HYDROGEOLOGY OF FRACTURED BEDROCK SYSTEMS IN SOUTH-WEST UGANDA

with special reference to

THE RIVER NYABISHEKI CATCHMENT OF MBARARA DISTRICT

Final Report to the Water Development Department
of the Ministry of Water and Mineral Development

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DEDICATION

This report is dedicated to the memory of Stephen Ssentamu, Principal Investigator and Project Manager of the Ugandan research team, who was tragically killed during the study on December 9th, 1987.

SUMMARY

Recognising that Precambrian basement rocks are currently the primary source of groundwater in Uganda, a two year hydrogeological research project was conducted which sought: 1) to define the regional extent of the aquifer systems in the basement rocks and overlying deposits in an area of southwest Uganda; 2) to understand site-specific local groundwater flow systems as these apply to borehole yields; 3) refine existing hydrogeological criteria for the siting of boreholes and improvement of yields; and 4) to train Ugandan hydrogeologists in the application of relevant hydrogeological techniques and methodologies, thereby strengthening the hydrogeological research capabilities of the Ministry of Water and Mineral Development's Water Development Department. It was intended that the generated knowledge would aid in the preparation of future drilling programs, reduce the number of dry boreholes and, possibly, increase the number of high-yielding holes suitable for community systems.

Funded primarily by the International Development Research Centre (IDRC), Canada, the project commenced in August 1987, focusing attention on the Nyabisheki Catchment, north of Mbarara. The work was conducted as a co-operative venture between the Groundwater Research Group of the University of Toronto, Canada and a research team from the Water Development Department (WDD), Entebbe. A third important component of the study was the involvement and cooperation of the UNICEF/WDD drilling project, particularly in terms of making boreholes available for testing and sampling and for providing local logistical support.

In its approach, the study team endeavored to adapt modern and advanced hydrogeological techniques to Ugandan conditions through the adoption of a comprehensive, multi-element research program involving constant yield discharge tests, packer tests, recharge analysis and major ion, minor ion and isotope hydrochemistry. In all, a total of 233 packer tests were conducted in 22 boreholes, and over 50 wells were sampled and comprehensively chemically analyzed.

By its completion, the project had proved to be extremely successful, developing a series of important if not always encouraging conclusions. The more important of these findings may be summarized as follows:

1) Groundwater flow in the unweathered bedrock is entirely due to secondary permeability in the form of fractures. Packer test studies indicate that these fractures occur throughout the depth of the well, but are usually few in number and often exhibit a relatively low permeability. Fracture zones were detected in most boreholes; however, these zones were frequently found to yield very little groundwater. Most of the higher yielding fracture zones occur near the top of the bedrock where the overlying regolith may be playing a contributory role. Based on all the packer test data collected, there is no clear relationship between hydraulic conductivity and depth within the upper 90 meters of rock tested. There is also no apparent relationship between the distribution of boreholes with shallow, intermediate or deep, high yielding fracture zones, and physiographic features. This is not surprising given the poor degree of fracture development in the study area.

2) Quantitative assessment of the hydrogeological properties of the Precambrian basement rock aquifer suggests that the unweathered bedrock constitutes an extremely weak aquifer with little transmissive capability and, very likely, a low specific yield. Across the study area, the hydraulic conductivity of the bedrock is generally low (less than 10^{-7} m/s). Transmissivity values determined through a comprehensive series of packer tests and single well tests are, with very few exceptions, less than 1 m^2/d. Based on these results it is estimated that that groundwater flow in the basement rock aquifer, in the vicinity of the River Nyabisheki, the primary discharge zone, is less than 3.5 x 10^5 m^3/year (equivalent to an annual recharge of just 0.15 mm).

3) Groundwater chemistry and potentiometric heads confirm that while groundwater recharge to the bedrock aquifer occurs throughout the study area it is primarily focused in two areas, one an extensive zone occupying most of the western extent of the study area, the other a relatively small zone around Kazo. The River Nyabisheki intercepts most of the flow. Soil moisture balance calculations indicate that annual recharge is in the range 10-15 mm per year, a value which agrees well with studies conducted in similar regions of Africa.

The most significant finding concerns the very weak nature of the bedrock aquifer and its very low rate of groundwater flow. It raises two important questions: 1) If recharge to the area is 10-15mm per year and only 0.15mm is being transmitted through the bedrock aquifer, where is the remainder going? 2) What is the long-term viability of the basement aquifer as a groundwater resource?

With regard to question 1) it is suggested that the overlying regolith may constitute a more important aquifer in the region than the basement rocks. Considerable quantities of groundwater flow are frequently encountered in the regolith during drilling. It is also significant to note that groundwater flow in the bedrock aquifer represents less than 10% of the estimated annual baseflow contribution to the Nyabisheki River, implying that the regolith could be supplying the remaining 90%.

With regard to question 2), it is significant that the annual flow in the basement aquifer is only marginally in excess of the potential rate of groundwater abstraction in the study area which is estimated to be approximately 2.3 x 10^5 m^3/year. Given the high hydraulic gradients and broad distribution of production wells in the region, it unlikely that more than a few per cent of the natural through-flow in the basement aquifer can intercepted by abstraction. This implies that the vast majority of currently abstracted water is being obtained from either i) aquifer storage or ii) vertical leakage from the regolith. There are currently insufficient data available to determine whether overdevelopment of the basement aquifer is able to utilize groundwater in the regolith by inducing vertical leakage. In the worst case scenario, the regolith and basement rock aquifers form essentially hydraulically discrete systems, in which case resource development of the deeper aquifer will mine the resource. Under this condition an <u>average</u> annual water level decline of between 0.008 and 0.08m per year may be anticipated depending on the aquifer's specific yield. In the immediate vicinity of production wells much high water level declines may be anticipated.

It must be concluded that the basement rocks of the study area form a weak aquifer which is highly susceptible to overproduction and water level decline. Future problems may include lowering of water levels in abstraction wells and drying up of natural springs. The risk of such problems imposes serious constraints on the aquifer's future use and development. On a more positive note, it is believed that the aquifer within the regolith may provide the key to future resource development in the region. Development of this aquifer may be achieved either through wells constructed in the regolith's water bearing zone, or, where conditions permit, through deeper bedrock wells inducing vertical leakage by pumping.

It is recommended that future studies should focus on the hydrogeologic characteristics of the regolith and its hydraulic relationship with the underlying bedrock. It is also important that the components of the water balance be more rigorously defined, particularly with regard to spring discharge and river flow. It is these key elements which will provide a basis for the development of a sound, national, water development and management policy so vital if the future availability of reliable, good quality water resources is to be assured. Such a policy would consider the interactive nature of ground and surface water and provide a program for long-term, effective and responsible, integrated development of these valuable and essential resources.

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1 INTRODUCTION

1.1 Background

Uganda occupies an area of 241,000 km^2 and, in 1985, the population was estimated to be 15.5 million. The country is situated between elevations of 1000 and 1500 m above sea level, and enjoys a mild equatorial climate.

More than 90% of the population live in rural areas and the moderately good to fertile soil, combined with generally adequate rainfall, ensures that throughout most of the country it is possible to sustain successful crop production.

Much of the rural water supply in Uganda comes from boreholes and, to a lesser extent, springs. The construction of boreholes began in the 1930s and, by 1980, more than 6000 had been constructed, being mainly equipped with handpumps. Unfortunately, due to the civil disturbances which took place over a number of years, many of the boreholes fell into disrepair and, by 1981, it was estimated that as many as 70% were not functioning. Thus there was a severe shortage of safe potable water for much of the rural areas. This situation led to an increase in the spread of water-borne diseases and a general deterioration in the health of the rural populations.

In 1980 the Government, assisted by UNICEF, embarked upon a program of borehole rehabilitation and also undertook to drill new boreholes in the rural areas. In the following years negotiations took place between the Government and various agencies of the United Nations which ultimately led to the establishment of the UNICEF Rural Water Supply Project.

The agreement between the Government and the UN agencies included new drilling rigs to permit the construction of the boreholes by the Government, through the Water Development Department, with technical assistance being supplied by UNICEF.

The drilling activities were initiated in the north of the country, which experiences a three month dry period each year, and the main emphasis was on constructing boreholes with yields adequate to justify their being equipped with hand pumps.

One of the original medium-term objectives of the Government and UNICEF was to construct 720 new boreholes in the north over a four year period. The Government's objective for the International Drinking Water Supply and Sanitation Decade (IDWSSD) was to construct between 6000 and 10000 new boreholes by 1990.

To carry out the drilling program 2 Halco air rotary rigs were initially supplied, followed by another 2, some time later. At the time of a mid-term evaluation of the UNICEF project in 1985, it became apparent that, although the project was being quite successful in the construction of new boreholes, the demands being placed on the small number of Ugandan hydrogeologists was not permitting any comprehensive collection and analysis of hydrogeological data. Thus the opportunity for obtaining a better understanding of the occurrence and movement of groundwater in Uganda was being largely missed.

In addition, due to the lack of data analysis and the resulting difficulty in significantly increasing the level of understanding of the groundwater regime, little was being done to improve the techniques for selecting drilling locations and improving the success rate of the drilling program.

Ultimately a proposal was submitted to the International Development Research Centre (IDRC) by the Ugandan Government for a project to study the occurrence and movement of groundwater, utilizing the drilling program of the UNICEF project. As the drilling was located in Northern Uganda the study area was also selected in that region.

The proposal was accepted by IDRC and the project was initiated in 1986. Unfortunately on-going civil unrest led to some delays in the actual start of the project and by the time that it was possible to proceed, the UNICEF project had left the north and was scheduled to start drilling in the southwest.

A field visit was made by a member of the Canadian team in December 1986 and a study area in the southwest, which most closely approximated the original study area in terms of geology and physiography, was selected.

The UNICEF rigs moved into the study area in April 1987 and the IDRC field program got underway in August of that year.

1.2 Objectives

The UNICEF drilling program has concentrated on developing boreholes in the crystalline Precambrian rocks but without a clear understanding of where the main water bearing horizons occur.

Discussions with drillers and hydrogeologists working on the drilling program revealed conflicting opinions about whether the rock generally yielded water from the upper zones or whether better yields were obtained from fractures at depth. Other questions which needed to be addressed involved recharge mechanisms and the possibility that the fracture systems being exploited by the boreholes were of limited extent and could ultimately be de-watered.

The proposal for the present project, developed by the staff of the Water Development Department and the University of Toronto, was designed to run in parallel with, and take advantage of, the drilling operation. The research aspect of the present project seeks to adapt modern hydrogeological techniques to conditions in Uganda in order to increase the knowledge of the occurrence and movement of groundwater within the crystalline rocks. The increased knowledge can then be used to prepare future drilling programs in order to reduce the number of dry boreholes and, possibly, increase the number of high-yielding holes suitable for community systems.

Specifically, the objectives of the study are to:

i) define the regional extent of the aquifer systems in the basement rocks and overlying deposits in an area of southwest Uganda;

ii) understand site-specific local groundwater flow systems as these apply to borehole yields;

iii) refine existing hydrogeological criteria for the siting of boreholes and improvement of yields;

iv) train Ugandan hydrogeologists in the application of relevant hydrogeological techniques and methodologies.

An additional, and important, objective of the study is to strengthen the research capabilities in hydrogeology in the Water Development Department in Uganda.

1.3 Study Approach

The essential component of the present study was the co-operation of the UNICEF/WDD drilling project in terms of making boreholes available for testing and sampling. The co-operation was readily forthcoming.

The techniques employed in the present study, which are described in detail in subsequent sections of this report, included well testing, packer testing and collection of water samples for major ion, minor ion and isotope analysis. At the outset of the project, a review of existing data, maps and reports was carried out.

The Canadian input to the project has consisted of co-operation in the preparation of the scope of work and proposed methodologies, followed by periods of field work at various stages. Initially the field visits by the Canadian team members concentrated on training the Ugandan investigators in the use of equipment such as the pneumatic packers and, at later stages, they reviewed the progress being made and assisted in carrying out the work. Finally two Ugandan hydrogeologists spent several weeks at the University of Toronto where all the team members co-operated on data analysis and the preparation of the report.

1.4 Report Format

The report contains eight chapters and an appendix. Following this introduction, Chapters 2 and 3 describe respectively the physical and geological characteristics of the region in preparation for a comprehensive description of the hydrogeology in Chapter 4. Chapter 4 also describes the various methodologies adopted for the investigation and presents, in each case, the major findings. The overall conclusions to the study are drawn together in Chapter 5, and these are further reviewed in the context of the project objectives in Chapter 6. Recommendations for future activity are listed and discussed in Chapter 7. The report concludes with a list of references (Chapter 8) and a comprehensive set of appendices.

2 PHYSICAL SETTING

2.1 Introduction

The project area is located in the northern part of Mbarara district, in southwestern Uganda (Figures 2.1 and 2.2). It lies between longitudes 30° 20'and 31° 05' east and latitudes 1° 30'north and 0° 15'south. With an area of approximately 2750 km^2, the basin encompasses the catchment of the River Nyabisheki and its tributary the River Oruyubu. The basin is broad in the south and tapers somewhat towards the north, terminating at the confluence of the Oruyubu and Nyabisheki rivers.

A few miles north of the confluence, the drainage flows into the River Mpanga which itself drains westward into Lake George and the Rift Valley drainage system. The study area is thus located just west of the major divide which separates the areas which drain eastward into Lake Victoria from those which drain westward into the Rift Valley.

2.2 Physiography

On a regional scale the southwestern part of Uganda can be considered to consist of two major morphological units (Doornkamp, 1970): the Rift Valley being one, and the region to the east of the Rift being the other. Within the area to the east there are upland and lowland areas and the actual project area encompasses both (Figure 2.3).

The lowland landscape occupies the largest proportion of the study area and the elevation increases from approximately 1200 metres above sea level in the east to in excess of 1500 metres in the west. Throughout most of the area, the lowland landscape is gently sloping with modest relief and represents a planation surface which abuts against the upland landscape along the southwestern boundary of the study area.

Within the lowland landscape there are higher areas formed by inselbergs, consisting of granites and gneisses, and long narrow ridges of quartzite. The quartzite ridges are up to 150 m higher than the surrounding area and sometimes extend above the upland landscape. Doornkamp (1970) suggests that the quartzite ridges may have been residual features within the upland landscape, prior to formation of the lowland areas.

The inselbergs are frequently grouped densely together to form regions of rugged topography within the lowland landscape, see Figure 2.3. The lowland landscape is essentially a planation surface where the slope seldom exceeds 1 in 10 and where the valleys are wide and frequently have flat floors consisting of depositional material.

Within the lowland areas small hills rise to an elevation of about 1400 metres in the north of the study area and about 1525 metres in the south. Conspicuous ridges and hills of greater elevation in the area are Kazo, Isya and Kiruhura.

Ibanda Hill is a flat-topped dome with much gullied sides which rises from a plateau at 1400 metres to a height of more than 1860 metres. Although a distinctive topographic feature, it is not a topographic unit in its own right but an isolated remnant of the Upland Landscape. It is bounded by a scarp and is more than 6 kilometers in length and more than 3 kilometers wide.

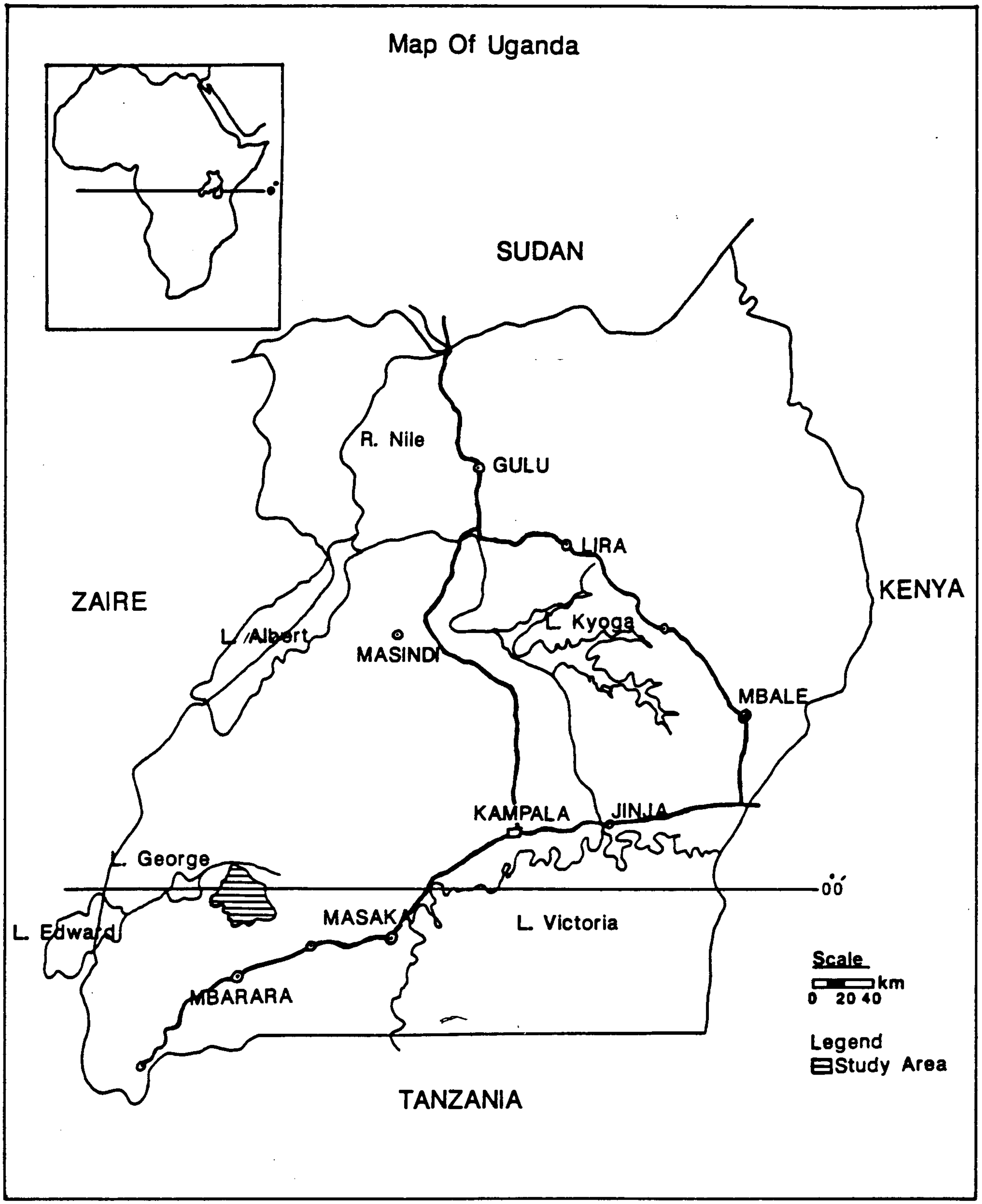


Figure 2.1 Location of Study Area

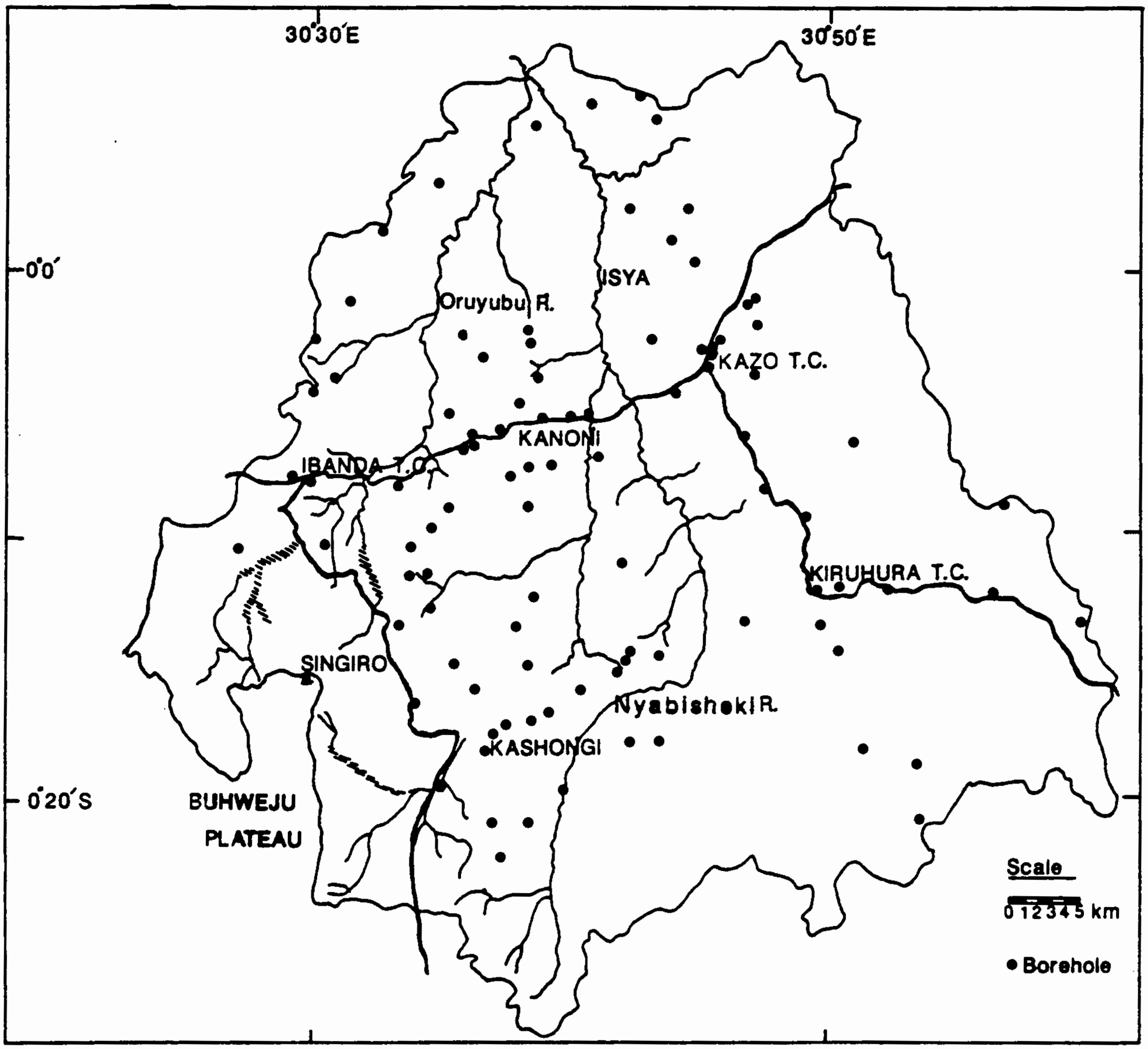


Figure 2.2 Field Study Area
Nyabisheki River Catchment - Mbarara District

The upland landscape occupies about 10% of the study area, occurring in the southeast, and is also found along the southwestern border. The catchment boundary is believed to run along the scarp of the Buhwezu Plateau and thus, in the southwest, the uplands are almost entirely outside the catchment boundary. However, on Figure 2.3 they have been included on the map in order to assist the reader in understanding the regional setting of the study area.

The upland landscape generally has low relief and the slope rarely exceeds 6 degrees (Doornkamp, 1970), being in a southerly direction. There are, however, residual landforms rising above the upland landscape, particularly on the southwest boundary of the study area, where the summit of Singiro reaches 2172 m. These higher residual landforms, occurring above the upland landscape, have more pronounced relief and more deeply incised drainage.

2.3 Drainage

Doornkamp (1970) notes that in southern Uganda there is frequently a disparity between the drainage direction suggested by the form of the valleys and the actual drainage direction of the streams which flow within them. He attributes this to the fact that some of the streams have been reversed within their valleys by the the tectonic upwarping associated with the development of the Western Rift Valley. It is significant, for example, that the Rift Valley runs some 50 kilometres west of the catchment and gradients are highest in the west of the study area, near the axis of upwarp.

The upwarping affected streams differently, depending on their original direction of drainage. As the axis of the upwarp was just to the west of the study area, the easterly draining streams within the study area would have their gradients increased. Westerly draining streams, by the same reasoning, would have their gradients decreased and possibly reversed.

The direct impact of upwarping on the gradient of the northerly draining Nyabisheki would be negligible, though changes in the flow regimes of the tributaries would obviously affect flows in the river. The implication of these changes in drainage direction, as they might relate to hydrogeology, are discussed elsewhere in this report.

The reversal of drainage is significant in that it has led to the development of relatively low divides between the eastward draining catchments, which flow to Lake Victoria, and those which drain westward to the Rift Valley. Swamps are frequently found along these low divides, with water draining out of the swamps in opposite directions.

Within the study area it is possible to classify the drainage according to valley type and flow system. In this way four types of drainage can be described:-

1) Scarp Flow
2) Retarded Flow
3) Broad Valley Flow
4) Discontinuous Flow

Scarp Flow

This occurs in a high rainfall zone with high energy surface flows cutting steep angular valleys. Where permanent flow occurs small water falls are common. Typical of first order streams in this environment, most of the time the valleys are dry and, due to mechanical weathering, the rock formations are very well exposed.

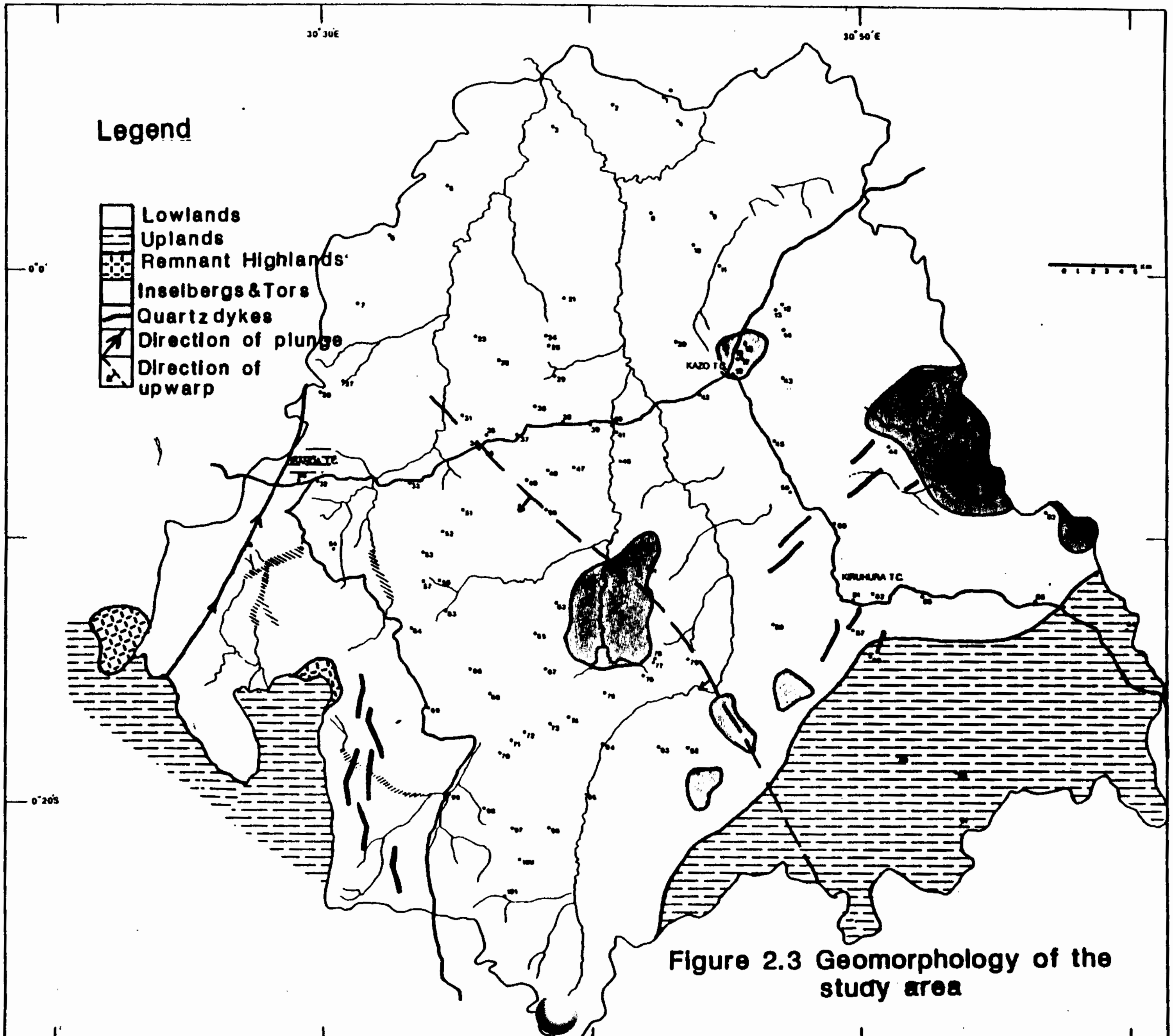


Figure 2.3 Geomorphology of the study area

Retarded Flow

At the base of the scarp there is a rapid change to a gentle gradient. Flow is suddenly checked, resulting in the formation of swamps. These swamps have been thought to be reservoirs which sustain flow throughout the year in the Oruyubu sub-catchment southwest of the project area. However recent work in Zimbabwe found that wetlands led to higher evapotranspiration losses and did not function as reservoirs, thus it is conceivable that the same processes could be taking place here. Papyrus is the typical vegetation of these areas.

Broad Valley Flow

Between Ibanda and Kazo the valleys of the Nyabisheki and Oruyubu streams are broad with gentle flow occurring through thickly vegetated areas of bushes and trees. Most of the valleys, except those feeding Oruyubu, have flow only during the rainy seasons.

Discontinuous Flow

East of the Nyabisheki drainage divide, scattered residual hills and very wide flat valleys lead to flooding during rains. Intermittent flow is characteristic with numerous pools of water occurring along the stream channels. Nyabisheki sub-catchment is rather drier. Rivulets in the sub-catchment bear significant volumes of water only during heavy rains, and large parts of the Nyabisheki system go completely dry between June and August.

2.4 Vegetation and Land Use

The vegetation is tropical with grassland and scrub on the lowland and wooded savanna in the higher areas. Short thick highland grass covers Ibanda hill and the scarps of Buhwezu plateau, with thick vegetation, including trees, in the gullies.

The southern half of the lowlands is cultivated with bananas and most natural bush has been cleared for cultivation and ranching. Overgrazing is an increasing problem. The northern half of the study area is still mainly uncultivated, with sparse population, and is mainly rangeland. Natural vegetation still survives but the bush is being cleared for grazing at an increasing rate. The vegetation within the study area is estimated to be 55% grassland and scrub, 15% wooded savanna and 30% cultivated.

2.5 Climate

Mean annual temperature in the study area is 22.5 to 25 ^{o}C but varies with altitude. Above 2100 m the mean annual temperature drops to 12.5 ^{o}C.

Annual rainfall also varies with altitude. It is about 1400 mm in the southwest and above 750 mm around Kiruhura. Highest rainfall occurs between April and May and from September to November. The dry season runs from June to August.

3 GEOLOGICAL SETTING

3.1 Introduction

Uganda is underlain predominantly by crystalline Precambrian rocks of the continental shield of Africa, some dating back 3,000 million years. Most of these rocks have been modified by deep-seated mountain-building processes which continued throughout the Precambrian and into early Cambrian times. A period of stability followed until Tertiary times.

The study area exhibits a good cross-section of the Precambrian rocks including granites, schists, gneisses, phyllites and quartzites. The Precambrian rocks have been sub-divided into three groups consisting of a gneissic Basement Complex (B.C.), the Buganda-Toro Formation (B-T) and the younger Karagwe-Ankolean System (K-A).

The study area has been largely affected by tectonic faulting and shallow folding. The most recent tectonic activity is related to the opening of the Western Rift Valley some 50km to the east of the study area.

3.2 Geomorphology

As described in Chapter 2, much of the study area is classified as lowland landscape consisting of rolling topography. This "late-mature" landform tends to occur where the rocks are less resistant.

The lowland landscape commonly contains inselbergs and quartzite ridges, both of which stand clear of the surrounding topography. Many of the valleys are floored with recent sedimentary deposits. The predominant rocks, however, are undifferentiated schists and acid gneisses of the Buganda-Toro System, which occupy about two thirds of the study area (see Figure 3.1).

The Buhwezu mountains form the highlands or upland landscape along the southwestern boundary of the study area. They are predominantly quartzites and phyllites. The lithological change from granites, gneisses and schists to quartzites and phyllites is marked by a steep scarp.

The remaining part of the study area, in the southeast, is underlain by undifferentiated acid gneisses of the Basement Complex with some later rocks of pre Karagwe-Ankolean age. This area tends to be higher than the more northerly lowlands and contains some of the residual uplands.

3.3 Geological History

As indicated previously, the region is underlain by rocks of three major Precambrian systems (Table 3.1). The oldest rocks are those of the Basement Complex, followed by the Buganda-Toro system (ca.1800 m y old.), and the younger Karagwe-Ankolean rocks (ca.1300 - 1400 m y.). Some of the rocks show granitisation. The granitisation has been classified by Combe (1926) into older gneissose granite of presumed basement age (G1), and younger post K-A unfoliated granites (G2).

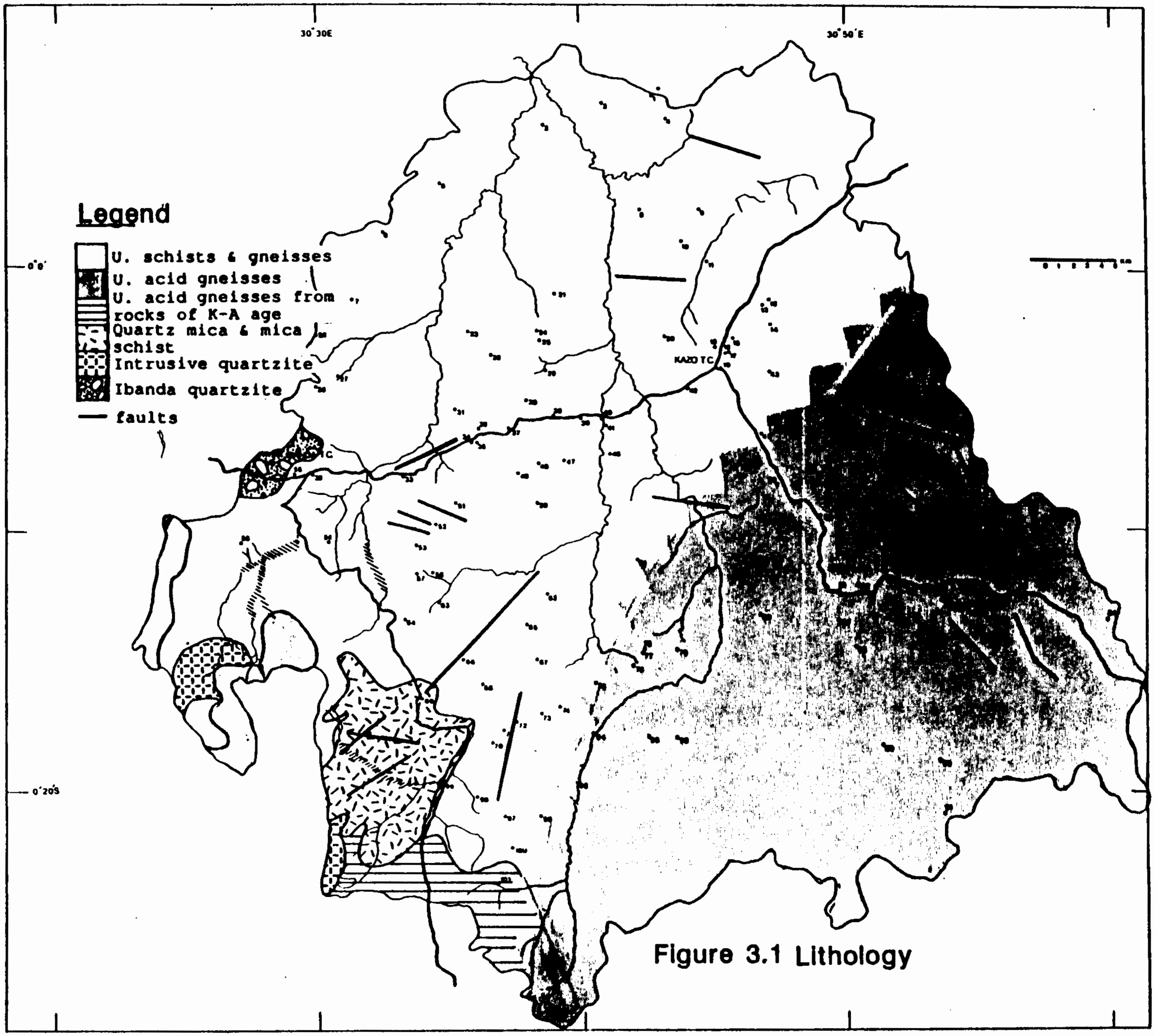


Figure 3.1 Lithology

The Basement Complex refers to a series of rocks which underlie the predominantly meta-sedimentary rocks of younger age. The Basement Complex is comprised essentially of igneous rocks which were later subjected to intense regional metamorphism (Cahen,1966).

The Buganda-Toro system is part of the Kibalian belt of Central Africa. Within the belt three litho-stratigraphic units have been described, namely the Buganda series and Toro system in Uganda, and the Kibalian in Zaire. The Buganda series and Toro system were reviewed by King (1959) who argued that no stratigraphic or structural break exists between the two. He thus proposed that the two units be grouped together as the Buganda-Toro system, often referred to as the B-T.

The B-T is the most extensive of the cover formations and occupies much of the southern, central and western parts of the country. The rocks show a general increase in metamorphic grade westward, and include phyllites, mica-schists, gneisses and quartzites. Regional metamorphism is characterised by lustrous mica schist. The age ranges from 1800-2000 my.

The Karagwe-Ankolean system is also part of the Kibalian belt which extends eastward from Angola through Shaba province of Zaire ,Burundi, Rwanda, and Tanzania. This system occupies a small part of the study area and unconformably overlies the B-T. Argillites of low metamorphic grade such as shale, mudstone and phyllites are predominant. Arenites, sandy rocks metamorphosed to quartzites, occur as thin bands regularly throughout the succession. The age ranges from 1300-1400 my.

3.4 Geology of the Study Area

As indicated by Figure 3.1 and Table 3.1, all the major geological units are represented in the study area with those of the B-T system dominant. All of the rock types are subject to varying degrees of weathering and laterite development. In some areas, particularly along valley bottoms, the weathered materials have been reworked and deposited as recent unconsolidated sediments.

The most abundant rock types are granites, granite-gneisses and schists. Phyllites are also present in the vicinities of Kashongi and Ibanda. There is little available information on the soils and recent sediments but clay sized materials and lateritic soils predominate. The primary geologic characteristics of the major soil and rock types are as follows.

Top Soil

Usually loam soil, clayey in the valley areas with an average depth of 1m.

Clay

Generally thick in valley areas and varies from black to grey depending on the environment of deposition. On average the clay is 5-10m thick overlying the B-T and K-A formations.

Phyllites

These rocks occur in the K-A system and are evident to the west of the study area near Ibanda and Kashongi. There is no thickness record of the phyllites being penetrated during drilling.

Granite Gneiss

The fresh granite gneiss is coarse grained and equigranular with abundant muscovite, biotite, feldspar and quartz. Weathered granite gneiss is recognised by its muscovite sheen and the presence of kaolinite. The rock type is abundant in the B-T system.

Table 3.1 Summary of major geological units and their distribution in the study area.

STRATIGRAPHIC UNIT	LITHOLOGY PROFILE	THICKNESS (metres)	DISTRIBUTION IN THE STUDY AREA NE	NW	C	SE	SW
KARAGWE-ANKOLEAN (K-A, 1300-1400ma)	Weathered Zone Quartzite Phyllite	15-20	X	V	V	V	X
BUGANDA-TORO (B-T, 1800ma)	Laterite Weathered Granite/ Gneiss Fresh Granite/ Gneiss and Schists	5-10 22	V	V	V	X	V
BASEMENT-COMPLEX (B.C. >3,000ma)	Laterite(gritty) Weathered Granite Fresh Granite	5 15-20 ?	X	X	X	V	X

Key: V = Present
X = Not identified

Granite

Granite normally occurs within the study area as isolated inselbergs. It is coarse grained, equigranular and generally leucocratic with more than 45% quartz content. Other constituent minerals are muscovite, biotite and feldspars. The granitic rocks in northern and south-western Mbarara district are largely gneissose (King, 1970), and represents migmitisation of granite schists of the B-T system.

3.5 Structural Geology

Within the study area jointing and faulting occur on a relatively small scale, and are largely due to:

a) tectonism
b) pressure release due to uplift and erosion.

3.5.1 Faulting

The faulting in the study area is related to earth movements of the Western Rift Valley, with the complementary uplift of the land. This contributed to the high topographic relief in the study area. It is suggested that warping seems to have occurred in sympathy with earlier fault movements in early Pleistocene times (Bishop, 1969). The faults are easier to detect in the K-A and B-T systems than in the B.C. system.

3.5.2. Joints (Fractures)

Jointing is mainly evident in the gneisses and quartzites. In some cases joints have become enlarged through solution and, to some extent, by mechanical erosion. Enlargement of joints is most notable along valley bottoms where the resulting "fissuring" is associated with dense vegetation. As indicated above, some joints are related to regional tectonics and others are due to localised pressure release. Given the highly irregular distribution of joints in the area, the former mechanism is probably the more significant.

4 HYDROGEOLOGY

4.1 Hydrogeological Setting/Framework

4.1.1 Groundwater Occurrence

As described in the Chapter 3, the study area is underlain by crystalline Precambrian rocks with alluvial sediments in the valleys.

Throughout most of the study area the basement rocks have suffered varying degrees of weathering and are generally capped by the regolith. The regolith is the solid product of weathering and in Uganda it can either exhibit a sharp transition to the unweathered zone or there may be a significant transitional zone up to several tens of metres thick.

Groundwater occurs in both the regolith and in the unweathered crystalline rocks. In the latter case, groundwater movement takes place within the fractures, the matrix being essentially impermeable.

Observations recorded during drilling suggest that there are two zones of weathering. There is an upper zone in which weathering produces clay minerals and the resulting permeability is low, and there is a lower weathered zone where the limited weathering may actually have opened up fractures and increased their capacity to store and transmit water.

One constraint on the present investigation has been the practice of UNICEF, at least within the project area, to develop water supplies only in the crystalline basement and not to attempt to extract water from the regolith or other overlying deposits. Thus their approach has been to drill down to competent crystalline rock and to case off the weathered zones without investigating their water-bearing potential. This means that the study team, in the course of the present study, has been unable to investigate directly the occurrence and movement of groundwater in the regolith.

In spite of the above constraint, it has been possible to obtain valuable information about the groundwater regime in the study area, and particularly about the distribution and variation of fracture systems with depth. It has also proved possible to generate useful information on the resource potential of the regolith through careful analysis of flow in adjacent ground and surface water systems.

4.1.2 The Regolith

About 90% of drilling in Uganda is in metamorphic and basement complex aquifers and in the project area this figure rises to 100%, with the rocks being those of the Karagwe-Ankolean (K-A), Buganda-Toro (B-T) and the Basement Complex (B.C). These metamorphic crystalline rocks occur throughout the entire area though in the valleys they are overlain by Quaternary sediments.

In the UNICEF drilling program, when hard competent rock is encountered, casings are inserted to the bottom of the borehole and drilling then continues. Lithologically, the depth to which the casing is inserted represents the base of the regolith and thus by plotting the depths of the casings installed in each borehole it is possible to get a general appreciation of variations in the thickness of the regolith throughout the study area. Such a map has been prepared by grouping the casing depths and the map is presented as Figure 4.1.

Casing depths in metres have been grouped as follows:

< 20 m
20 - 35 m
> 35 m

The deepest casing levels, and hence the greatest thickness of regolith, are in the south and southeastern part of the project area where the casings are sometimes more than 35m deep. A similar range of casing depths also occur in a few locations south and east of Ibanda, although these have not been grouped on Figure 4.1.

Boreholes with casing depths in the range of 20 to 35m occur throughout the study area, with a tendency to be grouped northeast of Ibanda, around Kazo and Kiruhura and in the south central part of the basin. The boreholes with the smallest casing depths, and hence shallowest depth of regolith occur in the mid-portion of the basin extending up to the northern boundary. In summary, it would appear that while there are some general patterns of casing depth and hence of regolith thickness, the picture is quite complex.

In reviewing these data and comparing the casing depth with the elevation of which the boreholes were terminated (Figures 4.1 and 4.2) it can be seen that there is no obvious correlation.

4.1.3 Borehole Yields

When a borehole has been drilled as part of the UNICEF program it is cleaned and developed by means of air-lifting. During the air-lifting process the drillers frequently make an estimate of the yield of the borehole.

In the case of the old boreholes, drilled by the cable-tool method, the yields had been estimated by means of bailer tests. A comparison of the bailer estimates with the constant discharge pumping tests carried out by the present study team showed a good correlation.

The yields based on the air-lifting of the UNICEF boreholes appear to be less accurate when compared with the constant discharge data, however they are still accurate enough to permit a general appreciation of the variability of yields within the catchment area. To this end, the yields from both the air-lifting of the new boreholes and the bailing of the old boreholes have been grouped into three categories and plotted on a map. The categories used were: < 500 l/h, 500-1000 l/h and >1000 l/h and the data are presented on Figure 4.3. Figure 4.3, shows that while there is variability throughout the study area, some general trends are discernible.

There is a paucity of data in the eastern part of the basin but, with the exception of the area around Kiruhura, there appears to be a tendency for yields to be less than 500 l/hr. In contrast, the western part of the basin, north and east of Ibanda,has a grouping of wells with yields above 1000 l/hr. This may be related to the occurrence of the Igara series of quartz-mica and mica schists which are present in the upper part of the B-T system.

Another zone of high yielding boreholes extends up to the centre of the basin in a north-south direction, approximating to the course of the Nyabisheki River. This zone contains rocks of the B-T and B.C. systems with alluvial sediments in the valleys.

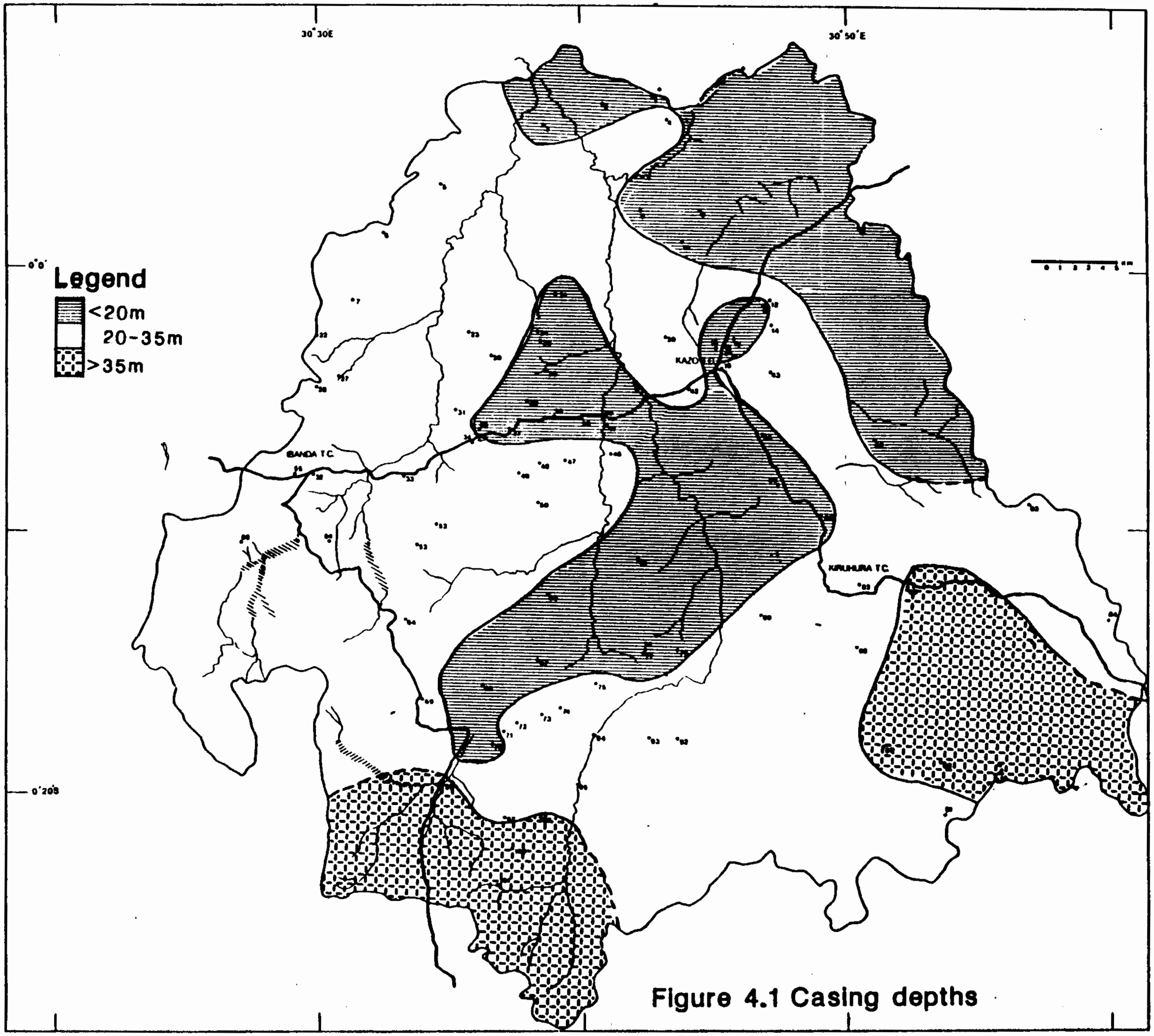


Figure 4.1 Casing depths

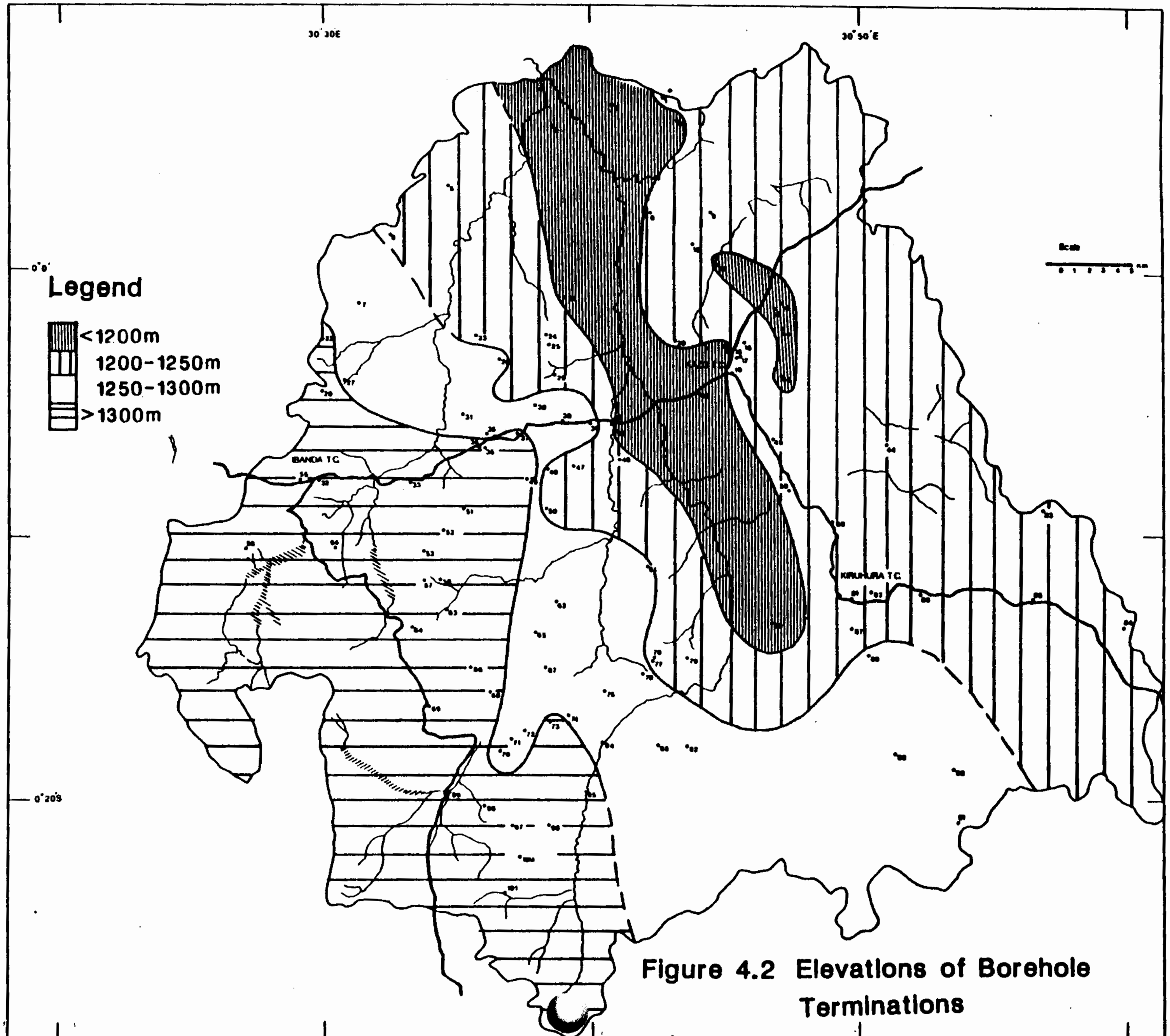


Figure 4.2 Elevations of Borehole Terminations

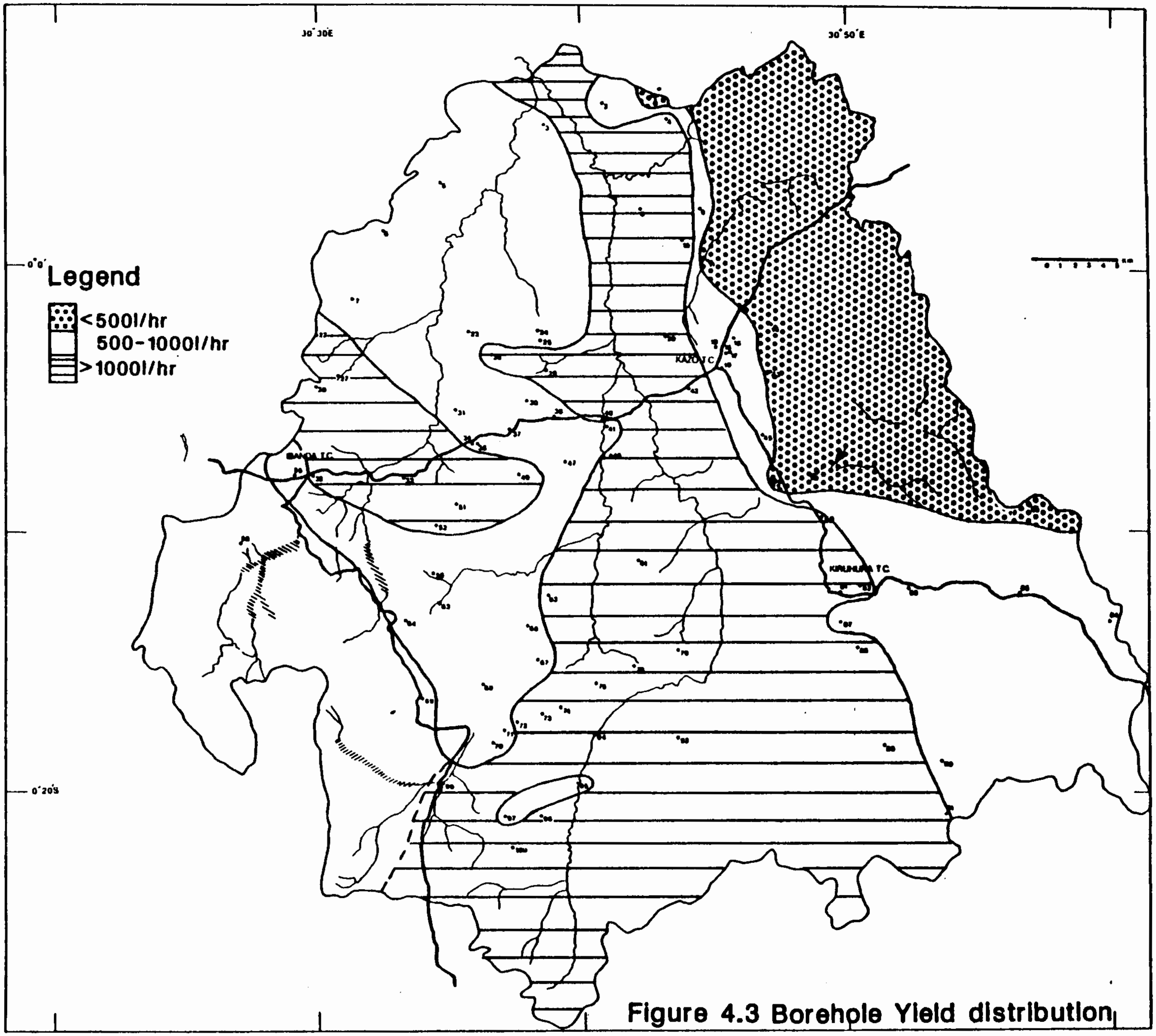


Figure 4.3 Borehole Yield distribution

Between the two areas of higher yielding boreholes described above there is a zone in which the majority of yields falls into the range of 500 to 1000 l/hr. This extends from the west-central part of the basin to the northwestern boundary.

4.1.4 Quartz Veins and Dykes

There are numerous quartz veins and dykes, particularly in the western half of the project area with fewer in the north-east. Some workers have suggested that the siting of boreholes on the upgradient side of dykes and veins may lead to improved yields, due to their functioning as barriers to groundwater movement.

4.1.5 Springs

Along the cliff in the southwestern part of the project area, and on Ibanda hill, springs discharge from the fractured quartzites, with yields ranging from 1800 to 6000 l/hr. At Ibanda, spring water flows down under gravity to serve the hospital and the trading centre. On the hill the springs occur mainly between elevations of 1505 m and 1670m. There are also numerous springs along the cliff above 1450m. No gravity scheme, at present, has been introduced to exploit these springs.

4.2 Hydrochemistry

4.2.1 Introduction

A hydrochemical study was conducted to determine water quality, investigate groundwater mixing and provide information on regional groundwater flow behaviour. This technique has been used successfully in the past (Chebotarev,1955; Howard and Lloyd, 1983 and Beck and Howard, 1985) to gain an understanding of natural groundwater evolution, to identify the primary areas of recharge, and to assist in the construction of a conceptual model of the flow system.

The hydrochemical investigation involved the collection of over 110 samples, 54 of which were analysed for major ions (HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+)and 100 for trace elements. Fifty wells were sampled for oxygen-18 and deuterium isotopes. Analysis for most of the major ions was conducted in Uganda. Trace and isotope analysis was carried out in Canada. The methods of collection and analysis are described in Appendix C. An effort was made to collect samples from throughout the area. This was not always possible due to demographic and physical constraints.

4.2.2 Major Ion Analysis

In an attempt to maintain quality control, all analyses were checked for reliability by applying the cation-anion balance method (Table 4.1). This was carried out to detect potential erroneous values which might have resulted from sampling or analytical procedure. As an additional check, duplicate samples were collected at several sites (Table A1.2 in Appendix A1).

Table 4.1 Reliability of chemical analyses using the cation-anion balance method.

Sample	Location Map No.	Total Cation (epm)	Total Anions (epm)	% Error
CD 91	82	11.75	6.25	30.53
CD 371	69	7.92	3.86	34.55
CD 403	95	4.98	4.75	2.36
CD 409	74	7.75	5.59	16.13
CD 479	60	9.49	8.17	7.48
CD 499	42	5.89	7.69	-13.23
CD 530	40	5.61	6.00	-3.40
CD 3009	24	7.18	5.48	13.46
CD 3017	11	6.31	7.54	-8.91
DS 719	71	7.71	5.21	19.35
DS 727	7	3.34	6.13	-29.48
DS 728	6	6.80	8.28	-9.81
DS 731	28	2.53	3.19	-11.42
DS 732	2	3.45	4.56	-13.84
GS 884	94	5.11	4.03	11.88
GS 1613	81	4.79	3.67	13.17
WDD 1534	8	3.18	3.80	-8.92
WDD 1536	9	5.68	6.96	-10.13
WDD 1537	20	3.71	3.89	-2.49
WDD 1538	46	6.31	7.46	-8.34
WDD 1548	39	3.27	2.03	23.52
WDD 1549	34	4.59	2.44	30.57
WDD 1550	30	5.36	7.02	-13.36
WDD 1712	15	3.36	3.36	-0.03
WDD 1712	15	2.66	2.73	-1.30
WDD 1713	17	6.49	6.22	2.06
WDD 1714	14	4.52	3.69	10.14
WDD 1715	12	7.00	6.35	4.85
WDD 1720	1	7.19	10.79	-20.03
WDD 2025	73	14.58	9.78	19.74
WDD 2027	4	3.70	3.93	-3.11
WDD 2036	51	5.31	3.68	18.23
WDD 2039	47	6.22	14.54	-40.09
WDD 2043	43	8.05	8.43	-2.33
WDD 2046	22	2.17	6.56	-50.26
WDD 2049	23	1.42	3.72	-44.92
WDD 2050	26	1.82	2.21	-9.63
WDD 2051	31	2.60	2.44	3.15
WDD 2052	29	9.18	13.50	-19.04
WDD 2083	86	4.41	3.13	17.00
WDD 2084	84	3.27	3.71	-6.30
WDD 2087	88	9.32	7.65	9.86

WDD 2187	27	2.07	7.21	-55.33
WDD 2190	5	0.50	2.33	-64.39
WDD 2209	45	5.74	5.21	4.86
WDD 2211	90	2.06	4.78	-39.77
WDD 2214	62	7.29	3.25	38.31
WDD 2215	67	10.88	8.63	11.55
WDD 2216	68	7.43	5.16	18.01
WDD 2218	72	11.66	1.86	72.44
WDD 2527	16	6.41	4.01	23.08
SPRING 2		0.46	0.51	-5.26
SPRING 4		1.14	0.60	30.52
SPRING 5		0.67	0.87	-13.04
SPRING 6		1.01	0.81	11.09
SPRING 7		1.42	0.76	30.27
SPRING 8		5.50	1.99	46.95

Charge balance errors are apparent for all the analyses, as shown in Table 4.1, and range from +72% to -55%. Of the 54 samples analysed only 19 were within the 10% error range normally considered as acceptable. 22 were high in cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) with the remainder high in anions (HCO_3^-, CO_3, SO_4^{2-} and Cl^-). When the charge balance errors are plotted on the regional map, a pattern of areal groupings are evident (Figure 4.4). In the extreme northwest all boreholes show consistently elevated anion readings. Cation dominant analyses are evident in the southwest and southeast (in the vicinity of Kazo T.C. (Trading Centre) and Kiruhura T.C.). When compared to the potentiometric contour map (see Figure 4.30 in Section 4.4) the high cation imbalances appear to be concentrated in areas of recharge, while the reverse seems to be true for the discharge zones. Possible explanations include i) the omission of nitrate in the analysis which may occur in the recharge zones and, ii) high percentage error in the determination of sodium which is more dominant in recharge areas than elsewhere.

In the duplicate analyses (Table A1.2 in Appendix A1) there is generally a reasonable agreement of results, though only 2 of the 7 sets of analyses show error balances within the acceptable 10% range. This would suggest that either the sampling procedure or the actual chemical analyses were not carried out correctly. Another problem which may have contributed to the unreliability of the results concerns the unavoidable long delay between collection and complete analysis of the samples.

4.2.3 Major Ion Interpretation

All major ion parameters were plotted on regional maps (Figures 4.5 - 4.12). Without exception all show similar trends with two main zones predominating. To the east a well defined zone (1) surrounding the Kazo-Kiruhura road occurs, while in the west a more subtle and laterally extensive zone (2) is found. As detailed in the list below, concentrations of chemical constituents generally increase to the east in each zone.

1) Low bicarbonate groundwaters occur in the two zones, where they are apparently indicative of recharge (Figure 4.5). In the west, low bicarbonate recharge waters occur extensively, showing an increase in concentration towards discharge zones, primarily along the river. The second zone in the east near Kazo confirms that the aquifer in the region receives additional recharge which mixes with older waters recharged in the west.

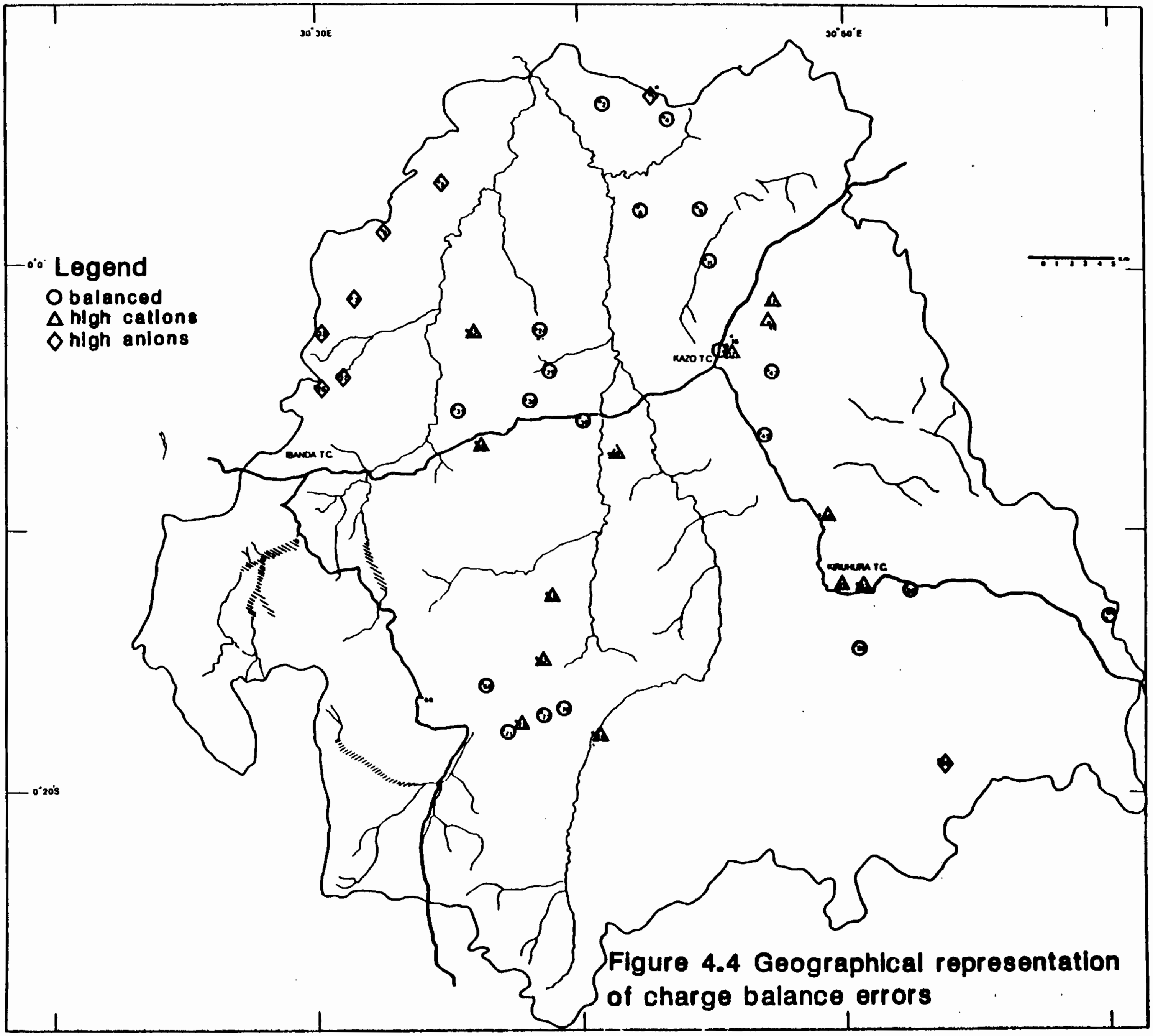


Figure 4.4 Geographical representation of charge balance errors

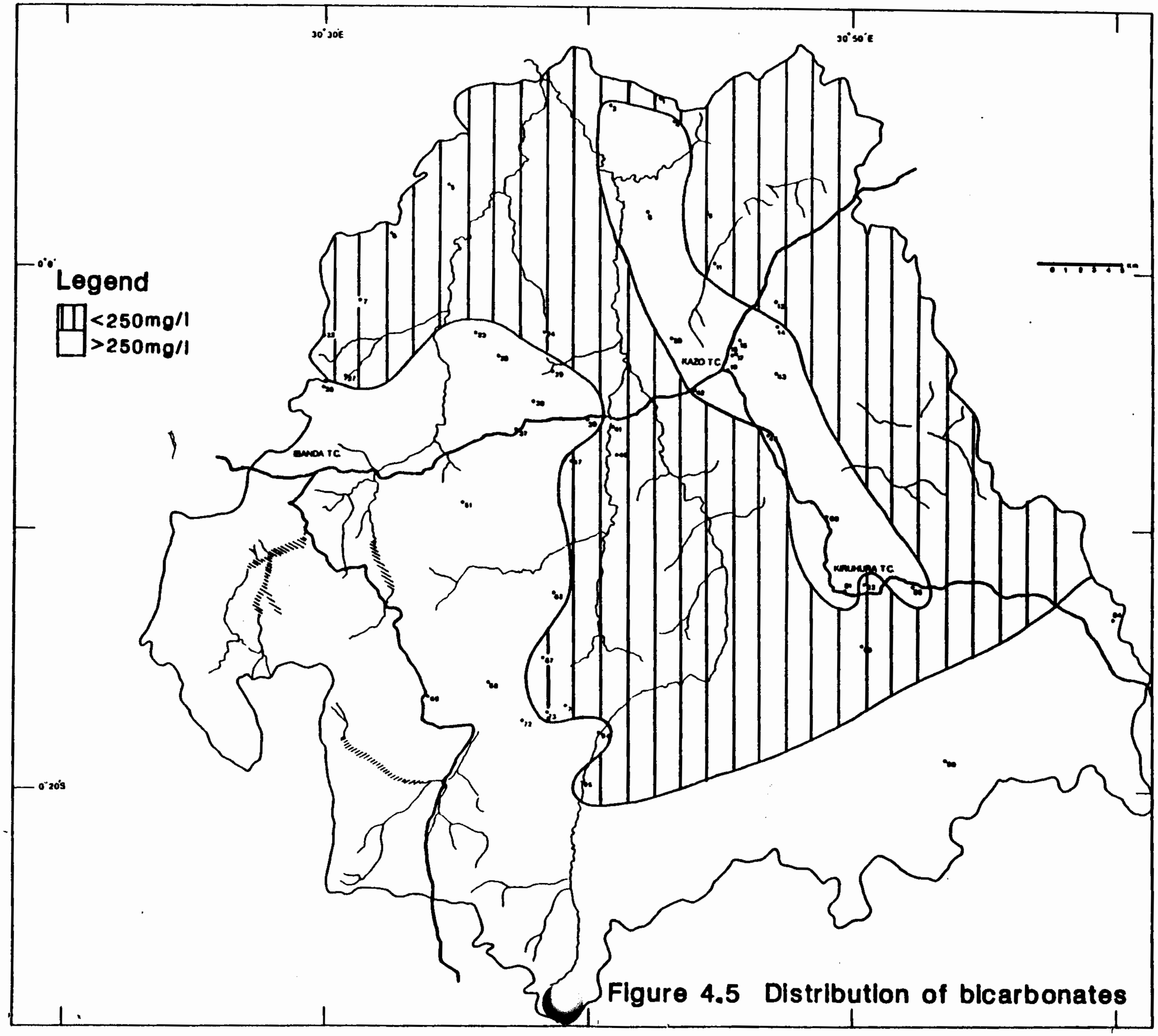


Figure 4.5 Distribution of bicarbonates

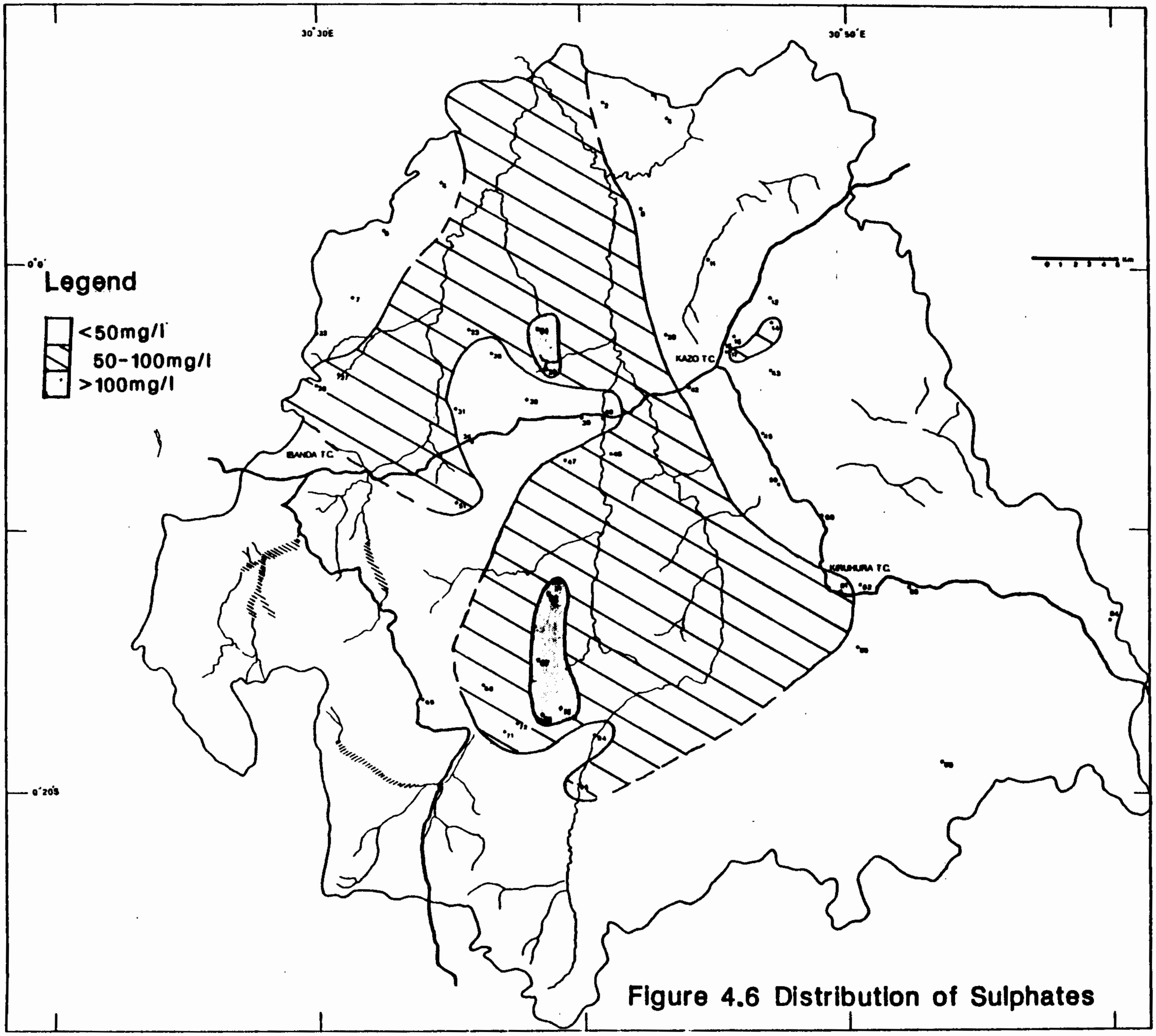


Figure 4.6 Distribution of Sulphates

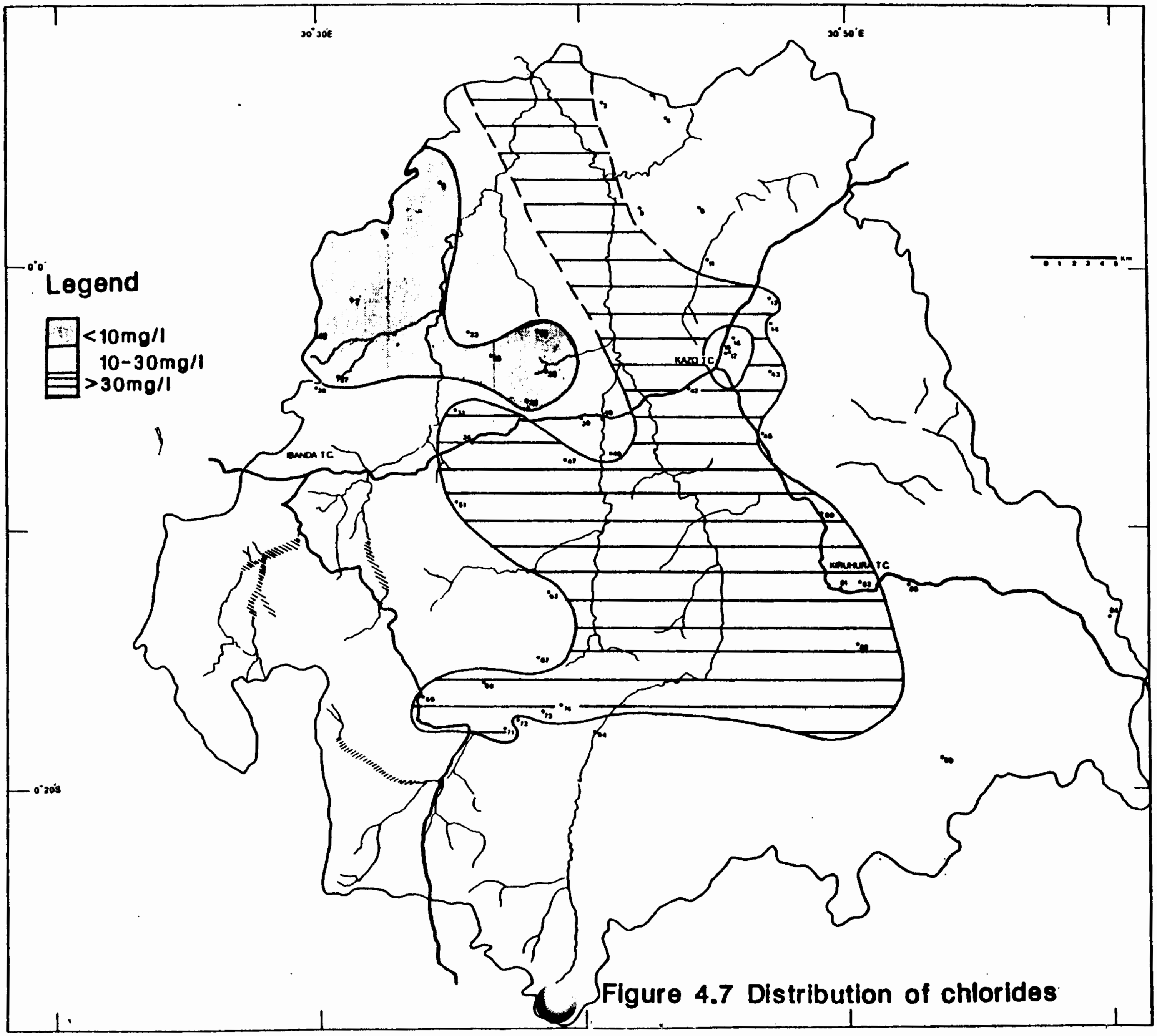


Figure 4.7 Distribution of chlorides

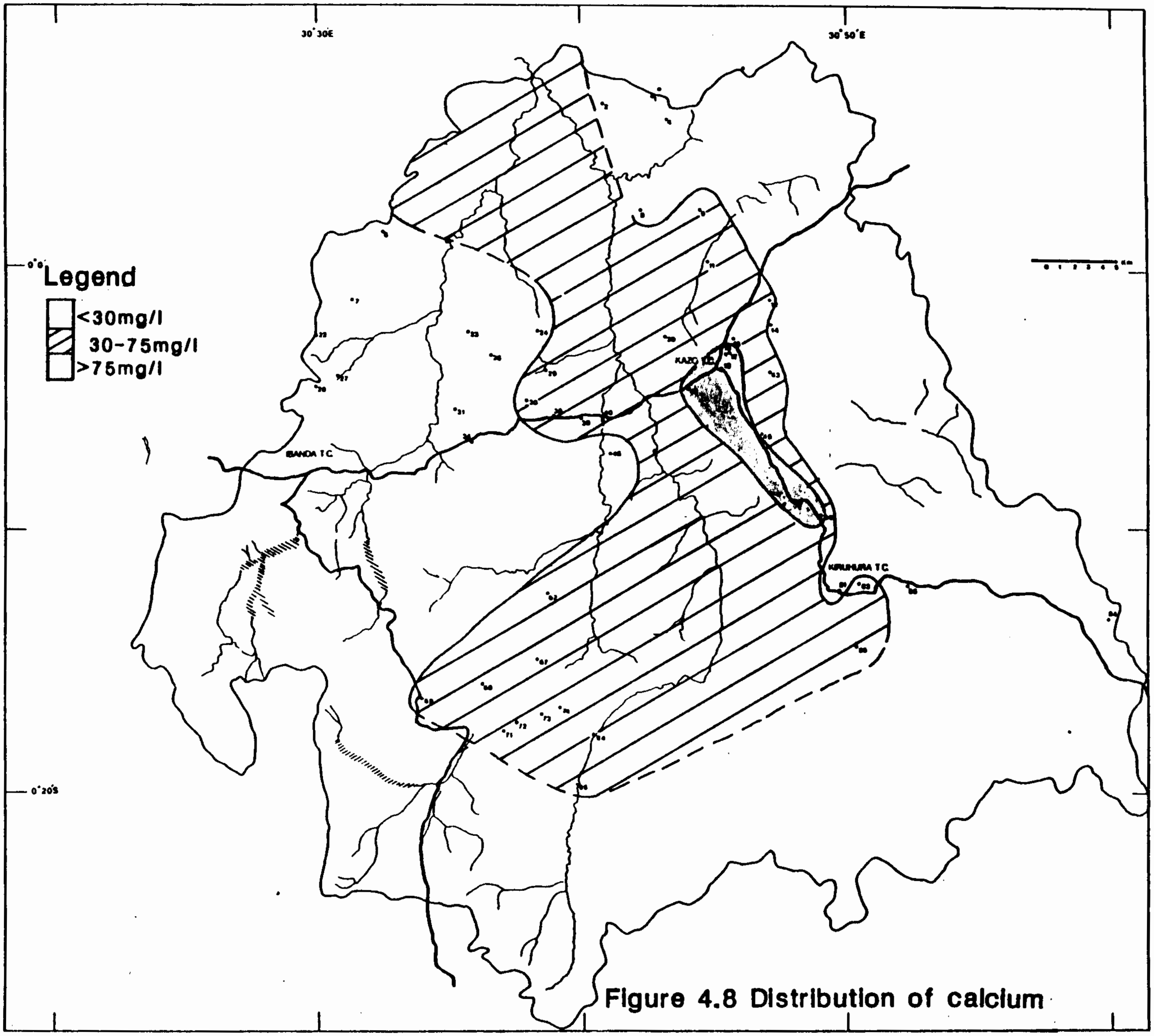
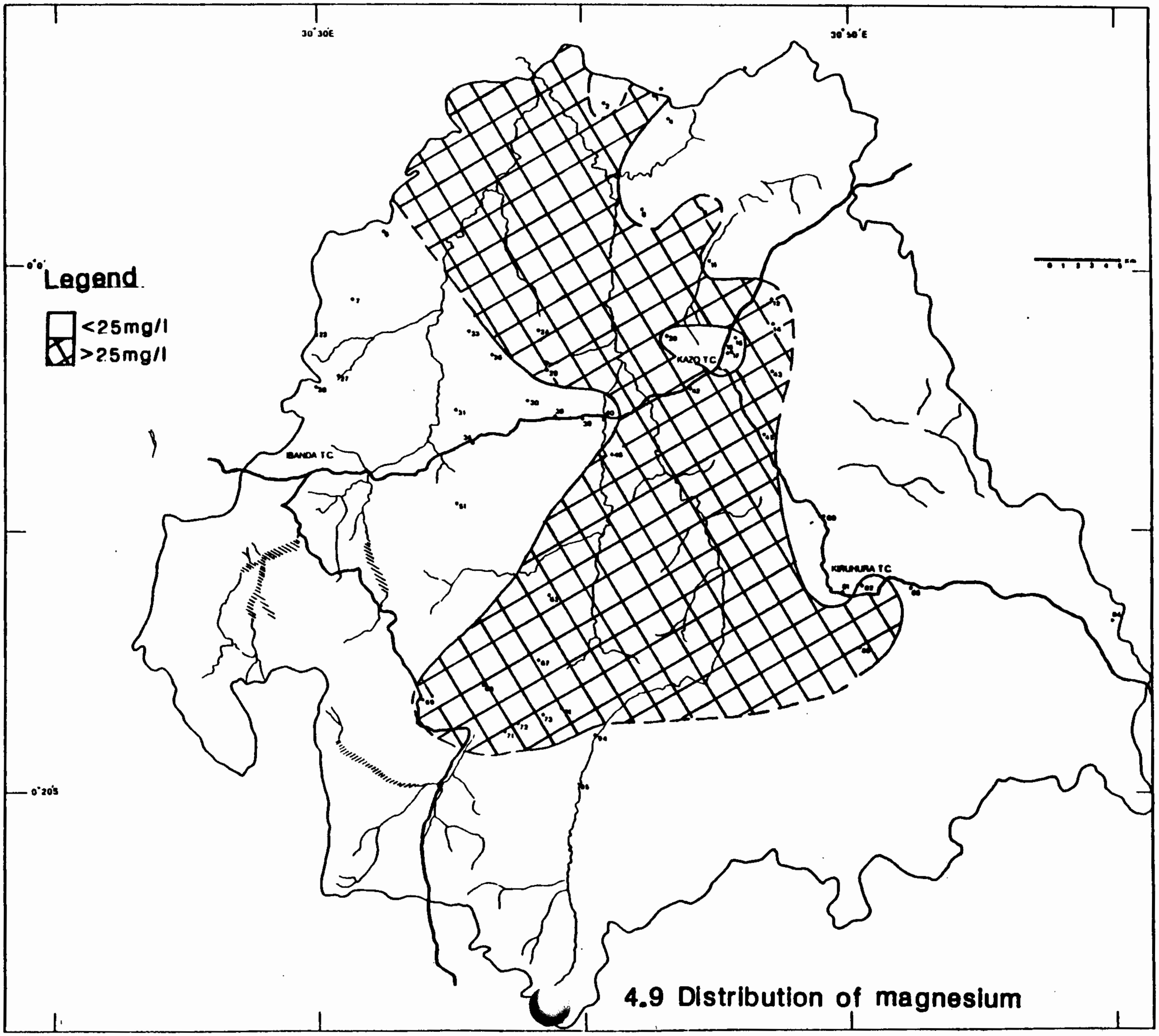


Figure 4.8 Distribution of calcium



4.9 Distribution of magnesium

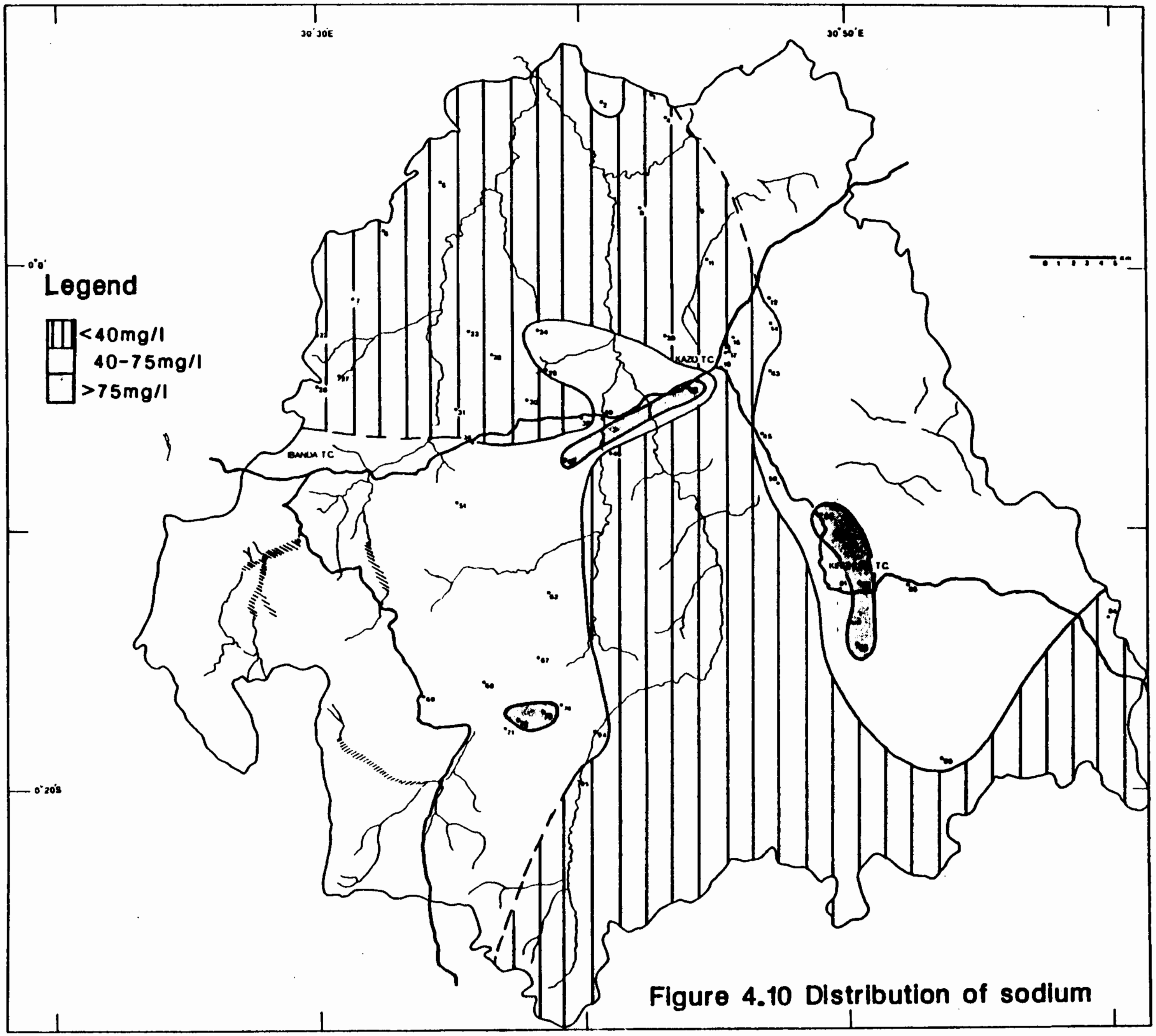


Figure 4.10 Distribution of sodium

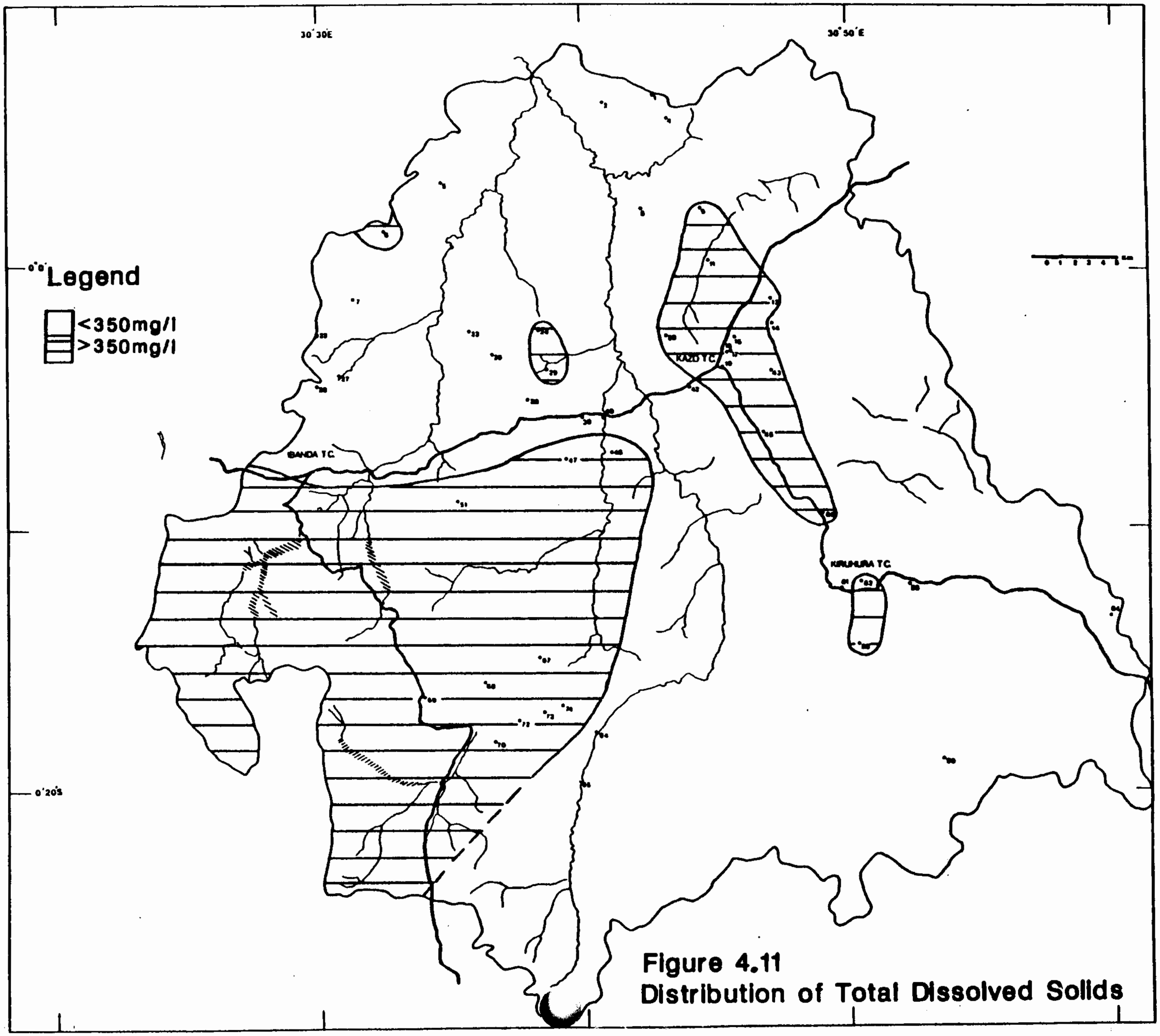


Figure 4.11
Distribution of Total Dissolved Solids

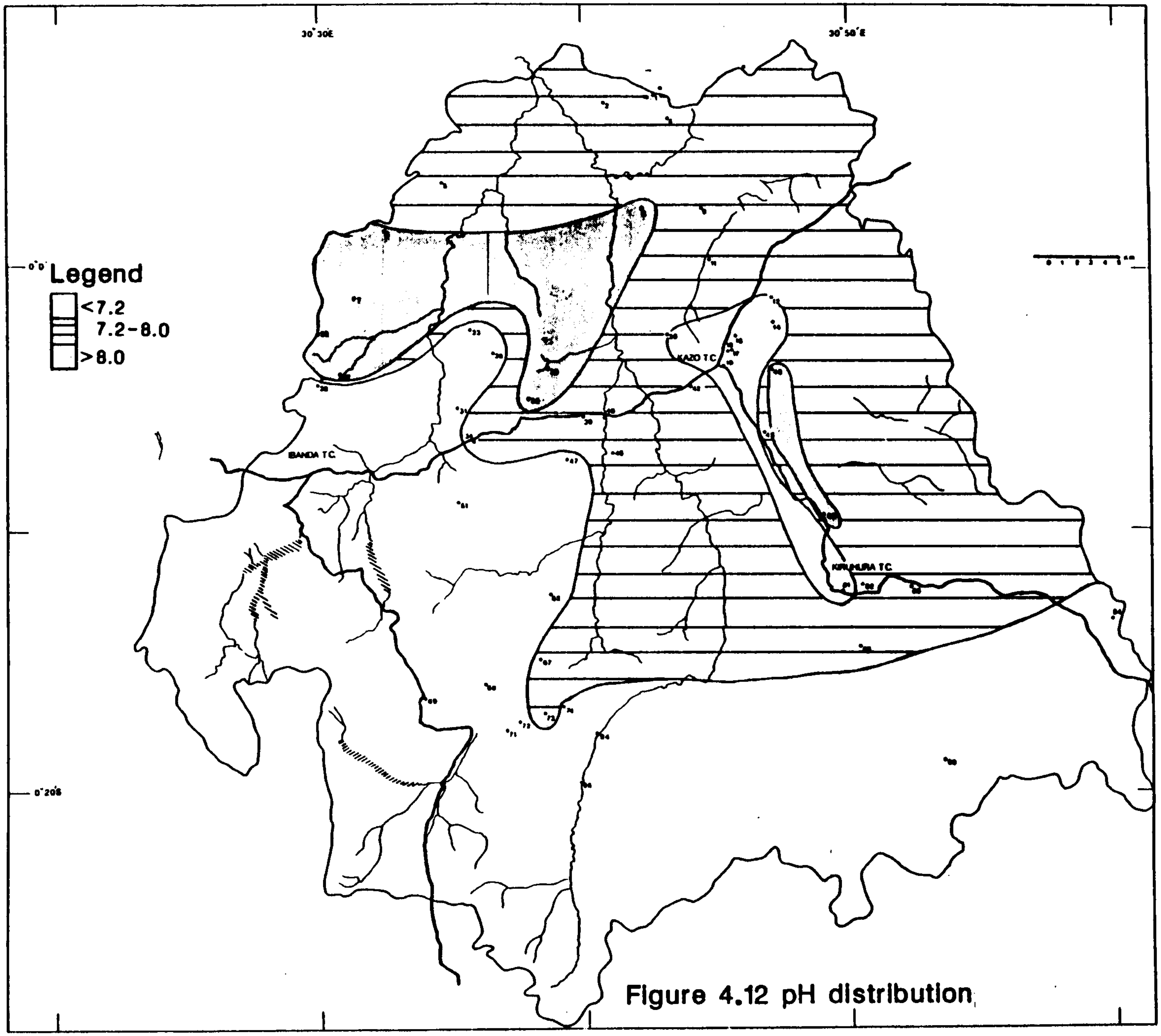


Figure 4.12 pH distribution

2) Sulphates show a similar trend to that of bicarbonates, they are low in the recharge areas of the west and around Kazo but increase along the flow path. In the southwest (Figure 4.6) a sharp increase in concentration, exceeding 200 mg/l, causes a westward deviation in the contouring. The average levels in the vicinity range from 30-140 mg/l. An explanation for the anomaly is suggested below.

3) Chloride (Figure 4.7) contours are similar in form to the other ions. The highest concentrations are found in south-central localities (51-111 mg/l). The region surrounding Kazo T.C. shows lowest concentrations of chloride (14-23 mg/l). Low values also occur in the northwest.

4) Calcium and magnesium concentrations conform to the regional distribution shown by the other ions (Figures 4.8 and 4.9 respectively), both showing an increase along the flow path towards the river.

5) High sodium values occur in three areas, as shown on Figure 4.10, with significantly elevated sodium levels (> 60 mg/l) in the Kiruhura T.C. area.

6) Potassium shows minimal variation in concentration throughout the study area except, once again, in the southwest where an anomaly exceeds regional levels by as much as a factor of four. In view of the overall lack of variation, potassium data were not presented on a figure.

Observations of the major ion chemistry suggest that 2 main areas of recharge occur. The first and most extensive is in the west where the groundwater is characterized by low concentrations of most, though not all ions. The other area is around Kazo T.C., where groundwaters are chemically similar to those in the west. As indicated, these groundwaters show low magnesium and sodium concentrations, and intermediate to high calcium levels. They are also characterized by high to intermediate TDS concentrations (Figure 4.11) and acidic pH readings (Figure 4.12) Significantly, while the recharge waters around Kazo are chemically similar to those in the west, they are less distinctive as a group, showing greater chemical variation. This can be explained by mixing of the recharge waters with older waters derived from the west.

The chemical anomalies noted in the south west and around Kiruhura T.C. (see Figure 4.10, for example) may reflect the geological transition from the Buganda-Toro system of the northwest to the Basement Complex of the south (see Figure 3.1 in Chapter 3). Trace element data for this area (Table A2.1 in Appendix A2) show elevated concentrations along this transition boundary.

Water Type Classification

As an aid to interpreting the major ion chemistry, the Durov diagram was used to characterize the water type. Figure 4.13 shows all major ion data plotted. Two main areas of concentration are shown, Group A dominated by magnesium bicarbonate chemistry and Group B plotting within the magnesium sulphate field. The data represented in Group A show slight lateral variation towards sodium enrichment. According to Back's (1961,1966) classification the waters belong predominantly to the calcium/magnesium bicarbonate facies type.

Within Group A a number of samples plot toward the bottom of the field. These samples represent spring discharge for a different hydrogeologic system and are therefore chemically unrelated to groundwaters from the study area aquifer. The chemistry of the spring waters is represented in Table A1.3 in Appendix A1. These waters are notably characterized by their overall low major ion concentrations.

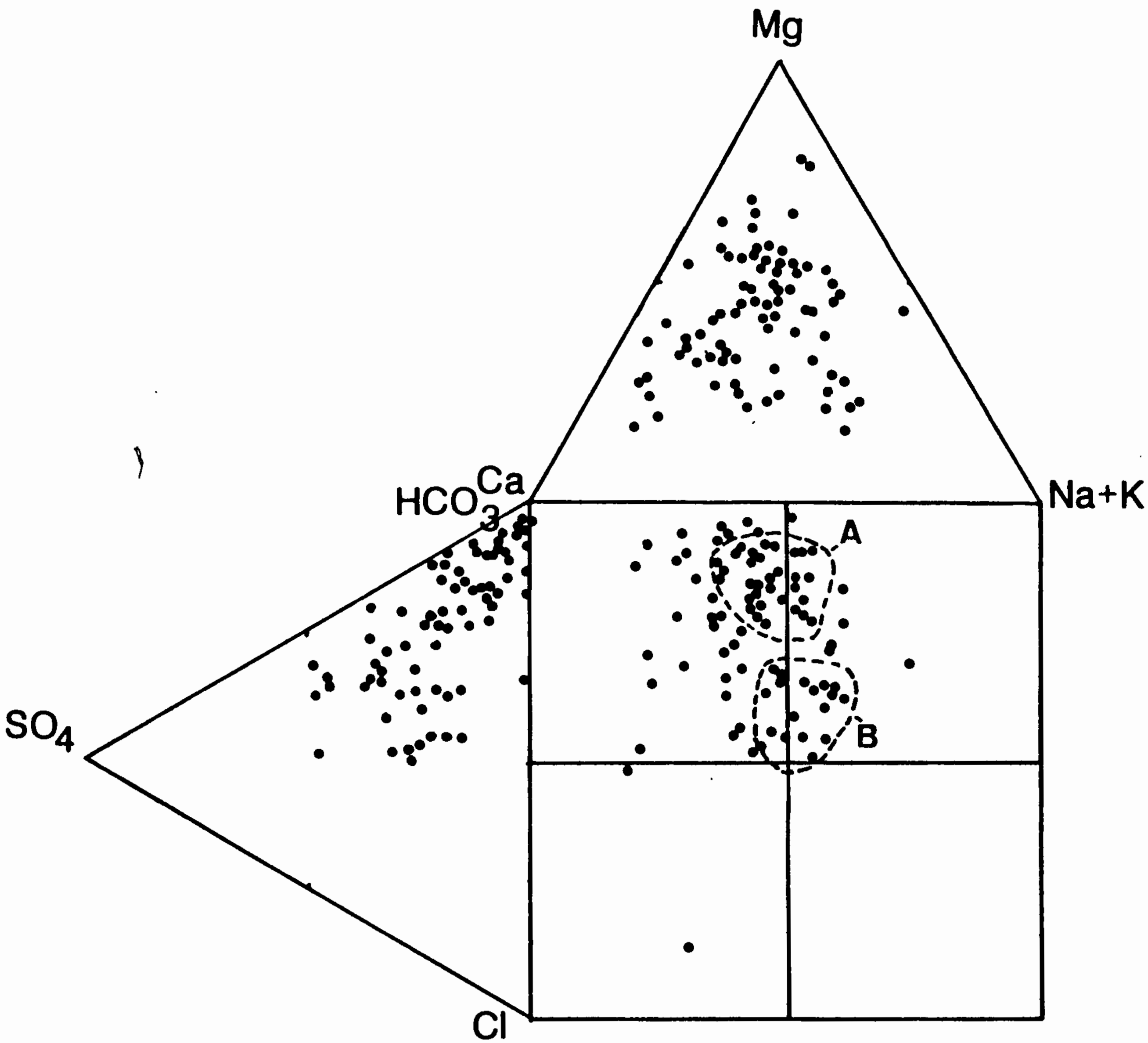


Figure 4.13 Chemical characteristics of the groundwaters

Groundwater Classification of Geographical Groupings

Ten geographical areas were identified on the regional map (Figure 4.14). Their major ion chemistries were plotted on the expanded Durov diagram (Figure 4.15) to identify any inherent similarities between boreholes within each group (see Table A1.4 in Appendix A1). Conclusions that may be drawn are as follows:

Area 1 samples plot predominantly in the magnesium bicarbonate field, though samples are also to be found in the calcium bicarbonate and magnesium sulphate field. Bicarbonates dominate their chemistry.

Area 2 samples also plot predominantly in the magnesium bicarbonate field. Samples are also to be found in the calcium bicarbonate field. The chemistry of area 2 samples is dominated by elevated bicarbonate and increased calcium values compared to area 1. Area 2 corresponds to the recharge area around Kazo T.C..

Samples from area 3 plot mainly in the calcium bicarbonate field. Sulphates are low but the TDS values are relatively high (450mg/l). Calcium is the dominant cation.

Areas 4 and 5 samples occupy the field of mixing/dissolution on the Durov plot. Calcium and bicarbonate values show a decrease while sodium and sulphate become more pronounced.

Samples from area 6 are noted for their high TDS, with values ranging up to 800mg/l; bicarbonates and sulphates also show a strong increase in concentration. All cations show elevated levels with no one ion dominating. The highest potassium values for the study basin are recorded here. This area corresponds to the geological transition zone.

Area 7 samples plot in the upper section of the magnesium bicarbonate field, and show no unique trend.

Area 8 samples plot in the lower part of the magnesium bicarbonate field. There is a reduction in sulphate values with an increase in sodium. Na^{+}/Ca^{2+} ratios are all above 1. Chlorides are generally elevated.

Samples analysed from Area 9, located in the northwest section of the study area, plot mainly in the magnesium bicarbonate field. They show increased pH values (>7.5), while TDS values are about 165mg/l. Chloride levels are the lowest for the study area. Cations also show low concentrations, with calcium and magnesium showing, on average, a ratio of 1.

Samples from Area 10, represent discharge springs. On the Durov diagram the samples show a vertical variation plotting in the lower section of the magnesium bicarbonate field and in the mixing zone of the magnesium sulphate field. Concentrations of all ions are low with the exception of spring #8 which has high TDS (600mg/l), sulphate and sodium values.

4.2.4 Trace Elements

Analyses were carried out on 51 samples, with 22 parameters being measured (see Appendix A2). Abnormally high readings were observed for iron, manganese and zinc. Also, silicon in the form of H_4SiO_4, occurs in elevated concentrations throughout, most likely a result of dissolution of matrix material from the geological formations (metamorphosed crystalline material) underlying most of the study area.

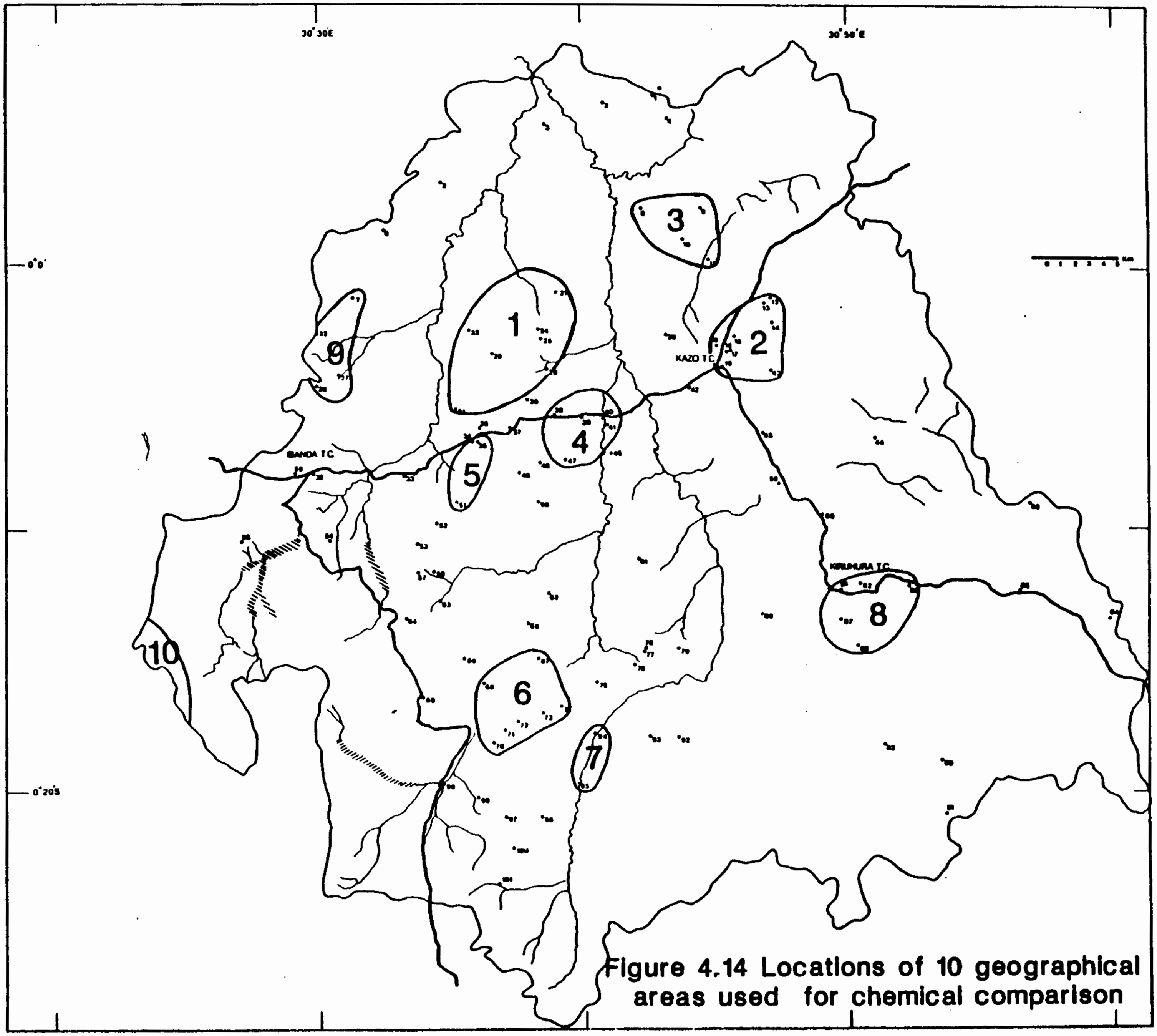


Figure 4.14 Locations of 10 geographical areas used for chemical comparison

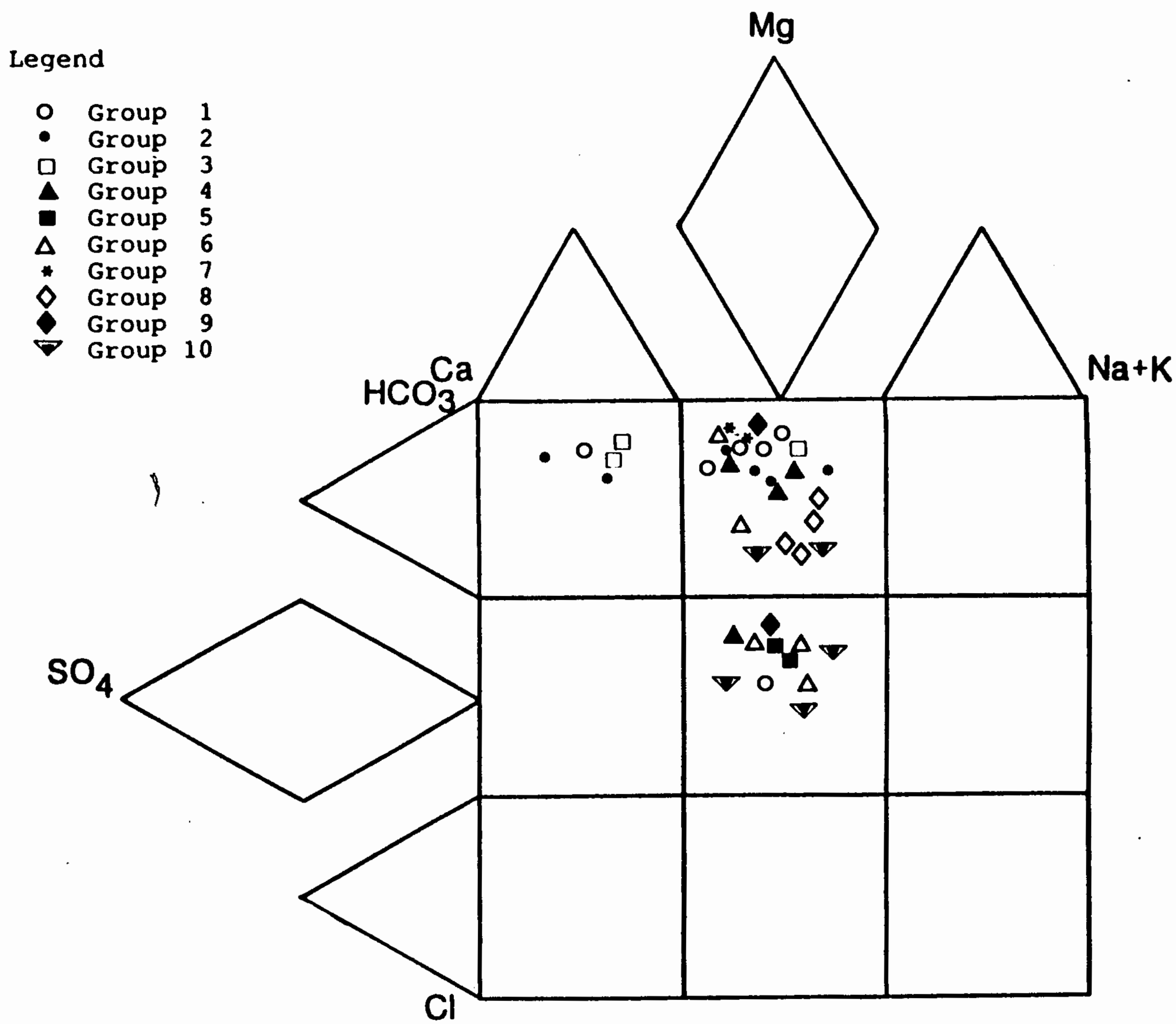


Figure 4.15 Chemical representation of the 10 geographical areas

High concentrations of Fe^{2+}, Mn^{2+} and Zn^{2+} occur in the north and southwest area bounding the Buhwezu mountains, a massive remnant quartzite intrusive, which is of interest because of its mineralization. Isolated high concentrations occur around Kiruhura and the north central part of the study area. The presence of iron is readily noticeable at borehole sites by its red-brown staining of the cement apron. In over 28 of the boreholes iron was above the acceptable standard. Samples collected for major ion analysis, if left exposed to the atmosphere, regularly exhibited the formation of a brown precipitate in the bottle. Levels above 5 mg/l were found to occur most frequently in older boreholes. Zinc levels in excess of 5mg/l (the maximum acceptable limit for drinking water, World Health Organisation (W.H.O.), 1971) were found to occur in more than 40% of the samples analysed (Figure 4.16). The high iron and zinc levels in the older boreholes could be derived from the borehole casing.

All other trace element parameters were found to be present at low concentrations (below the 5x determination level set for I.C.P. analyses (see Appendices A2 and C4.2)).

4.2.5 Isotopes

Introduction

Isotopes are particularly useful in the determination of the age of waters, identifying mixing of two or more waters and in the classification of a particular water type. They may also provide information on the climate at the time of aquifer recharge.

In this study, ^{2}H and ^{18}O isotopes were used as a complementary tool supporting hydraulic and hydrochemical methods in the investigation of the hydrogeological regime. The advantage of using these particular isotopes is their occurrence as natural components of the water molecule, thus giving information about the system *in situ*. In addition, the isotopes are relatively easy to measure and interpret.

Isotope samples were routinely collected throughout the study. 50 of these samples were submitted for analysis (Table 4.2), and primarily included samples of groundwater and precipitation.

Theoretical Background

The isotopic value of a specific water is determined as the difference between the hydrogen and oxygen ratios measured against a set standard (such as Standard Mean Ocean Water, SMOW). For oxygen and hydrogen respectively, analyses are presented as $\delta^{18}O$ and $\delta^{2}H$, where:

$$\delta\,^{18}O = \frac{(^{18}O/^{16}O)\text{sample} - (^{18}O/^{16}O)\text{standard}}{(^{18}O/^{16}O)\text{standard}} \times 10^3 \qquad (4.1)$$

$$\delta\,^{2}H = \frac{(^{2}H/^{1}H)\text{sample} - (^{2}H/^{1}H)\text{standard}}{(^{2}H/^{1}H)\text{standard}} \times 10^3 \qquad (4.2)$$

(Faure, 1986)

With enrichment of ^{18}O and ^{2}H, a positive value is recorded against the set standard, while depletion in the respective isotopes will register as a negative value.

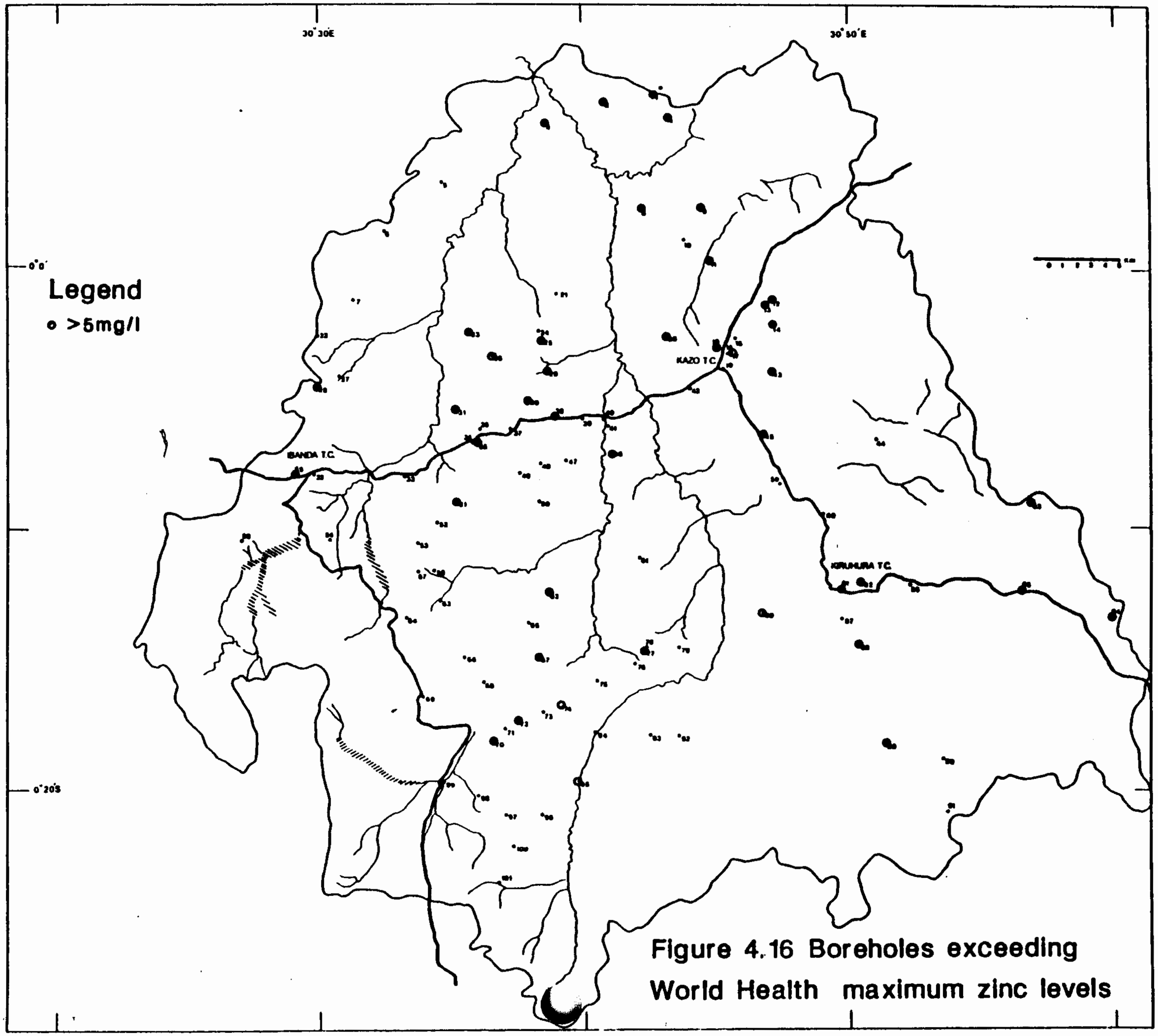


Figure 4.16 Boreholes exceeding World Health maximum zinc levels

Oxygen and hydrogen concentrations are controlled by vapour pressure. An inverse relationship exists between the mass of the molecule and its vapour pressure. This results in $H_2{}^{16}O$ having a higher pressure than $H_2{}^{18}O$. The same is true for the hydrogen isotopes. Thus, when water evaporates from a large body of water there is enrichment in the vapour of ^{16}O and ^{1}H and a depletion in ^{18}O and ^{2}H, while the liquid phase becomes enriched in the heavier isotopes.

With precipitation, a product of condensation, the isotopic concentration changes, the rain or snow that forms having higher ^{18}O and ^{2}H values than the remaining vapour phase. With subsequent condensation and precipitation events the vapour becomes depleted in both ^{18}O and ^{2}H. These condensation/precipitation phases are controlled by the Rayleigh process (Lloyd, 1986).

Faure (1986) lists a number of factors that may affect the isotopic value

- Isotopic fractionation, resulting from evaporation, condensation, chemical and biological reactions (Freeze and Cherry, 1979).
- Changes in temperature of the vapour affecting the fractionation process.
- Re-evaporation of water during precipitation and from surface water causing enrichment in the vapour phase.
- Evapotranspiration by vegetation which favours the ^{16}O and ^{1}H isotopes,resulting in ^{18}O and ^{2}H enrichment.

Dansgaard (1964), after collection and analysis of samples from around the world established a linear relationship between $\delta^{18}O$ and $\delta^{2}H$:

$$\delta^{2}H = 8\delta^{18}O + 10 \qquad (4.3)$$

which is commonly referred to as the meteoric water line (MWL). Due to the Rayleigh process, the ratio obtained for $^{18}O/^{2}H$ during condensation differs from that obtained during evaporation. This deviation from the meteoric water line allows the isotopic data to be used to gain information on the hydrogeological environment.

Table 4.2 Isotopic Values for Oxygen-18 and Deuterium

Borehole No.	δ ^{18}Oxygen per mil		δ Deuterium per mil	
CD 85	-2.61	-2.91	-14.00	
CD 91	-2.77		-12.40	
CD 91	-2.99		-12.70	
CD 119	-2.63		-11.40	
CD 360	-3.68		-16.60	
CD 368	-2.20		-7.90	
CD 371	-2.56		-8.80	
CD 403	-2.34		-8.60	-9.48
CD 409	-2.79		-10.20	
CD 415	-3.08		-8.80	
CD 447	-3.00		-8.90	

CD 461	-2.59		-6.60	
CD 479	-3.36		-10.90	
CD 479	-2.96	-3.13	-13.40	
CD 487	-2.91		-7.90	
CD 499	-3.37	-3.59	-12.90	
CD 499	-3.13		-13.30	
CD 510	-2.98		-4.80	
CD 3017	-2.00		-1.50	
CD 3040	-2.77	-2.71	-10.80	
CD 3418	-2.55		-9.10	
CD 3419	-2.93		-10.20	
CD 3449	-1.00	-0.82	9.00	
CD 3483	-2.75		-10.80	
CD 3497	-2.96	-2.96	-8.59	
CD 3497	-2.83		-4.04	
DS 719	-2.87	-2.95	-10.60	
DS 721	-2.74		-2.64	
DS 732	-1.96		-0.95	
DS 735	-2.43	-2.59	-8.80	
DS 736	-2.45		-10.10	
DS 741	-2.76	-2.71	-7.80	
DS 743	-2.40		-9.00	
DS 744	-2.05		-2.30	
DS 750	-2.29		-8.20	
DS 750	-2.53		-8.70	
DS 758	-3.26		-14.23	
GS 884	-2.31		-7.20	
GS 1023	-1.94		-2.00	
GS 1291	-2.57		-9.00	
GS 1514	-3.46		-14.80	
GS 1594	-3.43		-12.50	
GS 1613	-2.83	-2.99	-11.90	
GS 1613	-1.69		-3.50	
GS 1613	-2.97		-10.75	
GS 1615	-2.23	-2.68	-9.50	
GS 884	-2.31		-7.20	
WDD 1548	-2.17	-2.27	-2.19	-4.31
WDD 1549	-2.28		-8.70	
WDD 1715	-3.32		-8.83	
WDD 1717	-2.55		-8.20	
WDD 1719	-2.61		-10.40	
WDD 2027	-2.93		-6.71	
WDD 2027	-2.99	-2.99	-5.57	
WDD 3038	-2.65		-10.90	
WDD 2041	-2.85		-5.24	
WDD 2048	-3.30		-9.50	
WDD 2190	-2.95		-10.10	
WDD 2214	-2.37		-8.20	
WDD 2214	-2.31	-2.34	-7.90	
WDD 2218	-2.32		0.04	-1.11

Samples from Isolated Packer Zones

	Depth Interval metres				
WDD 2027	57.23-61.02	-2.91		-4.95	
WDD 2045	30.01-33.75	-3.41	-3.39	-6.48	
WDD 2049	32.96-36.7	-2.78		-7.52	
WDD 2050	55.4-59.14	-3.43		-5.08	
WDD 2213	40.45-44.19	-3.04		-10.01	
WDD 2213	66.63-70.39	-2.04		-4.02	-0.31
WDD 2213	70.85-74.59	-3.37		-6.44	
WDD 2527	50.06-53.8	-2.85		-2.30	-1.98
Rain Samples					
Rain 19 June		-0.25		16.22	19.91
Rain 19June		-0.25		16.56	16.59
Rain 20 June		-2.52		-4.45	
Rain 20 June		-2.48		-4.96	
Rain Mbarara		-7.80		-61.70	
Rain Mbarara		-0.83		7.00	
Rain Kazo		2.83		28.80	
Rain Kazo		-0.32		27.30	

Interpretation

The isotope data are plotted on Figure 4.17. Since the limited availability of isotopic precipitation data for the study area precluded construction of a localized meteoric water line, the global mean (MWL) of Dansgaard (1964) is included on the figure.

The groundwater samples all cluster around the $\delta^{18}O$ value of -2.5 per mil , with minimal deviation from the MWL. This suggests that the groundwater i) is of modern origin, ii) is derived from a relatively local source, iii) is recharged during short intense rainfall periods, during which potential evaporative and transevaporative processes are limited.

Several samples collected (DS732, CD3017 and WDD2218) show relative enrichment in isotopic content. Their locations coincide with wetland areas where intensive evaporation is occurring.

Mbarara rainfall samples show a large isotopic variation, which implies two independent source origins. The isotope content of M1 (-61 per mil $\delta^{2}H$) suggests either i) a distal source (e.g. Indian Ocean) or ii) re-evaporation and subsequent condensation from a high altitude/inland source. Samples M2-M4 show enriched $\delta^{18}O$ content (Figure 4.17) which would suggest a localised source of origin, most likely Lake Victoria. Rainfall samples K1-K2 from Kazo T.C. show isotope enrichment, most likely resulting from atmospheric evaporation. The source is assumed to be the same as for samples M2-M4.

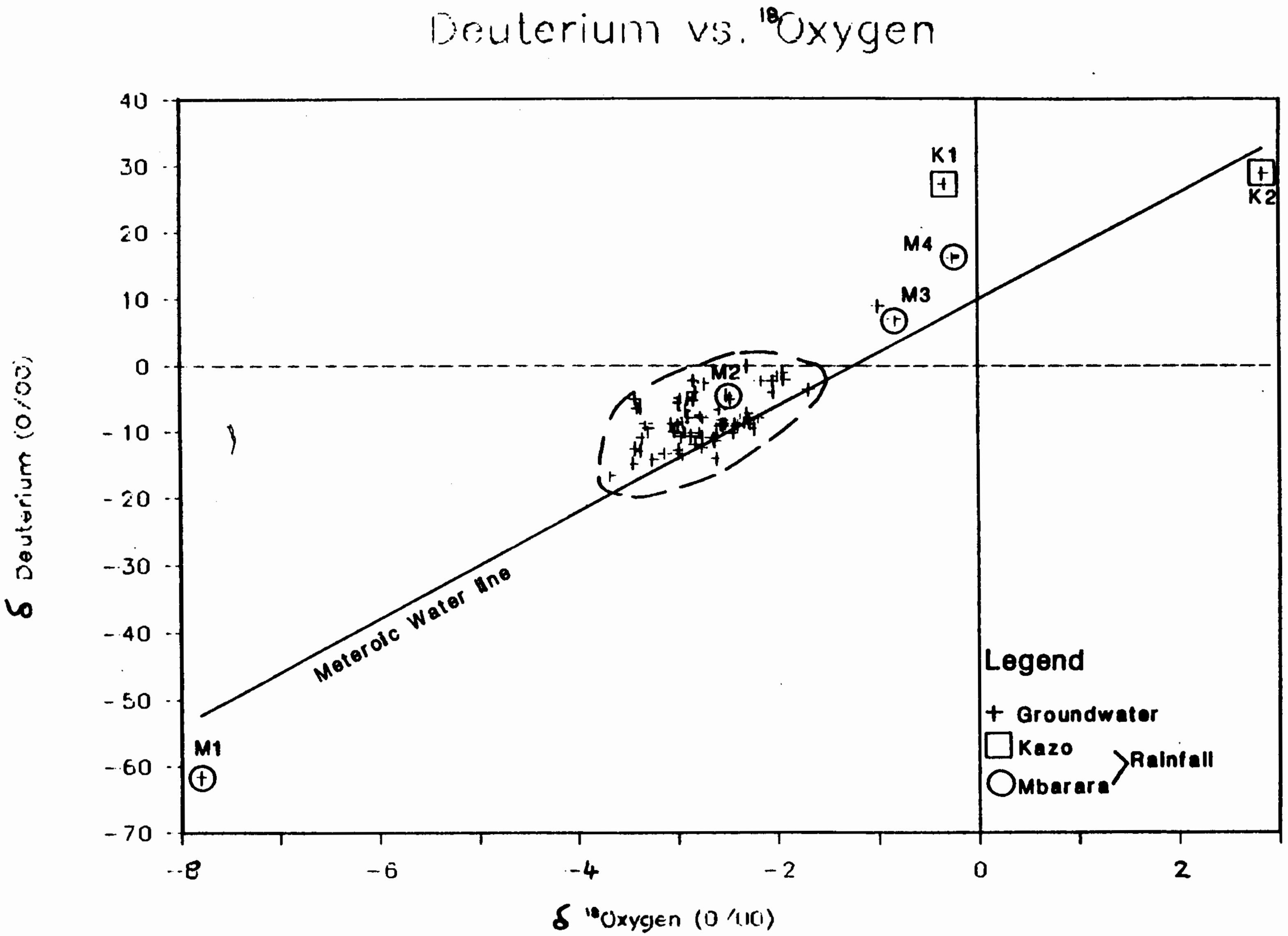


Figure 4.17 Plot of deuterium versus oxygen18

4.2.6 Conclusions

Groundwaters from the study area show little variation in chemical nature. This likely reflects the secondary permeability character of the aquifer and the chemical inertness of the rock matrix. It also suggests relatively short groundwater travel times. Most groundwater sampled can be classified as $MgSO_4$ or $MgHCO_3$, low TDS waters with good major ion water quality. Enriched concentrations of iron, manganese and zinc may be a problem locally.

Despite the close similarity of groundwaters across the region, subtle changes in chemistry are apparent which provide useful information on recharge/discharge behaviour. In particular, groundwaters in the west of the area show a chemical composition indicative of a recharge zone; HCO_3^- is dominant with only limited calcium development.

Similar chemical characteristics appear in groundwaters in the vicinity of Kazo, but are less distinctive. It is concluded that additional recharge is entering the system here, and is mixing with older waters moving at depth from the west (Figure 4.18). Contour maps of all the major ions show general agreement with the conceptual model, but are complicated by anomalies of various types. In some cases the anomalies are caused by errors in the chemical analyses; other, local anomalies are likely caused by changes in the hydraulic interaction between the bedrock and regolith, with regolith waters mixing with native bedrock water. Since no data on the chemical character of groundwaters of the regolith could be obtained, the degree to which the chemistry of these waters influence the chemistry of bedrock waters could not be determined. A third major type of anomaly occurs in the southwest and is thought to reflect geochemical nature of a major geologic transition zone.

Isotopic data suggest that recharge to the system is of modern origin. However, the source of precipitation appears to be variable and needs further sampling to provide confirmation. The clustering of groundwater sampling points around the $\delta^{18}O$ value of -2.5 per mil on the global meteoric water line suggests that recharge takes place during intense rainfall events with low evaporation/evapotranspiration losses.

4.3 Hydrogeological Parameters

4.3.1 Packer Testing

Objectives

A total of 233 packer tests were conducted in 21 boreholes located at different sites across the study area (see Figure 4.19) to: (1) identify the high and low yielding zones in the rock mass at each site; (2) measure the hydraulic conductivity of the bedrock at different locations and at different depths below the surface; and (3) collect groundwater samples from specific fracture zones in each borehole.

Equipment

A schematic drawing of the packer probe used to conduct these tests is shown in Figure 4.20. The probe consists of two inflatable, reinforced, rubber packers separated with steel pipe to provide a test interval 3.74 metres in length. Rigid 37mm I.D. ABS plastic riser pipe was connected to the top of the packer probe. A WaTerra inertial hand pump was installed inside this

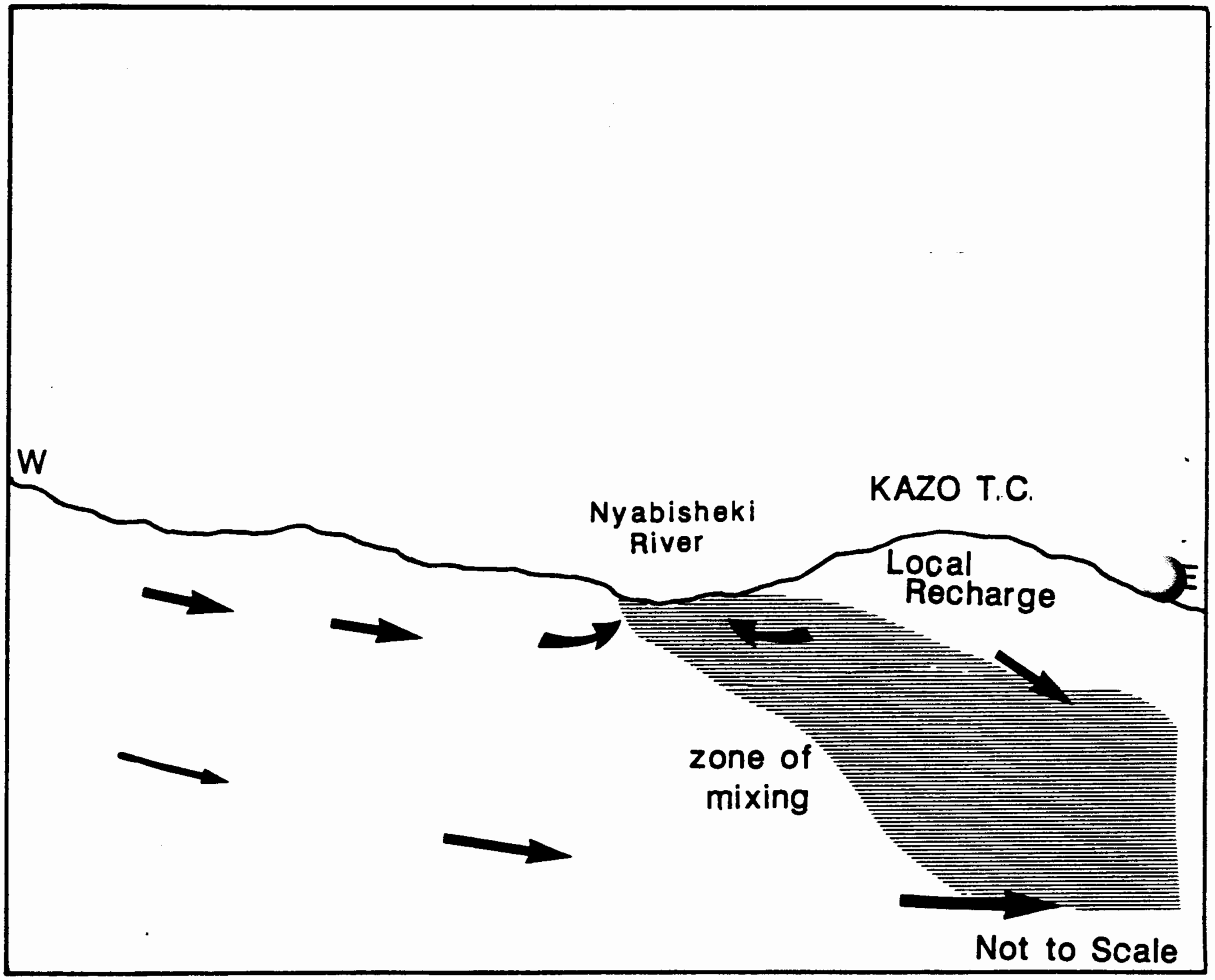


Figure 4.18 Local recharge in the Kazo area

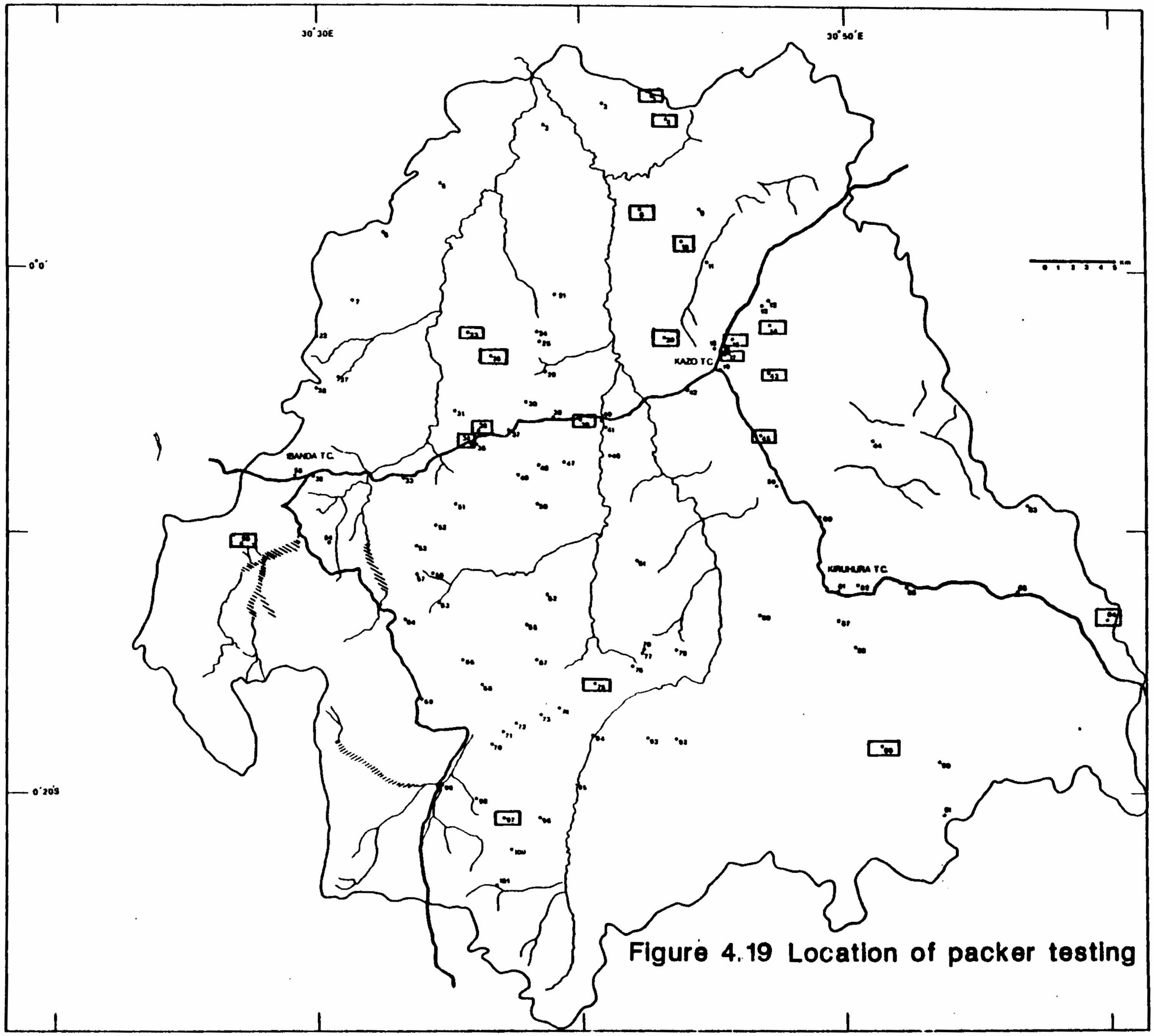


Figure 4.19 Location of packer testing

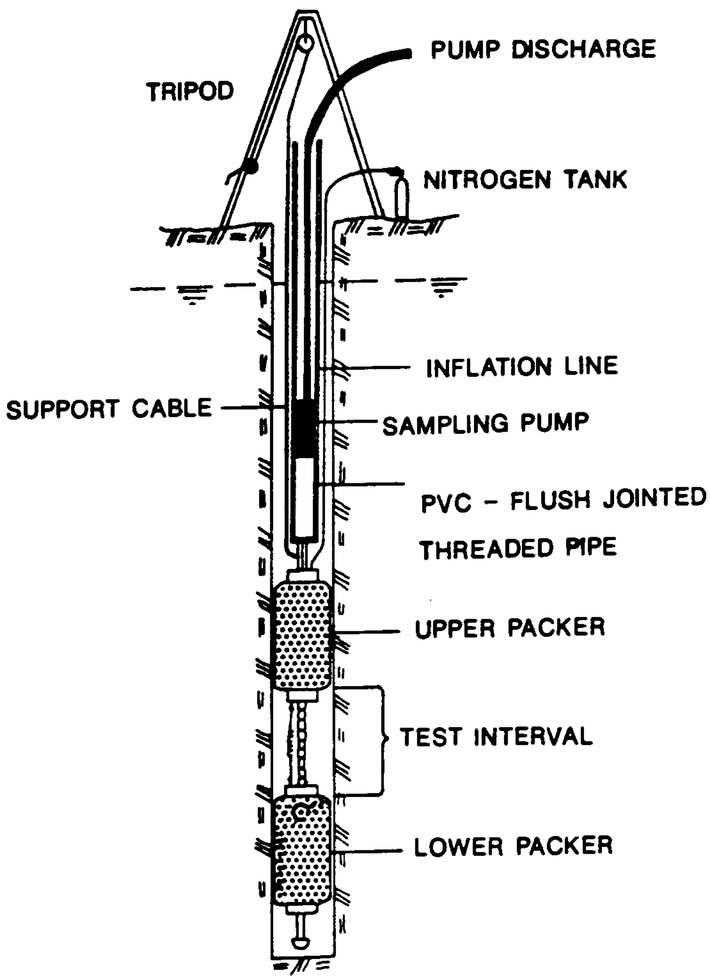


Figure 4.20

SCHEMATIC DIAGRAM OF PACKER TESTING EQUIPMENT plastic riser pipe for pumping groundwater from the test zone. When pumping, groundwater flows from the rock mass into the test zone, enters the perforated pipe connecting the two packers, and moves up through the centre pipe in the upper packer into the riser pipe.

Two electric water level tapes were used to record water levels in the test zone (i.e. inside the riser pipe) and, in the open borehole above the packers. The accuracy of water level readings taken with these tapes is ± 0.005 m.

The packers were inflated from the surface, through 6.35 mm O.D. high pressure plastic tubing, using compressed air cylinders.

Procedures

A 3.74 metre long test interval was used for all packer tests performed in this study. The boreholes were usually tested starting from the bottom and moving up in 3.74 metre increments until the casing was reached. In this manner, a continuous profile of the hydraulic characteristics of each borehole was obtained.

There are two stages to a packer test: (1) the equilibration stage where the water level in the test zone is monitored as it equilibrates with groundwater pressure in the surrounding rockmass, and (2) the hydraulic testing stage where water is pumped from the test zone under controlled conditions to determine the permeability (hydraulic conductivity) of the test zone.

Two methods were used to measure hydraulic conductivity. For very high permeability zones, a constant head test was conducted. A rising head test was conducted in zones of low to intermediate permeability. The specific procedures followed for both of these test methods are described in Appendix D.

Groundwater samples were collected from the most permeable zone(s) in each borehole. These samples were taken only after a large (pre-determined) volume of water had been pumped out to ensure that "fresh" formation water and not stagnant well water was being collected.

Results

A summary of results from the packer tests is presented in Figures A.1 to A.20 in Appendix A4. For cross-reference purposes, Appendix A4 includes a table which lists the borehole numbers used in this study together with their official government designations. Semi-log bar diagrams showing hydraulic conductivity versus depth are also presented in this Appendix to graphically illustrate the hydraulic conductivity profile of each well.

The results obtained for borehole WDD 1713, and borehole WDD 1712 are presented here in Figures 4.21 and 4.22 respectively as typical examples of conditions encountered in the study area.

Borehole WDD 1713 is a low yielding well (less than 200 l/hr) which derives most of the groundwater from a single zone near the bottom of the well. Figure 4.21 shows that the hydraulic conductivity varies considerably along the borehole from 2×10^{-8} m/s near the top to a low of 4×10^{-10} m/s in the interval 44.5 to 53 m.b.d. The hydraulic conductivity then rises again to a maximum of 5×10^{-7} m/s in the interval 72 to 75 m.b.d. Based on hydraulic conductivity values, the groundwater yield from this last zone alone would account for about 76% of the total yield from the borehole.

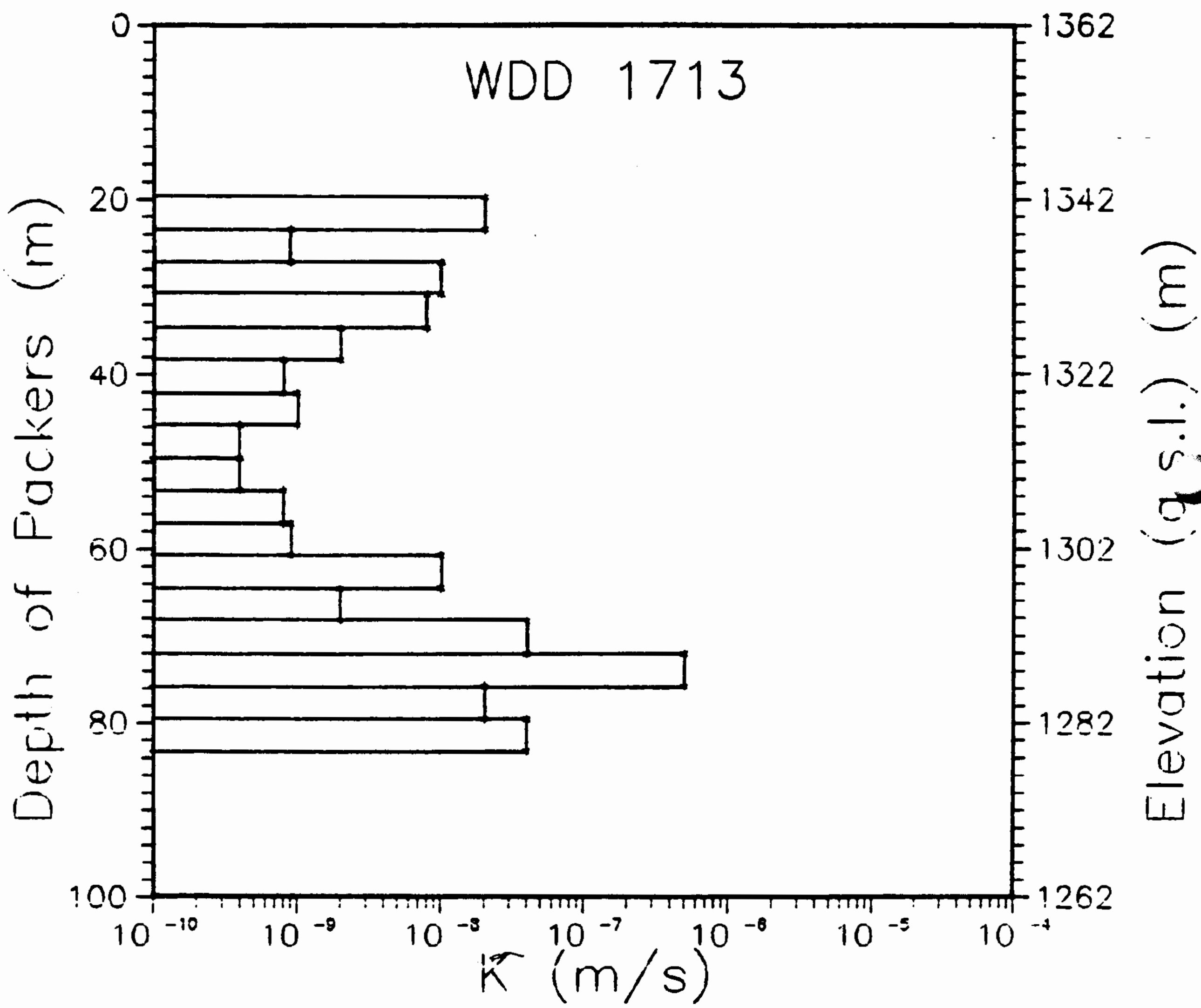


Figure 4.21 Hydraulic Conductivity versus Depth for WDD1713

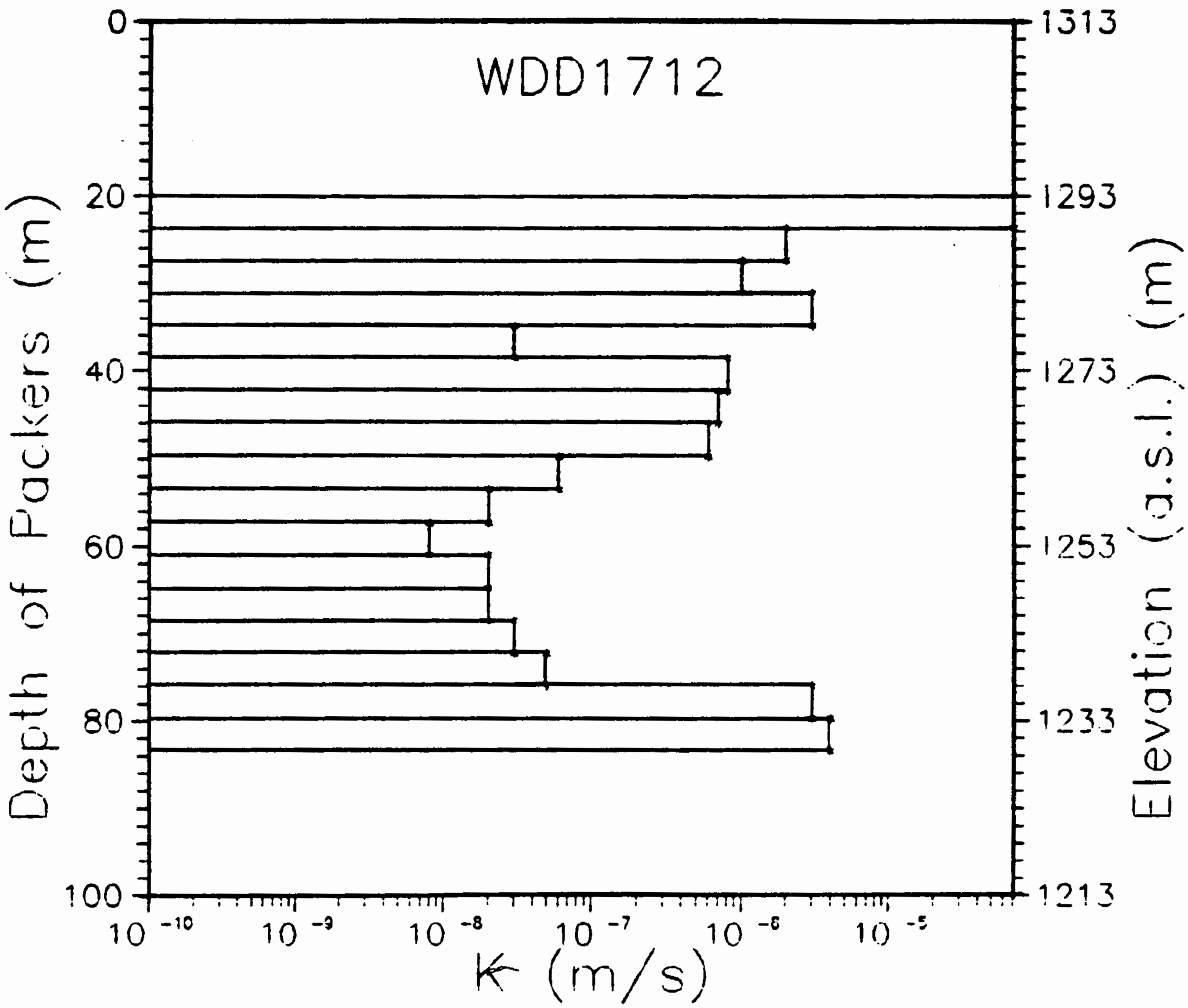


Figure 4.22 Hydraulic Conductivity versus Depth for WDD1712

Borehole WDD 1712 (Figure 4.22) is a relatively high yielding well (over 1800 l/hr) which again derives most of the groundwater (79%) from a single zone, in this case, located just below the casing at a depth of 19 to 23 m.b.d. Hydraulic conductivity values range from a high of 7 x 10^{-5} m/s near the top to a low of 8 x 10^{-9} m/s at a depth of about 60 metres. From this point, the hydraulic conductivity rises to 4 x 10^{-6} m/s for the bottom two test intervals.

Observations

The transmissivity of an aquifer is a measure of its capacity to transmit (or yield) water, and can be calculated from the packer test results by taking the sum of the transmissivity values (T = K x 3.74 m) determined for each test zone. The transmissivity, expressed in m^2/day, for each borehole is listed in Table 4.3. Also shown on this table are transmissivity values determined from open hole pumping tests performed on six of the packer tested boreholes (see Section 4.3.2 for details on these pumping tests).

Table 4.3 Packer and pumping test transmissivity data

Borehole Number	Transmissivity (Packer Tests) m^2/day	Transmissivity (Pumping Tests) m^2/day
1534	16.8	6.6
1712	28.5	
2048	9.72	5.3
1720	1.29	
2219	0.305	
2084	11.47	
2527	1.20	
2050	0.455	
1541	0.57	
2027	248.0	38.8
2049	1.62	
2043	0.065	0.28
1548	2.99	
2045	0.81	
1549	0.22	
2209	0.128	0.039
2225	0.772	
2213	0.83	
1713	0.21	
1535	0.284	
1714 Before hydrofracturing	0.44	0.369
1714 After hydrofracturing	1.03	
1537	0.076	

As shown by Figure 4.23 the packer test derived transmissivity values correlate closely with the pumping test derived values but tend to be higher in magnitude. This is understandable, given that the packer test results reflect the properties of the rock mass in the immediate vicinity of the borehole, whereas the pumping test results reflect conditions in a larger volume of rock mass around the borehole.

On the basis of borehole transmissivity values, the 22 wells that were.packer tested can be classified as follows:

19%	High Yielding	$T > 10\ m^2/day$
24%	Medium Yielding	$1 < T < 10\ m^2/day$
57%	Low Yielding	$T < 1\ m^2/day$

The actual proportion of low yielding wells in the study area is likely to be considerably greater than 57% since higher yielding wells were generally favoured in the selection of locations for packer testing.

More than half of the boreholes tested received most of their water (i.e. >75%) from a single test zone (3.74m long). Most of the remainder obtained water from just two test zones. Only one or two boreholes relied on flow contributions from three or more zones. The large variation of hydraulic conductivity with depth and the high percentage of "single permeable zone" boreholes demonstrate the important role discrete fracture zones play in determining the movement of groundwater in the rock mass. From the available data, there appears to be no correlation between the total well yield and the number of zones producing water.

All the holes tested have at least one zone with a hydraulic conductivity equal to or greater than the estimated average hydraulic conductivity of the bedrock of less than 10-7 m/s, with about a third of the holes having only one such zone and the remainder having two or more zones. If a hydraulic conductivity an order of magnitude greater (10^{-6} m/s) is used for the comparison of boreholes, on the basis that it represents a reasonable permeability for an aquifer, then only half the holes tested have a zone with a hydraulic conductivity equal to or greater than that value (10^{-6} m/s). Of these about half have only one zone and the remainder have two or more zones.

For about half the boreholes, the most permeable zone encountered was the first interval below the casing. However of the remaining portion the vast majority have their most permeable zone within the bottom half of the uncased section of the borehole.

The two highest yielding boreholes tested (WDD 2027 and WDD 2084) show different patterns of permeability profile. WDD 2084 has three adjoining sections in the lower part of the borehole with relatively high hydraulic conductivities (10^{-5} m/s) contrasting with the rest of the borehole where the hydraulic conductivities are at least two orders of magnitude less. In the upper zone, just below the regolith, the hydraulic conductivity is only $5x10^{-9}$ m/s. In WDD 2027 the upper seven zones all have hydraulic conductivities close to or greater than 10^{-5} m/s, with the highest being $2x10^{-4}$ m/s.

Of the next three highest yielding boreholes WDD 1534 and WDD 1712 both have their most permeable zones at the top of the uncased section, with other permeable zones at depth. In contrast WDD 2219 has its most permeable zone at depth, though it should be noted that this "high" value is only $8x10^{-7}$ m/s and is thus approximately two orders of magnitude less than the high values in the other two holes.

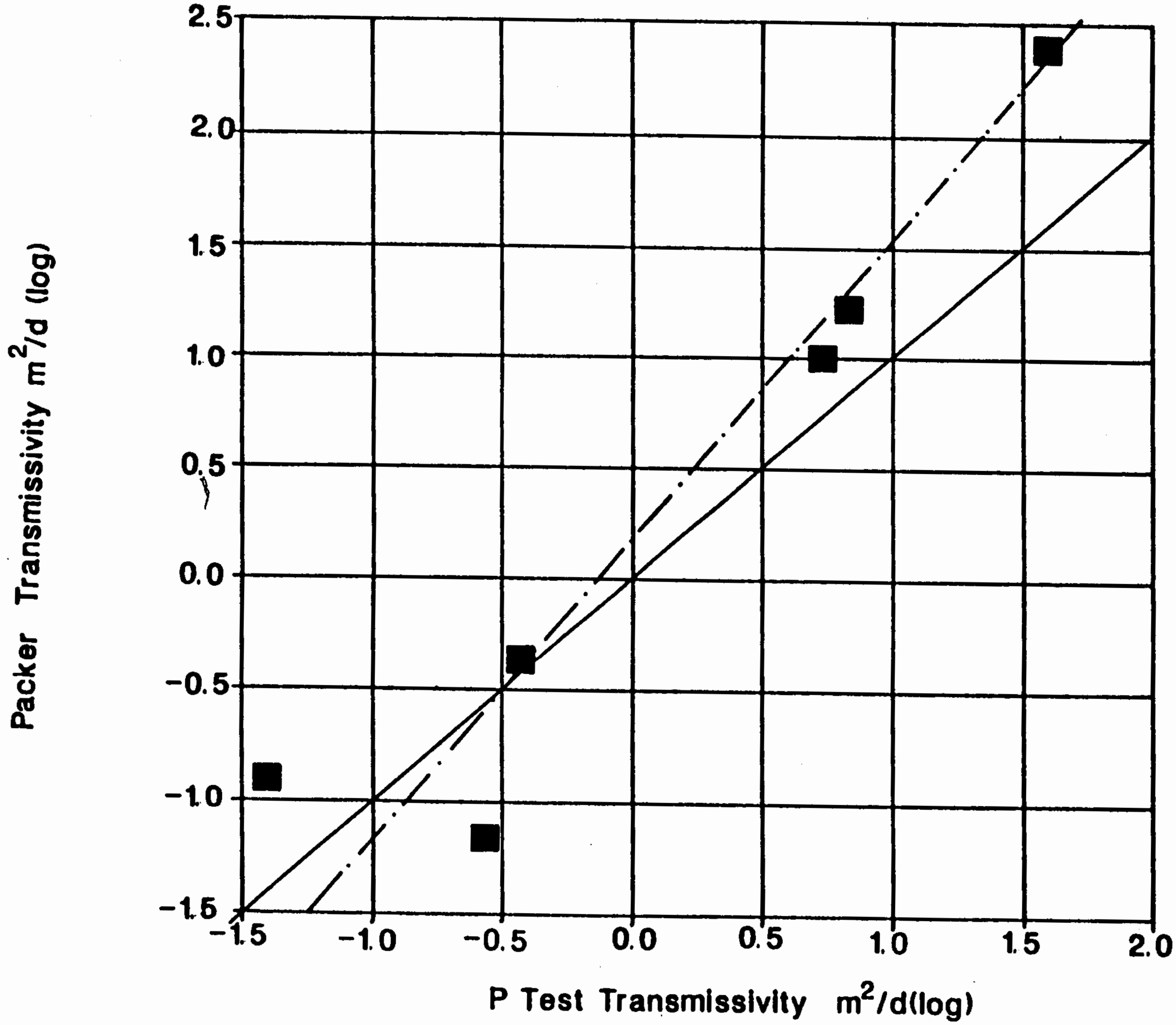


Figure 4.23 Plot of transmissivities for pump test versus packer tests

These data do not indicate any clear relationship between hydraulic conductivity and depth. This is also evident in Figure 4.24, which is a plot of hydraulic conductivity vs. depth for the 233 packer tests performed in this study. The more or less random scatter of data points on this plot indicates a poor correlation of hydraulic conductivity with depth below surface. The lack of correlation between hydraulic conductivity and depth also suggests a similar lack of relationship between borehole depth and yield. However, this is complicated somewhat by the extent to which fracture zones are connected to sources of recharge. It may be that a relatively permeable fracture zone has a low sustained yield because it becomes dewatered and is not readily recharged. Thus, if the regolith should prove to be a source of groundwater then it would be expected that the fracture zone which is found in about half of the boreholes, just below the regolith, would also be a good yielding zone. The data collected are inconclusive on this point, though it should be noted that of the two highest yielding boreholes tested, one (WDD 2084) has its most permeable zone at depth in the rock.

Hydraulic Fracturing of Boreholes

Hydraulic fracturing (or hydrofracturing) of a borehole is a method used to increase the well yield and involves injecting water under very high pressure into a sealed interval of borehole in order to dilate existing fractures or create new fractures in the rockmass. This procedure is currently used on UNICEF/WDD boreholes which have yields of less than 300 l/hr; thus it was possible for the IDRC study team to investigate the hydraulic conductivity profiles in some boreholes before and after hydrofracturing.

Figure 4.25 is a plot of hydraulic conductivity vs. depth for borehole WDD 1714 before (dotted lines) and after (solid lines) hydraulic fracturing. The arrows pointing to the right indicate zones where the hydraulic conductivity has increased. An increase was detected in six zones with the greatest change in hydraulic conductivity occurring in the intervals 51.5 to 55.24 m.b.d. (133 fold increase) and 70.2 to 73.94 m.b.d. (80 fold increase). Even with these seemingly large increases in permeability, the overall impact on the transmissivity (or yield) of the well is a small increase by a factor of about 3 from 0.33 to 0.99 m^2/day.

4.3.2 Pumping Tests

Transmissivity data were obtained from short-term single well pumping tests. Both drawdown and recovery data were interpreted. In most cases they showed excellent agreement. Figures 4.27 and 4.28 show histograms of the pumping test results for drawdown and recovery tests respectively. Similar distributions are revealed, with the majority of the values falling in the range 0-1 m^2/day. The median value for each set of data is 0.8 m^2/day, a value which agrees very closely with the median value obtained for the packer test data (see Section 4.3.1; Figure 4.26). In addition an excellent correlation was obtained between the pumping test recovery results and packer test results for wells which were tested by both means (Figure 4.23).

When transmissivity data are plotted on a regional map (Figure 4.29), highest values of transmissivity generally occur in the vicinity of the discharge zone, close to the river (see Section 4.4).

4.3.3 Conclusions on Bedrock Aquifer Properties

In general, the hydraulic conductivity of the bedrock across the study area is very low (less than 10-7 m/s). Higher permeability fracture zones were detected in most boreholes, but these zones often yielded very little groundwater.

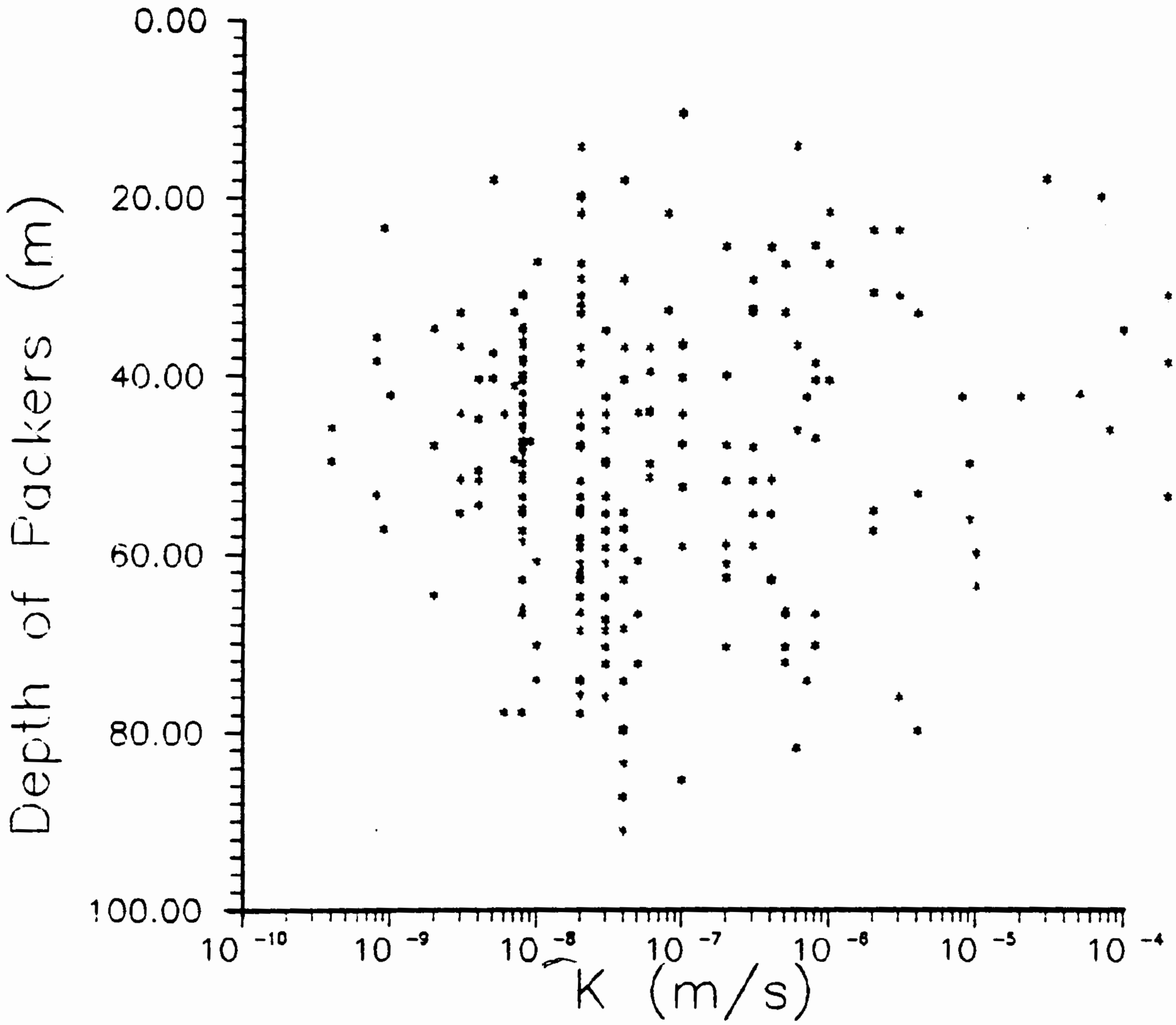


Figure 4.24 Plot of 233 packer hydraulic conductivites versus depth

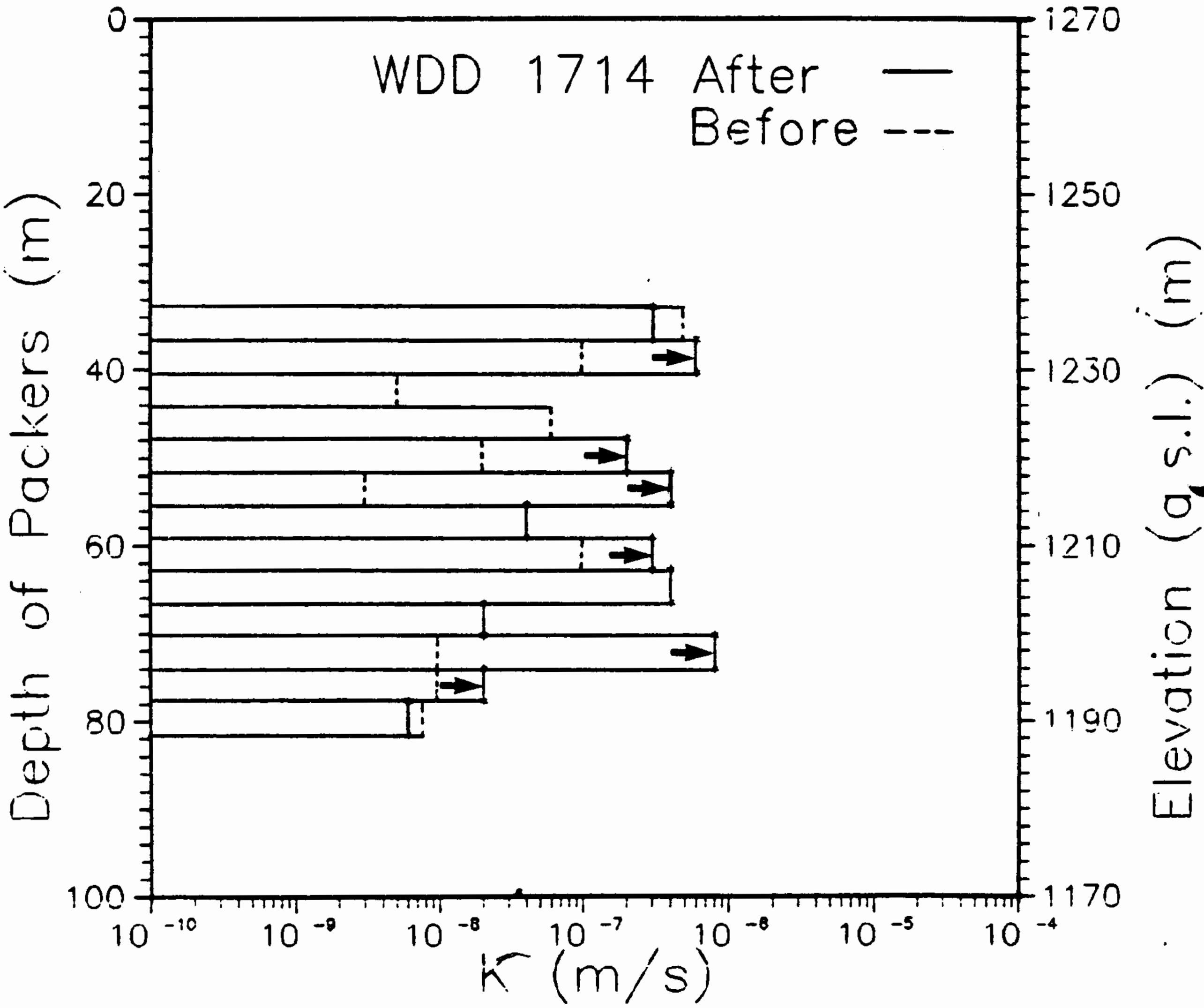


Figure 4.25 Hydraulic conductivity versus depth for WDD 1714 before and after hydrofracture

Figure 4.26 Plot of Frequency versus packer transmissivities

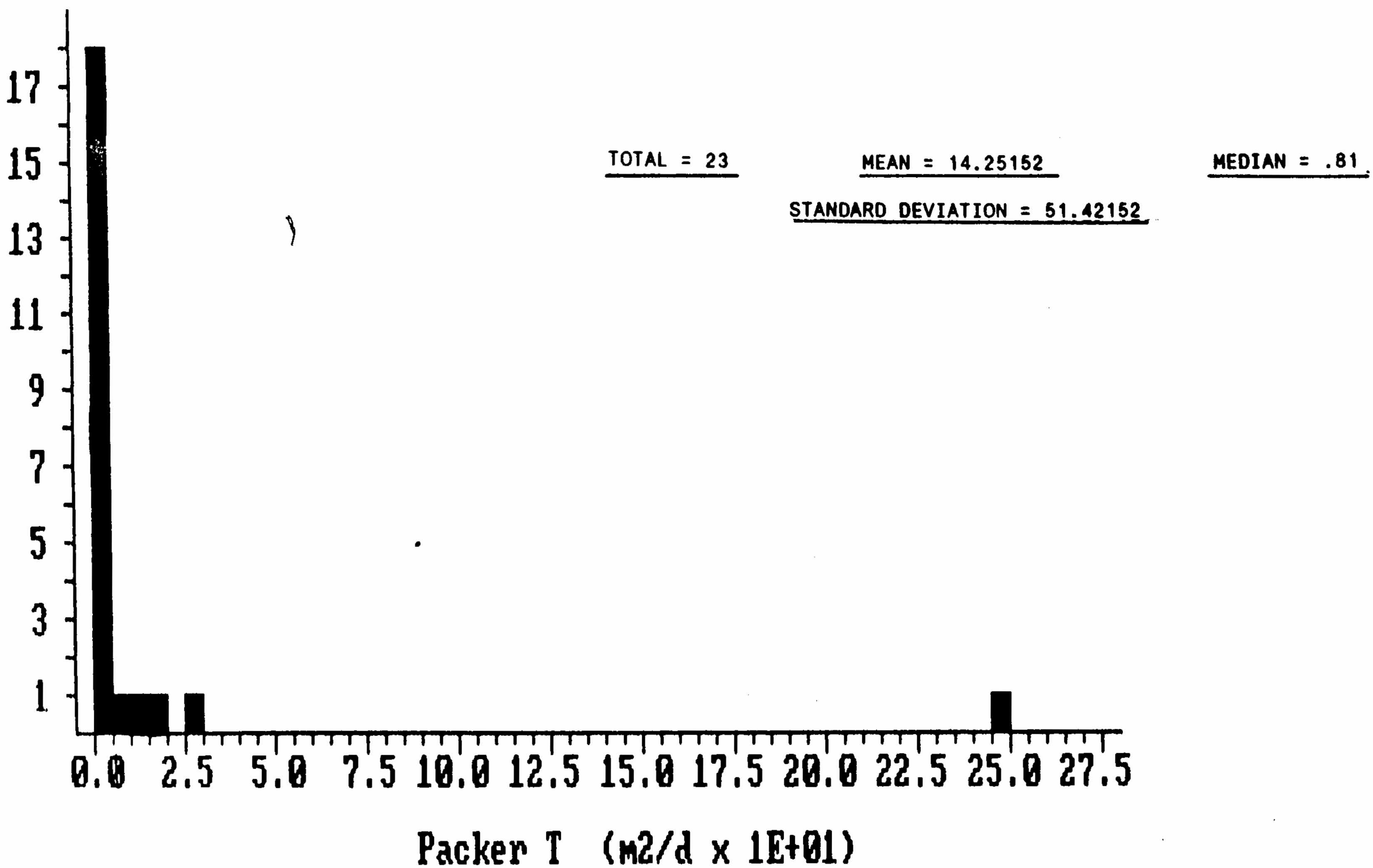
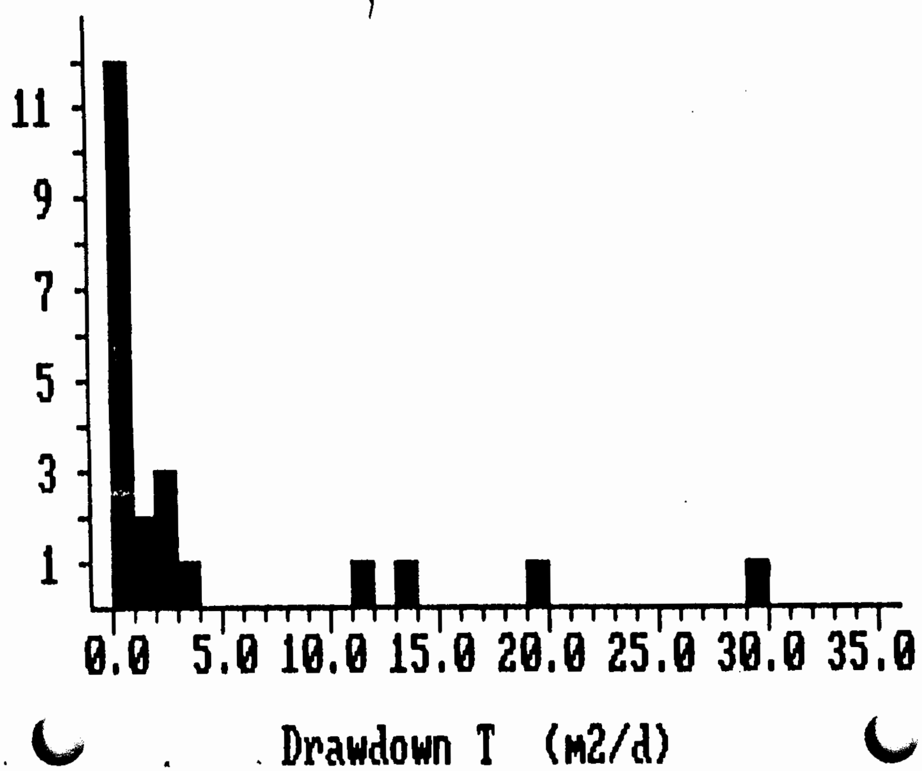


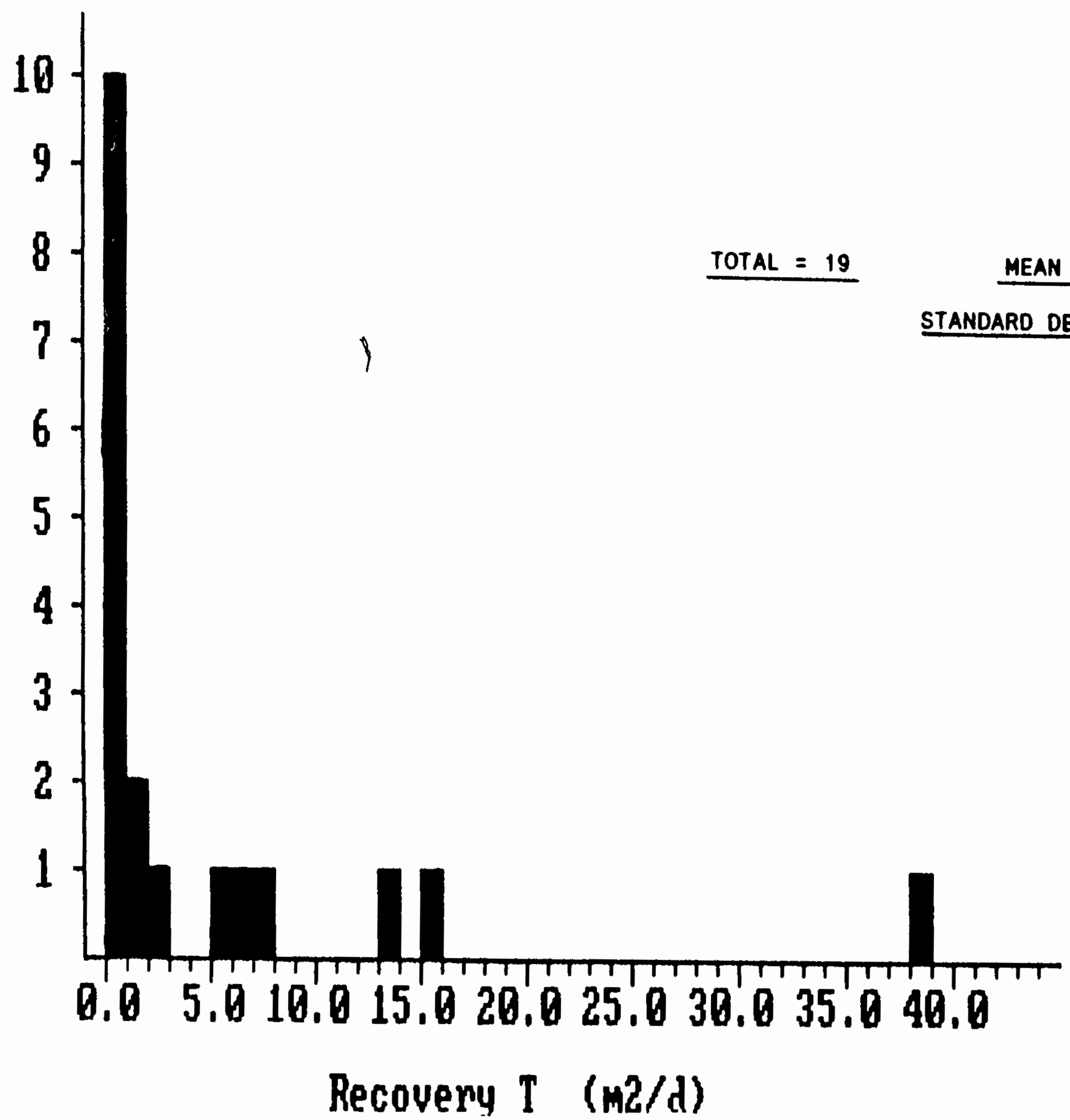
Figure 4.27 Plot of Frequency versus drawdown transmissivities

TOTAL = 22 MEAN = 4.104955 MEDIAN = .71

STANDARD DEVIATION = 7.565727



4.28 Plot of Frequency versus recovery transmissivities



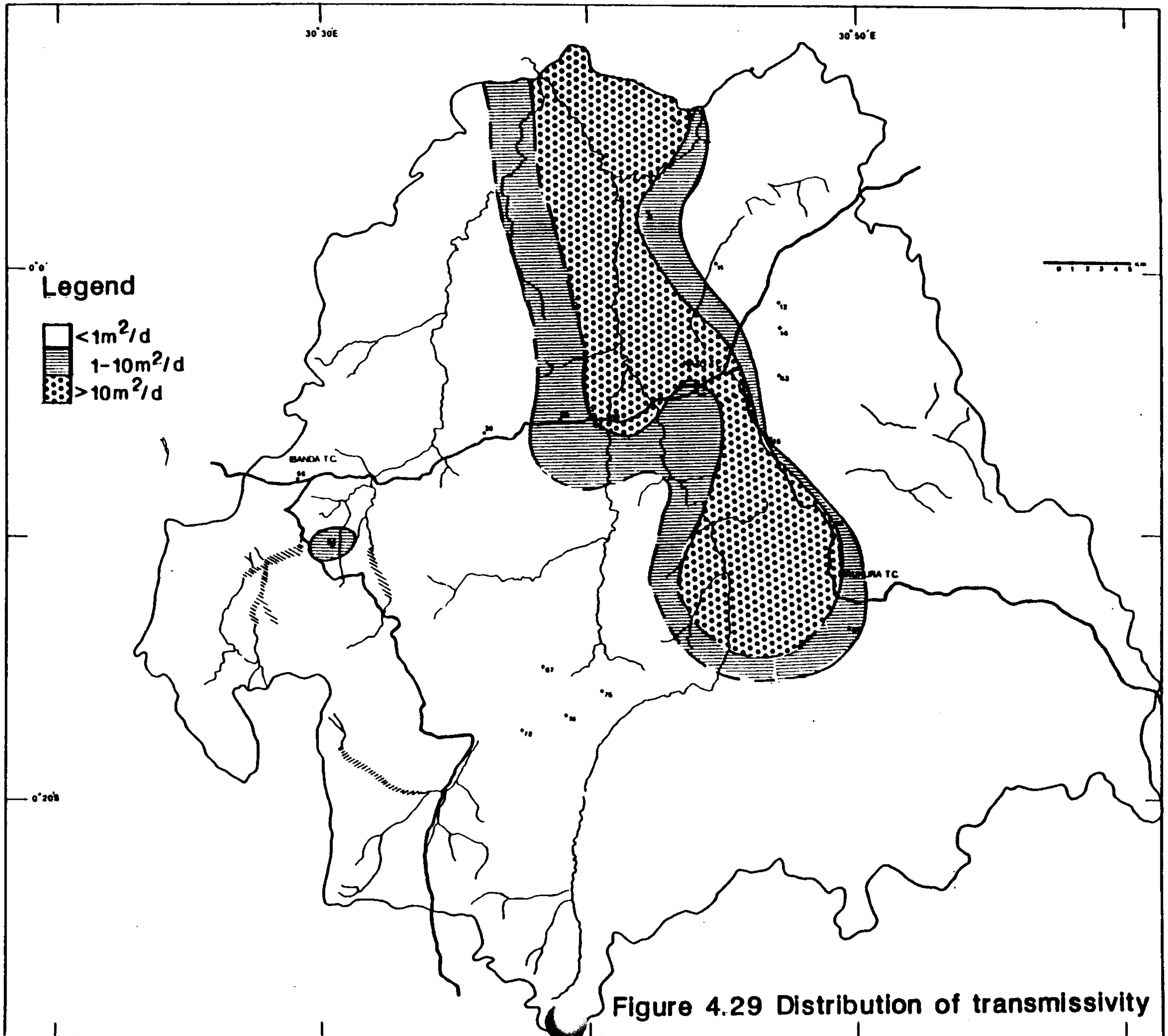


Figure 4.29 Distribution of transmissivity

Based on the packer testing results, there is no obvious relationship when depth is plotted against hydraulic conductivity for all 233 tests carried out. However, within individual boreholes there is a tendency for the highest permeability to occur just below the cased section (i.e. just below the regolith) and it may be that this zone is supplied with water from the regolith.

While there is no evident pattern in the geographic distribution of boreholes with shallow, intermediate or deep, high yielding fracture zones, there is an apparent relationship between a zone of higher transmissivity and the aquifer's primary discharge area.

Based on all the test data, the median transmissivity for the bedrock aquifer is 0.8 m^2/day.

Packer tests performed in a hydraulically fractured borehole showed where improvements in hydraulic conductivity were achieved. Overall, the borehole transmissivity increased by a factor of about 3 due to hydrofracturing. Several other boreholes should be tested before judging the effectiveness of hydraulic fracturing as a method of improving well yield.

4.4 Regional Potentiometric Map

Potentiometric contours were constructed on the basis of a survey of measurement conducted during a large part of 1988. The depth to rest water level was recorded in all available boreholes and the approximate elevations of the ground surface at each borehole location was determined by using altimeters. Although this method is less accurate than normal surveying techniques it was the only feasible method available in the study area.

As most of the boreholes were in use, water level readings were taken at a time when excessive drawdowns due to the continual use of the handpump had not occurred. Measurements taken at various times of the day showed that the drawdown in the boreholes was usually greatest in the evening, at around 6.00 p.m..

Potentiometric heads were calculated for all the boreholes and were plotted on a base map. Potentiometric contours were then drawn at an interval of 20 metres (Figure 4.30). Since all the elevations were in the range of 1000-1999 m the first digit (1) is omitted in the figure.

The potentiometric contours reveal a general trend of groundwater flow from the southwest towards the northeast. The curvature of the contours is highly influenced by the valley of River Nyabisheki, which is a major discharge zone and appears to intercept most of the east/northeasterly flow. It does not prevent, however, a small component of flow from moving across the boundaries of the study area to the east. This component of flow is referred to as trans-boundary flux. Significantly the potentiometric data are in good accord with the flow distributions indicated by the hydrochemistry.

4.5 Water Balance

4.5.1 Introduction

The water balance is one of the more critical elements of a hydrogeological study as it provides a quantitative assessment of aquifer inflows (I) and outflows (O) (Equation 4.1), an understanding of which is essential for responsible and efficient management of the resource. When aquifer inflows and outflows are balanced, the net change in aquifer storage (dS) is zero and the aquifer is said to be in a state of quasi-steady equilibrium. When inflows and outflows are not in

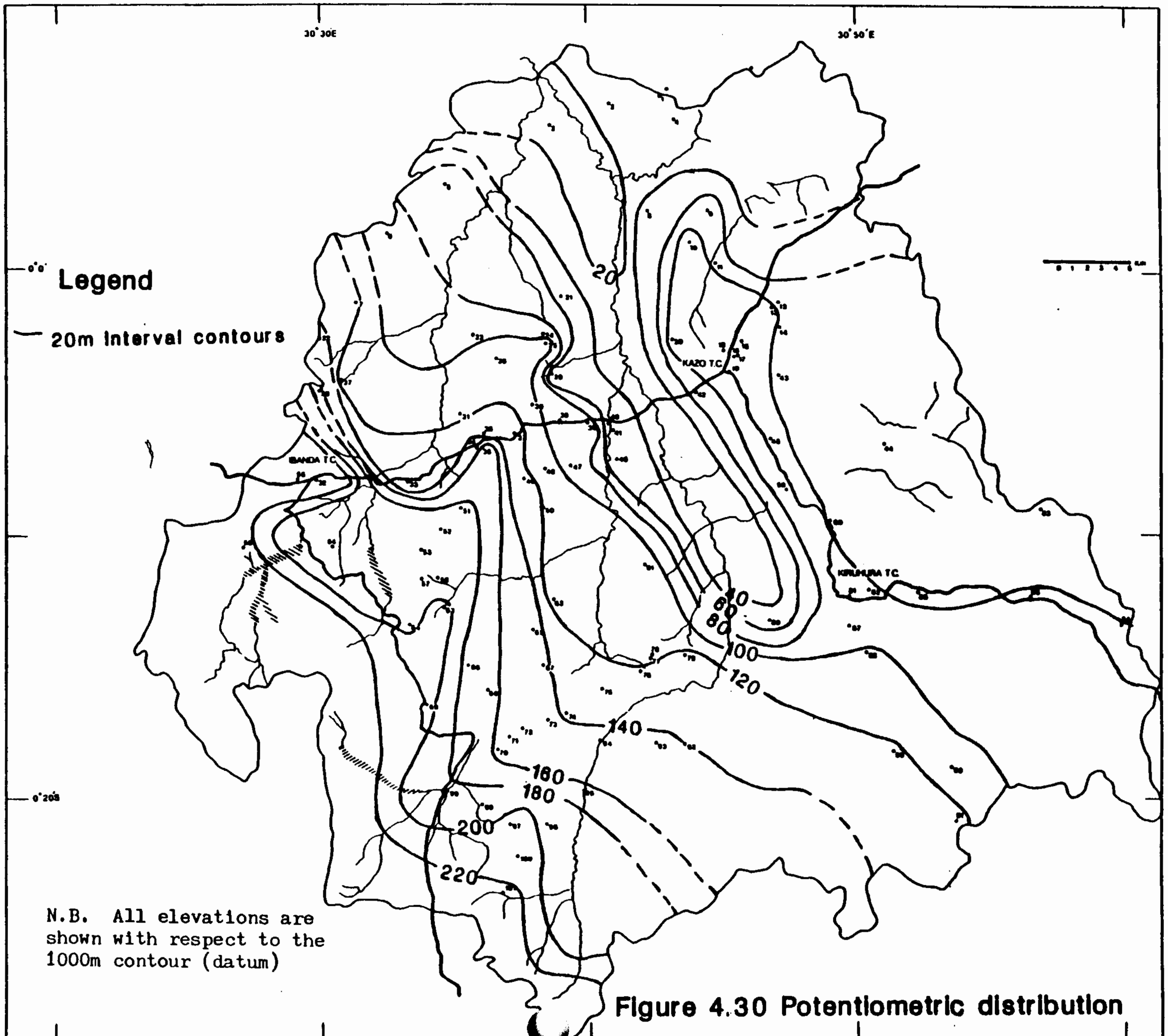


Figure 4.30 Potentiometric distribution

balance, dS adopts a positive or negative value indicating that water is being taken into or out of storage respectively. In practice, these states of disequilibrium are normally recognized by long-term changes in the aquifer's potentiometric level.

$$I = O \pm dS \tag{4.1}$$

Aquifer inflows are usually in the form of direct or indirect recharge. Direct recharge refers to water that infiltrates the ground directly as a result of a rainfall event. Indirect recharge refers to water that enters the aquifer via permeable sections of rivers and streams. In general indirect recharge only becomes important when a combination of high ground slopes and short duration, high intensity rainfall generates considerable overland flow. In the gently undulating study area, direct recharge is likely to be the primary source of aquifer replenishment.

Aquifer outflows can be either natural or artificial. Natural outflows include direct evaporation of water from the water table in wetland areas, and baseflow contributions to rivers and streams. Artificial outflows refer to flows that are caused by human intervention. The most common form of artificial outflow is water abstracted by wells, either mechanically or through artesian discharge.

It should be noted that "trans-boundary fluxes" may form a hidden component of the water budget. These fluxes refer to water that moves into or out of the hydrologic catchment by subsurface flow. They arise when the boundary of the surface water (or hydrologic) catchment is not co-incident with the boundary of the groundwater (or hydrogeologic) catchment. For the study area the presence of a trans-boundary flux is indicated by Figure 4.30 which shows declining potentiometric heads (i.e. a negative gradient showing positive flow) in the direction of the eastern border.

4.5.2 Aquifer Inflows - Direct Recharge

Direct recharge was estimated using a soil moisture balance technique first introduced by Penman (1950) and later described by Howard and Lloyd (1979). Soil moisture describes water held under the action of capillary forces acting within the soil. This water is extremely sensitive to the external influences of precipitation and evaporation (taken here to include plant transpiration), and as these factors are variable, so changes in soil moisture content occur throughout the year. During periods when precipitation exceeds evaporation, generally in the wet season, soil moisture will increase to its maximum value or "field capacity". When this condition is met, any excess of precipitation over evaporation (known as "effective precipitation") will drain freely under gravity and recharge will occur.

When evaporation exceeds precipitation the soil dries out, a soil moisture deficit (SMD) develops and, according to the classical model adopted for this investigation, all recharge will cease. Under normal atmospheric conditions plant transpiration or evaporation cannot completely dry out a soil and, in most cases, evaporation will proceed at the maximum or "potential rate" until a point is reached where the roots can no longer draw water at the maximum rate. This limit is termed the "root constant" or "drainage factor" (C). Beyond C evaporation proceeds at approximately 10% of its original rate (Lloyd et al., 1966) and the previous rapid rise in the soil moisture deficit is checked. While evaporation continues to exceed precipitation the soil moisture deficit will continue to increase at the the reduced rate until a maximum soil moisture deficit, also known as the wilting point (D) is reached.

As detailed in Appendix B, recharge estimates require periodic estimates of

Precipitation - P
Direct Surface Run-off (not including interflow) - RO
Potential Evaporation - PE

These permit calculation of effective precipitation (EP) where

$$EP = P - RO - PE \tag{4.2}$$

For the study area EP was calculated using 4 years of monthly precipitation data (P) for stations at Kazo and Ibanda (Table 4.4). Mean monthly potential evaporation data (PE) were obtained from the meteorologic station in Mbarara where Class "A" Pan evaporation data are available for the period 1961 to 1970. The average annual potential evaporation recorded at Mbarara (1450 mm) is in close accord with the range of potential evaporation expected for the study area (1400 to 1500 mm). The third hydrometeorologic data requirement in Equation 4.2 is surface run-off (RO) which was assumed to be negligible. Such an assumption is reasonable given that study area slopes are gentle and rainfall intensities are rarely likely to exceed soil infiltration capacities (approximately 10 mm / hour).

Other basic data requirements include the selection of root constants (C and D), and a starting soil moisture deficit (SMD) to initiate the computation. Table 4.5 lists C and D values for the types of vegetation and landuse typically encountered in the study area. Since the initial SMD was not known it was taken to be equal to C at the beginning of January, 1969. Given that during December, the preceding month, potential evaporation normally exceeds precipitation by over 50 mm, this is perhaps a reasonable approximation.

Table 4.4 . Sources of precipitation data for the recharge analysis

Station	Latitude	Longitude	Altitude	Precipitation (mm) Year 1969	1970	1971	1973
Kazo	0' 30"S	30' 46"E	1372 m	1043.4	878.4	913.8	759.1
Ibanda	0' 07"S	30' 30"E	1543 m	941.9	863.7	1117.3	1116.9

The soil moisture balance and recharge calculation are normally conducted on a monthly or ten-daily basis. However, Howard and Lloyd (1979) showed that this approach frequently leads to a serious underestimate of recharge, and that a daily balance should be performed, even if this requires generating daily data from monthly estimates. For the present study this was accomplished by distributing monthly precipitation totals equally amongst a specific number of days each month. The number of days varied from 1 to 17 and was determined according to meteorologic statistics for Mbarara (Table 4.6) giving the average number of days each month for which significant rainfall is recorded (i.e. is > 1mm). To generate daily evaporation data, monthly totals of potential evaporation were divided equally by the number of days in the month.

Table 4.5 Root constants for vegetation and land use in study area

Category	Land Use /Crop Type	C mm	D mm	Estimated % in Area
1	Permanent Grass	76	127	55
2	Woodland/Bushes	203	254	40
3	Short Root Crops	56	102	1-3
4	Unvegetated	44	44	1-2
5	Riparian Wetland (Outflow zone - C & D undefined)			2

Table 4.6 Mean annual meteorologic data for Mbarara

Month	Rainfall (1903-1970) mm	Pptn >1mm No. Days	Thunder No. Days	Pan Evaporation (1961-1970) mm
January	45	6	9	117
February	64	9	10	112
March	96	11	11	118
April	123	13	10	113
May	78	7	7	123
June	23	2	3	123
July	20	1	2	138
August	61	5	9	144
September	95	10	16	128
October	105	12	17	116
November	120	17	14	108
December	75	9	11	110
TOTALS:	1520	102	119	1450

The results of the recharge analysis are shown in Table 4.7. They reveal that the combination of high evaporation (approximately 1500 mm) and moderate precipitation (less than 1000 mm) produces minimal recharge in vegetated areas. Even unvegetated land receives only 50-200 mm recharge representing just 5-20% of the total precipitation. While these results may be somewhat disconcerting they should not be unexpected as they are typical of environments where precipitation both i) shows only minor to moderate seasonal variation and ii) is virtually always exceeded, even during the wetter months, by potential evaporation. Given the percentage distribution of land use and crop type categories in the study area (Table 4.5), it is estimated that mean annual recharge throughout the 2750 km^2 study area averages less than 10-20 mm.

Table 4.7 Recharge estimates (mm) for categories of land use shown in Table 4.5

	Kazo				Ibanda			
Category	1969	1970	1971	1973	1969	1970	1971	1973
1	0	12	6	0	18	0	60	137
2	0	0	0	0	0	0	0	10
3	2	35	26	0	57	19	100	157
4	139	181	166	59	88	58	129	180
5	(Zero Recharge - Outflow Zone)				(Zero Recharge - Outflow Zone)			

4.5.3 Aquifer Outflows

Natural Outflows

Recharge in the study area passes downward, through the unsaturated zone into the underlying regolith. From here, the groundwater will either continue downwards to recharge the underlying basement aquifer, or move laterally towards lowland areas where it evaporates directly to the atmosphere or discharges to tributaries of the River Nyabisheki. Groundwater reaching the basement aquifer may also discharge to the River Nyabisheki. However, as indicated above, some may also flow out of the hydrologic catchment (as defines the study area) as a trans-boundary flux.

The fate of groundwater moving within the basement aquifer can be determined through quantitative analysis of the potentiometric contours (see Figure 4.31). In the analysis it is assumed that groundwater crossing the "160" m contour between A and A' will ultimately discharge into the western tributary of the river, and that groundwater crossing the "60" m contour between X and X' will enter the major, central tributary. A third groundwater component is the trans-boundary flux which moves eastwards across the "80" m contour between Y and Y'. An estimate of these flows, based on Darcy's Law is shown in Table 4.8.

Ideally, it should be possible to confirm the estimate of discharge to the river by baseflow analysis of long-term river flow data obtained at calibrated weir installations. However, since such data are currently unavailable for the study area, coarse approximations were made based on spot estimates of dry-season tributary cross-sections and flow velocities, conducted along the

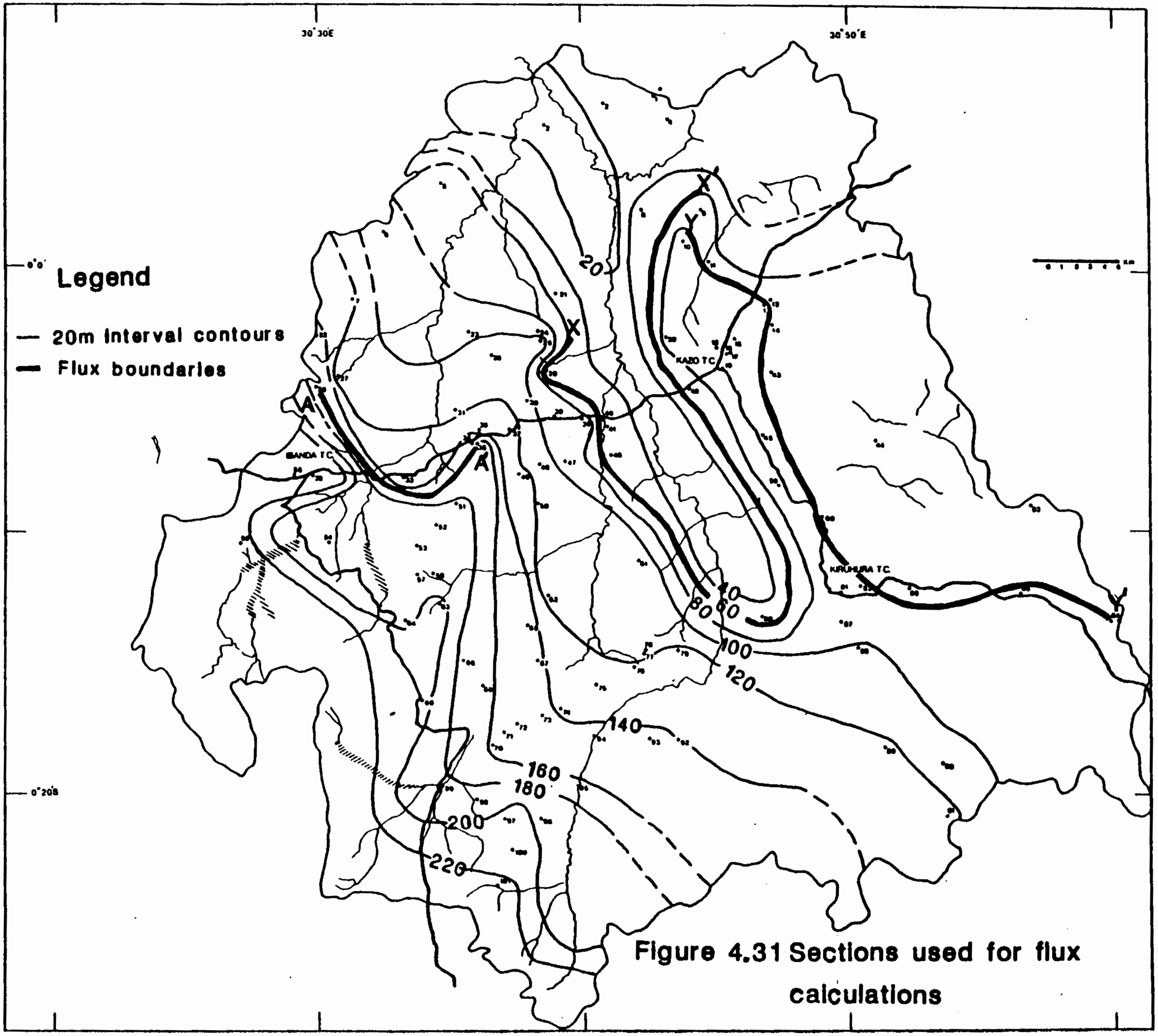


Figure 4.31 Sections used for flux calculations

Ibanda-Kazo road. The total baseflow estimate of 45 (+/- 20) x 10^5 m^3/year (equivalent to about 2mm annual recharge across the whole region), is substantially in excess of the annual discharge from the basement aquifer (3.1 x 10^5 m^3/year). Subject to confirmation of the river flow estimate, it is suggested that groundwater flow in the regolith may be the major source of baseflow to the river.

Table 4.8 Groundwater flows in the basement aquifer

	Contour	Length m	Hydraulic Gradient	T m^2/d	Flow m^3/year
To River					
	A - A'	19 000	0.02	0.8	1.1 x 10^5
	X - X'	68 000	0.01	0.8	2.0 x 10^5
				River Total: 3.1 x 10^5	
Trans-boundary Flux					
	Y - Y'	48 000	0.002	0.8	0.3 x 10^5

While river flow is the most easily recognized form of aquifer outflow, it is by no means the largest. Instead this distinction may be credited to a less obvious aquifer outflow, that of direct evaporation from wetland areas where the water table is close to or coincident with the ground surface. Wetlands normally occur in valley areas, sometimes extending several kilometers from the main stream channel. They are frequently characterized by the presence of phreatophytes, particularly the papyrus, plants which are capable of transpiring water at the full rate of potential evaporation with no restrictions. As a result, wetland areas cause a direct water loss (aquifer outflow) equal to the net difference between precipitation and evaporation, a quantity approximating 500 mm per annum. For the study area this represents a total outflow of 275 x 10^5 m^3/year (equivalent to a water depth of approximately 10 mm).

Abstraction

There are no firm data on the volume of water annually abstracted from the aquifer. However, assuming that the 150 wells in the area produce 7 l/min for 10 hours per day, it is estimated that the potential annual rate of abstraction may reach 2.3 x 10^5 m^3/year. This is equivalent to a mean annual recharge of just 0.1 mm. If all the abstracted water was to be drawn directly from aquifer storage, then assuming that the aquifer's specific yield is in the range 0.1 - 1 %, it would lead to an annual <u>average</u> water level decline of between 0.008 and 0.08 m. Rates of water level decline in the vicinity of individual production wells would be considerably higher than these values.

4.5.4 Conclusion on Water Budget

Given the scarcity of reliable, long-term meteorologic and hydrologic data for the region, the water balance can be little more than a gross approximation. Nevertheless, the results do provide a useful insight into the resource potential of the basement aquifer, and in particular draw attention to the aquifer's susceptibility to overdevelopment.

The most significant finding concerns the very low rate of groundwater flow in the basement aquifer. Total flow across sections A-A', X-X' and Y-Y' in Table 4.8 is less than 3.5 x 10^5 m^3/year (equivalent to an annual recharge of just 0.15 mm). While this value represents flow contributed by recharge throughout only 75% of the study area (i.e. south of the line A-A'-X-X'-Y-Y'), it only marginally exceeds the estimated potential abstraction of 2.3 x 10^5 m^3/year. It also represents less than 10% of the estimated annual baseflow in the Nyabisheki River.

Subject to confirmation of these data, and in particular the river flow data, it must be concluded that the basement rocks of the study area constitute a poor aquifer, and may be seriously threatened by overdevelopment. From a theoretical standpoint it is reasonable to assume that the River Nyabisheki could easily sustain a resulting 5% baseflow reduction if approximately 75% of the natural flow in the basement aquifer was fully utilized to meet the resource demand of 2.3 x 10^5 m^3/year. However, given the high hydraulic gradients and broad distribution of production wells in the region, it is unlikely that more than a few per cent of the natural through flow could be intercepted by abstraction, the result being that the majority of the abstracted water would ultimately come from either i) aquifer storage or ii) vertical leakage from the regolith.

The flow balance suggests that the regolith may provide well over 90% of baseflow to the river, and thus constitute a more important aquifer than the basement rocks. However, there are insufficient data currently available to determine whether overdevelopment of the basement aquifer could utilize the regolith's resource by inducing vertical leakage. In the worst case scenario, the regolith and basement rock aquifers form essentially hydraulically discrete systems, in which case resource development of the deeper aquifer will mine the resource. Under this condition an average annual water level decline of between 0.008 and 0.08m per year may be anticipated depending on the aquifer's specific yield. In the immediate vicinity of production wells, much higher water level declines may be anticipated.

5. CONCLUSIONS

1) Hydrogeological Character of the Bedrock Aquifer

From a resource development perspective, the unweathered bedrock aquifer has generally been regarded as the primary source of potable groundwater supply in the region. However, quantitative assessment of the hydrogeological properties of this unit, conducted during the study, suggests that the unweathered bedrock is an extremely weak aquifer with little transmissive capability and, very likely, a low specific yield. Across the study area, the hydraulic conductivity of the bedrock is generally very low (less than 10^{-7} m/s). Transmissivity values determined through a comprehensive series of packer tests and single well tests are, with very few exceptions, less than 1 m^2/d.

2) Fracture Characteristics.

Groundwater flow in the unweathered bedrock is entirely due to secondary permeability in the form of fractures. Packer test studies indicate that these fractures occur throughout the depth of the well, but are usually few in number and often exhibit a relatively low permeability. Fracture zones were detected in most boreholes; however, these zones were frequently found to yield very little groundwater. In approximately half of the boreholes tested the most permeable zone was found to occur at the top of the uncased section, just below the regolith.

Based on all the packer test data collected, there is no clear relationship between hydraulic conductivity and depth within the upper 90 meters of rock tested. There is also no relationship apparent between the distribution of boreholes with shallow, intermediate or deep, high yielding fracture zones, and physiographic features. This is not surprising given the poor degree of fracture development in the study area.

3) Hydraulic Fracturing

Packer tests performed in a hydraulically fractured borehole confirmed increases in borehole transmissivity by a factor of about 3. The tests were also able to show where improvement in hydraulic conductivity was being achieved. Several other boreholes should be tested before judging the effectiveness of hydraulic fracturing as a method of improving well yield.

4) Recharge and Regional Groundwater Flow

Groundwater chemistry and potentiometric heads confirm that while groundwater recharge to the bedrock aquifer occurs throughout the study area it is primarily focused in two areas, one an extensive zone occupying most of the western extent of the study area, the other a relatively small zone around Kazo. Groundwaters recharging in the west move eastwards towards the River Nyabisheki which intercepts most of the flow. Groundwaters recharging in the vicinity of Kazo move either westwards toward the same discharge zone or move eastwards where they leave the study area as trans-boundary flux. Soil moisture balance calculations indicate that annual recharge is in the range 10-15 mm per year, a value which agrees well with studies conducted in similar regions of Africa. The isotope data suggest that recharge to the system takes place during periods of moderate to intense rainfall when evaporative and evapotranspiration processes have least influence.

5) Water Balance

Given the paucity of reliable, long-term meteorologic and hydrologic data for the region, the water balance must be regarded as a relatively coarse approximation. Nevertheless, the results do provide a valuable insight into the resource potential of the basement aquifer.

The most significant finding concerns the very low rate of groundwater flow in the basement aquifer. In the vicinity of the River Nyabisheki, the primary discharge zone, total flow is less than 3.5×10^5 m^3/year (equivalent to an annual recharge of just 0.15 mm). Two major questions arise: a) If recharge to the area is 10-15 mm per year and only 0.15 mm is being transmitted through the bedrock aquifer, where is the rest going? b) What is the long-term, viability of the groundwater resource?

With regard to a), it is suggested that the regolith may constitute a more important aquifer in the region than the basement rocks. Considerable quantities of groundwater flow are frequently encountered in the regolith during drilling. It is also significant to note that groundwater flow in the bedrock aquifer represents less than 10% of the estimated annual baseflow contribution to the Nyabisheki River, implying that the regolith must be supplying the remaining 90%.

With regard to question b), it should be noted that the annual flow in the basement aquifer is only marginally in excess of the potential rate of groundwater abstraction in the study area which is estimated to be approximately 2.3×10^5 m^3/year. Given the high hydraulic gradients and broad distribution of production wells in the region, it unlikely that more than a few per cent of the natural through-flow in the basement aquifer can be intercepted by abstraction. As a result, it is likely that the vast majority of the currently abstracted water is being obtained from either i) aquifer storage or ii) vertical leakage from the regolith. There are currently insufficient data available to determine whether overdevelopment of the basement aquifer is able to utilize groundwater in the regolith by inducing vertical leakage. In the worst case scenario, the regolith and basement rock aquifers form essentially hydraulically discrete systems, in which case resource development of the deeper aquifer will mine the resource. Under this condition an average annual water level decline of between 0.008 and 0.08m per year may be anticipated depending on the aquifer's specific yield. In the immediate vicinity of production wells much higher water level declines may be anticipated.

It must be concluded that the basement rocks of the study area form a weak aquifer which is highly susceptible to overproduction and water level decline. Future problems may include lowering of water levels in abstraction wells and drying up of natural springs. The risk of such problems imposes serious constraints on the aquifer's future use and development.

6 PROJECT REVIEW/EVALUATION

While the conclusions of the study (Chapter 6) demonstrate its immense value, it is pertinent to review the project and the progress achieved in the context of the initial project objectives.

Funded primarily by the International Development Research Centre (IDRC), Canada, the project commenced in August 1987 as a co-operative venture between the Groundwater Research Group of the University of Toronto, Canada and a research team from the Water Development Department (WDD), Entebbe. A third important component of the study was the involvement and cooperation of the UNICEF/WDD drilling project, particularly in terms of making boreholes available for testing and sampling and for providing local logistical support.

The initial proposal, as accepted by IDRC, called for the study to commence in 1986 in northern Uganda. Unfortunately, on-going civil unrest not only forced delays in the start of the project but also necessitated relocation of the study area to the south-west of the country. UNICEF drilling rigs moved into the study area in April, 1987 and the IDRC field program began in August of that year.

Despite the relocation of the study area, the focus of the investigation remained essentially the same. As described in Section 1.2 the objectives of the 2-year project were 1) to define the regional extent of the aquifer systems in the basement rocks and overlying deposits in an area of southwest Uganda; 2) to understand site-specific local groundwater flow systems as these apply to borehole yields; 3) refine existing hydrogeological criteria for the siting of boreholes and improvement of yields; and 4) to train Ugandan hydrogeologists in the application of relevant hydrogeological techniques and methodologies, thereby strengthening the hydrogeological research capabilities of the Ministry of Water and Mineral Development's Water Development Department (WDD). It was intended that the generated knowledge would aid in the preparation of future drilling programs, reduce the number of dry boreholes and, possibly, increase the number of high-yielding holes suitable for community systems.

During early stages of the project, considerable difficulties were encountered. For example 1) borehole records for existing wells in the study area could not be accessed since they were located in a region of civil unrest; 2) water samples could not be readily obtained due to the poor condition of many of the wells; 3) travel within the study area was difficult due to delays in obtaining a "dedicated" project vehicle; 4) the WDD chemical laboratory proved incapable of providing reliable major ion analyses; and 5) the packer testing program was regularly interrupted due to the difficulty of obtaining supplies of compressed air in Kampala. However, all of these problems paled in comparison to the tragic death of Mr. Stephen Ssentamu, the Ugandan principal Investigator and Project Manager who was killed on December 17th, 1987. Stephen Ssentamu was a critical element in the research operation. Not only was he the primary Ugandan representative on the project. He also provided the project's essential liaison with UNICEF. His responsibilities included the day to day running of the project in Uganda; he was responsible for hiring of local staff and the procurement of supplies and equipment.

In many ways, the tragedy surrounding Stephen Ssentamu's death generated a new sense of purpose in the project staff. John Karundu replaced Stephen Ssentamu as the Ugandan Project Manager and a new, more dedicated Ugandan research team gradually emerged. In turn, the Canadian research team, seeing a need to conduct re-training and maintain closer liaison with the Ugandans, committed more time to the field. It is as a result of Stephen Ssentamu's death and the consequent period of reorganization that much of the work reported in this document did not commence until the summer of 1988.

It is to the considerable credit of both the Ugandan and Canadian research teams that the project reached a highly successful conclusion during the summer of 1989. Through hard work and a renewed sense of commitment the study teams completed a comprehensive, multi-element research program involving constant yield discharge tests, packer tests, recharge analysis and major ion, minor ion and isotope hydrochemistry. In all, a total of 233 packer tests were conducted in 21 boreholes, and over 50 wells were sampled and comprehensively chemically analyzed.

By its completion, the project had proved to be extremely successful, meeting <u>all</u> the planned objectives and developing a series of important if not always encouraging conclusions (Chapter 5). Among the more important achievements of the study are the following:

1) Aquifer Definition (Objective 1)

The unweathered basement rock aquifer (generally regarded as the the primary source of potable water in the region) is found to be regionally extensive but exhibits an extremely low transmissive capability. Water balance studies suggest that this weak aquifer transmits less than 2% of groundwater recharge in the catchment and contributes less than 10% of the annual baseflow (groundwater discharge) in the Nyabisheki River. These data suggest it is the overlying regolith, rather than the bedrock, which forms the major aquifer in the region.

2) Site-specific groundwater flow conditions and the relationship to borehole yields (Objective 2)

The packer testing study and its associated constant yield tests may represent one of the most comprehensive investigations of low-yielding "hard-rock" aquifers ever conducted. The study demonstrates that no clear relationship exists between hydraulic conductivity and depth within the upper 90 meters of rock tested. Also, no relationship is evident between the distribution of boreholes with shallow, intermediate or deep, high yielding fracture zones, and physiographic features. Fracture zones were detected in most boreholes; however, these zones were frequently found to yield very little groundwater. Most of the higher yielding fracture zones occur near the top of the bedrock where, significantly, the overlying regolith appears to be playing a role.

While most of these findings are somewhat "negative", they are important as they contradict the traditionally held notion that the siting of boreholes in fractured hard rock aquifers can be universally approached by mapping physiographic features (fault induced valleys and gulleys, for example) and utilizing geophysics. The study shows quite clearly that i) some hard-rock formations may exhibit poor and randomly developed fracture systems, and ii) the nature of the regolith may be a more important factor than fracture development in determining long-term borehole yields.

3) Refinement of hydrogeologic criteria for siting of boreholes and improvement of yields (Objective 3)

The water balance demonstrates that there is adequate groundwater flow in the region to meet most needs (equivalent to 10-15mm depth over the catchment) but that very little of this water is being stored and transported in the basement rock aquifer. It becomes apparent that the hydrogeologic criteria for siting of boreholes require considerably more than simple refinement. Instead there is a need for a totally new approach to borehole siting that recognizes the presence of aquifers in both the basement rocks and the overlying regolith, and that it is the nature of the hydraulic interaction between these "aquifer systems" which determines well yield. This new approach to the development of hard-rock aquifers represents an important step forward which has significant implications in many other similar hydrogeological regions both in Uganda and elsewhere.

4) Training (Objective 4)

During the study numerous Ugandan personnel gained considerable expertise in both practical and theoretical aspects of hydrogeology. In particular, two Ugandan hydrogeologists - John Karundu and Gideon Ngobi gained particularly useful experience. They participated in all aspects of the study, learnt field procedures for water sampling, packer testing, well testing etc., performed data analysis and wrote reports. They also came to Canada in April, 1989 to work with the Canadian team on the final report, finalizing data interpretation, preparing figures and contributing significantly to the writing of the report and its conclusions. Particularly encouraging was the high degree of self-confidence that the Ugandan team began to develop during the latter stages of the project. This confidence was particularly evident during the project conference, held at the Sheraton Hotel, Kampala on August 21st and 22nd, 1989, when the project findings were presented for discussion to an eager and receptive audience of over 30 invited delegates.

In conclusion, the collaborative study has proved to be highly successful, achieving all of its goals and generating a series of findings which are destined to have a major impact on groundwater management practice both in the study area and in the country as a whole. It raises grave concerns regarding the long-term viability of the fractured basement rock aquifer (previously regarded as the primary groundwater resource), and demonstrates how groundwater resource assessment must recognize the interdependence of ground and surface water and be approached through careful evaluation of all water balance components. It shows that there is a serious need for the development of a national water policy that would ensure the future availability of reliable water sources, by providing for effective, integrated development of ground and surface water. These and other specific recommendations for future undertakings are listed in Chapter 6.

7 RECOMMENDATIONS

1) The water balance requires considerable refinement. Good quality flow data must be acquired for the River Nyabisheki, and hydrograph separations performed; long-term daily precipitation data must be obtained for all study area gauging stations to allow soil moisture balance recharge calculations to be confirmed.

2) Estimates of long-term groundwater decline through over-development require reliable estimates of specific yield. This information can only be obtained through carefully designed, long-term (several day) pumping tests, using at least one observation well.

3) It is essential that several observation wells be established in the bedrock at strategic locations. These wells will provide long-term water level data necessary i) for confirming recharge estimates and ii) for monitoring changes in storage.

4) Given that the aquifer in the regolith may provide the key to future resource development in the catchment, not only is it important to establish the hydrogeologic characteristics of this potentially valuable unit, it is also important to develop an understanding of its relationship with the bedrock. For example, if development of the bedrock aquifer simply induces vertical recharge from the regolith, then overdevelopment of the bedrock aquifer may not be a problem. It is possible that good information on the hydraulic interconnectivity between regolith and bedrock can be obtained by installation of monitoring wells (stand-pipes) in the regolith during construction of bedrock wells.

5) Hydrochemistry offers a powerful means of investigating rates, directions and sources of groundwater flow. It is also important for establishing water quality. Data obtained during the study suggest that the existing WDD laboratory facilities are barely adequate. It is essential that these facilities be upgraded to provide reliable analyses for basic major ion and trace metal constituents.

6) To ensure the future availability of reliable water resources it is essential that a national water management policy be established which would recognize the interactive nature of groundwater and surface water (involving recharge, run-off, baseflow, spring discharge, wetland evapotranspiration and sub-surface flow and storage both within simple, discrete aquifers and within more complex aquifer systems) and provide a program for long-term, effective and responsible development of these valuable and essential resources on an integrated basis.

8 REFERENCES

Chebotarev, I.I., 1955. Metamorphism of natural waters in the crust of weathering. *Geochim. Cosmochim. Acta*, 8.

Combe, A.D., 1932. The Geology of Southwest Ankole. Memor. 2.

Cooper, H.H,Jr., J.D. Bredehoeft, and I.S. Papadopulos, 1967. Response of a finite-diameter well to an instantaneous charge of water. Water Resources Res., 3, 263-269.

Dansgaard, W, 1964. Stable isotopes in precipitation. Tellus, 16, No. 4, 436-468.

Doornkamp, J.C., 1970. The geomorphology of the Mbarara area. Geological Survey and Mines, Geomorphological Report No. 1.

Faure, G, 1986. Principles of Isotope Geology. John Wiley and Sons.

Freeze, R.A. and J.A. Cherry, 1979. Groundwater. Prentice-Hall.

Howard, K.W.F. and P. Beck, 1986. Hydrochemical interpretation of groundwater flow system in Quaternary sediments of southern Ontario. Can. J. Earth Sci.,23, 938-947.

Howard, K.W.F. and J.W. Lloyd, 1983. Major Ion characterisation of coastal saline ground waters. Ground Water, 21, 429-437.

Lloyd J.W. and Heathcote, J.A., 1985. Natural inorganic hydrochemistry in relation to groundwater. Oxford University Press.

Papadopulos, I.S., J.B. Bredehoeft, and H.H. Cooper, Jr., 1973. On the analysis of "slug test" data. Water Resources Research, vol. 9, No.4.

APPENDICES

APPENDIX A Data

Tables:

Figures:

A1 Major ion chemistry

Table A1.1 Major ion chemistry

Sample	Location Number	pH	Ec	TDS	CO3	HCO3	Cl	SO4	Ca	Mg	Na	K
D. METHOD		* DREL5	DREL5		DREL5	DREL5	DREL5	I.C.P	I.C.P.	I.C.P.	DREL5	DREL5
D.LIMIT mg/L							2.00					
BACKGRND												
ACC.LMT mg/L		6.5-8.5					250.00	500.00				
			us/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
CD 91	82	7.4	1033.00	559.54	0.00	269.90	64.80		74.0	40.8	105.00	5.00
CD 371	69	6.3	763.00	437.40	0.00	131.60	60.20	90.79	50.1	24.7	75.00	5.00
CD 403	95	6.9	492.00	420.97	0.00	289.90		34.46	46.0	16.6	25.00	9.00
CD 409	74	6.7	860.00	597.28	0.00	277.80	36.90	136.03	61.0	28.5	50.00	7.00
CD 479	60	9.0	1123.00	471.96	117.40	8.50	76.70	66.22	87.8	3.37	110.00	2.00
CD 499	42	7.5	1122.00	652.52	0.00	248.80	128.00	172.28	69.1	26.3	4.00	4.00
CD 530	40	8.4	525.00	477.76	17.20	260.40	30.96	60.52	25.9	19.8	60.00	3.00
CD 3009	24	7.1	627.00	494.11	0.00	319.50	8.45	38.05	25.0	39.1	60.00	4.00
CD 3017	11	7.5	888.00	611.05	0.00	429.60	17.60	47.04	68.7	22.1	22.00	4.00
DS 719	71	6.9	803.00	629.40	0.00	230.40	50.80	212.73	38.3	44.2	45.00	8.00
DS 727	7	8.4	342.00	377.49	38.30	253.10	2.21	25.23	17.4	18.3	21.00	2.00
DS 728	6	8.0	873.00	686.02	0.00	309.90	113.60	123.45	21.7	16.3	100.00	1.00
DS 731	28	6.9	271.00	348.77	0.00	154.40	23.20	120.75	10.5	7.94	30.00	2.00
DS 732	2	7.8	283.00	335.60	0.00	240.00	22.12	6.20	13.0	12.3	40.00	2.00
GS 884	94	6.8	417.00	361.90	0.00	230.60	8.70	18.07	45.9	10.6	40.00	8.00
GS 1613	81	6.8	462.00	330.74	0.00	150.20	43.00	46.44	20.9	20.2	45.00	5.00
WDD 1534	8	6.7	416.00	292.57	0.00	220.20	6.64	5.80	23.2	11.8	23.00	2.00
WDD 1536	9	7.0	690.00	524.73	0.00	383.80	23.60	14.75	43.0	26.5	28.00	5.00
WDD 1537	20	7.2	565.00	332.43	0.00	237.60		20.78	32.5	8.51	30.00	3.00
WDD 1538	46	7.2	1095.00	602.65	0.00	407.90	27.30	55.71	63.6	29.1	14.00	5.00
WDD 1548	39	7.9	365.00	222.04	0.00	92.00	18.43	48.66	23.1	11.9	24.00	4.00
WDD 1549	34	7.5	473.00	234.95	0.00	81.80	39.00	26.81	25.3	18.1	40.00	4.00
WDD 1550	30	8.8	526.00	390.94	93.80	124.30	10.32	63.63	49.3	21.6	23.00	5.00
WDD 1712	15	6.8	558.00	282.54	0.00	181.60	13.50	21.87	37.9	7.64	18.00	2.00
WDD 1713	17	7.2	795.00	545.96	0.00	357.00	13.20	54.12	75.5	20.2	22.00	4.00
WDD 1714	14	6.5	421.00	307.47	0.00	185.80	22.90	18.14	19.5	27.1	25.00	9.00
WDD 1715	12	7.2	603.00	530.06	0.00	336.00	30.00	30.61	42.3	26.2	60.00	5.00
WDD 1720	1	8.3	943.00	1089.97	0.00	635.10	13.50	298.39	62.9	33.1	7.00	40.00
WDD 2025	73	7.3	1274.00	958.81	0.00	405.40	111.00	182.94	54.2	85.3	100.00	20.00
WDD 2027	4	7.6	452.00	321.80	0.00	212.40	16.00	24.15	22.5	15.8	27.00	4.00
WDD 2036	51	6.1	603.00	377.12	0.00	139.60	49.19	83.04	24.5	16.7	60.00	4.00
WDD 2043	43	8.5	786.00	493.48	86.20	189.30	36.10	29.88	60.6	28.4	60.00	3.00
WDD 2046	22	8.1	240.00	459.00	0.00	385.20	8.85	24.50	10.6	9.82	18.00	2.00
WDD 2049	23	7.6	177.00	250.03	0.00	209.40	10.32	4.63	5.42	7.26	12.00	1.00
WDD 2050	26	6.2	195.00	167.04	0.00	120.00	8.45	5.53	6.39	9.67	15.00	2.00
WDD 2051	31	6.1	327.00	208.84	0.00	80.60	39.80	37.97	16.9	9.55	20.00	4.00
WDD 2052	29	8.9	948.00	604.63	248.40	59.10	4.05	120.91	93.7	31.4	40.00	7.00
WDD 2083	86	7.9	354.00	350.67	0.00	163.30	16.00	83.77	11.1	14.5	60.00	2.00
WDD 2084	84	6.7	360.00	313.10	0.00	210.90	8.90	27.47	27.6	8.19	25.00	5.00
WDD 2087	88	7.3	904.00	646.67	0.00	303.10	95.00	76.08	45.9	41.6	80.00	5.00
WDD 2187	27	8.3	249.00	556.77	0.00	429.60	5.90	85.22	7.33	12.7	14.00	2.00
WDD 2209	45	7.8	617.00	468.85	0.00	267.10	29.50	68.73	32.5	28.0	40.00	3.00
WDD 2211	90	6.7	515.00	361.02	0.00	244.30	27.50	40.22			45.00	4.00
WDD 2214	62	6.9	783.00	386.75	0.00	150.10	28.00	81.02	54.6	38.0	30.00	5.00
WDD 2215	67	7.4	932.00	747.72	0.00	503.10	13.50	33.19	81.1	48.8	60.00	8.00

WDD 2216	68	6.8	654.00	535.98	0.00	225.40	52.00	120.35	37.7	33.5	60.00	7.00
WDD 2218	72	6.2	1136.00	548.69	0.00	72.40	24.00	215.39	53.9	33.0	135.00	15.00
WDD 2527	16	7.2	576.00	354.43	0.00	216.20	16.50	0.00	77.2	17.5	24.00	3.00
SPRING 2		5.5	88.00	37.66	0.00	15.80	8.86	0.00			7.00	6.00
SPRING 4		5.9	106.00	71.15	0.00	30.00	4.00	11.45	4.73	1.98	14.00	5.00
SPRING 5		6.7	62.00	69.86	0.00	30.50	12.97	11.39	4.02	1.99	4.00	5.00
SPRING 6		5.9	89.00	81.44	0.00	42.20	4.20	12.25	5.98	2.80	7.00	7.00
SPRING 7		6.0	122.00	81.30	0.00	31.40	8.70	12.82	12.8	3.61	10.00	2.00
SPRING 8		6.3	1001.00	305.03	0.00	89.90	18.20	86.29	30.5	15.1	60.00	5.00

* Refers to a Hach Direct Read Environmental Laboratory kit

Table A1.2 Duplicate chemical analyses for selected boreholes

Sample	pH	Ec	TDS	CO3	HCO3	Cl	SO4	Ca	Mg	Na	K	Total Cations	Total Anions	% Error
D. METHOD	* DREL	DREL		DREL	DREL	DREL	I.C.P	I.C.P.	I.C.P.	DREL	DREL			
D.LIMIT mg/L						2.00								
BACKGRND														
ACC.LMT mg/L	6.5-8.5					250.00	500.00							
		us/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	(epm)	(epm)	
CD 499	7.5	1122.00	652.52	0.00	248.80	128.00	172.28	69.1	26.3	4.00	4.00	5.89	7.69	-13.23
CD 499	7.9	1042.00	725.48	0.00	258.00	55.50	163.30	75.4	29.3	140.00	4.00	12.36	5.79	36.16
CD 530	8.4	525.00	477.76	17.20	260.40	30.96	60.52	25.9	19.8	60.00	3.00	5.61	6.00	-3.40
CD 530	7.9	533.00	404.99	0.00	197.70	22.90	54.53	28.5	21.4	75.00	5.00	6.57	3.89	25.67
DS 750	8.0	456.00	325.81	0.00	130.80	60.00	35.36	20.7	16.0	60.00	3.00	5.03	3.84	13.50
DS 750	6.9	466.00	505.68	0.00	346.20	56.00	36.85	20.1	14.5	25.00	7.00	3.46	7.25	-35.37
WDD 1534	6.7	416.00	292.57	0.00	220.20	6.64	5.80	23.2	11.8	23.00	2.00	3.18	3.80	-8.92
WDD 1534	8.1	316.00	320.13	0.00	245.10	4.32	5.86	24.0	11.8	25.00	4.00	3.36	4.14	-10.3[illegible]
WDD 1534	6.2	308.00	257.56	0.00	177.90	8.86	6.45	26.6	12.8	23.00	2.00	3.43	3.17	4.00
WDD 1712	6.8	558.00	282.54	0.00	181.60	13.50	21.87	37.9	7.64	18.00	2.00	3.36	3.36	-0.03
WDD 1712	7.2	382.00	245.36	0.00	143.50	13.50	33.18	21.0	5.14	25.00	4.00	2.66	2.73	-1.30
WDD 1715	7.2	603.00	530.06	0.00	336.00	30.00	30.61	42.3	26.2	60.00	5.00	7.00	6.35	[illegible]
WDD 1715	7.0	278.00	453.36	0.00	304.70	18.30	0.00	39.2	26.2	63.00	2.00	6.90	5.51	[illegible]
WDD 2049	7.6	177.00	250.03	0.00	209.40	10.32	4.63	5.42	7.26	12.00	1.00	1.42	3.72	-44.92
WDD 2049	6.6	305.00	204.35	0.00	151.34	18.20	4.91	5.73	7.17	14.00	3.00	1.56	2.99	-31.44
WDD 2049	6.4	199.00	171.79	0.00	107.40	14.80	0.00	18.6	16.0	12.00	3.00	2.84	2.18	13.22

Table A1.3 Major ion chemistry for spring discharges

Sample	Location Number	pH	Ec	TDS	CO3	HCO3	Cl	SO4	Ca	Mg	Na	K
D. METHOD		* DREL5	DREL5		DREL5	DREL5	DREL5	I.C.P	I.C.P.	I.C.P.	DREL5	DREL5
D.LIMIT mg/L							2.00					
BACKGRND												
ACC.LMT mg/L		6.5-8.5					250.00	500.00				
			us/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
SPRING 2		5.5	88.00	37.66	0.00	15.80	8.86	0.00			7.00	6.00
SPRING 4		5.9	106.00	71.15	0.00	30.00	4.00	11.45	4.73	1.98	14.00	5.00
SPRING 5		6.7	62.00	69.86	0.00	30.50	12.97	11.39	4.02	1.99	4.00	5.00
SPRING 6		5.9	89.00	81.44	0.00	42.20	4.20	12.25	5.98	2.80	7.00	7.00
SPRING 7		6.0	122.00	81.30	0.00	31.40	8.70	12.82	12.8	3.61	10.00	2.00
SPRING 8		6.3	1001.00	305.03	0.00	89.90	18.20	86.29	30.5	15.1	60.00	5.00

* Refers to a Hach Direct Read Environmental Laboratory kit

A1.4 Major ion chemistry for ten selected geographical areas

Sample	Map Location Number	pH	Ec	TDS	CO3	HCO3	Cl	SO4	Ca	Mg	Na	K
			us/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Group 1												
CD 3009	24	7.1	627.00	494.11	0.00	319.50	8.45	38.05	25.0	39.1	60.00	4.00
WDD 1550	30	8.8	526.00	390.94	93.80	124.30	10.32	63.63	49.3	21.6	23.00	5.00
WDD 2049	23	7.6	177.00	250.03	0.00	209.40	10.32	4.63	5.42	7.26	12.00	1.00
WDD 2050	26	6.2	195.00	167.04	0.00	120.00	8.45	5.53	6.39	9.67	15.00	2.00
WDD 2051	31	6.1	327.00	208.84	0.00	80.60	39.80	37.97	16.9	9.55	20.00	4.00
Group 2												
WDD 1712	15	6.8	558.00	282.54	0.00	181.60	13.50	21.87	37.9	7.64	18.00	2.00
WDD 1713	17	7.2	795.00	545.96	0.00	357.00	13.20	54.12	75.5	20.2	22.00	4.00
WDD 1714	14	6.5	421.00	307.47	0.00	185.80	22.90	18.14	19.5	27.1	25.00	9.00
WDD 1715	12	7.2	603.00	530.06	0.00	336.00	30.00	30.61	42.3	26.2	60.00	5.00
WDD 2043	43	8.5	786.00	493.48	86.20	189.30	36.10	29.88	60.6	28.4	60.00	3.00
WDD 2527	16	7.2	576.00	354.43	0.00	216.20	16.50	0.00	77.2	17.5	24.00	3.00
Group 3												
CD 3017	11	7.5	888.00	611.05	0.00	429.60	17.60	47.04	68.7	22.1	22.00	4.00
WDD 1534	8	6.7	416.00	292.57	0.00	220.20	6.64	5.80	23.2	11.8	23.00	2.00
WDD 1536	9	7.0	690.00	524.73	0.00	383.80	23.60	14.75	43.0	26.5	28.00	5.00
Group 4												
CD 530	40	8.4	525.00	477.76	17.20	260.40	30.96	60.52	25.9	19.8	60.00	3.00
WDD 1538	46	7.2	1095.00	602.65	0.00	407.90	27.30	55.71	63.6	29.1	14.00	5.00
WDD 1548	39	7.9	365.00	222.04	0.00	92.00	18.43	48.66	23.1	11.9	24.00	4.00
Group 5												
WDD 1549	34	7.5	473.00	234.95	0.00	81.80	39.00	26.81	25.3	18.1	40.00	4.00
WDD 2036	51	6.1	603.00	377.12	0.00	139.60	49.19	83.04	24.5	16.7	60.00	4.00
Group 6												
CD 409	74	6.7	860.00	597.28	0.00	277.80	36.90	136.03	61.0	28.5	50.00	7.00
DS 719	71	6.9	803.00	629.40	0.00	230.40	50.80	212.73	38.3	44.2	45.00	8.00
WDD 2025	73	7.3	1274.00	958.81	0.00	405.40	111.00	182.94	54.2	85.3	100.00	20.00
WDD 2215	67	7.4	932.00	747.72	0.00	503.10	13.50	33.19	81.1	48.8	60.00	8.00
WDD 2216	68	6.8	654.00	535.98	0.00	225.40	52.00	120.35	37.7	33.5	60.00	7.00
WDD 2218	72	6.2	1136.00	548.69	0.00	72.40	24.00	215.39	53.9	33.0	135.00	15.00
Group 7												
CD 403	95	6.9	492.00	420.97	0.00	289.90		34.46	46.0	16.6	25.00	9.00
GS 884	94	6.8	417.00	361.90	0.00	230.60	8.70	18.07	45.9	10.6	40.00	8.00
Group 8												
CD 91	82	7.4	1033.00	559.54	0.00	269.90	64.80		74.0	40.8	105.00	5.00
GS 1613	81	6.8	462.00	330.74	0.00	150.20	43.00	46.44	20.9	20.2	45.00	5.00
WDD 2083	86	7.9	354.00	350.67	0.00	163.30	16.00	83.77	11.1	14.5	60.00	2.00
WDD 2087	88	7.3	904.00	646.67	0.00	303.10	95.00	76.08	45.9	41.6	80.00	5.00
Group 9												
DS 727	7	8.4	342.00	377.49	38.30	253.10	2.21	25.23	17.4	18.3	21.00	2.00
DS 731	28	6.9	271.00	348.77	0.00	154.40	23.20	120.75	10.5	7.94	30.00	2.00

WDD 2046	22	8.1	240.00	459.00	0.00	385.20	8.85	24.50	10.6	9.82	18.00	2.00
WDD 2187	27	8.3	249.00	556.77	0.00	429.60	5.90	85.22	7.33	12.7	14.00	2.00
Group 10												
SPRING 2		5.5	88.00	37.66	0.00	15.80	8.86	0.00			7.00	6.00
SPRING 4		5.9	106.00	71.15	0.00	30.00	4.00	11.45	4.73	1.98	14.00	5.00
SPRING 5		6.7	62.00	69.86	0.00	30.50	12.97	11.39	4.02	1.99	4.00	5.00
SPRING 6		5.9	89.00	81.44	0.00	42.20	4.20	12.25	5.98	2.80	7.00	7.00
SPRING 7		6.0	122.00	81.30	0.00	31.40	8.70	12.82	12.8	3.61	10.00	2.00
SPRING 8		6.3	1001.00	305.03	0.00	89.90	18.20	86.29	30.5	15.1	60.00	5.00

A2 Trace element analysis

A2.1 Trace element analyses

Sample	Mn	P	Mo	Ca	Al	Zn	Ni	Fe	Mg	Pb	Cu
D. METHOD	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.
D.LIMIT mg/L	0.003	0.178	0.034	0.007	0.082	0.020	0.068	0.006	0.068	0.230	0.011
BACKGRND ACC.LMT mg/L	0.050				5.000	5.000		0.300		0.050	1.000
CD 85	0.195	<0.178	<0.034	18.637	<0.082	5.071	<0.068	4.044	4.571	<0.230	<0.011
CD 85	0.194	<0.178	<0.034	18.119	<0.082	4.951	<0.068	3.979	4.358	<0.230	<0.011
CD 85	0.341	<0.178	<0.034	25.355	<0.082	0.215	<0.068	5.824	5.559	<0.230	<0.011
CD 91	0.428	<0.178	<0.034	74.044	<0.082	8.950	<0.068	0.356	40.799	<0.230	0.011
CD 91	0.408	<0.178	<0.034	69.029	<0.082	14.559	<0.068	2.014	39.036	<0.230	0.017
CD 360	0.274	<0.178	<0.034	56.371	0.127	2.030	<0.068	2.719	20.443	<0.230	<0.011
CD 368	1.985	0.460	<0.034	33.033	<0.082	0.038	<0.068	2.618	23.960	<0.230	<0.011
CD 371	0.641	<0.178	<0.034	50.070	<0.082	3.881	<0.068	1.081	24.742	<0.230	<0.011
CD 401	1.017	0.429	<0.034	7.500	7.054	2.386	0.119	44.447	3.135	<0.230	0.055
CD 401	0.970	0.420	<0.034	7.263	8.288	2.384	<0.068	44.966	3.042	<0.230	<0.011
CD 403	0.772	<0.178	<0.034	45.967	<0.082	20.884	<0.068	9.521	16.647	<0.230	<0.011
CD 409	1.560	0.365	<0.034	68.575	0.693	10.643	0.124	36.057	30.777	<0.230	0.131
CD 409	1.310	<0.178	<0.034	61.024	<0.082	3.910	<0.068	9.677	28.521	<0.230	<0.011
CD 415	0.911	0.183	<0.034	74.698	0.228	22.708	<0.068	6.837	17.944	<0.230	<0.011
CD 479	0.275	<0.178	<0.034	87.765	<0.082	0.989	<0.068	0.163	3.374	<0.230	<0.011
CD 479	0.268	<0.178	<0.034	80.709	<0.082	3.817	<0.068	0.175	2.903	<0.230	0.016
CD 487	0.167	<0.178	<0.034	49.881	<0.082	8.659	<0.068	3.110	15.965	<0.230	<0.011
CD 499	0.248	<0.178	<0.034	69.094	<0.082	1.543	<0.068	0.434	26.342	<0.230	0.036
CD 499	0.259	<0.178	<0.034	75.423	<0.082	1.581	<0.068	0.272	29.262	<0.230	<0.011
CD 510	0.579	<0.178	<0.034	75.014	<0.082	1.459	<0.068	0.101	33.822	<0.230	<0.011
CD 510	0.566	<0.178	<0.034	68.212	<0.082	3.081	<0.068	0.039	31.496	<0.230	<0.011
CD 530	0.119	<0.178	<0.034	25.892	<0.082	5.290	<0.068	2.573	19.785	<0.230	<0.011
CD 530	0.144	<0.178	<0.034	28.472	<0.082	2.208	<0.068	3.191	21.388	<0.230	<0.011
CD 530	0.144	<0.178	<0.034	17.697	<0.082	2.333	<0.068	3.057	12.350	<0.230	<0.011
CD 3009	0.480	<0.178	<0.034	24.049	<0.082	2.898	<0.068	7.635	35.470	<0.230	<0.011
CD 3009	0.490	<0.178	<0.034	24.970	<0.082	2.243	<0.068	8.493	39.141	<0.230	<0.011
CD 3017	0.198	<0.178	<0.034	68.737	<0.082	12.672	<0.068	2.026	22.069	<0.230	<0.011
CD 3148	0.090	<0.178	<0.034	29.250	<0.082	2.980	<0.068	11.620	8.658	<0.230	<0.011
CD 3148	0.090	<0.178	<0.034	29.010	0.154	3.154	<0.068	11.541	8.678	<0.230	0.014
CD 3418	0.071	<0.178	<0.034	31.015	<0.082	0.278	<0.068	1.657	9.554	<0.230	<0.011
CD 3432	0.172	<0.178	<0.034	24.347	<0.082	7.096	<0.068	1.090	27.600	<0.230	<0.011
CD 3497	0.514	0.401	<0.034	13.531	<0.082	11.476	<0.068	13.514	34.492	<0.230	<0.011
CD 3497	0.439	0.332	<0.034	13.189	<0.082	0.838	<0.068	0.271	14.934	<0.230	0.017
DS 715	0.864	0.323	<0.034	170.790	<0.082	6.772	<0.068	15.887	59.838	<0.230	0.022
DS 719	0.324	<0.178	<0.034	38.274	0.942	21.863	<0.068	25.463	44.195	<0.230	0.019
DS 727	0.486	<0.178	<0.034	17.366	<0.082	4.275	<0.068	5.766	18.290	<0.230	<0.011
DS 728	0.587	0.248	<0.034	21.749	0.555	1.888	0.091	16.996	16.325	<0.230	0.013
DS 731	0.227	<0.178	<0.034	10.480	<0.082	0.438	<0.068	2.285	7.941	<0.230	<0.011
DS 731	0.228	<0.178	<0.034	10.179	<0.082	0.292	<0.068	1.930	7.615	<0.230	<0.011
DS 732	0.354	<0.178	<0.034	13.013	<0.082	9.936	<0.068	16.399	12.261	<0.230	<0.011
DS 735	0.699	<0.178	<0.034	36.743	<0.082	9.179	<0.068	2.581	33.485	<0.230	<0.011
DS 744	0.040	<0.178	<0.034	58.435	0.112	1.718	<0.068	2.892	56.798	<0.230	<0.011
DS 750	0.063	<0.178	<0.034	20.665	0.095	0.906	<0.068	3.758	15.987	<0.230	<0.011
DS 750	0.038	<0.178	<0.034	20.132	<0.082	2.919	<0.068	2.112	14.490	<0.230	<0.011
DS 750	0.046	<0.178	<0.034	21.161	<0.082	0.649	<0.068	0.941	16.130	<0.230	<0.011
GS 721	0.979	0.541	<0.034	46.561	<0.082	11.245	<0.068	31.880	33.733	<0.230	<0.011

	Mn	P	Mo	Ca	Al	Zn	Ni	Fe	Mg	Pb	Cu
GS 731	0.237	0.225	<0.034	58.464	<0.082	44.708	<0.068	15.839	43.893	<0.230	0.052
GS 830	0.044	<0.178	<0.034	14.024	<0.082	2.157	<0.068	1.331	9.046	<0.230	<0.011
GS 884	0.603	<0.178	<0.034	45.904	0.114	3.861	<0.068	3.834	10.633	<0.230	<0.011
GS 1613	0.245	0.211	<0.034	20.923	<0.082	12.490	<0.068	8.644	20.176	<0.230	<0.011
GS 1613	0.149	0.307	<0.034	20.898	<0.082	21.521	<0.068	6.979	19.106	<0.230	<0.011
GS 1613	0.046	0.605	<0.034	19.260	<0.082	2.910	0.012	3.368	18.210	<0.230	<0.011
GS 1615	0.815	<0.178	<0.034	73.558	0.353	9.751	<0.068	3.388	47.605	<0.230	0.018
WDD 1514	0.012	<0.178	<0.034	22.907	0.178	16.658	<0.068	0.329	25.980	<0.230	0.030
WDD 1534	<0.003	<0.178	<0.034	23.173	<0.082	5.241	<0.068	0.054	11.752	<0.230	<0.011
WDD 1534	0.006	<0.178	<0.034	24.017	<0.082	3.316	<0.068	0.058	11.832	<0.230	<0.011
WDD 1534	<0.003	<0.178	<0.034	26.562	<0.082	3.177	<0.068	0.059	12.792	<0.230	<0.011
WDD 1536	0.041	<0.178	<0.034	43.033	<0.082	7.747	<0.068	0.281	26.543	<0.230	<0.011
WDD 1537	0.022	<0.178	<0.034	32.531	<0.082	29.754	<0.068	0.299	8.514	<0.230	0.018
WDD 1538	0.374	<0.178	<0.034	63.623	0.993	21.251	<0.068	0.857	29.121	<0.230	<0.011
WDD 1538	0.481	<0.178	<0.034	87.204	<0.082	25.379	<0.068	0.389	32.148	<0.230	0.019
WDD 1541	0.011	<0.178	<0.034	23.116	0.089	8.615	<0.068	1.368	28.349	<0.230	0.013
WDD 1548	0.006	<0.178	<0.034	23.084	<0.082	1.082	<0.068	0.134	11.868	<0.230	<0.011
WDD 1548	0.011	0.269	<0.034	29.253	<0.082	0.112	<0.068	0.570	11.591	<0.230	<0.011
WDD 1548	0.011	0.269	<0.034	29.253	<0.082	0.112	<0.068	0.570	11.591	<0.230	<0.011
WDD 1549	0.008	<0.178	<0.034	22.944	<0.082	3.936	<0.068	0.125	15.117	<0.230	<0.011
WDD 1549	0.058	<0.178	<0.034	25.267	0.087	1.642	<0.068	12.352	18.072	<0.230	<0.011
WDD 1550	0.015	<0.178	<0.034	49.329	0.879	6.691	<0.068	0.455	21.560	<0.230	0.012
WDD 1550	0.177	<0.178	<0.034	19.336	1.346	18.297	<0.068	0.728	7.732	<0.230	0.013
WDD 1712	0.053	<0.178	<0.034	37.933	0.466	4.844	<0.068	0.953	7.639	<0.230	0.019
WDD 1712	0.099	<0.178	<0.034	62.486	0.189	0.536	<0.068	0.338	11.004	<0.230	0.019
WDD 1712	0.035	<0.178	<0.034	21.031	0.459	1.372	0.070	0.800	5.144	<0.230	0.017
WDD 1712	0.036	<0.178	<0.034	69.043	<0.082	4.119	<0.068	0.104	38.114	<0.230	0.018
WDD 1713	0.389	<0.178	<0.034	75.458	<0.082	1.451	<0.068	0.094	20.182	<0.230	<0.011
WDD 1713 (ALT)	0.387	<0.178	<0.034	74.616	<0.082	1.456	<0.068	0.052	19.972	<0.230	<0.011
WDD 1714	0.012	0.283	<0.034	19.487	<0.082	21.270	<0.068	0.277	27.149	<0.230	<0.011
WDD 1714	0.041	<0.178	<0.034	13.109	<0.082	18.960	<0.068	3.899	21.790	<0.230	<0.011
WDD 1715	0.295	<0.178	<0.034	42.279	<0.082	12.187	<0.068	0.138	26.169	<0.230	<0.011
WDD 1715	0.037	0.159	<0.034	39.203	<0.082	15.324	<0.068	0.080	26.161	<0.230	<0.011
WDD 1715	0.037	0.159	<0.034	39.203	<0.082	15.324	<0.068	0.080	26.161	<0.230	<0.011
WDD 1716	0.476	<0.178	<0.034	57.925	0.395	7.054	<0.068	0.384	5.011	<0.230	0.379
WDD 1717	0.785	<0.178	<0.034	60.241	<0.082	4.280	<0.068	0.094	24.735	<0.230	0.015
WDD 1719	0.045	<0.178	<0.034	53.671	<0.082	10.167	<0.068	0.125	17.664	<0.230	<0.011
WDD 1720	0.006	<0.178	<0.034	62.882	0.498	2.386	<0.068	0.238	33.090	<0.230	0.011
WDD 1720	0.023	<0.178	<0.034	79.467	<0.082	1.044	<0.068	0.340	42.496	<0.230	0.014
WDD 1720	0.007	<0.178	<0.034	38.777	<0.082	20.632	<0.068	0.761	28.829	<0.230	0.013
WDD 2025	0.245	0.208	<0.034	54.176	<0.082	4.280	<0.068	0.156	85.300	<0.230	<0.011
WDD 2026	0.761	<0.178	<0.034	112.930	<0.082	16.838	<0.068	0.329	9.834	<0.230	<0.011
WDD 2027	0.011	0.194	<0.034	20.878	0.100	19.018	<0.068	1.481	15.336	<0.230	<0.011
WDD 2027	<0.003	0.341	<0.034	21.729	<0.082	1.978	<0.068	0.020	15.197	<0.230	<0.011
WDD 2027	<0.003	0.353	<0.034	22.488	<0.082	2.098	<0.068	0.025	15.757	<0.230	<0.011
WDD 2027	<0.003	0.341	<0.034	21.729	<0.082	1.978	<0.068	0.020	15.197	<0.230	<0.011
WDD 2036	0.135	<0.178	<0.034	24.548	0.095	3.129	<0.068	0.234	16.736	<0.230	<0.011
WDD 2036	0.113	<0.178	<0.034	29.763	<0.082	8.109	<0.068	11.669	21.639	<0.230	<0.011
WDD 2036	0.138	<0.178	<0.034	25.650	0.109	3.246	<0.068	0.244	17.749	<0.230	<0.011
WDD 2038	0.483	<0.178	<0.034	48.755	<0.082	6.555	<0.068	0.102	35.570	<0.230	<0.011
WDD 2038	0.485	0.203	<0.034	45.174	1.028	4.281	<0.068	0.873	32.112	<0.230	0.014
WDD 2041	1.039	0.220	<0.034	29.199	<0.082	27.200	<0.068	4.563	14.966	<0.230	<0.011
WDD 2041	1.039	0.220	<0.034	29.199	<0.082	27.200	<0.068	4.563	14.966	<0.230	<0.011
WDD 2043	0.044	<0.178	<0.034	60.623	0.404	39.080	<0.068	0.536	28.377	<0.230	<0.011
WDD 2045	0.008	<0.178	<0.034	19.208	<0.082	7.941	<0.068	0.273	13.415	<0.230	<0.011

	Mn	P	Mo	Ca	Al	Zn	Ni	Fe	Mg	Pb	Cu
WDD 2046	0.009	0.204	<0.034	10.630	<0.082	2.207	<0.068	1.334	9.823	<0.230	<0.011
WDD 2047	0.266	0.263	<0.034	11.832	<0.082	13.144	<0.068	0.279	7.866	<0.230	<0.011
WDD 2047	0.334	<0.178	<0.034	12.908	0.114	6.860	<0.068	0.151	8.244	<0.230	0.032
WDD 2047	0.275	0.262	<0.034	11.710	<0.082	11.955	<0.068	0.311	7.980	<0.230	<0.011
WDD 2048	0.091	<0.178	<0.034	27.872	0.206	4.478	<0.068	0.602	24.599	<0.230	<0.011
WDD 2048	0.045	<0.178	<0.034	28.097	0.159	1.735	<0.068	0.294	22.690	<0.230	<0.011
WDD 2049	0.027	<0.178	<0.034	5.422	0.357	9.301	<0.068	3.929	7.257	<0.230	<0.011
WDD 2049	0.020	<0.178	<0.034	5.730	0.111	6.592	<0.068	0.205	7.170	<0.230	<0.011
WDD 2050	0.012	<0.178	<0.034	6.386	<0.082	6.157	0.072	1.547	9.669	<0.230	<0.011
WDD 2050	0.043	<0.178	<0.034	8.656	<0.082	4.106	<0.068	0.095	11.406	<0.230	<0.011
WDD 2051	0.099	<0.178	<0.034	16.921	<0.082	17.991	<0.068	0.241	9.552	<0.230	0.015
WDD 2052	0.004	<0.178	<0.034	93.718	<0.082	9.347	<0.068	0.061	31.445	<0.230	<0.011
WDD 2053	0.006	<0.178	<0.034	11.490	0.092	3.849	<0.068	0.569	9.184	<0.230	<0.011
WDD 2055	0.035	0.246	<0.034	16.365	0.147	20.884	<0.068	0.208	35.858	<0.230	0.033
WDD 2081	0.044	<0.178	<0.034	21.079	0.153	12.794	<0.068	1.582	11.397	<0.230	0.035
WDD 2081	6.037	<0.178	<0.034	13.601	<0.082	36.399	<0.068	0.183	7.038	<0.230	0.022
WDD 2082	0.590	<0.178	<0.034	58.511	0.113	18.078	<0.068	0.241	18.738	<0.230	<0.011
WDD 2082	0.308	<0.178	<0.034	48.596	<0.082	27.742	<0.068	0.140	15.595	<0.230	<0.011
WDD 2083	0.134	0.300	<0.034	10.754	0.355	4.227	<0.068	0.419	14.800	<0.230	<0.011
WDD 2083	0.103	0.215	<0.034	11.072	<0.082	7.612	<0.068	0.230	14.535	<0.230	0.035
WDD 2084	0.316	<0.178	<0.034	27.632	<0.082	24.972	<0.068	0.297	8.193	<0.230	0.011
WDD 2085	1.988	0.344	<0.034	41.631	0.145	15.003	<0.068	0.312	65.207	<0.230	0.018
WDD 2087	0.061	<0.178	<0.034	45.861	0.517	17.087	<0.068	0.681	41.630	<0.230	0.036
WDD 2087	0.046	<0.178	<0.034	47.503	<0.082	25.909	<0.068	0.124	44.219	<0.230	<0.011
WDD 2187	0.018	<0.178	<0.034	7.326	<0.082	8.666	<0.068	0.694	12.727	<0.230	<0.011
WDD 2191	0.086	0.262	<0.034	4.867	0.096	8.464	<0.068	0.283	14.909	<0.230	<0.011
WDD 2205	0.359	0.181	<0.034	160.490	2.007	2.191	<0.068	2.926	23.326	<0.230	0.022
WDD 2209	0.009	0.201	<0.034	32.546	<0.082	12.841	<0.068	0.342	27.977	<0.230	<0.011
WDD 2213	0.019	<0.178	<0.034	41.921	0.307	27.084	<0.068	2.312	33.992	<0.230	<0.011
WDD 2214	0.309	0.505	<0.034	52.658	1.065	8.547	<0.068	0.714	34.953	<0.230	0.011
WDD 2214	0.310	0.539	<0.034	54.608	1.317	8.765	<0.068	0.847	38.029	<0.230	0.012
WDD 2215	0.758	<0.178	<0.034	81.082	0.869	16.615	<0.068	2.576	48.848	<0.230	<0.011
WDD 2216	1.052	0.299	<0.034	37.746	0.891	3.595	<0.068	0.693	33.488	<0.230	0.016
WDD 2217	1.406	0.270	<0.034	83.686	0.086	4.968	<0.068	0.175	87.083	<0.230	<0.011
WDD 2218	0.009	<0.178	<0.034	53.904	<0.082	11.385	<0.068	0.107	33.000	<0.230	0.016
WDD 2218	0.054	0.332	<0.034	46.328	0.067	2.308	<0.068	6.477	28.947	<0.230	<0.011
WDD 2218	0.054	0.332	<0.034	46.328	0.067	2.308	<0.068	6.477	28.947	<0.230	<0.011
WDD 2219	0.549	<0.178	<0.034	48.322	<0.082	19.930	<0.068	1.020	23.211	<0.230	0.021
WDD 2984	0.464	<0.178	0.085	33.573	<0.082	0.939	<0.068	<0.006	11.235	<0.230	<0.011
SPRING SITE 1	0.013	<0.178	<0.034	4.973	<0.082	<0.020	<0.068	0.008	2.627	<0.230	<0.011
SPRING SITE 3	0.005	<0.178	<0.034	9.868	<0.082	<0.020	<0.068	0.009	5.111	<0.230	<0.011
SPRING SITE 4	<0.003	<0.178	<0.034	4.729	<0.082	<0.020	<0.068	0.013	1.979	<0.230	<0.011
SPRING SITE 5	0.009	<0.178	<0.034	4.022	0.110	<0.020	<0.068	0.091	1.986	<0.230	<0.011
SPRING SITE 6	<0.003	<0.178	<0.034	5.984	<0.082	<0.020	<0.068	0.029	2.797	<0.230	<0.011
SPRING SITE 7	1.099	<0.178	<0.034	12.768	<0.082	<0.020	<0.068	0.011	3.608	<0.230	<0.011
SPRING SITE 8	0.012	<0.178	<0.034	30.536	0.161	<0.020	<0.068	0.224	15.099	<0.230	<0.011

A2.1 Trace element analyses continued.....

Sample	Co	Cr	Cd	S	As	Se	Sb	V	B	Ba	Be	Si
D. METHOD	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.	I.C.P.
D.LIMIT mg/L	0.017	0.012	0.016	0.066	0.113	0.211	0.188	0.008	0.022	0.001	0.001	
BACKGRND ACC.LMT mg/L		0.050	0.005		0.050	0.010		0.100	5.000	1.000		
CD 85	<0.017	<0.012	<0.016	10.938	<0.113	<0.211	<0.188	<0.008	0.075	0.033	0.001	33.929
CD 85	<0.017	<0.012	<0.016	10.592	<0.113	<0.211	<0.188	<0.008	0.049	0.041	0.002	32.699
CD 85	<0.017	0.023	<0.016	13.392	<0.113	<0.211	<0.188	<0.008	0.047	0.033	0.003	30.736
CD 91	<0.017	<0.012	<0.016	40.651	<0.113	<0.211	<0.188	<0.008	0.041	0.050	0.000	13.909
CD 91	<0.017	<0.012	<0.016	41.452	<0.113	<0.211	<0.188	<0.008	0.039	0.044	0.001	12.940
CD 360	<0.017	<0.012	<0.016	3.683	<0.113	<0.211	<0.188	<0.008	0.059	0.336	<0.001	14.783
CD 368	<0.017	<0.012	<0.016	22.384	<0.113	<0.211	<0.188	<0.008	<0.022	0.104	0.001	19.862
CD 371	<0.017	<0.012	<0.016	30.273	<0.113	<0.211	<0.188	<0.008	<0.022	0.129	<0.001	25.111
CD 401	<0.017	0.196	<0.016	4.638	<0.113	<0.211	<0.188	0.011	0.039	0.124	<0.001	29.095
CD 401	<0.017	<0.012	<0.016	4.504	<0.113	<0.211	<0.188	0.012	0.039	0.122	<0.001	31.227
CD 403	<0.017	<0.012	<0.016	11.524	<0.113	<0.211	<0.188	<0.008	<0.022	0.078	<0.001	21.316
CD 409	<0.017	0.204	<0.016	45.427	<0.113	<0.211	<0.188	0.011	<0.022	0.091	<0.001	27.116
CD 409	<0.017	<0.012	<0.016	40.243	<0.113	<0.211	<0.188	<0.008	<0.022	0.084	0.001	23.314
CD 415	<0.017	0.033	<0.016	26.990	<0.113	<0.211	<0.188	<0.008	<0.022	0.087	<0.001	22.014
CD 479	<0.017	<0.012	<0.016	22.073	<0.113	<0.211	<0.188	<0.008	0.443	0.041	0.001	12.628
CD 479	<0.017	<0.012	<0.016	98.167	<0.113	<0.211	<0.188	<0.008	0.082	0.116	<0.001	11.737
CD 487	<0.017	<0.012	<0.016	16.501	<0.113	<0.211	<0.188	<0.008	<0.022	0.087	0.002	17.740
CD 499	<0.017	<0.012	<0.016	54.475	<0.113	<0.211	<0.188	<0.008	0.032	0.065	<0.001	11.106
CD 499	<0.017	<0.012	<0.016	57.538	<0.113	<0.211	<0.188	<0.008	0.029	0.066	<0.001	11.041
CD 510	<0.017	<0.012	<0.016	29.067	<0.113	<0.211	<0.188	<0.008	<0.022	0.066	<0.001	17.046
CD 510	<0.017	<0.012	<0.016	26.347	<0.113	<0.211	<0.188	<0.008	<0.022	0.070	0.001	16.382
CD 530	<0.017	<0.012	<0.016	18.190	<0.113	<0.211	<0.188	<0.008	<0.022	0.104	<0.001	28.095
CD 530	<0.017	<0.012	<0.016	20.165	<0.113	<0.211	<0.188	<0.008	<0.022	0.070	0.001	27.902
CD 530	<0.017	<0.012	<0.016	6.711	<0.113	<0.211	<0.188	<0.008	<0.022	0.095	0.002	26.215
CD 3009	<0.017	<0.012	<0.016	13.120	<0.113	<0.211	<0.188	<0.008	0.043	0.094	0.001	12.623
CD 3009	<0.017	<0.012	<0.016	12.661	<0.113	<0.211	<0.188	<0.008	0.044	0.095	0.003	12.934
CD 3017	<0.017	<0.012	<0.016	15.663	<0.113	<0.211	<0.188	<0.008	<0.022	0.106	<0.001	17.279
CD 3148	<0.017	<0.012	<0.016	18.301	<0.113	<0.211	<0.188	0.009	<0.022	0.065	0.005	32.618
CD 3148	<0.017	<0.012	<0.016	18.461	<0.113	<0.211	<0.188	<0.008	<0.022	0.062	0.005	32.118
CD 3418	<0.017	<0.012	<0.016	19.870	<0.113	<0.211	<0.188	<0.008	<0.022	0.060	0.001	34.390
CD 3432	<0.017	<0.012	<0.016	25.751	<0.113	<0.211	<0.188	<0.008	<0.022	0.027	0.002	24.390
CD 3497	<0.017	<0.012	<0.016	3.217	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	9.330
CD 3497	<0.017	<0.012	<0.016	3.960	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	14.137
DS 715	<0.017	<0.012	<0.016	34.999	<0.113	<0.211	<0.188	<0.008	<0.022	0.050	<0.001	21.887
DS 719	<0.017	0.153	<0.016	70.970	<0.113	<0.211	<0.188	<0.008	0.026	0.061	<0.001	21.118
DS 727	<0.017	<0.012	<0.016	8.423	<0.113	<0.211	<0.188	<0.008	<0.022	0.103	<0.001	22.263
DS 728	<0.017	0.197	<0.016	41.183	<0.113	<0.211	<0.188	<0.008	<0.022	0.074	<0.001	30.068
DS 731	<0.017	<0.012	<0.016	40.303	<0.113	<0.211	<0.188	<0.008	<0.022	0.070	<0.001	23.022
DS 731	<0.017	<0.012	<0.016	9.347	<0.113	<0.211	<0.188	<0.008	<0.022	0.089	<0.001	22.239
DS 732	<0.017	0.021	<0.016	2.071	<0.113	<0.211	<0.188	<0.008	<0.022	0.127	<0.001	38.325
DS 735	<0.017	0.025	<0.016	<0.066	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	15.307
DS 744	<0.017	0.024	<0.016	43.134	<0.113	<0.211	<0.188	<0.008	<0.022	0.056	0.006	36.373
DS 750	<0.017	0.024	<0.016	6.052	<0.113	<0.211	<0.188	<0.008	<0.022	0.090	0.001	21.604
DS 750	<0.017	0.002	<0.016	11.823	<0.113	<0.211	<0.188	<0.008	<0.022	0.031	<0.001	21.051
DS 750	<0.017	<0.012	<0.016	12.252	<0.113	<0.211	<0.188	<0.008	<0.022	0.088	0.001	21.979
GS 721	<0.017	<0.012	<0.016	49.305	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	25.592

	Co	Cr	Cd	S	As	Se	Sb	V	B	Ba	Be	Si
GS 731	<0.017	<0.012	<0.016	54.138	<0.113	<0.211	<0.188	<0.008	<0.022	0.101	0.001	23.183
GS 830	<0.017	<0.012	<0.016	12.213	<0.113	<0.211	<0.188	<0.008	<0.022	0.014	<0.001	27.756
GS 884	<0.017	<0.012	<0.016	6.027	<0.113	<0.211	<0.188	<0.008	0.022	0.087	<0.001	26.542
GS 1613	<0.017	<0.012	<0.016	13.237	<0.113	<0.211	<0.188	0.010	<0.022	0.038	0.003	24.653
GS 1613	<0.017	<0.012	<0.016	15.652	<0.113	<0.211	<0.188	<0.008	<0.022	0.033	0.001	23.093
GS 1613	<0.017	<0.012	<0.016	12.420	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	29.061
GS 1615	<0.017	0.060	<0.016	37.102	<0.113	<0.211	<0.188	<0.008	0.035	0.059	<0.001	20.266
WDD 1514	<0.017	0.014	<0.016	16.786	<0.113	<0.211	<0.188	0.012	<0.022	0.042	<0.001	28.654
WDD 1534	<0.017	<0.012	<0.016	1.936	<0.113	<0.211	<0.188	<0.008	<0.022	0.055	0.001	27.703
WDD 1534	<0.017	<0.012	<0.016	1.955	<0.113	<0.211	<0.188	<0.008	<0.022	0.056	0.001	26.584
WDD 1534	<0.017	<0.012	<0.016	2.152	<0.113	<0.211	<0.188	<0.008	<0.022	0.055	0.001	25.415
WDD 1536	<0.017	<0.012	<0.016	4.923	<0.113	<0.211	<0.188	<0.008	<0.022	0.061	0.001	
WDD 1537	<0.017	<0.012	<0.016	6.937	<0.113	<0.211	<0.188	<0.008	<0.022	0.007	<0.001	26.085
WDD 1538	<0.017	<0.012	<0.016	18.592	<0.113	<0.211	<0.188	<0.008	<0.022	0.184	<0.001	20.325
WDD 1538	<0.017	<0.012	<0.016	23.894	<0.113	<0.211	<0.188	<0.008	<0.022	0.155	0.001	16.945
WDD 1541	<0.017	0.020	<0.016	15.582	<0.113	<0.211	<0.188	<0.008	<0.022	0.032	<0.001	27.264
WDD 1548	<0.017	<0.012	<0.016	16.241	<0.113	<0.211	<0.188	<0.008	<0.022	0.116	0.001	29.229
WDD 1548	<0.017	<0.012	<0.016	16.277	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	30.029
WDD 1548	<0.017	<0.012	<0.016	16.277	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	
WDD 1549	<0.017	<0.012	<0.016	25.713	<0.113	<0.211	<0.188	<0.008	<0.022	0.093	<0.001	28.271
WDD 1549	<0.017	0.031	<0.016	8.949	<0.113	<0.211	<0.188	<0.008	<0.022	0.059	<0.001	32.049
WDD 1550	<0.017	<0.012	<0.016	21.236	<0.113	<0.211	<0.188	<0.008	<0.022	0.045	<0.001	25.720
WDD 1550	<0.017	<0.012	<0.016	2.911	<0.113	<0.211	<0.188	<0.008	<0.022	0.047	<0.001	22.818
WDD 1712	<0.017	0.126	<0.016	7.852	<0.113	<0.211	<0.188	<0.008	0.048	0.004	<0.001	35.463
WDD 1712	<0.017	0.020	<0.016	17.639	<0.113	<0.211	<0.188	<0.008	<0.022	0.096	<0.001	30.250
WDD 1712	<0.017	0.162	<0.016	11.074	<0.113	<0.211	<0.188	<0.008	0.070	0.243	0.001	37.790
WDD 1712	<0.017	<0.012	<0.016	7.298	<0.113	<0.211	<0.188	<0.008	<0.022	0.119	<0.001	20.893
WDD 1713	<0.017	<0.012	<0.016	18.063	<0.113	<0.211	<0.188	<0.008	<0.022	0.028	<0.001	19.449
WDD 1713 (ALT)	<0.017	<0.012	<0.016	12.014	<0.113	<0.211	<0.188	<0.008	0.055	0.101	<0.001	19.290
WDD 1714	<0.017	<0.012	<0.016	9.075	<0.113	<0.211	<0.188	<0.008	<0.022	0.005	<0.001	24.221
WDD 1714	<0.017	<0.012	<0.016	6.053	<0.113	<0.211	<0.188	<0.008	<0.022	0.001	0.001	30.066
WDD 1715	<0.017	<0.012	<0.016	10.216	<0.113	<0.211	<0.188	<0.008	<0.022	0.048	0.001	16.177
WDD 1715	<0.017	<0.012	<0.016	46.702	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	11.194
WDD 1715	<0.017	<0.012	<0.016	46.702	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	
WDD 1716	<0.017	<0.012	<0.016	7.394	<0.113	<0.211	<0.188	0.009	0.024	0.024	<0.001	17.970
WDD 1717	<0.017	<0.012	<0.016	18.820	<0.113	<0.211	<0.188	<0.008	<0.022	0.071	<0.001	18.576
WDD 1719	<0.017	<0.012	<0.016	18.302	<0.113	<0.211	<0.188	<0.008	0.284	0.053	<0.001	16.526
WDD 1720	<0.017	0.041	<0.016	99.589	<0.113	<0.211	<0.188	<0.008	0.456	0.033	<0.001	23.503
WDD 1720	<0.017	<0.012	<0.016	7.424	<0.113	<0.211	<0.188	<0.008	<0.022	0.033	<0.001	21.680
WDD 1720	<0.017	<0.012	<0.016	6.384	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	16.209
WDD 2025	<0.017	<0.012	<0.016	61.055	<0.113	<0.211	<0.188	<0.008	<0.022	0.056	<0.001	25.745
WDD 2026	<0.017	<0.012	<0.016	33.413	<0.113	<0.211	<0.188	<0.008	0.043	0.067	<0.001	25.989
WDD 2027	<0.017	0.033	<0.016	8.061	<0.113	<0.211	<0.188	<0.008	<0.022	0.038	<0.001	36.933
WDD 2027	<0.017	<0.012	<0.016	9.142	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	38.000
WDD 2027	<0.017	<0.012	<0.016	9.092	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	38.589
WDD 2027	<0.017	<0.012	<0.016	9.142	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	
WDD 2036	<0.017	<0.012	<0.016	27.716	<0.113	<0.211	<0.188	0.009	<0.022	0.094	0.001	29.401
WDD 2036	<0.017	<0.012	<0.016	35.200	<0.113	<0.211	<0.188	<0.008	<0.022	0.066	0.001	32.940
WDD 2036	<0.017	<0.012	<0.016	29.291	<0.113	<0.211	<0.188	0.009	<0.022	0.095	0.001	31.010
WDD 2038	<0.017	<0.012	<0.016	21.778	<0.113	<0.211	<0.188	<0.008	<0.022	0.064	0.001	16.637
WDD 2038	<0.017	<0.012	<0.016	20.502	<0.113	<0.211	<0.188	0.008	<0.022	0.035	<0.001	16.451
WDD 2041	<0.017	<0.012	<0.016	5.000	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	26.082
WDD 2041	<0.017	<0.012	<0.016	5.000	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	
WDD 2043	<0.017	<0.012	<0.016	9.974	<0.113	<0.211	<0.188	<0.008	<0.022	0.092	<0.001	20.544
WDD 2045	<0.017	<0.012	<0.016	11.882	<0.113	<0.211	<0.188	<0.008	<0.022	0.060	<0.001	24.855

	Co	Cr	Cd	S	As	Se	Sb	V	B	Ba	Be	Si
WDD 2046	<0.017	<0.012	<0.016	8.177	<0.113	<0.211	<0.188	<0.008	<0.022	0.037	<0.001	28.536
WDD 2047	<0.017	<0.012	<0.016	6.407	<0.113	<0.211	<0.188	<0.008	<0.022	0.051	<0.001	43.465
WDD 2047	<0.017	<0.012	<0.016	5.853	<0.113	<0.211	<0.188	<0.008	<0.022	0.067	0.001	39.032
WDD 2047	<0.017	<0.012	<0.016	23.703	<0.113	<0.211	<0.188	<0.008	<0.022	0.050	<0.001	42.448
WDD 2048	<0.017	0.030	<0.016	15.800	<0.113	<0.211	<0.188	0.008	<0.022	0.119	<0.001	28.110
WDD 2048	<0.017	<0.012	<0.016	18.353	<0.113	<0.211	<0.188	0.009	<0.022	0.090	<0.001	25.990
WDD 2049	<0.017	<0.012	<0.016	1.547	<0.113	<0.211	<0.188	0.008	<0.022	0.020	<0.001	24.171
WDD 2049	<0.017	<0.012	<0.016	1.639	<0.113	<0.211	<0.188	<0.008	<0.022	0.017	0.001	22.460
WDD 2050	<0.017	<0.012	<0.016	1.847	<0.113	<0.211	<0.188	<0.008	<0.022	0.008	0.001	26.849
WDD 2050	<0.017	<0.012	<0.016	2.016	<0.113	<0.211	<0.188	<0.008	<0.022	0.011	<0.001	25.851
WDD 2051	<0.017	<0.012	<0.016	12.671	<0.113	<0.211	<0.188	<0.008	<0.022	0.031	0.001	32.236
WDD 2052	<0.017	<0.012	<0.016	40.355	<0.113	<0.211	<0.188	<0.008	<0.022	0.036	0.001	20.382
WDD 2053	<0.017	<0.012	<0.016	6.442	<0.113	<0.211	<0.188	<0.008	<0.022	0.039	0.001	21.363
WDD 2055	<0.017	0.028	<0.016	6.097	<0.113	<0.211	<0.188	<0.008	<0.022	0.065	<0.001	22.749
WDD 2081	<0.017	0.032	<0.016	2.474	<0.113	<0.211	<0.188	<0.008	<0.022	0.064	<0.001	38.407
WDD 2081	<0.017	<0.012	<0.016	7.400	<0.113	<0.211	<0.188	<0.008	<0.022	0.004	<0.001	41.102
WDD 2082	<0.017	0.028	<0.016	17.666	<0.113	<0.211	<0.188	<0.008	<0.022	0.050	<0.001	22.350
WDD 2082	<0.017	<0.012	<0.016	16.581	<0.113	<0.211	<0.188	<0.008	<0.022	0.044	<0.001	20.523
WDD 2083	<0.017	0.064	<0.016	27.957	<0.113	<0.211	<0.188	0.008	<0.022	0.059	<0.001	20.012
WDD 2083	<0.017	<0.012	<0.016	8.308	<0.113	<0.211	<0.188	<0.008	0.061	0.006	<0.001	18.384
WDD 2084	<0.017	<0.012	<0.016	8.169	<0.113	<0.211	<0.188	<0.008	<0.022	0.096	<0.001	33.054
WDD 2085	<0.017	<0.012	<0.016	44.849	<0.113	<0.211	<0.188	<0.008	<0.022	0.018	<0.001	24.946
WDD 2087	<0.017	0.013	<0.016	24.750	<0.113	<0.211	<0.188	0.010	<0.022	0.032	0.001	20.162
WDD 2087	<0.017	<0.012	<0.016	25.392	<0.113	<0.211	<0.188	<0.008	<0.022	0.024	<0.001	20.352
WDD 2187	<0.017	<0.012	<0.016	28.441	<0.113	<0.211	<0.188	<0.008	<0.022	0.044	<0.001	27.462
WDD 2191	<0.017	0.029	<0.016	4.986	<0.113	<0.211	<0.188	<0.008	<0.022	0.004	<0.001	21.986
WDD 2205	<0.017	0.040	<0.016	65.254	<0.113	<0.211	<0.188	<0.008	0.352	0.060	0.002	30.322
WDD 2209	<0.017	<0.012	<0.016	22.937	<0.113	<0.211	<0.188	<0.008	<0.022	0.015	<0.001	28.766
WDD 2213	<0.017	0.057	<0.016	18.286	<0.113	<0.211	<0.188	<0.008	<0.022	0.029	<0.001	25.981
WDD 2214	<0.017	0.020	<0.016	27.039	<0.113	<0.211	<0.188	<0.008	<0.022	0.061	<0.001	26.682
WDD 2214	<0.017	0.035	<0.016	24.214	<0.113	<0.211	<0.188	<0.008	0.079	0.124	<0.001	29.071
WDD 2215	<0.017	0.037	<0.016	11.077	<0.113	<0.211	<0.188	<0.008	<0.022	0.026	<0.001	20.295
WDD 2216	<0.017	0.123	<0.016	40.167	<0.113	<0.211	<0.188	<0.008	<0.022	0.055	<0.001	26.571
WDD 2217	<0.017	0.019	<0.016	88.299	<0.113	<0.211	<0.188	<0.008	<0.022	0.098	0.008	27.577
WDD 2218	<0.017	<0.012	<0.016	71.886	<0.113	<0.211	<0.188	<0.008	<0.022	0.034	<0.001	39.073
WDD 2218	<0.017	0.006	<0.016	67.477	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	40.776
WDD 2218	<0.017	0.006	<0.016	67.477	<0.113	<0.211	<0.188	<0.008	<0.022	<0.001	<0.001	
WDD 2219	<0.017	<0.012	<0.016	23.036	<0.113	<0.211	<0.188	<0.008	0.029	0.031	0.001	23.080
WDD 2984	<0.017	<0.012	<0.016	15.635	<0.113	<0.211	<0.188	<0.008	<0.022	0.109	<0.001	35.733
SPRING SITE 1	<0.017	<0.012	<0.016	3.382	<0.113	<0.211	<0.188	<0.008	<0.022	0.069	0.001	11.018
SPRING SITE 3	<0.017	<0.012	<0.016	4.296	<0.113	<0.211	<0.188	<0.008	<0.022	0.078	<0.001	12.564
SPRING SITE 4	<0.017	<0.012	<0.016	3.819	<0.113	<0.211	<0.188	<0.008	<0.022	0.071	0.001	27.844
SPRING SITE 5	<0.017	<0.012	<0.016	3.796	<0.113	<0.211	<0.188	<0.008	<0.022	0.037	<0.001	6.610
SPRING SITE 6	<0.017	<0.012	<0.016	4.086	<0.113	<0.211	<0.188	<0.008	<0.022	0.016	<0.001	7.765
SPRING SITE 7	<0.017	<0.012	<0.016	4.277	<0.113	<0.211	<0.188	<0.008	<0.022	0.094	<0.001	19.355
SPRING SITE 8	<0.017	<0.012	<0.016	28.833	<0.113	<0.211	<0.188	<0.008	<0.022	0.103	0.001	32.643

A3 Isotopic data

Table A3.1 Isotopic values for Oxygen-18 and Deuterium

Borehole No.	^{18}Oxygen per mil		Deuterium per mil	
CD 85	-2.61	-2.91	-14.00	
CD 91	-2.77		-12.40	
CD 91	-2.99		-12.70	
CD 119	-2.63		-11.40	
CD 360	-3.68		-16.60	
CD 368	-2.20		-7.90	
CD 371	-2.56		-8.80	
CD 403	-2.34		-8.60	-9.48
CD 409	-2.79		-10.20	
CD 415	-3.08		-8.80	
CD 447	-3.00		-8.90	
CD 461	-2.59		-6.60	
CD 479	-3.36		-10.90	
CD 479	-2.96	-3.13	-13.40	
CD 487	-2.91		-7.90	
CD 499	-3.37	-3.59	-12.90	
CD 499	-3.13		-13.30	
CD 510	-2.98		-4.80	
CD 3017	-2.00		-1.50	
CD 3040	-2.77	-2.71	-10.80	
CD 3418	-2.55		-9.10	
CD 3419	-2.93		-10.20	
CD 3449	-1.00	-0.82	9.00	
CD 3483	-2.75		-10.80	
CD 3497	-2.96	-2.96	-8.59	
CD 3497	-2.83		-4.04	
DS 719	-2.87	-2.95	-10.60	
DS 721	-2.74		-2.64	
DS 732	-1.96		-0.95	
DS 735	-2.43	-2.59	-8.80	
DS 736	-2.45		-10.10	
DS 741	-2.76	-2.71	-7.80	
DS 743	-2.40		-9.00	
DS 744	-2.05		-2.30	
DS 750	-2.29		-8.20	
DS 750	-2.53		-8.70	
DS 758	-3.26		-14.23	
GS 884	-2.31		-7.20	
GS 1023	-1.94		-2.00	
GS 1291	-2.57		-9.00	
GS 1514	-3.46		-14.80	
GS 1594	-3.43		-12.50	
GS 1613	-2.83	-2.99	-11.90	
GS 1613	-1.69		-3.50	
GS 1613	-2.97		-10.75	
GS 1615	-2.23	-2.68	-9.50	
GS 884	-2.31		-7.20	
WDD 1548	-2.17	-2.27	-2.19	-4.31
WDD 1549	-2.28		-8.70	
WDD 1715	-3.32		-8.93	

WDD 1717		-2.55		-8.20	
WDD 1719		-2.61		-10.40	
WDD 2027		-2.93		-6.71	
WDD 2027		-2.99	-2.99	-5.57	
WDD 3038		-2.65		-10.90	
WDD 2041		-2.85		-5.24	
WDD 2048		-3.30		-9.50	
WDD 2190		-2.95		-10.10	
WDD 2214		-2.37		-8.20	
WDD 2214		-2.31	-2.34	-7.90	
WDD 2218		-2.32		0.04	-1.11
Samples from Isolated Packer Zones					
	Depth Interval metres				
WDD 2027	57.23-61.02	-2.91		-4.95	
WDD 2045	30.01-33.75	-3.41	-3.39	-6.48	
WDD 2049	32.96-36.7	-2.78		-7.52	
WDD 2050	55.4-59.14	-3.43		-5.08	
WDD 2213	40.45-44.19	-3.04		-10.01	
WDD 2213	66.63-70.39	-2.04		-4.02	-0.31
WDD 2213	70.85-74.59	-3.37		-6.44	
WDD 2527	50.06-53.8	-2.85		-2.30	-1.98
Rain Samples					
Rain 19 June		-0.25		16.22	19.91
Rain 19June		-0.25		16.56	16.59
Rain 20 June		-2.52		-4.45	
Rain 20 June		-2.48		-4.96	
Rain Mbarara		-7.80		-61.70	
Rain Mbarara		-0.83		7.00	
Rain Kazo		2.83		28.80	
Rain Kazo		-0.32		27.30	

A4 Packer testing results

Table A4.1 Borehole Map Number and corresponding Government allocated Borehole Number

Map Number	Borehole Number	Map Number	Borehole Number
1	WDD 1720	51	WDD 2191
2	DS 732	52	WDD 2059
3	DS 735	53	WDD 2060
4	WDD 2027	54	CD 3294
5	WDD 2190	55	CD 3497
6	DS 728	56	WDD 2045
7	DS 727	58	WDD 2192
8	WDD 1534	59	WDD 2041
9	WDD 1536	60	CD 479
10	WDD 1535	61	WDD 2458
11	CD 3017	62	WDD 2214
12	WDD 1715	63	WDD 2093
13	WDD 1716	64	DS 725
14	WDD 1714	65	CD 461
15	WDD 1712	67	WDD 2215
16	WDD 2527	68	WDD 2216
17	WDD 1713	69	CD 371
18	CD 487	70	WDD 2447
19	DS 750	71	DS 719
20	WDD 1537	72	WDD 2218
21	WDD 2037	73	WDD 2025
22	WDD 2046	74	CD 409
23	WDD 2049	75	WDD 2219
24	CD 3009	76	GS 1430
25	WDD 2047	77	WDD 2026
26	WDD 2050	78	WDD 2455
27	WDD 2187	79	WDD 2457
28	DS 731	80	WDD 2085
29	WDD 2052	81	GS 1613
30	WDD 1550	82	CD 91
31	WDD 2051	83	WDD 2081
32	DS 756	84	WDD 2084
33	DS 714	85	CD 85
34	WDD 1549	86	WDD 2083
35	CD 3432	87	GS 1614
36	WDD 2048	88	WDD 2087
37	DS 757	89	WDD 2213
38	DS 751	90	WDD 2211
39	WDD 1548	91	WDD 2212
40	CD 530	92	WDD 2452
41	CD 510	93	WDD 2451
42	CD 499	94	GS 884
43	WDD 2043	95	CD 403
44	WDD 2210	96	WDD 2449
45	WDD 2209	97	WDD 2225
46	WDD 1538	99	CD 368
47	WDD 2039	100	WDD 2224
48	WDD 2296		
49	WDD 2036		
50	WDD 2044		

BOREHOLE NUMBER: WDD 2050

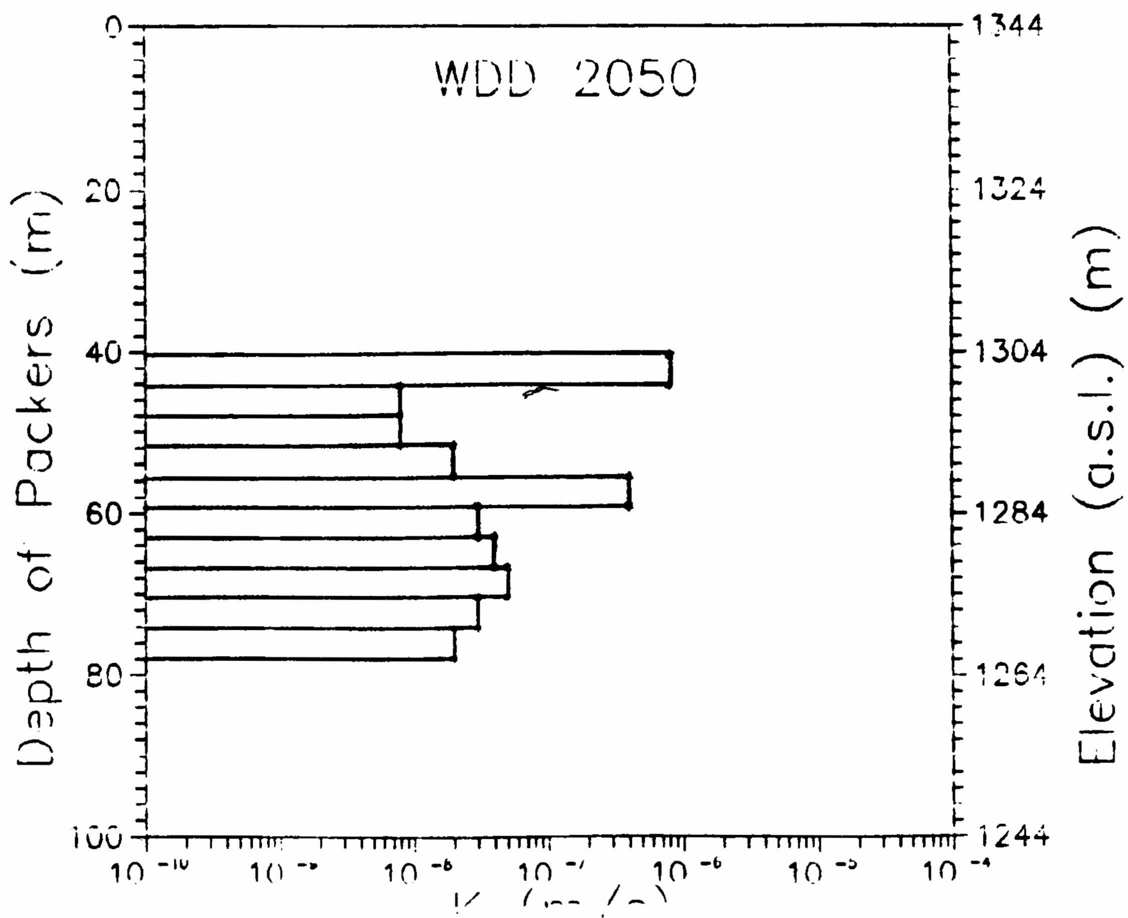
GROUND SURFACE ELEVATION: 1344 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
40.44	44.18	22.23	21.89	Rising	Head	Test	8E-07
44.18	47.92	21.94	21.89	4.83	0.18	0.04	8E-09
47.92	51.66	21.70	21.47	4.83	0.18	0.04	8E-09
51.66	55.40	22.50	22.89	4.78	0.35	0.07	2E-08
55.40	59.14	22.23	22.98	1.00	1.67	1.67	4E-07
59.14	62.88	22.63	22.36	4.63	0.53	0.11	3E-08
62.88	66.62	22.60	22.46	4.38	0.89	0.20	4E-08
66.62	70.36	22.61	22.30	4.42	1.06	0.24	5E-08
70.36	74.10	22.53	22.67	4.45	0.71	0.16	3E-08
74.10	77.84	22.36	22.09	Rising	Head	Test	2E-08

* Equivalent Porous Media Hydraulic Conductivity

WDD 2050 Packer test results

A.1 Plot of hydraulic conductivity versus depth for WDD 2050



BOREHOLE NUMBER: WDD 1534

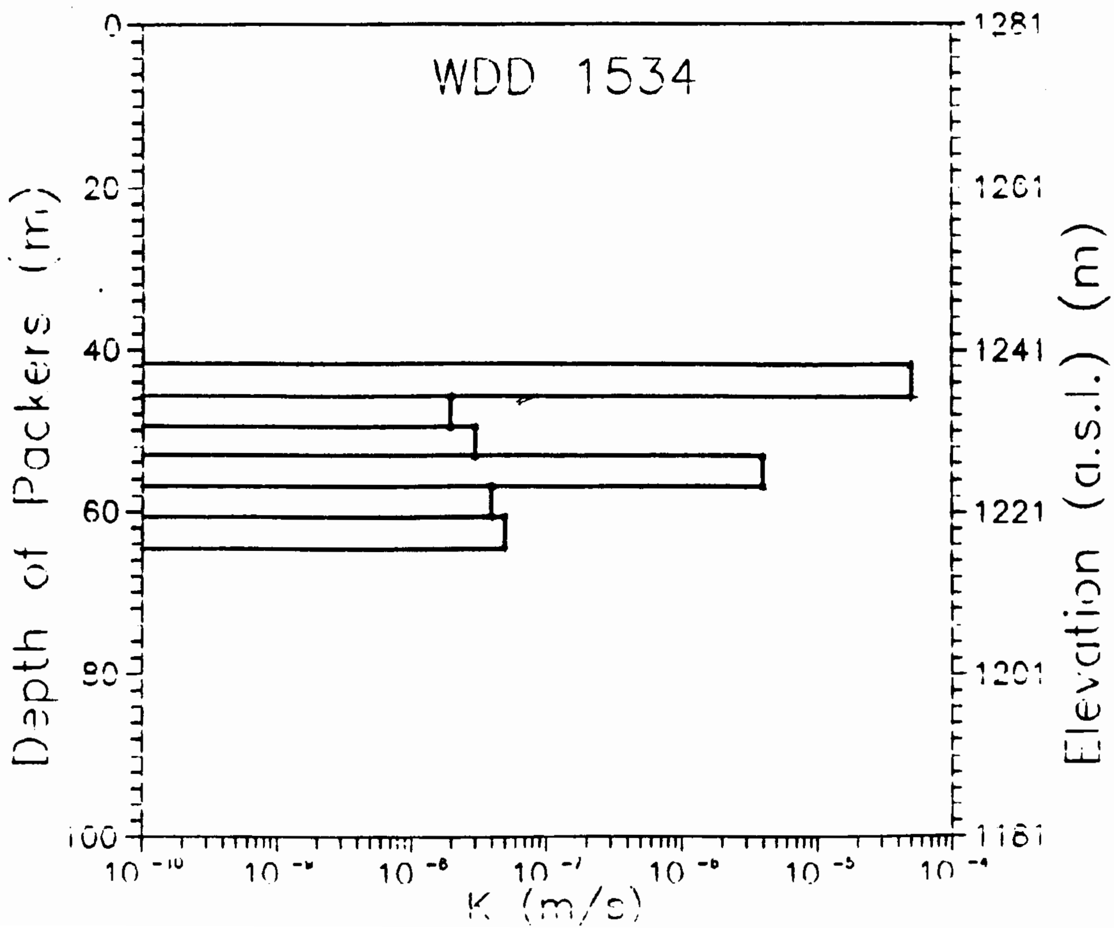
GROUND SURFACE ELEVATION: 1281 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
42.00	45.74	38.13	38.11	0.10	21.67	216.67	5E-05
45.74	49.48	38.10	37.76	4.78	0.53	0.11	2E-08
49.48	53.22	38.10	37.79	4.72	0.71	0.15	3E-08
53.22	56.96	38.08	38.05	1.00	20.00	20.00	4E-06
56.96	60.70	38.05	37.57	4.68	0.89	0.19	4E-08
60.70	64.44	38.01	37.55	2.70	0.62	0.23	5E-08

* Equivalent Porous Media Hydraulic Conductivity

WDD 1534 Packer test results

A.2 Plot of hydraulic conductivity versus depth for WDD 1534



BOREHOLE NUMBER: WDD 1712

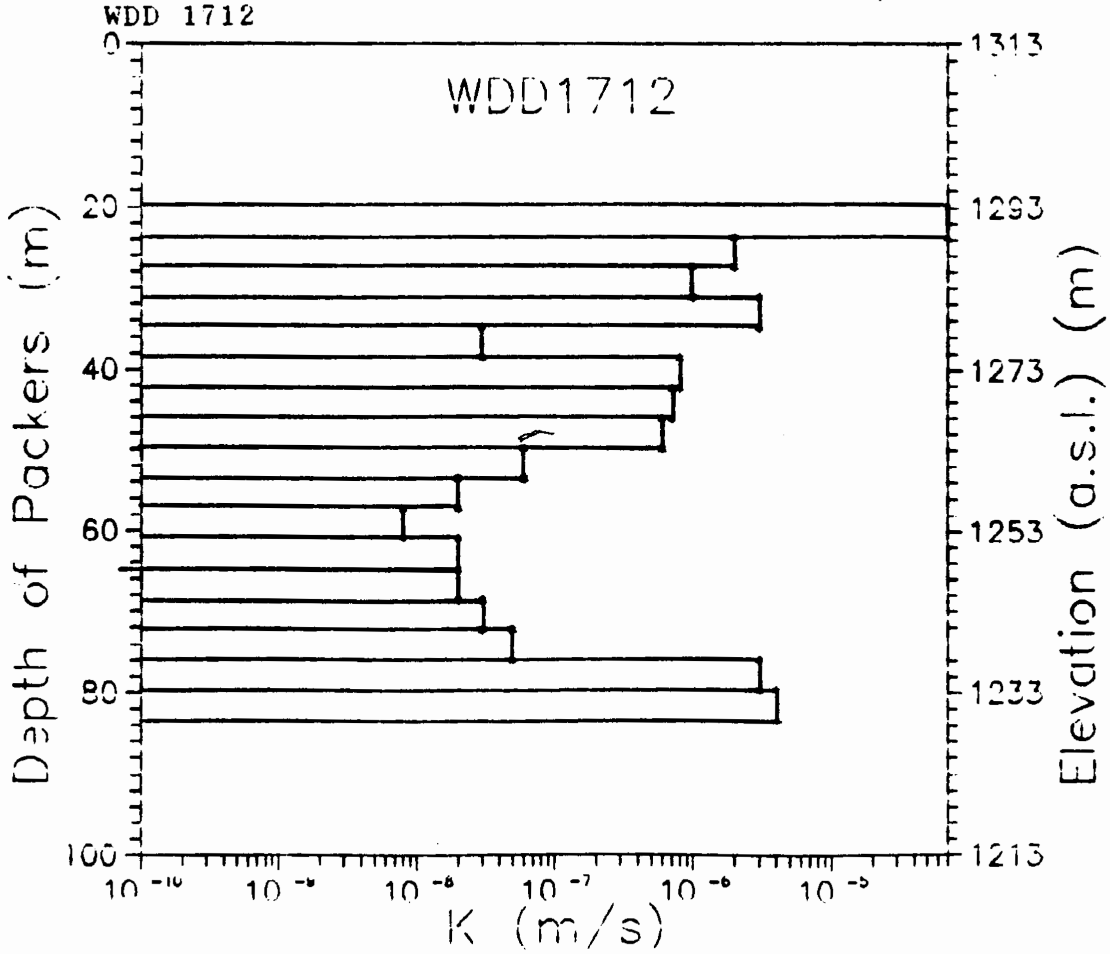
GROUND SURFACE ELEVATION: 1313 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
19.88	23.62	18.93	18.93	0.03	10.00	333.33	7E-05
23.62	27.36	18.97	18.91	1.00	10.00	10.00	2E-06
27.36	31.10	18.95	18.90	1.00	4.67	4.67	1E-06
31.10	34.84	18.93	18.80	1.00	11.67	11.67	3E-06
34.84	38.58	18.93	18.18	4.59	0.71	0.15	3E-08
38.58	42.32	19.19	18.89	5.00	18.67	3.73	8E-07
42.32	46.06	19.20	18.82	Rising	Head	Test	7E-07
46.06	49.80	19.21	18.68	Rising	Head	Test	6E-07
49.80	53.54	19.22	19.30	4.31	1.24	0.29	6E-08
53.54	57.28	19.24	18.65	4.94	0.44	0.09	2E-08
57.28	61.02	19.24	18.72	4.86	0.18	0.04	8E-09
61.02	64.76	19.25	18.92	5.23	0.53	0.10	2E-08
64.76	68.50	19.26	18.68	5.05	0.44	0.09	2E-08
68.50	72.24	19.26	19.27	4.29	0.53	0.12	3E-08
72.24	75.98	19.28	16.65	4.61	1.06	0.23	5E-08
75.98	79.72	19.28	18.75	1.00	15.00	15.00	3E-06
79.72	83.46	19.27	18.97	1.69	28.33	16.82	4E-06

* Equivalent Porous Media Hydraulic Conductivity

WDD 1712 Packer test results

A.3 Plot of hydraulic conductivity versus depth for WDD 1712



BOREHOLE NUMBER: WDD 2084

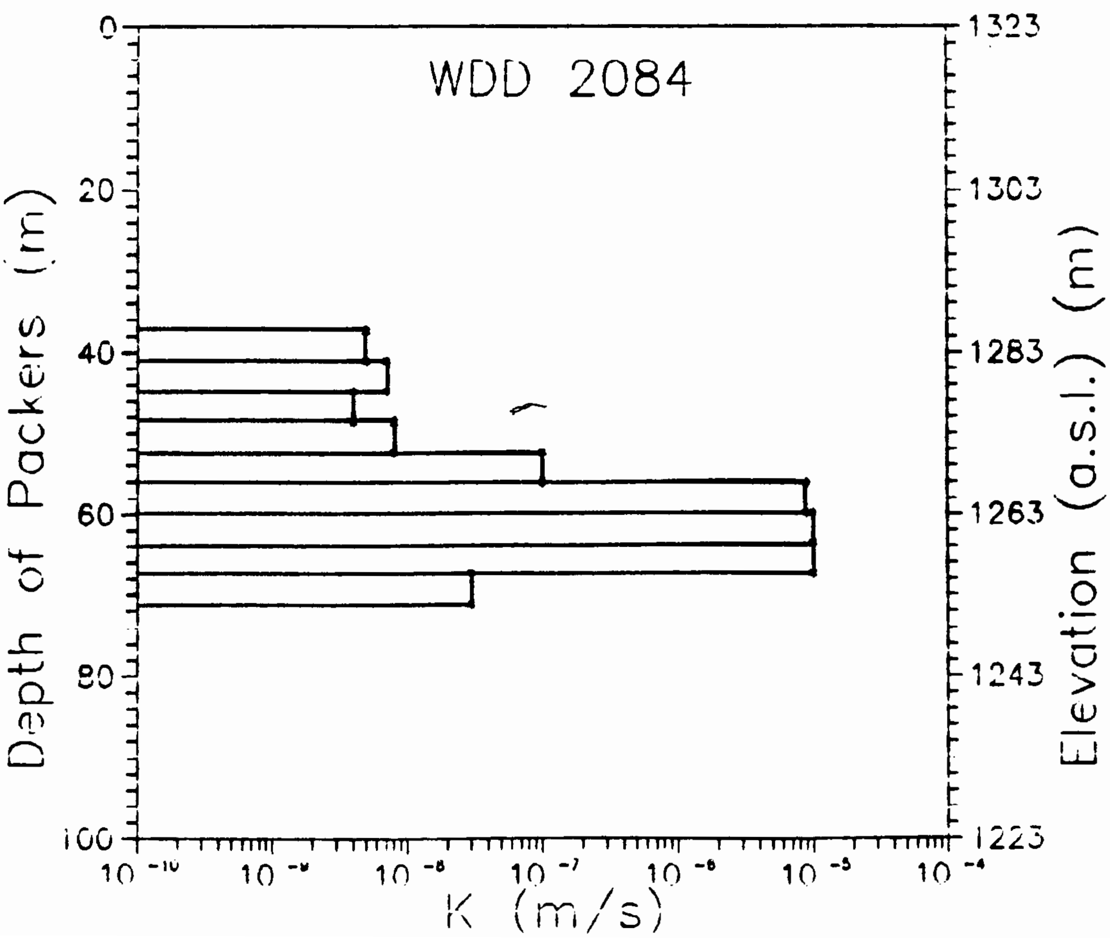
GROUND SURFACE ELEVATION: 1323 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
37.40	41.14	36.21	36.16	2.54	0.05	0.02	5E-09
41.14	44.88	36.13	35.89	5.23	0.18	0.03	7E-09
44.88	48.62	35.95	35.04	5.04	0.09	0.02	4E-09
48.62	52.36	36.07	35.83	4.97	0.18	0.04	8E-09
52.36	56.10	36.10	36.12	4.34	2.13	0.49	1E-07
56.10	59.84	36.18	36.20	0.40	15.83	39.58	9E-06
59.84	63.58	35.59	36.44	0.44	28.33	64.39	1E-05
63.58	67.32	36.68	36.12	0.28	16.00	57.14	1E-05
67.32	71.06	36.06	35.63	4.74	0.71	0.15	3E-08

* Equivalent Porous Media Hydraulic Conductivity

WDD 2084 Packer test results

A.4 Plot of hydraulic conductivity versus depth for WDD 2084



BOREHOLE NUMBER: WDD 1720

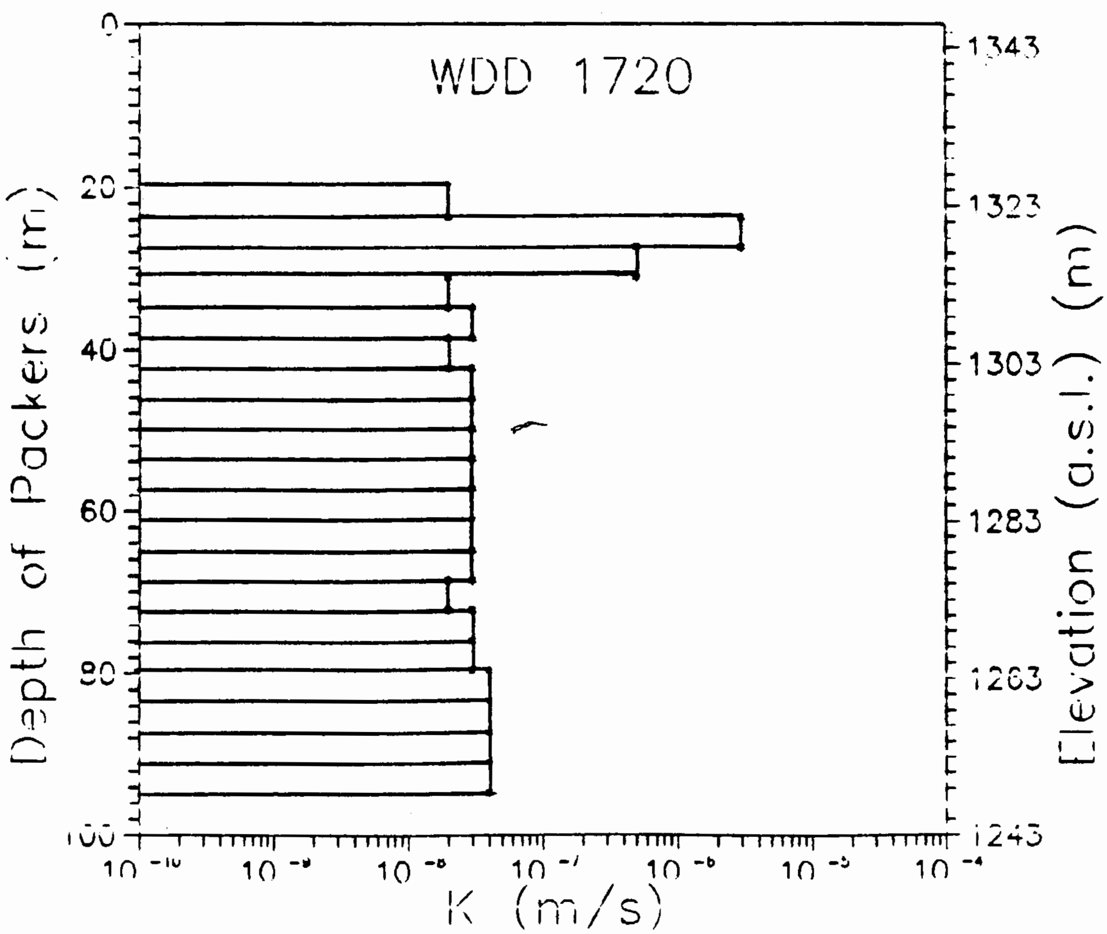
GROUND SURFACE ELEVATION:1343 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
19.88	23.62	11.49	11.45	4.89	0.35	0.07	2E-06
23.62	27.36	11.49	11.92	Rising	Head	Test	3E-06
27.36	31.10	11.47	11.54	5.00	10.33	2.07	5E-07
31.10	34.84	11.47	11.24	4.72	0.35	0.08	2E-08
34.84	38.58	11.45	11.26	4.60	0.53	0.12	3E-08
38.58	42.32	11.40	11.35	4.72	0.53	0.11	2E-08
42.32	46.06	13.32	13.18	4.69	0.71	0.15	3E-08
46.06	49.80	13.45	13.23	4.66	0.71	0.15	3E-08
49.80	53.54	13.50	13.31	4.59	0.71	0.15	3E-08
53.54	57.28	13.47	13.17	4.62	0.71	0.15	3E-08
57.28	61.02	13.45	13.14	4.58	0.71	0.15	3E-08
61.02	64.76	13.40	13.07	4.66	0.71	0.15	3E-08
64.76	68.50	13.24	12.67	4.65	0.53	0.11	3E-08
68.50	72.24	18.12	17.81	4.59	0.35	0.08	2E-08
72.24	75.98	18.29	18.13	4.65	0.53	0.11	3E-08
75.98	79.72	18.47	18.16	4.61	0.53	0.12	3E-08
79.72	83.46	18.75	18.43	4.53	0.89	0.20	4E-08
83.46	87.20	18.95	18.85	4.51	0.89	0.20	4E-08
87.20	90.94	19.24	18.98	4.47	0.89	0.20	4E-08
90.94	94.68	19.08	18.17	Rising	Head	Test	4E-08

* Equivalent Porous Media Hydraulic Conductivity

WDD 1720 Packer test results

A.5 Plot of hydraulic conductivity versus depth for WDD 1720



BOREHOLE NUMBER: WDD 2219

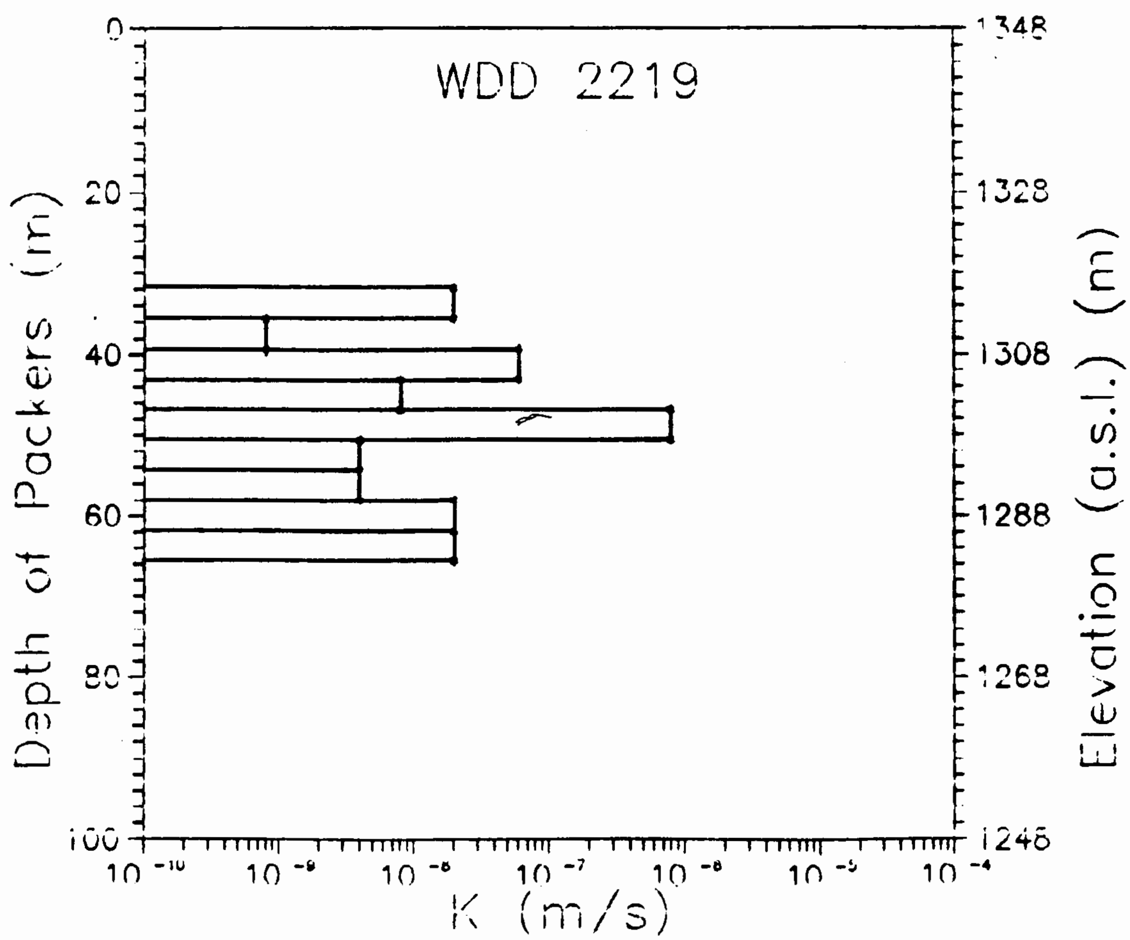
GROUND SURFACE ELEVATION: 1348 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
31.93	35.67	31.72	31.01	4.28	0.35	0.08	2E-08
35.67	39.41	31.72	51.53	5.05	0.02	0.00	8E-10
39.41	43.15	31.68	31.18	4.41	1.24	0.28	6E-08
43.15	46.89	31.65	31.48	5.10	0.18	0.03	8E-09
46.89	50.63	30.96	30.64	4.00	15.00	3.75	8E-07
50.63	54.37	30.55	30.54	4.99	0.09	0.02	4E-09
54.37	58.11	30.13	30.31	5.04	0.09	0.02	4E-09
58.11	61.85	29.91	29.56	5.88	0.53	0.09	2E-08
61.85	65.59	29.27	27.96	5.07	0.35	0.07	2E-08

* Equivalent Porous Media Hydraulic Conductivity

WDD 2219 Packer test results

A.6 Plot of hydraulic conductivity versus depth for WDD 2219



BOREHOLE NUMBER: WDD2527

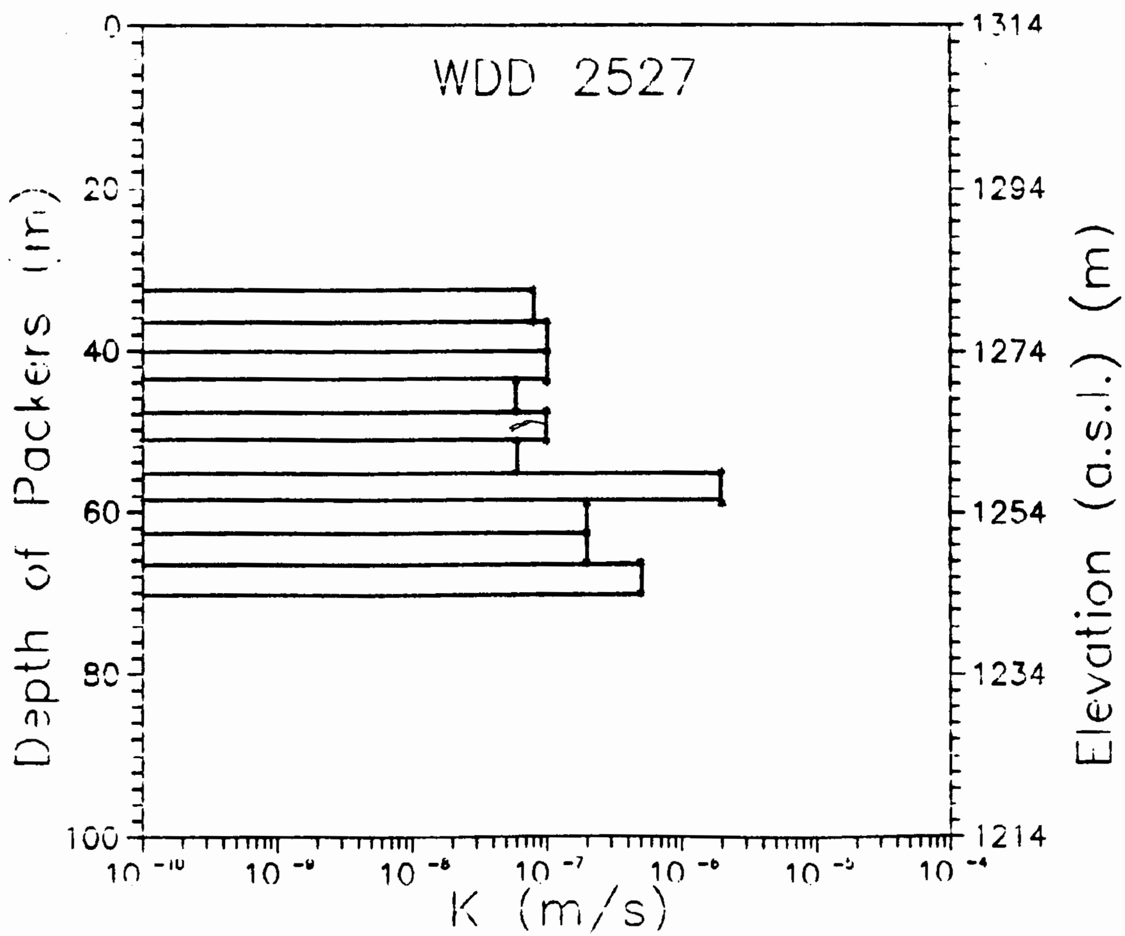
GROUND SURFACE ELEVATION: 1314 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
32.62	36.36	1.82	1.53	4.07	1.42	0.35	8E-08
36.36	40.10	1.99	1.24	Rising	Head	Test	1E-07
40.10	43.84	1.73	1.81	Rising	Head	Test	1E-07
43.84	47.58	2.02	1.90	4.24	1.24	0.29	6E-08
47.58	51.32	2.06	1.89	Rising	Head	Test	1E-07
51.32	55.06	2.20	2.40	Rising	Head	Test	6E-08
55.06	58.80	2.06	1.65	4.00	41.33	10.33	2E-06
58.80	62.54	1.75	1.92	Rising	Head	Test	2E-07
62.54	66.28	2.36	1.32	1.12	1.24	1.11	2E-07
66.28	70.02	1.19	0.65	Rising	Head	Test	5E-07

* Equivalent Porous Media Hydraulic Conductivity
** Test Zone Cancelled -Suspected Leakage

WDD 2527 Packer test results

A.7 Plot of hydraulic conductivity versus depth for WDD 2527



BOREHOLE NUMBER: WDD 1541

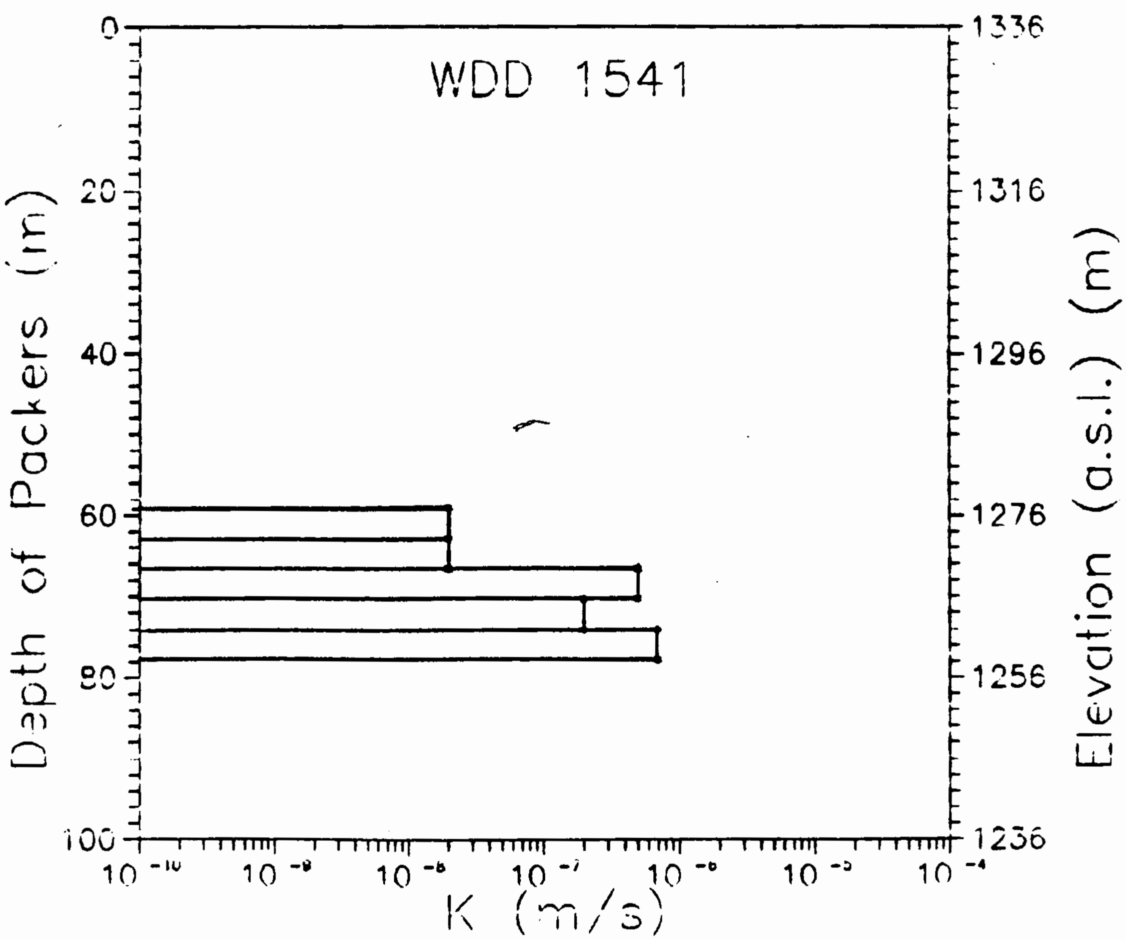
GROUND SURFACE ELEVATION: 1336 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL Top metres	Bottom metres	PRE-TEST WATER LEVELS Open Hole (m.b.d.)	Test Zone (m.b.d.)	H Hydraulic Head metres	Q Flowrate ml/s	Q/ H ml/s/m	K * m/sec
59.14	62.88	35.71	35.60	4.80	0.35	0.07	2E-08
62.88	66.62	35.41	35.23	4.69	0.53	0.11	2E-08
66.62	70.36	37.13	36.62	Rising	Head	Test	5E-07
70.36	74.10	36.99	37.06	Rising	Head	Test	2E-07
74.10	77.84	36.58	35.97	3.03	9.17	3.03	7E-07

* Equivalent Porous Media Hydraulic Conductivity

WDD 1541 Packer test results

A.8 Plot of hydraulic conductivity versus depth for WDD 1541



BOREHOLE NUMBER: WDD 2027

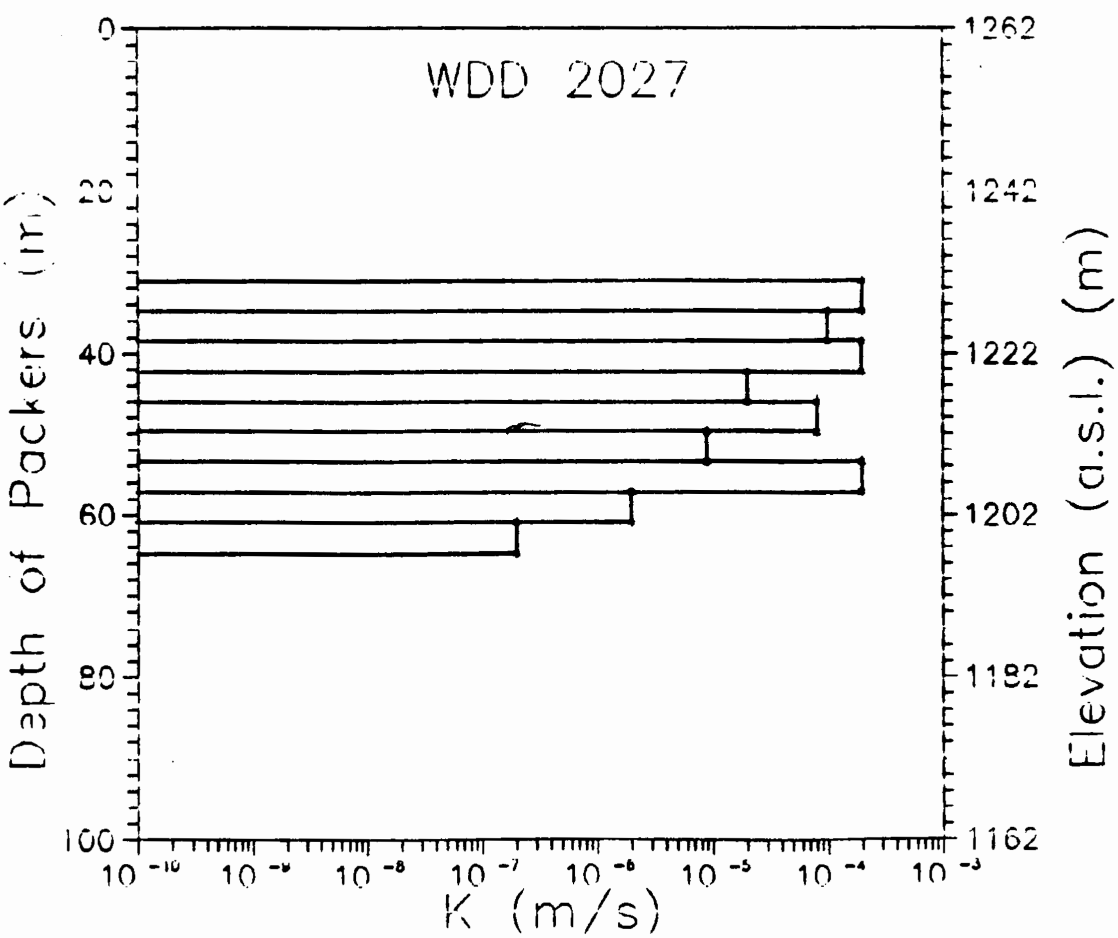
GROUND SURFACE ELEVATION: 1262 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
31.10	34.84	28.54	28.62	0.03	25.33	844.44	2E-04
34.84	38.58	28.60	28.67	0.03	14.67	488.89	1E-04
38.58	42.32	28.61	28.60	0.05	40.00	800.00	2E-04
42.32	46.06	28.63	28.61	0.59	45.00	76.27	2E-05
46.06	49.80	28.63	28.63	0.17	60.00	352.94	8E-05
49.80	53.54	28.60	28.63	1.37	55.00	40.15	9E-06
53.54	57.28	28.55	28.57	0.73	650.00	890.41	2E-04
57.28	61.02	28.58	28.58	3.42	31.67	9.26	2E-06
61.02	64.76	28.54	28.50	Rising	Head	Test	2E-07

* Equivalent Porous Media Hydraulic Conductivity

WDD 2027 Packer test results

A.9 Plot of hydraulic conductivity versus depth for WDD 2027



BOREHOLE NUMBER: WDD 2049

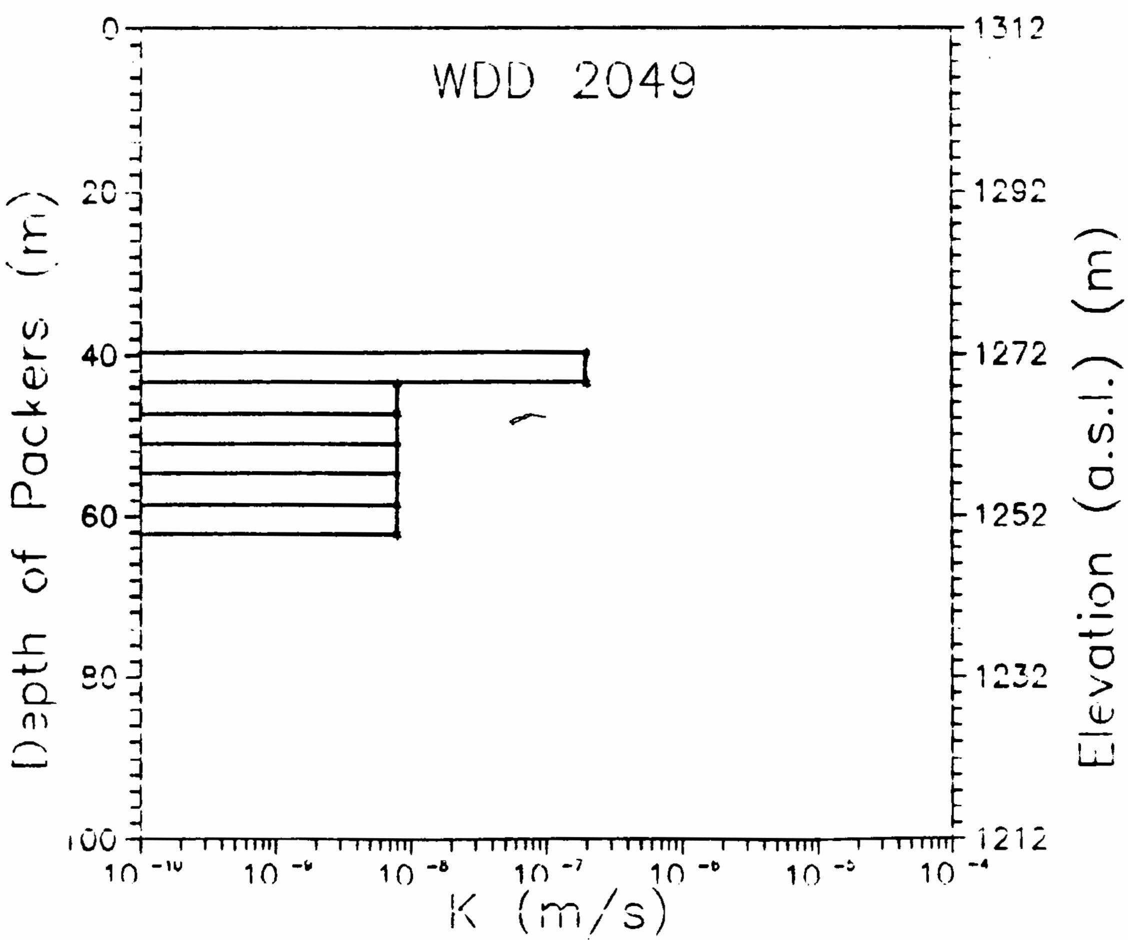
GROUND SURFACE ELEVATION: 1312 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
32.96	36.70	15.58	15.51	1.06	19.17	18.08	4E-06
36.70	40.44	15.51	15.30	4.27	1.24	0.29	6E-08
40.44	44.18	15.50	15.15	4.51	0.89	0.20	4E-08
44.18	47.92	15.50	14.77	4.53	0.53	0.12	3E-08
47.92	51.66	15.44	15.55	5.00	7.50	1.50	3E-07
51.66	55.40	15.45	15.41	Rising	Head	Test	3E-07
55.40	59.14	15.44	14.75	Rising	Head	Test	3E-07

* Equivalent Porous Media Hydraulic Conductivity

WDD 2049 Packer test results

A.10 Plot of hydraulic conductivity versus depth for WDD 2049



BOREHOLE NUMBER: WDD 2043

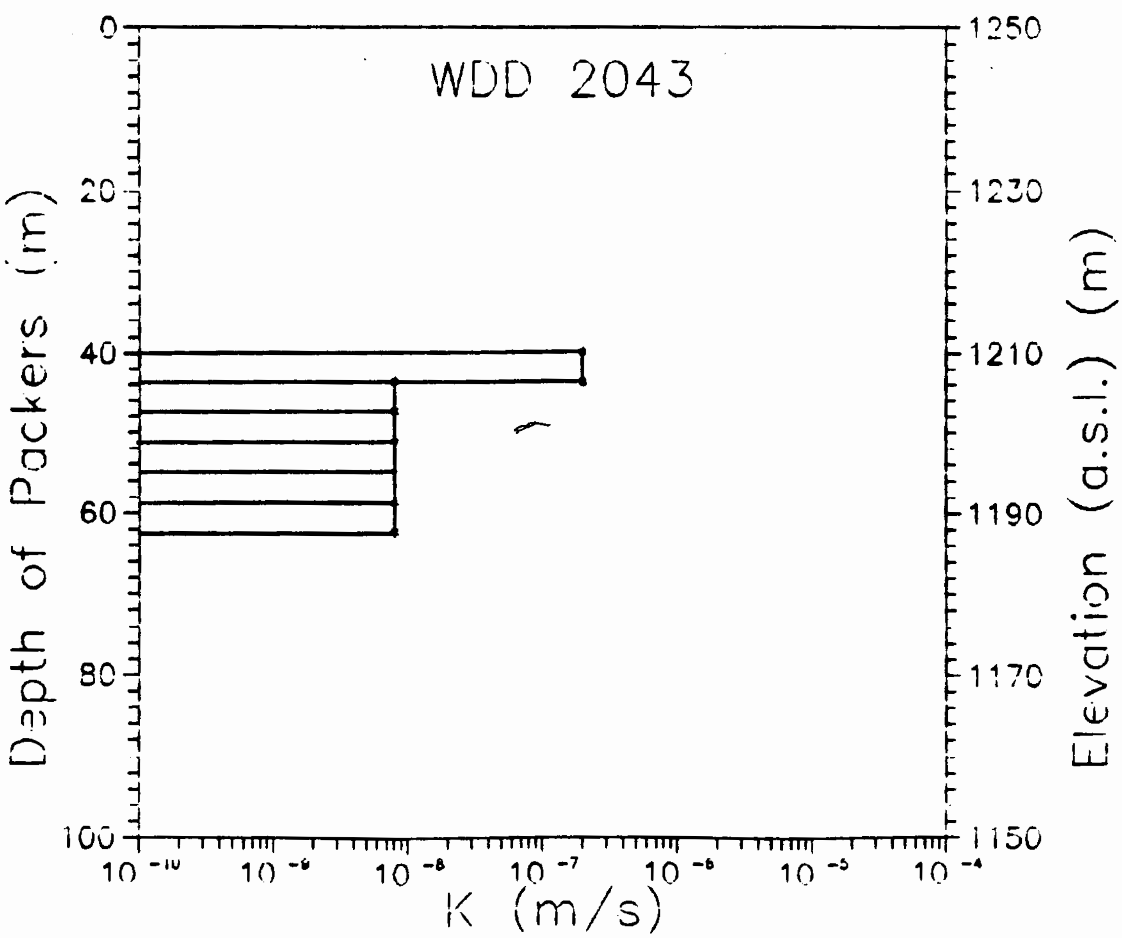
GROUND SURFACE ELEVATION: 1250 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
39.85	43.59	33.36	33.36	Rising	Head	Test	2E-07
43.59	47.33	33.32	33.66	4.58	0.18	0.04	8E-09
47.33	51.07	33.12	32.99	4.85	0.18	0.04	8E-09
51.07	54.81	38.95	33.35	4.88	0.18	0.04	8E-09
54.81	58.55	33.54	33.05	4.90	0.18	0.04	8E-09
58.55	62.29	33.29	32.36	4.93	0.18	0.04	8E-09

* Equivalent Porous Media Hydraulic Conductivity

WDD 2043 Packer test results

A.11 Plot of hydraulic conductivity versus depth for WDD 2043



BOREHOLE NUMBER: WDD 1548

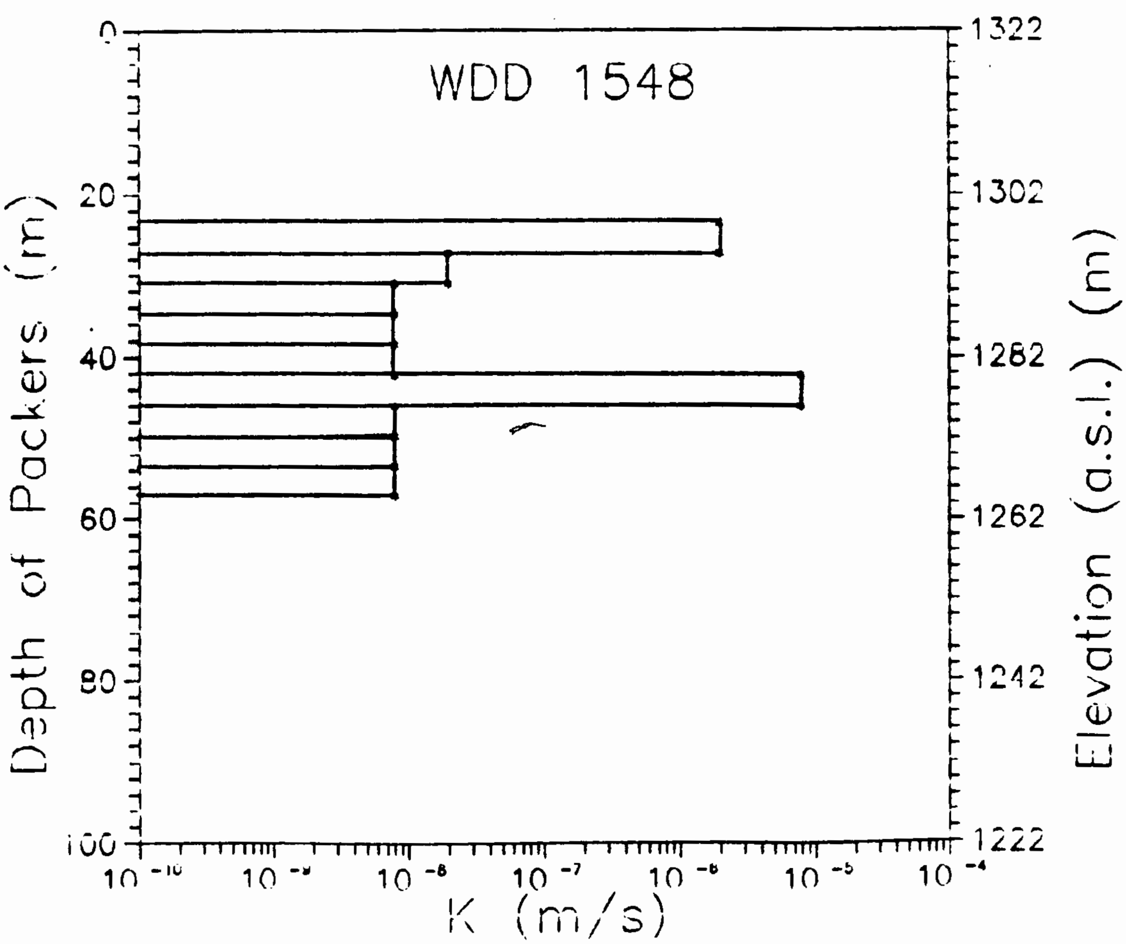
GROUND SURFACE ELEVATION: 1322 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
23.62	27.36	17.45	20.12	2.18	16.67	7.65	2E-06
27.36	31.10	17.73	19.30	4.75	0.35	0.07	2E-08
31.10	34.84	17.84	19.19	4.93	0.18	0.04	8E-09
34.84	38.58	17.88	19.02	4.92	0.18	0.04	8E-09
38.58	42.32	17.97	20.01	4.95	0.18	0.04	8E-09
42.32	46.06	18.76	21.43	1.11	38.00	34.23	8E-06
46.06	49.80	20.45	20.07	4.95	0.18	0.04	8E-09
49.80	53.54	20.45	19.84	4.93	0.18	0.04	8E-09
53.54	57.28	20.43	19.58	4.92	0.18	0.04	8E-09

* Equivalent Porous Media Hydraulic Conductivity

WDD 1548 Packer test results

A.12 Plot of hydraulic conductivity versus depth for WDD 1548



BOREHOLE NUMBER: WDD 2045

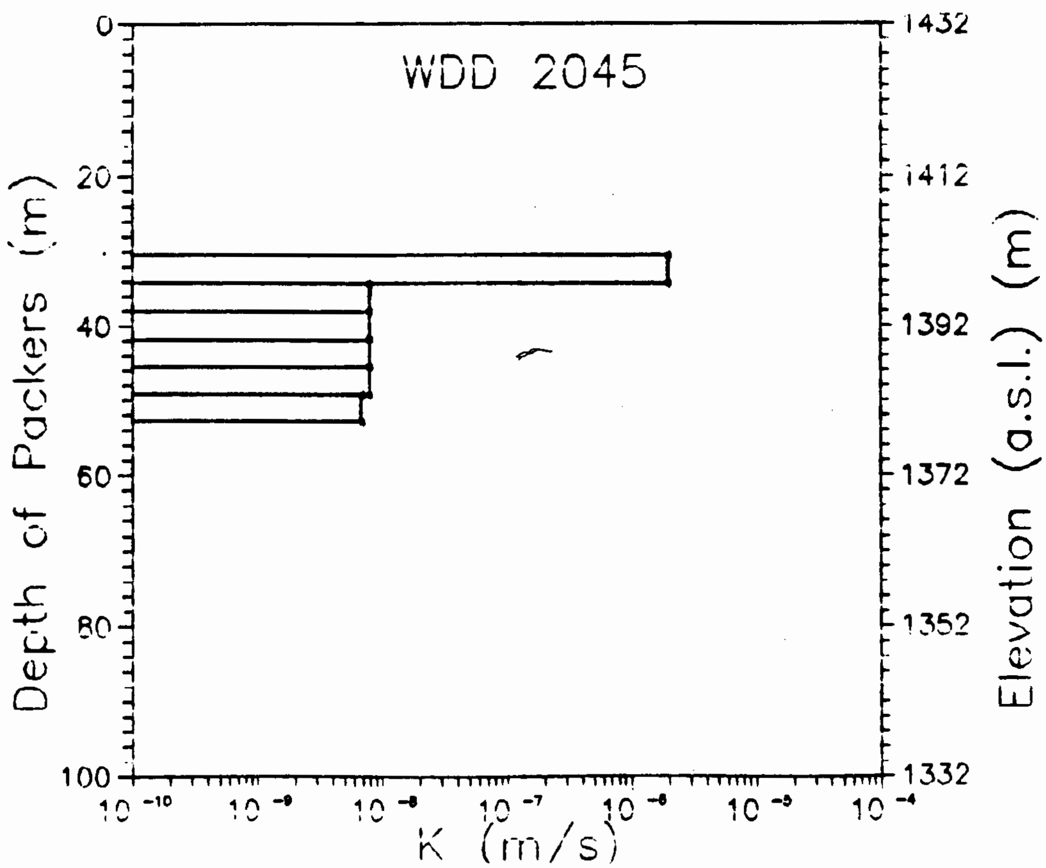
GROUND SURFACE ELEVATION: 1432 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
30.61	34.35	30.45	30.45	1.75	19.67	11.24	2E-06
34.35	38.09	30.30	30.33	5.06	0.18	0.04	8E-09
38.09	41.83	30.31	30.21	4.98	0.18	0.04	8E-09
41.83	45.57	30.36	30.52	4.94	0.18	0.04	8E-09
45.57	49.31	30.46	30.73	4.95	0.18	0.04	8E-09
49.31	53.05	30.56	30.20	5.93	0.18	0.03	7E-09

* Equivalent Porous Media Hydraulic Conductivity

WDD 2045 Packer test results

A.13 Plot of hydraulic conductivity versus depth for WDD 2045



BOREHOLE NUMBER: WDD 1549

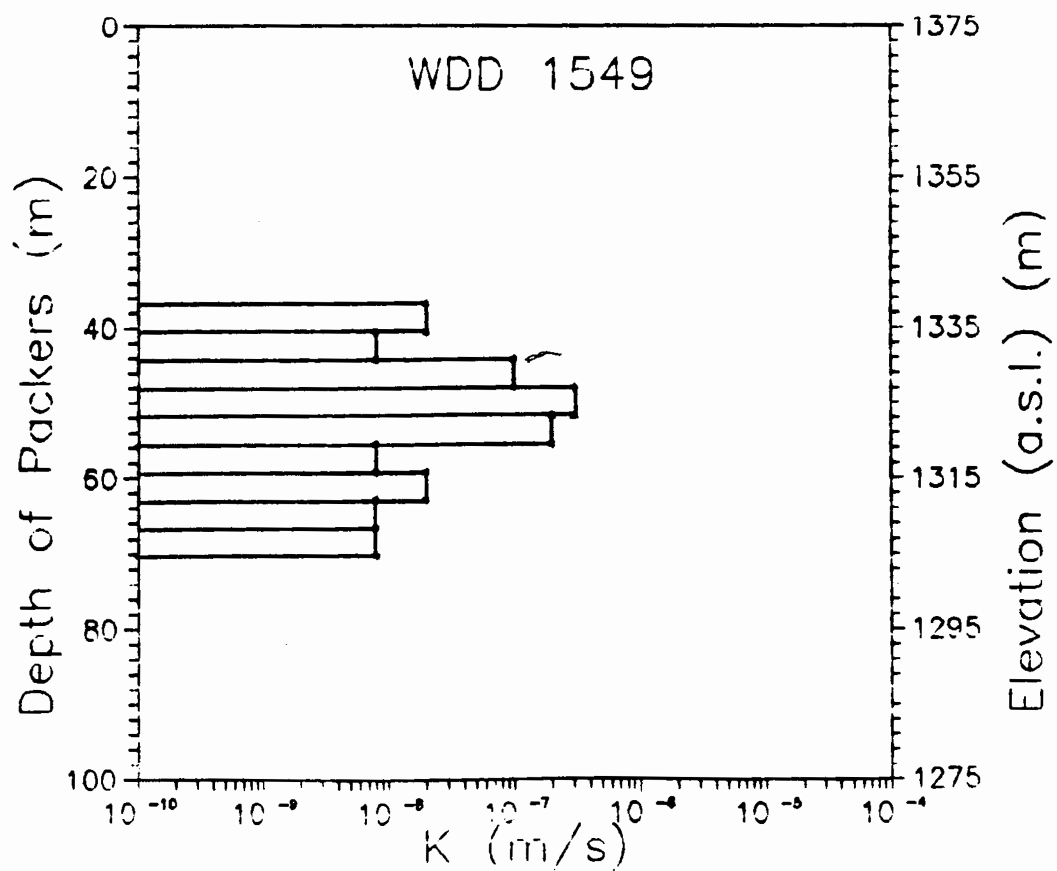
GROUND SURFACE ELEVATION: 1375 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
36.71	40.45	9.65	9.41	4.85	0.35	0.07	2E-08
40.45	44.19	9.65	9.34	5.12	0.18	0.03	8E-09
44.19	47.93	9.64	9.44	2.89	1.59	0.55	1E-07
47.93	51.67	9.65	9.74	1.48	1.95	1.32	3E-07
51.67	55.41	9.64	9.71	1.76	1.59	0.91	2E-07
55.41	59.15	9.63	9.15	4.99	0.18	0.04	8E-09
59.15	62.89	9.63	9.22	4.82	0.35	0.07	2E-08
62.89	66.63	9.63	9.26	4.86	0.18	0.04	8E-09
66.63	70.37	9.63	9.25	4.92	0.18	0.04	8E-09

* Equivalent Porous Media Hydraulic Conductivity

WDD 1549 Packer test results

A.14 Plot of hydraulic conductivity versus depth for WDD 1549



BOREHOLE NUMBER: WDD 2209

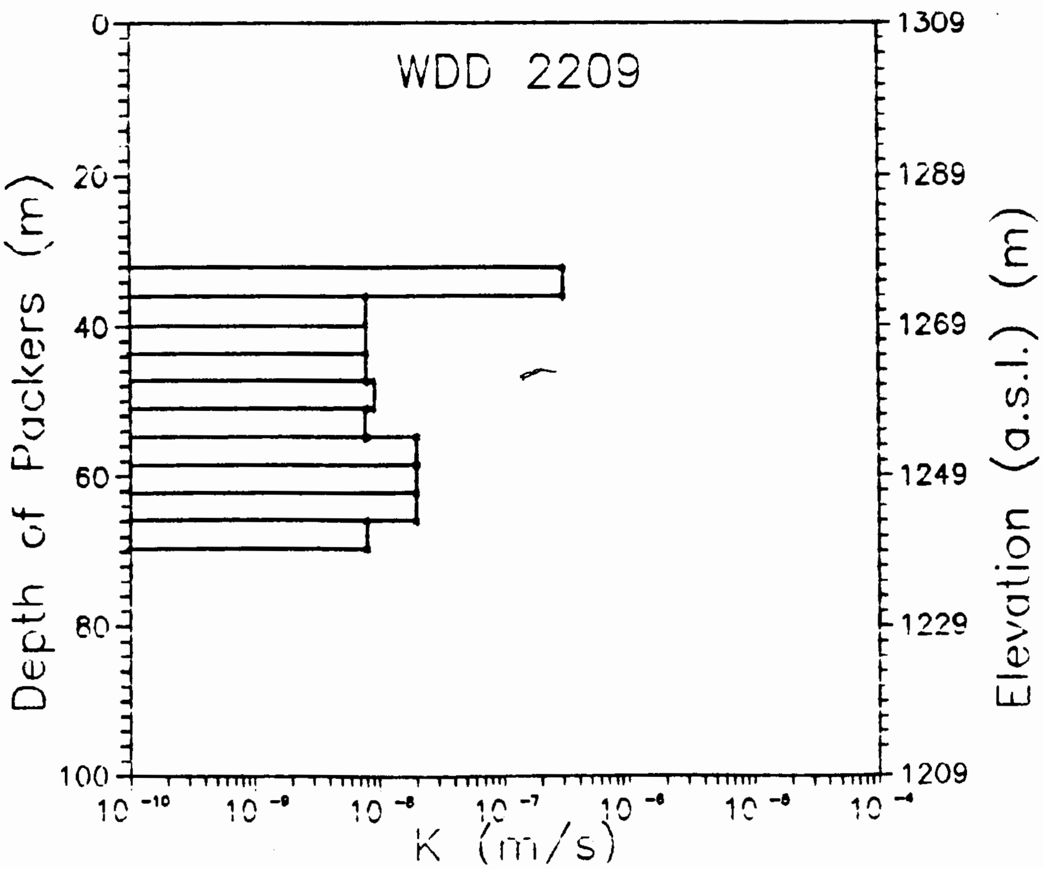
GROUND SURFACE ELEVATION: 1309 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
32.36	36.10	15.25	15.10	2.21	3.01	1.36	3E-07
36.10	39.84	15.32	14.78	5.13	0.18	0.03	8E-09
39.84	43.58	15.36	14.58	4.94	0.18	0.04	8E-09
43.58	47.32	15.40	15.03	5.14	0.18	0.03	8E-09
47.32	51.06	15.40	14.61	4.40	0.18	0.04	9E-09
51.06	54.80	15.28	15.23	4.64	0.18	0.04	8E-09
54.80	58.54	15.32	15.15	4.88	0.35	0.07	2E-08
58.54	62.28	15.16	15.17	4.63	0.35	0.08	2E-08
62.28	66.02	15.22	14.71	4.81	0.35	0.07	2E-08
66.02	69.76	15.25	14.60	4.79	0.18	0.04	8E-09

* Equivalent Porous Media Hydraulic Conductivity

WDD 2209 Packer test results

A.15 Plot of hydraulic conductivity versus depth for WDD 2209



BOREHOLE NUMBER: WDD 2225

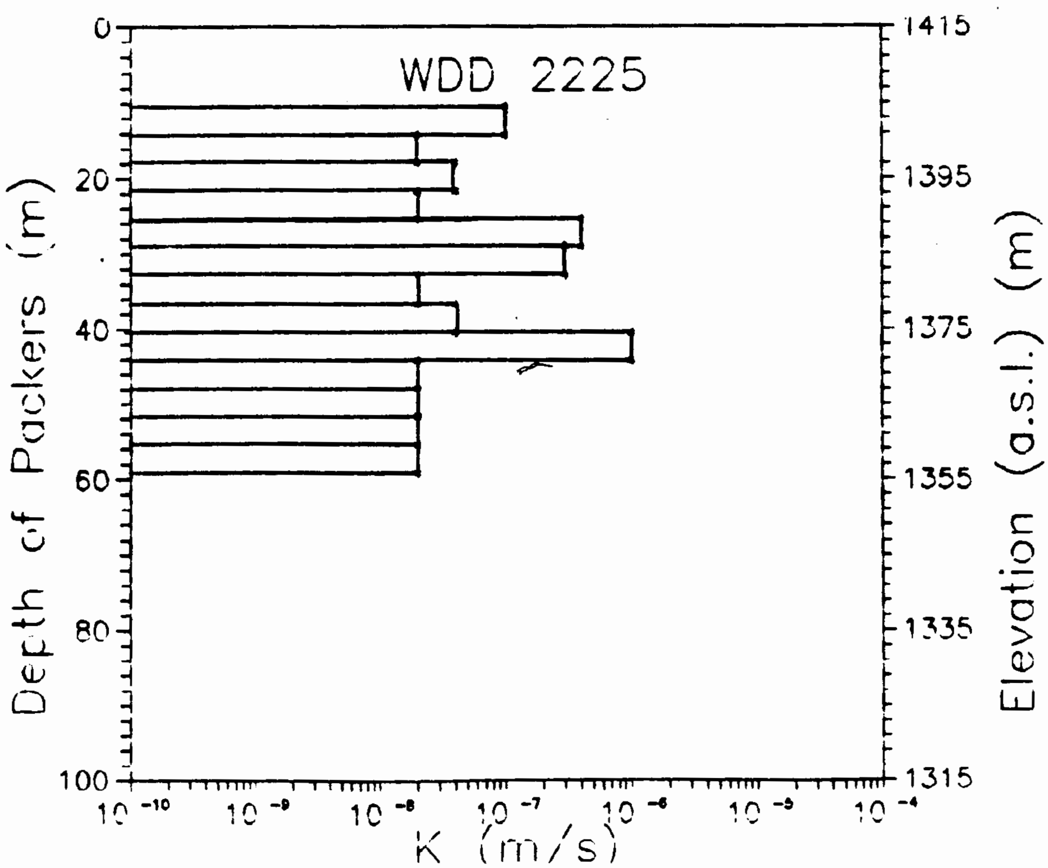
GROUND SURFACE ELEVATION: 1415 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL Top metres	Bottom metres	PRE-TEST WATER LEVELS Open Hole (m.b.d.)	Test Zone (m.b.d.)	H Hydraulic Head metres	Q Flowrate ml/s	Q/ H ml/s/m	K * m/sec
10.53	14.27	1.10	1.41	3.47	2.30	0.66	1E-07
14.27	18.01	1.16	1.39	4.83	0.35	0.07	2E-08
18.01	21.75	1.15	1.30	4.47	0.89	0.20	4E-08
21.75	25.49	1.12	1.35	4.83	0.35	0.07	2E-08
25.49	29.23	1.18	1.64	4.90	8.67	1.77	4E-07
29.23	32.97	1.24	1.16	5.00	7.33	1.47	3E-07
32.97	36.71	1.27	0.95	4.67	0.53	0.11	2E-08
36.71	40.45	1.30	1.15	4.63	0.89	0.19	4E-08
40.45	44.19	1.40	0.84	5.00	30.00	6.00	1E-06
44.19	47.93	1.50	1.11	4.79	0.35	0.07	2E-08
47.93	51.67	1.55	1.05	4.86	0.35	0.07	2E-08
51.67	55.41	1.58	1.04	4.68	0.53	0.11	2E-08
55.41	59.15	1.64	1.16	4.78	0.35	0.07	2E-08

* Equivalent Porous Media Hydraulic Conductivity

WDD 2225 Packer test results

A.16 Plot of hydraulic conductivity versus depth for WDD 2225



BOREHOLE NUMBER: WDD 2213

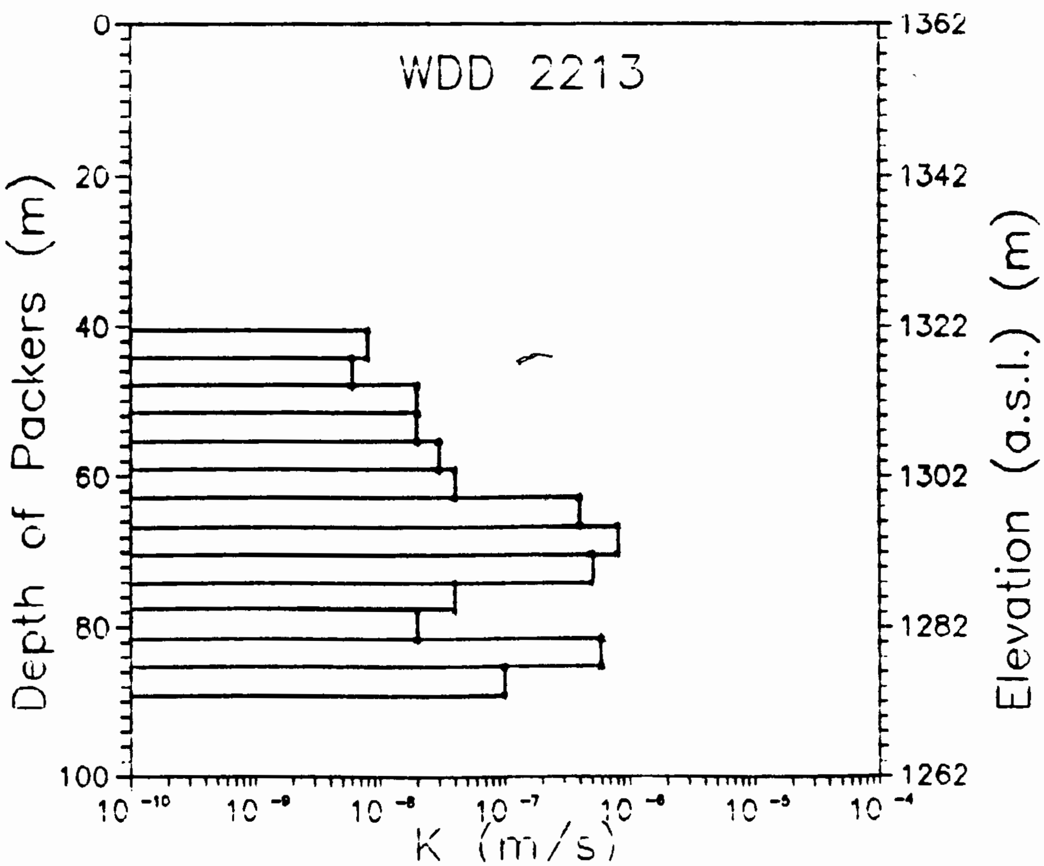
GROUND SURFACE ELEVATION: 1362 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL Top metres	Bottom metres	PRE-TEST WATER LEVELS Open Hole (m.b.d.)	Test Zone (m.b.d.)	H Hydraulic Head metres	Q Flowrate ml/s	Q/ H ml/s/m	K * m/sec
40.45	44.19	23.81	23.96	4.96	0.18	0.04	8E-09
44.19	47.93	23.73	23.92	6.05	0.18	0.03	6E-09
47.93	51.67	23.78	23.97	4.87	0.35	0.07	2E-08
51.67	55.41	23.80	23.86	4.72	0.53	0.11	2E-08
55.41	59.15	23.83	24.01	4.58	0.71	0.15	3E-08
59.15	62.89	23.96	24.19	4.40	0.88	0.20	4E-08
62.89	66.63	23.98	24.31	2.09	3.72	1.78	4E-07
66.63	70.37	24.08	24.23	5.01	18.00	3.59	8E-07
70.37	74.11	23.91	23.34	5.00	11.67	2.33	5E-07
74.11	77.85	23.75	23.56	4.36	0.71	0.16	4E-08
77.85	81.59	23.30	23.82	4.72	0.35	0.08	2E-08
81.59	85.33	23.82	23.72	5.00	13.67	2.73	6E-07
85.33	89.07	23.59	23.09	3.83	1.77	0.46	1E-07

* Equivalent Porous Media Hydraulic Conductivity

WDD 2213 Packer test results

A.17 Plot of hydraulic conductivity versus depth for WDD 2213

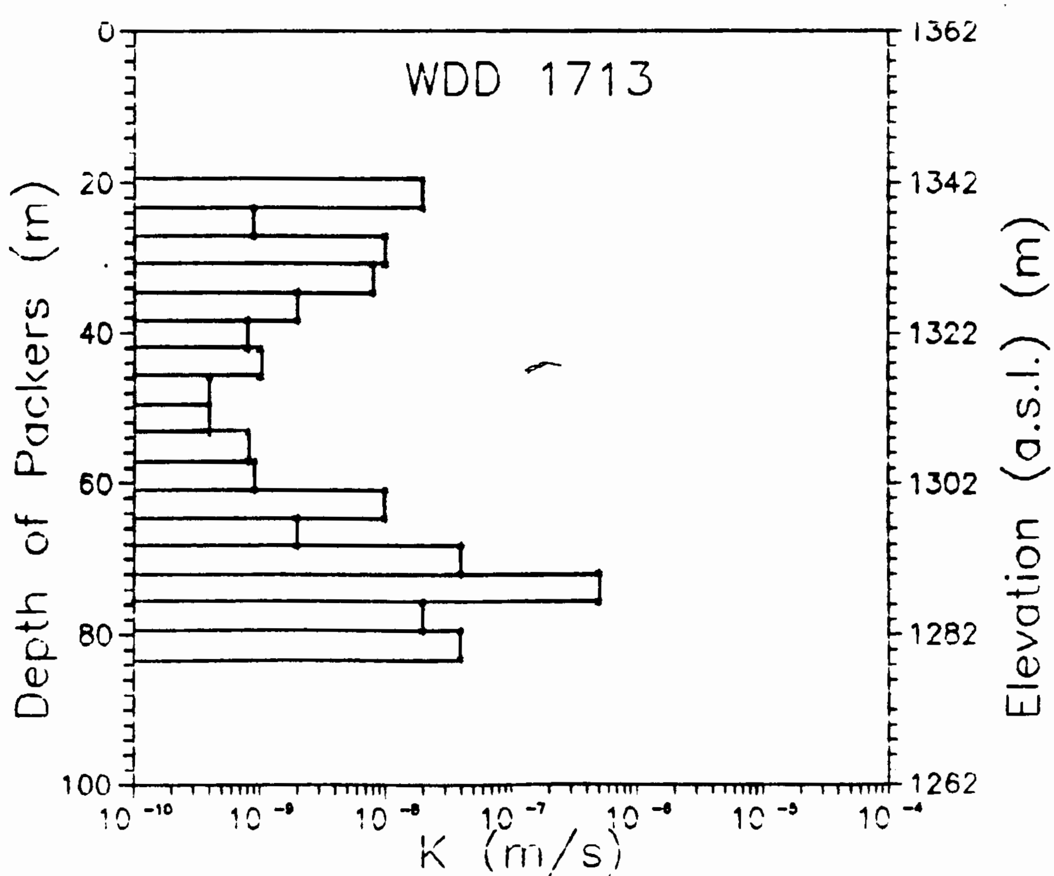


BOREHOLE NUMBER: WDD 1713

GROUND SURFACE ELEVATION: 1362 m
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
19.68	23.42	18.06	16.88	5.53	0.59	0.11	2E-08
23.40	27.14	19.66	18.54	23.60	0.09	0.00	9E-10
27.14	30.86	19.14	17.16	7.02	0.38	0.05	1E-08
30.84	34.58	20.29	19.85	4.19	0.15	0.04	8E-09
34.58	38.30	21.98	20.46	5.08	0.04	0.01	2E-09
38.18	41.90	21.71	20.57	10.38	0.04	0.00	8E-10
41.90	45.64	20.67	19.23	19.04	0.10	0.00	1E-09
45.64	49.38	21.97	21.97	18.17	0.04	0.00	4E-10
49.38	53.12	20.81	20.53	19.30	0.04	0.00	4E-10
53.12	56.86	18.98	22.02	17.15	0.07	0.00	8E-10
56.86	60.62	21.12	21.59	18.05	0.07	0.00	9E-10
60.60	64.34	20.53	19.83	18.95	1.08	0.06	1E-08
64.32	68.08	18.21	17.73	22.36	0.17	0.01	2E-09
68.08	71.82	16.09	16.39	18.61	3.22	0.17	4E-08
71.82	75.58	14.70	15.56	13.18	29.17	2.21	5E-07
75.56	79.30	14.59	14.19	1.91	0.21	0.11	2E-08
79.30	83.04	14.41	13.39	2.27	0.42	0.18	4E-08

* Equivalent Porous Media Hydraulic Conductivity



BOREHOLE NUMBER: WDD 1714 BEFORE HYDROFRACTURE

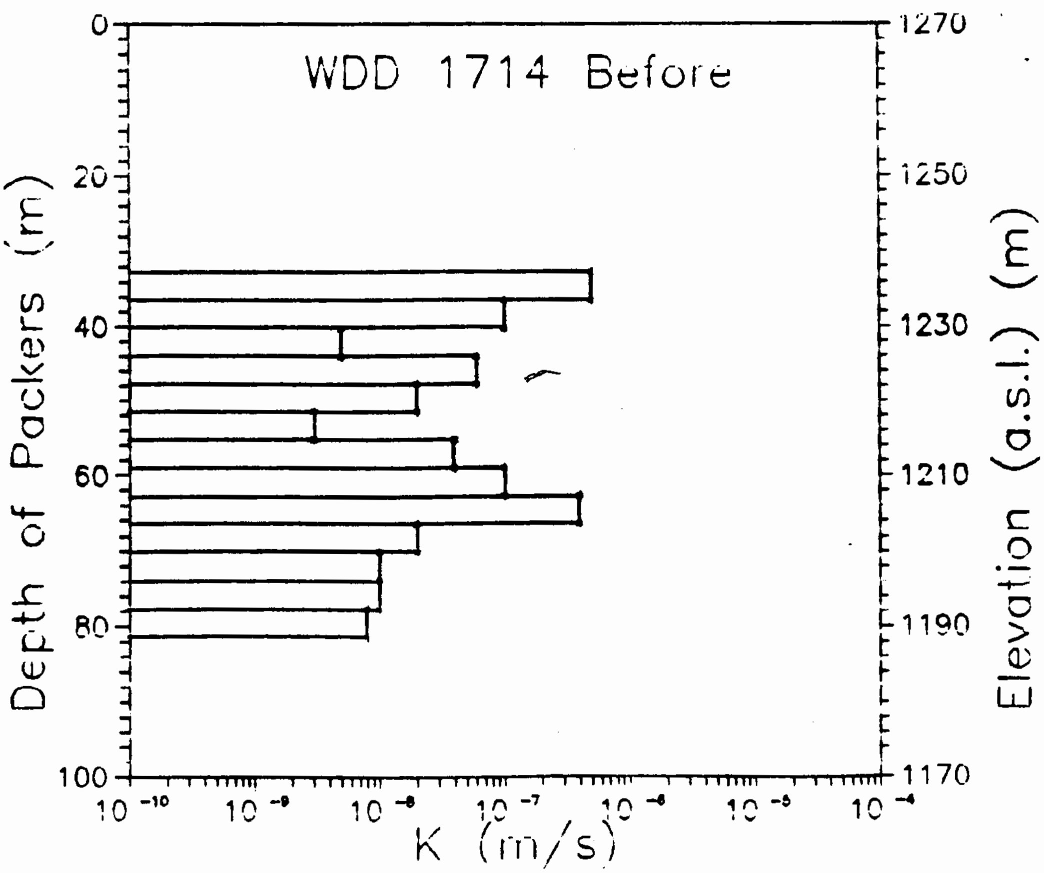
GROUND SURFACE ELEVATION:
Ri: 10m Rw: 0.0575m

TEST INTERVAL		PRE-TEST WATER LEVELS		H	Q	Q/ H	-K
		Open	Test	Hydraulic	Flowrate		*
Top	Bottom	Hole	Zone	Head			
metres	metres	(m.b.d.)	(m.b.d.)	metres	ml/s	ml/s/m	m/sec
32.80	36.54	30.82	29.58	2.12	5.05	2.38	5E-07
36.54	40.28	31.95	31.18	3.82	2.31	0.60	1E-07
40.28	44.02	32.10	30.95	4.94	0.11	0.02	5E-09
44.02	47.76	32.38	29.82	4.83	1.28	0.27	6E-08
47.76	51.50	31.67	31.30	4.93	0.35	0.07	2E-08
51.50	55.24	31.49	30.93	5.15	0.08	0.02	3E-09
55.24	58.98	30.76	29.71	6.35	1.06	0.17	4E-08
58.98	62.72	32.16	29.19	9.81	4.42	0.45	1E-07
62.72	66.46	30.50	29.35	9.00	18.33	2.04	4E-07
66.46	70.20	29.40	28.92	4.92	0.37	0.08	2E-08
70.20	73.94	28.95	28.50	4.90	0.24	0.05	1E-08
73.94	77.68	28.83	27.63	4.88	0.26	0.05	1E-08
77.68	81.42	27.17	26.28	5.11	0.18	0.03	8E-09

* Equivalent Porous Media Hydraulic Conductivity

WDD 1714 Packer test results, before hydrofracturing

A.19 Plot of hydraulic conductivity versus depth for WDD 1714, before hydrofracture



BOREHOLE NUMBER: WDD 1714 AFTER HYDROFRACTURE

GROUND SURFACE ELEVATION: 1270 m

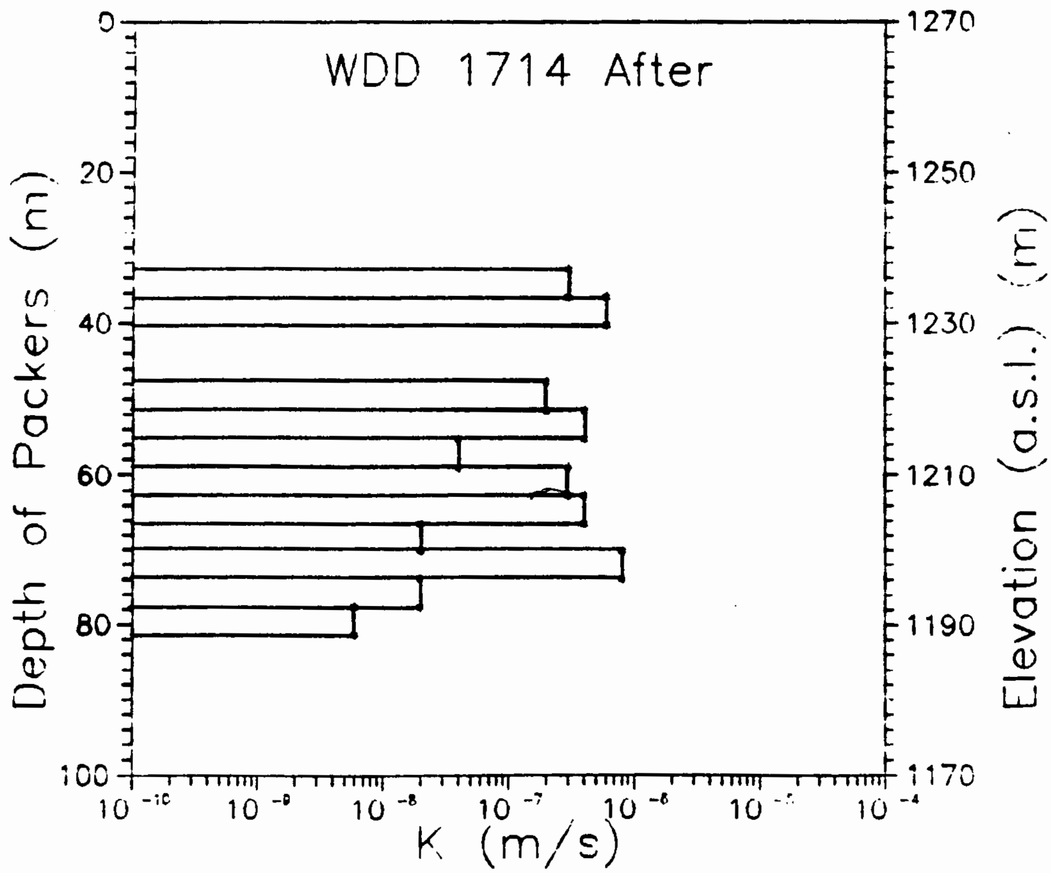
Ri: 10m Rw: 0.0575m

TEST INTERVAL Top metres	Bottom metres	PRE-TEST WATER LEVELS Open Hole (m.b.d.)	Test Zone (m.b.d.)	H Hydraulic Head metres	Q Flowrate ml/s	Q/ H ml/s/m	K * m/sec
32.80	36.54	28.65	28.65	0.04	0.06	1.50	3E-07
36.54	40.28	28.79	28.69	0.12	0.35	2.95	6E-07
40.28	44.02	28.64	28.74				
44.02	47.76	28.58	28.63				
47.76	51.50	28.84	33.40	7.23	6.83	0.95	2E-07
51.50	55.24	29.65	33.40	10.00	18.33	1.83	4E-07
55.24	58.98	29.78	36.44	8.52	1.69	0.20	4E-08
58.98	62.72	28.71	29.05	4.95	7.08	1.43	3E-07
62.72	66.46	29.05	28.94	9.06	17.50	1.93	4E-07
66.46	70.20	29.32	28.35	5.25	0.46	0.09	2E-08
70.20	73.94	29.20	28.26	5.08	17.72	3.49	8E-07
73.94	77.68	28.42	28.77	5.53	0.43	0.08	2E-08
77.68	81.42	27.00	26.10	5.44	0.15	0.03	6E-09

* Equivalent Porous Media Hydraulic Conductivity

WDD 1714 Packer test results, after hydrofracturing

A.20 Plot of hydraulic conductivity versus depth for WDD 1714, after hydrofracture



A5 Borehole parameter information

Borehole Number	Map Number	Elevation (m)	Hole Depth (m)	Potentio-metric Surface (m)	Water 1 Struck a.d. (m)	Main Supply a.d. (m)	Rest Level a.d. (m)	Casing Level a.d. (m)	Yield (L/hr)
WDD1720	1	1344	97.6	1294	1332	1294	1332.34	1337.2	340
DS732	2	1287	88.7	1233.6	1233.7	1233.6	1262.6	1267.5	787.4
DS735	3	1216	84.5	1139.7	1178.5	1139.7	1200.8	1197.4	681.4
WDD2027	4	1263	67.1	N/A	1233	1263	1235.6	1241.1	4000
WDD2190	5	1293	73	1263.7	ERR	1263.7	1271.9	1263.7	860
DS728	6		58.5	N/A	-47.3	-47.3	-11	-10.7	514.8
DS727	7	1341	70.1	1298.3	1298.3	1298.3	1319.7	1311.8	666.2
WDD1534	8	1281	69.1	1230.2	1236.3	1230.2	1246.54	1260.7	2000
WDD1536	9	1290	56.9	1263.6	1263.6	1263.6	1278	1275.8	800
WDD1535**	10	1325	63	1286.4	1286.4	1286.4	1311.8	1311	1600
CD3017**	11	1309	152.4	1206.8	1309	1206.8	1269.7	1309	303
WDD1715	12	1293	111	N/A	ERR	1293	1265	1259.2	dry
WDD1716**	13	1293	109.8	N/A	1250.3	1293	1290	1284.5	poor
WDD1714	14	1270	85.4	1193.8	1193.8	1193.8	1242	1243.2	450
WDD1712**	15	1314	85	1274	1294	1274	1296.4	1297.2	1800
WDD2527	16	1315	72	1259	1276	1259	1314.71	1297.6	720
WDD1713	17	1328	85.4	1254.8	1256	1254.8	1314	1314	600
CD487	18	1295	106.7	1215.7	1262	1215.7	1270.3	1276.1	355.8
DS750	19	1302	37.5	1276.1	1276.1	1276.1	1285.2	1278.9	757.1
WDD1537	20	1313	93.5	1223.6	1268.3	1223.6	1282.24	1282.4	1800
WDD2037	21	1289	91.5	N/A	1289	1289	1289	1285	dry
WDD2046	22	1362	48.8	1330	1330	1330	1344	1331.1	1200
WDD2049	23	1312	63	1267	1277	1267	1297	1279.5	800
CD3009	24	1301	89.3	1220.8	1301	1220.8	1261.4	1301	863.1
WDD2047	25	1315	87.4	1277	1266	1277	1310	1303.85	600
WDD2050	26	1345	81.3	1302	1302	1302	1323.8	1306.4	1000
WDD2187	27	1331	73.2	1297.5	1297.5	1297.5	1316.5	1305.8	1500
DS731	28	1382	45.7	1359.1	1359.1	1359.1	1375.9	1359.1	1022.1
WDD2052	29	1301	87.4	1224	1250.1	1224	1269	1271.95	2400
WDD1550	30	1345	75.2	1315	1315	1315	1325.8	1336.9	600
WDD2051	31	1345	93.5	1308	1313	1308	1315.4	1323.7	600
DS756	32	1461	46.1	1422.6	1422.6	1422.6	1434	1428.8	1620
DS714	33	1356	115.9	1263.9	1263.9	1263.9	1337.44	1327.3	3240
WDD1549	34	1376	75.2	1331.3	1336	1331.3	1366.56	1342.5	800
CD3432**	35	1378	64	N/A	1378	1378	1356.1	1378	522.4
WDD2048	36	1347	62.1	1325	1325	1325	1340.79	1326.7	2400
DS757	37	1354	39	1317.4	1324.1	1317.4	1336.77	1324.1	810
DS751	38	1327	45.8	1285.8	1285.8	1285.8	1292.83	1309.6	945
WDD1548	39	1322	63	1268	1304	1268	1303.6	1304.75	1000
CD530	40	1260	35.1	1226.4	1227.4	1226.4	1245.7	1246.6	8566.4
CD510	41	1262	106.7	1182.7	1178.2	1182.7	1243.7	1254.4	477
CD499	42	1282	91.4	1202.7	1231.6	1202.7	1255.5	1259.5	2454.2
WDD2043	43	1251	60.7	1212.7	1213	1212.7	1220.1	1220.1	500
WDD2210	44		93.5	N/A	0-	0	0	-17.5	dry
WDD2209	45	1308	75.2	1278	1278	1278	1295.63	1290.8	600
WDD1538	46	1278	75.2	1215	1215	1215	1257.55	1254.95	1000
WDD2039	47	1297	61	1269	1269	1269	1285	1297	600
WDD2295	48	1333	120	N/A	1333	1333	1333	1306	poor
WDD2036	49	1368	61	1330	1330	1330	1350.5	1368	1200
WDD2044	50	1349	105.7	1304	1349	1304	1319.05	1310.4	low
WDD2191	51	1492	61	1444	1492	1444	1453.2	1492	poor

WDD2059	52	1428	63	1378	1378	1378	1395.5	1394.5	1800
WDD2060	53	1446	93.5	1408	1446	1408	1412.64	1410.5	dry
CD3294	54				0	0	0	0	
CD3497	55	1489	124	1374	1489	1374	1453.25	1427.1	743
WDD2045	56	1432	61	1401.5	1401.5	1401.5	1402.28	1406.5	1500
WDD2192	58		61	N/A	0	-52	0	0	900
WDD2041**	59	1304	79.3	1276	1276	1276	1288.9	1288	450
CD479	60	1296	91.4	1242.6	1242.7	1242.6	1268	1280.2	2725.5
WDD2458	61	1345	68	N/A	1345	1345	1338.3	1340	1200
WDD2214	62	1321	63	1273	1281	1273	1306	1306.8	1000
WDD2093	63	1417		N/A	1417	1417	1417	1417	
DS725	64	1418	74.4	1376.3	1376.2	1376.3	1395.03	1391.5	792
CD461	65	1373	82.4	1294.3	1373	1294.3	1355.36	1373	625.5
WDD2215	67	1367	81.3	1309	1309	1309	1347.03	1352.8	300
WDD2216	68	1406	69.1	1358	1376	1358	1402.7	1391.8	800
CD371	69	1418	41.5	1377.7	1377.8	1377.7	1418.58	1390.9	416.4
WDD2447	70	1367	69.1	N/A	1344	1367	1358	1346.7	600
DS719	71	1371	88.4	1329.8	1371	1329.8	1334.4	1371	492.1
WDD2218	72	1371	75.2	1308	1314.1	1308	1353	1347.7	2000
WDD2025	73	1382	75.2	1328	1345.5	1328	1362	1349.5	3800
CD409	74	1358	61	1304.6	1358	1304.6	1329	1358	1059.9
WDD2219	75	1348	63	1297.2	1297.2	1297.2	1326.85	1319.6	1800
GS1430	76	1360	100.7	1271.5	1271.5	1271.5	1323.16	1360	720
WDD2026	77	1299	105.7	N/A	1299	1299	1266	1299	dry
WDD2455	78	1296	81.3	N/A	1296	1296	1268.23	1287.9	low yield
WDD2457	79	1278	56.9	1223	1244	1223	1267.72	1275	2500
WDD2085**	80	1281	117	1225.1	1231.2	1225.1	1229.4	1247.6	poor
GS1613	81	1324	68.9	1275.2	1324	1275.2	1295	1324	1703.4
CD91	82	1318	82.3	1266	1265.6	1266	1279.3	1286	4637.1
WDD2081	83		117	N/A	-31.5	0	-36	-29.3	360
WDD2084	84	1323	74.2	1265	1262	1265	1285	1304.7	4000
CD85	85	1312	63.1	1288.2	1288.2	1288.2	1294	1312	696.5
WDD2083	86	1304	74.2	1254.2	1254.2	1254.2	1271	1255.9	920
GS1614	87	1321	83	1278.3	1321	1278.3	1292.71	1321	608
WDD2087	88	1354	73.2	1320.5	1354	1320.5	1317.87	1326.8	1500
WDD2213	89	1362	93.5	1273	1273	1273	1341.5	1305.1	1200
WDD2211	90	1345	87.4	1262.5	1262.5	1262.5	1309.05	1309.4	600
WDD2212	91	1351	93.5	1279	1279	1279	1324.74	1318	1000
WDD2452	92	1356	75.2	1296	1316.4	1296	1340.4	1339.8	2500
WDD2451	93	1379	105.7	1277	1277	1277	1379	1350.6	dry
GS884	94	1370	76.2	1302.9	1330.3	1302.9	1355.7	1356.9	2271.2
CD403	95	1385	59.4	1333.2	1354.5	1333.2	1385	1378.4	757.1
WDD2449	96	1400	93.5	1348	1348	1348	1389.62	1358	1500
WDD2225	97	1415	75.2	1371.3	1371.3	1371.3	1412.27	1408.9	860
CD368	99	1382	47.5	1339.3	1339.3	1339.3	1367.4	1334.5	1514.2
WDD2224	100	1446	63	1402	1428.8	1402	1430.61	1409.4	1800
SPRING		1670							

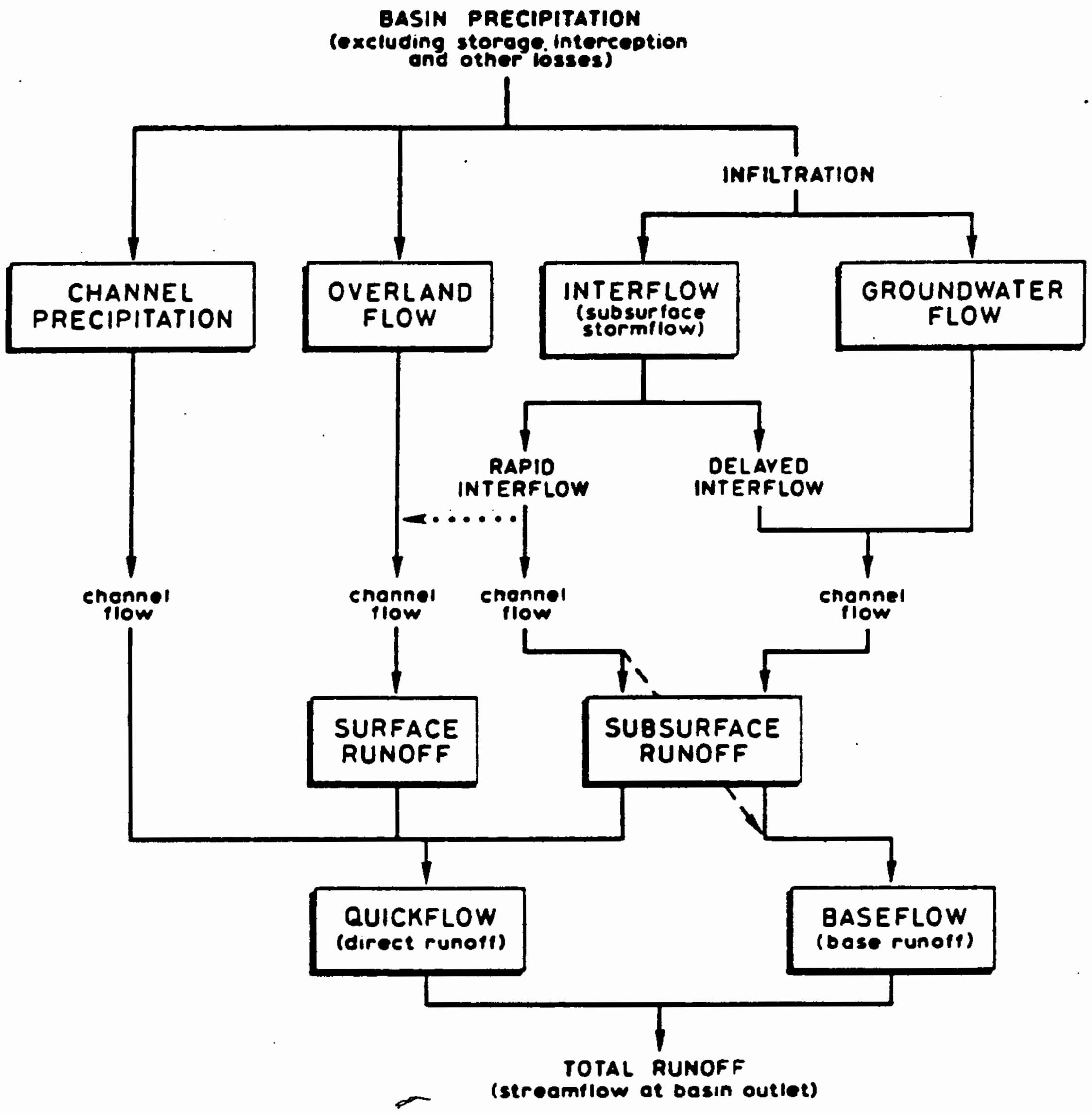


Figure B.1 Diagrammatic representation of the runoff process

APPENDIX B Soil Moisture Balance Approach to Estimating Recharge

Figure:

The soil moisture balance may be expressed by the equation

$$P = RO + AE + S \qquad \text{(B1)}$$

where

P = precipitation mm
RO = direct surface run-off mm (usually expressed as a percentage)
AE = actual evaporation mm
S = water available to soil moisture mm

or, writing in terms of water available to the soil moisture store:

$$S = P - RO - AE \qquad \text{(B2)}$$

Whereas precipitation and run-off are determined from field measurements, actual evaporation cannot be measured directly as it depends on the state of the soil moisture reservoir. The procedure for calculating actual evaporation may be considered in two stages. The first stage is to calculate the change to the soil moisture which would take place if evaporation was to occur at the potential rate. This quantity is termed effective precipitation (EP) and is calculated as

$$EP = P - RO - PE \qquad \text{(B3)}$$

where

PE = potential evaporation,

and the other terms are defined above.

For the second stage of the calculation, the procedure depends on whether effective precipitation is positive or negative.

If effective precipitation is positive, then sufficient rain has fallen to allow evaporation to take place at the potential rate, irrespective of any soil moisture deficit that may exist. The effective precipitation is first used to overcome any existing soil moisture deficit (SMD) and bring the soil to field capacity. Once field capacity is reached further surplus water will drain freely from the soil and recharge the aquifer.

When effective precipitation is negative, recharge will not (according to the classical model) occur under any combination of circumstances. The calculations that are carried out are necessary to determine the values of actual evaporation and the resulting soil moisture deficit. An initial estimate is made of the SMD that would arise if the evaporation remained at the potential rate. If this estimate does not exceed the root constant (C), actual evaporation is equal to the potential rate, and the calculated SMD will be reached. If, however, this estimate is greater than the root constant, or if it exceeds the wilting point (D), then some reduction in evaporation is necessary and the calculated SMD will not be achieved. Usually the rate at which the SMD declines is reduced to 10% of its original for starting SMD's between C and D, and is reduced to zero when the starting SMD is less than or equal to D.

Periodical estimates of P, PE, RO, C and D, allow actual evaporation (AE) and the resulting soil moisture deficit (SMD) to be calculated. Provided that the initial soil moisture deficit is known, progressive estimates of soil moisture deficit allow recharge to be estimated. While this recharge ("infiltration" on Figure B.1) will largely contribute to groundwater flow, it must be recognised that the total recharge, as calculated, also includes any interflow component.

APPENDIX C Hydrochemical Methodology

Table:

Figure:

C1 Introduction

Groundwater hydrochemistry was utilized to characterize groundwater quality and to interpret regional groundwater flow. Major ion (Ca, Mg, Na, K, SO_4, Cl, HCO_3) and trace constituent (Mn, P, Mo, Al, Zn, Ni, Fe, Cr, Co, Cd, As, Se, Sb, V, B, Be, Ba) analyses were used to gain an understanding of natural groundwater evolution and to assist in the construction of the flow network. Isotope analysis, measuring ^{18}O and ^{2}H, was also carried out. The approach was considered important as no previous water analysis had been carried out to characterize the study area on the basis of its hydrochemical parameters.

C2 Description of Sample Survey

Public boreholes were sampled throughout the study area along with the collection of samples from spring discharges in the mountainous region of the west. A total of 60 boreholes and 8 springs were sampled with the sample locations shown in Figure C.1.

C3 Collection and handling of well water samples

Since both major ion and trace constituents were to be measured, two water samples were obtained from each sample location. For major chemistry a 1l sample was collected while a 250 ml volume was sufficient for trace element analysis.

During sampling, every effort was made to ensure that the water samples collected were "flushed samples", fresh from the formation. To achieve this, the boreholes were pumped manually (using the installed India MkII pumps) for approximately 5 minutes. This removed stagnant water within the borehole and in the rising mains so a representative sample of formation (aquifer) water could be collected. If the borehole had been used immediately prior to sampling the procedure described above was deemed unnecessary.

For the analysis of the major ion parameters a 1 litre sample volume was required. Prior to collection, the sample bottle was flushed three times with borehole water. The bottle was then filled to capacity minimizing dead air space, capped and sealed. Once labelled, the sample was transported as quickly as possible to the laboratory.

For trace element collection, the polyethylene sample bottles were prepared by rinsing in a 10 per cent nitric acid bath, followed by rinsing 3 times with distilled water. The sample bottles were then filled to the brim with distilled water and sealed for storage. This procedure was carried out while in Canada due to the difficulty in obtaining chemicals and a constant supply of distilled water in Uganda. Prior to shipment to Uganda, the sample bottles were emptied.

During sample collection, the sample bottle was rinsed 3 times with well water to allow the sample to equilibrate chemically with the bottle surface. Once a 250ml sample had been collected it was preserved by acidifying with Ultrapure nitric acid. Due to time/equipment constraints, the normally prescribed procedure could not be used. The samples were then shipped to Canada for analysis.

Isotope sampling involved the collection of water in a 20ml volume polyethylene bottle. Due to the nature of the isotopes being determined for, special care was needed to minimize the introduction of atmospheric vapour to the sample. Also it was important to reduce the chances of

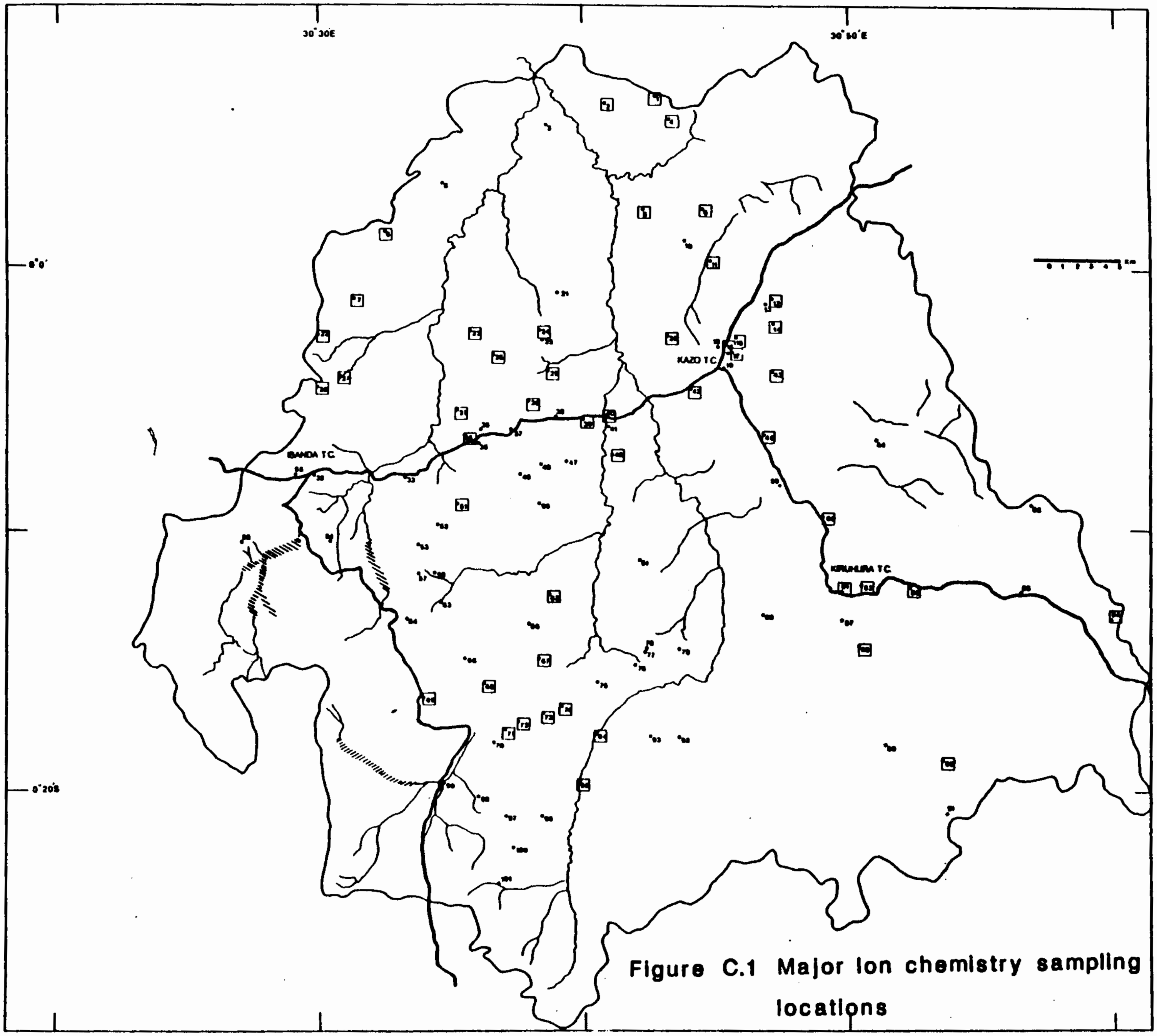


Figure C.1 Major ion chemistry sampling locations evaporation. Thus, once a sample was collected, and the bottle completely filled (with all air bubbles removed), it was tightly capped and secured with tape. The samples were then transported to Canada for analysis.

C4 Analytical Techniques

C4.1 Major Ion Analysis

Major and minor analyses were conducted using the DREL3 Spectrophotometer at the Water Development Departments chemistry laboratory in Luzira.

C4.2 Trace Element Analysis

The acidified well water samples were analyzed for trace constituents using inductively coupled plasma-atomic emission spectrometry or ICP-AES, at the ICP laboratories at the University of Toronto. A total of 22 elements were analyzed using ICP-AES and these are shown in Table C3.1 along with their theoretical detection limit (T.D.L.) and determination limit (D.L. = five times the theoretical detection limit).

Table C3.1 Parameters determined by ICP-AES analysis

Element	T.D.L(mg/L)	D.L.(mg/L)
Be	0.00029	0.001
Ba	0.00025	0.001
Fe	0.0012	0.006
Cr	0.0024	0.012
S	0.0132	0.066
Mg	0.0137	0.0685
As	0.0226	0.113
V	0.0016	0.008
Se	0.0823	0.2115
Mo	0.0068	0.034
Al	0.0164	0.082
Ca	0.0014	0.007
Zn	0.004	0.02
Cu	0.0023	0.0115
Sb	0.0377	0.1885
Pb	0.0460	0.23
Cd	0.0032	0.016
Co	0.0034	0.017
Ni	0.0137	0.0685
P	0.0357	0.1785
B	0.0045	0.0225
Mn	0.0006	0.0030

C5 Isotope Analysis

For deuterium analysis, samples are vapourised and passed over a uranium platelet set in a furnace environment at approximately 700^{o}C. Hydrogen is released which is then passed through a double collector mass spectrometer. An abundance signal is obtained which is converted and compared with respect to the IAEA standard (International Standard V SMOW).

The procedure for oxygen isotope analysis entails equilibration of CO_2 with the water sample in a temperature controlled bath. The preparation and extraction of the CO_2 is carried out on a fully automated system attached to a MM 903 mass spectrometer.

C6 Quality Control

An analytical quality control program is necessary to produce reliable laboratory data. This program should ideally consist of three parts; 1) utilizing analytical techniques which have been found acceptable by laboratories collaboratively; 2) analyzing control samples regularly; and 3) analyzing reference samples.

To determine the reliability of major ion analysis conducted in the Water Development Department laboratory, replicate samples were analyzed. Precision calculations were carried out on all samples using the cation-anion balance technique:

$$\text{Error (\%)} = \frac{\text{(Sum of cations)-(Sum of Anions)}}{\text{(Sum of Cations)+(Sum of Anions)}}$$

The maximum accepted range of error is normally $\pm 10\%$.

To gauge trace element accuracy, blanks of double distilled water were submitted for ICP analysis as a check for contamination. They were acidified in the same manner as the water samples. If the concentration of a particular element in the blank was greater than the detection limit for that element, the blank concentration was subtracted from the sample.

APPENDIX D Packer Testing

Figure:

D1 Packer Testing Procedures

D1.1 Locating and Inflating Packers

Raise (or lower) packer probe to the desired testing interval and record test zone depth and other general test information on the data sheet (see Figure D.1).

Measure and record the water level in the borehole before inflating the packers.

Calculate the packer inflation pressure to be applied using the following formula:

Packer Pressure = 200PSI+[1.42(PSI/M)x (A-C)]

Where A = Depth to top of test zone (m)
C = Depth to water level in the open borehole (m).

Inflate the packers to the above calculated pressure. Allow five minutes for the packers to inflate and the borehole to stabilize.

D1.2 Pre-Test Water Level Monitoring

Record water level readings every minute for 10 min. in the test zone (inside the ABS riser pipe) and every 2 min. for 10 min. in the open borehole above the packers.

D1.3 Measuring Hydraulic Conductivity

Pump water, using the WaTerra hand pump, out of the test interval at a steady and sustainable rate (approximately 3 to 4 l/min). Monitor the dropping water levels in the raiser pipe during the pumping, and continue pumping until either:

i) the water level has been drawn down 5 m from the level measured at the end of step 2.

or ii) 10 min of pumping has elapsed.

D1.3.1 Low Hydraulic Conductivity Zones

If the water level is drawn down 5 m in less than 60 seconds then the permeability of the test zone is very low. The hydraulic conductivity is determined by measuring the rate of recovery of the water level inside the riser pipe after pumping has stopped. Water levels are recorded every minute for a minimum of 10 minutes. An upper limit of the hydraulic conductivity for these low permeability zones is calculated using the steady state, constant head equation:

$$K = \{Q \ln(r_i/r_w)\} / 2HL \qquad \text{(D1)}$$

HYDRAULIC TEST DATA SHEET

DATE: 21st Sep '86

Borehole No.: WDD 2209

Hydrogeologist(s)

J.I.K ; AM ; FM

& Fee.

Test Interval: 32.36 TO 36.10
(a) (b)

Datum: Top of pedestal

Datum Elevation: 1265m

Open Hole Water Level: 15.45 m at 11:59 am
(c)

Packer Inflation Pressure: (a) - (c) x 1.42 + 200 psi = 224 psi
16.91

CLOCK TIME (T)	WATER LEVEL (W)	ΔW/ΔT	FLOWRATE (Q)	ΔQ/ΔT	COMMENTS
			packer pressure 230 psi		
12:03:40	15.07				15.28
12:04:40	15.07				
12:05:40	15.02				15.27
12:06:40	15.05	0.03			
12:07:40	15.06	0.01			15.27
12:08:40	15.07	0.01			
12:09:40	15.07				15.27
12:10:40	15.08	0.01			
12:11:40	15.09	0.01			15.26
12:12:40	15.09				
12:13:40	15.10	0.01			15.26
			packer pressure 230 psi		
Water level pumped down to 20.10 m					
(5m drawdown) in 2min: 40 sec.					
12:18:40	19.70				15.25
12:19:40	19.35	0.35			
12:20:40	19.05	0.30			15.25

FIGURE D.1 Sample packer data sheet

CLOCK TIME (T)	WATER LEVEL (W)	ΔW/ΔT	FLOWRATE (Q)	ΔQ/ΔT	COMMENTS
12:21:40	18.78	0.27			
12:22:40	18.48	0.30			15.25
12:23:40	18.26	0.22			
12:24:40	18.07	0.19			15.25
12:25:40	17.85	0.22			
12:26:40	17.65	0.20			15.25
12:27:40	17.48	0.17			
12:28:40	17.31	0.17			15.25
		packer		pressure	280psi
	$V=10.$	$63 ml/cm$			
	$Q=$	10.63	$ml/cm \times$	$17 cm$	$/min$
	$=$	$180.$	$71 ml/min$		
	$\Delta Q=$	180.7	$1 ml/min$	$\times 6^{-1} \times$	$10^{-7} m^3 s^{-1}$
	$=$	$180.$	$71 \times 6^{-1} \times$	$10^{-7} m^3 s^{-1}$	

CALCULATION OF HYDRAULIC CONDUCTIVITY

$$K = \frac{\Delta Q}{\Delta H} \frac{\ln(R_i/R_w)}{2\pi L}$$

K = Hydraulic conductivity

R_w = Radius of well: 0.115m

R_i = Radius of influence: 10m

L = Length of interval: 3.74m

$\Delta H = 2.21\ m.$

$\Delta Q = 180.71 \times 6^{-1} \times 10^{-7} m^3 s^{-1}$

$$K = \frac{180.71 \times 10^{-7} \times \ln\left(\frac{10}{0.115}\right)}{2.21 \times 2\pi \times 3.74 \times 6}$$

$$= 2.59 \times 10^{-7} ms^{-1}$$

Where

K = Equivalent Porous Media Hydraulic Conductivity (m/s)
Q = Flowrate during test (m^3/s). This value is obtained by multiplying the average rate of water level recovery (m/s) after pumping has stopped by the constant factor 1.06×10^{-3} m^3/m (displacement inside riser pipe).

r_i = Radius of influence of test (m). This value was estimated to be 10 m for all tests conducted in this study. Large variations in this value create only very small changes in the calculated hydraulic conductivity because of the natural logarithm function.

r_w = Radius of borehole = 0.115 m.

H = Water level drawdown at the end of 10 min. recovery period (should be close to 5 m).

L = length of the test zone = 3.74 m.

D1.3.2 High Hydraulic Conductivity Zones

If after 10 min. of pumping the water level in the riser pipe has been drawn down only a short distance, the hydraulic conductivity of the zone is relatively high. In this case, the hydraulic conductivity is again measured using the constant head method. However, instead of measuring recovery, pumping is continued at a controlled rate so that the drawdown (H) in the test zone (inside the riser pipe) reached after the 10 min. is maintained.

The flowrate (Q) is measured and recorded every minute for 10 min. using a graduated cylinder and a stop watch.

The stable H and Q values determined from this pumping test are used with the above constant head formula to calculate the hydraulic conductivity of the test zone.

D1.3.2 Intermediate Hydraulic Conductivity Zones

In some intervals, the water levels will be drawn down 5 m after 10 min. of pumping, and once pumping stops, will recover several metres in the following 10 min. period. Because the recovery in these zones is greater than 10% of the total drawdown (5 m), the constant head method cannot be used to analyse the data. For these zones, the unsteady, variable head test method is used (Cooper et al., 1967 and Papadopulos et al., 1973). For this method, the normalised drawdown values for the recovery period are plotted against the logarithm of elapsed time. The hydraulic conductivity is then determined by matching the recovery curve to the theoretical type curves (refer to references).

D2 Collecting Groundwater Samples

Groundwater samples are collected only from zones of high hydraulic conductivity. This is usually done immediately after completion of the hydraulic conductivity test.

Calculate the total amount of water pumped out of the test zone during the hydraulic conductivity test to determine if sufficient water was pumped out to displace the stagnant well water contained between the packers (30 l) and inside the riser pipe. Continue to pump,if necessary, to complete purging of the packer probe.

Collect the groundwater samples by pumping water directly into polyethylene sampling bottles. Label the bottles and record sample details on the data sheet.

APPENDIX E Contributors

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