	070985	04					6.0	5.4	14.0	2.4		4.2	2.9	1.7

* indicates laboratory measurement for pH and HCO3

TABLE 3. Chemical and isotope results for surface water samples - River Nile at Shendi, Wadi Awatabe and Wadi (Khor) Abu Delaig.

Seq No	Locality	Si	Sr	Ba	F	Br	Li	B	Fe	Mn	180	2H
							mg/l					
82 436	R.NILESHENDI	6.5	0.170	1.400			<0.0080	0.064	0.5710	0.0100	5.40	36.0
82 813	R.NILE SHEND											
82 814	R.NILE SHEND											
82 815	R.NILE SHEND											
82 816	R.NILE SHEND											
82 821	ELAWATABE										0.10	-17.0
82 822	ELAWATABE										-1.20	-8.0
82 823	ELAWATABE										-0.10	-5.0
82 824	ELAWATABE										3.40	28.0
83 884	WADI HAWAD										-5.70	-25.0
83 885	EL AWATABE										0.70	-3.0
83 887	EL AWATABE										-0.07	-3.0
83 888	EL AWATABE										-0.80	-5.0
83 889	EL AWATABE										-0.04	10.0
83 890	ABU DELAIG										-3.20	-13.0
83 891	ABU DELAIG										-4.00	-15.0
83 892	R NILESHENDI										-1.60	
83 893	R NILESHENDI										-5.10	-15.0
83 894	R NILESHENDI										-2.50	-6.0
83 895	R NILESHENDI										-0.50	5.0
84 150	ELAWATABE 1											
84 151	ELAWATABE 2											
84 152	ELAWATABE 3											
84 153	ELAWATABE 1											
84 154	ELAWATABE 2											
84 155	ELAWATABE 3											
84 396	RNILE SHENDI	3.5	0.117	0.020		0.050	<0.0100	<0.035	0.0100		1.00	16.0
85 110	EL AWATABE		0.150								3.10	29.0
851799	ABU DELAIG K											
851800	ABU DELAIG K											
851801	ABU DELAIG K											
851802	ABU DELAIG K											
851803	ABU DELAIG K											

*

Map No	Seq No	Locality	Date	Well type	Well depth	Temp C	pH	SEC uS/cm	Na	K	Ca	Mg	HCO3	SO4	Cl	NO3-N
									mg/l							
37	82 433	TIMEID	070482	08			8.00*	663	31.0	1.6	61.0	14.6	205*	37.0	19.5	12.9
	82 435	BIR KHARBANA	060482	08		31.5	8.27*	1622	224.0	1.3	48.0	15.4	283*	326.0	80.0	8.6
	82 441	DARESSALAAM	060482	08	26.0	31.2	8.20*	1044	135.0	1.2	28.0	11.4	265*	125.0	48.5	7.2
	82 627	DAR ES SALAM	160482	08	26.2	34.5	8.00*		141.0	1.9	54.0	12.3	166*	231.0	56.0	3.5
	82 628	IDD EL AHMIR	160482	08	11.48	34.0	8.10*		235.0	0.7	33.0	18.6	434*	152.0	80.0	9.3
34	82 629	ABABDA	220482	08	27.23	37.0	8.20*		34.0	1.7	57.0	13.0	227*	35.0	32.0	1.5
35	82 630	UMM KHATIM	170482	08	38.45	35.5	8.20*		178.0	1.8	44.5	48.0	425*	183.0	77.0	11.8
36	82 631	GARABAWIYA	180482	08	9.0	35.0	8.20*		275.0	1.5	31.0	22.3	431*	97.0	81.0	63.7
37	82 635	TUMEID	160482	08	9.05	40.0	8.20*		293.0	0.9	28.0	8.1	411*	115.0	99.0	36.1
38	82 636	UMM USHARA	180482	08	10.50	34.0	8.10*		85.0	3.1	51.0	13.9	192*	28.0	36.0	39.1
39	82 641	QAID	180482	08	12.87	36.0	8.10*		258.0	18.6	32.0	17.2	411*	83.0	75.0	57.6
	82 643	DAR ES SALAM	060782	08		34.5	8.00*		154.0	2.6	57.0	13.8	187*	275.0	61.0	3.5
	83 483	ABU DELAIG 1	231182	08	25.0	31.5	7.71	460	46.0	1.6	35.0	9.2	196	28.0	15.0	7.3
	83 484	ABU DELAIG 3	231182	08	27.0	30.2	7.60	721	83.0	2.5	42.0	22.0	304	42.0	39.8	2.8
	83 485	ABU DELAIG 4	231182	08	23.0	31.1	7.83	864	154.0	0.8	20.0	14.2	272	82.0	35.8	1.7
	83 486	ABU DELAIG 5	231182	08	22.0	30.6	7.54	692	56.0	1.2	41.0	36.0	384	27.0	20.4	2.8
	83 487	ABU DELAIG 6	231182	08	22.0	31.0	7.62	1330	199.0	1.5	69.0	31.0	554	222.0	76.0	<0.9
	83 488	ABU DELAIG 7	231182	08	22.0	30.7	7.87	730	126.0	0.7	17.0	10.5	304	73.0	28.3	1.7
	83 489	ABU DELAIG 8	231182	08	20.0	30.1	7.67	711	75.0	1.1	50.0	19.0	250	99.0	26.2	5.6
	83 490	ABU DELAIG10	241182	08	20.0	29.35	7.56	508	36.0	1.3	45.0	18.0	211	25.0	13.4	13.1
	83 491	ABU DELAIG11	241182	08	15.0	30.4		503	74.0	0.6	21.0	11.9	211	41.0	12.3	5.1
	83 492	ABU DELAIG12	241182	08	11.0	28.9	7.74	463	31.0	9.2	32.0	19.0	204	18.0	12.7	9.2
	83 493	ABU DELAIG13	241182	08	11.0	27.0	7.98	530	85.0	5.2	18.0	12.0	242	24.0	9.5	7.8
	83 494	ABU DELAIG14	241182	08	12.0	30.3	8.05	458	63.0	<0.5	17.0	10.9	238	43.0	2.6	4.6
	83 495	ABU DELAIG15	261182	08	17.0	28.1	7.68	368	9.8	3.5	56.0	3.7	133	9.9	8.7	12.9
	83 496	ABU DELAIG16	261182	08	7.0	28.2	7.71	335	22.0	1.1	30.0	12.5	154	21.0	4.0	5.6
	83 497	ABU DELAIG17	261182	08	7.0	26.7	8.14	1490	259.0	1.5	40.0	34.0	333	212.0	70.2	52.4
	83 498	ABU DELAIG18	261182	08	17.0	31.7	7.72	470	41.0	1.8	36.0	11.0	190	23.0	11.1	7.7
	83 499	ABU DELAIG19	271182	08	24.00	29.5	7.68	662	33.0	5.1	85.0	11.8	223	34.0	43.1	15.1
	83 500	ABU DELAIG20	271182	08	25.0	30.6	7.40	530	27.0	1.3	68.0	10.4	194	34.0	19.1	7.1
	83 501	ABU DELAIG21	271182	08	25.0	28.4	7.51	815	137.0	0.9	30.0	10.9	260	117.0	32.9	5.0
	83 502	ABU DELAIG23	271182	08	21.0	27.8	7.65	735	93.0	0.8	34.0	29.0	446	26.0	4.3	1.3
	83 503	ABU DELAIG24	271182	08	20.0	28.4	7.56	575	68.0	0.9	35.0	18.0	288	27.0	7.2	2.5
	83 504	ABU DELAIG25	271182	08	21.0	29.80	7.44	680	61.0	1.4	58.0	20.0	304	48.0	17.4	8.1
	83 505	ABU DELAIG26	281182	08	17.0	29.4	7.56	500	43.0	1.1	39.0	16.7	217	24.0	13.2	11.2
	83 506	ABU DELAIG27	281182	08	17.0	30.8	7.54	473	50.0	1.0	29.0	14.0	194	44.0	12.5	5.6
	83 507	ABU DELAIG28	281182	08	20.0	30.0	7.60	1620	258.0	1.2	69.0	35.0	288	351.0	210.0	10.8
	83 508	ABU DELAIG29	281182	08	21.0	30.2	7.69	1430	210.0	1.2	65.0	29.0	255	281.0	122.0	7.3
	83 509	ABU DELAIG30	281182	08	21.0	29.2	7.57	1220	173.0	1.2	68.0	23.0	276	226.0	83.3	10.8
	83 510	ABU DELAIG31	291182	08	24.0	30.0	7.79	1300	240.0	2.0	31.0	11.3	340	266.0	46.2	11.6

TABLE 5. Chemical and isotope results for shallow groundwaters at Abu Delaig (site numbers as shown in Figure 13 et. seq.) and also at other sites in Wadi Hawad and Nile Valley (some site numbers shown in Figure 6 et seq.).

Map No	Seq No	Locality	Si	Sr	Ba	F	Br	Li	B	Fe	Mn	180	2H
								mg/l					
37	82 433	TIMEID	14.8	0.850	0.308			<0.0080	0.120	0.0070	0.0490	-1.00	
	82 435	BIR KHARBANA	8.9	0.530	0.060			<0.0080	0.240	0.0570	0.0540	-2.20	-9.0
	82 441	DARESSALAAM	9.7	0.370	0.256			<0.0080	0.290	0.4950	0.0500	-2.10	-11.0
	82 627	DAR ES SALAM	8.6	0.502	0.064	1.85		<0.0080	0.135	0.0430	0.0060	-2.30	-12.0
	82 628	IDD EL AHMIR	19.9	0.970	0.055	0.29		<0.0080	0.526	0.0260	0.0220	-2.70	-20.0
34	82 629	ABABDA	8.0	0.411	0.144	0.37		<0.0080	0.099	0.1350	0.0510	-8.20	-66.0
35	82 630	UMM KHATIM	30.3	1.010	0.046	1.00		<0.0080	0.130	0.0970	0.0280	-2.20	-13.0
36	82 631	GARABAWIYA	15.4	1.050	0.140	2.55		<0.0080	0.465	0.0760	0.0080	-0.60	-14.0
37.	82 635	TUMEID	17.3	0.392	0.062	3.60		<0.0080	0.253	0.2200	0.0590	-2.90	-23.0
38	82 636	UMM USHARA	15.0	0.552	0.084	0.48		<0.0080	0.100	0.0510	0.0440	-2.30	-31.0
39	82 641	QAID	34.7	0.539	0.089	0.58		<0.0080	0.580	0.0480	0.0780	-1.80	-24.0
	82-643	DAR ES SALAM	9.5	0.539	0.058	1.95		<0.0080	0.137	0.0830	0.0130		
	83 483	ABU DELAIG 1	21.7	0.382	0.106	1.50			0.087	0.1200	0.0450	-1.70	-2.0
	83 484	ABU DELAIG 3	16.1	0.674	0.068	1.70			0.141	0.0490	0.2640	-2.10	-11.0
	83 485	ABU DELAIG 4	12.7	0.453	0.055	6.20			0.310	0.0790	0.0280	-2.60	-13.0
	83 486	ABU DELAIG 5	13.5	0.930	0.203	3.10			0.120	0.0480	0.1880	-2.90	-14.0
	83 487	ABU DELAIG 6	16.0	1.030	0.083	1.50			0.150	0.0230	0.1500	-2.90	-13.0
	83 488	ABU DELAIG 7	11.7	0.410	0.068	4.70			0.275	0.0470	0.0150	-2.70	-12.0
	83 489	ABU DELAIG 8	10.8	0.650	0.170	2.20			0.129	0.1450	0.0740	-2.70	-13.0
	83 490	ABU DELAIG10	12.7	0.680	0.128	0.90			0.107	0.0390	0.0140	-2.70	-13.0
	83 491	ABU DELAIG11	11.7	0.390	0.137	3.50			0.210	0.2200	0.0600	-2.60	-13.0
	83 492	ABU DELAIG12	11.2	0.780	0.142	2.10			0.159	0.0350	0.0120	-1.30	-4.0
	83 493	ABU DELAIG13	23.0	0.600	0.116	2.10			0.310	0.0710	0.0050	-0.90	1.0
	83 494	ABU DELAIG14	9.8	0.360	0.063	3.30			0.370	0.0290	0.0020	-2.00	-9.0
	83 495	ABU DELAIG15	10.3	0.190	0.073	0.51			0.035	0.9200	0.0310	-0.50	-1.0
	83 496	ABU DELAIG16	24.0	0.740	0.120	1.50			0.079	0.1970	0.0410	-1.30	-5.0
	83 497	ABU DELAIG17	18.1	1.110	0.190	2.10			0.690	0.4600	0.0130	-1.30	-7.0
	83 498	ABU DELAIG18	11.5	0.460	0.084	2.10			0.112	0.0270	0.0180	-2.40	-12.0
	83 499	ABU DELAIG19	15.3	0.540	0.182	0.34			0.090	0.0190	0.0060	-1.90	-9.0
	83 500	ABU DELAIG20	17.0	0.440	0.125	0.62			0.074	0.1230	0.0200	-2.40	-11.0
	83 501	ABU DELAIG21	10.1	0.360	0.054	3.40			0.270	0.0420	0.2200	-2.40	-12.0
	83 502	ABU DELAIG23	18.3	0.920	0.190	2.90			0.180	0.0330	0.0250	-3.00	-14.0
	83 503	ABU DELAIG24	13.2	0.620	0.142	2.50			0.200	0.0550	0.1900	-2.90	-13.0
	83 504	ABU DELAIG25	13.4	0.820	0.140	1.30			0.170	0.0160	0.0360	-2.60	-12.0
	83 505	ABU DELAIG26	15.3	0.740	0.140	1.50			0.120	0.3000	0.0070	-1.40	-3.0
	83 506	ABU DELAIG27	12.9	0.410	0.058	2.70			0.150	0.0350	0.0340	-2.10	-9.0
	83 507	ABU DELAIG28	9.8	1.140	0.079	2.80			0.380	0.0280	0.0530	-3.10	-17.0
	83 508	ABU DELAIG29	9.8	0.800	0.046	2.10			0.370	0.0180	0.0710	-3.10	-16.0
	83 509	ABU DELAIG30	8.8	0.750	0.052	1.70			0.270	0.0240	0.0050	-3.10	-15.0
	83 510	ABU DELAIG31	9.5	0.410	0.039	3.00			0.380	0.1090	0.0190	-1.20	-6.0

Seq No	Locality	Date	Well type	Well depth	Temp C	pH	SEC uS/cm	Na	K	Ca	Mg	HCO3	SO4	Cl	NO3-N
								mg/l							
83 511	ABU DELAIG33	291182	08	24.0	30.3	7.49	1880	301.0	1.6	97.0	30.0	300	499.0	135.0	15.9
83 512	ABU DELAIG34	291182	08	30.0	28.2	7.76	1290	205.0	1.0	37.0	20.0	300	249.0	78.2	9.4
83 513	ABU DELAIG35	291182	08	30.0	29.0	7.55	1720	265.0	0.7	91.0	33.0	300	591.0	33.6	6.7
83 514	ABU DELAIG36	291182	08	26.0	25.1	8.04	550	70.0	4.2	35.0	5.0	200	59.0	7.4	11.8
83 515	ABU DELAIG37	291182	08	23.0	27.7	7.83	1200	202.0	0.6	33.0	15.6	435	157.0	51.1	2.2
83 516	ABU DELAIG38	291182	08					76.0	1.8	25.0	8.3	259*	37.0	4.9	4.1
84 391	AWATABE	250684	08	11.5		8.20*		14.1	5.7	43.0	19.0	158*	13.8	6.0	4.0
84 393	ABU DOMAT	130784	08	21.6	32.5	8.60*	620	142.0	2.7	8.2	13.2	374*	33.0	45.0	1.4
84 395	ABU DOMAT W	130784	08	22.62	32.6	8.40*	580	87.0	4.1	30.0	28.0	367*	28.0	42.0	1.7
84 397	EL MASHAIKH	140784	08	8.3		8.50*		146.0	<0.8	29.0	87.0	488*	166.0	91.0	3.3
84 403	WADI HAWAD K	140784	08	14.1		8.10*		9300.0	26.0	650.0	1120.0	303*	10300.0	10600.0	142.3
84 404	BIGARAWIYA N	140784	08	10.3	30.3			64.0	5.2	39.0	17.9	192*	56.0	55.0	<1.0
84 405	BIGARAWIYA S	140784	08	9.9	31.7			132.0	2.9	41.0	37.0		154.0	31.0	9.9
84 407	WADI HAWAD K	140784	08			8.40*		90.0	7.4	69.0	18.8	336*	129.0	61.0	6.8

For pH and HCO3 * indicates laboratory measurement

*

Seq No	Locality	Si	Sr	Ba	F	Br	Li	B	Fe	Mn	18O	2H
		mg/1										
83 511	ABU DELAIG33	10.4	1.040	0.039	1.70			0.230	0.0630	0.0740	-1.70	-12.0
83 512	ABU DELAIG34	10.8	0.590	0.049	2.60			0.280	0.1300	0.0060	0.20	-6.0
83 513	ABU DELAIG35	11.9	1.240	0.050	2.20			0.230	0.0170	0.0270	-1.90	-10.0
83 514	ABU DELAIG36	7.4	0.330	0.072	0.57			0.087	0.0140	0.0050	2.40	21.0
83 515	ABU DELAIG37	12.6	0.600	0.053	2.20			0.290	0.0210	0.1100	-2.70	-12.0
83 516	ABU DELAIG38	13.4	0.320	0.078	2.40			0.210	0.0740	0.2200		
84 391	AWATABE	25.0	0.455	0.160		0.070	<0.0100	0.046	0.0200		-2.10	3.0
84 393	ABU DOMAT	13.5	0.224	0.040		0.260	<0.0100	<0.035	0.0100	<0.0030	-1.00	4.0
84 395	ABU DOMAT W	28.0	0.493	0.160		0.220	<0.0100	0.040	<0.0070	<0.0030	-0.60	4.0
84 397	EL MASHAIKH	58.0	1.110	0.060		1.160	<0.0100		<0.0070	<0.0030	-1.00	
84 403	WADI HAWAD K	9.2	13.200	0.050		61.000	<0.0100					-9.0
84 404	BIGARAWIYA N	25.0	0.337	0.040		0.560	<0.0100	<0.035	<0.0070	<0.0030	-0.30	7.0
84 405	BIGARAWIYA S	26.0	0.660	0.008		0.440	<0.0100	0.042	0.0080	<0.0030	-1.50	-3.0
84 407	WADI HAWAD K	13.8	0.578	0.150		0.670	<0.0100	0.067	<0.0070	<0.0030	-0.30	-3.0

*

Map No	Seq No	Locality	Date	Well type	Well depth	Temp C	pH	SEC uS/cm	Na	K	Ca	Mg	HCO3	SO4	Cl	NO3-N
									mg/l							
1	82 430	WAD EL HAMAD	070482	10	99.7	33.6	8.30*	864	63.0	1.8	76.0	19.0	328*	45.0	59.0	1.3
28	82 431	BIR BENNAGAR	070482	09		31.2	7.96*	517	23.0	2.1	54.0	13.0	242*	16.6	14.0	0.9
2	82 432	TIMEID HAJEL	070482	10	123.1	36.9	8.27*	1436	92.0	18.1	122.0	36.0	192*	115.0	268.0	6.0
29	82 434	WAD HASSUNA	060482	09		33.8	6.85	959	57.0	2.9	76.0	22.0	211*	105.0	56.0	13.3
3	82 437	EL GEHEID BH	070482	10	97.2	34.5	8.07*	864	58.0	1.6	83.0	21.0	341*	41.0	56.0	1.8
5	82 439	SYEIDAB BH	060482	10			8.15*	541	28.0	1.1	66.0	20.2	276*	19.0	14.0	<0.4
6	82 440	EL SITAIR	070482	10	192.6	36.6	8.00*	1304	89.0	8.8	95.0	26.0	259*	106.0	155.0	7.9
30	82 442	EL SHIKLE	060482	09			7.85*	1410	131.0	7.9	66.0	34.0	303*	215.0	70.0	14.5
8	82 632	SHEIN B/H	220482	10	131.0	38.0	8.00*		31.0	1.9	52.0	15.9	224*	25.0	40.0	1.0
31	82 633	AMBESA	170482	09	89.7	30.7	8.20*		55.0	1.8	58.0	15.1	276*	46.0	37.0	<0.7
9	82 637	SHERISHEH	200482	10	160.62	37.0	8.10*		96.0	5.7	91.0	25.1	221*	101.0	180.0	5.3
10	82 638	UMM SHADIDA	200482	10		38.0	8.20*		302.0	1.8	37.0	37.0	478*	158.0	260.0	<0.7
11	82 639	EL SAWAD	180482	10		37.0	8.10*		64.0	1.4	44.0	13.0	233*	52.0	42.0	1.5
12	82 640	UMM DURWA	180482	10	135.9	35.0	8.00*		38.0	1.1	46.0	15.6	223*	28.4	39.0	1.5
13	82 642	UMM RUWEISHD	170482	10		35.0	8.20*		41.0	53.0	60.0	25.0	329*	27.2	29.0	21.0
3	83 517	BIR ELGEHEID	011282	10	97.2	35.0	7.25	800	58.0	1.7	88.0	21.0	352	41.0	56.0	1.7
32	83 518	SHEIKH IDRIS	291182	09	53.0	31.3	7.48	420	36.0	2.0	37.0	8.3	227	11.7	11.5	3.6
33	83 519	EL AGIB	291182	09	57.0	31.5	8.04	712	33.0	7.9	57.0	10.8	412	7.7	13.5	22.6
6	83 520	SURIBA	051282	10	192.7	36.4	6.68	1100	91.0	8.8	104.0	27.0	247	105.0	159.0	7.2
12	83 521	UMM DURWA	301182	10	135.9	33.5	6.88		38.0	1.1	70.0	16.0	297	30.0	40.0	1.9
8	83 522	EL SHEIN	061282	10	131.0	34.7	6.93		31.0	1.5	65.0	16.0	244	27.0	30.5	1.5
2	83 523	TOMEID HELT.	051182	10	123.0	35.6	6.82	1430	95.0	18.3	127.0	38.0	190	118.0	269.0	5.8
14	83 524	EL DELAIG	061282	10		35.15	6.84		64.0	1.3	69.0	13.1	277	54.0	41.0	1.9
1	83 525	WAD EL HAMAD	101282	10	108.8	33.7	7.12	808	63.0	1.9	75.0	19.0	339	46.0	57.5	1.3
15	84 392	AWADAB	250684	10			8.40*		44.0	17.7	29.0	9.9	183*	23.0	36.0	<1.0
16	84 394	SAGADI	250684	10			8.40*		43.0	18.5	30.0	10.2	177*	23.0	33.0	<1.0
12	84 419	UMM DURWA	150784	10			8.30*		39.0	1.2	68.0	15.6	132*	32.0	41.0	0.5
8	84 420	SHEIN	150784	10			8.30*		31.0	1.6	63.0	15.6	137*	27.0	35.0	0.4

*-indicates laboratory measurement for pH and HCO3

TABLE 6a. Chemical and isotope results for borehole and deep dug well samples in in Nubian sandstone aquifer (excluding the Nile Valley). Site numbers refer to Figure 6 et. seq.

Map No	Seq No	Locality	Si	Sr	Ba	F	Br	Li	B	Fe	Mn	180	2H
								mg/1					
1	82 430	WAD EL HAMAD	7.6	0.580	0.120	0.	0.	<0.0080	0.092	0.0090	0.0160	-8.40	-66.0
28	82 431	BIR BENNAGAR	10.5	0.410	0.310	0.	0.	<0.0080	0.120	1.5700	0.1540	-9.10	-66.0
2	82 432	TIMEID HAJEL	7.4	1.250	0.069	0.	0.	<0.0080	0.051	0.1960	0.0440	-6.60	-44.0
29	82 434	WAD HASSUNA	7.5	0.770	0.075	0.	0.	<0.0080	0.110	0.1740	0.0700	-7.80	-57.0
3	82 437	EL GEHEID BH	7.8	0.590	0.181	0.	0.	<0.0080	0.097	0.0610	0.0050	-9.10	-68.0
5	82 439	SYEIDAB BH	6.2	0.500	0.168	0.	0.	0.0110	0.088	6.2700	0.2370	-10.50	-77.0
6	82 440	EL SITAIR	7.9	0.710	0.065	0.	0.	<0.0080	0.110	0.4830	0.0270	-8.50	-60.0
30	82 442	EL SHIKLE	0.	0.760	0.074	0.	0.	0.0120	0.130	0.0690	0.8860	-5.10	-34.0
8	82 632	SHEIN B/H	7.2	0.434	0.122	0.29	0.	<0.0080	0.093	0.0710	0.0510	-8.30	-63.0
31	82 633	AMBESA	8.0	0.471	0.070	0.55	0.	<0.0080	0.084	0.0160	0.0300	-6.40	-42.0
9	82 637	SHERISHEH	7.2	0.738	0.070	0.22	0.	<0.0080	0.051	0.3090	0.0950	-7.60	-59.0
10	82 638	UMM SHADIDA	11.8	0.858	0.055	0.34	0.	<0.0080	0.083	<0.0060	0.0190	-6.20	-51.0
11	82 639	EL SAWAD	7.9	0.416	0.395	0.22	0.	<0.0080	0.067	0.3070	0.0370	-9.50	-67.0
12	82 640	UMM DURWA	6.9	0.494	0.139	0.29	0.	<0.0080	0.105	<0.0060	0.0150	-8.30	-61.0
13	82 642	UMM RUWEISHD	31.6	0.621	0.034	0.47	0.	<0.0080	0.150	0.0250	0.0590	-1.00	-9.0
3	83 517	BIR ELGEHEID	7.9	0.610	0.180	0.32	0.	0.	0.100	0.1030	0.0090	-8.90	-64.0
32	83 518	SHEIKH IDRIS	9.0	0.320	0.111	0.66	0.	0.	0.087	0.0850	0.3300	-3.30	-14.0
33	83 519	EL AGIB	9.9	0.400	0.200	0.51	0.	0.	0.086	0.0470	1.0100	-3.20	-15.0
6	83 520	SURIBA	8.1	0.750	0.066	0.20	0.	0.	0.052	0.3700	0.0440	-8.60	-62.0
12	83 521	UMM DURWA	6.9	0.490	0.140	0.29	0.	0.	0.088	0.0840	0.0100	-9.50	-62.0
8	83 522	EL SHEIN	7.1	0.420	0.110	0.28	0.	0.	0.076	0.3400	0.0130	-8.50	-62.0
2	83 523	TOMEID HELT.	7.5	1.280	0.067	0.85	0.	0.	0.042	0.3500	0.0650	-6.30	-47.0
14	83 524	EL DELAIG	7.6	0.430	0.094	0.21	0.	0.	0.048	0.0330	0.0170	-8.30	-69.0
1	83 525	WAD EL HAMAD	7.8	0.580	0.115	0.40	0.	0.	0.084	0.0890	0.0160	-8.80	-64.0
15	84 392	AWADAB	7.8	0.644	0.190	0.	0.210	<0.0100	<0.035	0.0200	<0.0030	0.	-29.0
16	84 394	SAGADI	7.9	0.657	0.200	0.	0.210	<0.0100	0.039	0.0600	0.0300	-2.90	-16.0
12	84 419	UMM DURWA	7.7	0.492	0.160	0.	0.230	<0.0100	0.100	0.5600	0.0170	-8.30	-65.0
8	84 420	SHEIN	7.6	0.418	0.120	0.	0.180	<0.0100	0.094	0.0900	0.0200	-8.70	-63.0

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TABLE 6b. Chemical and isotope results for borehole samples from the Nile Valley. Site numbers refer to Figure 6 et. seq.

Map No	Seq No	Locality	Date	Well type	Well depth	Temp C	pH	SEC uS/cm	Na	K	Ca	Mg	HCO3	SO4	Cl	NO3-N
									mg/l							
4	82 438	SHENDI BH	070482	10	110.		7.90*	355	13.0	4.2	32.0	9.9	183*	<0.4	3.5	0.6
7	82 443	KABUSHIR B/H	070482	10	64.		8.24*	663	98.0	6.8	79.0	61.0	315*	344.0	63.0	1.4
17	84 398	METEMMA ARTO	130784	10	77.0	34.3	7.15	435	33.0	5.7	73.0	29.0	312*	51.0	14.4	<1.0
18	84 399	METEMMA MKT	130784	10		33.9	7.28	560	42.0	5.6	60.0	30.0	192*	38.0	33.0	9.9
19	84 400	METEMMA HOSP	130784	10		34.6	7.20	620	64.0	4.7	38.0	28.0	298*	43.0	24.0	12.4
20	84 401	KUMEIR	130784	10		34.7	8.30*		51.0	4.5	49.0	19.7	194*	31.0	57.0	<1.0
21	84 402	DIEM ELGRAY	140784	10		35.1	7.32		42.0	5.1	27.0	9.6	0*	19.6	5.2	<1.0
7	84 406	KABOUSHIR	140784	10		33.7	8.40*		92.0	5.4	109.0	52.0	140*	306.0	66.0	11.3
22	84 408	TARAGMA BH	140784	10		33.55	7.20		19.1	4.8	56.0	19.8	318*	2.0	<0.2	<1.0
23	84 409	EL GUWEIR	130784	10			7.20	390	17.9	7.4	66.0	22.0	208*	1.4	3.0	<1.0
7	84 410	KABOUSHIR 2	250684	10			8.40*		77.0	5.9	66.0	31.0	220*	120.0	57.0	14.0
24	84 411	ZAKIAP	120784	10		34.7	7.20	1400	285.0	5.4	64.0	41.0	579*	228.0	113.0	<1.0
25	84 412	TONDB	130784	10		34.6	7.15	460	56.0	5.2	51.0	25.0	336*	26.0	17.2	<1.0
26	84 413	MESAKTAB	140784	10		33.35	7.22		47.0	2.6	16.4	7.1	197*	4.7	3.0	<1.0

* indicates laboratory measurement for pH and HCO3

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p 1

Map No	Seq No	Locality	Si	Sr	Ba	F	Br	Li	B	Fe	Mn	18O	2H
			mg/l										
4	82 438	SHENDI BH	11.9	0.250	0.	0.	0.	<0.0080	0.023	0.0960	0.3350	0.60	12.0
7	82 443	KABUSHIR B/H	7.4	0.920	0.067	0.	0.	<0.0080	0.047	1.7400	0.3210	-1.80	2.0
17	84 398	METEMMA ARTO	17.1	0.537	0.130	0.	0.260	<0.0100	<0.035	0.5400	0.2500	-1.00	-1.0
18	84 399	METEMMA MKT	29.0	0.600	0.050	0.	0.270	<0.0100	0.041	0.0100	0.0070	-1.20	-1.0
19	84 400	METEMMA HOSP	32.0	0.549	0.020	0.	0.220	<0.0100	0.064	0.0400	<0.0030	-0.90	0.
20	84 401	KUMEIR	8.0	0.435	0.490	0.	0.200	<0.0100	<0.035	1.3000	0.0900	-0.30	7.0
21	84 402	DIEM ELGRAY	8.1	0.359	0.210	0.	0.	<0.0100	<0.035	0.4100	0.0100	-1.30	-2.0
7	84 406	KABOUSHIR	18.3	1.280	0.080	0.	0.250	<0.0100	<0.035	0.2000	0.2700	-1.70	-5.0
22	84 408	TARAGMA BH	8.7	0.348	0.560	0.	0.080	<0.0100	<0.035	0.0100	0.3600	-0.10	6.0
23	84 409	EL GUWEIR	10.3	0.402	0.720	0.	0.090	<0.0100	<0.035	0.5100	0.2500	-0.50	0.
7	84 410	KABOUSHIR 2	21.0	0.883	0.150	0.	0.640	<0.0100	<0.035	<0.0070	0.0040	-2.30	-4.0
24	84 411	ZAKIAP	25.0	0.786	0.090	0.	1.340	<0.0100	0.059	0.0700	<0.0030	-1.50	-3.0
25	84 412	TONDB	10.0	0.451	0.380	0.	0.200	<0.0100	<0.035	<0.0070	0.0100	-1.60	0.
26	84 413	MESAKTAB	7.9	0.144	0.380	0.	0.040	<0.0100	0.049	0.2800	0.0800	-1.30	3.0

APPENDIX 2

Table 13. Solute profile data for 1983 field season.

		DEPTH (cm)		ELUTRIATE						SOIL MOISTURE			
BGS No	Profile No	Top	Bottom	% moisture content (wet weight)	EC_{25}	CL	NO_3-N	Weight D.W. added	Dilution Factor	% M.C. dry weight corrected to oven dry	EC^c_{25}	CL^c	NO_3-N^c
83/121	A 0	0.	5.	2.63	157.	7.5	3.3	30.16	14.09	4.33	3.345	2.024	1.667
83/122	A 1	5.	30.	4.21	545.	75.0	0.5	30.16	19.77	6.58	3.769	2.907	0.731
83/123	A 2	30.	60.	4.59	1120.	175.0	0.5	30.16	10.21	7.01	4.058	3.252	0.708
83/124	A 3	60.	80.	4.66	1560.	181.0	2.6	30.16	10.12	7.08	4.198	3.263	1.420
83/125	A 4	80.	100.	5.58	1720.	190.0	1.8	30.16	9.02	8.14	4.191	3.234	1.210
83/126	A 5	100.	125.	4.82	2018.	184.0	1.4	30.16	9.90	7.27	4.301	3.261	1.142
83/127	A 6	125.	155.	4.29	2730.	163.0	1.3	30.16	10.65	6.67	4.464	3.240	1.141
83/128	A 7	155.	185.	6.39	2640.	211.0	1.3	30.16	8.25	9.08	4.338	3.241	1.030
83/129	A 8	185.	215.	7.38	2670.	227.0	1.0	30.16	7.48	10.26	4.301	3.230	0.874
83/130	A 9	215.	235.	4.62	2510.	252.0	5.0	30.00	10.12	7.04	4.405	3.407	1.704
83/131	A10	235.	270.	4.97	2230.	237.0	1.1	30.00	9.67	7.44	4.334	3.360	1.027
83/132	A11	270.	285.	4.94	1980.	209.0	1.1	30.00	9.71	7.40	4.284	3.307	1.028
83/133	A12	285.	305.	4.31	1900.	190.0	0.5	30.00	10.57	6.69	4.303	3.303	0.723
83/134	A13	305.	330.	4.44	1610.	147.0	0.5	30.00	10.38	6.84	4.223	3.183	0.715
83/135	A14	330.	360.	3.34	1250.	114.0	0.5	30.00	12.30	5.61	4.187	3.147	0.789
83/136	A15	360.	385.	6.91	1530.	139.0	0.5	30.00	7.79	9.70	4.076	3.034	0.590
83/137	A16	385.	400.	4.67	1240.	111.0	0.5	30.00	10.06	7.10	4.096	3.048	0.701
83/138	A17	400.	421.	3.00	1530.	125.0	1.2	29.50	12.86	5.24	4.294	3.206	1.188
83/139	A18	421.	443.	3.59	1560.	130.0	1.1	29.50	11.61	5.39	4.258	3.179	1.106
83/140	A19	443.	464.	3.66	1460.	113.0	0.5	29.50	11.48	5.96	4.224	3.113	0.759
83/141	A20	464.	486.	3.26	1475.	119.0	0.5	29.50	12.28	5.52	4.258	3.165	0.788
83/142	A21	486.	507.	3.80	1500.	113.0	0.5	29.50	11.23	6.12	4.227	3.104	0.749
83/143	A22	507.	529.	3.42	1475.	127.0	0.5	29.50	11.95	5.70	4.246	3.181	0.776
83/144	A23	529.	550.	4.33	1500.	118.0	0.5	29.50	10.38	6.71	4.192	3.088	0.715
83/145	A24	550.	572.	3.95	1190.	98.5	0.5	29.50	10.98	6.29	4.116	3.034	0.739
83/146	A25	572.	593.	4.21	1330.	112.0	0.5	29.50	10.56	6.58	4.148	3.073	0.723
83/147	A26	593.	615.	4.73	1260.	118.0	0.5	29.50	9.76	7.22	4.090	3.061	0.688
83/148	A27	615.	636.	4.95	1320.	136.0	0.5	29.50	9.55	7.41	4.100	3.113	0.679
83/149	A28	636.	658.	4.96	1320.	123.0	0.5	29.50	9.54	7.43	4.100	3.069	0.678
83/150	A29	658.	679.	5.23	1475.	164.0	0.5	29.50	9.22	7.73	4.133	3.180	0.664
83/151	A30	679.	701.	5.23	1570.	190.0	0.5	29.50	9.22	7.73	4.161	3.243	0.664
83/152	A31	701.	722.	5.37	1340.	182.0	0.5	29.50	8.55	8.47	4.059	3.192	0.631
83/153	A32	722.	744.	5.63	1234.	155.0	0.5	29.50	8.79	8.19	4.053	3.134	0.643
83/154	A33	744.	765.	5.38	1195.	141.0	0.5	29.50	9.05	7.91	4.034	3.106	0.656
83/155	A34	765.	787.	6.32	1034.	159.0	2.1	29.50	7.74	9.59	3.903	3.090	1.211
83/156	A35	787.	808.	5.69	1005.	133.0	1.0	29.50	8.73	8.26	3.943	3.065	0.941
83/157	A36	808.	830.	5.15	858.	117.0	0.5	29.50	9.31	7.64	3.902	3.037	0.668
83/158	A37	830.	851.	3.77	744.	100.0	0.5	29.50	11.29	6.09	3.924	3.053	0.751
83/159	A38	851.	873.	2.23	462.	48.0	0.5	29.50	15.00	4.40	3.841	2.857	0.875
83/160	A39	873.	894.	1.88	420.	40.5	0.5	29.50	16.25	4.02	3.834	2.818	0.910
83/161	A40	894.	916.	4.71	678.	85.0	1.1	29.50	9.85	7.14	3.825	2.923	1.035
83/162	A41	916.	937.	1.36	387.	46.0	0.5	29.50	18.59	3.47	3.857	2.932	0.968
83/163	A42	937.	959.	0.63	293.	30.0	0.5	29.50	23.42	2.70	3.836	2.847	1.069
83/164	A43	959.	980.	0.67	187.	22.5	0.5	29.50	23.09	2.74	3.635	2.716	1.062
83/165	B 1	0.	15.	2.21	146.	7.5	6.6	29.76	15.19	4.38	3.346	2.057	2.001
83/166	B 2	15.	30.	2.39	182.	4.5	5.5	29.76	14.61	4.57	3.425	1.818	1.905
83/167	B 3	30.	55.	2.72	257.	15.5	4.7	29.76	13.67	4.93	3.546	2.326	1.803
83/168	B 4	55.	80.	3.54	580.	64.0	2.3	29.76	11.80	5.83	3.835	2.878	1.434
83/169	B 5	80.	105.	3.23	738.	97.0	1.5	29.76	12.44	5.49	3.963	3.082	1.271
83/170	B 6	105.	130.	4.22	1250.	127.0	1.2	29.76	10.63	6.59	4.123	3.130	1.106
83/171	B 7	130.	155.	5.03	1560.	164.0	1.2	29.76	9.53	7.51	4.172	3.194	1.058
83/172	B 8	155.	180.	5.66	1630.	186.0	1.2	29.76	8.83	8.23	4.158	3.215	1.025
83/173	B 9	180.	205.	5.77	1390.	209.0	1.3	29.76	8.72	8.36	4.217	3.261	1.145
83/174	B10	205.	230.	6.22	1990.	236.0	1.6	29.76	8.30	8.88	4.218	3.292	1.123
83/175	B11	230.	248.	6.12	2070.	204.0	1.1	29.76	8.39	8.76	4.240	3.233	0.965
83/176	B12	248.	266.	6.13	2600.	251.0	1.4	29.76	8.33	8.83	4.336	3.320	1.067

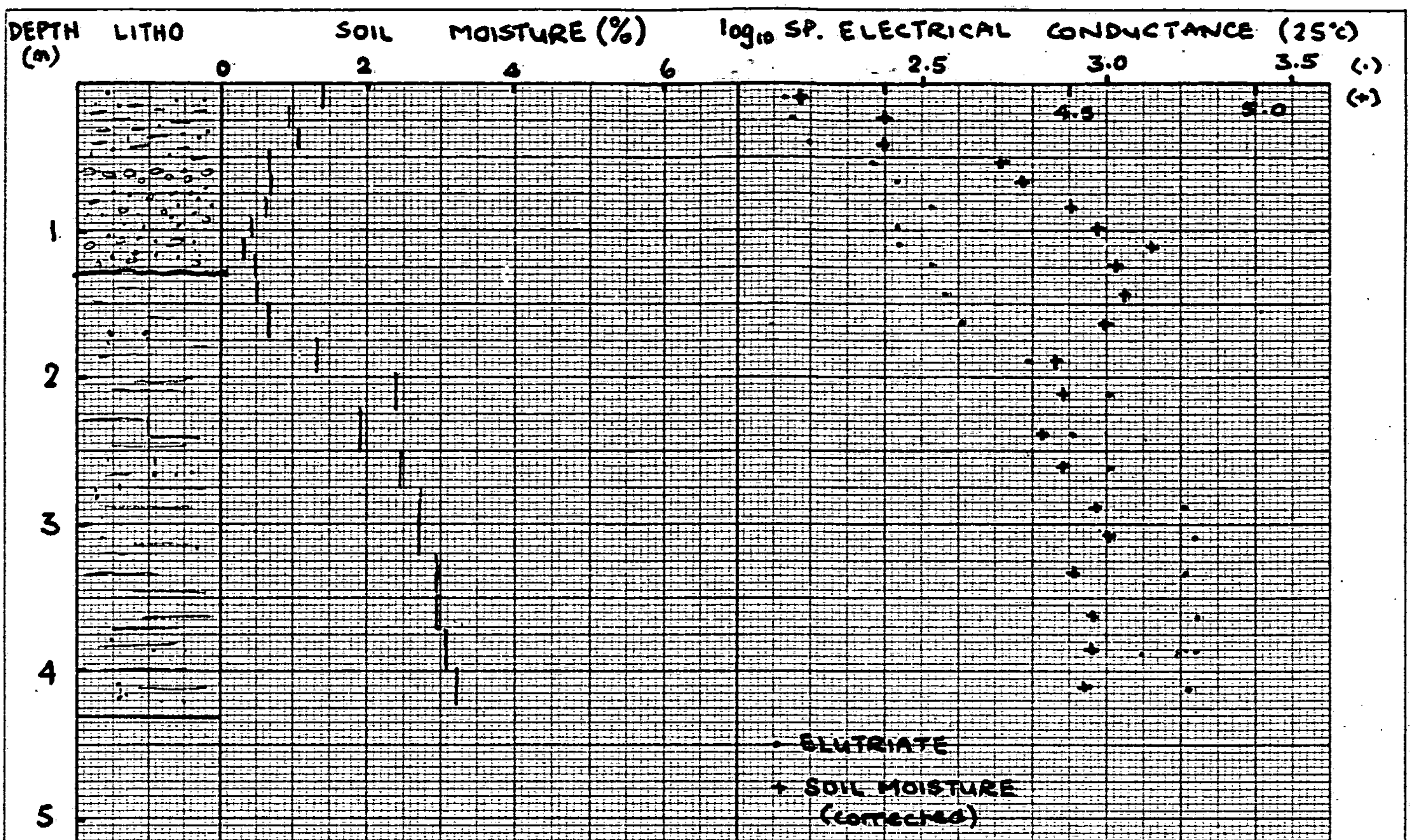
		DEPTH		ELUTRIATE						SOIL MOISTURE			
		(cm)											
BGS No	Profile No	Top	Bottom	% moisture content (wet weight)	EC_{25}	CL	NO_3-N	Weight D.W. added	Dilution Factor	% M.C. dry weight corrected to oven dry	EC_{25}^{c}	CL^{c}	NO_3-N
83/177	B13	206.	285.	5.82	2200.	218.0	1.1	29.76	8.67	8.42	4.280	3.276	0.979
83/178	C 1	0.	15.	1.67	328.	6.5	2.5	29.94	16.52	4.01	3.734	2.031	1.616
83/179	C 2	15.	30.	2.03	340.	11.5	5.9	29.94	15.91	4.18	3.733	2.262	1.973
83/180	C 3	30.	55.	2.23	510.	34.5	12.4	29.94	15.21	4.40	3.890	2.720	2.276
83/181	C 4	55.	80.	2.25	865.	116.0	26.3	29.94	15.14	4.42	4.127	3.245	2.600
83/182	C 5	80.	105.	2.66	1120.	140.0	20.9	29.94	13.91	4.86	4.192	3.289	2.463
83/183	C 6	105.	130.	2.50	2020.	236.0	12.8	29.94	14.36	4.69	4.463	3.530	2.264
83/184	C 7	130.	150.	1.79	2010.	213.0	17.9	29.94	16.85	3.93	4.530	3.555	2.479
83/185	C 8	150.	170.	1.39	1840.	234.0	11.7	29.94	16.44	4.03	4.481	3.585	2.284
83/186	C 9	170.	190.	1.75	1800.	247.0	9.7	29.94	17.01	3.88	4.486	3.623	2.218
83/187	C10	190.	210.	1.09	1460.	190.0	8.2	29.94	20.40	3.19	4.474	3.588	2.223
83/188	C11	210.	230.	1.00	1150.	152.0	7.2	29.94	20.97	3.09	4.382	3.504	2.179
83/189	C12	230.	255.	0.26	926.	119.0	7.2	29.94	27.43	2.32	4.405	3.514	2.295
83/190	C13	255.	280.	0.51	921.	116.0	7.3	29.94	24.83	2.58	4.359	3.459	2.258
83/191	C14	280.	305.	0.39	670.	87.5	6.0	29.94	26.01	2.45	4.241	3.357	2.193
83/192	C15	305.	330.	0.93	660.	83.5	5.8	29.94	21.45	3.02	4.151	3.253	2.095
83/193	C16	330.	346.	0.91	672.	85.5	5.5	29.94	21.59	3.00	4.162	3.266	2.075
83/194	C17	346.	363.	1.04	673.	87.5	5.8	29.94	20.71	3.13	4.144	3.258	2.080
83/195	C18	363.	380.	1.08	710.	91.5	6.0	29.94	20.46	3.17	4.162	3.272	2.089
83/196	C19	380.	396.	1.23	650.	85.0	5.5	29.94	19.57	3.33	4.104	3.221	2.032
83/197	C20	396.	413.	1.65	779.	95.5	6.5	29.94	17.45	3.78	4.133	3.222	2.055
83/198	C21	413.	430.	1.33	918.	113.0	7.2	29.94	16.68	3.97	4.185	3.275	2.080
83/199	C22	430.	453.	2.18	839.	106.0	6.4	29.94	15.38	4.35	4.111	3.212	1.993
83/200	C23	453.	476.	2.39	932.	119.0	6.7	29.94	14.70	4.57	4.137	3.243	1.993
83/201	C24	476.	488.	2.58	854.	105.0	6.2	29.94	14.13	4.78	4.082	3.171	1.943
83/202	C25	488.	500.	3.62	854.	106.0	6.4	29.94	11.72	5.92	4.000	3.094	1.875
83/203	D 1	0.	15.	1.40	133.	11.0	2.5	29.92	18.63	3.51	3.394	2.312	1.668
83/204	D 2	15.	30.	0.93	142.	2.0	2.6	29.92	21.43	3.02	3.483	1.632	1.746
83/205	D 3	30.	45.	1.06	158.	3.5	3.5	29.92	20.57	3.15	3.512	1.857	1.857
83/206	D 4	45.	59.	0.69	232.	13.5	7.0	29.92	23.24	2.77	3.732	2.496	2.211
83/207	D 5	59.	74.	0.70	273.	20.0	10.0	29.92	23.15	2.78	3.801	2.666	2.369
83/208	D 6	74.	88.	0.64	332.	31.0	12.9	29.92	23.65	2.71	3.895	2.865	2.484
83/209	D 7	88.	103.	0.44	269.	31.0	7.6	29.92	25.48	2.51	3.836	2.898	2.287
83/210	D 8	103.	118.	0.31	270.	36.0	5.6	29.92	26.84	2.37	3.860	2.985	2.177
83/211	D 9	118.	132.	0.49	338.	49.5	8.0	29.92	25.00	2.56	3.927	3.093	2.301
83/212	D10	132.	146.	0.50	372.	54.0	8.7	29.92	24.90	2.57	3.967	3.129	2.336
83/213	D11	146.	172.	0.64	410.	61.0	3.4	29.92	23.65	2.71	3.987	3.159	2.298
83/214	D12	172.	198.	1.32	618.	90.0	12.6	29.92	19.06	3.43	4.071	3.234	2.380
83/215	D13	198.	224.	2.36	1150.	143.0	10.6	29.92	14.78	4.54	4.230	3.325	2.195
83/216	D14	224.	250.	1.85	800.	120.0	11.9	29.92	16.59	3.99	4.123	3.299	2.295
83/217	D15	250.	276.	2.46	1200.	140.0	8.8	29.92	14.47	4.65	4.240	3.307	2.105
83/218	D16	276.	292.	2.71	1620.	161.0	7.5	29.92	13.76	4.92	4.348	3.346	2.014
83/219	D17	292.	318.	2.70	1730.	147.0	6.9	29.92	13.79	4.91	4.378	3.307	1.978
83/220	D18	318.	344.	2.94	1525.	181.0	5.4	29.92	13.17	5.17	4.303	3.377	1.852
83/221	D19	344.	370.	2.96	1760.	176.0	6.4	29.92	13.12	5.19	4.364	3.364	1.924
83/222	D20	370.	396.	3.05	1760.	195.0	7.5	29.92	12.91	5.29	4.356	3.401	1.986
83/223	D21	396.	420.	3.25	1790.	188.0	6.7	29.92	12.46	5.51	4.348	3.370	1.922
83/224	E 1	0.	15.	2.26	215.	15.0	6.5	29.75	15.02	4.43	3.509	2.353	1.990
83/225	E 2	15.	30.	2.48	1020.	64.0	73.3	29.75	14.34	4.67	4.165	2.963	3.022
83/226	E 3	30.	55.	2.64	1700.	106.0	150.0	29.75	13.88	4.84	4.373	3.168	3.319
83/227	E 4	55.	80.	2.42	2040.	126.0	195.0	29.75	14.52	4.60	4.472	3.262	3.452
83/228	E 5	80.	105.	2.38	2060.	127.0	198.0	29.75	14.64	4.56	4.479	3.269	3.462
83/229	E 6	105.	130.	2.60	1830.	125.0	171.0	29.75	13.99	4.80	4.408	3.243	3.379
83/230	E 7	130.	155.	2.40	1800.	147.0	165.0	29.75	14.58	4.58	4.419	3.331	3.381
83/231	E 8	155.	180.	2.64	1620.	136.0	129.0	29.75	13.88	4.84	4.352	3.276	3.253
83/232	E 9	180.	205.	2.55	1350.	131.0	101.0	29.75	14.13	4.75	4.281	3.268	3.155

BGS No	Profile : No	DEPTH (cm) Top	DEPTH (cm) Bottom	ELUTRIATE % moisture Content (wet weight)	ELUTRIATE EC_{25}	ELUTRIATE CL	ELUTRIATE NO_3-N	ELUTRIATE Weight D.W. added	ELUTRIATE Dilution Factor	SOIL MOISTURE % M.C. dry weight corrected to oven dry	SOIL MOISTURE EC_{25}^{c}	SOIL MOISTURE CL^{c}	SOIL MOISTURE NO_3-N^{c}
83/233	E10	205.	230.	2.35	1220.	144.0	75.5	29.75	14.73	4.53	4.255	3.327	3.046
83/234	E11	230.	255.	2.06	1190.	158.0	69.2	29.75	15.71	4.22	4.272	3.395	3.036
83/235	E12	255.	280.	1.73	818.	117.0	40.8	29.75	17.00	3.86	4.143	3.299	2.841
83/236	E13	280.	305.	1.73	668.	90.5	29.7	29.75	17.00	3.86	4.055	3.187	2.703
83/237	E14	305.	330.	1.53	605.	80.5	24.9	29.75	17.89	3.65	4.034	3.159	2.649
83/238	E15	330.	355.	1.54	621.	79.5	23.3	29.75	17.85	3.66	4.045	3.152	2.619
83/239	E16	355.	380.	1.25	539.	66.5	17.4	29.75	19.34	3.35	4.018	3.109	2.527
83/240	E17	380.	405.	1.15	500.	60.5	15.1	29.75	19.91	3.25	3.998	3.081	2.478
83/241	E18	405.	430.	1.12	392.	44.5	10.8	29.75	20.09	3.22	3.896	2.951	2.336
83/242	E19	430.	455.	0.90	307.	32.0	7.2	29.75	21.53	2.99	3.820	2.838	2.190
83/243	E20	455.	480.	0.90	250.	24.5	4.7	29.75	21.53	2.99	3.731	2.722	2.005
83/244	E21	480.	505.	0.96	196.	16.5	2.5	29.75	21.11	3.05	3.617	2.542	1.723
83/245	E22	505.	530.	1.00	163.	12.5	2.0	29.75	20.85	3.09	3.531	2.416	1.620
83/246	E23	530.	555.	1.25	195.	16.0	3.3	29.75	19.34	3.35	3.576	2.490	1.805
83/247	E24	555.	580.	1.47	259.	24.5	6.4	29.75	18.18	3.59	3.673	2.649	2.066
83/248	E25	580.	605.	1.74	210.	19.0	4.0	29.75	16.95	3.87	3.551	2.508	1.831
83/249	E26	605.	630.	1.92	212.	18.5	4.2	29.75	16.23	4.07	3.537	2.477	1.833
83/250	E27	630.	655.	1.99	146.	19.5	1.7	29.75	15.96	4.14	3.367	2.493	1.434
83/251	E28	655.	680.	1.59	140.	7.0	1.3	29.75	17.61	3.71	3.392	2.091	1.360
83/252	E29	680.	695.	2.07	158.	7.5	2.4	29.75	15.67	4.23	3.394	2.070	1.575
83/253	G 1	0.	15.	4.04	189.	3.5	1.3	29.73	10.91	6.39	3.314	1.582	1.152
83/254	G 2	15.	30.	3.72	197.	2.0	1.3	29.73	11.46	6.03	3.353	1.360	1.173
83/255	G 3	30.	55.	4.90	367.	21.0	2.7	29.73	9.68	7.36	3.550	2.308	1.417
83/256	G 4	55.	80.	5.11	580.	60.1	4.0	29.73	9.42	7.60	3.738	2.794	1.576
83/257	G 5	80.	105.	4.95	943.	127.0	12.2	29.73	9.61	7.41	3.957	3.087	2.069
83/258	G 6	105.	130.	4.92	1280.	181.0	24.9	29.73	9.65	7.38	4.092	3.242	2.381
83/259	G 7	130.	155.	4.88	1560.	227.0	34.7	29.73	9.70	7.33	4.180	3.343	2.527
83/260	G 8	155.	180.	5.70	2110.	276.0	44.3	29.73	8.78	8.28	4.268	3.384	2.590
83/261	G 9	180.	205.	4.97	2490.	298.0	46.0	29.73	9.59	7.44	4.378	3.456	2.645
83/262	G10	205.	230.	5.47	2000.	246.0	35.7	29.73	9.02	8.01	4.256	3.346	2.508
83/263	G11	230.	255.	4.62	1710.	190.0	26.7	29.73	10.04	7.04	4.235	3.281	2.428
83/264	G12	255.	280.	4.67	1810.	195.0	26.6	29.73	9.97	7.10	4.257	3.289	2.424
83/265	G13	280.	305.	4.57	1870.	204.0	27.4	29.73	9.71	7.32	4.259	3.297	2.425
83/266	G14	305.	330.	4.66	1720.	136.0	23.9	29.73	9.99	7.08	4.235	3.269	2.378
83/267	G15	330.	355.	3.72	1740.	196.0	26.0	29.73	11.46	6.03	4.300	3.351	2.474
83/268	G16	355.	380.	3.92	1500.	168.0	21.6	29.73	11.10	6.25	4.222	3.271	2.380
83/269	G17	380.	405.	3.70	1370.	144.0	17.1	29.73	11.49	6.01	4.197	3.219	2.293
83/270	G18	405.	430.	3.37	1460.	163.0	18.8	29.73	12.13	5.64	4.248	3.296	2.358
83/271	G19	430.	455.	3.61	1340.	154.0	17.9	29.73	11.66	5.91	4.194	3.254	2.320
83/272	G20	455.	480.	2.98	1260.	143.0	16.5	29.73	13.00	5.21	4.214	3.269	2.331
83/273	G21	480.	505.	2.92	1180.	131.0	15.3	29.73	13.14	5.15	4.191	3.236	2.303
83/274	G22	505.	530.	2.47	1010.	110.0	12.9	29.73	14.36	4.66	4.161	3.198	2.268
83/275	G23	530.	555.	2.65	1020.	114.0	14.3	29.73	13.84	4.35	4.150	3.198	2.297
83/276	G24	555.	580.	2.52	938.	104.0	13.6	29.73	14.21	4.71	4.125	3.170	2.286
83/277	G25	580.	605.	2.04	864.	95.0	13.1	29.73	15.77	4.19	4.144	3.176	2.315
83/278	G26	605.	630.	1.66	736.	78.0	11.5	29.73	17.29	3.79	4.105	3.130	2.298
83/279	G27	630.	655.	1.00	536.	51.0	9.2	29.73	20.83	3.09	4.023	3.026	2.283
83/280	G28	655.	680.	0.79	450.	47.0	11.0	29.73	22.31	2.87	4.002	3.021	2.390
83/281	G29	680.	705.	0.61	382.	33.0	10.2	29.73	23.76	2.68	3.958	2.956	2.385
83/282	G30	705.	730.	0.61	351.	34.5	11.0	29.73	23.76	2.68	3.921	2.914	2.417
83/283	G31	730.	755.	0.46	324.	30.0	9.4	29.73	25.13	2.53	3.911	2.877	2.373
83/284	G32	755.	780.	0.54	318.	30.0	9.7	29.73	24.33	2.61	3.890	2.864	2.374
83/285	G33	780.	805.	0.58	320.	29.5	10.1	29.73	24.02	2.65	3.886	2.850	2.385
83/286	G34	805.	830.	0.75	310.	29.5	10.4	29.73	22.62	2.83	3.846	2.824	2.371
83/287	G35	830.	855.	0.81	345.	34.0	12.3	29.73	22.16	2.89	3.883	2.877	2.453
83/288	G36	855.	880.	0.70	308.	29.0	11.7	29.73	23.01	2.78	3.851	2.824	2.430

		DEPTH		ELUTRIATE						SOIL MOISTURE			
BGS No	Profile No	(cm) Top	Bottom	% moisture content (wet weight)	EC_{25}	Cl	NO_3-N	Weight D.W. added	Dilution Factor	% M.C. dry weight corrected to oven dry	EC^c_{25}	Cl^c	NO_3-N^c
83/289	G37	880.	905.	0.65	282.	24.0	9.9	29.73	23.42	2.72	3.820	2.750	2.365
83/290	H 2	15.	30.	3.29	297.	9.5	9.3	30.00	12.40	5.55	3.560	2.071	2.062
83/291	H 3	30.	55.	5.50	523.	40.5	17.7	30.00	9.06	8.04	3.680	2.565	2.205
83/292	H 4	55.	80.	3.60	780.	63.5	36.2	30.00	11.78	5.90	3.963	2.874	2.630
83/293	H 5	80.	105.	4.17	1160.	89.0	55.3	30.00	10.79	6.53	4.097	2.982	2.779
83/294	H 6	105.	130.	4.48	1300.	107.0	70.7	30.00	10.32	6.88	4.147	3.043	2.863
83/295	H 7	130.	155.	4.53	1510.	111.0	73.7	30.00	10.25	6.94	4.190	3.056	2.878
83/296	H 8	155.	180.	5.31	1590.	103.0	68.6	30.00	9.27	7.83	4.168	2.980	2.803
83/297	H 9	180.	205.	4.99	1740.	107.0	69.6	30.00	9.64	7.46	4.225	3.014	2.827
83/298	H10	205.	230.	5.26	2440.	175.0	120.0	30.00	9.32	7.77	4.357	3.213	3.049
83/299	H11	230.	255.	4.62	1940.	131.0	80.5	30.00	10.12	7.04	4.293	3.123	2.911
83/300	H12	255.	280.	4.65	1860.	116.0	71.5	30.00	10.08	7.07	4.273	3.068	2.858
83/301	H13	280.	305.	4.36	1960.	131.0	86.4	30.00	10.49	6.75	4.313	3.138	2.957
83/302	H14	305.	330.	4.06	1975.	147.0	93.0	30.00	10.96	6.41	4.335	3.207	3.008
83/303	J 2	15.	30.	3.56	1240.	101.0	90.0	30.00	11.85	5.85	4.167	3.078	3.028
83/304	J 3	30.	55.	4.02	1390.	112.0	91.2	30.00	11.03	6.36	4.186	3.092	3.002
83/305	J 4	55.	80.	4.33	1530.	114.0	70.4	30.00	10.54	6.71	4.208	3.080	2.870
83/306	J 5	80.	105.	4.39	1330.	111.0	46.6	30.00	9.77	7.35	4.114	3.035	2.658
83/307	J 6	105.	130.	4.03	954.	88.5	34.0	30.00	11.01	6.38	4.021	2.989	2.573
83/308	J 7	130.	180.	3.47	1230.	107.0	46.6	30.00	12.03	5.75	4.170	3.110	2.749
83/309	J 8	180.	230.	4.31	1015.	98.0	40.2	30.00	10.57	6.69	4.031	3.015	2.628
83/310	J 9	230.	280.	3.12	882.	76.0	31.3	30.00	12.73	5.37	4.052	2.987	2.602
83/311	K 1	0.	15.	2.52	224.	3.0	2.2	29.48	14.10	4.71	3.499	1.626	1.492
83/312	K 2	15.	30.	3.46	259.	2.5	1.0	29.48	11.86	5.74	3.487	1.472	1.074
83/313	K 3	30.	55.	4.75	423.	11.0	2.0	29.48	9.79	7.19	3.617	2.032	1.292
83/314	K 4	55.	80.	5.97	980.	73.5	2.2	29.48	8.45	8.59	3.918	2.793	1.269
83/315	K 5	80.	105.	6.27	1340.	107.0	6.0	29.48	8.18	8.94	4.040	2.942	1.691
83/316	K 6	105.	130.	6.65	1590.	126.0	6.7	29.48	7.87	9.39	4.097	2.996	1.722
83/317	K 7	130.	155.	7.29	2430.	142.0	7.1	29.48	7.40	10.15	4.255	3.021	1.720
83/318	K 8	155.	180.	7.36	4670.	134.0	5.9	29.48	7.35	10.23	4.536	2.993	1.637
83/319	K 9	180.	205.	7.08	4950.	120.0	4.9	29.48	7.55	9.90	4.572	2.957	1.568
83/320	K10	205.	230.	7.72	5380.	144.0	3.4	29.48	7.12	10.67	4.583	3.011	1.384
83/321	M 1	0.	15.	0.95	144.	4.0	3.1	29.52	21.02	3.04	3.481	1.925	1.814
83/322	M 2	15.	30.	1.57	133.	5.0	5.1	29.52	17.58	3.69	3.369	1.944	1.953
83/323	M 3	30.	55.	1.78	449.	57.0	18.7	29.52	16.66	3.92	3.874	2.978	2.494
83/324	M 4	55.	80.	2.33	878.	133.0	39.0	29.52	14.69	4.51	4.111	3.291	2.758
83/325	M 5	80.	105.	2.03	934.	137.0	40.8	29.52	15.70	4.18	4.166	3.333	2.807
83/326	M 6	105.	130.	2.50	1330.	214.0	62.2	29.52	14.18	4.69	4.291	3.482	2.945
83/327	M 7	130.	155.	2.33	1240.	190.0	53.3	29.52	14.69	4.51	4.260	3.446	2.894
83/328	M 8	155.	180.	2.49	1060.	168.0	48.0	29.52	14.21	4.68	4.178	3.378	2.834
83/329	M 9	180.	205.	2.44	1210.	179.0	48.8	29.52	14.35	4.63	4.240	3.410	2.845
83/330	M10	205.	230.	2.20	1235.	195.0	48.2	29.52	15.11	4.37	4.271	3.469	2.862
83/331	M11	230.	255.	2.36	1080.	173.0	39.5	29.52	14.60	4.54	4.198	3.402	2.761
83/332	M12	255.	280.	2.11	957.	150.0	30.1	29.52	15.42	4.27	4.169	3.364	2.667
83/333	M13	280.	305.	1.97	828.	130.0	23.1	29.52	15.92	4.12	4.120	3.316	2.566
83/334	M14	305.	330.	1.90	682.	106.0	16.0	29.52	16.19	4.04	4.043	3.234	2.413
83/335	M15	330.	355.	1.42	652.	99.5	13.2	29.52	18.30	3.53	4.077	3.260	2.383
83/336	M16	355.	380.	1.47	582.	79.5	6.3	29.52	18.05	3.59	4.021	3.157	2.089
83/337	M17	380.	405.	1.51	520.	78.5	5.6	29.52	17.86	3.63	3.968	3.147	2.000
83/338	M18	405.	430.	1.63	521.	79.5	4.6	29.52	17.31	3.76	3.955	3.139	1.901
83/339	M19	430.	455.	1.61	529.	80.5	4.1	29.52	17.40	3.74	3.964	3.146	1.853
83/340	M20	455.	480.	1.72	530.	80.5	3.5	29.52	16.92	3.85	3.953	3.134	1.772
83/341	M21	480.	505.	1.74	570.	87.5	3.7	29.52	16.83	3.87	3.982	3.168	1.794
83/342	M22	505.	530.	1.39	535.	82.0	4.0	29.52	18.45	3.50	3.994	3.180	1.868
83/343	N 1	0.	15.	0.59	131.	7.5	0.5	29.52	23.77	2.66	3.634	2.251	1.075
83/344	N 2	15.	30.	0.37	247.	28.5	1.7	29.52	21.58	2.95	3.727	2.789	1.564

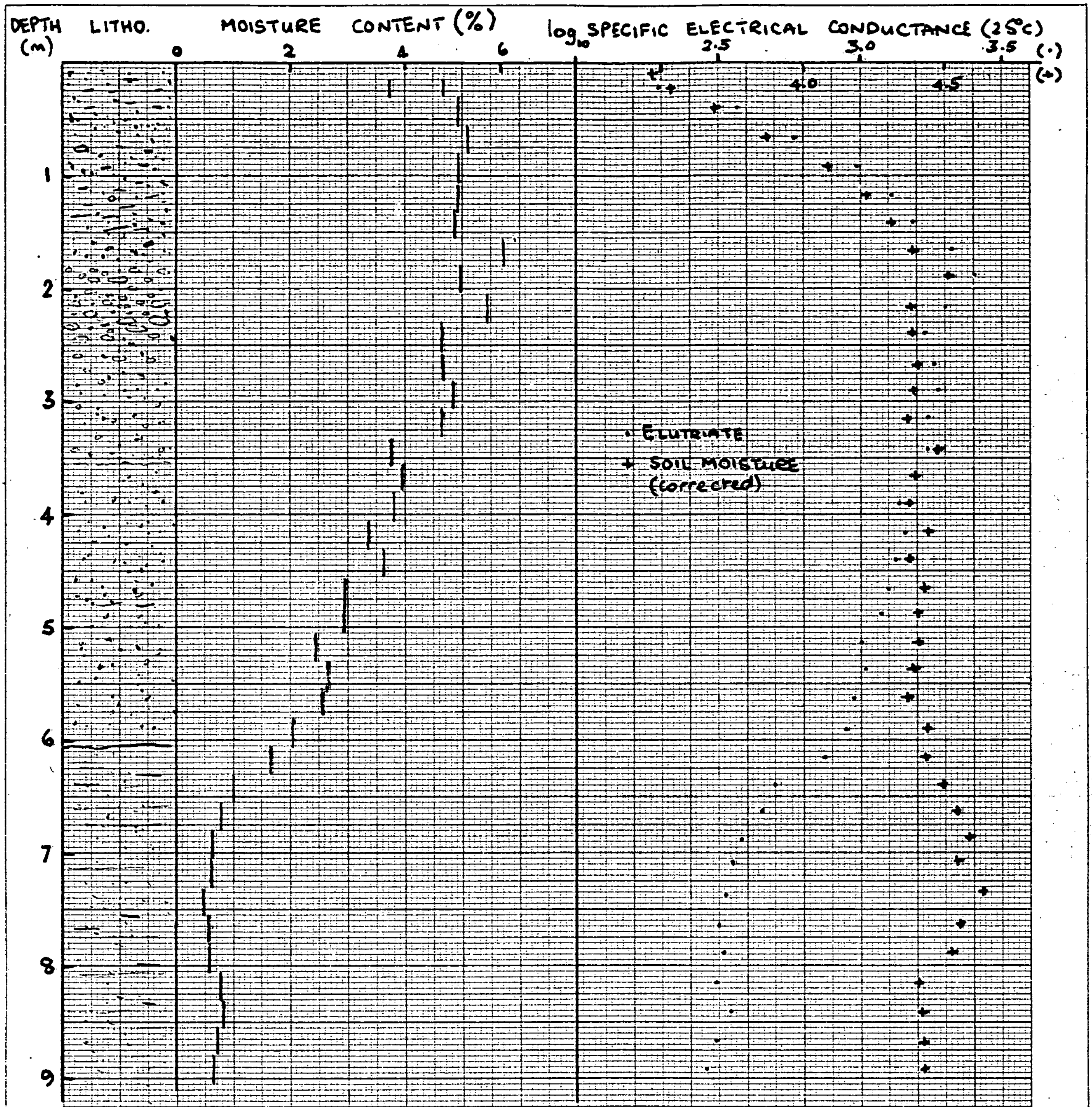
		DEPTH		ELUTRIATE						SOIL MOISTURE			
BGS No	Profile No	(cm) Top	Bottom	% moisture content (wet weight)	EC_{25}	CL	NO_3-N	Weight D.W. added	Dilution Factor	% M.C. dry weight corrected to oven dry	EC_{25}^c	CL^c	NO_3-N^c
83/345	N 3	30.	55.	0.83	869.	237.0	12.2	29.52	21.86	2.91	4.279	3.714	2.426
83/346	N 4	55.	80.	0.82	2660.	632.0	38.7	29.52	21.94	2.90	4.766	4.142	2.929
83/347	N 5	80.	105.	0.82	2070.	468.0	28.0	29.52	21.94	2.90	4.657	4.011	2.788
83/348	N 6	105.	130.	0.67	1640.	369.0	19.0	29.52	23.10	2.74	4.578	3.931	2.642
83/349	N 7	130.	155.	0.64	1440.	308.0	15.6	29.52	23.35	2.71	4.527	3.857	2.561
83/350	N 8	155.	180.	0.83	1380.	300.0	14.0	29.52	21.86	2.91	4.480	3.817	2.486
83/351	N 9	180.	205.	2.20	1790.	404.0	15.7	29.52	15.11	4.37	4.432	3.786	2.375
83/352	N10	205.	230.	4.53	2310.	544.0	18.6	29.52	10.10	6.94	4.368	3.740	2.274
83/353	N11	230.	255.	4.72	2330.	568.0	18.8	29.52	9.84	7.15	4.361	3.748	2.267
83/354	N12	255.	280.	5.43	1720.	434.0	13.1	29.52	9.00	7.96	4.190	3.592	2.072
83/355	N13	280.	305.	5.67	1810.	448.0	13.0	29.52	8.75	8.24	4.200	3.594	2.056
83/356	N14	305.	330.	4.37	1460.	404.0	10.9	29.52	10.33	6.76	4.178	3.620	2.051
83/357	N15	330.	355.	3.15	508.	304.0	6.0	29.52	12.52	5.40	3.804	3.581	1.876
83/358	N16	355.	380.	2.72	1560.	295.0	5.3	29.52	13.57	4.93	4.326	3.602	1.857
83/359	N17	380.	405.	2.40	1470.	277.0	3.9	29.52	14.47	4.58	4.328	3.603	1.752
83/360	N18	405.	430.	3.02	1563.	300.0	4.1	29.52	12.82	5.26	4.302	3.585	1.721
83/361	N19	430.	455.	3.71	2070.	377.0	4.2	29.52	11.40	6.02	4.373	3.633	1.680
83/362	N20	455.	480.	2.53	1650.	283.0	2.9	29.52	14.09	4.72	4.366	3.608	1.611
83/363	N21	480.	505.	1.94	1660.	267.0	2.8	29.52	16.03	4.09	4.425	3.632	1.652
83/364	N22	505.	530.	1.65	1380.	235.0	2.9	29.52	17.22	3.78	4.376	3.607	1.698
83/365	N23	530.	550.	1.47	1710.	185.0	1.7	29.52	18.05	3.59	4.490	3.524	1.487
83/366	N24	550.	580.	1.65	3690.	178.0	1.0	29.52	17.22	3.78	4.803	3.486	1.236
83/367	N25	580.	605.	1.60	3315.	187.0	1.3	29.52	17.44	3.72	4.762	3.513	1.356
83/368	N26	605.	630.	1.36	2376.	154.0	1.0	29.52	18.60	3.47	4.645	3.457	1.270
83/369	N27	630.	655.	1.03	1700.	142.0	1.0	29.52	20.50	3.12	4.542	3.464	1.312
83/370	N28	655.	680.	1.18	1464.	142.0	1.0	29.52	19.59	3.28	4.458	3.444	1.292
83/371	N29	680.	705.	1.06	1275.	140.0	1.0	29.52	20.31	3.15	4.413	3.454	1.308
83/372	P 1	0.	15.	0.18	161.	6.5	2.8	29.46	27.94	2.24	3.653	2.259	1.893
83/373	P 2	15.	30.	0.23	142.	1.5	4.8	29.46	27.35	2.29	3.589	1.613	2.118
83/374	P 3	30.	55.	0.30	231.	3.5	12.8	29.46	26.56	2.36	3.788	1.968	2.531
83/375	P 4	55.	80.	0.30	309.	6.0	19.7	29.46	26.56	2.36	3.914	2.202	2.719
83/376	P 5	80.	105.	0.36	360.	7.0	25.0	29.46	25.91	2.42	3.970	2.259	2.811
83/377	P 6	105.	130.	0.41	419.	9.5	30.0	29.46	25.40	2.47	4.027	2.383	2.882
83/378	P 7	130.	155.	0.58	413.	9.5	29.2	29.46	23.82	2.65	3.993	2.355	2.842
83/379	P 8	155.	180.	0.49	361.	8.5	25.1	29.46	24.63	2.56	3.949	2.321	2.791
83/380	P 9	180.	205.	0.52	277.	6.5	18.4	29.46	24.35	2.59	3.829	2.199	2.651
83/381	P10	205.	230.	0.66	278.	6.0	17.2	29.46	23.14	2.73	3.808	2.142	2.600
83/382	P11	230.	252.	0.29	223.	4.5	13.8	29.46	26.67	2.35	3.774	2.079	2.566
83/383	P12	252.	275.	0.32	224.	5.5	13.6	29.46	26.34	2.38	3.771	2.161	2.554
83/384	P13	275.	300.	0.40	296.	7.5	19.9	29.46	25.50	2.46	3.878	2.282	2.705
83/385	Q 1	0.	30.	3.26	682.	28.0	42.0	29.52	12.28	5.52	3.923	2.537	2.713
83/386	Q 2	30.	55.	3.80	1540.	129.0	74.5	29.52	11.24	6.12	4.238	3.161	2.923
83/387	Q 3	55.	80.	4.22	1640.	152.0	88.0	29.52	10.55	6.59	4.238	3.205	2.968
83/388	Q 4	80.	105.	4.59	2260.	234.1	111.0	29.52	10.02	7.01	4.355	3.370	3.046
83/389	Q 5	105.	130.	4.81	2320.	229.0	86.9	29.52	9.73	7.25	4.354	3.348	2.927
83/390	Q 6	130.	155.	5.01	2690.	246.0	66.6	29.52	9.48	7.48	4.407	3.368	2.800
83/391	Q 7	155.	180.	5.29	2640.	243.0	53.7	29.52	9.16	7.80	4.383	3.347	2.692
83/392	Q 8	180.	205.	5.67	2690.	247.0	50.5	29.52	8.75	8.24	4.372	3.335	2.646
83/393	Q 9	205.	230.	4.69	2440.	230.0	46.5	29.52	9.88	7.12	4.382	3.357	2.662
83/394	Q10	230.	255.	4.87	2180.	191.0	43.4	29.52	9.65	7.32	4.323	3.266	2.622
83/395	Q11	255.	280.	4.88	2220.	202.0	47.3	29.52	9.64	7.33	4.330	3.289	2.659
83/396	Q12	280.	305.	4.80	2120.	182.0	40.5	29.52	9.74	7.24	4.315	3.249	2.596
83/397	Q13	305.	330.	4.81	1970.	165.0	33.6	29.52	9.73	7.25	4.283	3.206	2.514
83/398	Q14	330.	355.	4.44	1850.	172.0	30.9	29.52	10.23	6.84	4.277	3.245	2.500
83/399	Q15	355.	380.	4.43	1900.	172.0	29.0	29.52	10.17	6.88	4.286	3.243	2.470
83/400	Q16	380.	405.	4.14	1830.	133.0	29.2	29.52	10.68	6.50	4.291	3.291	2.494

		DEPTH		ELUTRIATE						SOIL MOISTURE			
BGS No	Profile No	(cm) Top	Bottom	% moisture content (wet weight)	EC_{25}	CL	NO_3-N	Weight D.W. added	Dilution Factor	% M.C. dry weight corrected to oven dry	EC^c_{25}	CL^c	NO_3-N^c
83/401	Q17	405.	430.	3.96	1830.	173.0	26.8	29.52	10.97	6.30	4.303	3.278	2.468
83/402	Q18	430.	455.	3.30	1650.	149.0	23.8	29.52	12.20	5.56	4.304	3.260	2.463
83/403	Q19	455.	480.	3.15	1530.	160.0	24.1	29.52	12.52	5.40	4.282	3.302	2.480
83/404	Q20	480.	505.	3.18	1630.	148.0	23.4	29.52	12.46	5.43	4.308	3.266	2.465
83/405	Q21	505.	530.	3.11	1580.	140.0	20.0	29.52	12.61	5.36	4.299	3.247	2.402
83/406	Q22	530.	555.	2.28	1160.	99.0	11.6	29.52	14.85	4.45	4.236	3.167	2.236
83/407	Q23	555.	580.	2.25	1250.	100.0	14.3	29.52	14.95	4.42	4.271	3.175	2.330
83/408	Q24	580.	605.	2.19	1180.	101.0	12.0	29.52	15.14	4.36	4.252	3.185	2.259
83/409	Q25	605.	630.	2.19	1160.	93.0	10.7	29.52	15.14	4.36	4.245	3.149	2.210
83/410	Q26	630.	655.	1.96	1150.	95.0	9.6	29.52	15.96	4.11	4.264	3.181	2.185
83/411	S 1	0.	15.	0.49	1070.	62.0	66.4	29.52	24.68	2.56	4.422	3.185	3.214
83/412	S 2	15.	30.	1.50	1830.	136.0	123.0	29.52	17.91	3.62	4.515	3.387	3.343
83/413	S 4	55.	80.	2.17	2140.	200.0	115.0	29.52	15.21	4.33	4.513	3.483	3.243
83/414	S 5	80.	105.	2.84	3910.	222.0	33.2	29.52	13.26	5.06	4.715	3.469	3.043
83/415	S 6	105.	130.	3.47	4800.	171.0	49.3	29.52	11.85	5.75	4.755	3.307	2.767
83/416	S 7	130.	155.	3.32	4350.	161.0	40.2	29.52	12.16	5.59	4.723	3.292	2.689
83/417	S 8	155.	180.	3.66	4300.	174.0	33.8	29.52	11.49	5.96	4.694	3.301	2.589
83/418	S 9	180.	205.	3.57	4220.	193.0	33.2	29.52	11.66	5.86	4.692	3.352	2.588
83/419	S10	205.	230.	3.72	4380.	149.0	23.5	29.52	11.38	6.03	4.698	3.229	2.427
83/420	S11	230.	255.	3.63	4900.	164.0	25.1	29.52	11.55	5.93	4.753	3.277	2.462
83/421	S12	255.	280.	3.76	5180.	159.0	23.4	29.52	11.31	6.07	4.768	3.255	2.423
83/422	S13	280.	330.	3.98	4960.	130.0	16.9	29.52	10.93	6.32	4.734	3.153	2.267
83/423	S14	330.	380.	3.51	4700.	105.0	14.8	29.52	11.73	5.80	4.743	3.092	2.241
83/424	S15	380.	430.	2.69	3990.	80.0	12.9	29.52	13.65	4.90	4.736	3.038	2.246
83/425	T 1	0.	5.	2.31	392.	10.0	4.2	29.50	14.74	4.49	3.762	2.169	1.792
83/426	T 2	5.	10.	2.89	270.	7.5	3.5	29.50	13.12	5.12	3.549	1.993	1.662
83/427	T 3	10.	15.	6.00	325.	3.0	3.1	29.50	8.43	8.62	3.438	1.403	1.417
83/428	T 4	15.	20.	6.48	442.	11.5	5.8	29.50	8.01	9.19	3.549	1.964	1.667
83/429	T 5	20.	30.	6.89	865.	95.0	12.5	29.50	7.69	9.67	3.833	2.864	1.983
83/430	T 6	30.	40.	5.10	1430.	236.0	27.7	29.50	9.37	7.59	4.127	3.345	2.414
83/431	T 7	40.	50.	6.11	2010.	323.0	36.7	29.50	8.33	8.75	4.224	3.430	2.485
83/432	T 8	50.	60.	5.40	2550.	412.0	44.1	29.50	9.03	7.93	4.362	3.571	2.600
83/433	T 9	60.	70.	6.34	2720.	412.0	43.0	29.50	8.13	9.02	4.345	3.525	2.544
83/434	T10	70.	80.	6.91	3160.	419.0	46.9	29.50	7.68	9.70	4.385	3.507	2.556
83/435	T11	80.	90.	7.11	5410.	393.0	48.0	29.50	7.53	9.93	4.610	3.471	2.558
83/436	T12	90.	100.	7.96	4920.	406.0	55.4	29.50	6.97	10.96	4.535	3.452	2.587
83/437	U 1	0.	5.	0.89	338.	4.5	6.8	29.44	21.38	2.97	3.859	1.983	2.163
83/438	U 2	5.	10.	2.03	375.	4.0	8.4	29.44	15.66	4.18	3.769	1.797	2.119
83/439	U 3	10.	15.	3.01	617.	15.0	26.5	29.44	12.81	5.25	3.898	2.284	2.531
83/440	U 4	15.	20.	2.14	693.	26.0	17.2	29.44	15.27	4.30	4.025	2.599	2.419
83/441	U 5	20.	30.	1.47	2292.	215.0	90.0	29.44	18.01	3.59	4.616	3.588	3.210
83/442	U 6	30.	40.	6.25	2835.	233.0	132.0	29.44	8.19	8.92	4.366	3.365	3.034
83/443	U 7	40.	50.	4.87	3405.	364.0	153.0	29.44	9.63	7.32	4.516	3.545	3.168
83/444	U 9	60.	70.	5.55	3765.	415.0	76.0	29.44	8.86	8.10	4.523	3.565	2.828
83/445	U10	70.	80.	4.94	4755.	397.0	39.1	29.44	9.54	7.40	4.657	3.578	2.572
83/446	U11	80.	90.	4.96	7650.	378.0	29.0	29.44	9.52	7.43	4.862	3.556	2.441
83/447	U12	90.	100.	3.81	7530.	350.0	24.6	29.44	11.19	6.13	4.926	3.593	2.440
83/448	U13	100.	110.	4.80	6900.	379.0	27.0	29.44	9.72	7.24	4.826	3.566	2.419



Auger hole D 20/11/82 Open grassy area, sandy surface, flat, on terrace above wadi. No trees nearby. Lithology - grey/green soil above small grain gravel overlying weathered 'pink' Nubian sst. at 1.32m.

Figure 29. Field data sheets - auger hole 'd', Abu Delaig.



Auger hole G. Open area, grassy with gravel/rounded pebble surface.
Slope 2°. Nearest trees, bushes 30m.
Drilled 22.11.82
Geology: Coarse gravel at ca. 1.80m, matrix in this zone gy/gn 'clay'. To 3.80m still some gravel but below becoming browner (? weathered Nubian) Coarse grit, up to 1cm to 6.30 in sand/clay. Nubian sst at 6.30m, harder drilling, light, cream f.g. sst., little or no grit. Stop at hard band 8.80m.

Figure 30. Field data sheets - auger hole 'g', Abu Delaig.