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FEDERAL DEPARTMENT OF WATER RESOURCES LAGOS

FDWR / EDF WATER RESOURCES PROJECT

GROUNDWATER RESEARCH DEPARTMENT

National Water Resources Institute Kaduna

TRAINING MANUAL ON GROUNDWATER INVESTIGATION PROCEDURES

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CONTENTS

Text

Tables

Figures

CHAPTER 1

INTRODUCTION

1.1 Background to Project

A financing agreement (2503/NIG) was signed in Brussels on 18 July 1980 between the European Economic Community (EEC) and the Federal Government of Nigeria (FGN) to provide technical assistance under the Lome I Convention. A major part of the assistance was for building-up and strengthening the organisations responsible for the exploration, development and monitoring of Nigeria's water resources by providing funds for equipment and consultancy services.

An important aspect considered was groundwater which, since the early 1970s, has been increasingly exploited in an effort to satisfy the needs of urban and rural populations, and industrial and agricultural developments. However, this emphasis on exploitation, though laudable, invariably overshadowed the routine collection of data necessary to properly evaluate the potential and limitations of the groundwater resources being used.

In recognition of the urgent need to make up for this lapse the Federal Department of Water Resources (FDWR)/European Development Fund (EDF) Water Resources Project NIG/400/78 was set up; an Agreement for Engineering Services to execute the project was signed between the (then) Federal Ministry of Water Resources (FMWR) and MRT Consulting Engineers (Nigeria) Limited (the Consultant) on 20 July 1982.

The aim of the project was to train Nigerian staff in the collection of reliable groundwater data from hydrogeological and geophysical investigations and a drilling programme, using equipment procured from project funds. The project was based at the National Water Resources Institute (NWRI), Kaduna, where a Data Bank has been established to store and analyse water resources information for the whole of Nigeria. A new department was established within the Research Centre of the Institute - the Groundwater Research Department (GWRD) - to implement the project.

1.2 Project Implementation

Project implementation consisted of three parts:

(a) Procurement of equipment;
(b) Establishment of the Groundwater Research Department within the NWRI;
(c) Execution of a field programme (geophysical surveys and borehole drilling) with on-the-job training.

Procurement

Tender dossiers for the supply of five lots of drilling equipment, ancillary plant and vehicles were issued by the Consultant in June 1983; the tenders were opened at the FDWR on 17 August 1983. The contract to supply Lot 1 (drilling rig, hand tools, casing jacks, clamps, slips, mud pump, compressor, drill pipe, drill collars, drilling bits, down-the-hole hammers and bits, adaptors, fishing tools, bailers and drilling chemicals) and the services of an experienced driller mechanic (master driller) for a period of up to 24 months was awarded to the Halifax Tool Company Limited (Halco) on 9 December 1983.

The contract to supply Lots 2,3,4 and 5 (flat-bed truck with a cargo crane, water tanker, water trailer, fuel trailer, estate car, two four-wheel-drive vehicles, generator, two test pumpsets with trailer, cutting and welding gear, workshop tools, well casing and screen, and camping equipment) was awarded to Hydreq Ltd. on 7 December 1983.

The bulk of the equipment from these two contracts was delivered to Kaduna between 18 June and 13 August 1984. However, two crates and the test pump trailer from Hydreq's last consignment were held up in Lagos docks following a change in the clearance procedures, and were not delivered to Kaduna until April and June 1985.

Geophysical equipment, consisting of a McSeis-1500 seismic data aquisition system (for seismic refraction), an SIE Geo-source portable borehole logger, an ABEM Terrameter SAS 300 resistivity unit and a BGS-256 offset sounding system (for the offset Wenner array), arrived in Kaduna on 13 August 1984.

Establishment within the Institute

Establishment of the Groundwater Research Department in the Research Centre at the NWRI effectively began with the arrival in Nigeria of the Consultant's Hydrogeologist/Project Co-ordinator on 18 April 1984. It involved the preparation of office and workshop space, recruitment of Nigerian staff, provision of staff accommodation, the clearance and delivery of the imported equipment and vehicles, and the local procurement of materials and consumables.

In addition, a local budget for capital and operating expenses was prepared as part of a planning and budget document submitted to the Permanent Secretary of the Federal Ministry of Agriculture, Water Resources and Rural Development in May 1984. Although the document received full approval on 2 July funds for capital expenditure only became available towards the end of the project. For most of the time the project had to be supported by the Institute's own limited resources. The lack of adequate financing was a major problem in the implementation of the project.

Recruitment of the right calibre of technical and support staff was given high priority in the establishment of the department. The

following staff were recuited:

3	hydrologists/geologists
4	technicians/drillers
1	cartographer
1	confidential secretary
5	field assistants
3	drivers
9	labourers
1	welder
4	watchmen
31	total

For the execution of the field programme the technical staff were formed into a drilling team and a geophysical team (once the interests and capabilities of individuals became known) with the three hydrologists/geologists taking turns to supervise both the drilling and geophysical operations.

Some changes in staffing levels took place as the programme progressed, and the total number of staff allocated to the department at the end of the project was 25 (3 hydrologists/geophysicists, 11 members of the drilling team, 6 members of the geophysical team, 2 office staff and 3 watchmen).

In February 1985 the Insitute's principal hydrogeologist assumed the role of co-ordinator to liaise between the Consultant and the Institute in matters concerning project administration and staffing.

Field Programme

The field programme, utilising the equipment procured for the project, got underway in January 1985. The initial work was carried out in an experimental catchment area (ECA) close to Kaduna, chosen to provide a convenient test bed for research in all aspects of the hydrologic cycle by the Institute as a whole; some work was also carried out at the Institute itself. Further work in Kaduna and the ECA was undertaken in March - May 1986.

In June 1985 the programme moved away from the Kaduna base and work was carried out at Kwoi (near the southern boundary of Kaduna State) and on the Mar Farms near Nassarawa (Plateau State) at the request of the Federal Ministry of Agriculture, Water Resources and Rural Development (FMAWRRD).

In August work started on a research project proposed for the Niger State Water Board. Geophysical surveys were carried out on the Basement Complex at Suleja, to select the most favourable drilling sites, and at three villages where photogeological maps had been prepared by interpreting aerial photographs. Boreholes were drilled at Suleja and Minna, and in the Nupe Sandstones at Kutigi.

A programme of the work carried out to the end of April 1986 is shown on Figure 1. The locations of boreholes drilled are shown on Figure 2, and drilling results are summarised in Table 1.

1.3 Purpose of Manual

The aim of the project was to provide a professional groundwater investigation service to assist the Federal Government with the planning, development and management of the country's water resources.

In order to achieve this much emphasis was placed on staff training during the Consultant's input. Due to the nature of the work much of the training was essentially on-the-job. However, it was felt that a manual should be written to complement the lessons learnt in the field, and to provide a more complete guide to the planning, execution and evaluation of groundwater investigation programmes.

This manual is in fulfillment of that idea, and utilises the experience gained not only on this project, but also on projects involving major training elements undertaken by the Consultant elsewhere (particularly Pakistan, Indonesia, Burma and Malaysia).

1.4 Objectives and Sequence of Groundwater Investigations

The objectives are always similar, the main one being to predict how the required quantity of groundwater can be exploited at minimum cost without permanently depleting the producing system and causing unacceptable environmental damage.

Secondary objectives are usually:

- definition of the boundaries of the producing system(s);
- evaluation of the aquifer hydraulic properties and their variation;
- evaluation of groundwater quality and its variation;
- evaluation of the recharge-discharge characteristics and water balance of the system;
- evaluation of design criteria for exploitation/development.

Unless a sufficient quantity of reliable and relevant data is already available for a particular area, these objectives can only usually be fulfilled by a field programme involving drilling and pumping tests. However, some preliminary studies, followed by reconnaisance field surveys, should first be carried out - at small extra cost these ensure that the expensive drilling programme is used to the best advantage. Such studies should always include a review of existing data, mapping of geology and geomorphology, surveys of existing boreholes and springs (if any), and surface geophysics (if applicable).

The layout of this manual follows such a sequence. Chapters 2 and 3

Figure 1 Groundwater Research Department - Programme of Fieldwork

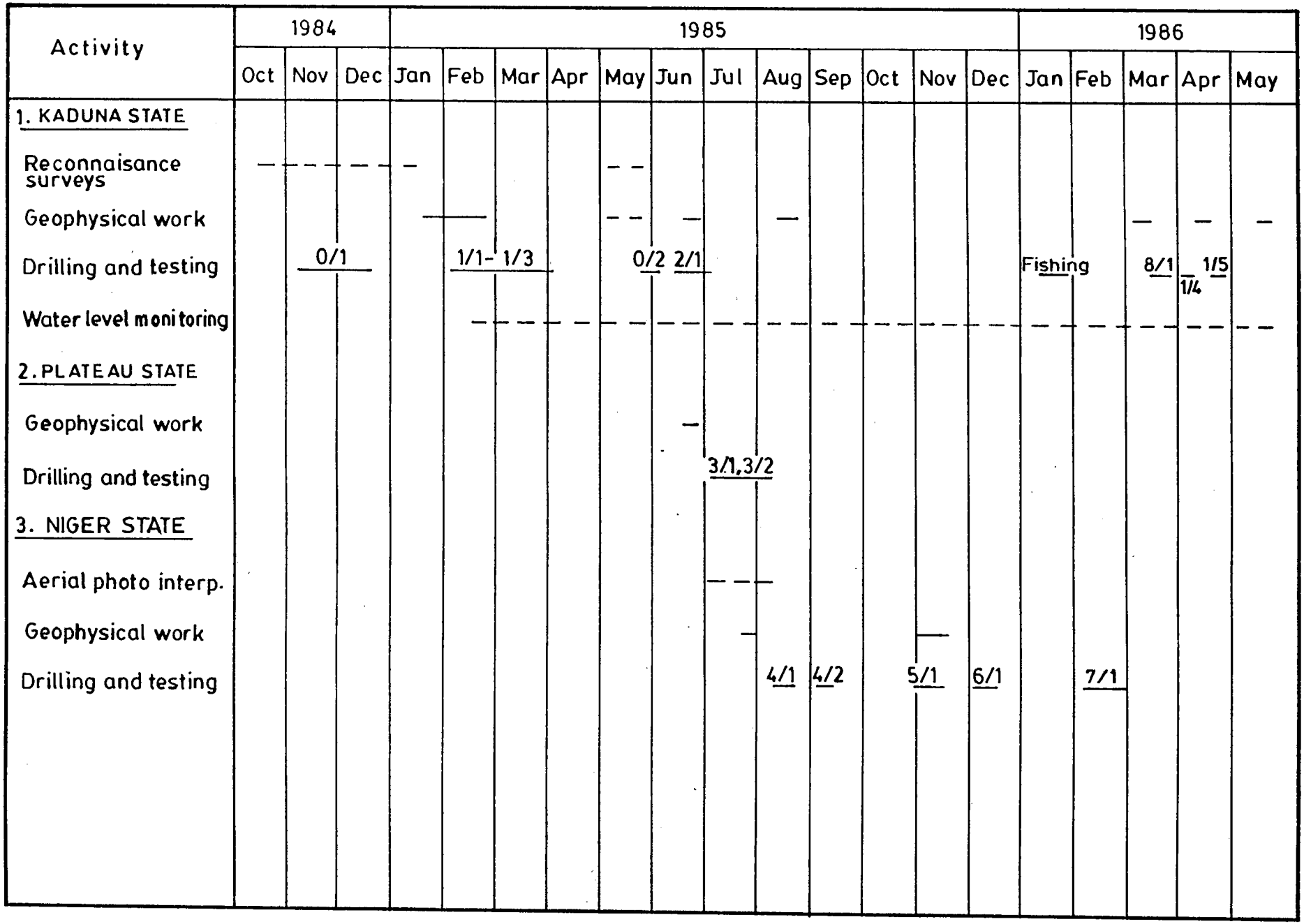


FIGURE 2 GROUNDWATER RESEARCH DEPARTMENT-LOCATION OF BOREHOLES

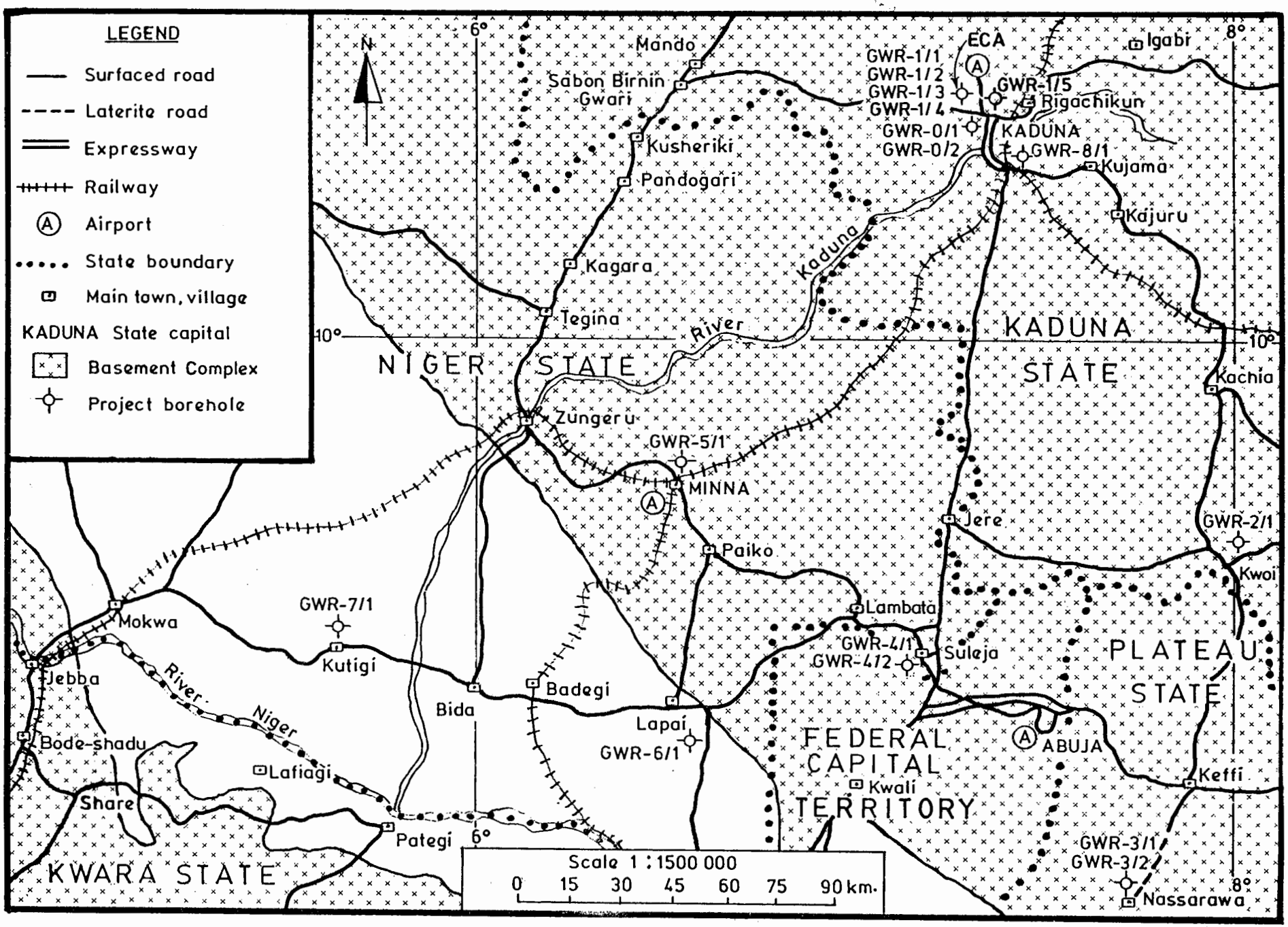


TABLE 1

GROUNDWATER RESEARCH DEPARTMENT - SUMMARY OF BOREHOLE RESULTS

Borehole nr.	Location	Co-ordinates		Ground Elevation (m)	Total depth (m)	Depth to fresh BC (m)	Completion		Test Discharge (m^3/h)	Pumping Duration (m)	SWL gl (m)	Draw-Down (m)	EC (u.S/cm)
		Longitude	Latitude				Screen (m)	Open hole (m)					
GWR-0/1	N.W.R.I	07° 25' 18"	10° 34' 55"	620.1	92.0	38	None	40.8-92.0	2.9	7	7.5	>43	280
" -0/2	"	" " "	" " "	617.6	29.0	27.1	13.1-23.7	None	1.0	128	6.8	5.0	200
" -1/1	ECA	07° 16' 21"	10° 38' 27"	575.1	102.0	16.0	None	18.0-102.0	0.6a	60	1.9	>80	410
" -1/2	"	" " "	" " "	574.8	15.0	15.0	6.8-13.9	None	7.4	1440	1.9	5.0	190
" -1/3	"	" " "	" " "	574.1	40.1	28.0	5.3-11.3)) 26.3-32.3)	None	-	-	1.1	-	-
" -1/4	"	" " "	" " "	574.3	10.0	-	8.3-9.8	None	-	-	1.7	-	-
" -1/5	"	07° 20' 50"	10° 39' 17"	605	67.3	5.9	None	6.1-67.3	5.0	35	2.9	40.6	350
" -2/1	Kwoi	08° 00' 16"	09° 26' 46"	775	61.3	11.4	None	13.1-61.3	0.5	330	10.1	32	95
" -3/1	Nassarawa	07° 43'	08° 34'	?	43.5	14.9	6.0 - 30	30 - 43.5	1.2	196	3.3	24.4	400
" -3/2	"	" "	" "	?	61.4	12.8	5.3 - 14.3	14.3-61.4	1.6	1445	2.2	32.0	350
" -4/1	Suleja	07° 10' 21"	09° 10' 22"	410	40.0	5.2	None	9.0-40.0	0.4	1440	4.0	3.4	140
" -4/2	"	07° 10' 35"	09° 10' 49"	415	60.0	8.0	None	8.9-60.0	2.8	1440	6.6	21.3	150
" -5/2	Minna	06° 28'	09° 41'	?	70.0	4.7	None	5.4-70.0	1.4	45+	4.7	10.4	420
" -6/1	Lapai	06° 36' 13"	09° 00' 47"	145	61.3	22.8	13.0-24.4	24.6-61.3	2.5	420	13.8	19.6	250
" -7/1	Kutigi	05° 37'	09° 12'	140	114.9	>114.9	17.1-20.1)) 40.2-45.9)) 54.6-57.6)) 100.5-103.5)	None	3.1	660	8.7	<36	85
" -8/1	Kaduna S.	07° 25' 15"	10° 28' 02"	615	73.3	24.0	12.9-24.3	24.5-73.3	7.2	1440	6.7	16.9	105
				Total	941.1								

deal with the preliminary studies and surface geophysical surveys respectively. Chapter 4 discusses planning for a drilling and testing programme, and subsequent chapters deal with the main elements of direct concern to the hydrogeologist: formation logging (Chapter 5), borehole design and completion (Chapter 6), pumping tests (Chapter 7) and groundwater chemistry (Chapter 8).

A more general aspect of groundwater investigations, that of assessing natural recharge, is discussed in Chapter 9. Recharge only becomes an issue when large quantities of groundwater are due to be extracted, such as for an irrigation scheme or to supply a large town or industrial plant. In Nigeria, such uses for groundwater will be restricted to the sedimentary basins and coastal areas. On the Basement Complex aquifers tend to be localised, and borehole yields low (generally less than 3 m3/h) - because of the huge catchment areas available, borehole extractions are unlikely to have any significant impact on the recharge to the aquifer zones.

On the completion of the field programme, and evaluation of the data, a report should be produced; details should be given on the techniques employed, results obtained and conclusions reached. Advice on the format for such a report is given in Chapter 10.

CHAPTER 2

PRELIMINARY STUDIES

2.1 Collection of Existing Data

Existing data should be collected from as many sources as possible. In Nigeria the main sources for borehole records, geophysical survey reports and hydrogeological investigation reports are listed below:

- River Basin and Rural Development Authorities;
- Agricultural Development Project offices;
- State Water Boards;
- Federal Department of Water Resources (head office and zonal offices);
- Drilling contractors;
- Consulting firms in engineering and agricultural development;
- National Water Resources Institute;
- Universities and Institutes of Technology;
- Geological Survey.

The Federal, State, and parastatal agencies in the above list should also hold hydrological and some meteorological data; the primary source of meteorological data is the Department of Meteorological Services in the Federal Ministry of Transport and Aviation.

The Data Bank at the NWRI is being set up to act as the national respository of all of Nigeria's water resources data. Although the emphasis has so far been on hydrological (stream flow) and to some extent meteorological data, it is hoped that the Bank will eventually have the records of every existing borehole on its files.

Many of the reports that have been produced on groundwater and water resources investigations are held by the NWRI - a full list is given in Appendix A. However, some important existing reports have never been received; in order to correct this situation a recommendation was made to the FMAWRRD early in 1985 that all government and aid agencies involved in groundwater work should include a clause in future terms of agreement with contractors, consultants and others required to produce reports, that at least two copies of any report must be delivered to the Institute.

As many organisations should be contacted as possible, even though there may be an overlap of the data received - this serves as a check on the data's consistency and reliability. Data, aerial photography and maps should not be restricted to the actual area under investigation, but should also include the rest of the geological environment or river basin in which the area lies in order to form a regional picture.

It is often necessary to devote a lot of effort to discover and obtain some of the records and reports; however, it is effort well spent and almost invariably leads to better planned geophysical and

drilling programmes later on which avoid the pitfalls of data duplication.

Aerial photographs are held by the Geological Survey in Kaduna South, although the NWRI does have its own copies of photography for the Kaduna area. The Survey discourages the loaning out of photographs (presumably because so many were lost or never returned in the past), but facilities exist to study them on the premises.

Photography is available at 1:40,000 scale (taken in 1962) and 1:25,000 scale (taken in 1970s). The former photography was used to prepare the basic 1:100,000 and 1:50,000 scale topographic map sheets for the country; the photographs are catalogued according to the 1:100,000 scale sheet numbers. Copies of topographic maps are available from the Federal Survey Department in Kaduna and at other state capitals.

Geological and photogeological maps at 1:100,000 scale, aeromagnetic maps at 1:50,000 scale and Bouger gravity maps at 1:50,000 scale are available for certain parts of the country from the Geological Survey. However, the photogeological maps, which are largely based on the interpretation of the 1:40,000 scale 1962 photography, are only available in draft form and can only be inspected on the Survey's premises.

The extent of the available geological, photogeological and geophysical maps is shown on an index for the 1:100,000 scale topographic sheets on Figure 3.

Other forms of remote sensing which might be useful to groundwater investigations are Side-Looking Airbourne Radar (SLAR) and LANDSAT (satellite) imagery. Both SLAR mosaics and LANDSAT images have been taken for the whole country and can be inspected at the Federal Department of Forestry at Ibadan.

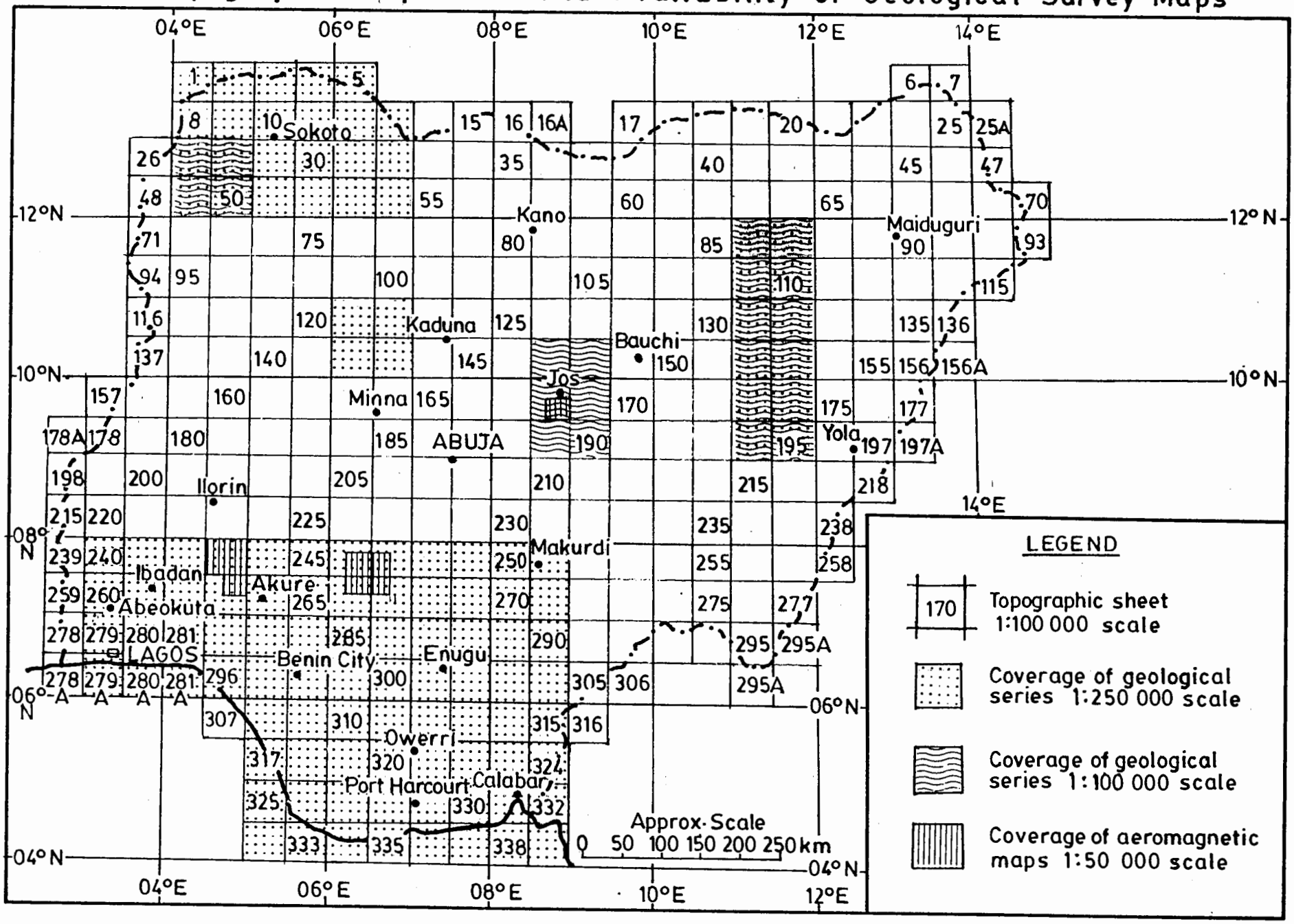
Reconnaissance trips should be made to get a 'feel' for the area under investigation, and to carry out preliminary checks on the data collected. Local people should be interviewed for information on traditional wells and the occurrence of springs, swamps and other water features - often the locations of human settlements, and agricultural practices are governed by the distribution of accessible groundwater.

2.2 Aerial Photograph/Remote Sensing Interpretation

Although satellite images tend to be of small scale - generally 1:500,000 and 1:1,000,000 - they can give a good overall picture of the region in which the area under investigation lies, and pick out macro features such as major fissure and joint lines which might not be so obvious from larger scaled aerial photography.

LANDSAT images are particularly useful in showing vegetation cover and drainage lines, and, because each part of the Earth's surface is

Figure 3 Topographic Map Index and Availability of Geological Survey Maps



recorded every time it passes beneath the scan of the satellite, vegetation and drainage can be assessed for different times of the year. The main limitation of LANDSAT is that the images cannot penetrate cloud cover. SLAR overcomes this disadvantage - it is not affected by cloud cover.

Drainage, topography and vegetation features are the product of geological structure, changes in lithology and effect of erosion. Linear features are often indicative of faulting and folding, and fractures. Changes in the intensity or type of vegetation may indicate changes in soil and drainage which are themselves a function of a change in rock type.

Although satellite images are fascinating, a prologed or detailed analysis of them is usually not necessary for groundwater investigation. Once the hydrogeologist has gained an overall immpression of the regional setting of the study area he should move on to the interpretation of aerial photographs. The 1:40,000 scale photographs should be used for regional work and the 1:25,000 scale ones for more detailed study. Although aerial photographs can be studied individually and used rather like topographioc maps, they come into their own when studied in pairs under a stereoscope - a 3D picture is obtained which dramatically illustrates the form of the land's surface.

The basic aim of aerial photograph interpretation (api) for groundwater investigations is to map the geological structure and aquifer limits, and detect spring lines, swamps, and if possible, likely areas of recharge. Api should proceed on the assumption that all features in the photograph have some reason for being there; some, of course, may be man-made but most are in some way influenced by land form, drainage, soils and climate. For example, parallel lines of drainage may indicate lines of weakness caused by fractures and faults.

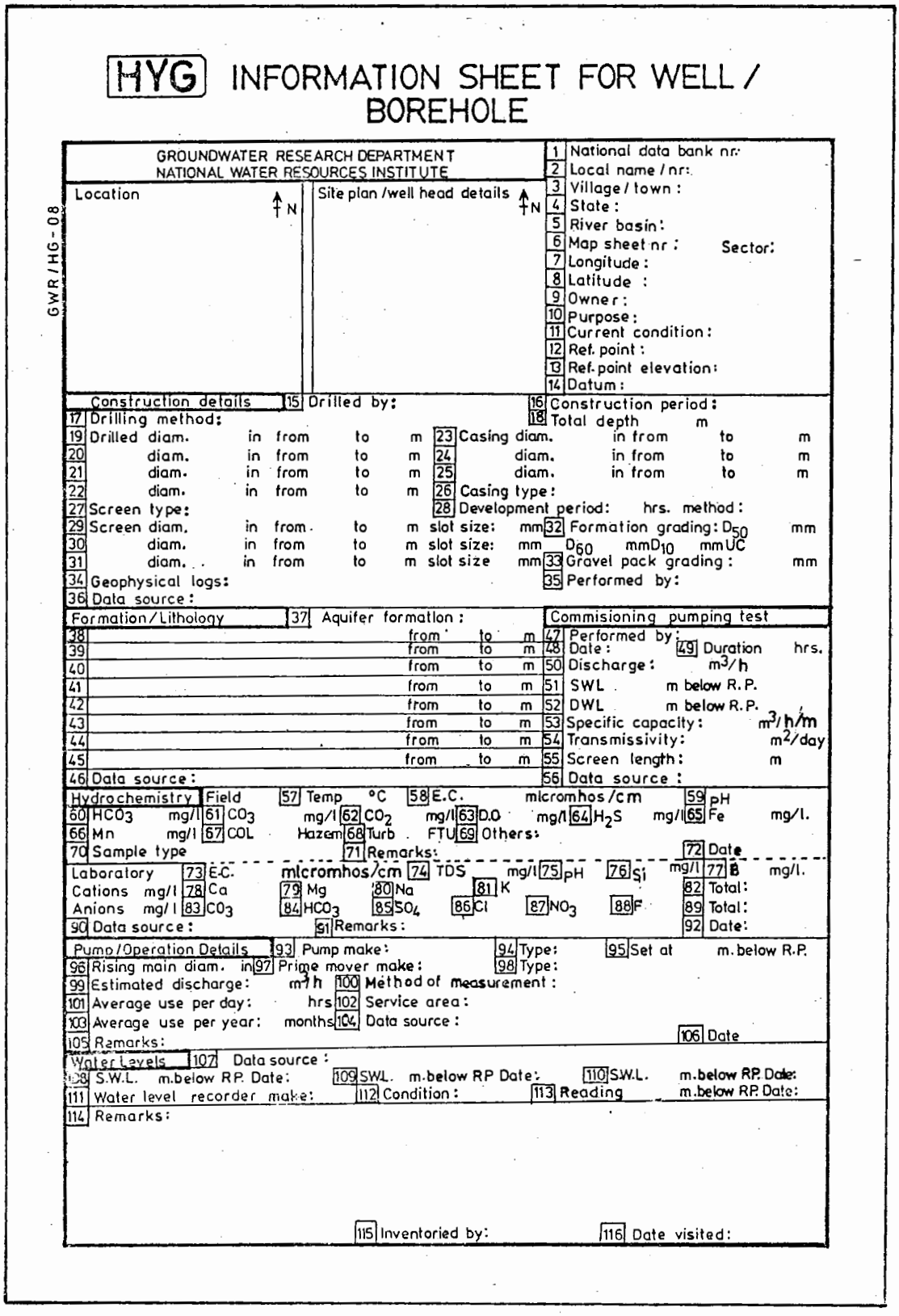
In an area where the geology is not well known or clear from the photographs some field checks will be necessary to verify the interpretation. However, care should be taken not to spend too much time on detailed geological mapping since many aspects of geology, such as age determination and fossil content of formations, are of little relevance to groundwater investigations.

2.3 Water Point Inventory

An inventory of existing boreholes, wells and springs is usually the first aspect of the investigation involving extensive fieldwork.

Whenever feasible, measurements should be taken of water level, water quality and water use. For boreholes and wells a standard form, HYG, has been developed to record these measurements and to include any data previously collected from existing sources. The form, shown as Figure 4, is coded so that the data can be keyed into a computerised storage and retrieval system. It is important that

Figure 4 Information Sheet for Well/Borehole



HYG INFORMATION SHEET FOR WELL / BOREHOLE

GWR/HG-08

GROUNDWATER RESEARCH DEPARTMENT
NATIONAL WATER RESOURCES INSTITUTE

Location ↑N | Site plan /well head details ↑N

1 National data bank nr:
2 Local name / nr:
3 Village / town :
4 State :
5 River basin:
6 Map sheet nr : Sector:
7 Longitude :
8 Latitude :
9 Owner :
10 Purpose :
11 Current condition :
12 Ref. point :
13 Ref. point elevation:
14 Datum :

Construction details | 15 Drilled by: | 16 Construction period:
17 Drilling method: | 18 Total depth m

19	Drilled diam.	in	from	to	m	23	Casing diam.	in	from	to	m
20	diam.	in	from	to	m	24	diam.	in	from	to	m
21	diam.	in	from	to	m	25	diam.	in	from	to	m
22	diam.	in	from	to	m	26	Casing type:				
27	Screen type:					28	Development period:		hrs.	method:	
29	Screen diam.	in	from	to	m	slot size:	mm	32	Formation grading: D_{50}		mm
30	diam.	in	from	to	m	slot size:	mm		D_{60} mm	D_{10} mm	UC
31	diam.	in	from	to	m	slot size	mm	33	Gravel pack grading :		mm
34	Geophysical logs:							35	Performed by:		
36	Data source :										

Formation / Lithology | 37 Aquifer formation :

38	from	to	m	
39	from	to	m	
40	from	to	m	
41	from	to	m	
42	from	to	m	
43	from	to	m	
44	from	to	m	
45	from	to	m	

46 Data source :

Commisioning pumping test

47 Performed by:
48 Date: | 49 Duration hrs.
50 Discharge: m^3/h
51 SWL m below R.P.
52 DWL m below R.P.
53 Specific capacity: $m^3/h/m$
54 Transmissivity: m^2/day
55 Screen length: m
56 Data source :

Hydrochemistry | Field | 57 Temp °C | 58 E.C. micromhos/cm | 59 pH

60 HCO_3 mg/l | 61 CO_3 mg/l | 62 CO_2 mg/l | 63 D.O mg/l | 64 H_2S mg/l | 65 Fe mg/l.
66 Mn mg/l | 67 COL Hazem | 68 Turb FTU | 69 Others:
70 Sample type | 71 Remarks: | 72 Date

Laboratory | 73 E.C. micromhos/cm | 74 TDS mg/l | 75 pH | 76 Si mg/l | 77 B mg/l.

Cations mg/l | 78 Ca | 79 Mg | 80 Na | 81 K | 82 Total:
Anions mg/l | 83 CO_3 | 84 HCO_3 | 85 SO_4 | 86 Cl | 87 NO_3 | 88 F | 89 Total:

90 Data source : | 91 Remarks: | 92 Date:

Pump / Operation Details | 93 Pump make: | 94 Type: | 95 Set at m. below R.P.

96 Rising main diam. in | 97 Prime mover make: | 98 Type:
99 Estimated discharge: m^3/h | 100 Method of measurement :
101 Average use per day: hrs | 102 Service area :
103 Average use per year: months | 104 Data source :
105 Remarks: | 106 Date

Water Levels | 107 Data source :

108 S.W.L. m.below R.P. Date: | 109 SWL. m.below R.P Date: | 110 S.W.L. m.below RP. Date:
111 Water level recorder make: | 112 Condition : | 113 Reading m.below RP. Date:
114 Remarks:

115 Inventoried by: | 116 Date visited:

the hydrogeologist takes active control of the inventory since a lot of significant information can be gathered by asking questions outside the scope of the form. This is particularly true of well failure, the reason for which can be of importance.

Measurements in the field should be immediately cross-checked with those in the previously collected data (if available). Any large mismatches must be checked out to confirm that the borehole/well being measured is actually the same one as indicated for that particular location in the data at hand. If the hydrogeologist is certain that he is dealing with the same borehole/well then he has to judge whether the previous data are erroneous or whether the marked shift in the parameter being measured is in fact plausible.

If a borehole or well already has an existing reference number then this should used on the inventory form; otherwise a new serial number - together with a suitable code representing the area under study - should be assigned to it; for example, ECA-01, 02, 03,etc., for the Experimental Catchment Area. Try to avoid the situation in Saudi Arabia where some government wells had up to seven numbers assigned to them by different drilling and maintenance contractors, and consulting firms. If possible the reference number, whether existing or new, should be physically marked onto the borehole, by painting or etching or some other technique - however, the owner's permission should be sought before this is done.

Caliper and gamma logs should be run in boreholes where access and permission can be gained. E-logs are usually not applicable at this stage since most existing boreholes in Nigeria, even in the Basement Complex, are cased and screened.

If a water sampler is procured in the future then this should be used to collect samples from different depths for chemical analysis.

Pumping tests should be attempted on boreholes already fitted with motor-driven or electric submersible pumps if the borehole owner is willing to cooperate.

After the completion of the inventory some boreholes and wells should be selected for monitoring water level and possibly water quality. Observations should be taken at least monthly or if possible at shorter intervals. A form for this purpose, GWR/HG-07(01), has been prepared, and a completed example is shown as Figure 5.

2.4 Equipment

The following equipment is required to carry out the preliminary studies as described in this chapter:

- desk stereoscope and pocket stereoscope;
- geological hammer, chisel, *10 hand lens, compass/inclinometer;
- 3m spring tape and 50m measuring tape;

Figure 5 Well Monitoring Form

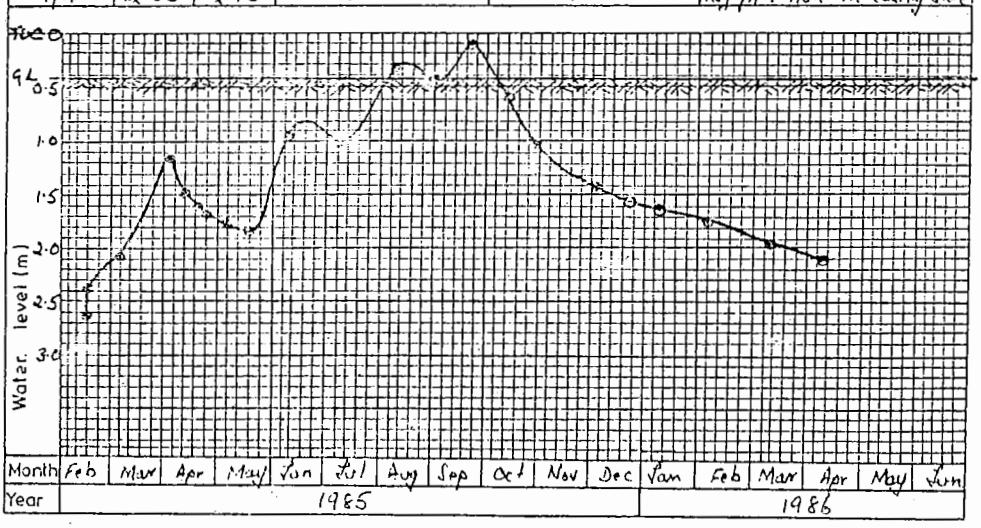
GROUNDWATER RESEARCH DEPARTMENT - NATIONAL WATER RESOURCES INSTITUTE

WELL MONITORING FORM

BOREHOLE NR : GWR-1/1

LOCATION : Experimental Catchment Area
REFERENCE POINT : Top of casing
ELEV. REF. POINT : 575.6 m

Date	Time	WL (m)	Measuring instrument	Observer	Notes
17/2/85		2.60	dip KL 50	R.S. Jackson	
18/2		2.35	" " "	'Sola	
19/2		3.22	" " "	"	After sampling test
4/3	08.47	2.05	" " "	"	
3/4	10.30	1.15	" " "	"	Heavy rain 29-31/3/85
11/4	08.42	1.47	" " "	"	Reduction in streamflow
18/4	09.16	1.58	" " "	"	Stream channel dry
23/4	09.17	1.64	" " "	"	" " "
3/5	08.19	1.74	" " "	"	
15/5	09.59	1.82	" " "	"	
6/6	10.20	0.94	" " "	"	Stream ~ 0.5 m deep
5/7	10.15	1.00	" " "	"	
6/8	13 41	0.33	" " "	"	Stream overflowing
29/8	12.59	0.46	" " "	"	Flood, stream channel full
18/9	09.51	0.12	" " "	"	Flood, stream overflowing
9/10	09.00	0.62	" " "	"	Site fairly dry, stream lower
25/10	11.32	1.03	Chalked tape	"	Stream still flowing
28/11	11.48	1.40	dipper	"	0.08 m water in stream
20/12	11.52	1.53	"	Ciculabi	Stream almost dry
7/1/86	08.08	1.62	"	'Sola	Stream dry
3/2	13.45	1.72	"	M.O Edwine	" "
7/3	08.12	1.94	"	'Sola	" "
27/3	—	—	—	"	Borehole blocked
7/4	12.00	2.10	?	?	Ref pt: hole in casing side



GWR / HG-07(01)

Page of

- 50m electric water level sounding tape;
- electrolytic conductivity (EC) meter;
- portable chemical laboratory;
- water sample bottles;
- manometer or pressure gauge for mesuring artesian peessure (if necessary);
- logging unit (caliper, gamma and E-log);
- bucket or drum of known volume for measuring borehole yields.

CHAPTER 3

GEOPHYSICAL INVESTIGATIONS

3.1 Introduction

3.1.1 General

Applied geophysics is a collection of survey methods which can be used to investigate the geology of an area by measurement of certain physical parameters. Such studies may be of a purely scientific nature, but usually they have a practical purpose. Geophysical surveys are used very extensively in the search for oil, gas, and minerals. The use of geophysics in groundwater exploration and for civil engineering investigations is of much less importance in terms of the amount of work done worldwide, but is still of considerable potential value.

The aim of this chapter is to provide an introduction to the geophysical methods which are of possible use in groundwater exploration, by outlining the basic theory of each method, the equipment required, the way in which a survey is carried out, the principles of interpretation, possible applications, and limitations. It is also intended for people involved in other aspects of groundwater development as background information.

3.1.2 Summary of the Principal Geophysical Methods

Geophysical survey methods can be divided into two main types, namely those which measure a naturally occurring field and those which measure the response of the ground to an artificial signal. The most widely used techniques are listed below with a very brief description of each. Only surface geophysical methods are considered; borehole logging and remote sensing methods can be of great value but are outside the scope of this chapter(see Chapter 2 for remote sensing and Chapter 5 for borehole logging).

(a) **Gravity** : variations in the density of the rocks underlying an area cause slight variations in the gravitational field; can be useful for assessing the depth of sedimentary basins and so relevant to investigations of major sedimentary aquifers.

(b) **Magnetic** : the presence of certain minerals affects the magnetic field; only likely to be of value in certain specific cases in groundwater exploration, such as locating faults or intrusions such as dykes.

(c) **Self potential** : electrochemical interaction between minerals and water, or variations in the salinity of water, can cause small voltages; not useful in groundwater exploration except as a borehole logging method.

(d) **Radiometric** : measures radiation caused by radioactive minerals; only used in groundwater exploration as a borehole logging method.

(e) **Seismic** : uses seismic waves which are essentially sound waves and includes two main variants -

(i) **Reflection** : uses the reflection of seismic waves at the boundaries between different rock types; could in principle be useful for investigating deep sedimentary aquifers but generally far too expensive.

(ii) **Refraction** : depends on the variation of seismic wave velocities with rock type and the refraction of seismic waves at interfaces; can be useful for investigating thicknesses of alluvium or weathered rock.

(f) **Electrical resistivity** : by far the most important method for groundwater exploration.

(g) **Induced polarisation** : based on the ability of the ground to store electrical charges; could be used in special cases for groundwater exploration.

(h) **Electromagnetic (EM) methods** : a variety of methods which assess electrical conductivity indirectly by measuring the distortion of an alternating magnetic field by induced currents within the ground ; certain versions are very useful as a reconnaissance method in groundwater exploration.

(i) **Temperature** : for location of shallow aquifers, or areas of discharge from deep aquifers.

The above is not a complete list of geophysical methods, but other methods are of less practical value, and are very unlikely to be of use in groundwater exploration.

3.1.3 Advantages of Geophysical Methods

The obvious limitation of geological mapping is that generally it has to be based on what can be observed at the ground surface. It is possible to make certain deductions about the subsurface geology with a reasonable degree of confidence where there are sufficiently frequent outcrops. However, if an area has few outcrops, it may be possible to gain only a very general picture of the geology from geological mapping and the study of aerial photographs. Yet it is often the details of the geology which are of great importance in the effective development of groundwater resources, while areas with numerous outcrops are of little interest generally, as they tend to be less suitable for agriculture and large-scale exploitation of groundwater.

Drilling can supplement surface observations, but it is generally expensive and is limited in the amount of information it can

provide. Firstly, it only provides information at one point on the map; while it may be possible to extrapolate information on, for example, gently dipping sedimentary beds, in more complex geological situations any attempt at extrapolation, or even interpolation between boreholes, may be very misleading. Secondly, the information is often very limited, being based on the examination of cuttings, recorded drilling rates etc.; core drilling gives better information but its use is restricted by the extra cost. Thirdly, in groundwater exploration the reason for studying the geology is commonly to select locations for production boreholes, so that it is desirable to have as much information as possible before the drilling even starts.

Drilling boreholes at random may be acceptable in some areas, for example if there is known to be an extensive, consistent aquifer underlying the entire area. In other cases, it is likely to result in a rather high proportion of unsuccessful boreholes. An example of this is the Basement Complex of northern Nigeria, where the most productive boreholes will usually be those which intersect a sizeable fracture zone, with the water coming either from the fractures within the rock or from a deep weathered zone associated with the fracturing. In areas of low relief and in valley bottoms (i.e. where a borehole is most likely to be drilled and to be productive), a fracture zone may have little or no surface expression, and what surface evidence there is may be obscured further by vegetation. It is possible that a difference of only a few metres in the position of a borehole could make the difference between success and failure. Even where there are no well developed fracture zones, there are likely to be local variations in the depth of weathering which could cause significant variations in the yield of boreholes relying on water stored in the weathered zone.

Although there is little or no chance of detecting some of these localised variations in subsurface geology by examination of the ground surface, a geophysical survey may be able to locate them. It can therefore be worth carrying out such a survey in the hope of identifying a borehole location which has a better chance of success than one selected at random. There is certainly no guarantee that the geophysical survey will give a satisfactory answer; there may simply be no better than an average location for a borehole in the area surveyed, or the survey (because of some of the limitations discussed later) may fail to detect the most favourable locations. Even the best location in the area may not be good enough. Drilling will still remain something of a gamble; the aim of a geophysical survey is to improve the odds, not to give a certainty. Given the relatively low cost of, for example, a resistivity survey compared with that of drilling, this improvement in the odds is often sufficient to justify a geophysical survey in economic terms. In some instances, particularly where extensive use of geophysics and the correlation of the survey results with boreholes allows a high degree of confidence, unfavourable geophysical results may prevent any borehole being drilled at all.

3.1.4 Limitations of Geophysical Methods

Each geophysical method has its own specific limitations, as will be described in later sections. One thing that is common to almost all geophysical surveys is that they are an indirect approach to a problem, in that what is actually measured is very rarely what it is desired to know, but rather something from which this answer must be interpreted. This can be illustrated by considering the main steps involved in a gravity survey.

(a) Field work is carried out to produce raw data in the form of gravimeter readings taken at selected stations (points whose coordinates and elevation have been accurately determined) at known times, plus supplementary observations.

(b) The field data is reduced by applying corrections for instrument drift and tidal effects, to give a value for the observed gravity at each station.

(c) Further corrections are applied to remove the effects of station elevation, latitude, and the topography of the surrounding area, to give a value of the gravity anomaly at each station.

(d) The pattern of the anomalies is interpreted to determine a distribution of the density of the underlying rocks which would give rise to the same anomalies as those actually found. This density distribution will be referred to as a physical model.

(e) The physical model must be interpreted into a geological model.

This description of the process is somewhat simplified, to emphasise that there are effectively two stages to the interpretation process, namely the derivation of a physical model and the explanation of this model in geological terms. In practice, the geophysicist usually has some knowledge of the geology, and uses this in setting up a physical model (i.e. steps (d) and (e) are effectively reversed). Theoretically, there are an infinite number of physical models which will be consistent with the results of a survey, and step (d) above can only be tackled by making a number of assumptions, to reduce the interpretation to a very simple case which can be solved explicitly; or by a process of trial and error, assuming a model and then seeing how consistent it is with the survey results. Even with the use of a computer, the complexity of the physical models which can be considered is in practice limited. If additional data become available, steps (d) and (e) will normally be repeated to refine the interpretation.

At each stage of field work, data reduction and interpretation, it is inevitable that certain errors will be incorporated in the data and that these errors will tend to accumulate. Also, at each of the two stages of interpretation, there is a considerable amount of ambiguity. No geophysical survey can ever be completely accurate, and no conclusions drawn from a geophysical survey can be regarded as being absolutely certain. The accuracy and the reliability of a

geophysical survey will of course depend on the quality of the equipment used and the competence of the people carrying out the survey, but usually the controlling factors are the geology and surface conditions at the survey site. In favourable geological conditions, it may be possible to obtain results which are accurate to within perhaps 5 or 10%, but in unfavourble conditions a geophysical survey may be completely uninterpretable.

3.1.5 Combining Geophysics with Other Work

In the previous section, it was indicated that a geophysical survey cannot reasonably be carried out without a certain amount of information being available first, so that the suitability of the proposed method can be assessed and that the choice of possible physical and geological models be narrowed down. In groundwater exploration, a likely programme is as follows:

(a) Hydrogeological assessment of the area, based on available information (maps, reports, well records etc.), inspection of the geology and geomorphology, and study of aerial photographs etc., leading to a selection of possible borehole sites.

(b) Geophysical surveys of the selected sites, to assess whether they are in fact suitable and if so, the exact locations at which the boreholes should be drilled.

(c) Drilling and testing of the boreholes.

If several boreholes are to be drilled, it is likely that the geophysical field work and the drilling will overlap; if the number of boreholes is large, then all three phases may overlap. In any case, there will normally be the opportunity to use the results from the earlier boreholes to check on the results of the geophysical survey, which may lead to an adjustment of the interpreted results; in other words borehole data can be used to 'calibrate' a geophysical survey in a specific area. Exceptionally, a comparison of geophysical and borehole data might lead to a modification in the field procedures used for the geophysical surveying.

It is important that any geophysical survey forms an integral part of a groundwater exploration programme, and that it is not treated as something separate. The latter possibility is a real risk if there is insufficient communication between the people carrying out the geophysical work and those involved in other aspects of the exploration programme. If, for example, the geophysical work is carried out by a specialist contractor, a report on the geophysical survey will normally be prepared before drilling starts; it is likely that it will not be revised in the light of additional data from drilling. While a comprehensive report is essential for future reference, a continuing involvement of the geophysicist is likely to be of more immediate benefit to the programme. It may then be desirable to delay the preparation of a final geophysical report until after all the boreholes have been drilled, in which case brief

interim reports can be issued at suitable intervals.

3.2 Electrical Resistivity Surveys

3.2.1 Basic Theory

The electrical resistance of, for example, a piece of wire is defined by Ohm's Law as the potential difference (voltage) across it divided by the current flowing through it:

$$R = V / I$$

The resistance is a function of the dimensions of the wire and the resistivity of the material of which it is made:

$$R = @ . L / A$$

where @ = resistivity;
L = length;
A = cross-sectional area.

For geophysical work, resistivities are usually quoted in units of ohm.metres; the inverse of resistivity is conductivity, for which the unit is the mho/metre. An alternative way of expressing Ohm's Law is that the potential gradient is equal to the product of the current density and the resistivity.

The resistivities of rocks and soils are very variable, and depend largely upon the water contained within them. Most rock-forming minerals, such as quartz, other silicate minerals, and calcium carbonate, have very high resistivities. Although some minerals have low resistivities (e.g. native metals, graphite, most sulphides and some metal oxides), these do not very often occur in such abundance as to affect the overall resistivity of the rock greatly (and when they do, this is more relevant to mineral exploration). As a result, the resistivity of the solids making up a soil or rock is almost invariably at least several orders of magnitude greater than that of any water contained in pores and joints, and usually only a minute fraction of any electric current flows through through the mineral grains.

The two main factors governing the bulk resistivity of a formation are therefore its water content and the salinity of that water. The water content is a function of the porosity of the formation and its degree of saturation. This means that a given rock or soil type can have very different resistivities above and below the water table, while the resistivities of soils above the water table can be expected to vary with time, and will depend on the recent history of infiltration and evapotranspiration. A third factor, which has a lesser effect on the resistivity, is the extent to which the water forms a continuous network, and how tortuous that network is. As this also affects the permeability, there may be some correlation between permeability and resistivity in certain cases.

Although it is not possible to identify a rock or soil on the basis of its resistivity alone, it may be possible to make certain

deductions about the geology of an area on the basis of a resistivity survey, interpreted along with other information. However, an advantage of a resistivity survey is that it is possible to make deductions about the hydrogeology, rather than simply the geology. For example, a formation with a high resistivity is very unlikely to be an aquifer, as it probably contains virtually no water or only water trapped in isolated vugs or pores. A formation with an extremely low resistivity may well be an aquifer, but the water within it will almost certainly be saline, unless the low resistivity is due to conductive minerals. The best target for drilling will normally be a formation with a moderately low resistivity. Unfortunately, sand saturated with fresh water and a clay may have similar resistivities, so it is impossible to identify an aquifer solely on the basis of a resistivity survey.

If the ground were completely uniform, so that the resistivity did not vary either vertically or horizontally, it would be possible to measure its resistivity simply by passing a current through it via two electrodes positioned some distance apart, and simultaneously measuring both the current and the potential difference between the electrodes. The resisistivity would then be the measured resistance between the two electrodes multiplied by a geometric factor, which is a function of the electrode spacing. Most of the potential difference would arise in the ground very close to the electrodes where the current density is highest; in between, the current would spread out to give a large effective cross-sectional area, and therefore a low resistance. If the contact resistance between the electrodes and the ground were very high, this would introduce a very large error into the reading.

It is therefore normal practice to use four electrodes; two are used to pass the current into the ground and two to measure a resulting potential difference. Again, the resistivity of the ground (assuming this to be completely uniform) is given by:

$$\rho = K * V / I$$

where K is the geometric factor. (Note that in this case the ratio of potential difference to current is not a resistance, although it is quoted in ohms, since the current and potential difference are not being measured between the same points.)

An advantage of this arrangement is that the contact resistance at the potential electrodes is of little importance, since with suitably designed equipment very little or no current passes between these electrodes and the ground while a measurement is being made, while a high contact resistance at the current electrodes merely increases the voltage that must be applied to these electrodes to pass an adequate current into the ground. Also, measures to decrease the contact resistance at the current electrodes (such as wetting the ground, or using two or more closely spaced electrodes) should not cause any significant error.

A number of different electrode arrangements (arrays) can be used.

Most have the four electrodes in a straight line. The Wenner array comprises four equally spaced electrodes, and is characterised simply by the electrode spacing 'a' (Figure 6). Conventionally, the two outer electrodes are the current electrodes and the inner ones are the potential electrodes (though theoretically the same results will be obtained if the current and potential electrodes are interchanged).

The Schlumberger array is similar except that the inner (potential) electrodes are more closely spaced; the parameters which are used to characterise it are the distances of the current and potential electrodes from the centre of the array, AB/2 and MN/2 respectively. The ratio of MN/2 to AB/2 can vary between about 1/5 and 1/50.

For reasons discussed in later sections, the Wenner array is the one commonly used for resistivity traversing, while the Schlumberger array is the standard array for vertical electrical soundings.

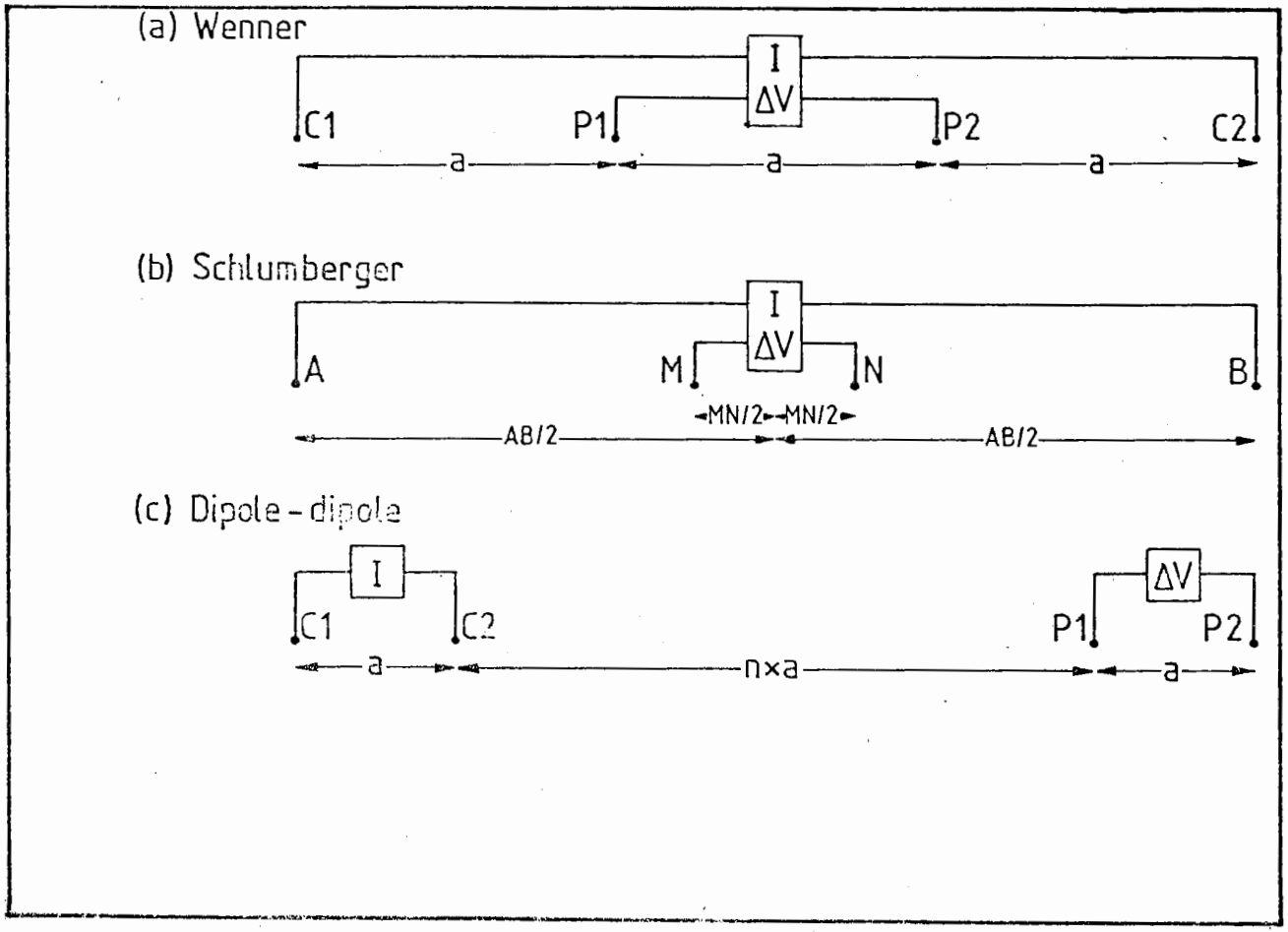
A third array type, the dipole-dipole array, uses currrent electrodes at a spacing 'a', and potential electrodes at the same spacing 'a', with a multiple of this spacing, n*a, between the two pairs of electrodes. This may occasionally be useful when working with large array lengths to obtain large depths of investigation, if the equipment design allows the use of a transmitter, connected to the current electrodes, and a separate receiver, connected to the potential electrodes, without any interconnecting cable between the two instruments; the power output required for accurate measurements with this array is, however, higher than for the other two arrays described above.

The resistivity of the ground is not uniform, and the resistivity value which can be measured, as outlined above, is not the resistivity of any clearly defined part of the ground. The current spreads out through a volume of ground which theoretically is unbounded; however, there is a zone of influence below and beside the array through which most of the current flows, and which can influence the measurement to a significant extent. The measured resistivity is a complicated function of the resistivity distribution within this zone, and is therefore called the apparent resistivity. Thus the apparent resistivity can be defined as the resistivity which, if the ground were completely uniform, would give the same ratio of potential difference to current as the actual distribution of resistivities within the ground. In many cases it is reasonable to think of the apparent resistivity as a weighted average of the resistivities within the zone of influence, but if there are large lateral variations this is not true. There are zones (between the current and potential electrodes for the Schlumberger and Wenner arrays) where the effect of high resistivities is to decrease the apparent resistivity.

Since the depth to which the zone of influence extends is roughly proportional to the array length, it is possible to investigate vertical variations in resistivity by varying the electrode spacing; this is known as vertical electrical sounding (VES). Alternatively,

Figure 6

COMMMON ELECTRODE ARRAYS



horizontal variations can be investigated by keeping a constant electrode spacing, chosen so as to give an appropriate depth of investigation, and moving the entire array; this is constant separation traversing. These methods are discussed separately in later sections.

This ability to vary the depth of investigation by varying the array length is another reason for using four electrodes. If only two electrodes were used, and if there were a high resistivity surface layer, this would dominate the reading regardless of the electrode spacing used.

3.2.2 Equipment

In its simplest form, resistivity equipment could consist of a source of direct current (such as a battery), an ammeter and a voltmeter. Such a system would be of limited accuracy. The potential differences measured would include components due to naturally occurring voltages within the ground (self potential) and to voltages set up between the electrodes and the ground by their electrochemical interaction. The latter can be prevented by the use of non-polarising electrodes (e.g. copper rods inside a porous pot filled with saturated copper sulphate solution) as the potential electrodes. The effects of self potential can be mostly cancelled out by taking the average of two readings with opposite current directions; complete cancellation is not normally possible because the self potential varies slightly with time.

Most resistivity equipment avoids these problems by using either a low frequency alternating current or a commutated direct current, i.e. by automatically switching the current direction at regular intervals. The main disadvantage of the use of alternating currents is that electromagnetic effects can be significant. An alternating current causes a fluctuating magnetic field which can induce secondary currents and potentials. Related to this is the "skin effect", which tends to confine alternating current to the ground surface and which can in certain conditions drastically limit the depth penetration possible with low powered resistivity equipment.

With older types of equipment, it is generally necessary to adjust a potentiometer until a null reading is obtained on a meter; there is then no current flowing through the potential electrodes. Commonly, there is provision for applying a voltage to "back off" self potential; this voltage is adjusted before passing a current through the current electrodes. These adjustments require considerable care if they are to be made correctly, and there is therefore likely to be a certain amount of operator bias in the results, as well as a risk of operator error. The power source may be a battery or a generator; the latter allows higher currents to be used, improving the accuracy and the maximum depth of investigation. The disadvantages of using a generator are reduced portability and hence slower field operations, and the need for great care as potentially lethal voltages and currents are produced.

Newer equipment makes use of digital electronics. An example of such equipment is the ABEM Terrameter SAS 300. This incorporates a microprocessor. Each reading is an average of measurements taken with different current directions; a number of such readings can be automatically averaged and the final result is displayed digitally. The microprocessor automatically carries out self-checking procedures; in the event of a malfunction, or if an inappropriate range or current setting is used, an error code is displayed. There is therefore much less chance of operator error, and obtaining readings is generally faster. The averaging of a number of readings allows acceptable accuracy with a lower power ouput than would otherwise be needed, which in turn means that the instrument is easily portable. Power is supplied by a rechargeable battery pack.

The other equipment required consists of cables and electrodes; the latter normally consist of steel stakes which can be pushed or driven into the ground.

3.2.3 Vertical Electrical Sounding

(i) Theory and Field Methods

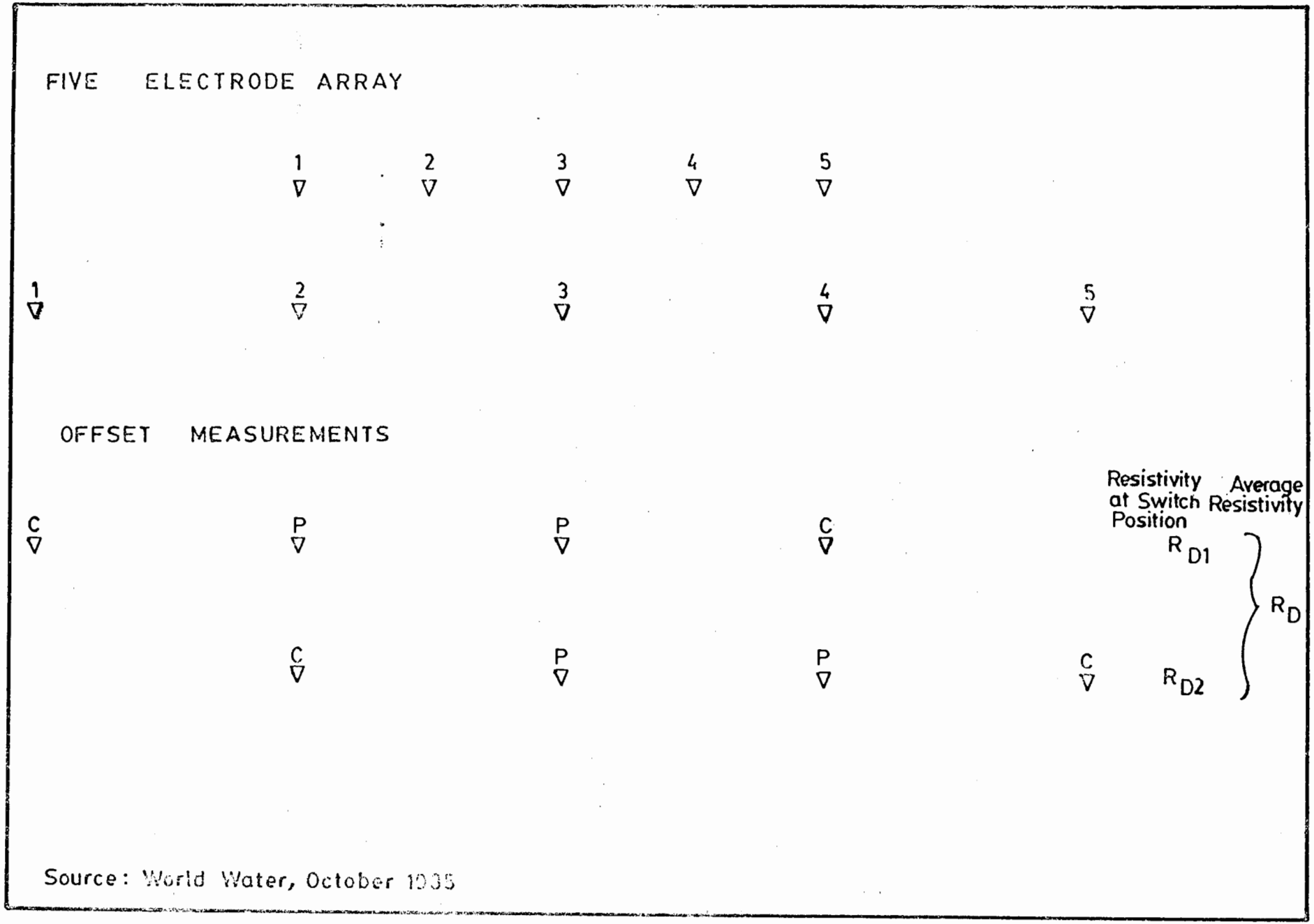
To investigate the way in which the resistivity of the ground varies with depth, a series of readings are taken with differing electrode spacings and with the centre point of the array being kept constant. The apparent resistivity measured with the smallest spacing should be virtually the resistivity of the surface layer; as the spacing is increased, progressively deeper layers influence the apparent resistivity.

The electrode array most commonly used for vertical electrical soundings is the Schlumberger array. The first reading is taken with AB/2 equal to (usually) 1 metre; MN/2 might be 0.2m or 0.25m. Several readings are then taken with progressively larger values of AB/2, while MN/2 is kept constant. Then MN/2 is increased while AB/2 is unchanged for one reading; several more readings are taken with increasing values of AB/2 and a constant value of MN/2, and so on. The values of AB/2 are chosen so that they are approximately equally spaced when plotted on a logarithmic scale.

One of the advantages of the Schlumberger array is that fewer moves of the electrodes are needed than with the Wenner array, where all four electrodes have to be moved between each reading. A second, more important, advantage is that lateral variations cause greater errors when the potential electrodes are moved than when the current electrodes are moved. The duplication of readings with same values of AB/2, but different values of MN/2, allows an approximate correction to be made for the effects of lateral variations, as described in the section on interpretation.

An alternative is the Offset Wenner array. At each electrode spacing, five equally spaced electrodes are used, the centre electrode being kept fixed for all electrode spacings (Figure 7). At each spacing five different readings are taken with different combinations of four electrodes. Two of these are similar to conventional Wenner readings, but are offset in opposite directions from the centre of the array. When these two values are averaged, the effects of moderate lateral variations are largely cancelled out. It is possible to calculate apparent resistivity values for intermediate electrode spacings, and for two additional values at spacings greater than the largest spacing that is actually used, although these interpolated and extrapolated values must be used with caution, as they will be less accurate than the measured values. Furthermore, error values can be calculated which provide a check on the probable accuracy of the readings and on the magnitude of any lateral variations. With ordinary single core cables, this method would be very slow. With special multicore cables it can be faster than a Schlumberger sounding. These cables have contacts at spacings of 0.5, 1, 2, 4 metres etc. up to 128 metres. The cables are connected to the instrument via a switch box; one switch selects one of the 9 available electrode spacings, and a second switch selects one of the five combinations of electrodes for that spacing.

Figure 7 The Offset Wenner Sounding



Source: World Water, October 1985

In selecting a position at which a sounding is to be carried out, and the orientation of the array, it is important to remember that the interpretation will be based on the assumption that there is no lateral variation in the resistivity. Although this assumption is never strictly true, it is often near enough the truth for an interpretation based on it to be useful. However, it may well be that the lateral variations are too great to allow an acceptable accuracy of interpretation. This may not become clear until after the sounding has been carried out, but sometimes it is obvious from an inspection of the location that the lateral variations will be very large. For example, the assumption of horizontal layering includes the assumption that the ground surface is horizontal. If the topography in the immediate vicinity of the sounding is very rough, then this will distort the resulting sounding curve so much that it cannot be reliably interpreted. The effect of a gully will be greatest if it crosses the line of the array close to the centre. A sounding which extends from a strip of alluvium along a stream valley onto a valley side would have to be interpreted with extreme caution.

(ii) General Field Procedures for Resistivity Surveying with the Terrameter

1 Electrodes

Where the ground is very hard, do not hammer the electrodes into the ground if this can possibly be avoided. It is much better to make a hole in the ground first with one of the spikes made for this purpose; these are designed to be driven into the ground with a piece of wood, striking the top, not the cross piece. If the spike will not go in far enough, pull it out, pour a little water down the hole and try again. Repeat this as often as necessary to get the hole deep enough, then take out the spike, add some more water to the hole and put in the electrode. The electrodes can be positioned by placing one piece of wood through the loop and then tapping this wood with a second piece. If it is impossible to get an electrode in more than a few centimetres, it may be necessary to use two or more electrodes in a line at right angles to the sounding or traverse and connected together.

2 Cables

When using separate cables, try to keep the cables to the current electrodes (the outer electrodes of the array) separated by at least a metre from the cables to the potential electrodes. If they do cross, they should do so at right angles, and be separated vertically. If the insulation is damaged, wrap it with insulating tape. If the cable breaks, it can be temporarily joined by knotting the two ends and by twisting together the bare wires; either wrap insulating tape around the join or take good care that the exposed metal does not touch the ground while a reading is being taken. A proper splice, with solder and a piece of wire wrapped round as a mechanical reinforcement, should be made before the start of the

next day's field work. If there are several splices within a short length of cable, it may be better to cut this section out (but do not throw it away - you may find it useful one day).

The cables for the Offset Wenner array must be treated very carefully; they should never be pulled along the ground. In the event of damage to one of these cables, it is probably not wise to attempt to repair it in the field.

Always clamp cable reels when transporting them, to prevent the cable from unwinding and tangling, and always slacken the clamp fully before unwinding a cable.

3 Taking Readings

Always use the highest possible current setting, as this will give the greatest accuracy. Start with 20 mA and reduce the current one step at a time until error code 1 does not appear. If error code 1 appears even at the lowest current setting, then almost certainly the current circuit is incomplete; either an electrode is not connected, or the cable is not connected to the Terrameter, or there is a break in the cable. If error code 5 appears during a sequence of readings, it will be necessary to reduce the current setting by one switch position. For subsequent readings, increase the current setting by one or two positions if the setting is low and decrease it again if error code 1 appears; this is the only way of being sure that you are using the correct current setting each time, as it may vary unpredictably from one electrode position to the next.

Always use the lowest possible range setting, as this will give the maximum possible resolution. Start with the range switch at the 1 ohm position, and increase the range one position at a time until error code 2 no longer appears. With subsequent readings, if there is any doubt about the correct range setting, reduce the range by one switch position; if error code 2 appears, return to the previous setting, otherwise decrease the range still further, if this is possible, and try again. Using too high a range will cause a decrease in the number of significant (i.e. generally non-zero) figures in the value displayed.

The number of cycles should normally be set at 4. If the successive values which are displayed vary significantly, then it may be sufficient to increase the number of cycles to 16. If this fails to give satisfactory results, then try to increase the current by using more water at the current electrodes and/or additional current electrodes. The 64 cycle setting should be regarded as virtually a last resort. A set of readings should not be accepted if there are significant differences between the last two or three values displayed; an upper limit of 2 in the last decimal place would be reasonable for these differences. If there is a very large jump in values during a set of readings, reject that set immediately by switching the Terrameter off and back on if this is going to be quicker than waiting for it to complete the set.

4 Weather

Do not work if there is a thunderstorm anywhere in the vicinity. Do not work in very heavy rain; it is possible to work in light rain if the Terrameter and switchbox are kept dry. Try to keep the Terrameter in the shade in hot weather.

5 Planning

As a general rule, start with a sounding or two or three, select a spacing, cover the area with a grid of traverses, and finish of with soundings at selected locations. With traversing, if in doubt what spacing to use, select the largest you have been considering; too small a spacing is worse than too large a spacing. The aim is to use a spacing appreciably larger than that at which the minimum occurs on any sounding within the survey area.

With soundings, try to extend them far enough to define the rising part of the curve well. Use the Offset Wenner array as far as possible because it is more convenient, but consider the Schlumberger array where there is not much space available or where there might be a risk of damage to the cables.

(iii) Field Procedures for Vertical Electrical Soundings, Offset Wenner Array

1. Select the centre point and the orientatation of the array so that there is a sufficient length in each direction without major obstacles, and so that there are no deep gullies, or other abrupt topographic features, close to the centre. The direction should if possible be such that the array is entirely within a single geomorphologic element. If there is a stream close to the centre point of the sounding, it may be better to orientate the array at right angles to it. If possible, avoid fences, pipes and cables which may conduct electricity; failing this, the array must cross them at right angles. In practice, the above 'rules' may clash with each other, so use your judgement to decide what orientation is likely to cause the fewest problems.

2. Describe the location fully on the field sheet. If necessary, show both the general location and the exact location by means of detailed sketches. Note bearings and/or distances to suitable reference points, such as trees, buildings, roads, etc. Also note at least the approximate orientation of the array.

3. Anchor both cables to the centre electrode and start laying out the cables. The best procedure will depend on the terrain and vegetation. One possible method is to select a suitable landmark, such as a conspicuous tree, and start laying out one cable directly towards it. The direction for the other cable can then be determined by sighting back along the first cable. Alternatively, long poles could be used to mark out the line. In thick bush it will be necessary for a line to be cut first, and this could best be done by labourers working in advance of the group carrying out the soundings.

4. While the cables are being laid, connect the cables and the centre electrode to the switch box, and the switch box to the Terrameter. Position and connect the first few electrodes on either side. Do not use very much water, if any, at these electrodes, or insert them very deep in the ground.

5. Start taking readings while the remaining electrodes are being positioned. First check the battery voltage and then select 4 cycles, 1 ohm and 20 mA as the initial settings.

6. Take all the readings using the lowest possible range and the highest possible current. Before taking a reading with the switch at B, reduce the range setting by one position if it is not already set at 1 ohm. Always increase the current setting by one or two positions (unless it is already at 10 or 20 mA) before taking each reading.

7. For each set of readings, use the tripotential check (B approximately equal to A-C) to ensure that there are no serious measurement errors. If there is a large difference between D1 and D2 consider repeating these as a check. As a preliminary check that the

values are reasonable, calculate the approximate value of the apparent resistivity as (D1+D2)*pi*A, where A is the electrode spacing (1 for switch position 2, 16 for switch position 6, etc.)

8. If it is necessary to extend the sounding to a tenth electrode spacing to define the ascending part of the curve, decide this as early as possible so that work can start on positioning the additional electrodes and cable in good time. The additional electrodes have to be 256 metres beyond the electrodes at the ends of the multicore cables, and are to be connected to the last contacts on these. The electrodes at the end of the multicore cables are to be connected to the eigth connector (coloured yellow). Take the readings with the selector switch at spacing 9.

9. Repeat any readings for which suspicious-looking values have been obtained, if necessary increasing the number of cycles and/or taking measures to increase the current. If the readings still look strange, and especially if there appear to be very large lateral variations (large differences between D1 and D2), then consider a crossed sounding as a check.

10. When all readings have been taken, disconnect and collect the electrodes and wind up the cables by walking with the cable reel so that the cable is not pulled along the ground. Check that all electrodes are picked up, and that all cable reels have been securely clamped for transit.

11. When the centre electrode is removed, put a suitable marker peg in its place and check that your description of the location on the field sheet is sufficiently detailed for the point to be relocated if necessary. Also check that any features which may possibly have influenced the readings have been clearly noted on the field sheet.

Note. If a fault is suspected in one of the cables, due to a broken conductor, first attempt to identify the connector affected by referring to the diagram showing the electrodes used for current and potential in the BGS manual. Remember that two consecutive spacings will be affected by a single fault. Then disconnect that contact from the electrode and connect one end of one of the single core cables to the contact. With the multimeter from the toolkit, set to a resistance range, check the continuity between the other end of the single core cable and all the connection at the plug which connects the multicore cable to the switch box. If all of these appear to be open circuit (no deflection of the multimeter needle) then the fault has been correctly identified. Continue field operations by connecting the electrode affected to the correct yellow terminal on the switch box by means of the single core cable - but remember that this will depend on the electrode spacing selected. Do not attempt to repair a multicore cable in the field. Unless the fault is the connector at the end of the cable or can be definitely located, do not attempt to repair it.

(iv) Interpretation

The first stage in interpreting the results of a sounding using the Schlumberger array is to convert the readings to apparent resistivity values by multiplying them by the corresponding geometric factors. These apparent resistivity values are plotted on a graph against the current electrode spacings AB/2 using logarithmic scales. The resulting graph will consist of separate segments for each value of MN/2 which was used, and will generally need to be smoothed. This can be done graphically by shifting the second segment vertically to join up with the first, then shifting the third segment to join up with the second, and so on. (An equivalent numerical procedure can be used instead.) Although this correction is somewhat arbitrary, it will normally reduce the effects of lateral variations. The resulting smoothed curve is then taken to be the field curve for interpretation. For the Offset Wenner array, the calculation of the apparent resistivities is more complicated, and will not be described here, but these again are plotted against electrode spacings on logarithmic scales to give a field curve.

The principle behind the interpretation procedure normally used is to assume a model comprising several horizontal layers and specified by the thickness and resistivity of each layer. (The deepest layer is always assumed to be of infinite thickness.) The theoretical sounding curve for this model is then compared with the field curve, and the model is adjusted and the theoretical and field curves compared again, and so on until a satisfactory match is obtained. To facilitate this, various sets of master curves have been published, giving the theoretical curves for a range of models. To reduce the number of curves, the resistivity and thickness of the first layer are assumed to be unity, and other values are then given as ratios with respect to these. When the curves are plotted on logarithmic scales, multiplying all the layer resistivities by a constant shifts the curve vertically, and multiplying all the layer thicknesses by a constant shifts the curve horizontally; the shape of the curve is not changed in either case. This then is one reason for plotting field curves on logarithmic scales.

In a two layer case, only a single set of curves is required, and these can be printed on a single sheet of paper. The field curve is plotted on transparent paper on the same scales as the master curves (normally 62.5 mm per cycle), overlaid on the master curves, and shifted horizontally and vertically (keeping the axes of the two graphs parallel) until the field curve corresponds with one of the master curves. The resistivity and thickness of the first layer are then read off as the values on the field curve graph corresponding to a cross marked on the master curve sheet. The ratio of the two layer resistivities is the value shown for the master curve which matches the field curve. Interpolation between master curves is possible.

For three layers, the procedure is more complicated because there are two resistivity ratios and a thickness ratio to be considered.

This means that a comprehensive set of master curves consists of a large number of pages, and it is necessary to work logically to find the best match. Interpolation between curves becomes more difficult, and there is often a considerable amount of ambiguity in that several curves may all appear equally good approximations to the field curve. For four or more layers, really comprehensive sets of master curves become impractical, and it is then necessary to use other methods, such as partial curve matching, for interpretation. Such methods are time consuming and not very accurate.

An alternative method which has become practicable in recent years is the calculation of theoretical curves using a computer (Figure 8). This method is more flexible than using master curves. Master curves can only show a limited number of resistivity and thickness ratios, while a computer program can accept values to whatever degree of precision is appropriate. Increasing the number of layers results in an increase in computation time, but not so as to limit the number of layers which can be used for the model. Typically, a computer program will accept and store the values for the field curve, plot a graph of the field curve on the screen, and accept values specifying a model. It will then calculate the theoretical curve for that model and display it on the screen along with the field curve. If the match is not satisfactory, the model can be changed and the process repeated as often as necessary. The initial model could be obtained by a rough comparison with master curves, but the computation of theoretical curves by computer is normally fast enough for it to be quicker to use even a very rough guess as the first model.

There are methods which can be used to obtain a direct interpretation; using a suitable programme, the field results are entered and the computer calculates the model. However, these methods either require the field curve to be extrapolated (which could introduce serious errors) or make certain arbitrary assumptions. In either case it would not be wise to accept the results uncritically; it would be better to refine the results using the iterative method described above.

Regardless of whether master curves or a computer is used, it is necessary to be aware of the fact that there is normally a certain amount of ambiguity in the interpretation procedure. This takes two forms.

When a thin layer lies between two layers, one having a higher resistivity and the other a lower resistivity, then various combinations of the resistivity of the intermediate layer and the thicknesses of the layers will give very nearly identical sounding curves. It may be possible to eliminate the intermediate layer altogether without changing the theoretical curve significantly. (Conversely, it is possible to include a thin intermediate layer between two adjoining layers without much effect on the theoretical curve.) This is known as the Principle of Suppression.

When a layer has a lower resistivity than the layers above and

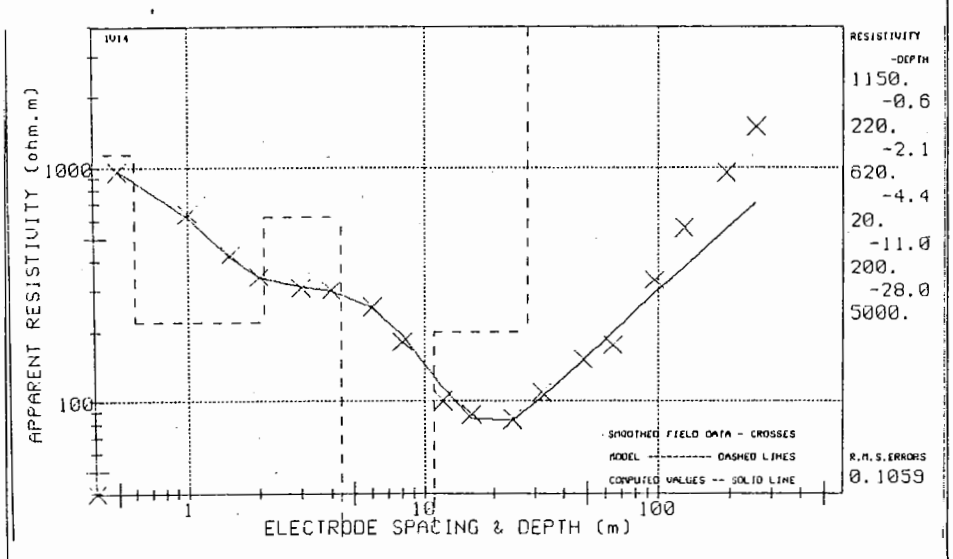
Figure 8 Vertical Electrical Sounding Data Sheet

VERTICAL ELECTRICAL SOUNDING (OFFSET WENNER ARRAY)
Data Reduction & Interpretation

No. 1V14

LOCATION EXPERIMENTAL CATCHMENT AREA. Site of GWR-1/3.

Switch position	Errors (%) observed	offset	lateral	Electrode spacing (m)	Apparent resistivity (ohm-m)	Electrode spacing (m)	Apparent resistivity (ohm-m)
1	0·256	-1·307	-17·993	0·5	961.3		
2	-0·032	-8·135	-50·872	1	633.4	1·5	426·8
3	0·337	0·368	-6.302	2	341.2	3	306·3
4	-0·074	9.187	-7.516	4	298.2	6	254.3
5	-0.314	14.485	53.308	8	180-5	12	99.8
6	0.611	-6.178	-1.760	16	87·9	24	83.9
7	-1.973	-46.353	-32.566	32	105.9	48	151.5
8	0.534	-39·540	37.783	64	174.9	96	331.6
9	-1.459	-134.535		128	557·7	192	948·5
10				256	1496.1	384	
R.m.s. errors	0·880	49·679	32·961	512			



COMMENTS

Groundwater Research Department National Water Resources Institute Kaduna

III-16

below, then its resistivity and thickness can be varied within certain limits, provided that their ratio remains constant, without the theoretical curve changing very much. Similarly, if an intermediate layer has a higher resistivity than the layers above and below, then its resistivity and thickness can be varied within certain limits, provided that their product remains constant, without the theoretical curve changing very much. This is known as the Principle of Equivalence.

3.2.4 Resistivity Traversing

(i) Theory and Field Methods

Traversing provides a means of studying lateral variations in the resistivity of the ground. In principle, any electrode array could be used, but for practical reasons it is normal practice to use the Wenner array. In its simplest form, a traverse is carried out by shifting the array by a distance equal to the electrode spacing between successive readings. It is also possible to move the array a multiple or submultiple of the electrode spacing, the choice being made on the basis of the need for detailed information on the one hand, and speed of field operations on the other.

The selection of the electrode spacing must be made on the basis of the required depth of investigation and the vertical distribution of resistivity values. This can be done by carrying out at least one vertical electrical sounding first, or by using any available information to estimate the vertical distribution of resistivities and looking at the corresponding theoretical sounding curve (or the curves for the probable range of subsurface conditions) from a set of master curves or by computation. In the common case where the sounding curve falls to a minimum and then rises again, the spacing chosen should usually be somewhat greater than the spacing corresponding to the minimum on the sounding curve. This ensures that a change in either the thickness or the resistivity of the intermediate, low resistivity layer will have an effect on the results of the traversing. However, particular problems and particular geological conditions will need to be considered individually.

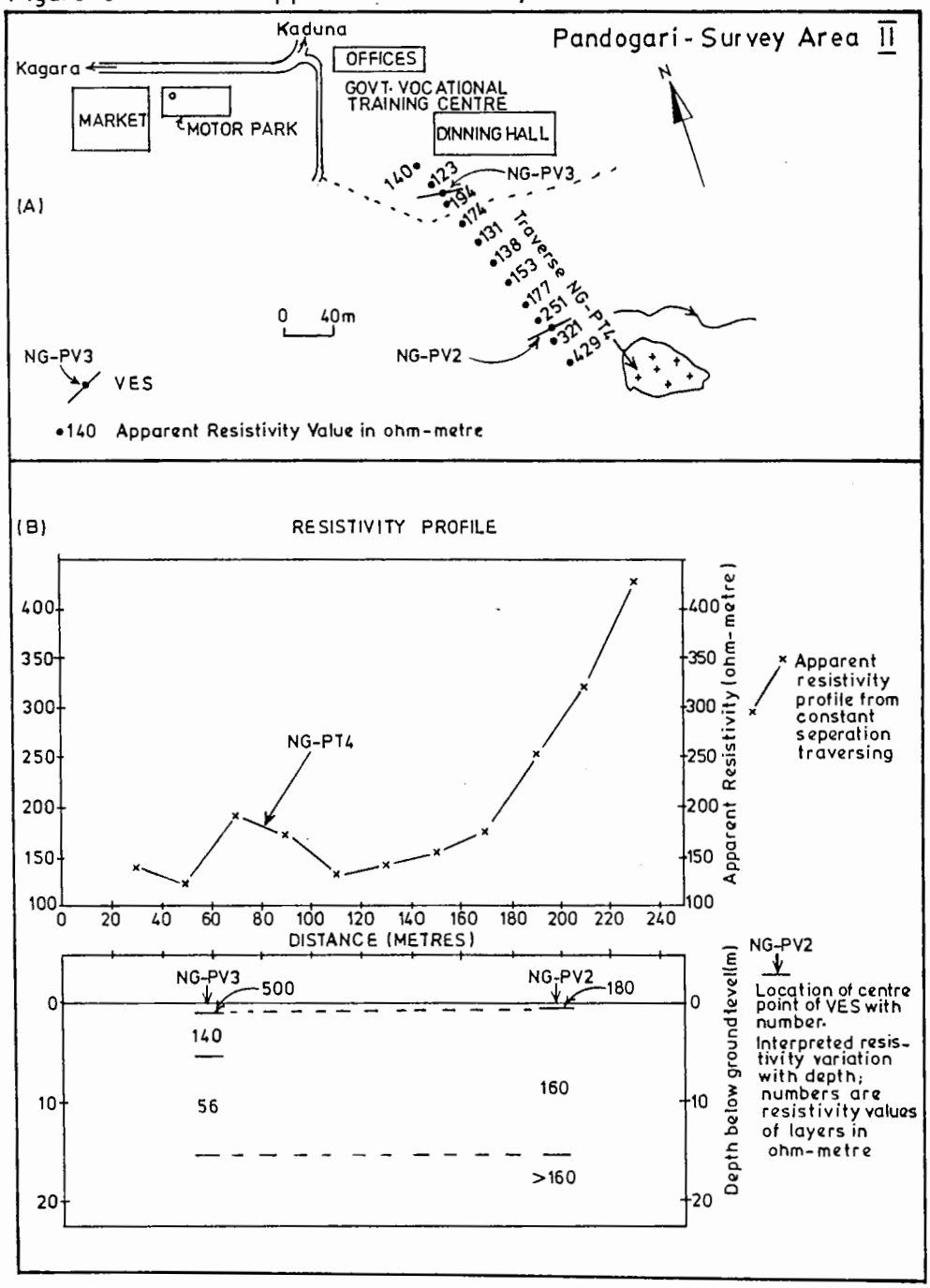
(ii) Interpretation

Only in the case of very simple geological conditions is it possible to work out mathematically a theoretical resistivity profile, and so comparison of a theoretical profile with the field results is not practicable as a routine method of interpretation. Any realistic model is likely to require a large number of parameters to define it adequately, so that the number of parameters to be determined is greater than the number of useful data values. The situation is thus similar to trying to solve simultaneous equations where the number of unknowns is greater than the number of equations - there is no unique answer, but an infinite number of possible solutions. Modelling needs a powerful computer, and iterative modelling would

require too much time to be practicable. Interpretation of resistivity traversing is therefore normally only qualitative.

The apparent resistivity values are plotted as a profile (an example is shown on Figure 9); in most cases a linear scale is most convenient, but where there are large variations a logarithmic scale could be used for the resistivities. Depending on local conditions, the best location for a borehole might be where the profile shows a minimum, or it might be where the profile shows a certain range of values if very low resistivities are believed to be due to saline groundwater or clays.

Figure 9 Apparent Resistivity Profile



3.2.5 Application to Groundwater Exploration

The most important application of resistivity surveying in Nigeria is probably selection of borehole sites in areas underlain by the Basement Complex. Other applications can include mapping the thickness of shallow unconfined aquifers and the depth of the water table within them, and investigating the distribution of saline water, particularly in coastal areas.

The optimum use of resistivity surveys will depend on local hydrogeological conditions and the availability of other data. Where lateral variations are fairly gradual, it may be practicable to map these variations by suitably spaced vertical electrical soundings. This is most likely to apply if the area is underlain by flat-lying sediments. Where lateral variations are likely to be large within short distances, soundings alone would be an inefficient survey method. It will usually be better to select the locations for soundings on the basis of resistivity traversing, an electromagnetic survey, geological mapping, inspection of aerial photographs, or some combination of these.

In interpreting the results, all available relevant data should ideally be used. Depending on the geological conditions, the criteria for selecting a borehole site will vary from area to area. As a number of borehole results for one area become available which can be correlated with electrical soundings, it could become possible to assess the suitability of a site simply by inspection of the sounding curve. However, a full interpretation should still be made if time allows.

3.3 Seismic Refraction Surveys

3.3.1 Basic Theory

Vibrations can be transmitted through the ground as three types of seismic waves which are as follows:

- P waves or compressional waves in which vibration is in the same direction as the propagation of the waves - these are in fact sound waves;
- S waves or shear waves in which vibration is at right angles to the direction of propagation;
- surface waves in which the motion is elliptical.

Of these, P waves always have the greatest velocity and normally are the only waves which are of any interest in seismic refraction work. For the rest of this discussion, any reference to seismic waves will mean P waves, and the seismic velocity of a material will mean the velocity of P waves within that material.

If a small explosive charge is detonated at a point just below the surface of the ground, seismic energy will radiate outwards from the shotpoint and can be detected by geophones (also known as seismometers) placed at varying distances from the shotpoint. The time from the instant of the shot to the first detectable arrival of seismic waves at a given geophone is referred to as the travel time for that geophone. If the ground were completely uniform, then a graph of travel times plotted against distance from the shotpoint would be a straight line whose slope would be the reciprocal of the seismic velocity.

In most places the ground can be divided into several layers on the basis of the seismic velocity. Normally the seismic velocity increases with increasing depth, because the seismic velocity is controlled mainly by the elastic moduli of the material.

Consider first the case in which there are two layers separated by a horizontal interface. Some energy which initially travels downwards will be refracted at the interface between the layers. This refraction is analogous to the refraction of light and is governed by Snell's Law:

$$\sin(i)/\sin(r)=V1/V2$$

where i = angle of incidence,
r = angle of refraction,
V1 = seismic velocity of first layer,
V2 = seismic velocity of second layer.

For an angle of incidence equal to the critical angle ic = arc sin(V1/V2), the refracted energy will travel parallel to the interface at the velocity V2. At each point along the interface, some of this critically refracted energy leaks back into the upper layer, being refracted once again, and travels back to the surface.

At large distances from the shotpoint, this refracted energy will arrive before the direct wave which travels just below the ground surface, since although the total distance travelled by the refracted wave is greater, its average velocity is higher. At some intermediate distance (called the critical distance) the direct arrival and the refracted arrival will coincide. A time-distance graph will therefore consist of two straight line segments, intersecting at the critical distance and with slopes 1/V1 and 1/V2 respectively. The depth to the interface can be calculated from the velocities and either the critical distance or the intercept time, which is found by projecting the second segment of the time-distance graph back to the shotpoint.

This basic theory can readily be extended to cover the case of three or more layers. Provided each layer is sufficiently thick, the time distance graph will show a corresponding straight line segment, from the slope of which the velocity for that layer can be determined, while thicknesses can be calculated from the various critical distances or intercept times.

Another extension of the theory allows for a dipping interface. The slope of the second segment of the time-distance graph is then a function of both the velocity and the dip of the interface. If a second time-distance graph is obtained by firing a second shot at the opposite end of the spread, then the profile is said to be reversed, and it is possible to work out the velocity of the second layer and the depths of the interface below each of the shotpoints.

Generally the segments of the time-distance graphs will not be exactly straight lines, as there will be some scatter caused by variations in seismic velocities and irregularities in the interfaces between the layers. In one method of interpretation (known as the plus-minus method), these deviations from a straight line are used to calculate variations in the seismic velocity of, and depth to, the deepest layer detected. In shallow refraction surveys, this deepest layer will generally be 'bedrock', i.e. relatively unweathered rock; the overlying layer or layers will be weathered rock, alluvium, soil etc. and can be collectively referred to as overburden. To take full advantage of the plus-minus method, at least two further shotpoints are required, in line with the spread but at a distance from the nearest geophone greater than the critical distance for the bedrock.

It is important to note certain fundamental limitations of the seismic refraction method.

Firstly, it assumes that each layer has a seismic velocity greater than that of the layer above. If a low velocity layer underlies a high velocity layer, then the low velocity layer cannot be detected, and the depths calculated for any deeper layers will be wrong. If such a velocity inversion occurs, it may remain unsuspected until it is found that geophysical results are in serious disagreement with, for example, borehole data. One situation where the possibility of a velocity inversion should be suspected is where there is known to be

a hard surface layer such as laterite or calcrete. In such cases a refraction survey is likely to be a waste of time and effort. If one is carried out, it will need to be carefully checked against other data before the results can be trusted.

Secondly, if an intermediate layer is too thin, it will not be detected and again the depths calculated for deeper layers will be in error. The minimum thickness of layer which can be detected depends mainly on its depth and the seimic velocities involved, but it is also affected by the spacing between geophones. Where it is suspected that there is such a hidden layer, it is possible to assess its maximum possible thickness provided its velocity can be estimated. In favourable circumstances, by using data from other spreads and/or boreholes, it may be possible to obtain a reasonable interpretation, but this will have to be used with considerable caution.

3.3.2 Equipment

A typical set of equipment for shallow seismic refraction surveys is based on a 12 channel digital seismograph. The geophones are connected to this by a multi-core cable with takeouts for geophone leads at equally spaced intervals. If explosives were used, a blaster would be needed to fire the charge and to transmit the time of the shot (the shotbreak) to the seismograph. Commonly, a sledgehammer striking a metal plate is used as a source of seimic waves, but the terms 'shot' and 'shotpoint' are still used. An inertia switch on the sledgehammer is used to signal the moment of impact to the seismograph.

The seismograph itself contains 12 identical amplifiers which can be individually set to a suitable gain, bearing in mind the distance of each geophone from the shotpoint. The signal from each amplifier is digitised and stored in memory. This allows the signals resulting from several successive shots at the same shotpoint to be summed; this process is known as signal enhancement. The stored signals are displayed on a cathode ray tube, and can be printed out on paper when the operator wants. The record length can be varied from about 50 milliseconds upwards; the sampling interval corresponding to the minimum record length is 50 microseconds. A delay can be introduced between the shotbreak and the start of the record, so that the best use can be made of the record length when there is a considerable distance from the shotpoint to the nearest geophone. Filters can be switched in to reduce interference from power cables and high frequency noise if necessary.

3.3.3 Field Methods

In selecting the exact position for a spread, it is best to avoid very irregular ground, as it is not practicable to correct fully for the effects of topography in interpretation. Locations near busy roads and similar sources of noise have to be avoided, as the seismic signals may be completely obscured.

Once a location has been selected, the geophone cable is laid out in a straight line. Mostly the spacing between geophones will correspond to the interval between takeouts on the cable, but spacings may be reduced if necessary, in which case they will have to be measured with a tape. The geophones are fitted with a short spike which has to be pushed firmly enough into the ground to ensure good coupling.

When all the connections have been made, reasonable gain settings are chosen for the first shotpoint and one or more hammer blows are used to provide the signal. If the gains are unsuitable, they are changed, the seismograph's memory is cleared, and the process is repeated. When the operator is satisfied with the record, as seen on the c.r.t. display, he adjusts the amplitude of the displayed signal for each channel to ensure that the first breaks are all as clear as possible and then prints out a paper copy of the record. This procedure is then repeated for each shotpoint in turn.

To survey a long line, it is necessary to use a number of spreads, each having at least one geophone position in common with the previous spread. Although for a single spread the exact positions of any outshots is not critical, it may be worth planning adjoining spreads so that the same shotpoints are used.

More detailed notes on field procedures using the equipment actually supplied for the project (McSeis 1500 Seismic Data Aquisition System) are given below:

1 Selection of Site

The site will normally be selected on the basis of geology, access, etc., but where possible avoid crossing abrupt changes of slope and especially deep gullies with a seismic spread. Try to stay clear of sources of noise, such as busy roads, and structures which could affect the results, such as pipes or culverts parallel to the spread. Do not lay the geophone cable across any track or road unless you can positon people to stop any traffic, as vehicles must never be allowed to drive over the cable.

Do not forget the need for outshots if a complete interpretation using the plus-minus method is to be carried out. Often problems can be avoided by a small shift in the position or direction of a spread.

Aim for a spread length about twice the critical distance to bedrock. In the case of the first spread in an area, it will only be

possible to make a rough estimate, but for later spreads the spread length can be adjusted on the basis of earlier results.

2 Setting Up

Where possible, position the vehicle close to one end of the spread and a few metres off the line of the spread. Lay the geophone cable out in a straight line; one person should hold the first takeout at the position of the first geophone while a second person, with the cable reel on his back, walks slowly along the line. The clamp on the cable reel must be fully released first. If it is necessary to adjust the position of the cable, this is best done by someone walking along the line and repositioning the cable carefully, as dragging it along the ground can damage it.

When using a short spread, tape out the geophone positions before laying out the cable, so that each takeout can be positioned close to the geophone.

The operator should either place and connect the geophones himself, or check that this has been done correctly. It is important that the geophones are securely embedded in the ground, even if this means that the geophones are slightly off the line or not at the nominal spacing. The connections at the takeouts must be the right way round, and if the ground is wet the takeouts and clips must be kept clear of the ground to reduce the risk of leakage and crosstalk between channels.

The operator must also ensure that all necessary information about the spread is recorded on the field sheet, or on the envelope in which the records will be stored. This includes the spacings between the geophones. Where two consecutive geophones are both close to their takeouts and the cable in between is straight, then the distance between the geophones can be taken as being the nominal spacing of 7.5m; otherwise the actual spacing must be measured with a tape measure. Any features which might possibly affect the results must also be noted on the sketch of the spread.

Wherever possible, keep the seismograph either in the vehicle or in the shade, as direct sunshine can quickly cause the internal temperature of the equipment to excede its operating limit.

Before connecting the geophone cable to the amplifier unit, make sure that both the plug and the socket are clean. Be very careful when making this connection to put the plug in straight and to do up the locking ring. Be similarly careful when connecting together the two units of the seismograph; put the red plastic covers onto the backs of the connectors to keep them safe.

Before switching on the seismograph, check the connections to the battery are the right way round. Be very careful to avoid shorting the battery. Check the battery voltage when you switch on and do not continue with the survey if the voltage is too low.

3 Recording

Check the geophones for continuity. It is not necessary to check for leakage every time if the ground is dry; once or twice a day is enough. Leakage can cause excessive noise on one or more channels, and is often caused by takeouts touching wet ground or vegetation, or by moisture in the connector on the end of the geophone cable.

Set all gains high and look at the noise levels. If 50 Hz noise is present (pickup from power lines) then use the notch filters. Leave the low pass filters out initially. Switch off. Reset the gains for the geophones nearest the shotpoint to lower values and set all the trace size controls to either half or maximum. Select a suitable record length (usually 50 or 100 msec) and zero delay.

Switch on and start stacking. If there is a lot of high freqency noise, clear the memory, select the low pass filters and try again. As individual traces show a good fist break and adequate amplitude, freeze the memory for those traces. After a reasonable number of blows (not normally more than ten, not counting any that have failed to trigger the seismograph), tidy up the display and, if the result looks reasonable, print out a record.

Switch off, reset the trace size controls, check that all channels are unfrozen, and change gains and/or the record length if you think that the ones used before might not have been optimum. Then obtain another record. If it is not possible to identify clear first breaks for each channel on at least one of the records, consider a third attempt, but if that still does not work then it is unlikely to be worth any more tries for that shotpoint.

Check also that the bedrock arrivals are sufficient to define the bedrock velocity. If the critical distance is more than about 2/3 of the spread length, then an outshot is probably worthwhile even if the is no intention of using the plus-minus method of interpretation.

If the critical distance is less than about 1/3 of the spread length, then the surface layer velocity and/or the velocities of any intermediate layers may not be properly defined; in this case the only remedy is to repeat the spread with the geophones more closely spaced. It is common practice when shooting longer spreads to also shoot very short spreads, perhaps at each end of the main spread, to get better information about the near surface layers which is then used in interpreting the results from the main spread. This should not be necessary with a relatively short geophone cable, but the possibility (like that of combining adjoining spreads) should be kept in mind.

Mark all records clearly with the date and the spread and shotpoint numbers before putting them in an envelope for safe keeping. Field sheets and, later, lists of arrival times should be kept with the records.

4 Problems

If one channel develops a fault, then continue with field work but modify the spread so that there is no gap because of the missing channel. In the event of any other failure, check the power supply and the fuses; if those are alright then pack up and return to base. In either case, carefully remove the circuit board where the fault might be, such as the individual amplifier if it is one channel, or the main panel at the bottom of the amplifier unit if none of the channels are working. There is very little clearance between boards so it is important to keep a board straight while taking it out. Inspect the board very carefully for obvious signs such as damaged or discoloured components or bad connections. Clean the edge connector and replace the board, making sure that it goes correctly into place.

If the fault persists, check other boards, the wiring inside the case, and even the cable connecting the two units. It may be difficult in some cases to know even whether a fault is in the amplifier unit or the display unit. If all this fails, the equipment will have to be checked by an electronics engineer with a full set of test equipment; it may be best to return it to the manufacturers for repair.

If the recording paper runs out, it is possible to continue by shifting the record on the display to the left until the first arrival on one channel is just at the left hand edge, noting the time displayed, and repeating this for the remaining channels. Obviously care will have to be taken that the correct value has been selected, and two or three sets of arrival times should be noted and then averaged if there is any doubt.

3.3.4 Interpretation

The first stage in interpretation is the identification of the first breaks on the records. This requires considerable care, as the first breaks may be obscured by, or confused with, noise, and the first part of the signal may become very weak or even disappear altogether at large distances from the shotpoint. Once the first breaks have been picked and the travel times read off the record, the time distance graph is drawn. At this stage any suspicious travel times are checked and perhaps revised.

The second stage is to divide the time distance graph into segments and fit a straight line to each segment, either by inspection or by linear regression. From these, intercept times and apparent velocities are determined. True velocities can be calculated from updip and downdip apparent velocities, either for the one shotpoint or for adjacent shotpoints. Some averaging of the velocities may be necessary; this is a point where the judgement of the interpreter is required. Finally, the depths to each interface are calculated for each shotpoint using the velocities and the intercept times.

This level of interpretation would be sufficient in many instances. Where more detail is required, and the quality of the records justifies it, the 'plus-minus' method is used, but it is considerably more complex than the method described above.

More detailed notes on seismic refraction interpretation, based on the techniques developed for this project, are given below:

1. Examine the records and list the travel times. Beware of possible errors due to noise, interference between direct and refracted arrivals, or the dying out of the first half cycle or cycle of the signal. Make use of all available records for each shot point. If you cannot select a first break with reasonable confidence, do not guess; a wrong value is worse than a missing value.

2. Plot the time-distance graph. Suitable scales are 1:500 horizontal and 1cm = 2.5msec vertical. Use different symbols (e.g. crosses and circles) for the two directions of shooting. Travel times should be plotted in pencil at this stage, and if lines are drawn between the points these should be drawn very lightly. Leave room on the paper below the graph for noting down figures. (Alternatively, enter the data into the computer, and obtain a graph on the screen.)

3. Examine the time-distance graph carefully to see if any of the points appear anomalous. If so, check the picking of the first breaks on the records and revise the travel times accordingly.

4. Ink in the points on the graph if one has already been drawn. If not, plot a graph on paper or at least obtain a printout, unless the graph is very straight forward.

5. Divide the time-distance graph into segments, each corresponding to one layer. Plotted points may be common to two consecutive segments, but more commonly the division will be between plotted points. Where outshots and/or a centre shot have been used, then those parts of the graph with a nearly constant difference in travel times represent bedrock arrivals - working on paper, a pair of dividers is useful for checking this quickly. If there is any possible ambiguity, try to keep the apparent velocities similar from one shotpoint to the other.

6. Fit straight lines to each segment. On paper, this can be done using a transparent setsquare. Draw the line lightly in pencil, extending it back to the shotpoint. Calculate the apparent velocity and write this and the intercept time next to the line. When using the computer, the values of apparent velocity and intercept time should be noted down, preferably on a graph.

7. Calculate true velocities from updip and downdip velocities, for the one shotpoint or two adjacent shotpoints. Use values from adjoining spreads, if any. Be very careful not to use apparent velocities for two different layers, as could happen if an

intermediate layer is not recognisable at all the shotpoints.

8. Use the true velocities and intercept times to find depths at the shotpoints. If a hidden layer is suspected, the depths should also be calculated using an estimated velocity and the minimum intercept time compatible with the data, i.e fit a line with the appropriate slope which passes through one of the plotted points and above the rest for that shotpoint.

9. If outshots have been used, it is possible to use the plus-minus method. The additional steps are as follows:

(a) Complete a set of composite times for each direction, forward and reverse. First find the average difference in travel times for bedrock arrivals for the outshot(s) and the endshot. Then subtract this difference from the outshot travel times for those geophones too close to the shotpoint to show bedrock arrivals for the endshot.

(b) Calculate the plus and minus times for each geophone;
plus time = (Tf+Tr-Rt)/2
minus time= (Tf-Tr)/2
where Tf,Tr are the composite times for the forward and reverse directions, and Rt is the reciprocal time (effectively the average of the travel times from the endshots to the furthest geophones).

(c) Plot the minus times, and divide the graph into sections according to the gradient. Calculate the average velocity in bedrock by dividing the length of a section by the difference of the minus times for the geophones at each end.

(d) At each shotpoint, divide the depth to bedrock (from step 8 above) by the plus time for the nearest geophone; this value is a depth conversion factor for that geophone.

(e) Obtain depth conversion factors for each remaining geophone by interpolation (best done graphically) and multiply the plus time by this factor to obtain the depth to bedrock.

(f) On a topographic profile with equal vertical and horizontal scales, plot each geophone position, and draw an arc with that as its centre and a radius corresponding to the bedrock depth at the geophone. Draw a curve tangential to these arcs as the bedrock profile.

(g) Complete the profile by plotting the intermediate layers and the velocities.

Steps (a) to (c) can be carried out on the computer. The method of calculating composite times is more complex than the simple version given above, and makes use of travel times for a centre shot if one has been used. Graphs of the composite times and the plus and minus times will be drawn; the composite times should be nearly the same

as the travel times for the endshots where they are for bedrock arrivals.

Computer Program for Seismic Refraction Interpretation

The program stores the basic data (distances, travel times) in a disc file, so the spread name specified at the start must be acceptable as a file name. There is no provision for recovering from an error caused by the disc being full, so be sure there is enough room on the disc before starting to enter the data.

The following conventions must be adhered to:

(a) shotpoints are numbered from 1 to n consecutively in the same direction as the geophones;

(b) the direction in which shotpoint and geophone numbers increase is the forward direction;

(c) all distances are in metres from geophone 1;

(d) all times are in milliseconds, all velocities in metres/second.

The shot points used are specified by entering their total number followed by the numbers of the endshots. The distances of the shotpoints are entered; for outshots approximate values are good enough (remember they will be negative at the geophone 1 end). For geophones 2 to 12, enter the distances from the previous geophone, or just press RETURN to enter a value of 7.5m. Travel times are entered in sequence. The data is tabulated on the screen (and can be printed out). The option is given of editting data; otherwise a graph is drawn (which can be printed out).

For each end or centre shot, enter the first and last geophone for each layer segment from the surface down - see steps 5 & 6 above. (It does not matter which geophone number is entered first.) If in doubt whether to include a point in a segment, it is usually best to leave it out. The program fits a line on a least mean squares basis (i.e. linear regression) and plots a line on the screen. In the case of the first layer, the line is forced to have an 'intercept' of less than 1 millisecond.

The program will then go on to the calculation of true velocities. It does not matter which apparent velocity is entered first. As many values as necessary can be calculated, but they are not stored for subsequent use. Entering two zero values (i.e. just pressing RETURN twice) will move the program on to the calculation of depths, which is done for each endshot and twice for any centreshot. The depths are stored.

If there are enough shotpoints, the option is given of using the plus-minus method. For each direction, specify the limits of the bedrock arrivals, first for the endshot and then for the outshot(s)

and the centre shot(s), if any. If in doubt, leave a point out rather than risk including an arrival time which is from an intermediate layer. Again, the order in which the two geophone numbers are entered is unimportant. A new graph will be drawn with the composite, plus and minus times all shown (the plus and minus times being the two lower lines, while the minus time line has the greater slope of the two). This graph can be printed. The results can then be tabulated on the screen and, optionally, printed.

At any stage where the program halts without displaying a question or prompting for data, press the space bar to continue.

If additional depth calculations are to be made, this can be done by using the short seismic program which only provides for calculating true velocities and depths at shotpoints.

An example of the computer analysis is shown on Figure 10.

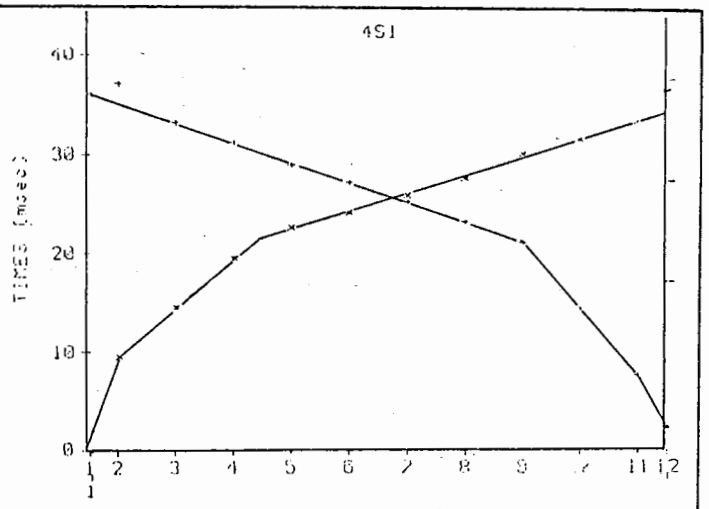
3.3.5 Application to Groundwater Exploration

The principal use of seismic refraction in groundwater exploration is the assessment of thicknesses of alluvium or weathered rock overlying hard rock. An important limitation is that, if a sledgehammer is used as the energy source, the maximum depth of investigation is around 10 metres, although this will vary from one locality to another. It is then difficult or impossible to use it to identify areas where the depth to hard rock is particularly great. However, this limitation can be overcome by the use of explosives, but then field operations are much slower and more expensive, so that normally the method is much less cost effective than resistivity. A possible exception is in desert areas, where resistivity may be limited by the extremely high resistance of a surface layer of dry sand or gravels. Seismic refraction may then be the best way of assessing the thickness of wadi(dry river course) deposits.

Figure 10 Seismic Refraction Data Sheet

4S1

G.	TIMES	
1	2.0	36.0
2	9.5	32.0
3	14.5	33.0
4	19.5	31.0
5	22.5	28.8
6	24.0	22.0
7	25.2	25.0
8	32.4	23.0
9	29.8	21.0
10	31.2	14.2
11	34.0	2.5
12	36.0	2.2



4S1

SP	1	2
X	0.0	40.0

G	1	2	3	4	5	6
X	0.0	2.0	6.0	10.0	14.0	18.0

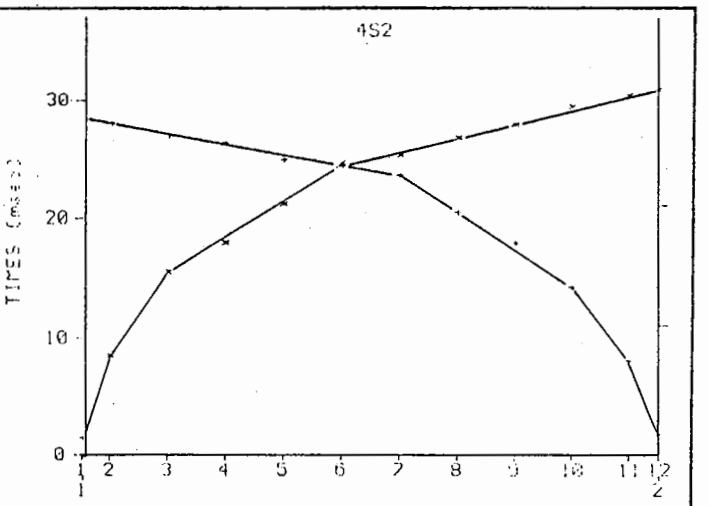
G	7	8	9	10	11	12
X	22.0	26.0	30.0	34.0	38.0	40.0

4S1

	1	depth(m)	2	depth (m)	average depth (m)
V1	235		256		
T1	2.0	0.9	4.1	0.7	0.8
V2	800		593		
T2	16.1	4.0	15.5	4.6	4.3
V3	2240		1832		

4S2

G.	TIMES	
1	1.5	30.5
2	8.5	28.0
3	15.5	27.0
4	18.0	26.4
5	21.2	25.0
6	24.8	24.5
7	25.5	23.2
8	27.0	20.5
9	28.0	18.0
10	28.5	14.2
11	30.5	8.0
12	31.0	1.8



4S2

SP	1	2
X	0.0	30.0

G	1	2	3	4	5	6
X	0.0	1.5	4.5	7.5	10.5	13.5

G	7	8	9	10	11	12
X	16.5	19.5	22.5	25.5	28.5	30.0

4S2

	1	depth (m)	2	depth (m)	average depth (m)
V1	194		211		
T1	5.0	0.5	5.9	0.7	0.6
V2	429		680		
T2	10.5	2.0	10.8	2.0	2.0
V3	965		1057		
T3	19.3	6.4	19.1	5.7	6.05
V4	2594		2216		

3.4 Resistivity and Seismic Equipment Lists

3.4.1 Resistivity Equipment

1. Terrameter
2. Two battery packs
3. Offset Wenner switchbox and four interconnecting cables, plus cable for connecting to centre electrode
4. Two Offset Wenner cables
5. Four single core cables and four cables for connecting from reels to electrodes
6. Electrodes and spikes for making holes for electrodes
7. Clipboard and field sheets
8. 30 metre tape
9. Compass
10. Tool kit including:
    a. Screwdrivers
    b. Pliers
    c. Sharp knife
    d. Multimeter
    e. 12 volt soldering iron and solder
    f. Insulating tape
    g. Brush
    h. Spare fuses etc.
    i. Extra interconnecting leads
11. Photocopy of equipment manuals
12. Waterproof felt tip marker pen
13. Cutlasses
14. Jerricans for water
15. Battery charger with connecting leads and power cable (required at base)

3.4.2 Seismic Equipment

1. Amplifier unit with the following in the lid:
   a. Power cable
   b. Interconnecting cable
   c. Screwdriver (for adjusting potentiometers)
   d. Spare fuses (2)

2. Display and printer unit with the following in the lid:
   a. Power cable
   b. Hood for display screen (3 parts)
   c. Spare fuses (2)

3. Geophone cable on reel

4. Geophones (12 + 4 spare)

5. Sledgehammer with impact switch

6. Striker plate(s)

7. Spare impact switch

8. Extension cable for hammer

9. Power cable (for connecting to Land Rover dashboard sockets)

10. Spare roll(s) of paper for printer

11. Clipboard and field sheets

12. 30 metre tape

13. Compass

14. Tool kit including:
    a. Screwdrivers
    b. Pliers
    c. Sharp knife
    d. Multimeter
    e. 12 volt soldering iron and solder
    f. Insulating tape (various colours)
    g. Brush

15. Photocopy of equipment manuals

3.5 Other Survey Methods

3.5.1 Gravity Surveys

The gravitational field at the Earth's surface varies slightly with elevation and latitude, and also with time because of tidal effects. There are also smaller variations caused by different rock types having slightly different densities. Although the measurement of the gravitational field to a high degree of accuracy is not practicable outside a laboratory, it is possible to measure the variations in the gravitational field using a gravimeter, which is effectively an extremely sensitive spring balance, with a sensitivity of about 0.01 mgal. (1 mgal is defined as 0.001 cm/sec/sec, and is thus about a millionth of the gravitational field at the Earth's surface.)

Field procedures vary with the scope of the survey, etc., but typically the gravimeter is read first at a base station, then at a number of survey stations, and finally at the base station again. The times of all readings are noted. Generally the two readings at the base station will differ because of instrument drift and tidal effects. All readings are corrected for drift on the assumption that the drift has been linear with time. (If the interval between base station readings is long, and if a high level of accuracy is required, then a theoretical tidal correction is applied before the correction for drift; otherwise, a single correction is sufficient.) If the survey area is extensive, a number of base stations will be established by repeated measuremnts of the gravity differences between them. Sometimes a survey is tied into a previous survey, but this is not necessary, since the survey is not concerned with absolute values but with differences.

Further corrections are then made for elevation, latitude, and usually topography. For reconnaissance surveys, heights may be obtained with sensitive aneroid barometers, and latitude from a map. For more detailed surveys, station positions and especially heights must be measured accurately, and this greatly increases the cost of a survey. The end product of the data reduction is usually in the form a map showing what are called Bouguer anomalies, sometimes with a correction for regional trends to emphasize the local anomalies.

Quantitative interpretation involves assuming a model (i.e. a plausible distibution of densities on the basis of what is known about the geology), calculating the theoretical anomalies that would result, comparing this with the field results and making adjustments to the model to give agreement between the two.

The only likely application to groundwater exploration is in the investigation of sedimentary basins. A reconnaissance survey could help define the extent and depth of the basin, particularly in areas of subdued topography with few outcrops. Combined with limited borehole information, gravity data could allow the depths to aquifers to be estimated in those parts of the basin where no boreholes have yet been drilled. Gravity surveys may also indicate the location of major faults which would affect the continuity of

aquifers and aquicludes.

3.5.2 Magnetic Surveys

The Earth's magnetic field shows local variations in both intensity and direction which are due to variations in the magnetic properties of the underlying rocks. Two main effects are involved, of which the second is the more important. Firstly, some minerals (such as magnetite) acquired permanent magnetism when they formed. Secondly, minerals with a high magnetic susceptibility have the effect of intensifying the magnetic field.

The intensity of the magnetic field can be measured with a variety of different instruments. Some are similar to an ordinary balance, except that instead of comparing two weights they compare the force acting on a magnet with a weight. These are slow to use, as they must be accurately levelled, and are now obsolete. Different versions measured either the vertical or the horizontal component of the magnetic field. The types which are more likely to be met with are the fluxgate and nuclear precession magnetometers. The fluxgate magnetometer measures the component of the magnetic field along its axis, and for ground surveys is normally used to measure the vertical component, as it can then be oriented with a simple circular spirit level. The nuclear precession magnetometer measures the total magnetic field, not a component of it, and only needs to be aligned very roughly at right angles to the field. Both types are fully electronic, and give digital readouts. For surveys in tropical countries, where the vertical component is relatively small, measurements should be of either the horizontal component or the total field.

Because the magnetic field varies with time, accurate or large scale surveys often make use of a base station, where a magnetometer continually records the magnetic field so that the field data can be corrected. Also, if a magnetic storm (related to sunspot activity) causes large, rapid fluctuations in the base station record, field work is halted until the storm subsides. For surveys of relatively small areas, and where high accuracy is not required, a base station magnetometer is not necessary. Instead, readings are taken at frequent intervals at a convenient point (say the centre of the survey area) to provide a warning of any magnetic storm and to allow corrections to be made to the field data if these seem likely to be significant.

In presenting the results of a magnetic survey, it is common practice to subtract some constant value (usually an approximate average for the survey area) from all the data to obtain 'anomalies' and then produce a contour map of the anomalies. Regional trends may be removed to emphasize local anomalies.

The most likely application to groundwater exploration is the mapping of igneous intrusions. In some places, dolerite dykes cutting sediments act as underground dams, so that it can be

important to map these if groundwater resources are to be developed efficiently. Fortunately, such dykes often show up clearly on a magnetic anomaly map, particularly if they have an east-west trend. Quantitative analysis is complicated, but qualitative interpretation is often sufficient.

Another use is the evaluation of depth to basement, i.e. to igneous or metamorphic rocks. Where basement rocks outcrop or are overlain by only a thin layer of sediments, the magnetic anomalies have large amplitudes but often narrow widths. With increasing thicknesses of overlying sediments, the anomalies become smoother and broader. This is because sediments are usually non-magnetic compared with the basement rocks. This method is often used with the results of airborne magnetic surveys to assess the depths of sedimentary basins. While it would not be economically feasible to carry out an airborne survey for groundwater exploration, aeromagnetic maps have been published for some parts of the world.

3.5.3 Electromagnetic Surveys

If an alternating current is passed through a coil, an alternating magnetic field is created. A second coil can then be used to detect this field. If the ground were non-conducting, the magnetic field could easily be predicted. The presence of electrically conducting zones within the ground means that the magnetic field generates eddy currents within these zones, which in turn generate a secondary magnetic field. The combination of this secondary field with the primary field shows as a distortion of the magnetic field.

There is a very wide variety of electromagnetic (EM) methods and equipment. Some use a fixed transmitter coil, such as a large loop of wire laid out on the ground surface, and one or more receiver coils which are moved around the survey area. Others use two mobile coils, for the transmitter and receiver, which are kept a constant distance apart. Others make use of VLF (very low frequency) radio transmissions from one or other of the small number of stations using these for long range communications.

In some cases the receiving coil is oriented at right angles to the transmitting coil, so that in the absence of any conducting zones no signal would be received. The coil is then rotated until no signal is received; the tilt required is thus a measure of the distortion of the magnetic field. The phase shift between transmitted and received signals may also be measured. Alternatively, the receiving coil may be kept in a fixed orientation and the amplitude and phase of the signal measured.

Although VLF equipment has been used for groundwater exploration, the type of EM equipment most likely to be used is that with two mobile coils at a fixed separation. The effective depth of penetration can be varied by changing the spacing. This method can be used for traversing to locate low resistivity zones in Basement Complex areas, where it has the advantage of being very much faster,

and thus cheaper, than constant separation resistivity traversing. Although quantitative interpretation can be difficult, qualitative interpretation is often sufficient, particularly when any location provisionally selected on the basis of EM traversing is checked by a vertical electrical sounding.

3.5.4 Induced Polarisation Surveys

When a direct current passing through a circuit consisting of a resistor and a capacitor in parallel is interrupted, the voltage across the circuit decays exponentially. If an alternating current is passed through the same circuit, its impedance is a function of the frequency of the current as well as of the resistance and capacitance of the circuit components. The ground can show chargeability, which causes similar effects to capacitance in the example above, although the mechanisms by which electrical charge is stored are not the same as in a capacitor. (One mechanism relates to the difficulty of ions moving through the narrow pores blocked by clay particles, while others relate to the presence of certain minerals such as sulphides and graphite.) The induced polarisation (IP) method is based on the measurement of this chargeability.

There are two main types of IP equipment, i.e. frequency domain and time domain. Freqency domain equipment allows the impedance of the ground to be measured at two frequencies, typically a fraction of a hertz and several hertz. The percentage difference between these two impedances is the percentage frequency effect (p.f.e.) and is zero if there is no chargeability. The impedance at the lower frequency is very nearly the d.c. resistivity of the ground and is taken as such. Similar electrode arrays can be used as for the resistivity method. Commonly the dipole-dipole array is used, in which the transmitter (current) electrode pair and the receiver (potential) electrode pair each have a constant separation 'a', and the two electrode pairs are separated by a distance n*a where n = 1,2,3,4. The results are plotted in the form of two pseudosections, one for the resistivity and one for the p.f.e., where each value is plotted below the point representing the centre point of the array and at a 'depth' proportional to the value of n.

In the case of time domain equipment, a direct current is passed through the ground for a while and then interrupted; measurements of the voltage are made automatically at preset intervals after the interruption of the current to define how the voltage decays. Although the method is quite different, the results obtained are comparable to those from frequency domain apparatus.

The IP method has been used mostly for mineral exploration, although some experimental work has been done in the past on potential applications to groundwater studies. The main drawback is that the IP response of the ground is a complex function of particle size, clay content, type of clay, and groundwater salinity. In favourable circumstances it may be capable of distinguishing between clean sands and clayey sands; unfortunately the IP response caused by clay

reaches a maximum at a rather low clay content, and sediments with either no clay content or a moderate to high clay content show little or no IP response. Any application would therefore need careful preliminary studies to ascertain whether IP surveys would provide any useful additional information compared with resistivity surveying.

CHAPTER 4

DRILLING PROGRAMME PLANNING

4.1 Preliminary Considerations

Drilling, together with well testing, is invariably the most expensive item in groundwater investigations. Careful initial planning is therefore required to ensure that the best possible use is made of it. The following questions should be considered:

(a) Is drilling really necessary ?
(b) If so, what should be the density of investigation ? - numbers of boreholes, test wells, piezometers, etc. What is the minimum number that will suffice ?
(c) What information should be collected ? - from cutting samples, core samples, particle size analyses, geophysical logs, etc.
(d) What are the general guidelines for borehole design ? - diameters, depths, casing and screen types, etc.
(e) What should be the phasing of the programme ? - when to start and finish in relation to other studies.

There are no general answers to these questions and each investigation project has to be considered on its own merits. Although ideally the decisions involved should be made on technical grounds, often they have to be based on logistical considerations and the availability of funds.

Invariably, as the drilling proceeds the findings may be different from the conclusions reached based on the previous investigations. It is important, therefore, that the programme is sufficiently flexible to allow for changes to be made in its execution so that new hydrogeological discoveries can be further investigated as they come to light. This is why it is generally better for groundwater investigations to be undertaken by a government institution or department, such as the NWRI, rather than a contractor.

Exploratory drilling is a slow process, with many delays for checking, analysis, testing and other forms of investigation - generally these cannot readily be translated into specific contract items, which makes it difficult to prepare a meaningful contract document for bidding by contractors. Also, most contractors like to get on with the job - drilling, making 'hole' - and don't like too many fiddly interruptions.

One clear principle that emerges from all drilling and well testing programmes is that a relatively small amount of preliminary study and field work, thoroughly analysed before proceeding further, helps to define the problems clearly. If adequate thinking time is not allowed to digest the results of the premilinary investigations and to define the objectives for further work, drilling programmes are likely to be much more costly than they need be.

The sort of information that a drilling and well testing programme should produce is outlined below:

(a) accurate lithological log, by a study of cutting samples, driller's records and geophysical logs;
(b) particle size distribution of sand and gravel aquifers (if present) by sieving representative formation samples;
(c) aquifer geometry and hydraulic properties;
(d) groundwater quality, and its variation with depth (by carrying out airlift sampling tests at different depths);
(e) changes in water level with depth.

4.2 Types of Boreholes

A drilling programme may involve exploratory boreholes, test wells and piezometers.

Exploratory boreholes are generally slim, and drilled to collect accurate data on the aquifer geometry and makeup, and to guide the design of subsequent test wells and piezometers. The boreholes may be abandoned after drilling and any casing and screen used withdrawn, or they may be completed for supply purposes. However, if airlift water sampling tests are carried out at different depths in unconsolidated formations the boreholes generally have to be abandoned because the pumping results in the collapse of the hole around the pipes.

Test wells are usually of larger diameter, cased, screened and sometimes gravel-packed as appropriate. Their main purpose is for pumping tests, to determine the hydraulic properties of the aquifer, and well characteristics.

Piezometers are slim boreholes, cased and screened as appropriate, and often used in conjunction with test wells to obtain more reliable estimates of aquifer hydraulic properties. As their name implies they are used for the measurement of piezometric pressure or water levels. Often they are monitored over a length of time (perhaps for several years) to determine the patterns of water level fluctuation - sometimes they are fitted with automatic recording instruments for this purpose.

4.3 Drilling Density and Site Selection

One major consideration in planning a drilling programme is how many exploratory boreholes and test wells are required to solve the problems posed by the preliminary studies. It is impossible to lay down hard and fast rules for this since the numbers will invariably depend on the availability of existing data for a particular area, the objectives of the drilling programme, and the degree of accuracy required.

In Nigeria there is obviously going to be a difference in approach between the Basement areas and sedimentary basins. In the Basement,

most boreholes will be drilled in fairly narrow zones along fracture traces which offer the best chances of finding reasonable supplies of groundwater in what is essentially an impermeable rock mass. In sedimentary basin study areas, however, a more widespread approach could be adopted - based on the experience in sedimentary formations elsewhere it is suggested that a density of one hole per 15 km2 be used as a general guideline and that one test well should be drilled for every 10 exploratory boreholes.

Borehole sites are normally selected in the first instance on the basis of hydrogeological considerations; that is, the drilling should produce information which will contribute to the understanding of the aquifer system and provide data useful to groundwater development planning. However, because drilling is expensive, where the borehole is actually to be drilled should also take into account the fact that a successful borehole could be reamed out and converted to a test or production well; that is, siting should keep in mind a possible end use for the borehole, whether for drinking water supply, irrigation or some other purpose.

Physical access is obviously an important practical consideration and should be kept as simple as possible unless geological conditions or end-user requirements dictate otherwise.

4.4 Drilling Depth

This is determined by the conclusions reached on likely aquifer depth and thickness during the pre-drilling investigations. However, in the Basement areas in Nigeria available data indicate that fissure systems rarely extend beyond 50m (Clarke,1985), and drilling boreholes deeper than, say, 60m will be unjustified in most cases.

In the sedimentary basins some initial boreholes should be drilled to, say, 250 or 300m in order to obtain as complete a picture as possible of the formation sequence and occurrence of likely aquifers. Later boreholes could be shallower, once the zones of interest have been identified.

Test well depths of course depend on the findings of the exploratory drilling phase. The depths of piezometers to be drilled should be determined from the distribution of screens or water producing zones in the test well; in a multi-layered aquifer case, it is often useful to install piezometers to different aquifer layers.

4.5 Supervision

Proper supervision of drilling and well testing by a hydrogeologist is very important to ensure that the required data are being collected, and as accurately as possible. For this purpose the hydrogeologist will need the same equipment as used in the preliminary studies for supervisionary work (see Section 2.4), plus

the following items:

(a) plastic bags for storing cutting samples;
(b) marker pens;
(c) set of seives, and if possible a mechanical shaker;
(d) sufficient copies of the forms to record drilling and penetration rate data, cutting sample descriptions, particle size analyses, geophysical logging data, pumping test data and the completed composite log;
(e) semi-log graph paper.

Before the start of any drilling programme, or an individual borehole if necessary, the hydrogeologist should brief himself on what his supervisionary functions are to be. Generally they will involve:

(a) ensuring that sound formation and water sampling techniques are employed;
(b) describing and testing these samples;
(c) ensuring that drilling and penetration rate data are being recorded, and that the drilling fluid qualities (if relevant) are being tested, as these can affect later geophysical logging;
(d) carrying out geophysical logging;
(e) checking that the borehole dimensions and alignment are correct, and checking the diameters and installation depths of casing and screeen;
(f) ensuring that well development is adequate;
(g) checking that water level and discharge measurements during pumping tests are accurate, and with the aid of field data plots deciding whether the tests should be run longer than the standard periods.

CHAPTER 5

FORMATION IDENTIFICATION

5.1 General

The techniques used for formation identification are basically of three different kinds:

(a) observation of the drilling process; rotary air or mud flush and down-the-hole-hammer (DHH);

(b) collection, inspection and analysis of formation samples;

(c) geophysical logging.

All three are very important and should be used to the full, though the expense of some of the more sophisticated methods of geophysical logging limits their use in the water well industry.

5.2 Observation of the Drilling Process

The most obvious observation which, when carried out during drilling, gives a clue to the lithology of the formation drilled is the speed of penetration. Clearly slower penetration rates can be expected in hard, consolidated rock than in, say, loose sand. This is an extreme example but, in fact, much more subtle differences can be picked up. Thus, in consolidated formations rotary drilling is often faster in shale than in sandstone or limestone. In unconsolidated strata the opposite is true and drilling in sand and/or gravel is faster than in clay.

It is impossible to assign specific penetration rates to individual rock types because of the enormous variations in equipment, drilling method, bit size, bit type, drilling depth and the pulldown applied to the drilling string. However, an accurate penetration log can be most helpful in the delination and identification of the drilled strata, and such logs should always be kept.

The normal practice in the GWRD is to note the time taken to penetrate each metre. The penetration rate is normally recorded on the Daily Drilling Log (GWR/D-01) and shown on the Composite Bore Log (GWR/HG-01); examples of these completed forms for borehole nr. GWR-3/1 are shown on Figures 11 and 12 respectively.

Features to look out for are:

- clay or shale layers tend to slow down penetration; where the bit tooth configuration is not suited (for instance, if a hard formation tricone bit is being used), shales and clay are extremely difficult to drill because of bit balling and blockage. It is sometimes possible with thin sand-shale

Figure 11 Daily Drilling Log

GWR/D-01

Groundwater Research Department
National Water Resources Institute

Figure 11

DAILY DRILLING LOG

PROJECT : (Mar Farms, Nassarawa)
RIG NR : Halco V866
BOREHOLE NR : GWR-3/1
DATE : 17/7/85

DRILLING OPERATIONS

Drill Pipe, Tools and Bit	Conductor / Temporary Casing
Tricone bit 7 7/8" to 29m, followed by DHH 7" to 43.5m	15m 8" steel casing to 14.5m.

Depth (m) From	Depth (m) To	Clock Time Start	Clock Time Finish	Elap. Time	Formation (Drillers Description)	Circ. Fluid & Measurements	Remarks (eg. water struck, loss circ)
18	19	08.54	09.08	13	Weathered rock + laterite		Weight 70 bars
19	20	09.08	09.26	18	" " " "		
20	21	09.26	09.55	29	Weathered rock, small laterite		
21	22	09.56	10.30	34	" " " "		Rock becomes harder
22	23	10.31	10.55	24	Highly weathered rock		
23	24	10.55		32	Slightly weath. rock chippings		
24	25	11.49	12.14	25	" " " , small laterite		
25	26	12.15	12.40	25	" " "		
26	27	12.41	13.06	25	Weathered rock		
27	28	13.07	13.27	20	" "		
28	29	13.28	13.46	16	Weathered rock, small laterite		Broken ground at 28.5m, water struck, foam used to clean hole.
29	30	16.01	16.06	5			
30	31	16.24	16.27	4			
31	32	16.33	16.36	3	Darkish rock chippings		
32	33	16.37	16.40	3			
33	34	16.47	16.51	4			
34	35	16.52	16.57	5			
35	36	17.04	17.09	5			
36	37	17.11	17.21	10			
37	38			7			
38	39	17.42	17.46	4			
39	40	17.52	17.56	4			
40	41	18.00	18.05	5			
41	42	18.06	18.11	5			
42	43	18.12	18.19	7	Darkish green chippings.		Drilling completed at 43.45m.

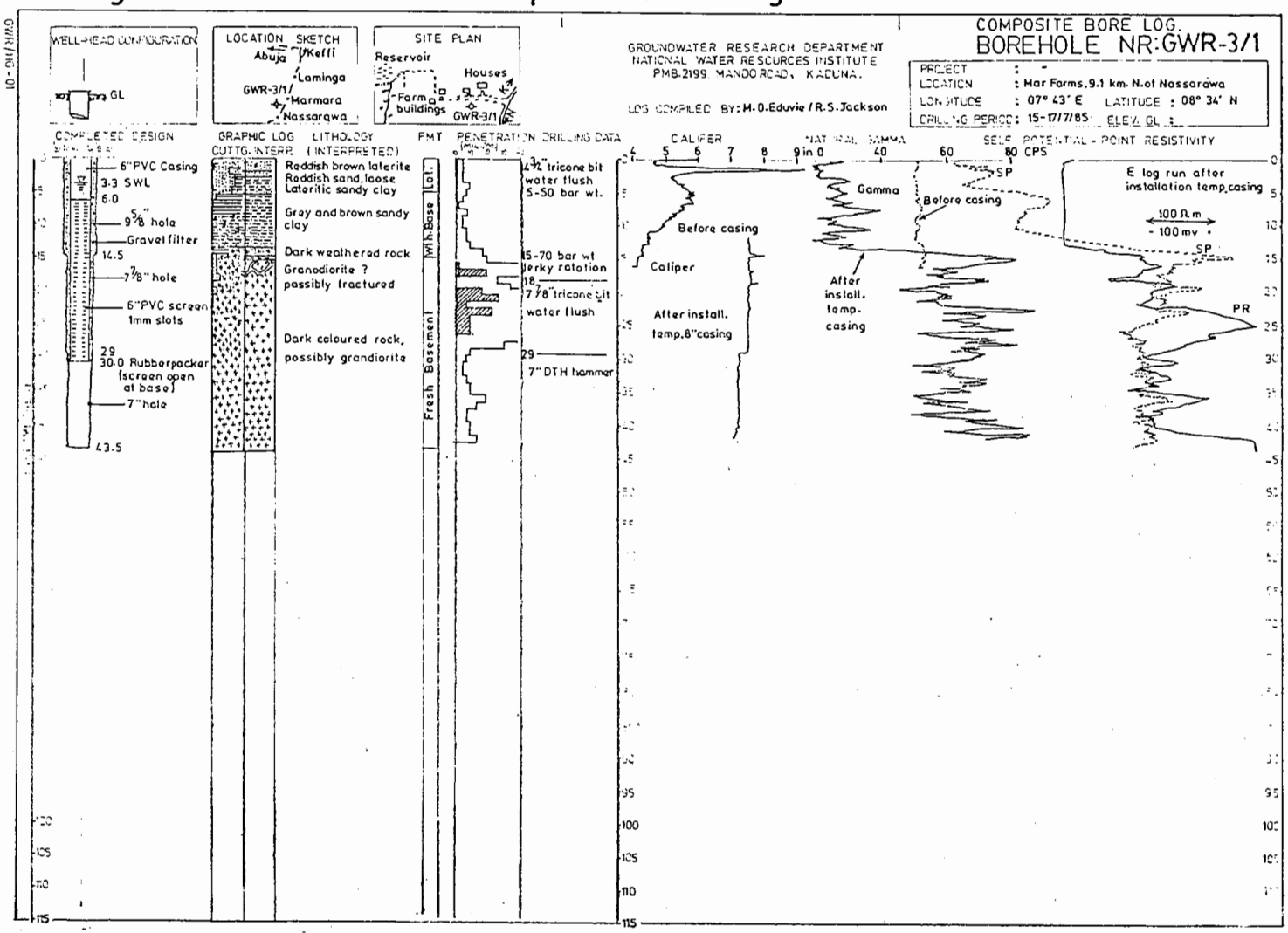
OTHER OPERATIONS / REMARKS

Clock Time From	Clock Time To	

Page 3 of 6

Signed 'Sola

Figure 12 Composite Bore Log



sections to accurately correlate small penetration rate variations with gamma and caliper logs;

- a slowing down of penetration in the weathered Basement zone as the fresh rock is approached. The lower part of the weathered zone consists essentially of blocks of decomposed rock set in a matrix of weathered products. Typical rates in the weathered zone lie in the 1 to 10 minutes/m range but can slow to around 15-20 minutes/m in the lower part;

- very slow panetration in fresh Basement rock, to rates well over 20 minutes/m. However, once the DHH is used penetration is very fast - typical rates lie in the 1-10 minutes/m range.

In addition to keeping an accurate penetration log, a good driller can often obtain valuable relevant information from the general behaviour of the drill, particularly in shallow holes. For example, in unconsolidated formations drilled with a drag bit, the action of of the drill is much smoother in clays than in sands and coarse gravels; in the latter, vibrations of the drill string can often be actually seen at the surface. In Basement areas a good indication that the fresh rock or the base of the weathered zone has been reached by a tricone or drag bit is a jerky rotation of the drill string.

Another major source of useful information is the behaviour of the flushing fluid during drilling. An extreme example is the total loss of circulation, which is common only in karst limestone aquifers. It signifies the penetration of a fracture or fissure system, into which the drilling fluid is lost. In granular aquifers, drilled with bentonite mud, the formation of a mudcake on the hole wall should eventually seal off the formation so that no fluid loss occurs. However, in the interim, the mud filtrate invasion of the pemeable beds may lead to partial circulation loss; this should register in the mud level in the pits and should be noted.

During the air drilling action, the point at which water bearing strata are encountered (water cut or strike) will be indicated by the issue of water with the return air stream; the driller should note this together with approximate fluid flows and major changes in returned fluid flow during successively deeper penetration by the bore. The site hydrogeologist or technician should periodically test the electrical conductivity of the water produced.

5.3 Sample Collection

Formation samples are normally collected from the drilling fluid return system, but in both air flush and mud flush rotary methods it is difficult to obtain representative samples because of recirculation of cuttings, comminution (breaking into small fragments), loss and mixing. In both mud and air flush rotary and DHH drilling, the driller seeks optimum and efficient clearance of

cuttings from the bore. He does this by adjustment of drilling mud viscosity and weight, by variation in pressure and annular velocity in the circulating system and by use of appropriate stilling systems or cuttings sieves in the surface mud pits. Ideally, cuttings should leave the cutting bit face and travel to the surface for immediate collection.

Samples recovered during air flush drilling should arrive at the surface within seconds of being cut if optimum annular uphole velocities are used, but hole enlargement and partial loss of circulation may delay cuttings return. Drilling cuttings from DHH operations consist of dust from softer strata and rock chips from harder materials. Lithological examination of a dust sample by the hydrogeologist may be difficult and a portable microscope may be needed.

It may be difficult to interpret cuttings recovered from mudflush holes mainly because these are often mixed up and out of sequence. In deep boreholes, a considerable time lag occurs between the cutting of a sample and its arrival at surface and this must be allowed for when assigning a true depth to a cuttings sample. Some strata are ground up so finely that the cuttings mix with the mud and become part of it; thickening of the mud is a sign that clay cuttings are contributing to mud viscosity. A large cutting may take longer to reach the surface than does its immediate neighbour, whilst some cuttings often do not reach the surface at all and remain down-the-hole suspended in the mud or stuck to the sides of the bore.

Sample mixing often occurs in the following typical situations:

- drilling thinly bedded deposits;
- when penetrating formation boundaries (e.g. alluvium to weathered bedrock);
- when drilling in a very hard formation beneath an unconsolidated overburden which is prone to caving.

In such cases, the sample is liable to contain material from two separate strata. If he is doubtful what the strata really is, the hydrogeologist should instruct the driller to go through the following procedure:

- suspend the drill string one metre above the bottom of the hole;
- circulate until the drilling fluid is completely free of any formation material;
- drill one metre depth;
- carefully collect all the formation material as it comes to surface.

A sample collected in this manner should be completely representative of the 1m depth interval drilled.

Prompt settlement and collection of cuttings from a viscous mud stream also poses considerable difficulties because an adequate

stilling tank volume is never available. Large oil rigs simply pass the mud stream over mechanically agitated sieves (shakers) but such devices are not available to the GWRD; in any case these devices allow the loss of formation fines from the sample which, in alluvial sand aquifers, is undesirable. In most water bore drilling, the formation cuttings are allowed to settle in some kind of a sampling box (or sampling pit) inserted into the mud return channel.

Inevitably, in drilling unconsolidated formations with a thick and viscous mud, there is some separation of the drilled material into finer and coarser fractions while travelling upwards with the mud column. Further, the samples are contaminated with the mud and have to be washed clean with water at the surface. It is not possible to do that without, at the same time, washing away some of the finer constituents of the formation. Therefore, often the sampled formation appears coarser than it really is. Sampling methods thought appropriate to the GWRD are as follows:

- collect samples 'little and often', for each metre drilled;
- hold a very fine sieve (200 mesh) under the mud return flow for a few seconds at a time and constantly empty contents into a bucket;
- use several buckets to catch the sample and mud together and allow settlement; dilute if mud is very viscous;
- trap cuttings in a long baffled trough set into the mud channel system.

An example of how misleading cutting samples can be was illustrated during the drilling of GWR-1/3 in the ECA near Kaduna. The upper 10m or so of the weathered zone was described as sand, but this could not be supported by the geophysical logs - they indicated a more clayey formation instead.

In routine sampling, drill cuttings are normally collectd at 1 metre depth intervals. The samples should be laid out in clearly labelled compartmented boxes for inspection and geological description. Samples should be placed in the sample box according to some fixed sequences; left to right from the top downwards - book fashion - is suggested. They should then be packed in separate plastic bags (again clearly labelled) for transport to a laboratory or to the office.

Undisturbed formation samples or cores have not yet been taken by the GWRD because of the lack of the necessary equipment. However, it is hoped that core barrels can be procured in the future since core samples give a much better idea of the formation than cuttings alone.

Good core recovery can be expected from coring consolidated strata or clays but recovery is usually poor in the non-cohesive, unconsolidated sands and gravels which form good aquifers; rather, such materials can only be sampled by use of a bailer and line.

Whilst cores can indicate true formation lithology, grain size and

composition, they tend to suffer compression and distortion during the coring and core extraction process; this means that permeability values derived from core permeability tests may differ markedly from permeabilities derived from bore pumping tests.

5.4 Sample Description and Analysis

5.4.1 Lithologic Description

All formation samples collected should be described on site by a competent technician, hydrogeologist or geologist. In each case, the following characteristics should be described and recorded on the Formation Sample Description Form (GWR/HG-03):

(a) Hard Rock - rock types in sample, by **percentage**. Describe each type with respect to the following characteristics:

- major mineral constituents (quartz, feldspar, etc.), accessory minerals (mica, etc.);
- colour, texture, hardness; size of rock cuttings and whether abraded;
- cleavage, laminations, break patterns.

(b) Soft Rock, Alluvium - in addition to the above, soft, granular unconsolidated sediments should be described in terms of grain composition, grain size, degree of sorting (or grading), degree of roundness and angularity of individual grains, the presence of accessory or matrix material (clay, limonite) upon the grain surface. Where granular aggregates occur in the sample (i.e. sand grains incompletely broken by the drill action) record any intergranular cement or matrix.

An example of a completed sample description form (reference GWR/HG-03) is shown as Figure 13. Much of the description is necessarily qualitative and subjective, particularly with regard to the individual's perception of percentages, degree of sorting and angularity. To obtain a degree of conformity between different hydrogeologists it is suggested that a standard text book on rock classification is chosen and only this book is referred to.

For accurate description, samples must be examined with a *8 or *10 hand lens or, preferably, with a low power binocular microscope. Whatever methods are adopted, the end result should be a description of the whole sample which is concise and understandable to workers not directly involved in the same investigation. The description of each sample, in terms of component percentage, is then used in conjunction with geophysical borehole logs and information aquired from observation of the drilling process to give an interpretative geological log.

It is important that a distinction is made between the two types of lithologic description used by the hydrogeologist, namely:

Figure 13 Formation Sample Description Form

GWR/HG-03

Groundwater Research Department
National Water Resources Institute

FORMATION SAMPLE DESCRIPTION

PROJECT : (Mar-Farms, Nassarawa) BOREHOLE NR : GWR-3/1

Depth (m) From	Depth (m) To	Sample typ	%	Sample Description	Graphic Log 20 40 60 80
0	1	WC	100	Reddish brown laterite with sand	
1	2	"	60 40	Dark reddish brown laterite soil with Reddish sand	
2	3	"	80 20	Reddish brown laterite mixed with about Yellowish, mottled clay	
3	4	"	80 20	Dark brown laterite mixed with Reddish grey clay with small qtz. fragments	
4	5	"	70 30	Laterite, reddish brown with sandy clay Sandy clay	
5	6	"	80 20	Greyish brown compacted cloy with Ferruginous concretions	
6	7	"	90 10	Brownish clay mixed with about Reddish brown laterite	
7	8	"	100	Brownish mottled clay	
8	9	"	100	Brown sandy cloy with gravel	
9	10	"	100	As above	
10	11	"	90 10	Brown sandy clay mixed with Reddish brown laterite nodules	
11	12	"	100	Grayish brown sandy clay with few Laterite nodules	
12	13	"	100	As above	
13	14	"	40 60	Dark gravelly cuttings of weathered basement Brown clay	
14	15	"	80 20	Dark gravelly chippings of weathered materials Ferruginous concretions (Laterite)	
15	16	"	"	As above	

Page 1 of 3 Signed: Martin Eduvie

- the lithologic description of the whole sample recovered from the drill. This description should be recorded in percentage terms without interpretation or judgement;

- the interpreted lithologic log which appears in the composite bore log. This log is the hydrogeologist's opinion of the true nature of the subsurface strata and is based both on the lithologic percentage description, the geophysical bore logs and drill evidence.

5.4.2 Sample Analysis

The most important analysis of samples of cuttings consisting of loose, granular material is the determination of the grain size distribution; this should ideally be done by dry sieving 0.5 to 1 kg of sample through a set of standard sieves. The results are plotted on to graph paper, of linear or log-linear type, in terms of the cumulative percentage of the sample passing the standard size openings of the sieves used. The standard graph as used by the GWRD (reference GWR/HG-04) is given as Figure 14. The results are plotted in this way to gain a statistical picture of grain size distribution, which is relevant to the water bearing properties of the formation, and to borehole design.

With the help of such graphs, a granular formation can be described in terms of grading, sorting and grain size distribution by use of the following parameters:-

- Median Grain Size; that size which devides the sample into two equal parts, one containing all larger grains, the other containing all smaller grains. Also known as the 50% size or D50;

- Effective Grain Size; sometimes used in technical literature for 10% size (D10); that is, that size which 90% of the sample is larger than;

- Upper and Lower Quartiles; 75% and 25% sizes (D75 and D25) respectively;

- Uniformity Coefficient; the ratio of 60% size to 10% size (D60/D10); a measure of the variety of grain sizes in a sample. Sometimes given as the ratio D90/D10;

- Coefficient of Sorting; defined as the square root of the ratio of the upper to lower quartiles (D75/D25); again a measure of the variety of grain size in a sample.

The grain size classification used by the GWRD is also shown on Figure 14.

The degree of sorting of a sample is commonly described in terms of the uniformity coefficient as follows:

Figure 14 Particle Size Analysis Form

GWR/HG-04

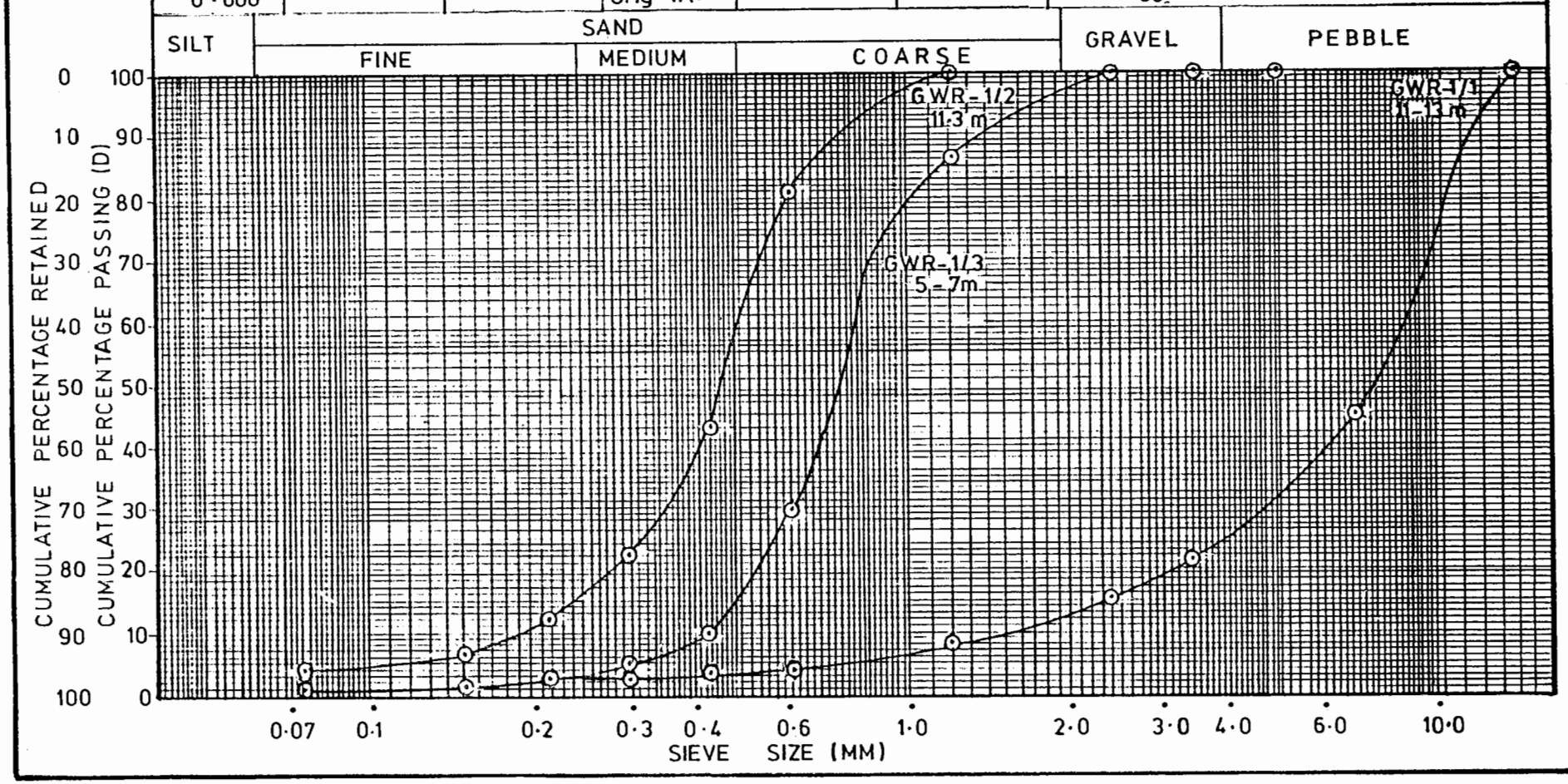
GROUNDWATER RESEARCH DEPARTMENT
NATIONAL WATER RESOURCES INSTITUTE KADUNA

PARTICLE SIZE ANALYSIS

Sieve size(mm)	Cum·wt·retain(g)	Cum·%retained	Sieve size(mm)	Cum·wt·retain(g)	Cum%retained
13·2			0·425		
6·7			0·300		
4·75			0·212		
3·35			0·150		
2·36			0·075		
1·18			Bottom pan		
0·600			Orig·wt.		

BOREHOLE NR :
SAMPLE DEPTH(M) :
ANALYSIS DATE :
SIGNATURE :

D_{10} =
D_{50} =
D_{60} =
$\frac{D_{60}}{D_{10}}$ =



Uniformity Coefficient	Description
<2	Well sorted
2 to 4	Moderately well sorted
4 to 8	Poorly sorted
>8	Very poorly sorted.

The main practical use of accurate grain size data is for borehole design, specifically for the design of artificial gravel packs and screen slot sizes (see Chapter 6).

However, aquifer grain size is also related to permeability; the simplest relation, claimed by some writers, simply states that permeability is proportional to the effective grain size. Another simple formula, after Hazen, states:

$(D10)^2 = K$ cm/sec,

where D10 is the 10 percentile size
and K is permeability.

At best, such a formula gives only a very approximate estimate of true permeability; values so derived often differ considerably from pump test derived permeabilities.

Most formation grain size distribution curves are of a single S-shape (GWR-1/3 in Figure 14). However, in some cases the plots come out as a double S-shape curve: this is rare and in such cases it is probable that the sample represents a mixture of two different formations. The curves of GWR-1/2 and GWR-1/3 indicate moderately well sorted and well sorted medium and coarse sands respectively (UC's of 2.4 and 1.8).

The use of grain size curves in borehole design is discussed in Chapter 6.

5.5 Geophysical Logging

5.5.1 Introduction

Electrical and radioactive properties of geological strata are related to formation lithology and groundwater quality. These properties can be measured by techniques known as electric and radioactivity logging.

The basic equipment used for such logging consists of a power source, a reel of armoured co-axial cable to which a probe is attached, a measuring circuit including amplifiers, and a chart recorder. The probe is lowered into the borehole and signals from it are amplified and recorded at the surface.

The GWRD takes geophysical borehole logs on a routine basis using the SIE T450 portable borehole logger; the equipment allows caliper, natural gamma, spontaneous potential-point resistivity (SP-PR or E, electric, logs) to be run in bores up to 450m depth. The logs obtained are used together with the sample lithologic descriptions and drilling data to make proper formation identifications and to judge formation boundaries, screenable zones and transmissive cracks in hard rock aquifers. All the information, including the geophysical logs, is incorporated in composite bore logs (see Figure 12).

The GWRD has logged each of the 16 boreholes drilled so far (except boreholes of less than 15m depth); the majority of the logged sections has been in largely air or DHH drilled bores in fresh and deeply weathered Basement rocks, such as granites, granodiorites, gneisses and schists. The caliper log has been the more useful log in these hard rocks since it directly identifies cracks or fissures which constitute the aquifer zones in what is essentially an impermeable mass. Gamma and electric log response in hard rocks is often difficult to interpret; these logs give more meaningful results in mud drilled alluvial or sedimentary formations where they can be used to delineate sand and clay beds.

5.5.2 Electric Logging

A normal electric log consists of a spontaneous potential (SP) curve and one or more resistivity curves; the GWRD instrument will run only one resistivity curve, the point resistivity (PR). Schematic circuits for SP and PR logging are shown on Figure 15. For electric logging, the drilled bore has to be uncased and has to contain electrically conductive fluid; the fluid will commonly be a bentonite-water mixture in rotary mud flush drilling. However, electric (SP) logs can be run in cased bores where they are used to make a log of casing collars or threads.

Much of the GWRD drilling work has been by the rotary air flush or air operated down-the-hole hammer (DHH) methods which means that logs have often had to be run in a bore filled with water only (usually formation water with an EC less than 400 uS/cm). In such bores, electric logs of rather poor quality are obtained.

SP and PR logs are recorded simultaneously. The SP is a record of natural potential differences measured between a probe in the borehole and a reference electrode on the surface. The PR log is a record of resistivity of the formation measured by passing a known current through it and recording the voltage drop. Both these measurements are a function of the properties of the formation, formation fluid and the drilling fluid.

To be able to interpret electric logs, it is necessary to understand the effects of drilling with a flushing fluid and the resultant distribution of fluids in and around the hole. Because of the function of the drilling fluid's electrical properties electric logs run in bores drilled by air flush or DHH are seldom of much use and cannot be readily interpreted; they are certainly of no quantitative use.

During drilling, the hydraulic pressure exerted by the mud column on the walls of a hole exceeds the natural pressure of the formation. Consequently the mud infiltrates into permeable formations. During this process the mud separates into its solid constitutents which settle on the hole wall forming a mud cake and a fluid, known as mud filtrate, which invades the formation. Part of the invaded zone, immediately adjacent to the hole, is completely flushed out by mud filtrate. The rest contains a mixture of filtrate and formation water. The strata outside the invaded zone is uncontaminated by any foreign fluids, as are all impermeable formations such as clays and shales. The interrelation of the various zones around a mud drilled hole is shown in Figure 16.

Spontaneous potential (SP) is generated by currents of electrochemical origin flowing around the junction of a permeable bed with an adjacent clay bed and the mud column. It consists of two main components:

Figure 15 Schematic Circuits for Measuring Spontaneous Potential and Point Resistivity

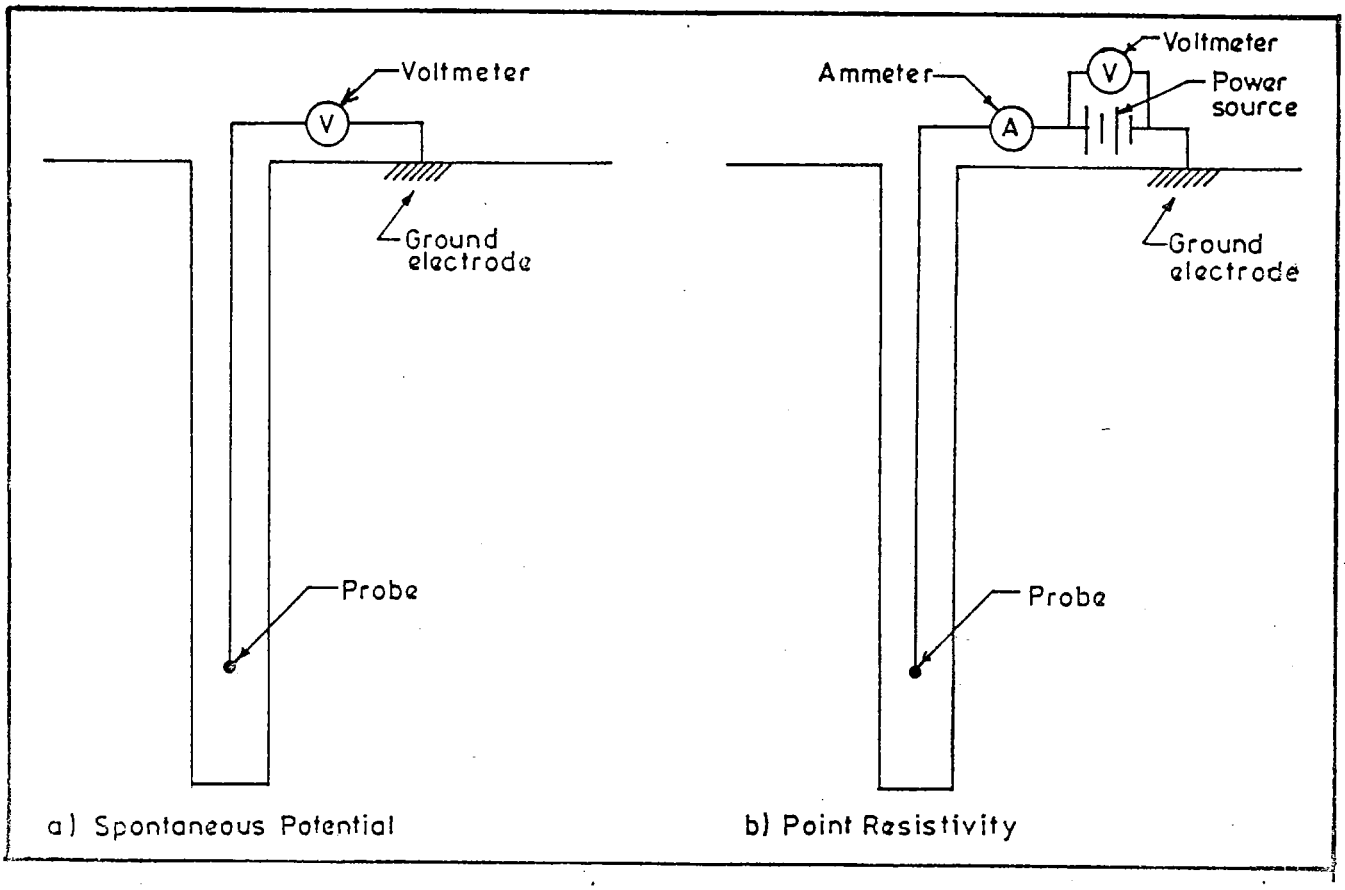
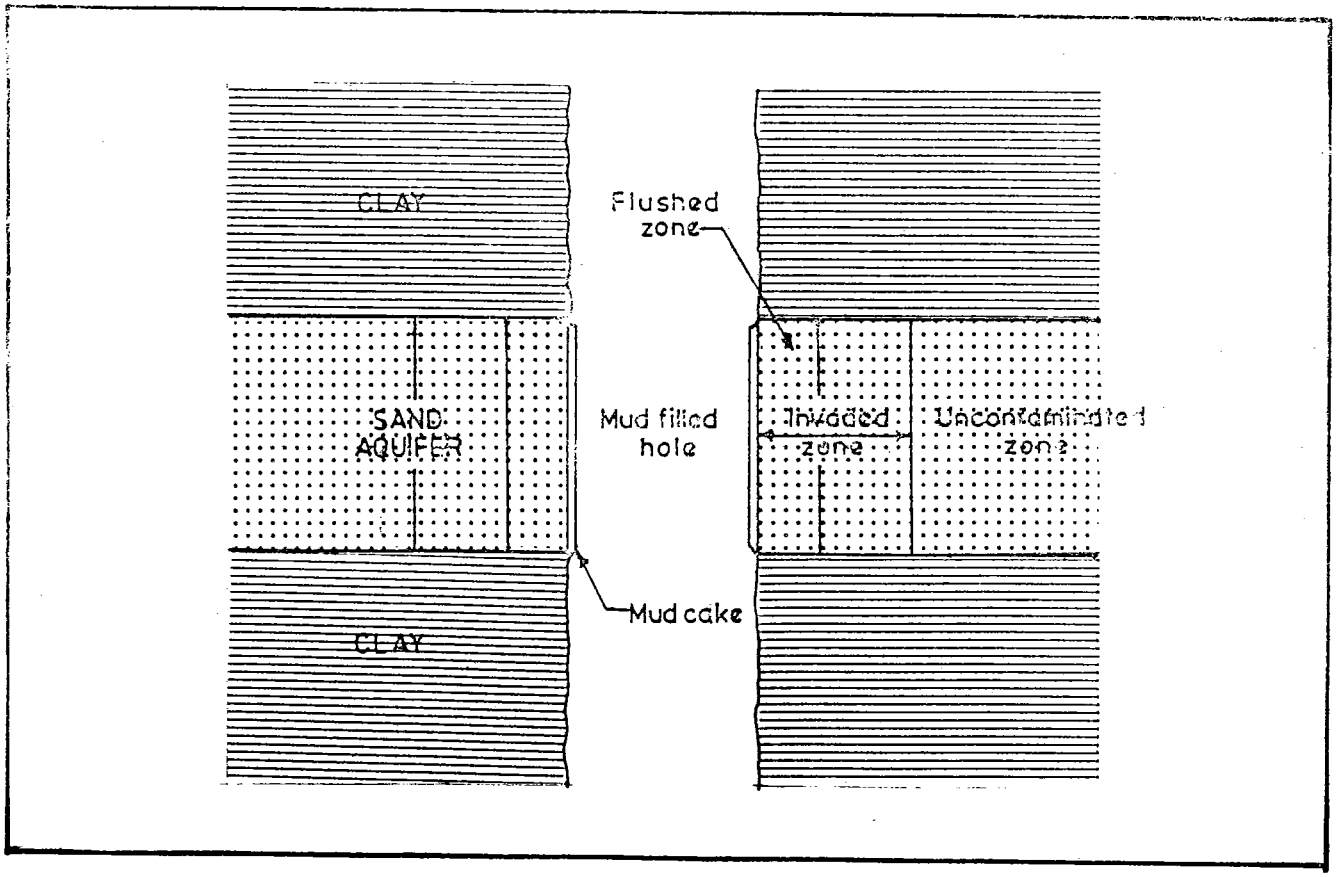


Figure 16 Schematic Section of Mud Flush Drilled Hole



- membrane Potential (Em); this is set up by the currents flowing between two electrolytes (formation water and drilling fluid) separated by clay;

- liquid junction potential (Ej); this is set up by the currents flowing across the junction of two electrolytes (formation water and mud filtrate) in the same permeable bed.

The origin of these two potentials is shown diagramatically in Figure 17.

The main factor determining the direction and amplitude of SP is the difference between the formation water and drilling fluid salinities and, consequently, their resistivities. If the formation water has a higher EC than the drilling fluid, then the potential generated opposite permeable beds is negative (that is it shows a shift to the left with conventional logging polarity). Conversely, if the permeable beds contain water with a lower EC than the drilling mud, a positive potential anomaly is usually (but not always) generated.

Figure 18 shows an idealised electric log which might be expected for a formation consisting of beds of various lithologies with different formation fluid salinities.

Most drilling muds are fresh; consequently, the SP developed in fresh water formations is generally small, and the SP log as a whole rather flat and featureless (as in the upper part of the log shown in Figure 18). In saline formations the contrast between groundwater drilling fluid resistivities is usually large and consequently the SP curve is sharp and well defined (lower part of log in Figure 18). The boundaries of various beds can be defined by the inflection points on the SP curve.

In the oil industry, the SP log is used quantitatively to calculate formation fluid resistivity (and hence salinity), using the expression:

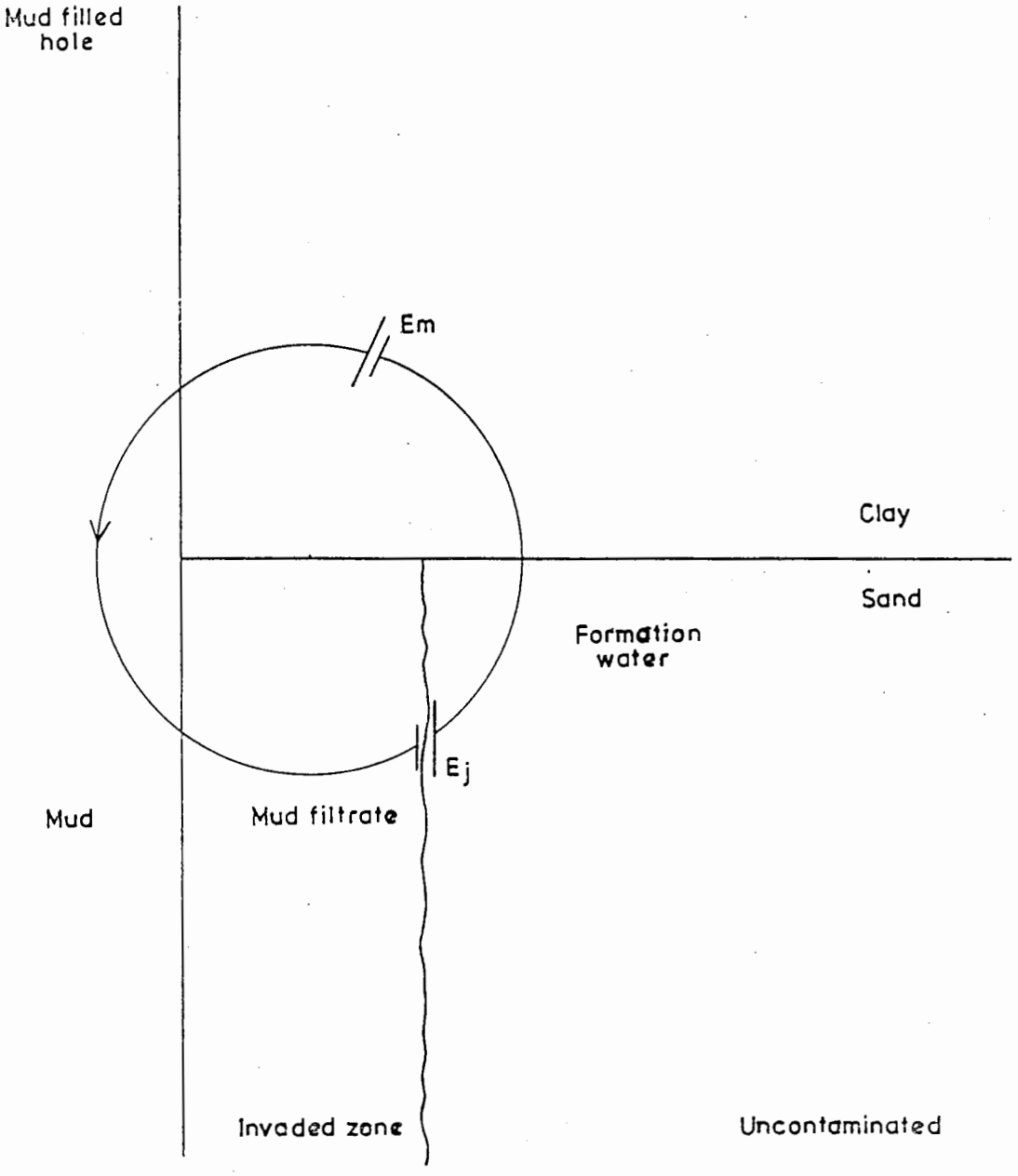
$$SP = K \log Rw/Rmf,$$

where Rw = resistivity of formation fluid
Rmf = resistivity of mud filtrate
K = factor depending on nature of the strata, chemical composition of the two fluids and temperature of the system.

The above equation is approximate but it has been rigorously derived. However, in its application to field data it is necessary to make a series of empirical corrections depending on the geometry (hole diameter, bed thickness) and resistivities of the system. These corrections (published by Schlumberger, 1959) have been established for hard, oil-bearing strata and do not appear to be strictly applicable to unconsolidated alluvial or sedimentary aquifers.

Figure 17

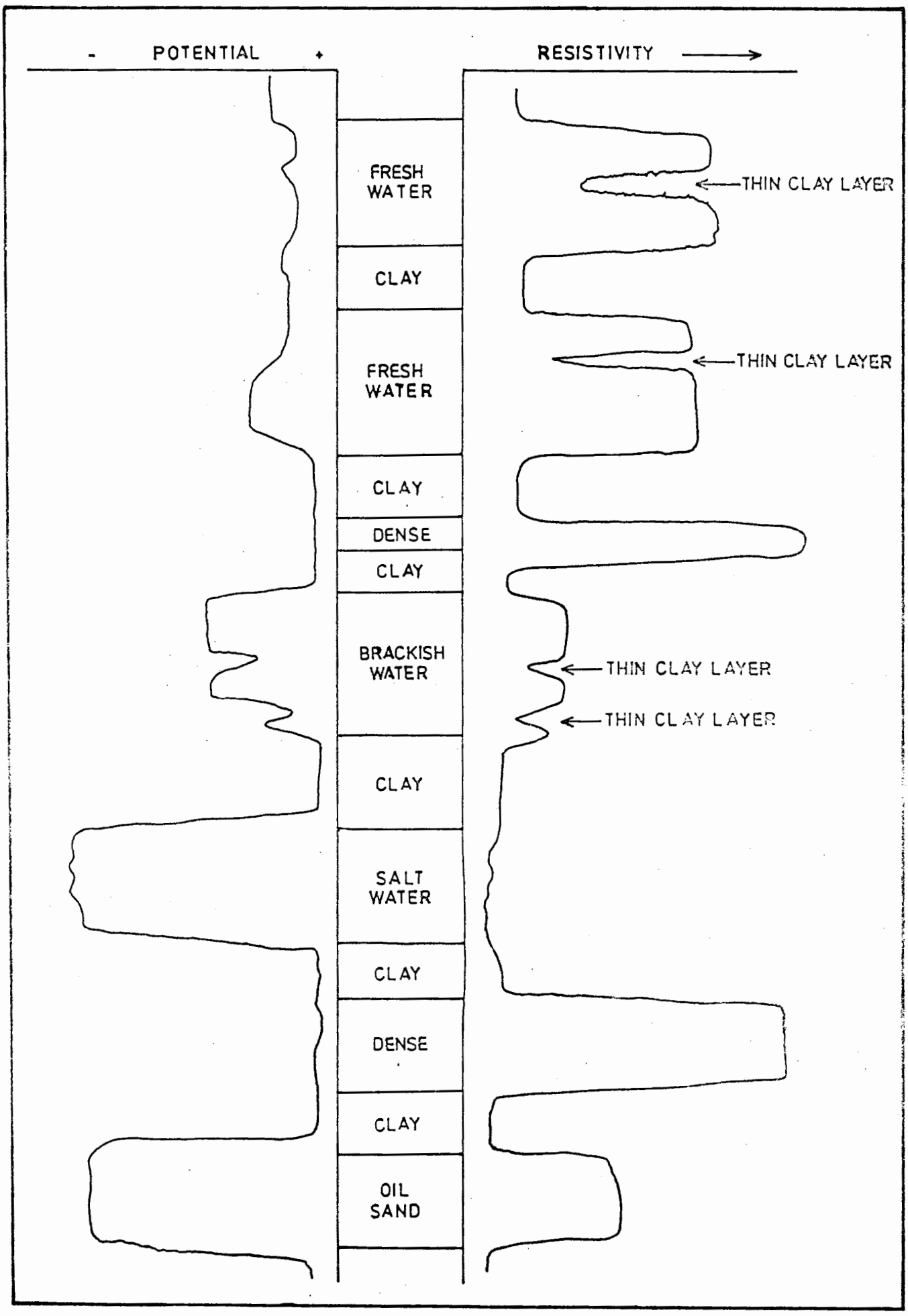
The Origin of Spontaneous Potential Currents



E_m Membrane potential set up by the series, formation water-clay-drilling mud

E_j Liquid junction potential set up by the series, mud filtrate formation water

Figure 18 Idealised Electric Log



The SP log can sometimes be used in air drilled, water filled bores as a casing collar detector. Spontaneous potentials exist at the threaded union or collar of casing joints or at other joints in the casing-screen string, particularly where components are of dissimilar metals. The log is useful in deep bores where the driller is uncertain of the length of casing string.

The resistivity of a geological formation is determined by its lithology, porosity, saturation, temperature and the salinity of the interstitial fluid. The PR curve is a function of the resistivities of the formation and of the drilling fluid. The radius of investigation of the PR device is small. Normally only the material within 45cm (18") or so of the centre of the bore affects the readings. Consequently the curve is strongly influenced by factors such as hole diameter, mud resistivity and depth of invasion. For this reason geophysical logs, particularly E-logs, should be taken in slim boreholes (preferably less than 6" diameter).

Nevertheless, the PR log usually allows differentiation of lithology and often gives an indication of groundwater salinity. Clays normally have higher porosities and therefore exhibit lower resistivities than sand saturated with water of similar salinity. Further, the contrast between sand and clay is less in saline formations than that in fresh ones. Consequently the PR curve is usually sharp and clear in fresh water formations and flat and featureless in saline beds. Figure 18 shows an idealised PR curve which might be expected in various formations containing different kinds of interstitial fluids.

It should be stressed that for proper interpretation the SP and PR logs should be viewed together, and with other geophysical logs, sample descriptions and drilling data. Figure 19 shows the SP and PR logs from an alluvial borehole in Pakistan, together with their interpretation.

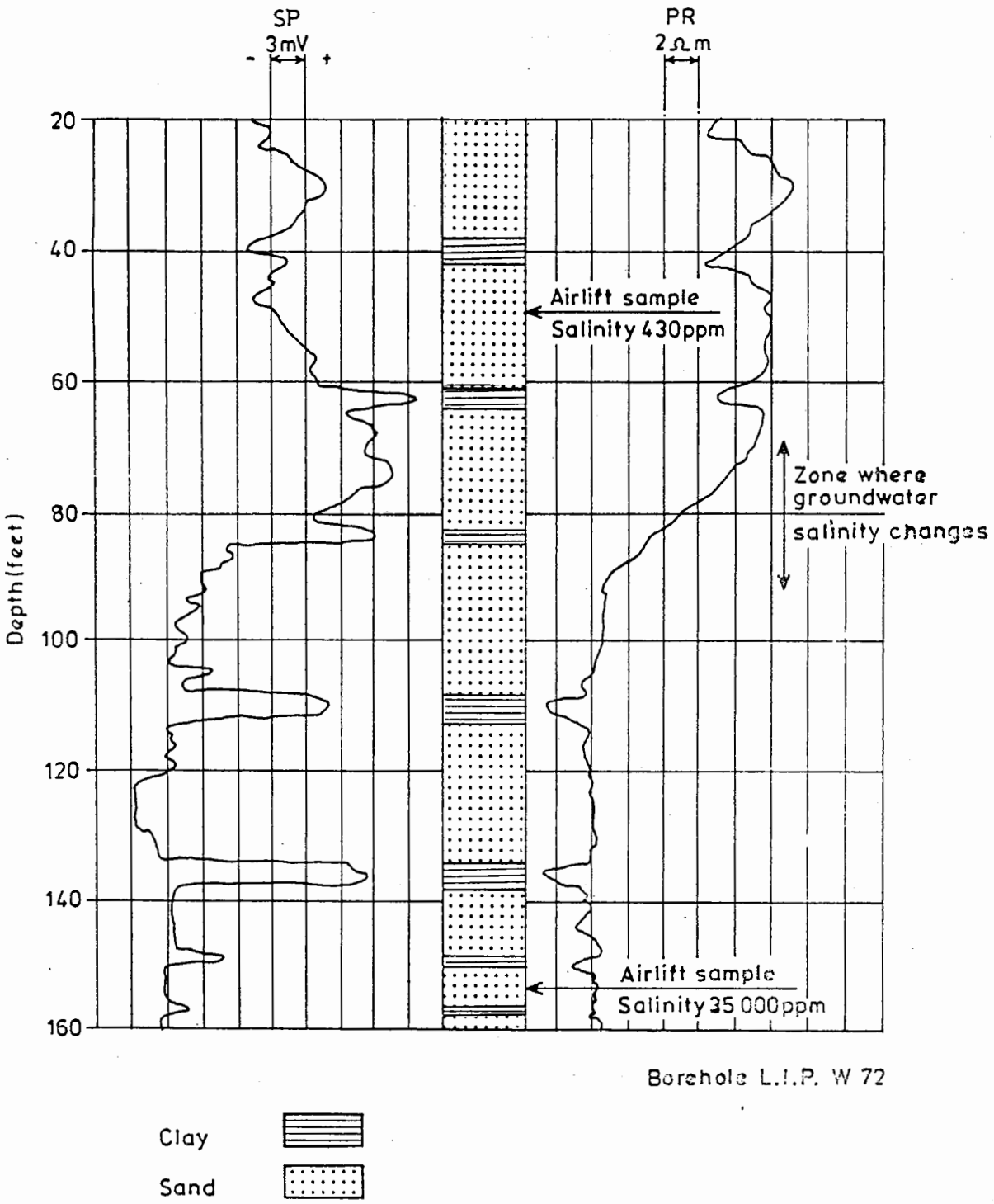
The GWRD has yet to drill and satisfactorily log any deep alluvial or sedimentary bores and, hence, most examples of SP-resistivity logs are poor - being mainly taken in hard rock (Basement) sections. However, typical examples of the logs so far obtained is shown on Figure 20.

There is usually an increase in resistivity down through the weathered zone, with a marked increase in to the fresh Basement (Figure 20A). Resistivity lows in the fresh rock are thought to indicate fracture zones containing water, particularly where they tie in with kicks on the caliper log (Figure 20B).

5.5.3 Radioactivity Logging

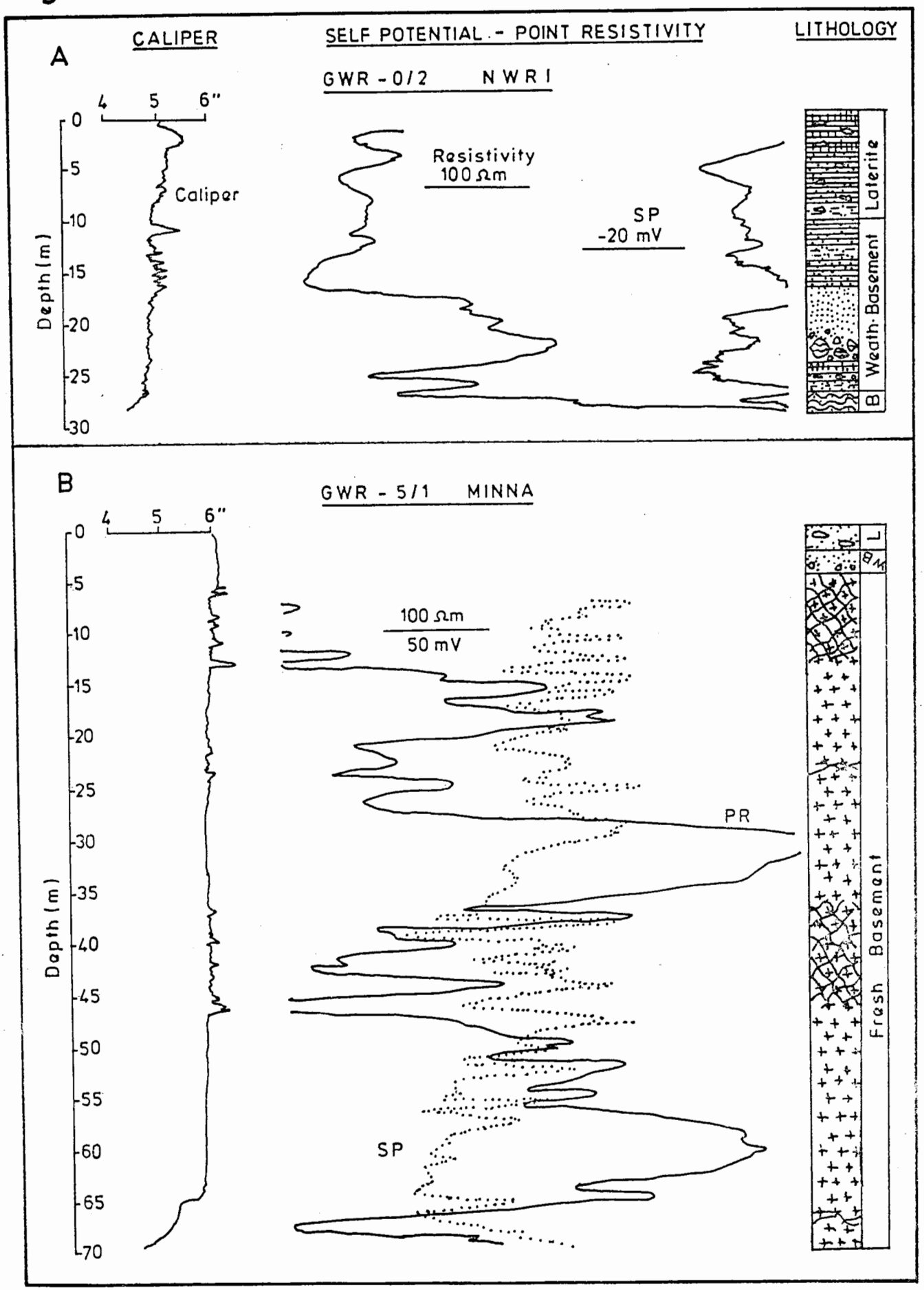
There are many different geophysical logs making use of radioactive or radioactivity-related properties of geological strata; only one type of these, namely natural gamma ray, will be discussed here.

Figure 19 Example of SP-PR Log in Sediments



Note: The SP Log shows that the drilling fluid salinity was marginally fresher than the formation water salinity

Figure 20 Example of SP-PR Logs in Basement



The natural gamma ray log measures part of the radioactivity caused by the spontaneous change of one element into another amongst the natural constituents of the formation. Although several different rays are emitted during this process, only the gamma rays have sufficient penetration to be of practical use in logging the natural radioactivity of rocks.

In contrast to electric logging, gamma ray measurements do not require a bore full of a conductive fluid and can be successfully taken in boreholes lined with casing of steel or any other material. However, casing supresses the gamma emissions and there is usually a marked shift on the log in open holes where the surface casing ends.

All natural rocks contain some radioactive material. The most important natural radioactive minerals, which in normal strata are found only in trace proportions, are: uranium, thorium and a radioactive isotope of potassium. These minerals are normally present in greater abundance in clays, shales and marls than in sands, sandstones and limestones. Therefore, under favourable conditions it is possible to differentiate between these lithologies using a gamma ray log.

The radioactive levels for common rock types are shown in Figure 21. As can be seen, these overlap to some extent and it is possible to get a sand with higher natural gamma ray count than that of clay - particularly, highly micaceous sands with abundant potash mica. Another complication is found in areas of Basement granites and other rocks containing potassium feldspars. The gamma activity in these granites may be similar or higher than in the kaolinite clays of their weathering products.

Gamma activity is attenuated by both steel casing and by the annular distance between the gamma downhole probe and the bore or casing wall. The best gamma log definition is achieved in uncased, small diameter bores - preferably less than 6"; log quality diminishes where the log is run in large diameter or cased bores.

GWRD gamma logging has often demonstrated that where bore enlargement takes place, the gamma signal needs to traverse a greater distance to the gamma detector in the sond and consequently is attenuated. Gamma lows are therefore frequently seen opposite bore washouts or aquifer cracks; such lows do not necessarily represent formation changes. For such reasons, gamma log interpretation must not proceed without information on bore casing size, bore fluid and supporting lithological information.

Examples of gamma attenuation due to casing, and hole enlargement in boreholes drilled by the GWRD are shown on Figure 22.

A further source of difficulty in gamma ray log interpretation is the so called statistical variation or statistical noise. The intensity of radiation, which affects the logging instrument is not constant, but fluctuates due to the random number of atomic

Figure 21 Radio Activity Levels of Various Rock Types

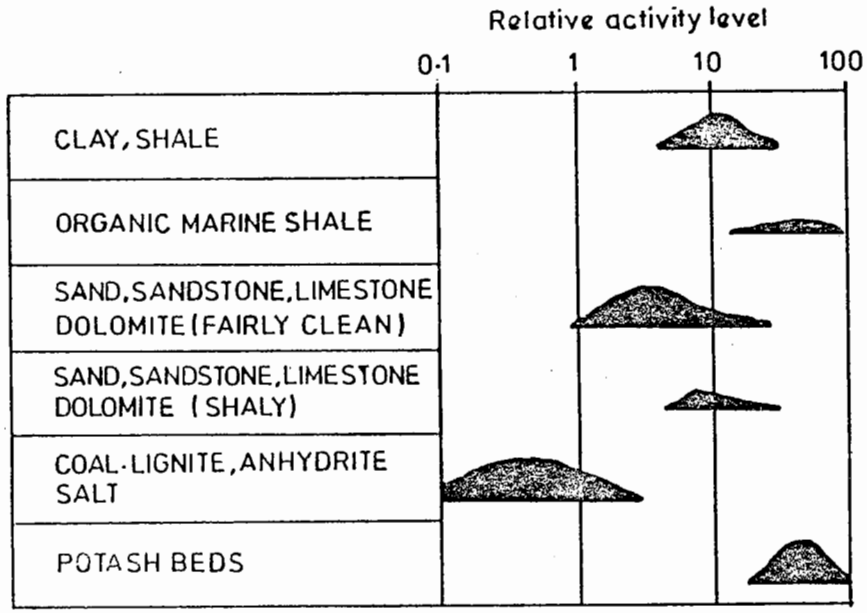
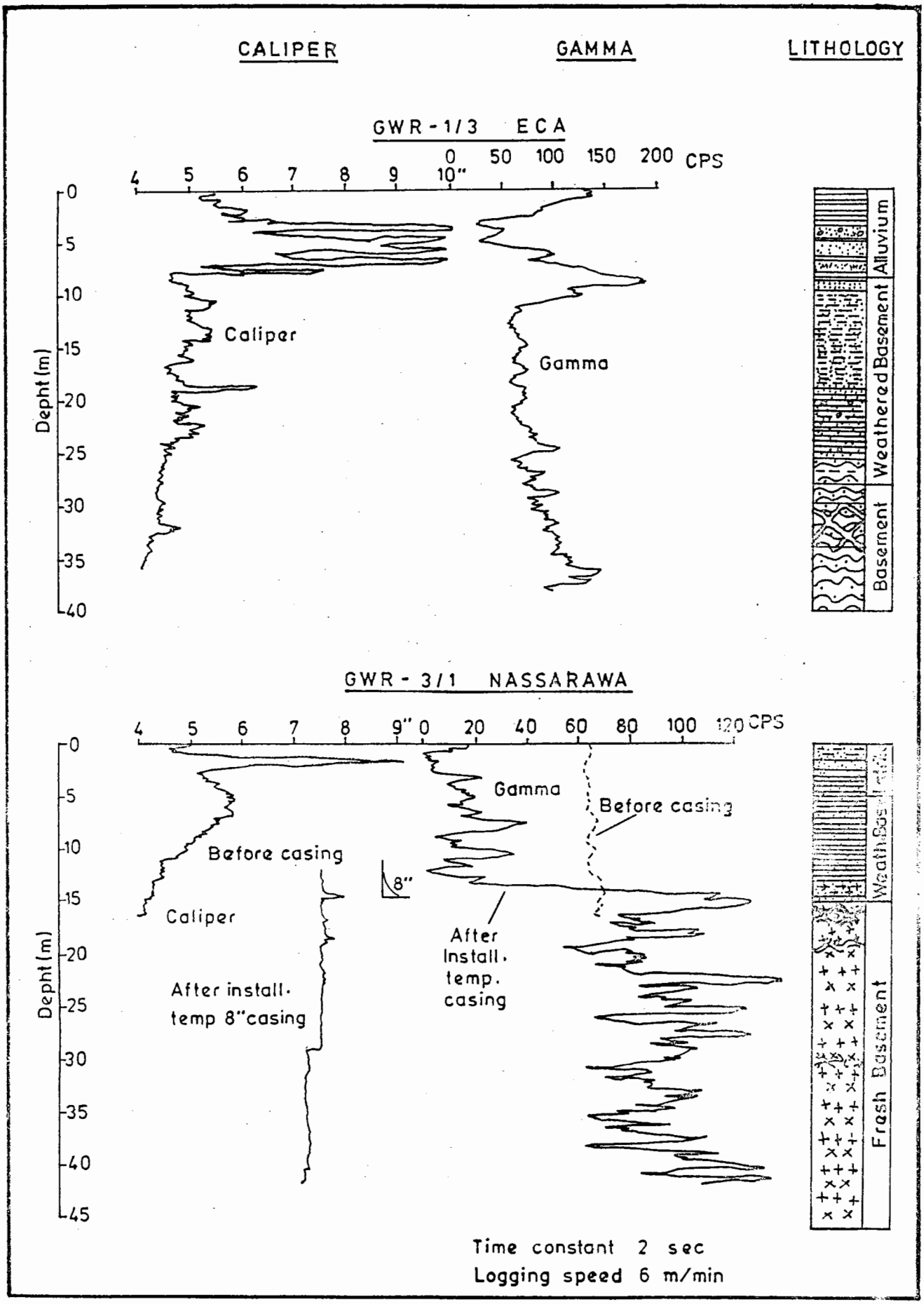


Figure 22 Examples of Gamma Logs



distintegrations at any given instant.

It is therefore necessary to count these over some time interval (the time constant) to get a reliable characteristic of the formation. The greater the time constant the more accurate is the reading obtained, but the time constant must be related to the logging speed, or thin beds might be missed. Figure 23 shows the results of logging the same succession with different time constants and logging speeds. Clearly, curve A shows considerably more statistical noise than curve D and is unacceptable.

However, despite these difficulties gamma ray logs can be extremely useful in formation identification. A good gamma log run in straightforward lithologies should look rather similar to an SP log and be just as easy to interpret.

5.5.4 Caliper Logs

The Basement rocks in Nigeria are frequently drilled by means of air rotary or DHH methods; under these conditions, the caliper log is perhaps the most useful geophysical tool because it can often directly identify voids, cracks, fractures or shattered weathered zones cut by the bore. Such discrete zones represent the aquifer in what is essentially an impermeable rock mass. Examples of caliper logs illustrating the existence of fractures are shown on Figures 20 and 22. Measurements of water yield changes during air drilling can often be correlated with a specific joint as seen on the caliper log.

In the alluvial and weathered Basement zones caliper logs can assist in identifying bore wall washout zones associated with loose sand - a good example of this is shown for GWR-1/3 in Figure 22.

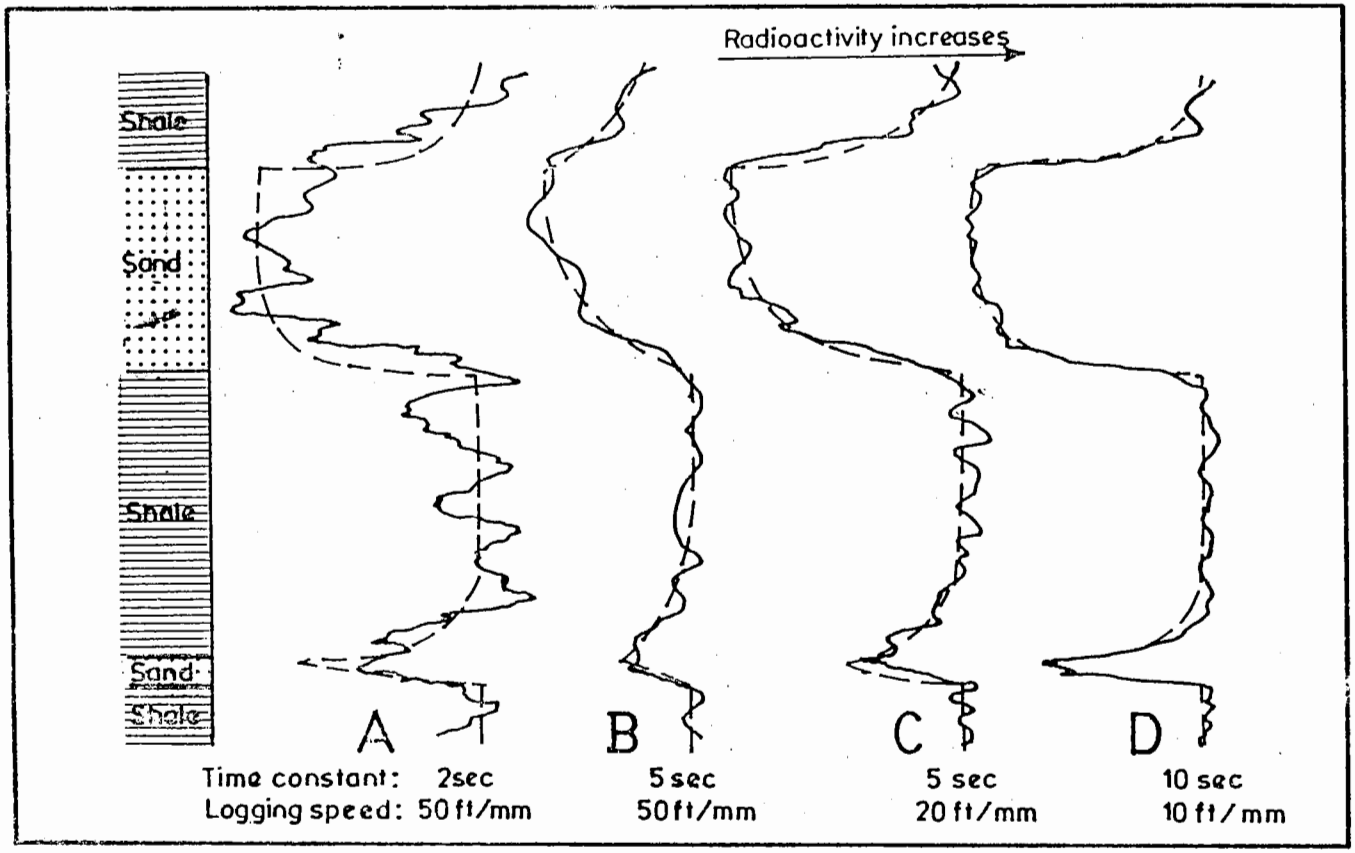
Caliper logs can also used to check bore condition before the installation of a casing string.

5.5.5 Log Records

During logging, the following information - needed for later access and interpretation of the records - should be collected:

- bore number, location, logging date;
- log type, interval logged, datum for log depth measurement, vertical scale;
- bore depth, diameter and construction, drilling fluid and fluid level;
- for gamma: time constant, recording scale range in cycles per sec. (cps) and loggind speed;

Figure 23 Gamma Ray Logs Run at Different Speeds and with Different Time Constants



- for electric logs: resistivity and SP recording scale ranges and borehole fluid resistivity.

The form used by the GWRD for this purpose (reference GWR/HG-10) is shown on Figure 24.

The SIE instrument comes with comprehensive and easily understandable operating instructions and maintenance manuals. More detail on the interpretation of logs mentioned above, particularly the more quantitative interpretations used by the oil industry, can be found in the various manuals of the oil bore logging companies such as Schlumberger. Some references are given at the end of this manual.

Figure 24 Geophysical Logging Data Form

GWR/HG-10

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GEOPHYSICAL LOGGING DATA

1. BOREHOLE DATA

Number ..... Location .....
Drilled depth (driller)..... m Drilled diameter (driller) ..... in
Casing diameter, type, depth (driller) .....
Drilling fluid type ..... level (gl) ..... m

2. ELECTRIC LOG

Run nr.	Date	Time start	Time finish	Datum	Log depth(m)	SP range	Resistivity range	Chart speed	Fluid EC(uS/cm

3. GAMMA LOG

Run nr.	Date	Time start	Time finish	Datum	Log depth(m)	TC	CPS range	Chart speed	Winch speed

4. CALIPER LOG

Run nr.	Date	Time start	Time finish	Datum	Log depth(m)	Chart speed

5. NOTES

PERFORMED BY:.....

CHAPTER 6

BOREHOLE DESIGN AND COMPLETION

6.1 Introduction

Borehole design, as discussed in this chapter, is generally to do with production boreholes, where the objective is to secure the highest sustainable yield at the minimum total cost. However, because of the intrinsic differences in groundwater occurence between the Basement Complex and the sedimentary basins in Nigeria, borehole design criteria will be considered seperately for each case.

In the Basement Complex, where groundwater is limited to a thin, poorly permeable zone, and fractures in the fresh rock below, there are usually not many options open to borehole design - generally the aquifer, such as it is, has to be tapped in its entirety in order to maximise yields. Because of the uncertainty of finding sufficient supplies of water, a production borehole has to drilled as if it was an exploratory one, and it may have to be abandoned if the required yield is not reached - in fact, in some areas, even with the best geophysical and photogeological siting techniques, several boreholes may have to be drilled before a successful production one is attained.

In sedimentary formations, however, where groundwater occurence is usually more extensive, borehole design can be governed as much by economic considerations as by aquifer conditions. In a reasonably uniform sedimentary aquifer sequence it is usually possible to determine the optimum drilling depth for a given required yield.

In practice, the principles governing borehole design for both geological areas are identical and should include:

(a) identifying the zones of maximum yield potential and constructing the bore so as to minimise hydraulic resistance to inflow from these zones;

(b) constructing a stable bore so that the yield from production zones is diminished as little as possible by longer-term effects such as blockage or borehole collapse;

(c) completing the bore through the production zones at the correct diameter for the maximum potential yield so as to minimise upflow losses;

(d) completing the bore in the pump-chamber section (the casing in which a permanent pump will lie) to such a diameter, depth and straightness that no unnecessary limitations are placed on pump choice;

(e) generally constructing the bore to such standards that

maintenance liabilities are minimised.

It is only the application of these principles which differs between Basement and sedimentary aquifers.

The designs of boreholes drilled during the project had to be tailored to the sizes and types of bits and well components supplied; these items are summarised in Tables 2 and 3.

6.2 Basement Borehole Design

The following factors should be considered in the design of boreholes drilled into the Basement Complex:

(a) depth of weathered zone;

(b) depth of water table, and likely maximum value for the end of the dry season;

(c) existence of fractures in the fresh rock.

The yields that can be expected from the Basement Complex are generally less than 4 m3/h, and the use of casing or screen larger than 6 inch nominal diameter (150 mm) is not justified. The aquifer in the weathered zone should be screened, but only where there is a sufficient saturated thickness (say, at least 6m). PVC screen is suitable for this purpose. The fresh rock below could be completed open hole, but should be screened to the pump setting depth if any unstable zones, such as large cavities containing loose material, are present. In either case the base of the screen should be left open. As mentioned previously (Section 4.4) fractures are unlikely to exist below 50m, and drilling deeper than 60m will be unjustified in most cases.

Drilling methods will depend on the borehole design to be adopted since the weathered zone needs to be cased off while drilling into the Basement rock - PVC is not suitable for this purpose; steel casing has to be used, and then withdrawn after the PVC string has been emplaced. For 4 inch (100mm) and 6 inch diameter completions, 6 and 8 inch (200mm) diameter flush-jointed steel casings should be used respectively.

The borehole drilling and design approach developed during the project is summarised on Figure 25 - however, this should be used as a guide only, since actual drilling conditions may sometimes vary from the adopted model. The resulting designs are shown on Figure 26, illustrated by actual examples where appropriate.

Temporary casing should be flush-jointed, for ease of withdrawal, and of good quality since it will be reused many times. Permanent steel casing (designs B-4 and B-5) can be collar-jointed or buttress-welded.

Table 2

Bits Supplied For Project

Item	Type	Diameter in	Diameter mm	Qty
1	Tricone - soft formation	14 3/4	375	1
2	" " "	12 1/4	311	2
3	" " "	9 5/8	244	1
4	" " "	7 7/8	200	1
5	" " "	5 7/8	149	2
6	" " "	4 3/4	121	2
7	Tricone - medium hard formation	14 3/4	375	1
8	" " " "	12 1/4	311	2
9	" " " "	9 5/8	244	2
10	" " " "	7 7/8	200	2
11	" " " "	5 7/8	149	2
12	" " " "	4 3/4	121	2
13	Drag bit 3-blade set and reaming stabiliser	15	381	1
14	Ditto	12 1/4	311	2
15	Ditto	9 7/8	251	
16	Ditto	7 7/8	200	2
17	Ditto	5 7/8	149	2
18	Down-the-hole-hammer button bit	9 5/8	245	2
19	" " " " " " , MACH 60	7 7/8	200	3
20	Ditto	5 7/8	150	6

TABLE 3

CASING AND SCREEN SUPPLIED FOR PROJECT

Contract item	Description	Diameters - nominal (in)	Diameters - inside (mm)	Diameters - over collar or socket (mm)	Length (m)	Quantity in contract document	Quantity actually supplied
4/2	Conductor casing (flush-jointed)BS879	14	333.6	355.6	1.5	12	12
4/3	" " " " "	16	381.4	406.4	1.5	4	4
4/5a	Steel casing (collar-jointed)	4			6.0	25	25
4/5b	" " " " "	"			3.0	15	15
4/5c	" " " " "	"			1.5	4	4
4/6a	" " " " "	6			6.0	100	102
4/6b	" " " " "	"			3.0	60	60
4/6c	" " " " "	"			1.5	15	15
4/7a	" " " " "	8			6.0	50	43
4/7b	" " " " "	"			3.0	30	30
4/7c	" " " " "	"			1.5	8	8
4/8a	" " " " "	10			6.0	20	19
4/8b	" " " " "	"			3.0	8	8
4/8c	" " " " "	"			1.5	4	4
4/9	Conductor casing (flush-jointed)BS879 with 1 set head & 2 drive shoes	6⅝	149.3	168.3	3.0	30	10
4/11(a)	PVC casing SBF-K	4	103	120	5.7	43	43
4/11(b)	" " "	"	"	"	3.0	30	30
4/11(c)	" " "	"	"	"	1.5	10	10
4/12(a)	" " "	6	150	174	5.7	33	33
4/12(b)	" " "	"	"	"	3.0	27	27
4/12(c)	" " "	"	"	"	1.5	20	20
4/13(a)	PVC screen SBF-K 1.0mm slot	4	103	120	5.7	33	33
4/13(b)	" " " " "	"	"	"	3.0	27	27
4/13(c)	" " " " "	"	"	"	1.5	20	22
4/14(a)	" " " 0.5mm "	"	"	"	5.7	8	10
4/14(b)	" " " " "	"	"	"	3.0	9	10
4/14(c)	" " " " "	"	"	"	1.5	19	9
4/15(a)	" " " 1.0mm "	6	150	174	5.7	27	32
4/15(b)	" " " " "	"	"	"	3.0	22	22
4/15(c)	" " " " "	"	"	"	1.5	21	21
4/16(a)	" " " 0.5mm "	"	"	"	5.7	1	2
4/16(b)	" " " " "	"	"	"	3.0	5	23
4/16(c)	" " " " "	"	"	"	1.5	20	5
4/17(a)	PVC screen SBF-K 1.0mm slot	8	205	239	5.7	15?	17
4/17(b)	" " " " "	"	"	"	3.0	12?	13
4/17(c)	" " " " "	"	"	"	1.5	20?	10
4/18(a)	" " " 0.5mm "	"	"	"	5.7	1	4
4/18(b)	" " " " "	"	"	"	3.0	5	6
4/18(c)	" " " " "	"	"	"	1.5	20	6
4/19(a)	" " " 1.0mm "	10	255	293	5.7	1	5
4/19(b)	" " " " "	"	"	"	3.0	5	5
4/19(c)	" " " " "	"	"	"	1.5	20	-
4/20(a)	" " " 0.75mm "	"	"	"	5.7	1	5
4/20(b)	" " " " "	"	"	"	3.0	5	5
4/20(c)	" " " " "	"	"	"	1.5	20	20
4/21	Stainless steel screen 1.0mm slot	4			2.9	14	14
4/22	" " " " "	6			2.9	14	14
4/23	" " " 0.5mm "	"			2.9	7	7
4/24(a)	Steel to plastic adaptor	4			-	5	5
4/24(b)	" " " "	6			-	10	10
4/24(c)	" " " "	8			-	5	5
4/24(d)	" " " "	10			-	5	5
4/32	Mild steel reducer 8 - 10"	-	-	-	-	3	3
4/33	" " " 8 - 6"	-	-	-	-	5	5
4/34	" " " 6 - 4"	-	-	-	-	5	5
4/35	Plastic reducer 10 - 8"	-	-	-	-	1	1
4/36	" " 8 - 6"	-	-	-	-	1	1
4/37	" " 6 - 4"	-	-	-	-	5	5
4/38	Mild to stainless steel reducer 8-6"	-	-	-	-	5	5
4/39	" " " " " 6-4"	-	-	-	-	5	5
4/40	Mild steel to plastic reducer 10 - 8"	-	-	-	-	1	1
4/41	Steel casing (buttress-ended)	6⅝	155.7	168.3	6.0	15	15

Figure 25 Approach to Design of Boreholes in Basement Complex

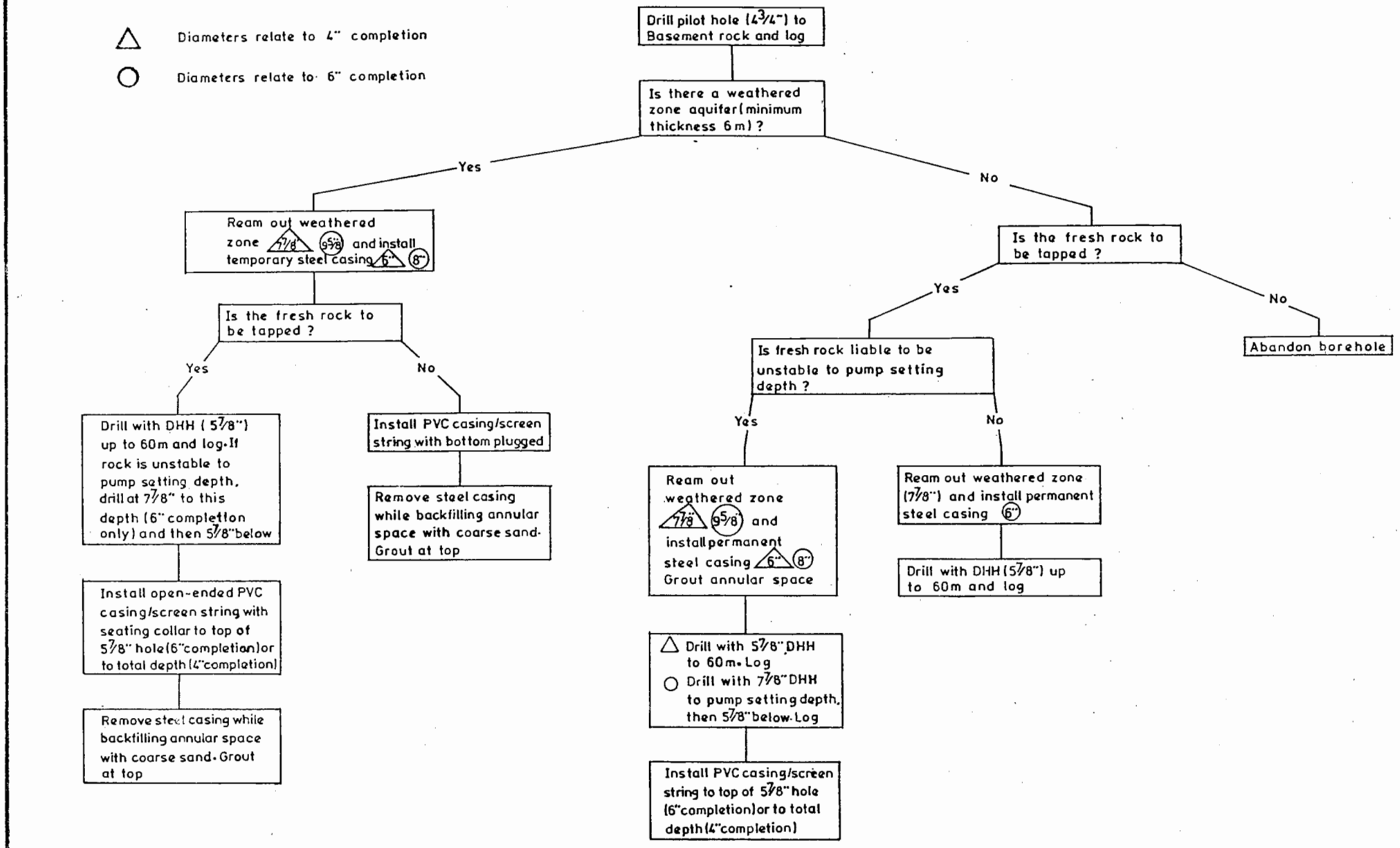
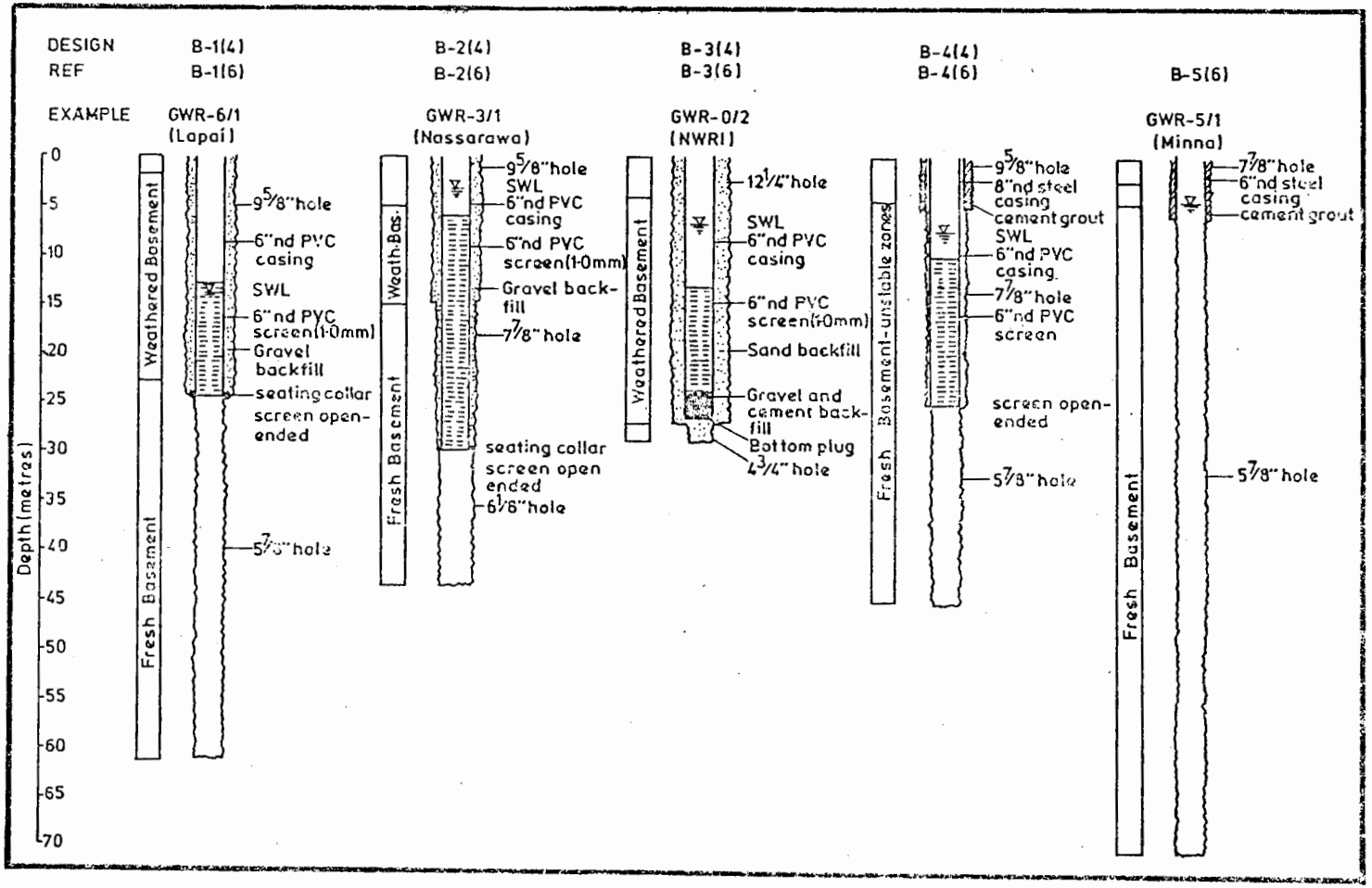


Figure 26 Borehole Designs in Basement Complex (6 inch completion)



PVC screen should be placed opposite the saturated zone in the weathered Basement, and to the pump-setting depth in unstable fresh rock (if applicable); in the latter case a safety factor of, say, 3m, should be added to accommodate possible future pump lowering. Since the water-bearing part of the weathered zone generally consists of poorly-sorted material, ranging from coarse sands and gravels to gritty clays, the largest slot-size available, 1.0 mm, could be used - however, if layers of fine sand or silt are encountered and can be identified, the smaller slot-size of 0.5 mm, should be used opposite such layers. The size of the annulus backfill material is not critical - coarse sand has been found to be the most convenient material.

Where the 6 inch PVC string is to sit on top of or within an open hole of slightly smaller diameter (5 7/8 inch) in the fresh rock, inner tubes or sacking should be wrapped around it to form a 'seating collar' and a seal against the inflow of coarse sand backfill from above. The sand should lie on a bed of gravel and chippings immediately above the seating collar as an added measure against inflow.

6.3 Borehole Design for Sedimentary Formations

6.3.1 General

Most sedimentary formation aquifers in Nigeria are largely unconsolidated or alluvial. Unconsolidated aquifers differ from hard rock aquifers in that generally they do not stand in open hole and that usually their permeability is well distributed through their total depth. Drilling generally has to be by direct circulation mud flush, and on completion some form of screen is required to retain the unconsolidated formation in the yielding zones. Because of the permeability distribution, potential bore yield usually increases almost linearly with screened thickness.

Most intergranular materials vary considerably in permeability and screenable aquifer thickness, and a pilot or exploratory hole should first be drilled before a test well design is made.

Test wells in intergranular aquifers usually have a configuration consisting of an upper, larger diameter pump chamber and a lower, smaller diameter string of screen and casing; screen is placed opposite coarse layers and casing opposite fine layers (geophysical logging is crucial to distinguish these). However, in order to tap shallow aquifer layers it may sometimes be necessary for screen to form part of the pump chamber.

The function of the screen is to physically hold in place the unstable aquifer formation while allowing free passage of water inflow. Screens are usually sized so as to allow some of the formation to be pulled into the well during the 'development' process when drilling detritus is also cleaned off the borehole wall. This regrading of formation material in the immediate

vicinity of the borehole wall is assumed to increase the local permeability and the water inflow.

6.3.2 Drawdown

Drawdown in a borehole is a function of two, and only two, factors:

(a) hydraulic losses due to flow in the aquifer;
(b) hydraulic losses due to flow into and up the well.

The first factor, termed the aquifer loss, is directly proportional to transmissivity (T) and hence, for a constant permeability (K), to the effective aquifer thickness (D). Allowing for partial penetration effects, D is itself related to screen length (L). Thus, for an unrestrained aquifer:

$$T = KD = K * \text{function of } (L).$$

As L increases, so T increases and drawdown decreases.

The second factor, termed the well loss, is a function of screen and gravel pack design (length, open area, diameter, configuration, etc.) and of how effeciently the borehole has been developed. It is proportional to discharge squared (Q2) and is usually only significant in very productive aquifers with small drawdowns at high pumping rates.

Borehole drawdown(s) is usually estimated by using the Logan approximation of the well known Theim formula, modified to take into account well losses. A version commonly used is:

$$sw = \frac{1.32Q}{T} = \frac{1.32Q}{KD}$$

This expression can be used to arrive at pump chamber setting depths, providing an allowance is made for pump submergence, seasonal fluctuations and long term water level decline.

6.3.3 Screen Slot Size

If the formation is poorly graded and reasonably coarse, natural development (without an artificial 'gravel pack' in the annulus between the screen and borehole wall) can be used. Formation grading is generally expressed in terms of the Uniformity Coeffieient (UC), defined as the ratio of the 60 and 10% passing sizes (D60 and D10) determined from a particle size analysis of the formation (Figure 27). For uniformity coefficients greater than about 3.0 naturally developed wells are considered feasible provided the resulting screen slot size is not too small.

The screen slot size for naturally developed wells should be such as

Figure 27 Screen and Gravel Pack Design GWR/HG-04

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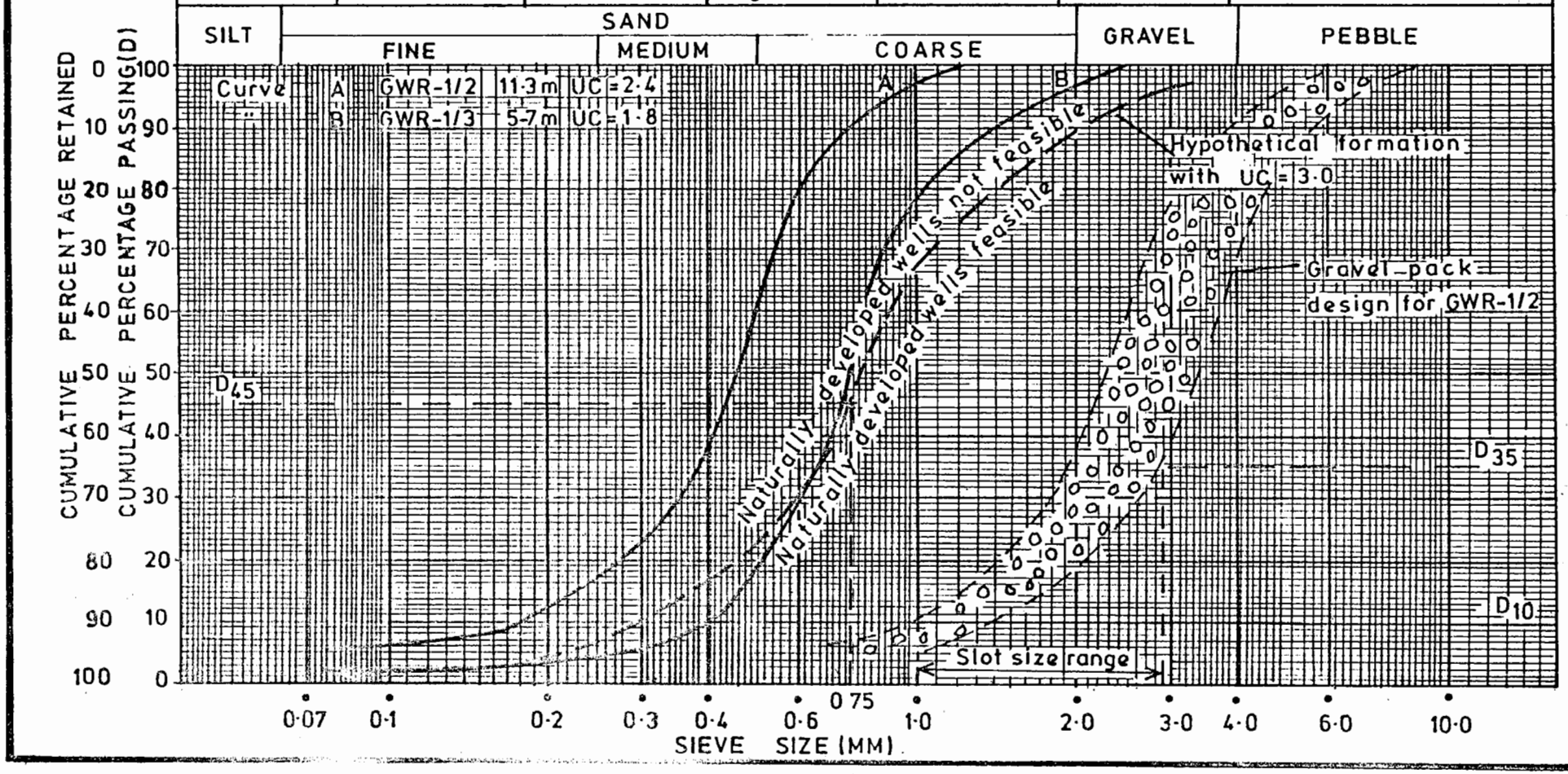
PARTICLE SIZE ANALYSIS

Sieve size(mm)	Cum.wt.retain(g)	Cum.% retained	Sieve size(mm)	Cum.wt retain(g)	Cum.% retained
13·2			0·425		
6·7			0·300		
4·75			0·212		
3·35			0·150		
2·30			0·075		
1·18			Bottom pan		
0·600			Original wt.		

BOREHOLE NR :
SAMPLE DEPTH(M) :
ANALYSIS DATE :
SIGNATURE :

D_{10} =
D_{50} =
D_{60} =
$\frac{D_{60}}{D_{10}}$ =



to retain about 55% of the aquifer material (D45), but retention of anything between 35 and 85% would be satisfactory. However, vertical formation variability has to be carefully watched to avoid screening any major layers of formation too fine for the slot size; this might result in incurable sand pumping.

The breakpoint between naturally developed and artificially gravel packed wells is often taken as the point where screen slot sizes for natural development fall below about 0.75mm. Thus, in terms of the screen supplied for the project, only that with slot sizes of 0.75mm and 1.00mm should be used for naturally developed wells -, but only where the formation UC is greater than 3.0. Effectively, this means that naturally developed wells are only feasible in aquifers consisting mostly of poorly sorted coarse sand. Figure 27 shows that borehole GWR-1/3, which was naturally developed and produced a lot of sand, should have been completed with a gravel pack. GWR-1/2, which was gravel packed, produced no sand.

Care should be taken when interpreting paticle size analysis results. Because the sampling procedure is fairly crude many of the fines may be lost and the sample appear much coarser than it really is. If in doubt always use a gravel pack, even though this means a larger diameter drilled hole.

6.3.4 Gravel Pack

Where the formation UC consistently falls below 3.0 in the yielding zone or the required slot size falls below 0.75mm, an artificial gravel pack is usually deemed necessary. In fact the term 'gravel' is a misnomer since the material often required as a filter is a coarse sand. However, the term is in wide usage and will be retained here.

Several rules of thumb in gravel design are:

(a) gravel should have similar uniformity (UC) to formation;
(b) gravel median size should be 5 to 8 times the formation median size D50 (although 5 to 15 can work by dynamic bridging);
(c) screen slot size should be D10 to D35 of gravel filter.

The use of these criteria in the design of a gravel pack for GWR-1/2 is shown on Figure 27. Although the most suitable composition for a 1.00mm slot size should have been 60% gravel (2.0-4.0mm) and 40% coarse sand (0.5-2.0mm), the right material could not be found locally and a coarser (pebble-sized) pack was used instead without any adverse effect on the performance of the borehole. In fact, because of the great variation in the grading of most natural formations considerable latitude can be applied to the selection of gravel pack material.

The minimum recommended thickness for a gravel pack is about 3" (76mm). Thus the hole diameter should be at least 6" (150mm) greater than the nominal diameter of the screen. For example, with

the bit sizes at hand, a 12 1/4" hole is needed for 6" nd screen, and 9 5/8" for 4" nd screen. A similar annular space is needed around the pump chamber for the emplacement of gravel.

Gravel should be placed continuously and at a steady rate to avoid segregation of graded material into single grain sizes and bridging of particles in the annulus. If possible the emplacement should be rapid and completed in one operation since it tends to scour the mud cake from the hole wall which increases the risk of collapse of unstable formations. Bore development **must** follow as soon as possible after emplacement, to consolidate the gravel and to clean out drilling detritus before it sets hard in the gravel/formation interface.

Verticality and straightness are of little importance in screen below pump settings, but the screen must be capable of being centred in the drilled hole (by the use of centralisers) to allow satisfactory gravel pack emplacement. The pump chamber should of course be vertical and straight.

6.3.5 Screen Type

The project was supplied with about 1,088m of PVC slotted pipe screen (4 to 10" nd) and 102m of stainless steel wire-wound screen (4 and 6" nd only). For most gravel pack applications in Nigeria the PVC screen will be perfectly adequate.

The more expensive wire-wound screen will only be superior in highly productive aquifers, say with a permeability of more than 400 m/day. This is because it is better able to reduce the entry and approach flow losses associated with the high velocities of the water flowing towards a well from such an aquifer rather than a slotted pipe screen. Normally, in an aquifer with relatively low permeability, say less than 200 m/day, upflow losses in the casing/screen string tend to predominate over inflow and entry losses, no matter what sort of screen is used. In fact, an analysis of several hundred pumping tests in Bangladesh showed that wire-wound screen upflow losses were significantly higher than slotted pipe losses because of the relative internal hydraulic roughness of wire-wound screen as opposed to the smooth internal surface of slotted pipe.

For naturally developed bores on the other hand, wire-wound screen has an edge over slotted pipe because it allows development processes, particularly high pressure water jetting coupled with airlift pumping, to be far more effective.

To summarise then, wirewound screen should only be used in gravel pack bores where the aquifer permeability is greater than about 400 m/day, or in naturally developed bores. However, it is suspected that these conditions will not be met often in Nigeria.

6.3.6 Bore Configurations

The project was supplied with steel and PVC casing, and stainless steel and PVC screen, ranging in sizes from 4 to 10 inches nd (Table 3). The use of a particular size largely depends on the anticipated yield of the bore, as shown in the table below:

Discharge (m3/h)	Pump casing/(screen) nd (inches)	Lower bore casing/screen nd (inches)
<4	4	4
4-29	6	4
30-54	6-8	4
55-90	8-10	6
91-108	10	6-8

In situations where naturally developed bores are practical, the 'drill-through' process is strongly recommended. For this, the pump setting needs to be evaluated in advance (Section 6.3.2) and the pump chamber setting depth decided.

A hole with a very small annualar clearance (say 3/8" annular or

5/8" diametric) over the pump chamber couplings is first drilled to this depth. After the chamber has been landed and set, the lower hole for the casing and screen string is then drilled through it, again with the smallest feasible annular clearance over actual coupling diameters (only steel casing is suitable for drilling through). The lower casing and screen is quickly placed through the pump casing using a back-off tool, and a seal is placed between the two casing strings (there should be some overlap for this); the seal could consist of a push-fit rubber arrangement (inner tubes for example) or cement.

Screen should be set opposite the major aquifer layers. However, in a thick aquifer sequence screen should be set at intervals, separated by blank casing, in order to economise on available stocks. A plug should be placed at the base of the string to prevent sand backfill during development.

For gravel packed bores a single-string configuration with a casing reducer is usually most appropriate. A pilot hole is normally drilled first and then reamed out to the appropriate diameters for the upper and lower casing/screen strings after allowing for at least 3 inches annular space for the gravel pack. The bore components are then lowered in a single string connected by a concentric reducer, and hung from the surface for gravel emplacement. It is good practice to have a 3m length of casing below the bottom screen interval to prevent screen string buckling during lowering.

The screen string should be fitted with centralisers to ensure a uniform gravel thickness, but none should be fitted to the pump chamber casing. As soon as gravel placement has been completed to above the reducer connection, the pump chamber should be positively tensioned for verticality and straightness. Backfill in the pump chamber annulus may be any suitable sealing material (clay, cement, etc.).

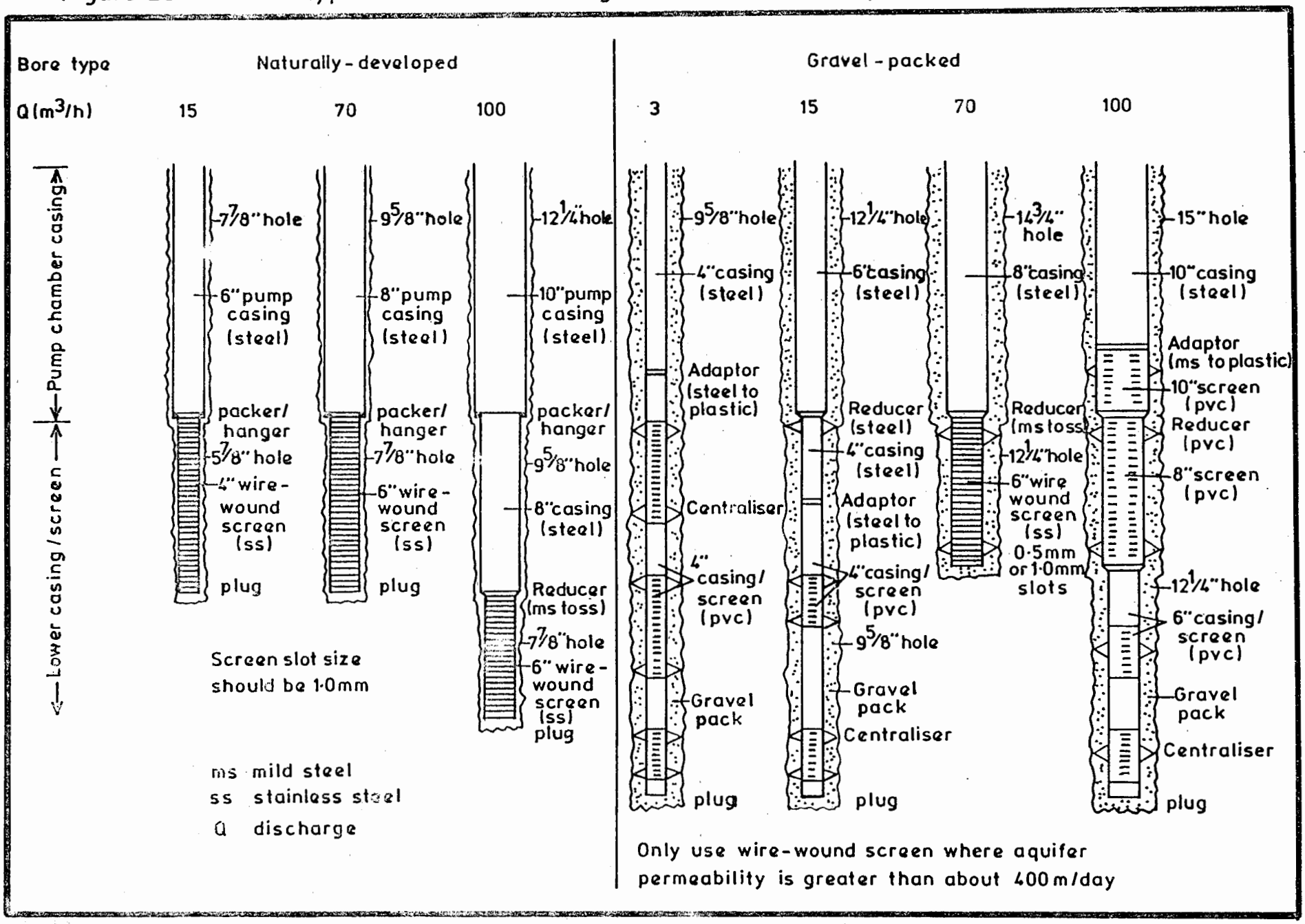
Typical configurations using the materials at hand are illustrated on Figure 28.

6.4 Borehole Development

The purpose of development is to minimise the effects of the drilling process upon the hydraulic performance of the completed bore. Much more development is needed in bores drilled with mud and completed with screen and gravel pack than in bores drilled in hard rock with air flush.

In hard rock bores the action of the air flush removes most of the fines from the hole as it is being drilled. A few hours airlift jetting opposite fractures and the screened section in the weathered zone, until the discharging water is clear and the EC constant, is normally all that is required.

Figure 28 Typical Borehole Designs for Sedimentary Formations



In mud-drilled holes the aquifer formation is invaded by the mud around the periphery of the hole and a mud cake is formed on the walls of the hole. Development is needed to remove this mud, and to violently agitate the formation material or gravel pack behind screen sections to remove fines to form a stable permeable filter. To be effective the development process should cause a regular reversal of flow across the screen, the outflow to break down any bridging of granular particles and the in-flow to bring in fines.

Recognised methods of development include high pressure water jetting coupled with airlift pumping (to remove the fines), air jetting, overpumping and backwashing, and surging with a surge block. For most applications air jetting, with periods of overpumping and backwashing will be adequate. The jetting tool should consist of a number of nozzles pointing radially outwards and extending to within about 25mm of the well screen. However, care should be taken not to overpump at first since high differential pressures between the inside and outside of the bore may be produced which can collapse a blocked screen.

Development is judged to be completed when no further increase in bore performance can be achieved and sand content during pumping falls to less than 5 ppm (as measured in an Imhoff cone).

CHAPTER 7

AQUIFER CHARACTERISTICS AND PUMPING TESTS

7.1 Introduction

An aquifer test comprises the pumping of a borehole at a known discharge rate (Q), and observing the pressure changes (drawdown) both in the pumped borehole and in the aquifer around it that this pumping induces. The data obtained from such a test can be analysed to estimate the performance characteristics of the borehole, and the transmission and storage properties of the aquifer. It is necessary to know these parameters to design production boreholes and to evaluate the groundwater resource to be developed.

In most cases the information required is best obtained from a standard package of pumping and recovery tests carried out in a strictly controlled manner.

There are numerous publications dealing with the theory of aquifer tests (Kruseman and de Ridder, 1983, for example) - this chapter only aims at an introduction to the subject, and discusses some of the simpler methods of test data interpretation, with an emphasis on practical applications.

For a pumping test, arrangements should be made for the discharging water to be drained well away (say, at least 100m) from the site to avoid the danger of recycling back into the aquifer. Channels should be dug, or pipes installed to achieve this.

If piezometers are used, they should be installed in a line from the pumping bore at distances of about 15, 30 and 60m (at least three piezometers are ideal), and be completed to a depth approximately at the mid-point of the pumped-bore's screened section.

7.2 Test Pumps

The project has three diesel driven Mono test pumps with column pipe and drive shafts for a 50m setting. The characteristics of these pumps for this setting are summarised below:

Model	Min. bore diam (mm)	Q (m3/h)	Speed (rpm)	Column pipe diam(mm)
P301	100	0.4	100	50
"	"	11.8	1450	"
P63	100	10.0	1000	50
"	"	14.3	1435	"
BH250	150	34.0	700	100
"	"	64.0	1130	"

The minimum borehole diameters are for a production installation and

are too small to allow an electric water level measuring tape to enter the annulus between the column pipe and casing; the annulus needs to be at least 50mm for this. Thus, the P301 and P63 pumps should be used in 150mm (6 inch) diameter boreholes and the BH250 pump in 200mm (8 inch) boreholes.

For most situations in the Basement Complex only the P301 pump is suitable for testing purposes since borehole yields are generally below the operating ranges of the other two pumps. In sedimentary areas with higher yielding aquifers, it is likely that the P63 and BH250 pumps will be more applicable.

7.3 Execution of Pumping Tests

7.3.1 General

Pumping test execution should be carried out in accordance with the guidelines in the British Standard code of practice for test pumping water wells (1983).

A standard procedure in general use consists of a step-drawdown test followed by a constant discharge test with intervening and terminal recovery tests. However, the water level in the borehole should first be monitored for a few days before the tests start to discover any natural (diurnal or seasonal) fluctuations; if these are significant, then the test results should be corrected to take them into account.

7.3.2 Step-Drawdown Test

A step-drawdown test (or step-test) involves pumping a borehole at several different discharge rates and observing the drawdowns. The ideal procedure is to pump the borehole at 25, 50, 75 and 100% of its maximum capacity; however, this is not always possible, particularly in the Basement where maximum yields are generally so low as to limit the range of pumping equipment capabilities.

Normally the borehole is first pumped at the lowest rate for a minimum period of 100 minutes. Then the discharge is increased, without stopping the pump, and the borehole pumped at the next rate for the same period. This procedure is repeated until the maximum discharge rate is reached. On completion, recovery measurements are taken and the borehole left to regain its original water level.

7.3.3 Constant Discharge Test

During a constant discharge test the borehole is pumped continuously for at least 24 hours, and drawdown is observed in the borehole itself and in any nearby piezometers (especially installed for the test package) or existing wells in the vicinity. For discharge rates over about 20 m3/h the test should be run for longer periods.

7.3.4 Recovery Test

This test involves measuring the recovery of the water level(s) after the cessation of pumping and should continue until the rate of recovery becomes zero. A duration of at least 12 hours may be required for this to be attained.

7.3.5 Measurements

During all the tests, water level measurements should be taken at logarithmically increasing time intervals. The intervals adopted during the project are summarised below:

Time period (min)	Measurement frequency (min)	Nr. measurements
0 - 10	1	10
10 - 30	5	4
30 - 60	10	3
60 - 240	20	9
240 - 480	30	8
480 - 1080	60	10
1080 - 1440	120	3

Discharge should also be measured (and any adjustments made to maintain a constant rate) at these time intervals after the first 10 minutes. The most appropriate method for low discharges (below about 12 m3/h or 3.3 l/s) is by timing the filling up of a bucket or drum of known volume. For higher discharges the project's weir tank with a 30 degree V notch would be sufficiently accurate. Adjustments to the discharge rate are normally done by means of a gate valve in the discharge pipe or by altering the speed of the diesel engine.

The sand content and EC of the discharging water should be measured at regular intervals (say, every 30 minutes during the step-drawdown test and 3 hours during the constant discharge test). A chemical analysis should be carried out at the borehead once the EC has stabilised and the water is clear.

The distances between the pumping borehole and any piezometers or nearby existing wells monitored during the tests should be accurately measured by tape measure for use in the analysis of the drawdown data.

An example of the format used to collect pumping test data during the project is shown on Figure 29.

Figure 29 Pumping Test Data Form

GROUNDWATER RESEARCH DEPARTMENT NATIONAL WATER RESOURCES INSTITUTE

PUMPING TEST DATA-FORM 1

Type of test : Constant discharge — Observations in Borehole Nr : GWR-1/2

Type of Pump : Mono pump P 301 — Pump setting : 12·3 m

Reference point description : Top of pump frame

Height of pl. above gl. : 0·10 m SWL ref. pt. : 1·93m time : 12.00 date : 7/4/86

Date	Clock time	t (min.)	WL (m)	s (m)	Discharge meas. data	Q	Notes
7/4/86	12.00	0	1·93	0·00			
	01	1	3·62	1·69			
	02	2	3·71	1·78			
	03	3	3·80	1·87			
	04	4	3·88	1·95			
	05	5	3·94	2·01			
	06	6	4·01	2·08			
	07	7	4·05	2·12			
	08	8	4·10	2·17			
	09	9	4·12	2·19			
	10	10	4·18	2·25	212 l/102 s	2·08	Q measured by timing filling up of 212 litre drum
	15	15	4·32	2·39	100 s	2·12	
	20	20	4·44	2·51	24 l/10 s	2·4	Q measured by timing filling up of 24 litre bucket
	25	25	4·58	2·65			water clear and sand-free last tested head
	30	30	4·65	2·72	100 s	2·12	
	40	40	4·78	2·85	100 s	2·12	EC_{25} = 200 uS/cm
	50	50	4·90	2·97	101 s	2·09	EC_{25} = 195 uS/cm
	13.00	60	4·98	3·05	101 s	2·09	EC_{25} = 195 uS/cm
	20	80	5·15	3·22	102 s	2·07	EC_{25} 195 uS/cm
	40	100	5·25	3·32	103 s	2·05	EC_{25} = 205 uS/cm

GWR/HG - 06 (1/5) page of

7.4 Interpretation of Step-Drawdown Test Data

The purpose of a step-test in any aquifer is to evaluate the performance of the borehole in terms of discharge and drawdown.

Drawdown in a discharging borehole can be written as:

$$sw = sa + sb \qquad (1)$$

where sa = drawdown due to the flow of water through the aquifer towards the borehole (aquifer loss)
sb = drawdown due to the flow through the screen and to the pump intake inside the casing (or well loss).

In most cases the total drawdown can be described by the equation:

$$sw = AQ + BQ^2 \qquad (2)$$

where A and B are constants, though A is time dependent.

Dividing equation (2) by Q gives:

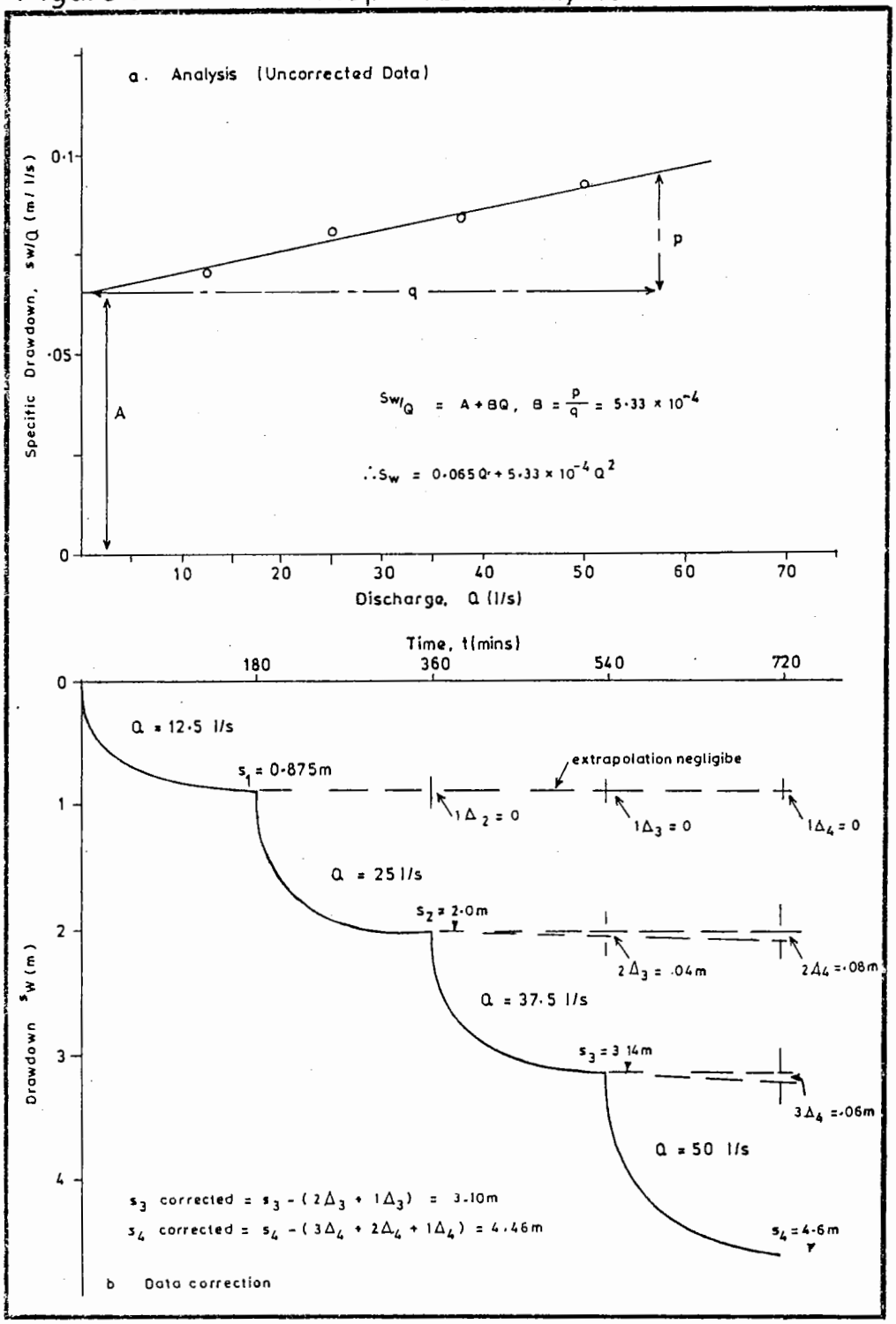
$$sw/Q = A + BQ \qquad (3)$$

Equation (3) is that of a straight line in terms of discharge (Q) and specific drawdown (sw/Q), where A is the intercept on the sw/Q axis and B the slope, as shown in Figure 30. Given the discharge and drawdown measurements from a step test, A and B can be calculated and the well loss BQ2 computed.

Application of equation (3) requires that the data ought to be derived from conditions where the time-variable is identical in each case and drawdown is in a semi-equilibuium state. This would imply separate steps, each with a full recovery period between them so that the bore could be regarded as having been pumped for an equal time at each discharge. The step test as employed is clearly only an approximation of this situation but a correction can be made by using the principle of superimposition. This entails extrapolating the drawdown for each lower discharge step to estimate what the water level would have been had the bore continued pumping at the same rate for the next time increment. The drawdown used in the analysis is then the gross drawdown less the sum of the differential extrapolated drawdowns, as shown on Figure 30. The application of such a correction is related to the shape of the discharge/drawdown plot obtained - the closer the steps come to 'equilibrium', the less necessary will be the correction.

In Basement aquifers consisting of fracture zones the specific drawdown/discharge plot may come nowhere near forming a straight line, and instead form a marked upward curve. This is most likely due to the fractures becoming progressively dewatered, resulting in a reduced inflow zone, higher entrance velocities and hence higher well losses. Interpretation of such data can at best only be qualitative.

Figure 30 Step Test Analysis



7.5 Interpretation of Constant Discharge Test Data

7.5.1 General

Constant discharge tests are mainly run to determine the transmissivity (T) and permeability (K) of the aquifer, and the storage coeficient (S) if piezometers or observation wells are used. However, in order to interpret the data meaningfully some understanding of aquifer conditions, and the assumptions on which the interpretative methods are based, is needed. The basic theory of groundwater flow will not be dealt with here since it is complex, and in any case can be found in any standard text book on hydrogeology.

7.5.2 Definitions and Assumptions

Aquifer types. A confined or artesian aquifer is a permeable formation containing water under pressure, confined at the top by a layer of restricted permeability (aquiclude). In an unconfined aquifer there is no such layer at the top, and the upper surface of the water body (the phreatic surface or water table) is free and open to the atmosphere. The main difference between the two aquifer types is that confined flow can be horizontal whereas unconfined flow always has both horizontal and vertical components, and the direction of flow varies with depth (Figure 31).

Leaky aquifers are those which, when pumped, are replenished from either above or below by seepage through beds of low permeability (aquitards).

In Nigeria aquifers in the weathered Basement and fadama alluvium are largely unconfined. In sedimentary basins, however, the aquifer layers are likely to be confined with leakage through intervening clayey layers.

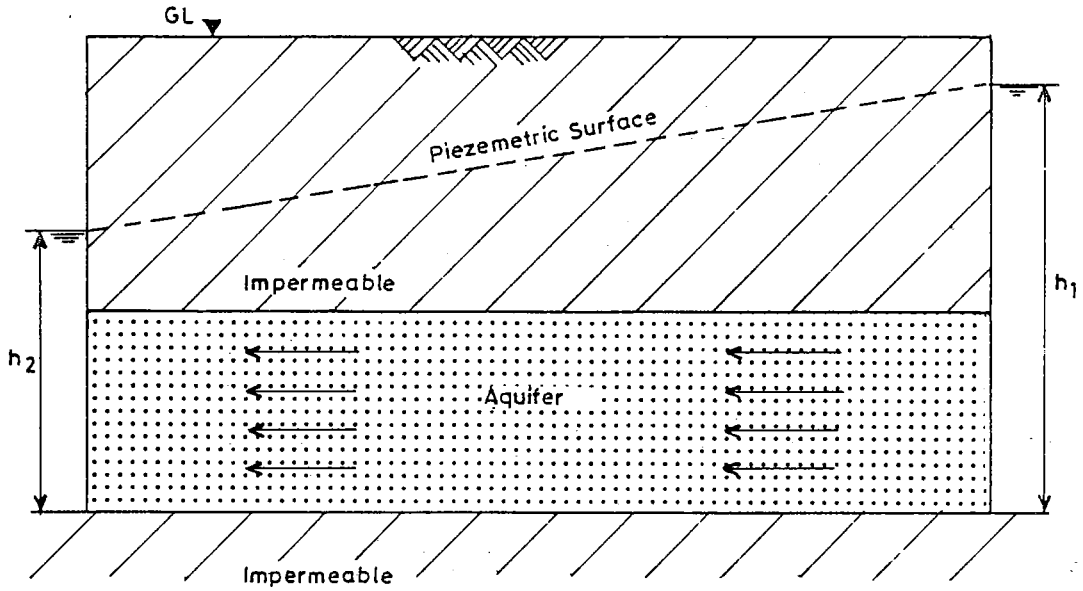
Partial penetration. A partially penetrating bore is one which taps less than the full thickness of the aquifer (Figure 32). The ratio of screened bore depth to total aquifer depth is termed the penetration factor (b/D).

Groundwater flow. Three conditions are recognised: equilibrium (or steady state), non-equilibrium (or non-steady state) and semi-equilibrium. Steady state flow should rarely, if ever, occur in theory, but is common in practice - it is attained when the rate of change of drawdown, ds/dt, approximates zero or is constant at considerable distances from the bore (Figures 33, 34 and 35).

Semi-equilibrium flow is the condition when for distances close to the bore or for long pumping times, the complex time-drawdown functions can be simplified using the expression ds/d log t = constant.

Figure 31 Confined and Unconfined Flows

a) Confined flow



b) Unconfined flow

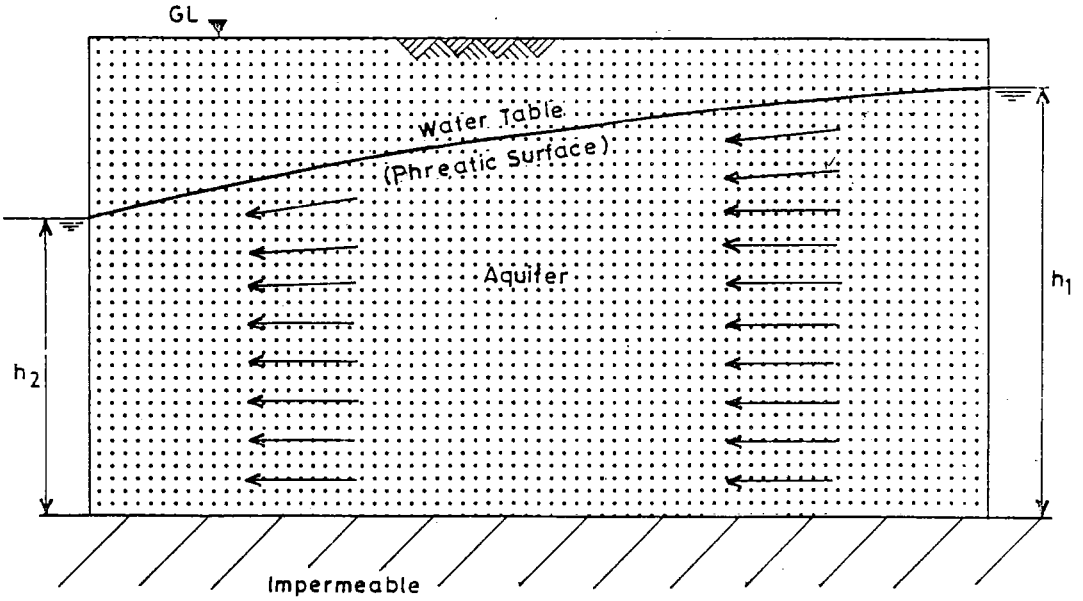
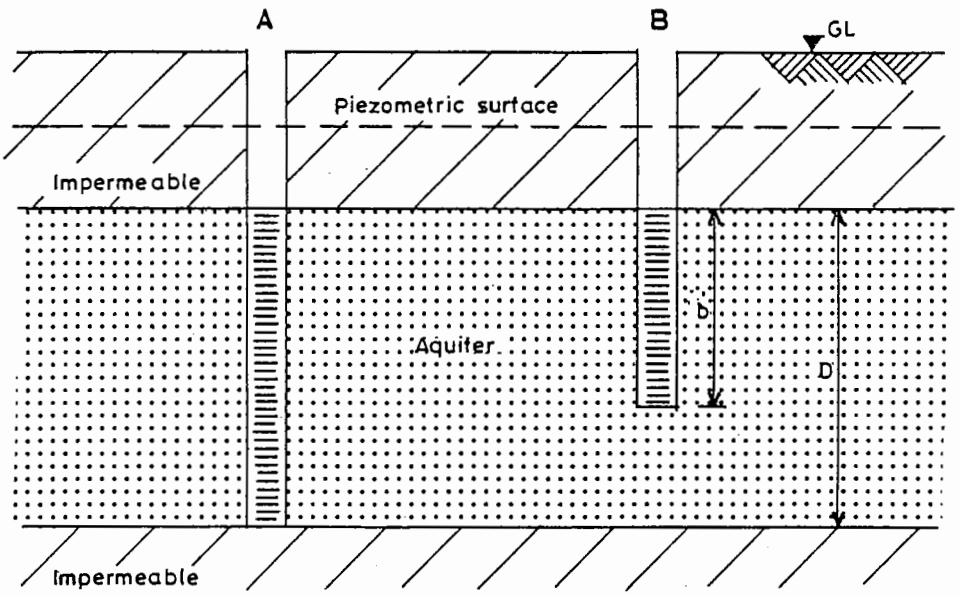


Figure 32 Well Penetration



Fully(A) and partially(B) penetrating wells in a confined aquifer

Figure 33 Steady State Confined Flow

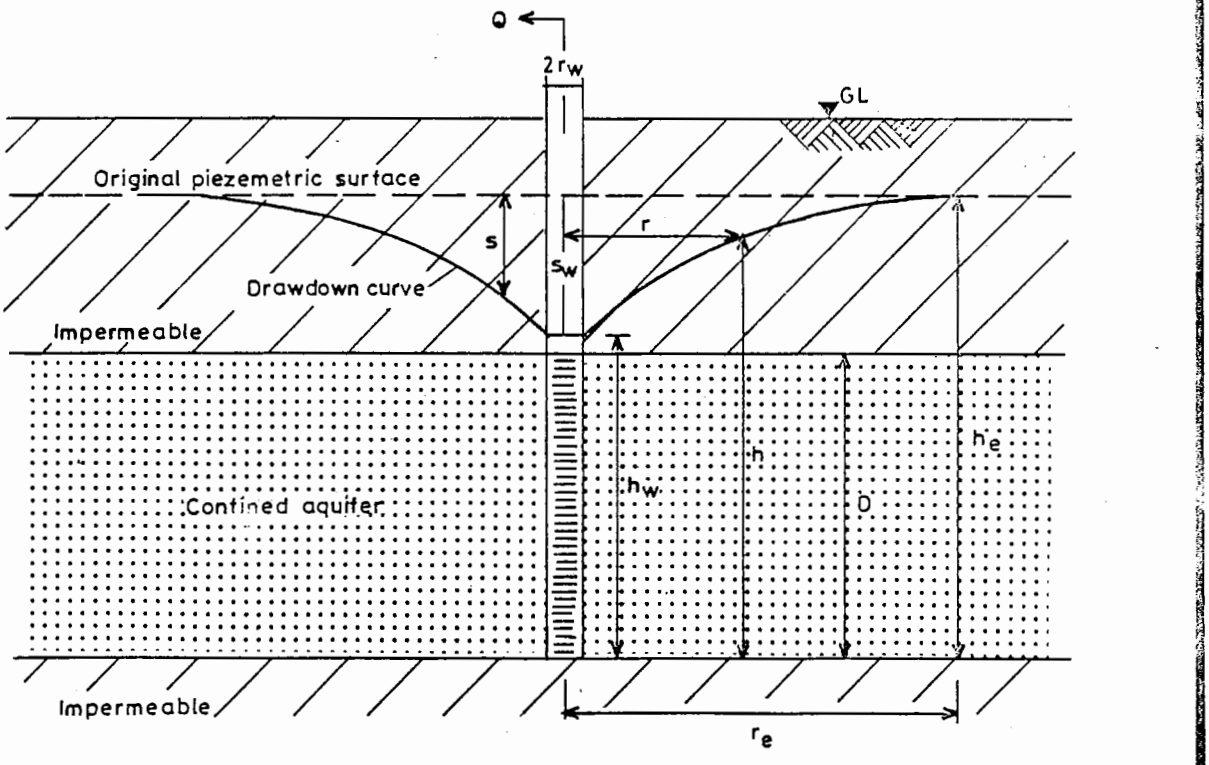


Figure 34 Steady State Flow - Unconfined Aquifer

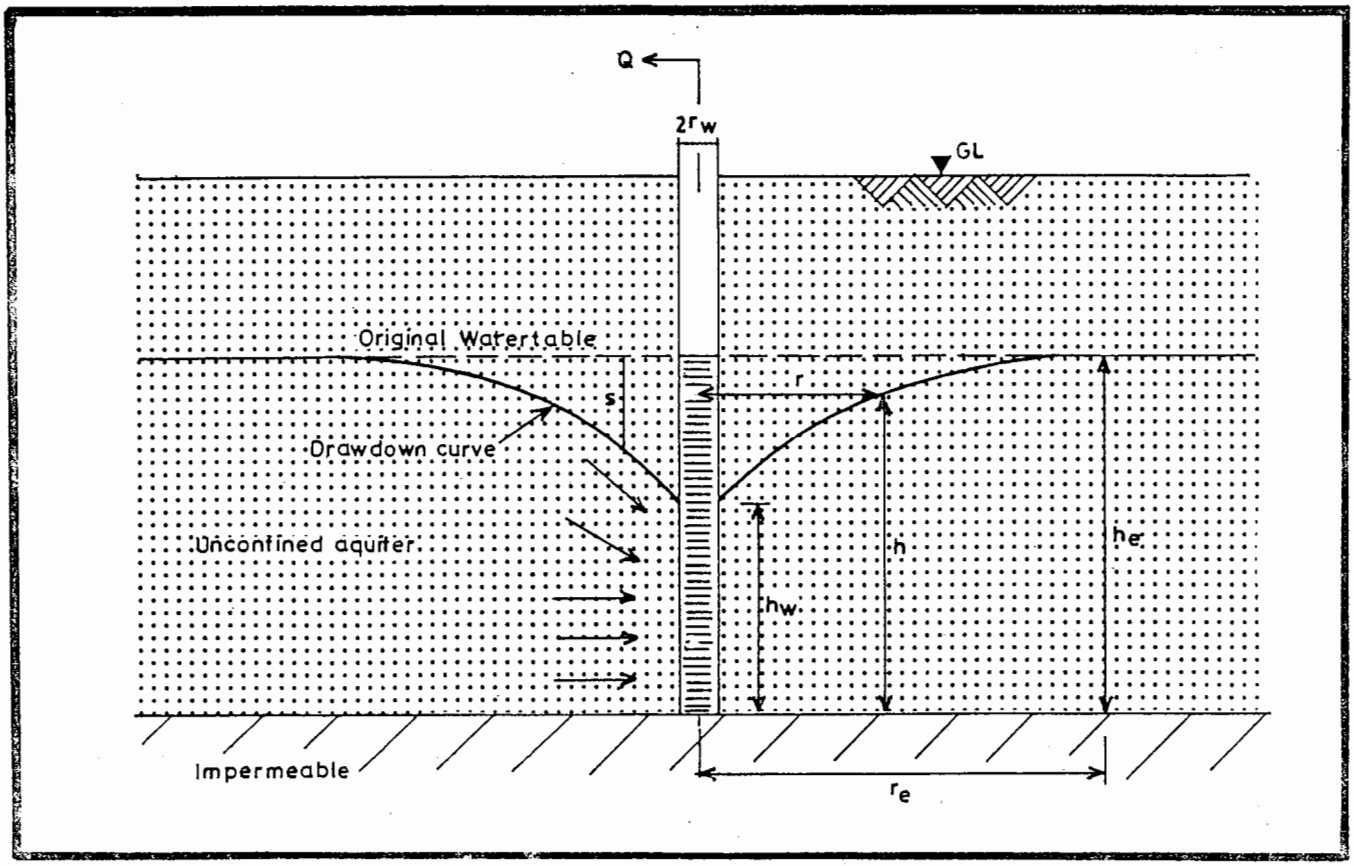
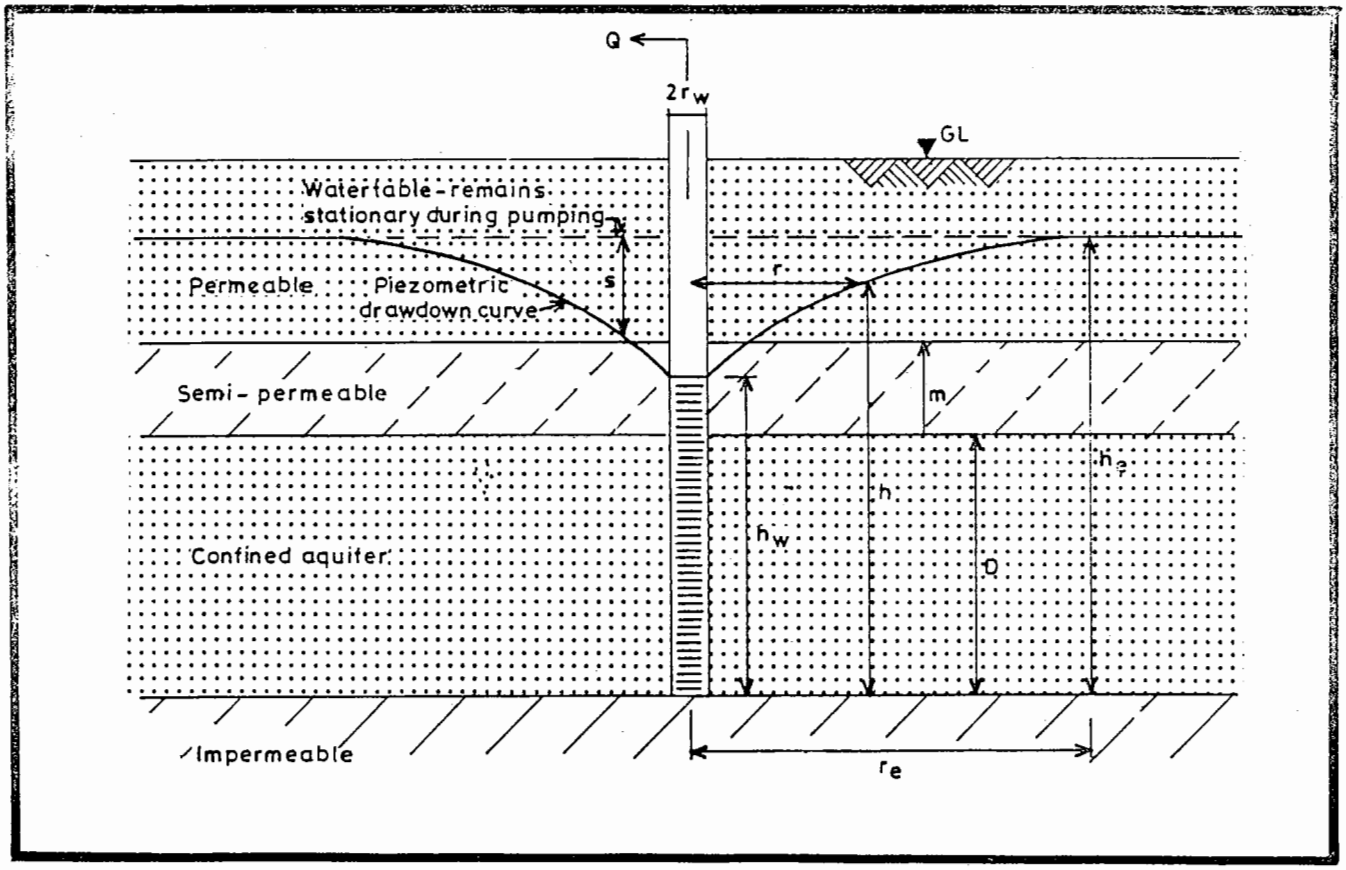


Figure 35 Steady State Flow - Leaky Aquifer



Non-equilibrium flow is the condition when the interpretative method recognises that the rate of drawdown in the aquifer various both with time and distance with respect to the bore; complex functions are necessary to describe this variance.

Boundary effects. The rate of drawdown can be deflected from its normal pattern if a physical boundary is near the bore. The drawdown is increased if a barrier, such as the Basement rock bordering a fadama strip, is reached, and decreased if a recharging river is reached, for example.

Darcy's Law. The basis of the analytical treatment of groundwater flow is Darcy's Law which in its simplest form may be stated as follows:

$$v = K \frac{dh}{dL} \qquad (4)$$

where v = flow velocity
K = permeability (constant)
h = hydraulic head
L = length of flow

The term dh/dL is termed the hydraulic gradient.

Darcy's Law states that the flow in a porous medium is proportional to the hydraulic gradient, with the constant of proportionality being the property of the porous medium and known as the coefficient of permeability. Though Darcy's Law has limits of application (it does not apply to high flow velocities), it is the basis of all aquifer test theory.

The methods derived for interpreting aquifer tests are based on the following main assumptions:

(a) all the flow is horizontal;
(b) the flow system has a complete radial symmetry;
(c) the coefficients of transmissivity and storage of the aquifer are constant at all times and distances;

whilst, to obtain usable solutions, further conditions have to be stipulated.

Obviously, these conditions are rarely, if ever, perfectly found in nature. However, despite this, pumping tests can be interpreted to give plausible estimates of aquifer hydraulic properties, particularly in fairly uniform alluvial and sedimentary formations.

The results of tests in aquifers consisting of fracture zones and exhibiting fissure flow (as in the Basement) have to be treated with some caution since the inherent turbulence in the vicinity of the pumping bore may create a condition where Darcy's Law does not

apply. T values in such situations can rarely be applied to regional through flow calculations and in any case transmissivity itself is practically meaningless because of its variability, depending as it does on the number and size of fractures penetrated by the borehole. There is little point in using piezometers in such aquifers since the same fractures may not be intersected as in the pumping bore.

7.5.3 Equilibrium Interpretative Method

At equilibrium, variations of drawdown with respect to time are negligable, i.e., the hydraulic gradient has become constant. A formula describing this condition was developed by Theim which can written in the following form:

$$sw = \frac{2.3\ Q}{2\pi T} \log \frac{re}{rw} \qquad (5)$$

where re = distance from bore where drawdown is nil
rw = radius of bore.

Unfortunately, the ratio re/rw is never known in practice. However, the calculated value of T is remarkably insensitive to large variations in re and rw, depending as it does on the log of the ratio, and several workers have developed empirical relationships to simplify Theim's equation. Perhaps the best known such relationship is the one due to Logan:

$$sw = \frac{1.22\ Q}{T} \qquad (6)$$

This is basically a statement of Darcy's Law for the radial geometry of single bore systems. It will give a good estimate of T provided that the following conditions are satisfied:

(a) the bore is at or close to equilibrium;
(b) well losses are small compared to aquifer losses;
(c) there are no recharge or barrier boundraies in the vicinity of the bore.

However, in practice, even if a pumped bore has not reached steady-state, equilibrium drawdown can be extrapolated, while well losses can be estimated a by step-test, and boundary effects identified from drawdown curve discontinities (such as a pronounced kink in the time-drawdown data plot). In the absence of a step-test and the determination of well loss, a higher Logan coefficient could be used, say 1.32 instead of 1.22, to arrive at T.

The value of the Logan approximation is that it is rarely far wrong and it provides a useful yardstick against which to measure the accuracy of results obtained by supposedly more theoretically rigorous and complex analyses.

The Logan formula can of course be applied to step-test data; sw/Q is simply the value of the intercept A in Figure 30. However, it should be borne in mind that equilibrium conditions are more likely to be reached in a constant discharge test lasting 24 hours rather than a step test lasting 100 minutes, providing no boundary effects are encountered. Hence, in most cases, Logan T derived from a constant discharge test should be used in preference to that derived from a step-test.

The Theim formula can be applied to drawdowns in piezometers around a discharging bore. The normal procedure is to plot drawdown (taken at a time when equilibrium conditions are considered to be approximated, but before the onset of any boundary effects) against log distance. The plot should be a straight line with a slope ds/d log r, which when measured over one complete log cycle is termed simply Δs. T is calculated from the expression:

$$T = \frac{2.3\ Q}{2\pi\Delta s} \qquad (7)$$

An example of such a plot, taken from observations in GWR-1/3 and GWR-1/4 during a test on GWR-1/2, is shown on Figure 36.

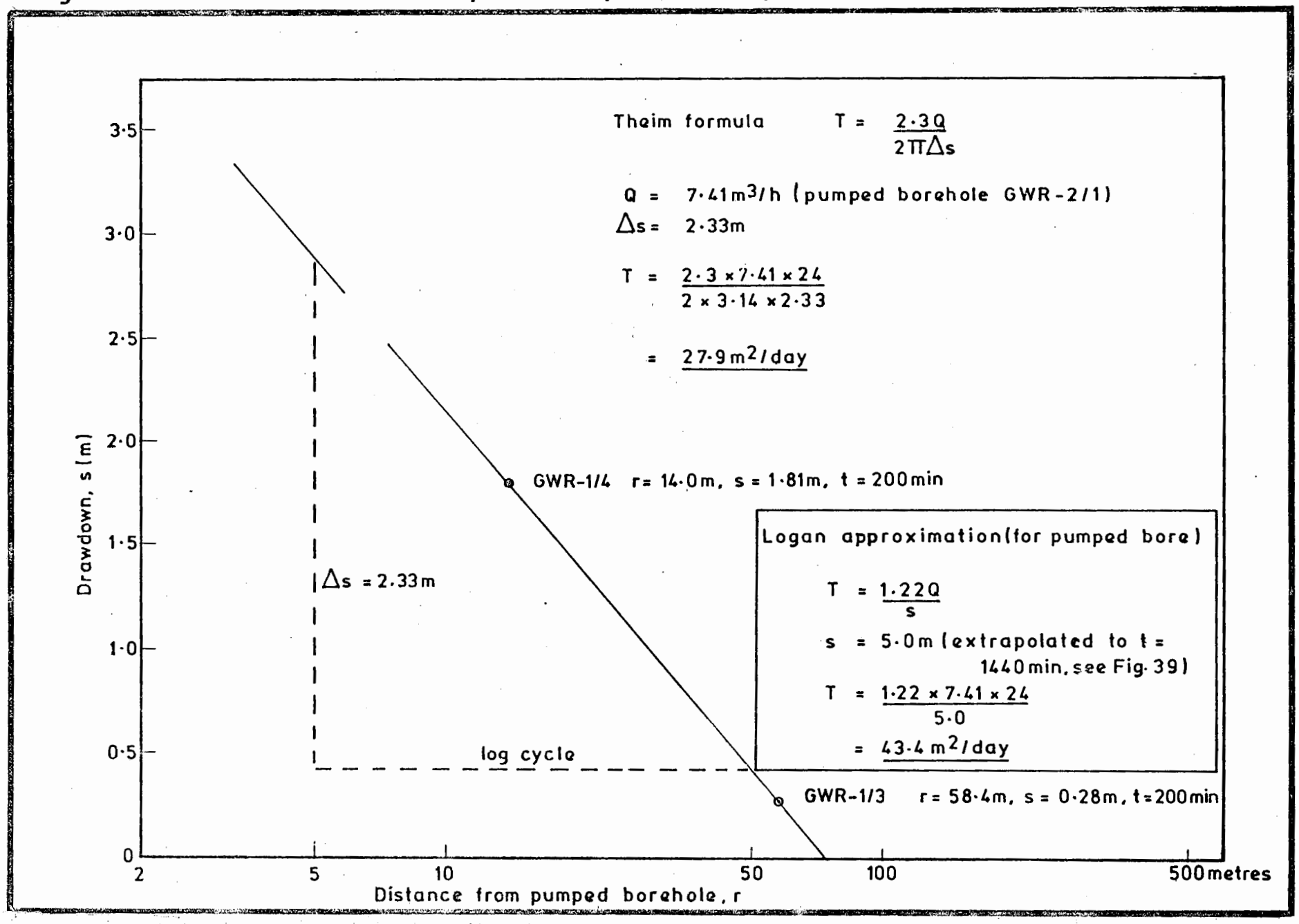
Strictly speaking, the above discussion of the equilibrium method only applies to confined aquifers, where all the flow is horizontal, as shown on Figure 33. However, equilibrium methods can also be used for unconfined aquifers (Figure 34) and leaky confined aquifers (Figure 35).

In unconfined (water table) aquifers the assumptions of completely horizontal flow and constant T at all distances, implicit in the basic theory, are not true. It can be seen in Figure 34 that the flow has a vertical component, particularly near the pumping bore, and that the saturated thickness of the aquifer and consequently its transmissivity decreases towards the bore. This can be partially compensated for by placing greater reliance on the piezometers furthest from the pumping bore, say those at 30m or more distance. (It should be noted that when using piezometers distant from the bore, the derived T is more likely to apply to the total effective aquifer thickness rather than simply that part tapped by the bore).

A closer approximation for water table aquifers can be obtained by allowing the Dupuit-Forcheimer assumptions for confined flow and correcting for decreasing saturated thickness. These assumptions are:

(a) the flow everywhere is horizontal or, more correctly, vertical gradients are small compared to horizontal ones and so can be neglected;
(b) the hydraulic gradient to all depths is given by the slope of the watertable.

Figure 36 Equilibrium Theim Analysis



Accepting the above assumptions, the following variant of the equilibrium formula can be obtained:

$$h2^2 - h1^2 = \frac{2.3\ Q}{\pi K} \log \frac{r2}{r1} \qquad (8)$$

where h1 and h2 are the heights of the water level above the impermeable aquifer base at distances r1 and r2 from the bore, with r2 being large (greater than 200m).

The analysis of the behaviour of leaky aquifers (Figure 35) is more complex. If equilibrium analyses fail, more specific variants, such as the Hantush and De Glee methods, should be applied (see Kruseman and de Ridder, 1983).

7.5.4 Non-Equilibrium Interpretative Methods

The best known method of the treatment of non-equilibrium flow is that due to Theis. The derived equation can be written as:

$$s = \frac{Q}{4\pi T} W(u) \qquad (9)$$

or, in logarithmic form:

$$\log s = \log \frac{Q}{4\pi T} + \log W(u) \qquad (10)$$

where W(u) = well function. The argument (independent variable), u, of the function can be expressed as:

$$u = \frac{r^2 S}{4Tt} \qquad (11)$$

or, in logarithmic form:

$$\log \frac{r^2}{t} = \log \frac{4T}{S} + \log u \qquad (12)$$

Equations (10) and (12) indicate that s and r2/t are related in a similar manner to W(u) and u, and t/r2 to 1/u. In fact, if plotted on logarithmic paper the two curves have exactly the same shape. A graphical solution to the equations is therefore possible.

A 'type curve' of W(u) against 1/u (for a left to right curve) is plotted on double logarithmic graph paper from tabulated values of W(u) and 1/u (given in any hydrogeological book, for instance Kruseman and de Ridder, 1983). A plot of s against t/r2 is then prepared on similar, transparent paper and superimposed on the type curve. The co-ordinate axes of the two graphs are held parallel and the data plot transferred to a position representing the best fit between the two curves. An arbitrary match point is then selected anywhere on the paper and values of W(u), 1/u, s and t/r2 read off. These values are then substituted into equations (9) and (11) to calculate T and S respectively. An example of the analysis, for GWR-1/4, is given in Figure 37.

Care should be taken with the value of S obtained with the Theis method. Except in the cases of low storage, highly confined aquifers, most estimates of S are probably far too low. This is because in most real aquifers (which tend to be leaky and semi-confined to unconfined) storage is something which takes a very long time to fully manifest itself, longer than is practical for most aquifer tests. The real storage value will be higher than that indicated by the test analysis since percolation from shallow water

Figure 37 Non-Equilibrium Theis Analysis

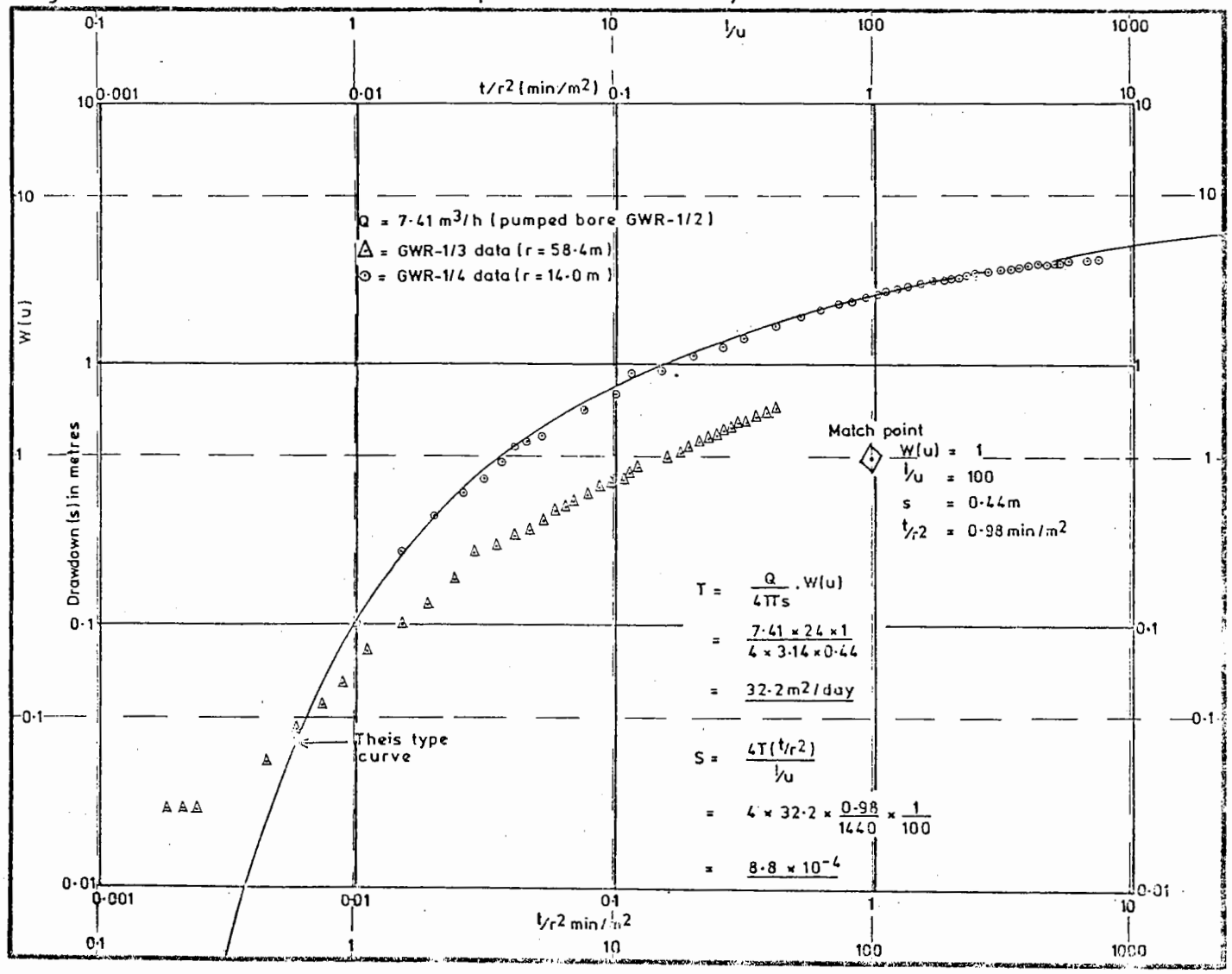


table horizons, in which the long term storage coefficient 'resides', may take an extremely long time to reach the aquifer actually being tested by the bore. Aplication of the Theis methodology may lead to two separate 'fits' of the type curve to the data plot:

(a) a 'fit' to the early time data, suggesting some T value and a low storage coefficient pertinent to a confined aquifer;
(b) a possible 'fit' to late time data, generating a similar T but a much higher storage coefficient. Although this fit is often difficult because of the logarithmically decaying value of equal time increment data from even an extended constant discharge test, it should nevertheless be attempted since it may give a better estimate of true phreatic (water table) storage coefficient.

These factors were recognised by Boulton in the derivation of his 'delayed yield' type curves, which present a more rigorous method of analysing aquifer tests and take into account the phenomenom of an apparent variable storage coefficient. The analyses according to Boulton should be studied in the relevant text books and applied wherever the simple Theis analysis fails.

7.5.5 Semi-Equlibrium Interpretative Methods

Various semi-equilibrium methods of aquifer test analysis have been credited to different workers, most notably Jacob. These are based on the recognition that the Theis equation could be greatly simplified if certain restictions as to elapsed pumping time or distance from the pumped bore could be made, essentially restrictions to the value of u. The approximations, sometimes called semi-equilibrium methods since they postulate a constant value for the term ds/ds log t, rely on only treating data from very small values of u, i.e., from small radii (such as the pumped bore itself) or from piezometers only after very long pumping times.

Taking these factors into consideration Cooper and Jacob derived the following expression for drawdown:

$$s = \frac{2.3\ Q}{4\pi T} \log \frac{2.25\ Tt}{r^2 S} \qquad (13)$$

Equation (13) is solved by plotting linear drawdown versus logarithmic time for each piezometer and reading off two parameters:

(a) Δs, the single log-cycle drawdown increment;
(b) to, the time when the straight line portion of the plot, extrapolated backwards, cuts the zero drawdown axis.

T and S are determined from the following expressions:

$$T = \frac{2.3\ Q}{4\pi\Delta s} \qquad (14)$$

$$S = \frac{2.25\ Tto}{r^2} \qquad (15)$$

This type of solution is illustrated for piezometer GWR-1/4 on Figure 38. The analysis can also be applied to the pumping bore, but of course only T can be determined (Figure 39). The short, late-time section of the data to which the analysis is applicable can be clearly seen.

Theis' own application of the approximation was to the recovery of groundwater levels on the cessation of pumping. He stipulated that the recovery can be simulated by assuming that the bore continues discharging but superimposing a recharge bore of equal yield on top of it.

The practical solution of the Theis recovery method, as it is called, is to plot drawdown during recovery (residual drawdown, s') linearly against the ratio t/t' logarithmically, where t' is the time since pumping stopped. This usually results in a curved plot at small t', but becoming a straight line as t' increases, as in the previous Cooper-Jacob method. The single log-cycle slope, $\Delta s'$, is measured, and substituted in the following expression to determine T:

$$T = \frac{2.3\ Q}{4\pi\Delta s'} \qquad (16)$$

The Theis recovery solution is commonly used on pumped bore data since there are practically no well losses involved in the determination of s'. An illustration of the analysis for GWR-1/2 is given in Figure 40.

7.6 Evaluation of Results

In most cases pumping tests are carried out without any observation piezometers. Therefore the most important methods of interpretation will be those applicable to the pumped bore itself.

The simplest and most reliable of these is the equilibrium formula. The sources of major errors here are few and can usually be identified and corrected for. Thus, in the absence of any contradictory information, a good estimate of T should always be obtained from some variant of the equilibrium formula, the best known of which is the Logan approximation. If a step-test has been carried out and the well loss can be derived, drawdowns can be

Figure 38 Semi-Equilibrium Jacob Analysis (Piezometer Data)

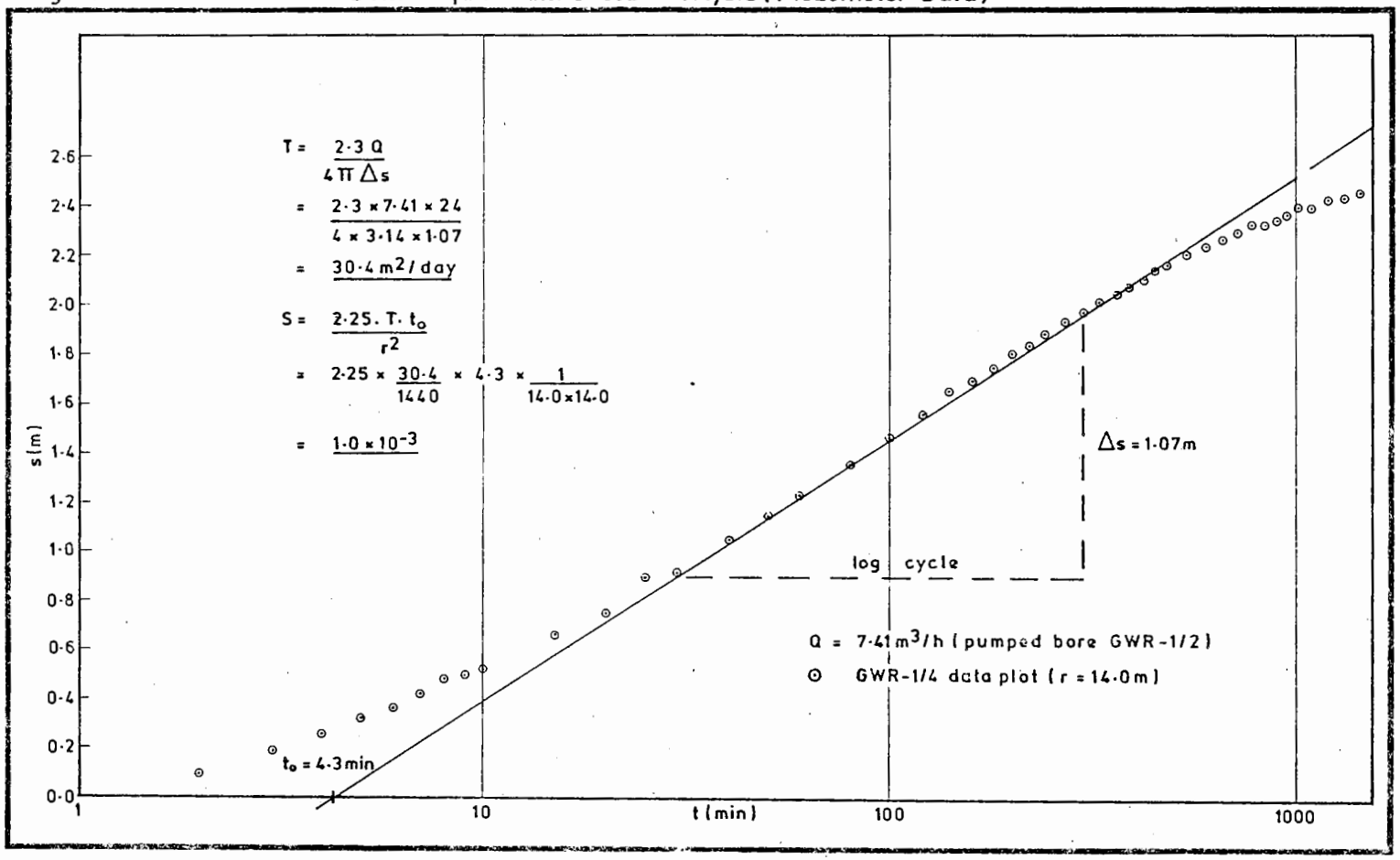


Figure 39 Semi-Equilibrium Jacob Analysis (Pumped Bore Data)

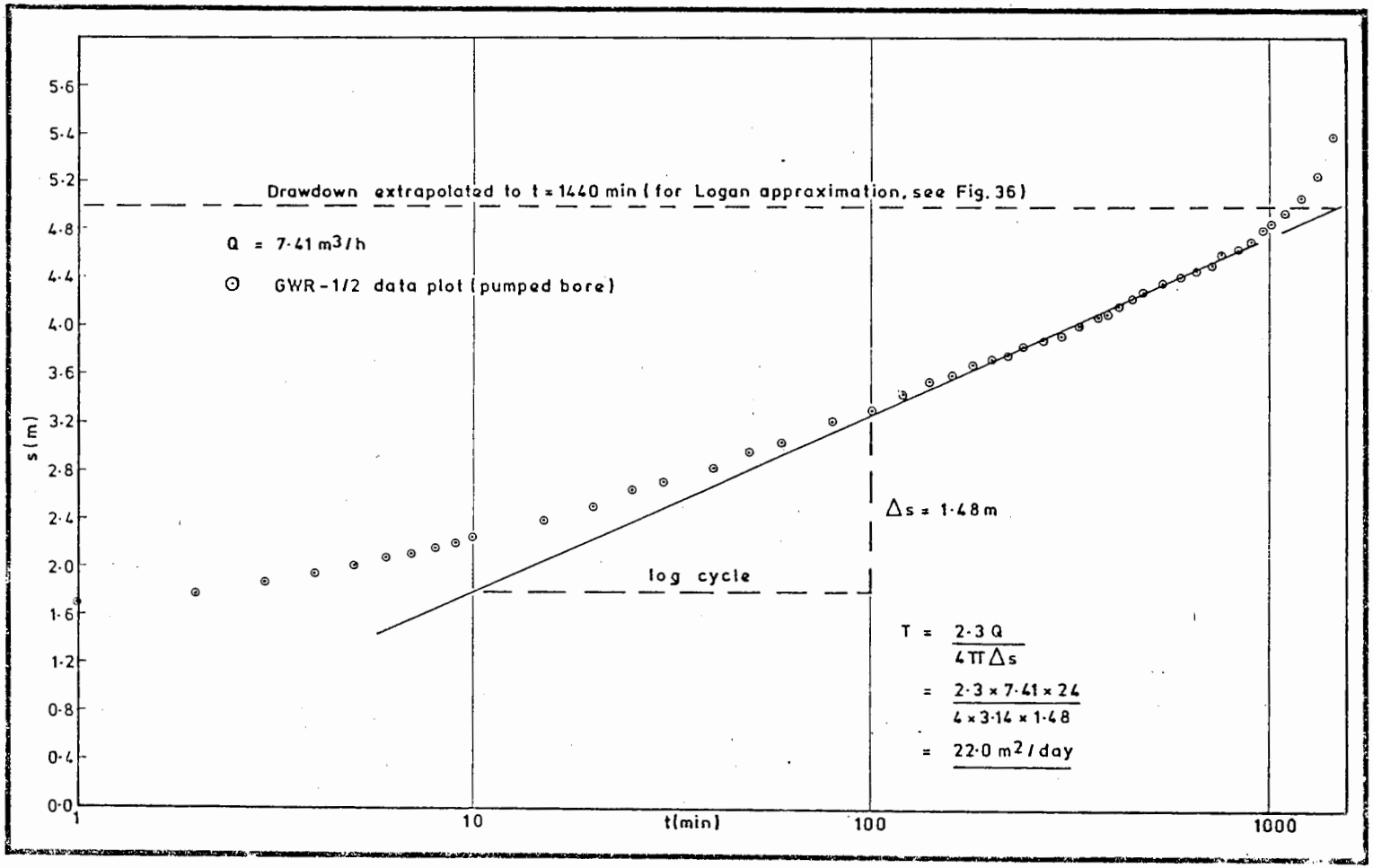
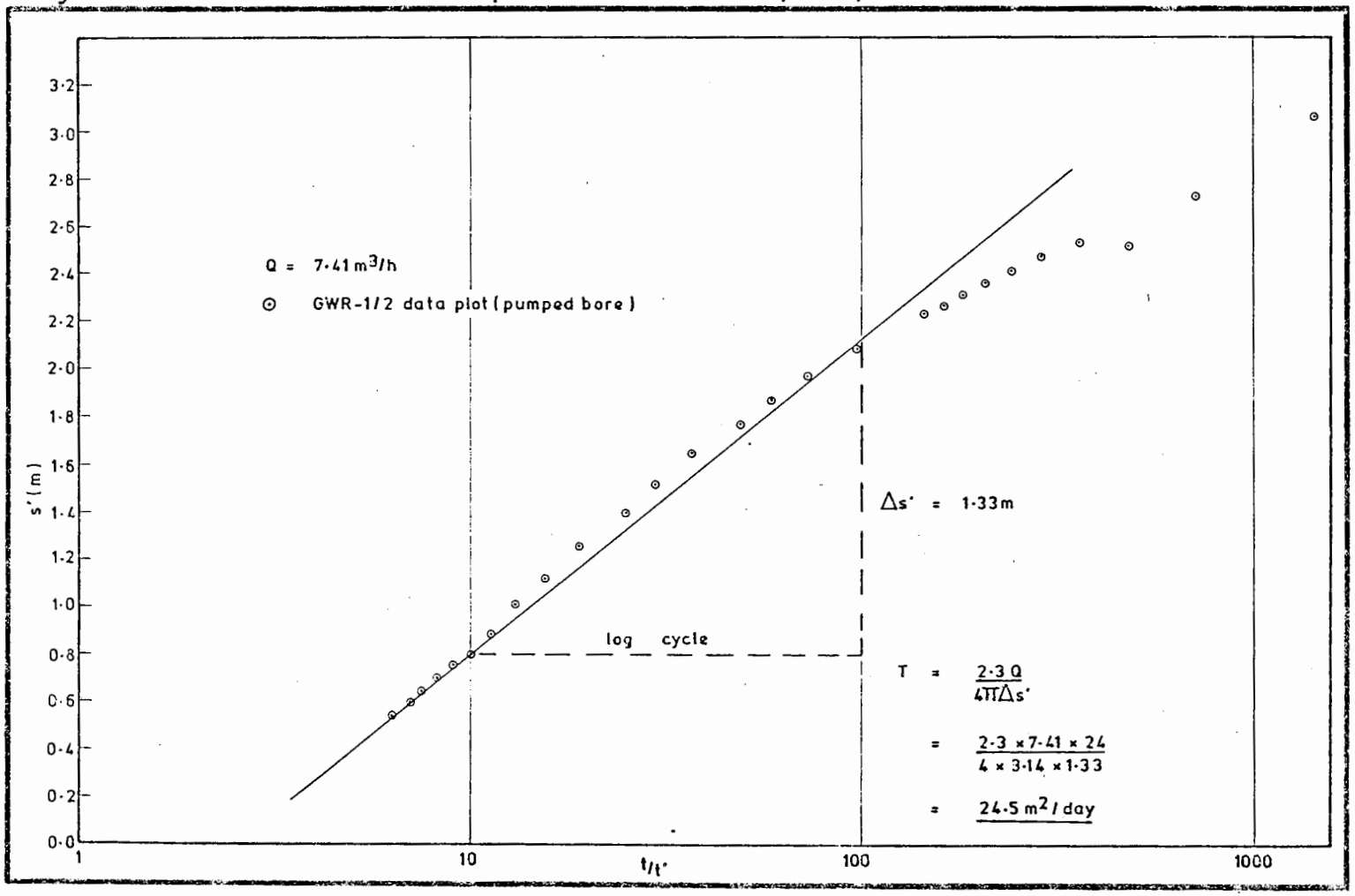


Figure 40 Semi-Equilibrium Theis Recovery Analysis



corrected to give a better estimate of T.

In the case of application of the non-equilibrium methods to the pumping bore, there are both theoretical and practical problems.

To obtain his solution Theis had to assume that the bore was a 'line sink', i.e., it had a finite length but infitesimally small radius. Whereas this assumption is reasonable when considering points in the aquifer some distance away from the bore, clearly, it is not when applied to the bore itself. Further, pumping bore drawdown can seldom be fitted to any type curves because of surges and the generally low curvature of the time/drawdown plot after the first few seconds of pumping.

The theoretical objection is equally applicable to the Theis recovery formula. A further complication is that the recovery is often S-shaped and more than one straight line can be drawn through different portions of it. However, there is no doubt that recovery in a pumped bore is a function of T and that, in some cases, the Theis recovery formula works well. Nevertheless, in the case of conflict of results obtained by the equilibrium method and by the Theis recovery method, the former (the Logan approximation) should be preferred.

An evaluation of results is illustrated in Table 4, for the test on GWR-1/2 in the ECA with GWR-1/3 and GWR-1/4 as piezometers at distances 58.4 and 14.0m respectively. Results from the piezometric data were not compatible (see Figure 37), and T obtained from the Logan approximation should be taken as being the most plausible.

Table 4

GWR-1/2 - Results of Pumping Test Analyses

Flow assumption	Method	Data	T (m2/day)	S
Equilibrium	Theim	Both piezometers	27.9	
"	Logan	Pumping bore	43.4	
"	Logan (corrected for assumed well losses)	Pumping bore	47	
Non-equilibrium	Theis	GWR-1/4	32.2	0.00088
Semi-equilib.	Jacob	pumping bore	22.0	
" "	"	GWR-1/3	92.3?	0.00014
" "	"	GWR-1/4	30.4	0.001
" "	Theis recovery	pumping bore	24.5	
" "	" "	GWR1/3	103.8	
" "	" "	GWR-1/4	25.0	

Note: GWR-1/2 pumping bore, GWR-1/3 and GWR-1/4 piezometers.

CHAPTER 8

GROUNDWATER CHEMISTRY

8.1 General

A survey of groundwater chemistry by the hydrogeologist normally has three main objectives:

(a) the determination of the groundwater flow system, including the distribution of the recharge and discharge areas;

(b) the study of groundwater qualiity in relation to its intended use, for example as potable, irrigation or industrial supply water;

(c) the recognition of any potential corrosion or incrustation problems with tubewell components and pumps.

8.2 Chemical Concepts and Definitions

The chemical parameters which are most important in groundwater chemistry, and should therefore normally be analysed for, are: major ion concentrations, total dissolved solids, pH, alkalinity, hardness, dissolved gases and redox potential. The temperature of the groundwater should also be recorded. Other physical characteristics of water, such as taste, odour and turbidity, are easy and useful to note. Bacteriological quality is only recorded in groundwater in relation to a specific water quality problem.

The concentrations of dissolved salts in a water sample are usually expressed in milligrams per litre (mg/l) or their numerical equivalent, parts per million (ppm). The dissoloved salts in water exist as dissociated ions: positively charged cations and negatively charged anions, which react with one another in definite weight ratios, that is, according to their equivalent weights. One equivalent weight of cation will exactly combine with one equivalent weight of anion. Therefore, the concentrations of cations and anions in a water sample should balance when expressed in equivalent weight units, commonly milliequivalents per litre (meq/l) or equivalents per million (epm); these are obtained by dividing the concentration of the ions in mg/l by its equivalent weight. If the cation and anion concentrations are not equal, this indicates that either one or more ions present in the water have not been analysed for, or the chemical analysis is incorrect.

The major ions in groundwater are shown in Table 5.

Table 5 Major Ion Constituents of Groundwater

	Chemical symbol	Equivalent weight
Cations		
Calcium	Ca	20
Magnesium	Mg	12.2
Sodium	Na	23
Potassium	K	39.1
Anions		
Carbonate	CO3	30
Bicarbonate	HCO3	61
Sulphate	SO4	48
Chloride	Cl	35.5

Calcium, magnesium, bicarbonate, carbonate, chloride and sulphate concentrations can be determined in the field using a portable chemical laboratory (such as the Hach DR-EL/4) - the sulphate by a colorimetric technique (spectrophotometer) and the others by titration.

Sodium and potassium have to be measured in a laboratory by the atomic adsorption method. (The Water Quality Laboratory at the Institute is being fitted with an atomic adsorption spectrophotometer as part of the NWRI/EDF Water Resources Project).

Ions, which are usually present in small concentrations but are often important groundwater quality criteria, are: iron, silica, boron, nitrate, lithium, aluminium, strontium and iodide.

The concentration of total dissolved solids (TDS), which is determined in a laboratory by evaporation, can be measured indirectly in the field using an electrolytic conductivity (EC) meter. TDS is approximately proportional to EC. The relationship varies depending on the composition of the water, but an approximate expression applicable for most waters is:

EC (in micromhos/cm) at 25oC x 0.64 = TDS in mg/l

EC is temperature dependent and is therefore usually recorded at the standard temperature of 25oC.

The pH of a solution is a measure of the hydrogen ion concentration and hence the acidity or alkalinity. The scale ranges from 0 to 14 with 7 as neutral, below 7 acid and above 7 alkali. The pH of groundwater is unstable and must be measured at the well head. The pH recorded in a laboratory analysis often differs significantly from the real pH of the groundwater.

Alkalinity is the capacity of a solution to neutralise acid. In

most groundwaters, alkalinity is due to the presence of bicarbonate and, to a lesser extent, carbonate. It is expressed as equivalent titratable amounts of calcium carbonate, that is:

$$HCO3(mg/l) * \frac{(CaCO3)}{(HCO3)} + CO3(mg/l) * \frac{(CaCO3)}{(CO3)} = \text{total alkalinity as mg/l CaCO3}$$

where the ratios are in equivalent weights.

Total hardness (TH) is a measure of the calcium and magnesium content of a water. It is analysed for by titration and the result is again expressed as mg/l CaCO3. The amount of magnesium in a sample can be found by subtracting the calcium concentration (as CaCO3) from the total hardness. The total hardness may be comprised of both carbonate and non-carbonate hardness. The latter occurs where the metals are associated with anions, such as chloride, sulphate and nitrate, and may be found from the expression:

TH - Alkalinity = Non-carbonate hardness.

The dissolved gases, oxygen (O2), carbon dioxide (CO2) and hydrogen sulphide (H2S), are unstable and must be measured at the well head. The O2 and CO2 are determined by titration. H2S is detectable in small concentrations by its 'rotten egg' smell and can be measured by a colorimetric method.

The redox potential, Eh, is an indication of the oxidising or reducing tendencies of a water. The potential is measured in millivolts between a metal (normally platinum) electrode and a standard reference electrode using an electronic meter. It is important to prevent the sample from coming into contact with air during measrurement. Therefore naturally flowing boreholes are most suitable for testing. The sample should be tapped from the discharge outlet from a point before aeration is possible and passed through a slightly pressurised sampling bottle containing the measuring electrodes. The normal range for redox potential in groundwater is between +500 mV and -100 mV. A positive reading is generally indicative of an oxidising system and a negative reading of a reducing system.

A standard form was prepared during the project to record chemical analyses. A completed example is shown on Figure 41.

8.3 Sampling

A good analysis is dependent on good sampling.

Before sampling, the borehole should be pumped until the temperature of the discharging water (TQ), pH and EC are constant. Potential contamination and alteration of chemical equilibrium must be minimised by taking the sample from the nearest point to the borehead (generally the end of the discharge pipe). Samples taken

Figure 41 Chemical Analysis Form

GROUNDWATER RESEARCH DEPARTMENT- NATIONAL WATER RESOURCES INSTITUTE

CHEMICAL ANALYSIS OF WATER SAMPLE

Location Rural Health Centre, Koligi Borehole nr. GWR-7/1
Sample nr. – Test section(m) 17.1 – 75 m
Date sample collected 1/3/86 field analysis 1/3/86 lab. analysis –
Field analysis by. Tunde Celusanya lab. analysis by. –

Total hardness	46	mg/l	$CaCO_3$	
Calcium hardness	31	"	"	(× 0·02 = meq/l)
Magnesium hardness	15	"	"	(× 0·02 = meq/l)

Calcium (calcium hardness × 0·40)	12·4	mg/l	× 0·04990	0·62	meq/l
Magnesium (magnesium hardness × 0·243)	3·65	"	× 0·08224	0·30	"
Sodium	–	"	× 0·04350		"
Potassium	–	"	× 0·02558		"
			Total cations		"

Phenolphthalein alkalinity	Nil	mg/l	$CaCO_3$	
Total alkalinity	35	"	"	
Carbonate alkalinity	Nil	"	"	(× 0·02 = meq/l)
Bicarbonate alkalinity	35	"	"	

Carbonate (carbonate alkalinity × 0·60)	Nil	mg/l	× 0·03333	–	meq/l
Bicarbonate (bicarbonate alkalinity × 0·61)	21·4	"	× 0·01639	0·36	"
Sulphate	5·0	"	× 0·02082	0·10	"
Chloride	45	"	× 0·02820	1·27	"
			Total anions	1·73	"

Total cations and anions		meq/l
Error (difference/total) × 100		%

Total dissolved solids	–	mg/l
Electrolytic conductivity	86	µmhos/cm. (temp. compensated)
Water temperature (sampling point)	17	°C
pH	6·25	

Silica	> 5·0	mg/l
Total iron	< 0·05	"
Nitrate nitrogen (N)	1·9	"
Nitrate (nitrate nitrogen × 4·4)	8·36	"
Fluoride	0·3	"

Notes / other analyses

GWR / HG - 09

from open tanks, municipal treatment plants and filter systems are useless for geochemical studies.

Water temperature should always be read while the thermometer is actually in the discharge water. Don't read it while out of the water, otherwise evaporation will rapidly cool the bulb.

For analyses with the Hach portable laboratory all glassware must be kept clean and washed with deionised water after use.

8.4 Hydrochemical Diagrams

The Stiff diagram is probably the best method to represent water quality data graphically since different water chemistries are easily distinguished by the shape. Figure 42 shows the areal variation in water chemistry around Riyadh, Saudi Arabia, with Stiff diagrams.

The concentrations of the eight major ions can be represented on trilinear diagrams by grouping the potassium with the sodium, and the carbonate with bicarbonate, thereby reducing the number of parameters for plotting to six. Two examples of trilinear diagrams are the Piper and Durov (Figures 43 and 44 respectively). On the Piper diagram, the relative percentates of the cations and anions are plotted in the lower triangles, and the resulting two points are extended into the central field to represent the total ion concentration (actual concentrations may be depicted by drawing circles with dameters proportional to the dissolved salts concentration). The degree of mixing between waters can also be illustrated; for example, a mixture of two waters plotted in the central field should lie on a straight line between the two parent water plots, provided that the ions have not reacted chemically as a result of mixing.

The Durov diagram, with a similar plotting procedure to the Piper, is particularly suited to illustrating chemical changes which may occur within a groundwater basin. Because all the analyses on the example shown are sodium chloride waters, percentage composition has been plotted on an expanded form of the diagram.

8.5 Hydrochemistry and Groundwater Movement

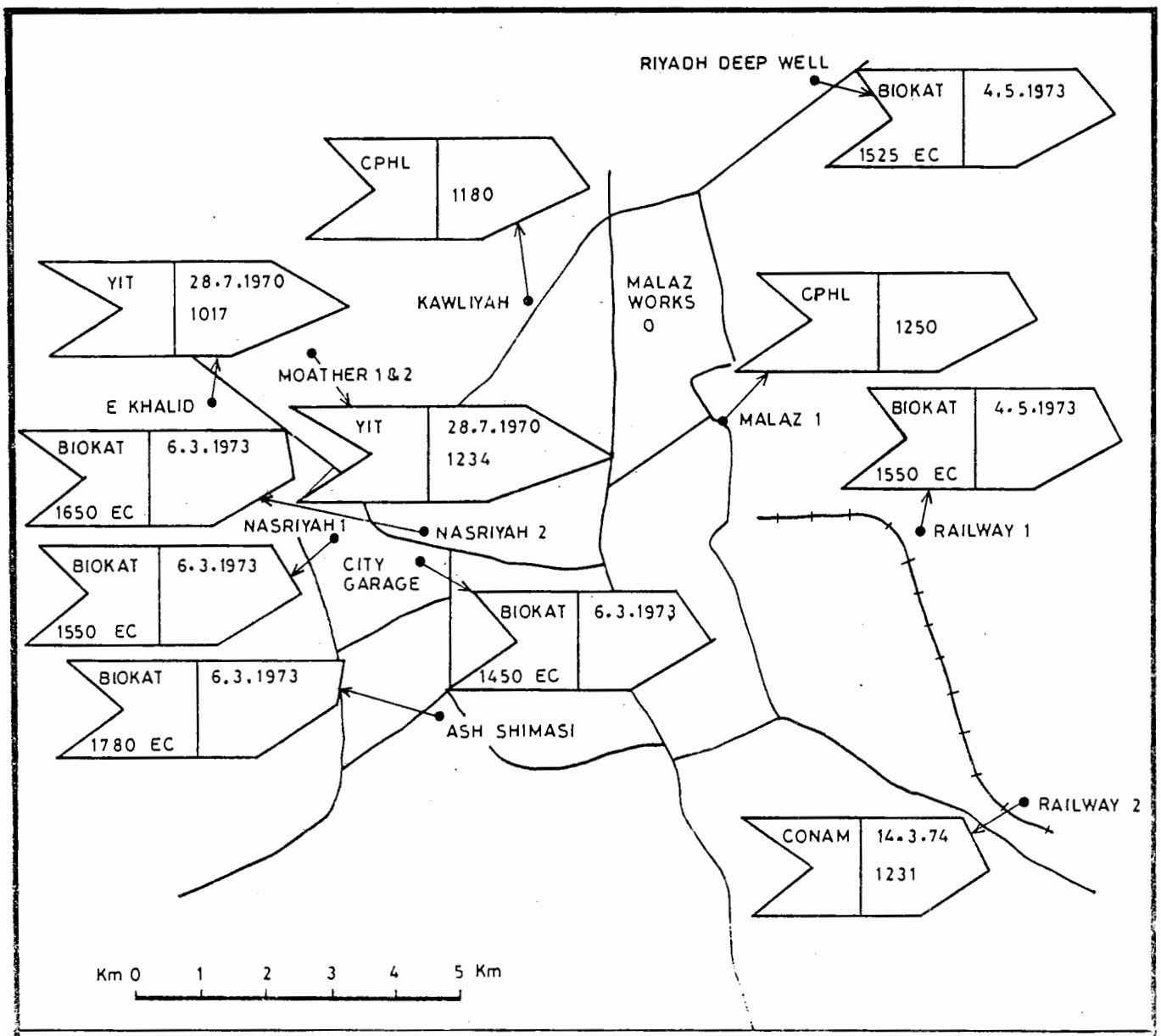
8.5.1 Processes of Chemical Change in Aquifers

For the interpretation of chemical analyses, it is necessary to understand the main chemical processes which may alter the composition of a groundwater during its flow underground. Four of the most important of these are: solution, evaporation, ion exchange and sulphate reduction.

Solution is the action whereby groundwater dissolves mineral matter while moving through an aquifer. Consequently, recharge water is

Figure 42

Use of Stiff Diagrams for Representation of Chemical Analyses



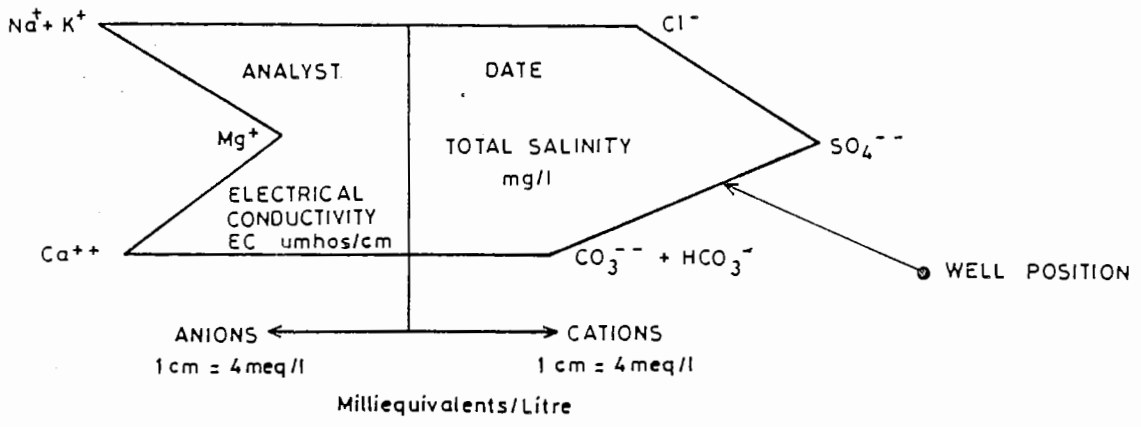


Figure 43 Piper Diagram with Plotting Examples

Percent of total milliequivalents per litre

	BH1	BH2
Ca	50	26
Mg	30	24
Na + K	20	50
Cl	6	60
SO_4	8	10
$CO_3 + HCO_3$	86	30
TDS (ppm)	450	800

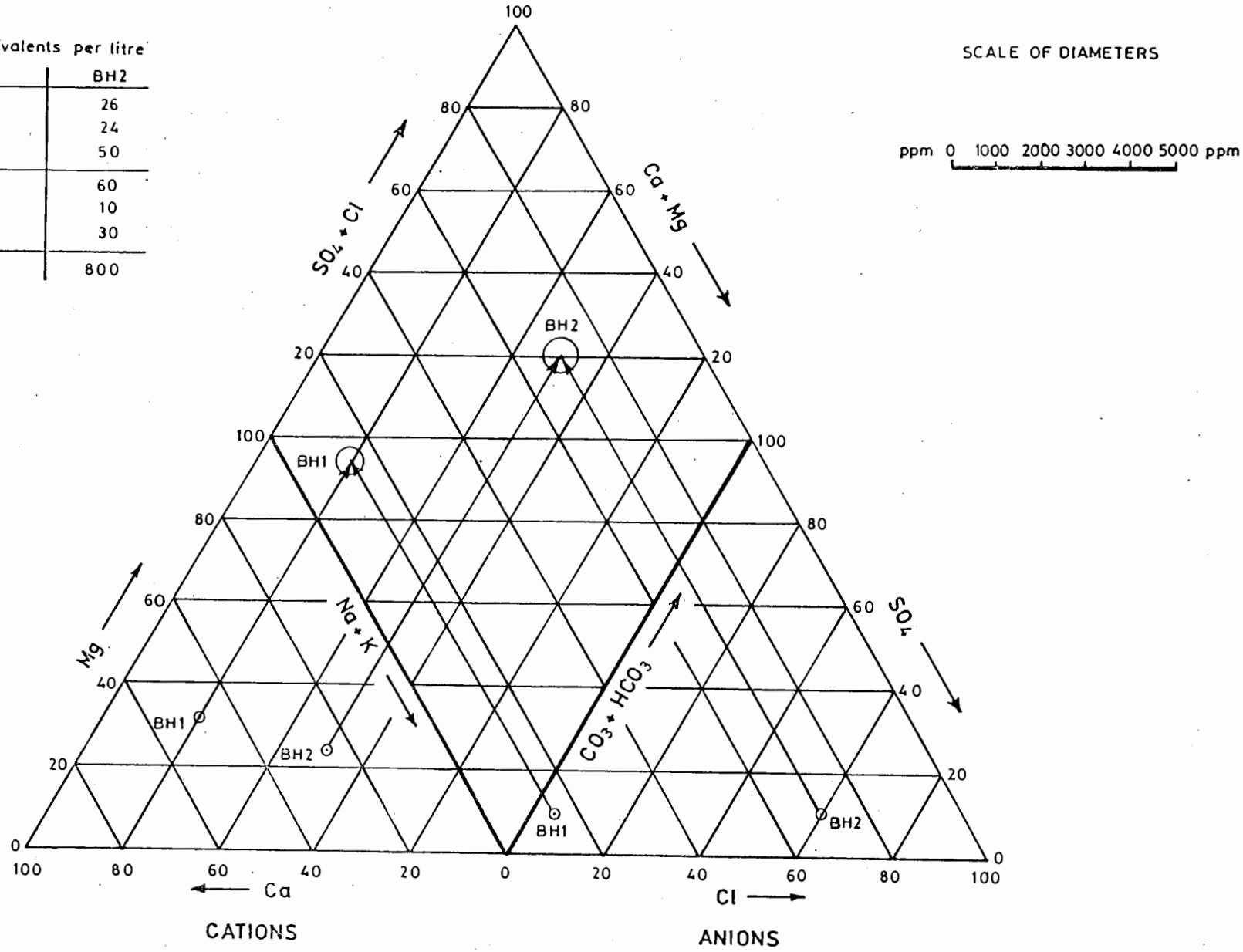
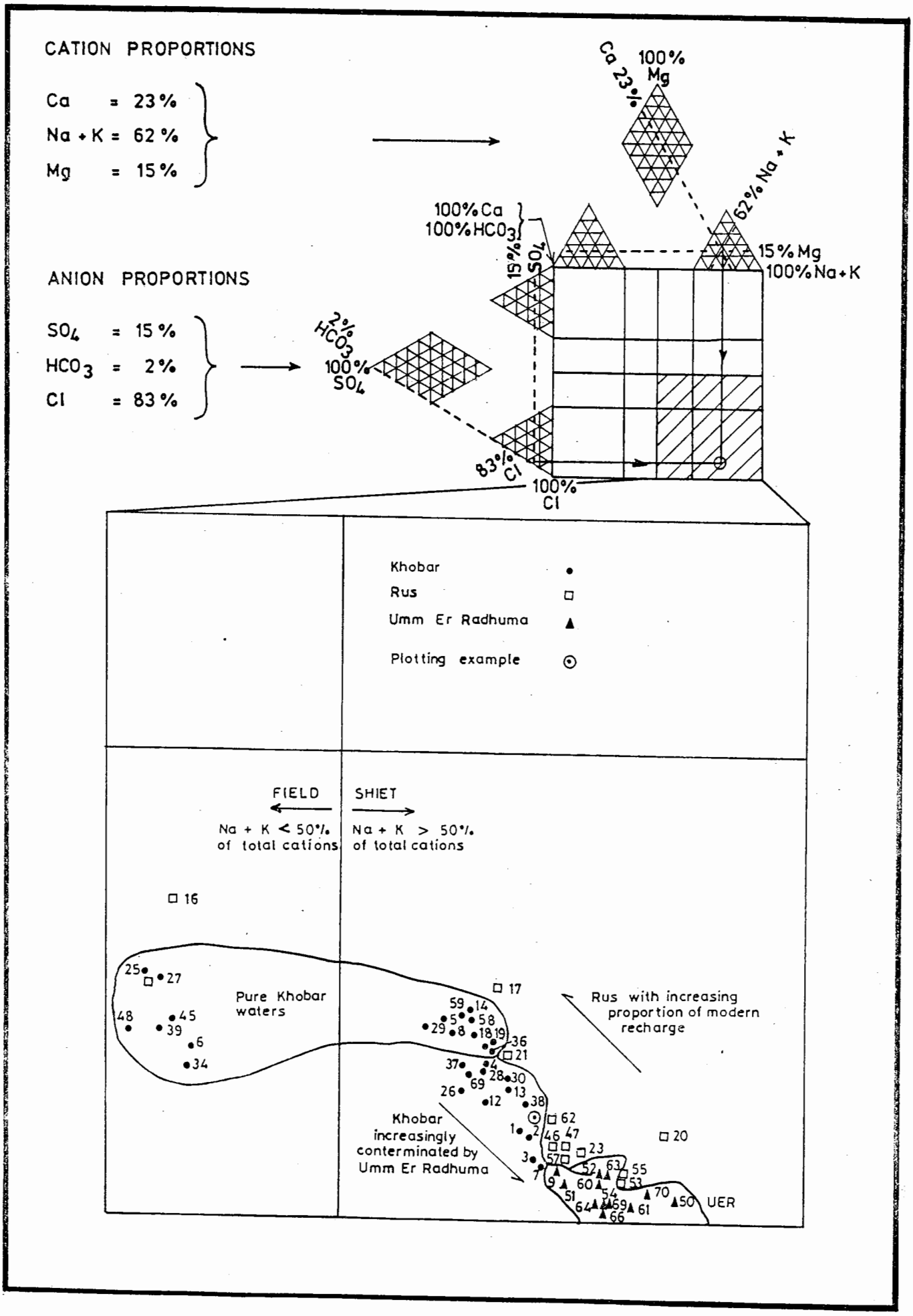


Figure 44

Expanded Durov Diagram with Plotting Example from Saudi Arabia



normally low in dissolved solids content while discharge water is relatively high. The nature and extent of solution are dependent on a number of factors, the most important of which are: the availability of carbon dioxide, the composition of the aquifer(s) and the solution chemistry of the particular minerals, the duration of contact, the temperature and pressure, the materials already in solution, the pH and the redox potential.

As an example, the solution of calcium carbonate takes place in the following (simplified) manner: groundwater containing CO2 derived from the atmosphere or soil forms a weak solution of carbonic acid which reacts with the fairly insolable CaCO3 to produce insoluble Ca(HCO3)2. Magnesium carbonate is added to water by a similar reaction. The solution of calcium (and magnesium) carbonate results in an increase in the pH, alkalinity and hardness of the groundwater. In sedimentarty rocks the most common mineral sources of calcium are calcite, aragonite, dolomite (CaMg(CO3)2), anhydrite and gypsum.

The sources of some of the other important ions in sedimentary aquifer waters are: sodium from decomposition of plagioclase feldspars and from clay minerals; sulphate from gypsum, anhydrite and pyrite minerals; chloride from halite minerals, from original sea water or from concentration by eaporation.

Evaporation, like solution, causes an increase in the dissolved salt concentration of a groundwater. It take place mainly when the water is in the soil zone.

Ion exchange is the interchange of an ion in solution with another ion on a surface-active material. Normally in groundwaters ion exchange involves the exchange of sodium ions held on clay minerals from calcium and magnesium ions in solution. The capacity for a matrix or mineral to allow exchange of cations is called the cation exchange capacity (CEC), which is expressed in terms of milliequivalents per 100g of material. Montmorillonite has by far the highest CEC value (70 to 120) of the clay minerals. Ion exchange causes the softening of the water and may result in all the calcium and magnesium being exchanged.

The reduction of sulphate in groundwater is caused by anaerobic bacteria and it results in the production of hydrogen sulphide gas. It is associated with an absence of dissoved oxygen (used up in oxidation reactions and consumed by bacteria) and a corresponding low Eh value.

The efects of chemical actions such as those discussed above lead to the following generalisations:

- young recharge water is usually dominated by calcium and magnesium bicarbonate;
- throughflow water is typically of a sodium bicarbonate type;
- and parts of groundwater basins where there is limited flow, such as in fine grained formations or near flow-barriers like

impermeable faults, are characterised by high chloride waters; this is mainly because chloride is very soluble and remains in solution through most of the processes which remove other ions, fo example precipitation, ion exchange, sulphate reduction, etc.

8.5.2 Illustration of Chemical Changes

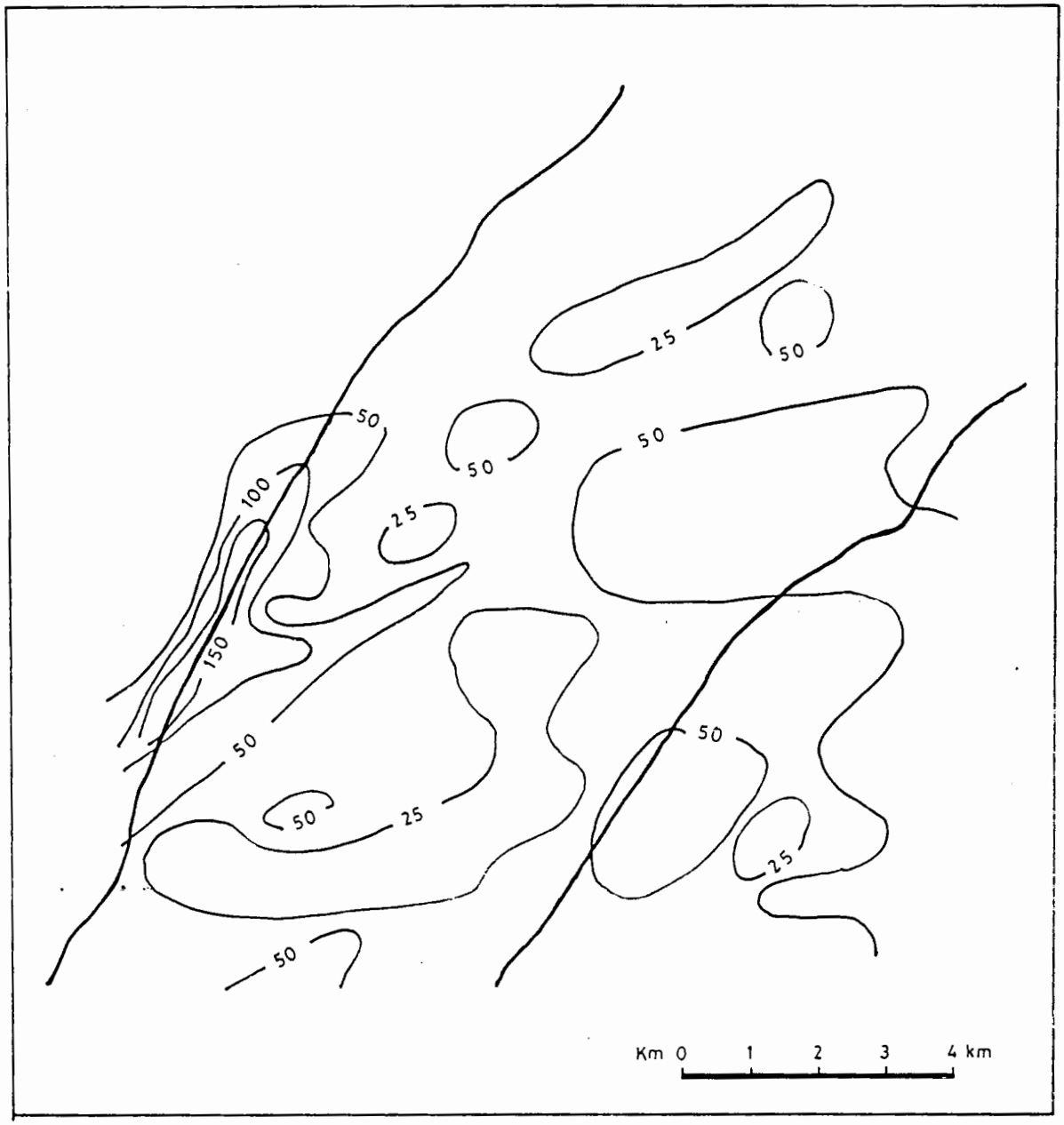
Variations in groundwater chemistry through an aquifer can be well illustrated on thematic maps, Stiff diagrams, trilinear diagrams (Piper and Durov) and graphs showing the value of a particular parameter plotted against distance from recharge area.

Maps which indicate the areal distribution of a particular parameter may help in the determination of the flow pattern, the geological structure and the distribution of the recharge and discharge areas. Often the most useful hydrochemical maps for this purpose are those for TDS (or EC) and alkalinity, both of which usually increase in the direction of flow. The occurrence of a geological structure such as an impermeable fault may be indicated on a map by the presence of relatively saline water (Figure 45).

Individual ions, or ratios of ions, may also be usefully represented on maps, for example (Mg + Ca)/Na to illustrate ion exchange. Figure 46 is an example of the plotting of the SO4/Cl and Mg/Ca ratios. Both increase in the direction of flow - the former because the aquifer is relatively rich in sulphates and poor in chlorides, the latter, which is generally the case, because water becomes saturated with CaCO3 fairly rapidly and also because CaSO4 dissolves more slowly than MgSO4.

Hydrochemical maps are also, of course, important in showing the distribution of various parameters relevant to water quality, such as areas unsuitable for irrigation from groundwater due to the presence of boron in toxic concentrations.

Figure 45 Contour Map of Chloride Ion Concentration



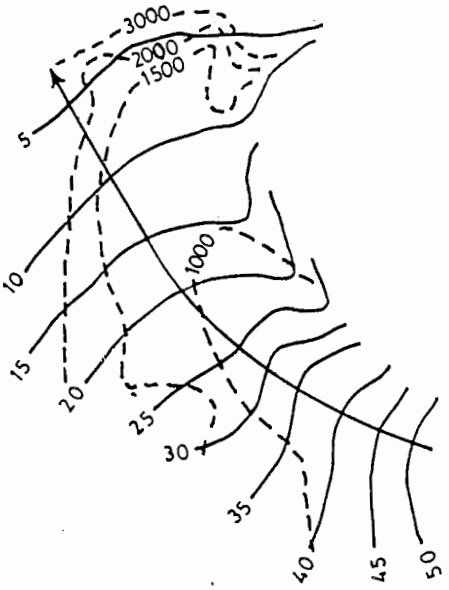
Legend

Contour, mg/l —— 50 ——

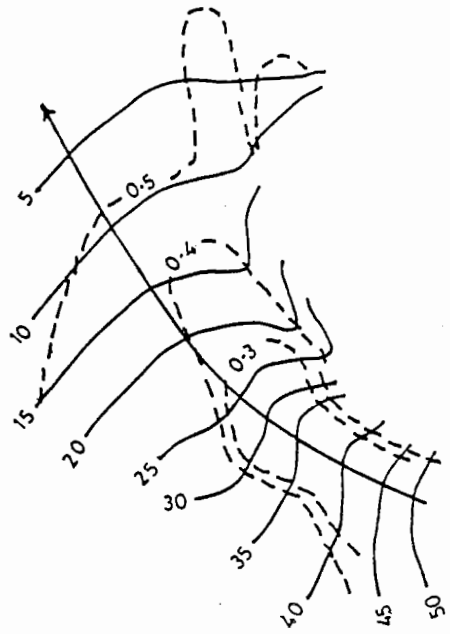
Fault ——————

Figure 46 Examples of Hydrochemical Maps

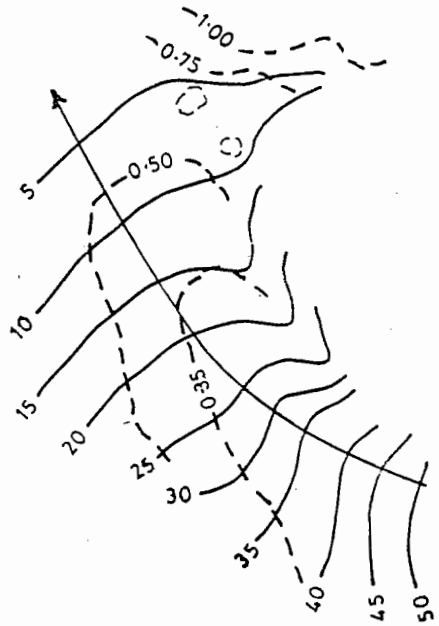
a) Contours of total dissolved solids ppm



b) Contours of ratio SO_4 : Cl



c) Contours of ratio Mg : Ca



Legend

Flow direction

Equipotential line 25

Contour line 0·40

Km 0 1 2 3 Km

8.5.3 Radioactive Isotopes

Isotopes can be used to date groundwater and to trace its movement. Dating is carried out by measuring some of the natural isotopes in water, particularly those of carbon and hydrogen.

Radioactive isotopes undergo natural decay at rates described by their half-lives, which are the times required for one half of the atoms to decay. Therefore, in simple terms, by measuring the present concentrations in a groundwater and from a knowledge of the original recharge water concentrations, the approximate age of the water can be determined. The radioactive isotope carbon-14 has a half-live of 5,730 years and can be used to date waters from 500 to 50,000 years old. The hydrogen isotope tritium (3H) has a half-life of 12 1/4 years and, because the thermomuclear tests, which began in 1952, produced far greater amounts of tritium in the atmosphere than before, this isotope is particularly suitable as an indicator of whether recharge occurred before or after this date.

Natural isotope age determinations can be used to indicate the direction of groundwater flow. Artificial tracers may also be introduced for this purpose, for example tritium or 82Br.

8.6 Irrigation Water Quality

Irrigation waters are evaluated according to their constituents which affect soil characteristics or crops. The most important characteristics are:

(a) total dissolved solids;
(b) the relative amount of sodium;
(c) the concentration of toxic elements such as boron.

Total Dissolved Solids

High salinities are detrimental to crop performance. Some relative tolerances of crops to salt concentrations are shown on Table 6. The EC values on the table, in mmhos/cm, refer to soil water. The EC of the soil solution is usually 2 to 10 times greater than that of the applied irrigation water due to the effects of concentration by evaporation. Unless adequate subsoil drainage exists and sufficient water moves through the root zone to remove the excess salt, the increase in soil water EC is cumulative. The fraction of the applied irrigation water that must, over a period of time, be removed as drainage water to maintain a given salt concentration at the bottom of the root zone is termed the Leaching Requirement, which is calculated from the relationship:

$$LR = \frac{ECiw}{ECdw} \quad 100\%$$

where ECiw is the EC of the irrigation water, and ECdw is the EC of

Table 6

Soil Salinity Tolerances of Crops
(Average salinity, within the effective rooting zones of particular crops, likely to lower potential yield by 0, 10, 25, 50 and 100 per cent)

	ECe(1)				
	0%	10%	25%	50%	100%(2)
Field Crops					
Barley(3)	8.0	10.7	14.0	18.0	27.0
Cotton	7.7	7.7	12.7	16.7	26.0
Sugar beet	7.0	8.8	11.2	15.1	23.0
Wheat(3)(4)	6.0	7.3	9.7	13.4	19.5
Sunflower	5.3	6.3	8.0	10.4	14.5
Soya beans	5.0	5.5	6.5	8.0	10.0
Sorghum	4.0	5.4	7.8	11.3	17.5
Groundnuts	3.2	3.5	4.1	4.9	6.5
Rice	3.0	4.2	5.4	7.5	11.5
Sesbania	2.3	3.7	5.9	9.4	16.5
Maize(corn)	1.7	3.3	4.5	6.3	10.0
Linseed	1.7	2.5	3.9	6.0	9.5
Broad beans	1.6	2.7	4.1	6.4	11.0
Cowpeas	1.3	2.0	3.1	4.9	8.5
Vegetable Crops					
Beetroot	4.0	5.4	7.1	9.8	15.0
Broccoli	2.8	3.9	5.5	8.2	13.5
Tomatoes	2.5	3.7	5.5	7.7	12.0
Cucumber	2.5	3.3	4.4	6.3	10.0
Musk melons	2.2	3.6	5.7	9.1	16.0
Spinach	2.0	3.3	5.3	8.6	15.0
Cabbage	1.8	2.7	4.3	7.0	15.0
Potatoes	1.7	2.5	3.8	5.9	10.0
Green peppers(chillies)	1.5	2.2	3.3	5.1	8.5
Lettuce	1.3	2.1	3.2	5.2	9.0
Radish	1.2	2.0	3.1	5.0	9.0
Onions	1.2	1.8	3.1	4.2	7.5
Carrots	1.0	1.7	2.8	4.6	8.0
Green beans	1.0	1.5	2.2	3.6	6.5
Fodder/Forage Crops					
Bermuda grass	6.9	8.5	10.8	14.7	22.5
Barley(3)	6.0	7.4	9.5	13.0	20.0
Alfalfa(lucerne)	-	3.0	5.0	8.0	-
Berseen(Egyptian clover)	1.5	2.2	3.3	5.2	10.0

Table 6 (continued)

	ECe(1)				
	0%	10%	25%	50%	100%
Fruit Crops					
Dates	4.0	6.8	10.9	17.9	32.0
Figs, olives, pomegranates	2.7	3.8	5.5	8.4	14.0
Grape fruit	1.8	2.4	3.4	4.9	8.0
Oranges, lemons, apples, pears	1.7	2.3	3.2	4.8	8.0
Walnuts	1.7	2.3	3.2	4.7	8.0
Peaches	1.7	2.2	2.9	4.1	6.5
Apricots	1.6	2.0	2.6	3.7	6.0
Grapes	1.5	2.5	4.1	6.7	12.0
Plums	1.5	2.1	2.9	4.2	7.0
Almonds	1.5	2.0	2.8	4.1	7.0

Notes: (1) ECe means electrical conductivity of the saturation extract of soil, measured in mmhos/cm at 25oC. For 10% yield reduction, ECe is the threshold salinity at which yield is expected to decline.

(2) At this salinity, crop growth stops because osmosis reduces crop water availability to nil.

(3) Barley and wheat are less salt-tolerant during the germination and early seeding stages. ECe should not exceed 4-5 mmhos/cm in the top 25cm.

(4) These figures may be wrong for the new, semi-dwarf wheat cultivars.

Sources: Maas & Hoffman (1977), Proc. Intl. Salinity Conf. Texas, Tech. Inst., Lubbock, Aug. 1976, p.187.
University of California Committee of Consultants (1974).
Shainberg, 1. and Oster, J.D. (1978), Intl. Irrig. Information Centre, Bet Degan, Isreal.

the drainage water.

Relative Amount of Sodium

The extent to which soils adsorb sodium from water is influenced by the concentration and composition of the soluble salts and is important because above certain levels the adsorbed sodium has an adverse effect upon the physical properties of the soil - namely, permeability, infiltration rate and tilth.

Criteria which are used to define the sodium hazard of irrigation waters include: the sodium adsorption ratio (SAR), a modified version termed the adjusted SAR, and the residual sodium carbonate (RSC).

The SAR is defined and calculated from the equation:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

where the ion concentrations are expressed in meq/l. If an irrigation water has a high SAR - high sodium relative to calcium and magnesium - the sodium may be adsorbed on to the soil replacing calcium and magnesium already there. This reaction can be reversed by adding gypsum.

Recently, the SAR criterion has been modified to include the effects of the carbonate and bicarbonate content of the water on the adsorption process. The new term is called the adjusted SAR and is defined by the expression:

$$adj.\ SAR = SAR(1 + (8.4 - pHc))$$

where pHc is the theoretical pH of a water in equilibrium with CaCO3 (according to Langelier). A pHc value greater than 8.4 indicates a tendency for the water to dissolve CaCO3 from the soil, while a value less than 8.4 indicates a tendency for the water to precipate CaCO3. The procedure for calculating the pHc and the adj. SAR is given on Table 7. The adj. SAR is generally greater than the SAR.

The presence of free sodium carbonate or bicarbonate, or 'residual sodium carbonate' (RSC) as it has been termed, in irrigation water is considered to have harmful effects on soil properties. It is calculated by subtracting the calcium and magnesium concentrations from the bicarbonate and carbonate concentrations, all expressed in meq/l. The RSC concept is not as widely used now as before.

Toxic Ions

Three of the most common ions in natural waters which can be toxic to certain crops are boron, lithium and chloride.

Table 7

Tables for Calculation of pHc Values in Water

Concentration Ca + Mg + Na (meq/l)	pK'2-pK'c	Concentration Ca + Mg (meq/l)	p(Ca + Mg)	Concentration CO3 + HCO3 (meq/l)	p(Alk)
0.5	2.11	0.05	4.60	0.05	4.30
0.7	2.12	0.10	4.30	0.10	4.00
0.9	2.13	0.15	4.12	0.15	3.82
1.2	2.14	0.20	4.00	0.20	3.70
1.6	2.15	0.25	3.90	0.25	3.60
1.9	2.16	0.32	3.80	0.31	3.51
2.4	2.17	0.39	3.70	0.40	3.40
2.8	2.18	0.50	3.60	0.50	3.30
3.3	2.19	0.63	3.50	0.63	3.20
3.9	2.20	0.79	3.40	0.79	3.10
4.5	2.21	1.00	3.30	0.99	3.00
5.1	2.22	1.25	3.20	1.25	2.90
5.8	2.23	1.58	3.10	1.57	2.80
6.6	2.24	1.98	3.00	1.98	2.70
7.4	2.25	2.49	2.90	2.49	2.60
8.3	2.26	3.14	2.80	3.13	2.50
9.2	2.27	3.90	2.70	4.00	2.40
11.0	2.28	4.97	2.60	5.00	2.30
13.0	2.30	6.30	2.50	6.30	2.20
15.0	2.32	7.90	2.40	7.90	2.10
18.0	2.34	10.00	2.30	9.90	2.00
22.0	2.36	12.50	2.20	12.50	1.90
25.0	2.38	15.80	2.10	15.70	1.80
29.0	2.40	19.80	2.00	19.80	1.70
34.0	2.42	-	-	-	-
39.0	2.44	-	-	-	-
51.0	2.48	-	-	-	-
59.0	2.50	-	-	-	-
67.0	2.52	-	-	-	-
76.0	2.54	-	-	-	-

Notes:
(1) pK'2 - pK'c obtained from Ca+Mg+Na concentration(A)
(2) p(Ca+Mg) obtained from Ca+Mg concentrations (B)
(3) p(Alk) obtained from CO3 + HCO3 concentration (C)
(4) Then pHc = (pK'2 - pK'c) + p(Ca+Mg) + p(Alk)
(5) Values of pHc below 8.4 indicate solution of CaCO3 by the water; values above 8.4 indicate solution of CaCO3 by the water.

Boron, which occurs in most natural waters, is essential for plant growth but the quantity required is very small. It is very toxic to certain plant species, particularly citrus. Table 8 shows a classification of irrigation waters according to their boron content for various crops.

Lithium is particularly toxic to citrus; when present in groundwater it is usually derived from micaceous minerals.

Chloride is harmful to some crops if its concentation in the applied irrigation water exceeds about 5 meq/l (180 mg/l), but other crops have much higher tolerances.

Irrigation Water Standards

A multitude of different irrigation quality standards have been proposed over the years. One of the most commonly used is that of the US Salinity Laboratory which classifies waters in terms of their SAR and EC (Figure 47).

It is important when applying this or any other water quality standard to take into account other factors such as soil properties and climate. For example, a high SAR in an irrigation water will obviously be more detrimental to a poorly drained soil containing montmorillonite clay (with its high cation exchange capacity) than to, say, a well drained sandy loam - (in the latter case, the SAR of the water may almost be irrelevant).

Again, high EC and SAR values will be more harmful to soils in arid areas rather than in high rainfall areas because there will be less chance of the leaching requirement being met.

8.7. Drinking Water Quality

Some examples of potable water standards issued by the World Health Organisation (1971) and the EEC (1980) are given in Table 9.

Analyses carried out on the project to date (Table 10) indicate that the ions determined do not exceed the WHO highest desirable levels, and that the water is chemically suitable for drinking purposes. However, in the absence of bacteriological data, it must be assumed that shallow groundwater is likely to be contaminated with pathogenic organisms in urban areas, and such water must always be boiled thoroughly before drinking.

8.8 Corrosion and Incrustation

8.8.1 Processes

Corrosion is the eating away of a metal by reactions which are electrochemical in nature. An electrochemical action is a chemical change resulting from the flow of electric current between metallic

Table 8

Tolerances of Crops to Boron

Tolerant (2-4 ppm)	Semi-tolerant (1-2 ppm)	Sensitive (0.3-1 ppm)
Broad bean	Potatoes	Deciduous fruit
Onion	Cotton	Citrus
Cabbage	Tomatoes	Navy beans
Lettuce	Wheat	
Turnip	Maize	
Carrot	Chillies	
Lucerne	Peas	
	Pumpkins	
	Sweet potatoes	
	Sunflower	
	Lima bean	

Source: Wilcox, L.V. (1960), Boron injury to plants, US Dept. Agric., Bull. No. 211.

Figure 47 Irrigation Water Classification

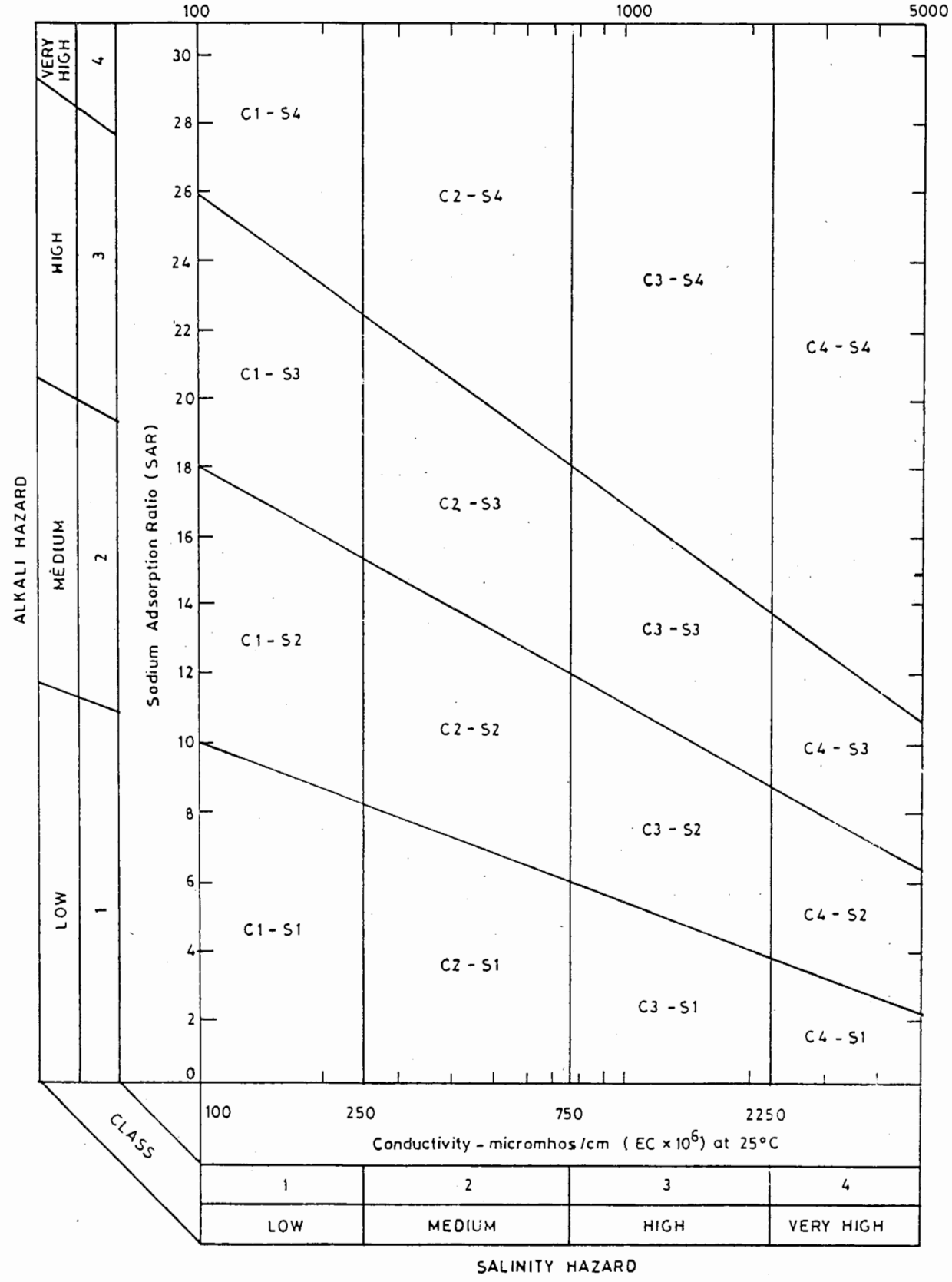


Table 9

Drinking Water Standards
(Some Examples of Recommended Concentrations)

Characteristic	Highest desirable level WHO	Guide level EEC	Maximum permissible level WHO	Maximum admissable concentrat. EEC
Total solids	500	1	1500	1500
Colour(oH)	5	1	50	20
Turbidity	5	1	25	10
Chloride	200	25	600	-
Iron	0.1	0.05	1	0.20
Manganese	0.05	0.02	0.5	0.05
Copper	0.05	0.1	1.5	-
Zinc	5	0.1	15	-
Calcium	75	100	200	
Magnesium	30	30	150	50
Sulphate	300	25	400	250
Total hardness (as CaCO3)	100	60	500	-
Nitrate (as NO3)	45	25	-	50
Phenols	0.001	-	0.002	0.0005
Synthetic detergents (ABS)	0.2	-	1.0	-
Carbon chloroform extract	0.2	0.1	0.5	-
pH (units)	7-8	6.5- 8.5	min 6.5 max 9.2	-
EC(u.S/cm) at 20oC		400		

Note: Concentratins in mg/l except where noted

Toxic substances	Tentative maximum concentration (mg/l)	
	WHO	EEC
Arsenic	0.05	0.05
Cadium	0.01	0.05
Chromium (6+)	0.05	0.05
Cyanide	0.05	0.05
Lead	0.10	0.05
Mercury	0.001	0.001
Selenium	0.01	0.01

Sources: WHO, International Standards for Drinking-Water, 1971.
EEC, Council Directive of 15 July 1980 relating to the quality of water intended for human consumption.

TABLE 10

GROUNDWATER RESEARCH DEPARTMENT - RESULTS OF CHEMICAL ANALYSES

Borehole[1] nr.	Longitude	Latitude	Sampling date	Ca^{++}	Mg^{++}	SO_4	Cl^-	EC[2] (u.S/cm)	T_0[3] (^{0}C)	pH	SiO_2	Fe[4]	NO_3^-	F^-
				(Milligrams / litre							(milligrams / litre)			
GWR-0/1	07° 25' 18"	10° 34' 55"	21/5/85	23	8.0	-	29	280	-	7.2	-	-	-	-
" -0/2	" " "	" " "	3/6/85	13	2.2	9.0	28	200	19	9.5**	-	0.05	11	-
" -1/1	07° 16' 21"	10° 38' 27"	19/2/85	-	-	5.0	-	410	-	-	-	0.16*	-	-
" -1/2	" " "	" " "	1/3/85	24	2.2	-	92	140	-	-	-	0.55*	-	-
" "	" " "	" " "	8/4/86	9.6	18?	-	75	190	-	-	-	-	-	-
" -1/5	07° 20' 50"	10° 39' 17"	23/4/86	-	-	-	-	350	-	-	-	-	-	-
" -2/1	08° 00' 16"	09° 26' 46"	3/7/85	2.0	5.8	41	4.0	90	20	6.3**	32	0.35*	18	<0.1
FDWR-8/12	" " "	" " "	12/6/85	7.6	4.9	2.0	21	290	17	6.5	18	0.30*	26	5
GWR-3/1	07° 34'	08° 34'	22/7/85	62	5.8	15	25	400	19	6.9	32	0.15*	17	1.2
" -3/2	" "	" "	2/8/85	32	11	4.0	15	350	18	7.4	28	0.05	7.9	0.2
" -4/1	07° 10' 21"	09° 10' 22"	19/8/85	6.0	7.0	3.0	68	140	19	6.3**	16	0.30*	24	1.1
" -4/2	07° 10' 35"	09° 10' 49"	11/9/85	10	3.9	2.0	56	150	16	6.1**	160	<0.05	24	0.6
" -5/1	06° 28'	09° 41'	14/11/85	26	16	12	95	420	14.5	6.8	-	-	-	-
" -6/1	06° 36' 13"	09° 00' 47"	15/12/85	24	8.7	1.0	0.5	250	15	7.7	75	0.02	7.9	0.4
" -7/1	05° 37'	09° 12'	1/3/86	12	3.7	5.0	45	85	17	6.3**	>50	<0.05	8.4	0.3
" -8/1	07° 25' 15"	10° 28' 02"	27/3/86	12	1.7	3.0	8.0	100	28	7.3	45	0.05	10	0.04

Notes: (1) All boreholes are located on the Basement Complex except GWR-7/1

(2) Temperature compensated

(3) Water temperature at discharge point

(4) Total Iron

* exceeds WHO highest desirable level but below maximum permissible level

** exceeds WHO permissible range.

areas of differing potential. Corrosion occurs at the anode. Hydrogen atoms are deposited at the cathode causing polarisation and the slowing down of further corrosion if they are not removed. The conducting fluid, in our case water, is termed the electrolyte.

The anodic-cathodic couples which form corroding cells (galvanic cells) can result from many different causes; for example, the coupling of dissimilar metals, local impurities in the composition of the metal, differing degrees of surface protection, exposure of different parts to different conditions (such as aeration or salt concentration), and differences in the treatment of discrete areas of metal, such as cold working, welding and screw cutting.

A schematic representation of the corrosion processes under reducing and oxidising conditions is given in Figure 48.

Figure 49 shows the electric potential log of a completed tubewell (in Pakistan), illustrating the relative potential differences which may exist between the various sections of a well cased in mild steel. The most important potential difference in this case is that between sections of slotted and blank casing, because, since they are made of identical materials, the corrosion is obviously concentrated at the slots. This increases the normal structural weakness problem induced by metal loss.

8.8.2 Corroding Agents

These are those substances or characteristics present in the electrolyte which participate in, or encourage, the chemical reactions of corrosion. Some of the more important corroding agents are: water velocity, pH, CO2, O2, Eh, H2S, TDS, Cl and temperature.

High water velocities can increase corrosion primarily because they can cause the removal of the protective polarising film.

The lower the pH of the groundwater, generally speaking, the higher the corrosive potential.

Carbon dioxide in solution forms carbonic acid with a resultant lowering of the pH. The solublity of CO2 is dependent on pressure and temperature.

A low Eh in a water may be indicative of potential corrosion - a low Eh water is capable of carrying in solution relatively large quantities of ferrous ions (reduced) and is also capable of reacting with the reducing ferric ions (oxidised form) which form part of ferric oxide protective films on steel. Conversely, a high Eh water is capable of oxidising ferrous ions to the ferric form, tending to reduce corrosion by reinforcing the protective film.

Low Eh values generally result from bacterial processes which consume dissolved oxygen, yielding both a reducing environment and a supply of carbon dioxide with a resultant low pH. Figure 50 shows

Figure 48

Schematic Representation of Two Simple Corrosion Cells

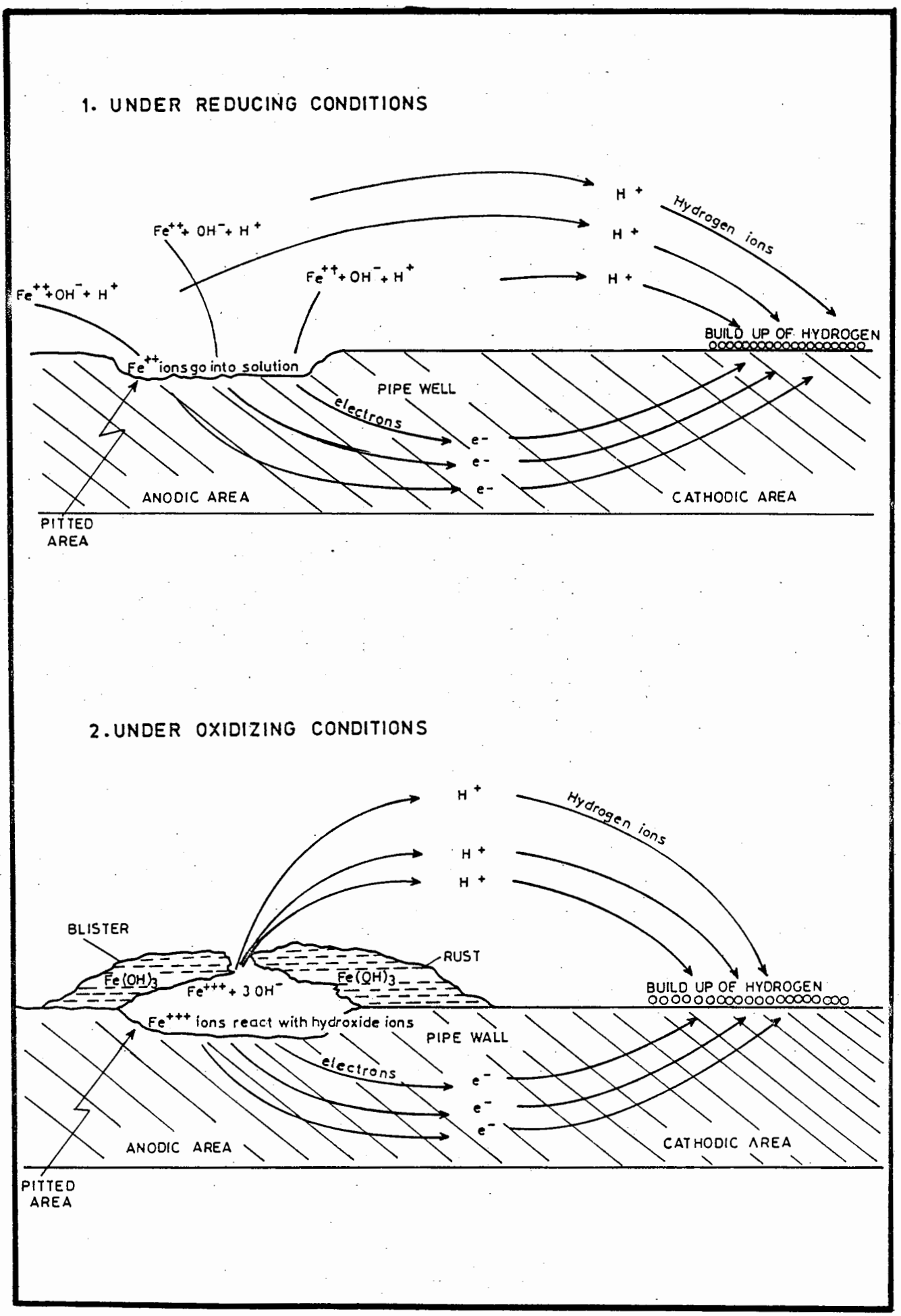


Figure 49 Potential Log of a Cased Tubewell

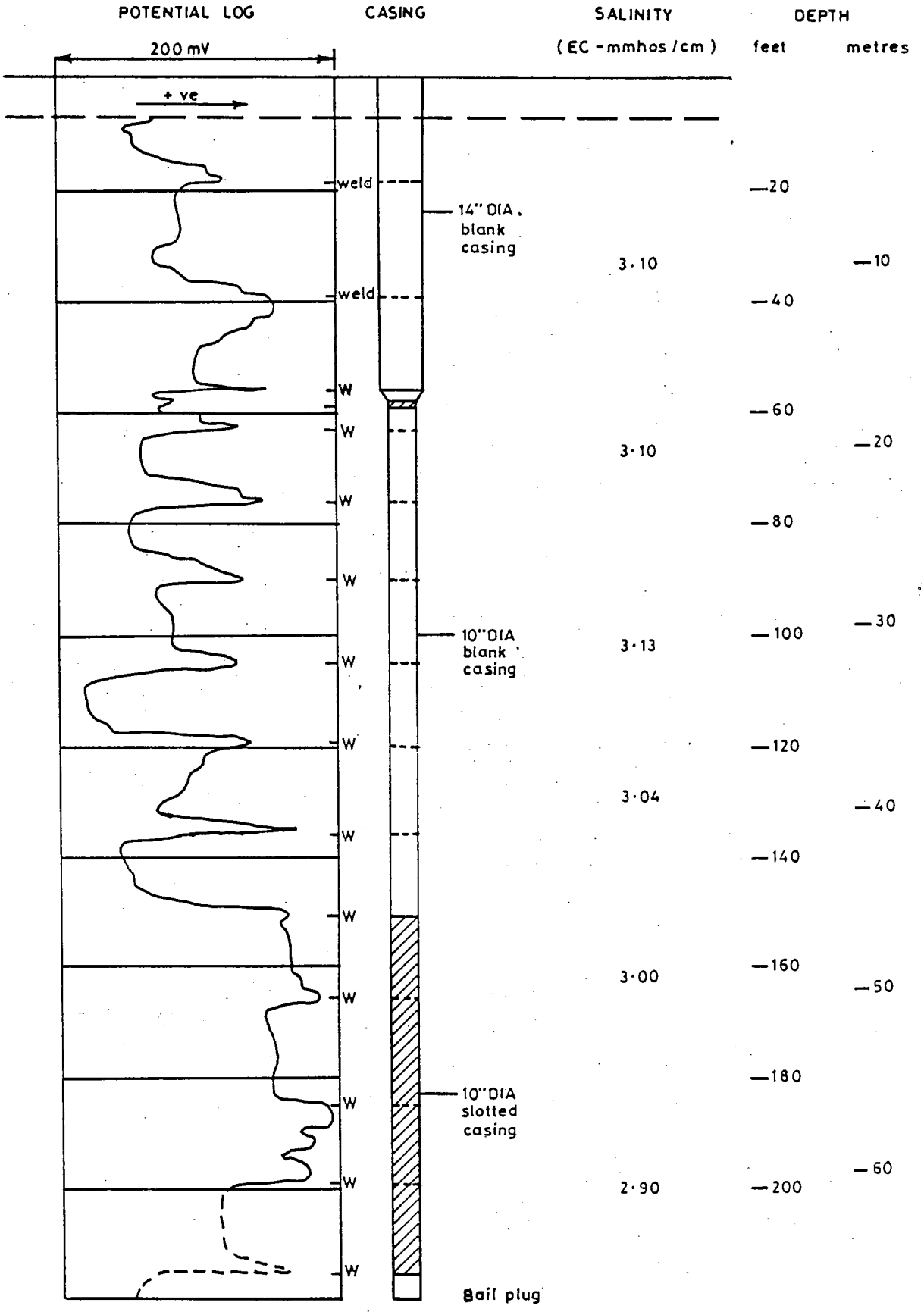
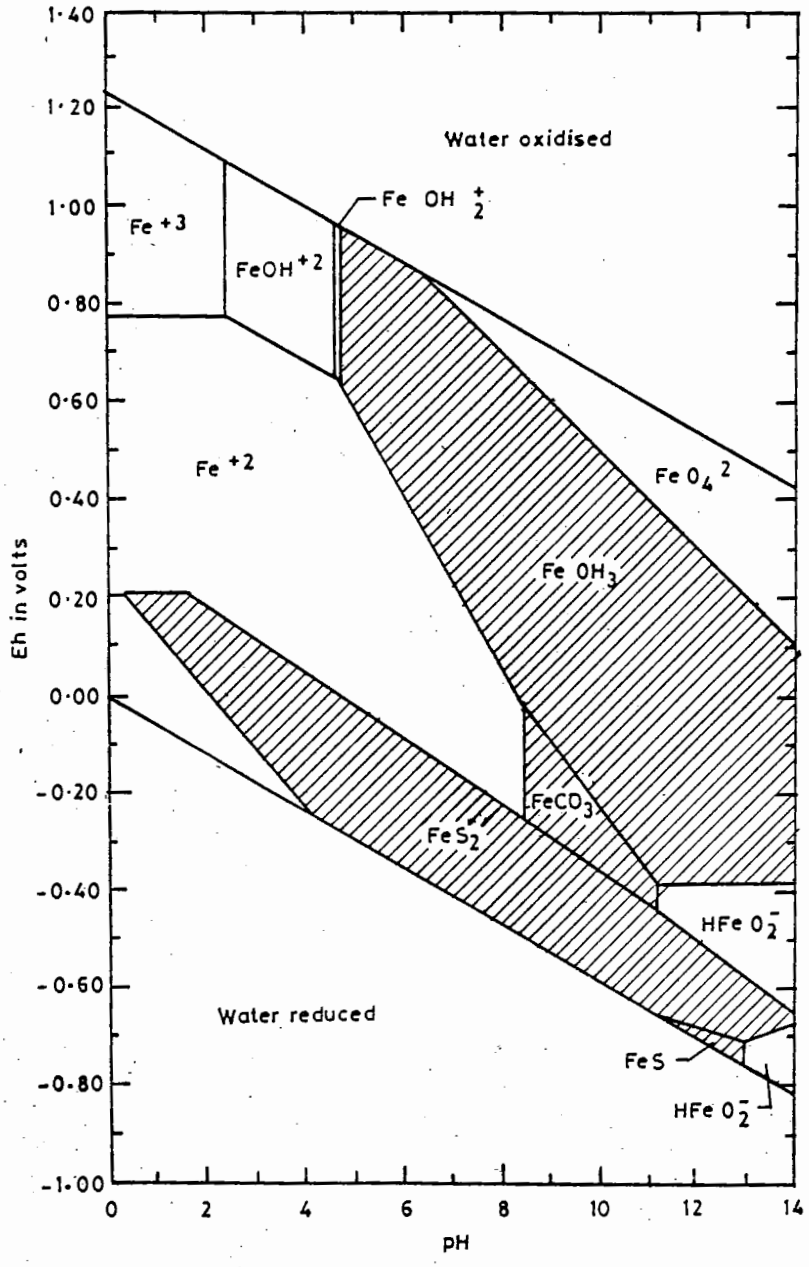


Figure 50

Stability Fields for Compounds of Iron as a Function of Eh and pH



Insoluble forms

Soluble forms

Notes

Ambient conditions :

1. 25°C at 1 atmosphere pressure
2. Sulphur activity 96 mg/l as SO_4
3. Carbon dioxide activity 1000 mg/l as HCO_3
4. Dissolved iron 0 0056 mg/l

the relative corrosiveness of waters in terms of solubility of iron as their Eh and pH values vary.

Hydrogen sulphide (H2S) produced by the reduction of sulphate by bacteria under low Eh conditions is extremely corrosive in small concentrations (for example, 0.1 mg/l). Irrigated land is an excellent breeding place for bacteria, which can be introduced into wells during drilling, or they may permanently infect the aquifers (the latter is probably more common).

The total salt concentration and composition of the groundwater also materially affect corrosion rates. In general, the higher the concentration the more corrosive will be the environment. Certain salts, such as any form of chloride, are more important than others because of their capability to dissociate into ions which increase the efficiency of the groundwater as an electrolyte. It is normally considered that waters with a chloride content in excess of 500 mg/l are harmful to mild steel.

Temperature is important as a corroding agent, since most chemical reactions proceed more rapidly at higher temperatures.

8.8.3 Incrustation

This is the precipitation of chemicals, or the deposition of formation materials (salt, sand), slime, etc., on surfaces such as screen slots and pumps.

The major incrusting chemicals in groundwaters are: carbonates (and, to a lesser extent, sulphates) of calcium and magnesium; and iron compounds, usually oxides, hydroxides or sulphides.

The precipitation of carbonate is associated with a decrease in the dissolved carbon dioxide content of the water, which may be caused by velocity-pressure changes due to the effects of pumping. Incrustation normally starts at the screen slots where velocity is highest. It is often associated with corrosion (for example, the corrosion products of iron are common incrustants in mild steel wells). The degree of supersaturation of a groundwater with respect to CaCO3 can be determined using the pHc criterion of Langelier mentioned in Section 8.6. If the measured pH of water exceeds the calculated pHc value, this indicates oversaturation and a tendency to crystallise CaCO3 out of solution.

The tendency for a groundwater to precipitate iron can be estimated by considering its main solubility controls - pH, Eh, dissovled carbon dioxide and type of sulphur species. Figure 50 shows fields of stability for solid (shaded) and dissolved forms of iron as a function of pH and Eh for fixed concentrations of iron, sulphur and carbon dioxide. Groundwaters within the normal pH range of 5 to 9 can maintain a lot of iron in solution by having an Eh between +200 mV and -100 mV. However, if dissolved oxygen is introduced into the system, such as might occur during pumping, the resultant increase

in Eh will cause a precipitation of iron as ferric hydroxide.

Sulphate is not a common incrustant in boreholes as it is not normally found in large concentrations in groundwater. Sulphate incrustation is usually only considered to be a potential problem if the calculated concentration of calcium sulphate in the water is in excess of 25 meq/l.

8.8.4 Materials

It is important, where possible, to use resistant materials for all boreholes where there is a potential corrosion and incrustation problem. Of the resistant metals, stainless steels are probably the best compromise between cost and corrosion resistance. However, fibreglass and good PVC are as resistant as stainless steel, cheaper, sufficiently strong and almost as efficient hydraulically. Inferior materials include mild steel, cheap PVC and coated or galvanised materials.

8.8.5 Well Cleaning and Sterilisation

Cleaning normally involves the circulation of an acid or other agent to dissolve the incrustants. It is important to apply the process before all slot openings are blocked, otherwise the process will be ineffectual. The acid most often used is hydrochloric acid, which is best agitated with a bailer or surge block - however, it is very damaging to galvanised steel. The detonation of primacord opposite screen sections before acidising can improve the efficiency of the treatment by loosening the incrustants.

Sterilisation of wells to inhibit bacterial action and to prevent sulphide attack is usually carried out with reagents such as bleaching powder or copper sulphate. Obviously treatment will only be effective if the bacteria were introduced during drilling and are not normally present in the groundwater.

CHAPTER 9

ASSESSMENT OF NATURAL AQUIFER RECHARGE

9.1. Definitions

Recharge can be defined as the amount of water reaching a groundwater system from all sources. It is a concept properly applied to whole and hydrologically discrete groundwater basins rather than single aquifers. Recharge of a particular basin is a quantity which normally varies from month to month and year to year. Moreover, it can be artificially altered, either positively - by increasing abstactions or by installing artificial recharge systems such as infiltration basins and check dams -, or negatively - by lining surface water channels and diverting surface water to other basins.

In groundwater resource studies, attempts are normally made to quantify "the average annual recharge under existing hydrological conditions", which is a key parameter in estimating safe yield (defined as the amount of groundwater that can be withdrawn annually from a basin without producing any major undesirable effects such as long term regional water level declines).

Of all the elements in the water balance of an aquifer system, recharge is the most difficult to quantify because, in spite of recent advances in techniques for direct assessement, it is still usually necessary to rely on indirect methods based on hydrogeological, hydrological and meteorological data.

Both direct and indirect methods of recharge assessment are discussed in this chapter. Unfortunately, both suffer from the problem - common throughout hydrogeology - of extrapolating measurements made on small samples to large, non-uniform areas.

9.2 Identification of Recharge Areas

Figure 51 shows unconfined groundwater flow in a basin in a humid area. It is clear from this flow net that water moves through the aquifer from the interfluve highlands to the river valley, from recharge areas to the discharge area. An can be seen, under recharge areas, the groundwater flow must have a downward component and beneath discharge areas there must be an upward flow component. This fact gives one way of identifying recharge and discharge areas of a basin. A recharge area has net saturated flow directed away from the watertable; that is, there is a downward pressure gradient (pressure decreases with depth). In discharge areas there is normally an upward pressure gradient.

The example shown is one of a gaining (or effluent) river - however, some rivers, or at least portions of some rivers, are losing or influent, that is, their water levels are above those of the

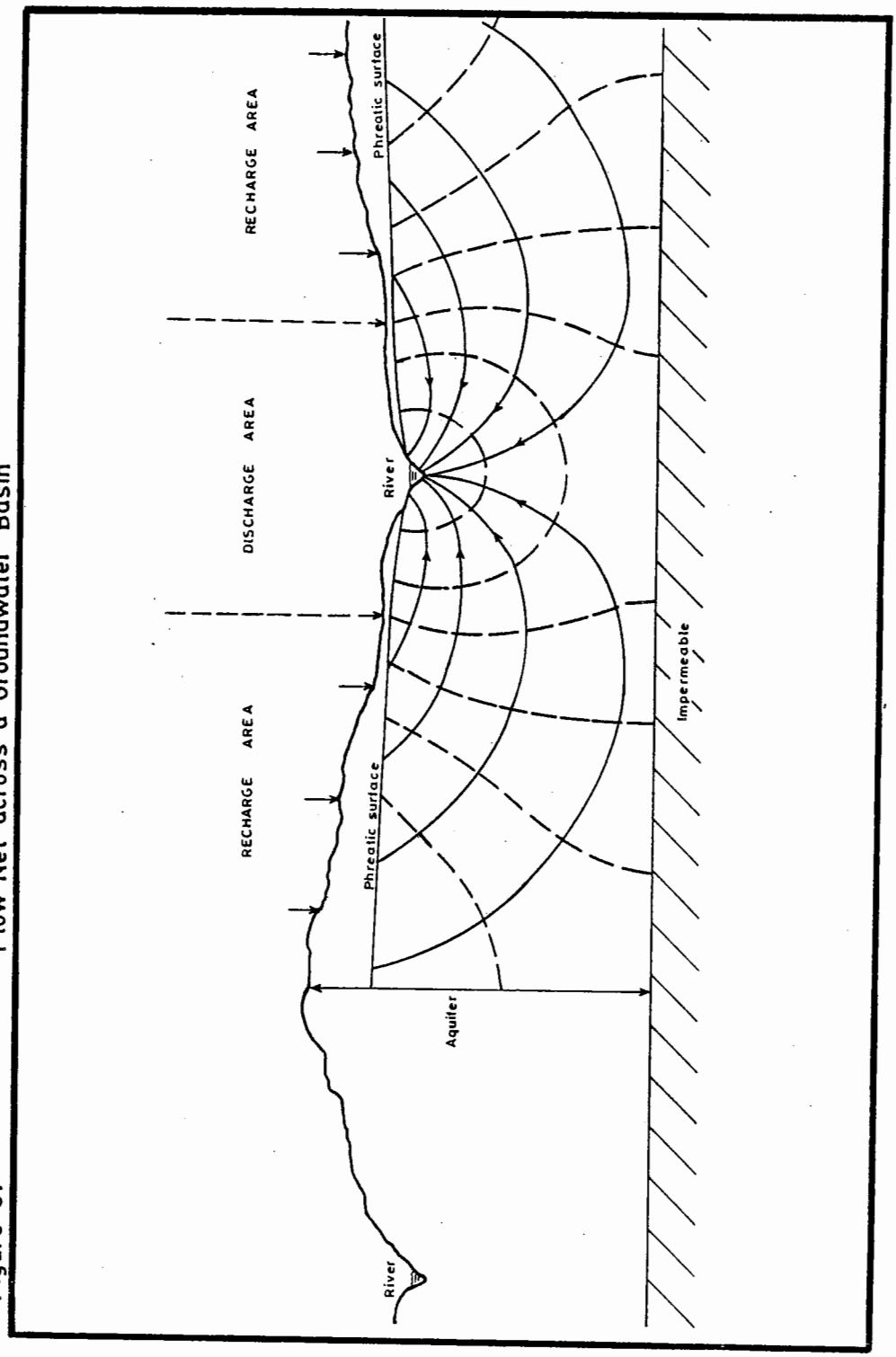


Figure 51 Flow Net across a Groundwater Basin

adjacent groundwater bodies and there is a net loss of water from the river to the groundwater system. The flow net of such a situation would be practically indentical to that shown except that the flow direction would be reversed.

If rainfall and/or river flow is strongly seasonal, the direction of groundwater flow in a river basin may be temporarily reversed, perticularly if there are significant groundwater abstrations in the interfluves.

Nevertheless, in all these cases the definitions given above hold true; that is, in recharge areas pressure (or head) decreases with depth and in discharge ares it increases with depth; this is the evidence that is most easily observed in the field.

Additional evidence for the presence of recent recharge in an aquifer (and thus proximity of a recharge area) can be obtained from the chemical and isotopic composition of the groundwater. Groundwater moving through an aquifer from recharge to discharge areas, particularly under confined conditions, shows fairly consistent chemical changes, which are illustrated in Figure 52. Thus, calcium bicarbonate water with detectable dissolved oxygen usually indicates local recharge.

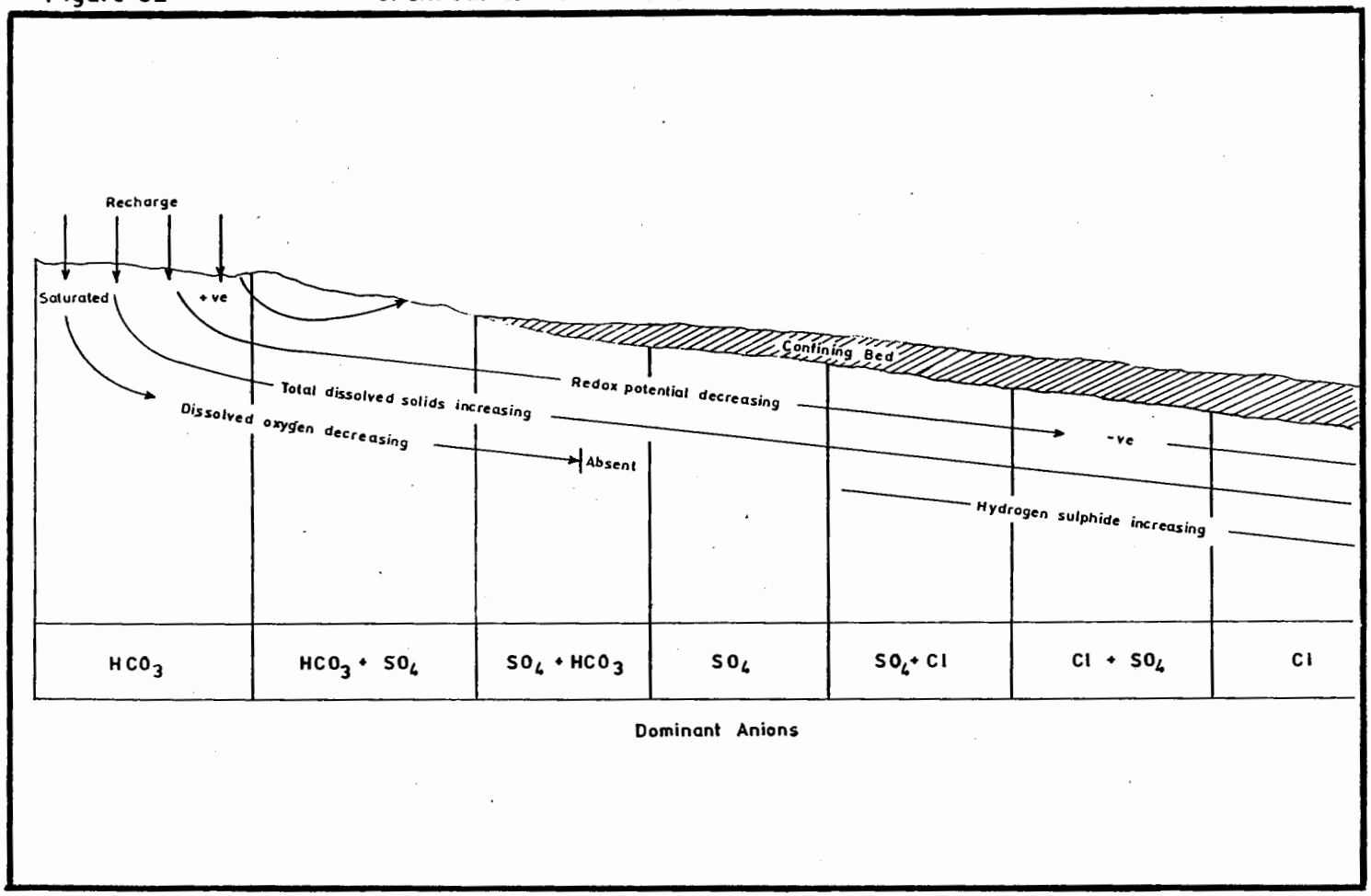
The presence of the radioactive isotope tritium (H3) indicates at least a component of recharge within the last thirty years, whereas the proportions of the stable isotopes deuterium (H2) and oxygen-18 in the water can identify the climatic conditions at the time of recharge and, by inference, its age, provided that the climatic history of the region is known.

Other ways of identifying recharge areas can be purely geological, such as the outcrops of confined, dipping aquifer beds, or hydrological such as rivers whose channels cut into aquifer layers.

9.3 The Hydrological Cycle

Groundwater constitutes a part of the earth's water circulatory system known as the hydrological cycle. The main input to this cycle is precipitation, and it can be taken that the original source of all natural aquifer recharge is meteoric water. Precipitation reaching the earth's surface may undergo a wide variety of fates. Evaporation may occur from the ground surface, from soil-held water, from the capillary fringe of the groundwater body or from leaves and steams of plants. Vegetation can take up and subsequently transpire water from any depth below ground level, down to the limit of its root system. Water which does not evaporate may reach stream channels, either by surface (sheet) flow, or interflow through the vadose zone, or may, by the same processes, reach static surface water bodies such as lakes and ponds. Alternatively, it may infiltrate into the vadose (unsaturated) zone, where it can be retained as soil moisture or percolate more deeply and become groundwater recharge. Finally, through human intervention, water

Figure 52 Chemical Evolution of Groundwater



destined to leave the catchment as surface run-off may be diverted elsewhere for irrigation and thus begin the process again.

Some of the permutations of this complex system are illustrated in Figure 53.

The complete hydrological cycle for a groundwater basin can be expressed by the equation of hydrological equilibrium as follows:

$$Qsi + Qgi + P + Qim +/- \Delta Ss + \Delta Sg = Qso + Q\,go + E + T + Qex \qquad (1)$$

where Qsi = surface inflow
Qso = surface outflow
Qgi = subsurface inflow
Qgo = subsurface outflow
Qim = imported water
Qex = exported water
P = precipitation
E = evaporation
T = transpiration
ΔSs = change in surface water storage
ΔSg = change in groundwater storage

Equation (1) can often be greatly simplified by eliminating certain items as negligible; such simplified forms are the most common means of estimating groundwater recharge.

9.4 Direct Methods of Recharge Assesment

9.4.1 The Water Balance

Introduction

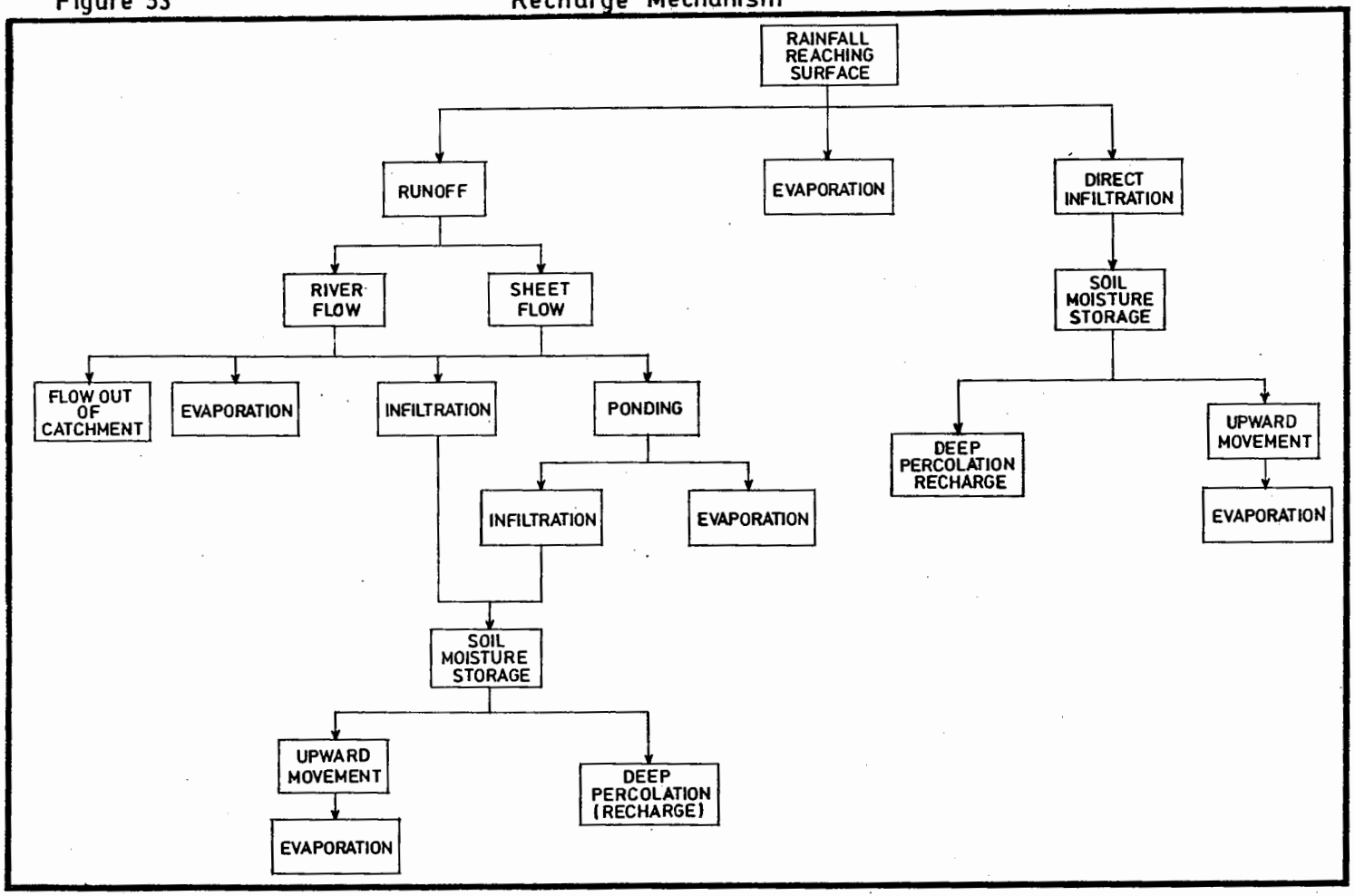
The relationship commonly used for the water balance approach to recharge calculations is based on equation (1). By taking a surface catchment as the areal unit, the mass balance equation may sometimes be reduced to:

$$R = P - ET - Ss - RO \qquad (2)$$

where R = recharge
P = precipitation
ET = evapotranspiration
Ss = soil storage
and RO = surface run-off

To use equation (2) for recharge calculations, it is necessary to estimate the four components - precipitation, evapotranspiration, soil storage and run-off. Beside the absolute mass balance, the rates of precipitation, evapotranspiration and infiltration, relative to each other, are highly significant in determining the portion of precipitation which becomes aquifer recharge.

Figure 53 Recharge Mechanism



All measurements of meteorological parameters and soil properties suffer from the deficiency of being made on extremely small samples of large, usually non-uniform, systems. An understanding of the ways in which these measurements can be best interpreted is thus essential to an appreciation of the problems of recharge assessment.

Precipitation

Although much work has been carried out in recent years on the use of radar for direct measurement of areal rainfall, it is still usual to gauge precipitation at a point and then extrapolate these data to estimate precipitation over the area of interest. The object of point precipitation gauging is to measure the rainfall which would have fallen at that point, had the gauge not been there. Numerous designs of rain gauge are in use throughout the world and there is little standardisation. The main problems, which gauge design and siting must overcome, are errors caused by the following:

- underexposure or overexposure;
- the effect of eddies;
- splashing;
- evaporation;
- leakage and overflow;
- blockage;
- human or animal interference.

Correct siting is obviously very important. Overshadowing can be avoided by maintaining a separation between the gauge and the nearest object, of at least twice the height of the object. The effect of the gauge on local air flow, causing eddies which lift the air stream over the gauge and reduce the catch, is usually the most important source of error. Besides avoiding obviously exposed sites, the eddy effect can be minimised by keeping the gauge orifice as close to the ground as possible, without allowing splash in from surrounding ground. Splashing into the gauge is minimised by surrounding it with short grass whilst splashing out of gauge, evaporation and blockage can be largely avoided by good gauge design.

The number of gauges required to assess precipitation over a particular area depends on its size, topography, the climate and, of course, on the accuracy required; recommendations on gauge spacing are given by the World Meteorological Organisation.

Ideally rain gauges should be sited so as to fairly reflect the distribution of altitude and vegetation in the area concerned; in practice, they have usually to be positioned so as to coincide with observer availability.

Aerial precipitation estimates are obtained by attributing the gauge point precipitation values to specific areas. Three weighting systems are in common use:

(a) the Theissen polygon method; this is the most widely used technique. Polygons are drawn by joining the rain gauge points in triangular network and then bisecting the sides of each triangle. As any point in the area enclosed by a polygon is nearer to the gauge at its centre than to any other, the rainfall measured at that gauge is attributed to the whole area of the polygon;

(b) the triangulation method; here, rainfall within a triangle is taken as the mean of that measured at the rain gauges at its apexes;

(c) isohyets; these are contours linking points of the same rainfall, and are particularly useful for assessing rainfall in areas where there are rapid local variations.

Using one of the above methods total annual rainfall on some given area can be expressed as volume of water, which is suitable as an input to equation (2).

Evapotranspiration

Evaporation and transpiration are physically similar processes which cannot be really separated and are therefore grouped together under evapotranspiration.

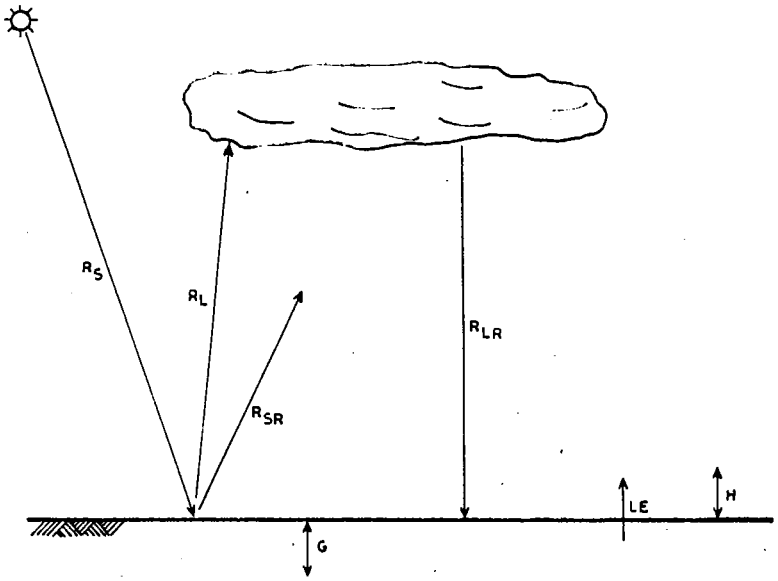
Open water potential evaporation is normally assessed either by measuring the loss from an open pan or by calculation from other measured meteorological parameters. Evaporation pans are conceptually very simple but even for evaporation from lake or pond surfaces, the pan results need correction because of the disparity of size of the water bodies. For evaporation from a land surface, further corrections are required and, for these reasons, calculated estimates of evaporation are usually preferable.

Evaporation is controlled by two processes: the energy balance and the aerodynamics, of which the former usually predominates. These processes are illustrated separately in Figure 54.

Although it is possible to evaluate evaporation by a consideration of the energy balance alone, the Penman method (Penman, 1948) offers a means of calculating evaporation and potential evapotranspiration by combining the energy balance and aerodynamic processes. This has gained wide acceptance. Penman's equation, in general form, can be written as:

$$E_o = \underbrace{\frac{\Delta}{\Delta+\gamma}\left[R_A\,(1-\alpha)\,(a+b\frac{n}{N}) - \sigma T^4\,(c-d\sqrt{e})\,(0.1+0.9\frac{n}{N})\right]}_{\text{energy balance term}} + \underbrace{\left[\frac{\gamma}{\Delta+\gamma}\;0.27\,(f+gu)\,(e_s-e)\right]}_{\text{aerodynamic term}} \qquad (3)$$

Figure 54 Energy Balance at Earth's Surface



$R_n = H + LE + G$ where $R_n = (R_S - R_{SR}) - (R_L - R_{LR})$

also $R_{SR} = aR_S$ where a = albedo

$R_{LR} = \varepsilon R_L$ where ε = atmospheric emissivity

where R_n = net radiation

H = sensible heat transfer between surface and air

LE = heat used in converting liquid to vapour; L being latent heat and E, the evaporation

G = heat flux in surface layer of the earth

R_S = incoming solar radiation

R_{SR} = reflected solar radiation

R_L = emitted radiation

R_{LR} = long wave radiation absorbed by water vapour in the atmosphere

where Eo = potential evaporation, mm/d
Δ = slope of saturation vapour pressure/temperature curve at temperature T
γ = psychrometric constant
α = albedo (proportion of incoming radiation reflected from the particular surface considered)
RA = incoming short wave radiation, cal/cm2
n = actual hours of sunshine
N = theoretical hours of sunshine
σ = Stefan Boltzman constant
T = mean air temperature (degrees Kelvin)
e = mean vapour pressure, mm Hg
es = saturation vapour pressure, mm Hg
u = wind run, km/d

a, b, c, d, f and g are constants which vary on a regional basis. For tropical countries a commonly used form of equation (3) is that after Clover and McCulloch (1958) where:

a = 0.29 cos (0 - latitude) d = 0.08
b = 0.52 f = 1
c = 0.56 g = 0.0067

Although the Penman formula has been found to work well under varied conditons, it does contain a number of approximations and potential inaccurancies. Most obvious among these is the omission of soil heat flux; the assumption here is that, if a long enough period (usually 10 days) is considered, the net effect will be negligible. Another weakness is the fact that measurements taken at 2m height are used to evaluate the evaporation process at the earth's surface.

In order to calculate evaporation using the Penman method, meteorological records are necessary for temperature, relative humidity, wind speed (at 2m height), and sunshine hours or solar radiation. The other factors used are derived from the above measurements, or are obtained from standard tables.

The Penman equation gives potential evaporation or evapotranspiration. This is applicable only to systems in which water is not limiting. When water supply is limiting, actual evaporation or evapotranspiration proceeds at a slower rate than potential depending on the degree of moisture deficiency in the soil. This subject is further discussed later in this chapter.

Due to the expense of setting up and maintaining complex meteorological stations, it is usually necessary to work with much lower data density for evapotranspiration than for rainfall. Such complex stations are usually found only at airports and major agricultural development and research establishments.

Soil Moisture

(i) Infiltration

Infiltration is the process of movement of water from the surface into the soil or the superficial deposits. The rate at which infiltration occurs can be a crucial factor in how much recharge an aquifer receives. Infiltration is a combination of two physical processes: flow by gravity and capillary forces. Flow by gravity takes place through the larger openings of the soil, is ralatively rapid and involves appreciable quantities of water. Capillary forces then disperse the water through the smaller pores; these may act in any direction according to the moisture gradient, that is, from wet to dry. Capillary movement is relatively slow and the quantity of water in motion is small.

The maximum rate at which water can enter the soil at a particular point under a given set of conditions is termed the infiltration capacity. Infiltration capacity is not a constant, but varies with time during the course of a single precipitation event, as illustrated in Figure 55. The infiltration curve is described by an equation of the form:

$$ft = fc + (fo - fc)e^{-kt} \qquad (4)$$

where
- ft = infitration rate at any time
- fo = initial infiltration capacity
- fc = final infiltration rate (constant)
- t = time
- k = constant dependent on the nature of the soil.

The asymptotic value, fc, is a function of soil permeability under saturated conditions. The initial infiltration capacity depends also on the previous precipitation history. Field determinations of infiltration capacity, often an important part of a recharge assessment study, are normally made using two concentric rings driven into the soil, as illustrated in Figure 56. A constant head is maintained within the rings and the volume of water added to the central ring is recorded against time. The normal range of infiltration rates for various soil types is shown in Table 11.

Figure 55 Variation of Infiltration Rate With Time

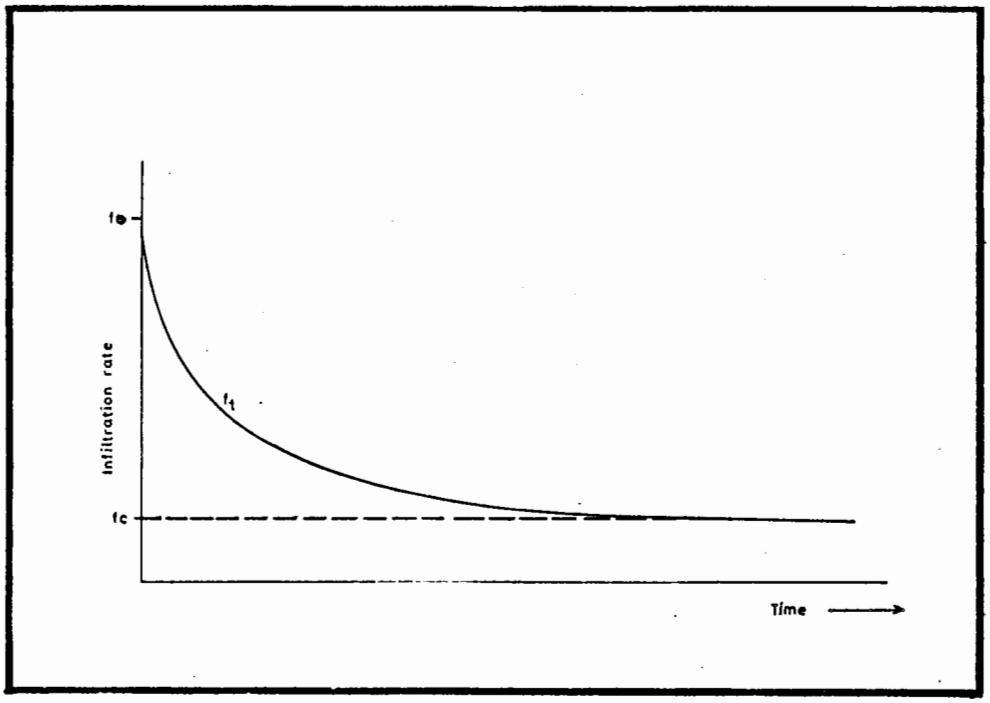


Figure 56 Measurement of Infiltration Rate

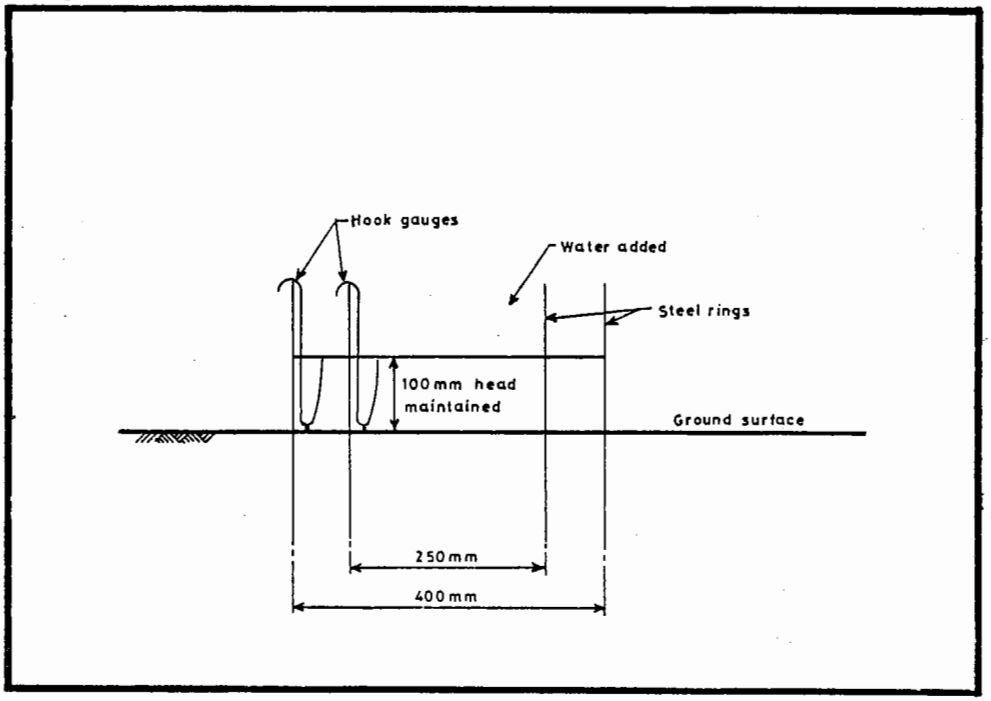


Table 11 Representative Infiltration Rates and Water Properties of Common Soil Types

Soil texture	Infiltration rate (mm/h)	Total porosity %	Total moisture content at field capacity %	Available moisture %
Sandy	25 - 250	32 - 42	6 - 12	6 - 10
Sandy loam	10 - 80	40 - 47	10 - 18	9 - 15
Loam	7.5 - 20	43 - 49	18 - 26	14 - 20
Clay loam	2.5 - 15	47 - 51	23 - 31	16 - 22
Silty clay	0.3 - 5	49 - 53	27 - 35	18 - 23
Clay	1.2 - 10	51 - 55	31 - 39	20 - 25

(ii) Retention of Water by the Soil

All soils have a water retention capacity, termed the field capacity, which must be satisfied before significant deep percolation and groundwater recharge can occur. Water is retained in the soil by a number of different mechanisims including chemical bonding to minerals and soil colloids, surface attraction by soil particles and capillary retention within small pore spaces. During dry periods, some of this water may be removed from the soil by evapotranspiration, thereby depleting the moisture content below the field capacity. Water from the upper part of the soil profile, usually the top 15 to 30cm, may be removed by capillary transfer to the evaporating surface. Moisture from the deeper soil layers is normally withdrawn by plant transpiration and only part of the total soil water can be thus removed (the available moisture).

Thus, the extent to which a soil moisture deficit can develop is determined principally by the type of vegetation and, in particular, on its root depth. This is normally expressed by the root constant. The root constant is a measure of soil water readily available within the root range, expressed as an equivalent rainfall; it is not merely a soil property within the rooting depth of a particular plant asemblage but also takes into account the ability of the vegetation to extract water at high moisture tensions. A root constant of 75mm implies that, during a dry period, evapotranspiration proceeds at the potential rate until a deficit of 75mm has been built up. After then, evapotranspiration decreases until the permanent wilting point is reached and the plants can extract no more water from the soil.

Theoretically no recharge can occur whilst a soil deficit exists; any rainfall will first go towards restoring the soil to field capacity. In practice, however, some recharge does occur at times of moisture deficit, partly due to the enhancement of soil permeability by shrinkage and cracking, and partly due to the normal presence of highly transmissive preferential flow paths in naturally porous media.

Calculation of Recharge

(i) Large Scale Water Balance

Recharge can sometimes be estimated by using equation (2) in its broadest context, at a regional scale. In this approach, precipitation is integrated areally by one of the methods discussed earlier. The change in the soil storage is taken as zero by assuming that over some convenient water year, the moisture held in the soil at the end of the period is the same as that held at its beginning. Run-off should, of course, be gauged at some suitable point. Actual evapotranspiration is most difficult to estimate but it is possible to make a reasonable estimate; in the rainy season it is often valid to assume that the actual evaporation is equal to the potential; in the dry season an allowance is normally made for field capacity at the beginning, and thereafter evaporation from the watertable can be estimated using a function such as that developed by Gardner and Fireman (1958), relating evaporation depth of watertable. In forest areas, transpiration by trees from the watertable should also be allowed for. Run-off may be difficult to estimate, particularly if the area considered cannot be easily isolated in terms of hydrology.

Despite the difficulties described above, a general water balance is very often a useful first estimate of recharge. It also provides a general check in so far that annual recharge anywhere seldom exceeds 30% of precipitation and is much more often of the order of 5 or 10% of the total rainfall.

(ii) Soil Moisture Budget

The attraction of the soil moisture balance method is that it does not require large scale measurements of run-off, and that it treats the recharge problem on a micro scale, that is on the basis of small areal units; although, of course, ultimately the results have to be extrapolated to the whole area under study.

The method makes use of standard hydrometeorological data and is based on the concept of soil moisture deficit described above; the method has been used successfully in monsoonal and semi-arid climates.

When the soil is saturated to field capacity, evapotranspiration takes place at the potential rate. The quantity of water which remains when evapotranspiration and direct run-off are substracted from precipitation are taken as percolation to the groundwater reservior. If the soil is not at field capacity, then a soil moisture deficit (SMD) exists and no recharge is assumed to take place. Any infiltration (precipitation less run-off) that occurs reduces the SMD. Evapotranspiration from the soil continues at a lower rate, dependent on the magnitude of the SMD. If the SMD is greater than the root constant, then the actual evapotranspiration is usually taken as 10% of the potential value. Finally, at wilting point, evapotranspiration from the soil ceases.

Unfortunately this method of calculating recharge contains at least one conceptual inaccuracy, as it has always been known that some recharge does occur in the presence of soil moisture deficit. Current practice in the United Kingdom is to allow an empirical fraction of effective precipitation in excess of a threshold value to enter the aquifer as direct recharge. These empirical values are normally taken as 15% and 5mm respectively. Recent work has shown that recharge calculations using the soil moisture budget, performed on the basis of time intervals longer than 10 days, seriously underestimate recharge; ideally calculations should be on a daily basis.

9.4.2 The Use of Lysimeters

In concept lysimeters are very simple; they are devices used to isolate plots of land with their soil profiles so that these can be studied in detail. They were originally developed for crop water use investigations but have also been adopted for groundwater recharge studies. To obtain accurate results from lysimetry, it is necessary to ensure that the conditions inside the lysimeter are identical in all respects to those outside.

In practice, lysimeters suffer from a number of severe drawbacks, of which the following ar the most serious:

- they are usually relatively small in size so that root development may be restricted and edge effects are relatively large;

- the soil and strata within a lysimeter are always to some extent affected by its construction so that root development and water flow are no longer as natural;

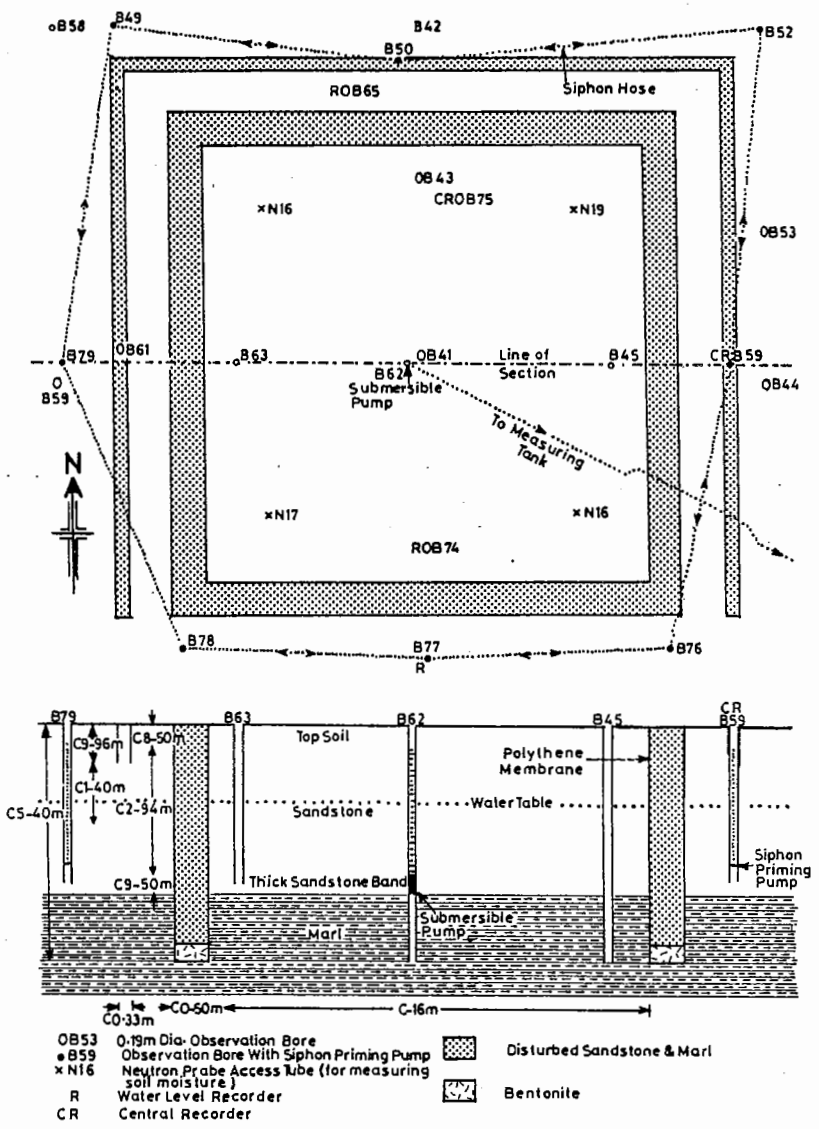
- free drainage from a normal lysimeter means that the base boundary condition is not the same as that on adjacent land and therefore the conditons within the lysimeter may not be representative;

- if an adequate surround planted with the same type of vegetation is not provided, a lysimeter may act as an 'oasis' so that conditions within do not correspond with those outside;

- the high cost and lack of mobility.

Nevertheless, the lysimeter concept can be adopted to give significant results in recharge studies. The problems listed above can be minimised by careful site selection and design of the lysimeter so that a sufficiently large area (about 100m2) of natural soil and aquifer is isolated. Figure 57 shows a lysimeter adopted for recharge studies at Nottinghamshire in England. This system has been in use for several years and is considered to give a more accurate measure of recharge than the soil moisture budget approach described above. Its design could be easily adapted to, for example, a thin alluvial aquifer ovelying Basement.

Figure 57 Lysimeter Installation in a Sandstone Aquifer



The water table in the aquifer surrounding the Lysimeter is equalised by the siphon hose. The water table within the Lysimeter is maintained at the same level as that outside by pumping from the central borehole to a measuring tank
Recharge = volume of water pumped ÷ area of Lysimeter

9.4.3 Isotope Techniques

Natural Tritium Profiles

The presence of tritium in groundwater indicates recharge within the last 30 years. In fact the amount of tritium in rainfall has been related to the testing of thermonuclear devices in the atmosphere, and in some years tritium in rainfall has been particularly high; groundwater derived from rainfall in those years may sometimes be identified.

Where a groundwater body is overlain by a thick unsaturated zone, this may have a storage capacity equivalent to several years recharge. On the basis of the assumption that moisture is displaced progressively through the unsaturated zone by a piston flow mechanism, it should be possible to trace the substantial variations in tritium content of rainfall (and hence recharge) which have occurred over the past 20 years. The rate of movement of specific tritium peaks in the profile should be related to the recharge rate by a simple equation of the form.

$$\Delta R = \Delta Y * Sm \qquad (5)$$

where ΔR = recharge rate
ΔY = rate of displacement
Sm = moisture content

Tritium profiles have indeed been identified and their displacement with time observed. An example from the chalk of Dorset, United Kingdom, is illustrated in Figure 58.

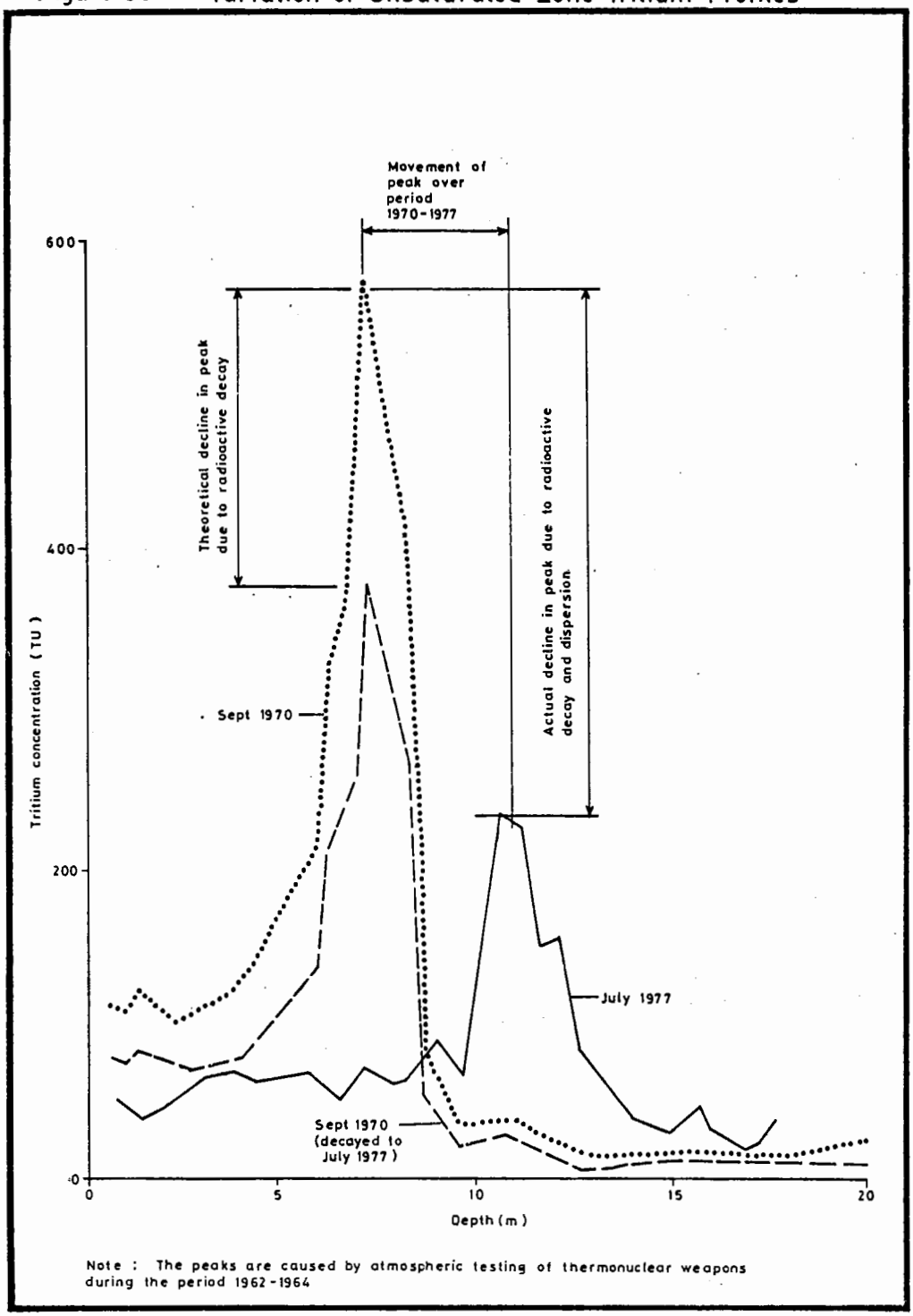
In spite of considerable work on the problem, uncertainties caused by areal variation in the tritium content of rainfall (tritium content of rain is monitored at very few locations worldwide), variation in the recharge mechanism with rainfall intensity and difficulties of determining moisture content of unsaturated rock, make the interpretation of tritium profiles difficult. Nevertheless, in some cases, this can be a useful method of estimating recharge in areas where other approaches to the problem may be difficult.

Tritium Injection

Some of the uncertainties involved in the natural tritium profiling can be avoided by the artifical emplacement of a tritium tracer of known activity. The method is particularly suitable for areas with strongly seasonal rainfall, and has been successfully used in the Manet Basin, India, to estimate recharge due to a single south-east monsoon.

The method is also particularly suitable for estimating recharge due to a single irrigation season on irrigated land. In this method, a

Figure 58 Variation of Unsaturated Zone Tritium Profiles



Note : The peaks are caused by atmospheric testing of thermonuclear weapons during the period 1962-1964

charge of tritiated water is emplaced in the soil profile below the rooting depth of the local vegetation, prior to the start of the recharge season. At the end of the recharge season an undisturbed core is recovered from the same location and the position of the centre of gravity of the tritium dispersion is found. Recharge is then determined from the displacement of the original position of the tritiated slug. This method assumes a piston flow mechanism of recharge and obviously cannot be used where preferential flow paths exist such as in fissured karst limestone.

9.4.4 Recharge from Sources Other than Rainfall

Irrigation Recharge

Aquifer recharge resulting from irrigation is usually taken as the difference between water applied and crop consumptive use (crop evapotranspirations). With a centralised irrigation system, direct measurement of water applied is possible but, more usually, it is necessary to estimate this by field observation of local irrigation practice coupled with an assessment of the area under each crop; the latter is often obtained by air photo interpretation. Crop water requirements under the prevailing conditions can usually be obtained from published literature. Where drainage is installed, it is important to gauge this.

Leakage from Surface Water Bodies

Seepage to the groundwater reservoirs from rivers, lakes and canals may be significant but is often difficult to estimate. The direct method is to observe water losses from the surface body, compute evaporation, measure surface inflows and outflows and thus calculate the contribution to the groundwater system. However, this is often difficult to do and it often suffers from the usual source of inaccuracy of comparing two large quantities to find a small difference. It is sometimes advantageous to use a method of estimating seepage that does not involve the volume of the surface water body. If the surface water is directly connected to the watertable, then seepage can be computed by flow net analysis or even a direct calculation of subsurface flow using Darcy's Law and the Dupuit/Forchheimer assumptions.

If strong chemical or isotopic contrast between surface water and groundwater exists, a qualitative estimate of recharge from a surface body can be obtained by studying the mixing ratio using one or more of the hydrochemical graphical techniques.

Leakage from Other Aquifers

Recharge to an aquifer from underlying or overlying aquifers, separated from it by confining beds of restricted permeability, is described by the equation:

$$Q = A\,Kv\,\frac{dh}{dz} \qquad (6)$$

where Q = the groundwater inflow
A = area of flow
Kv = vertical permeability of the confining bed
h = hydraulic head
z = the vertical coordinate

The main problem in applying this equation to actual problems such as multilayer alluvial aquifers lies in determing Kv. There are

three possibilities: laboratory dererminations on core samples, pumping tests using the leakance theory and the calibration of mathematical models.

As with surface water leakage, hydrochemical and isotope techniques can sometimes provide a qualitative insight into the inter-aquifer leakage.

9.5 Indirect Methods of Recharge Assessment

9.5.1 Watertable Hydrograph Analysis

The methods of estimating groundwater recharge described above attempt to qualify the inflow into the aquifers directly, or by computing losses from surface water. The watertable hydrograph method examines the behaviour of an unconfined or phreatic groundwater body under the influence of recharge and, from its behaviour, attempts to deduce the magnitute of this recharge.

Water levels in unconfined aquifers often respond quickly to recharge, showing sharp peaks. In climatic environments with a well defined wet season, the watertable hydrographs may sometimes be used for estimating recharge. For short term fluctuations, where the gradient of the water surface can be ignored, recharge can be approximately computed merely from the rise of the watertable in the rainy season. A hydrograph on which such a calculation could be based is shown in Figure 59(a). In such cases it can be taken that:

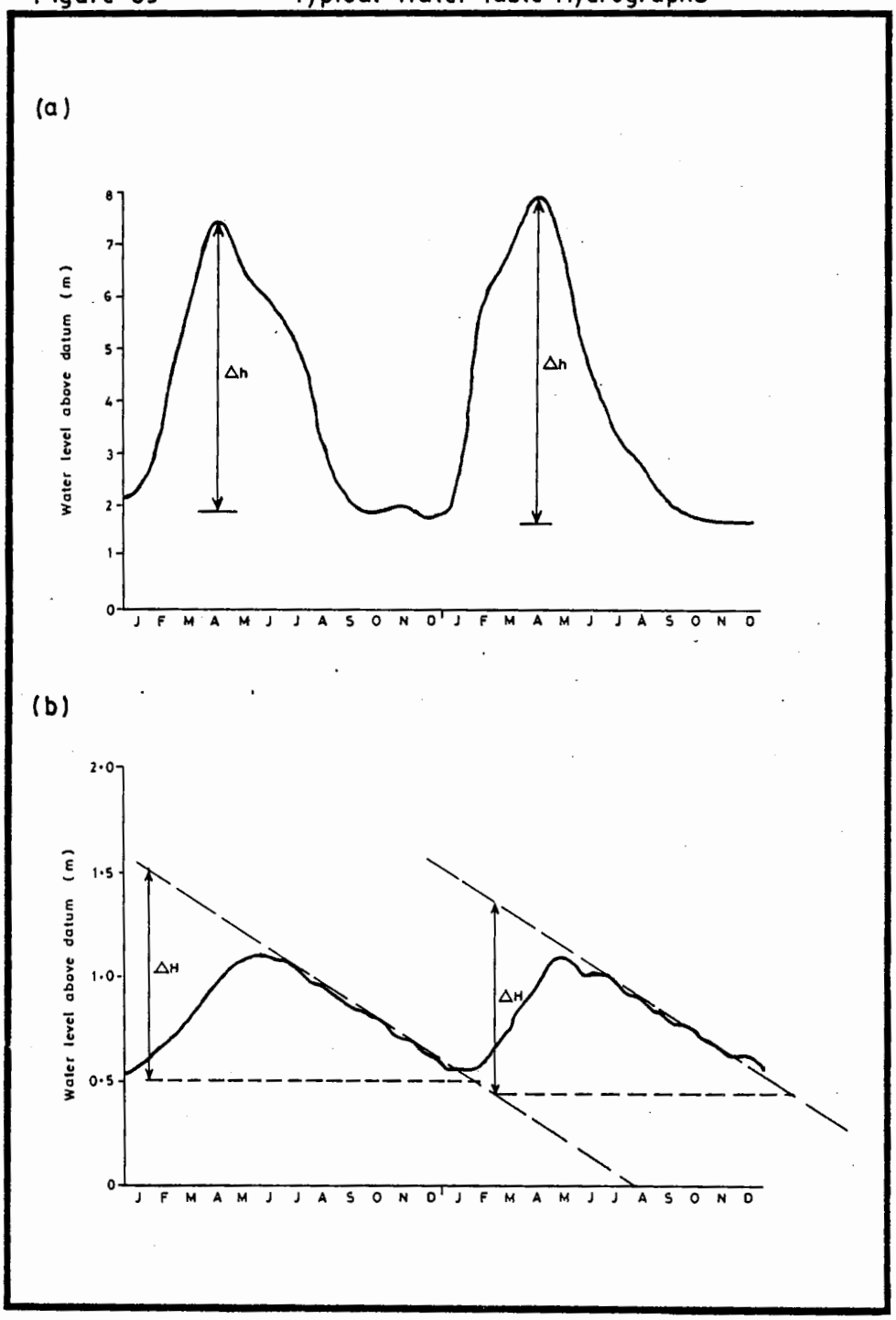
$$R = \Delta h * Sy * A \qquad (7)$$

where Sy = specific yield of the strata in the watertable zone
and A = area of the recharged basin.

Equation (7) tends to underestimate recharge, as it ignores groundwater drainage during the time when the watertable is rising; it also ignores any recharge which occurs during watertable recession. A further problem is that the specific yield of the material of the zone in which the water level oscillates is seldom known with any degree of accuracy. Nevertheless, this method often provides a useful check to ensure that the quantity of recharge, calculated by other methods, is sensible.

These complications can often be avoided by basing the recharge estimate on the recession of the hydrograph; in some cases the recession appears to be linear with time (Figure 59(b)). Assuming that this can be interpreted as a constant rate of groundwater drainage, independent of the actual elevation of the watertable, it can be extrapolated to a full year and the annual recharge again estimated using the expression:

Figure 59 Typical Water Table Hydrographs



$$R = \Delta H * Sy * A \qquad (8)$$

where ΔH is as defined by Figure 59(b) and the other symbols are as before.

9.5.2 Throughflow

Recharge to an aquifer, which can be assumed to be in a long term state of equilibrium, can sometimes be estimated by calculating groundwater throughflow at some convenient place, using the Darcy equation. Ideally this method applies to confined aquifers only, such as is shown on Figure 60.

The flow system is visualised as originating with infiltration on the outcrop, and subsequent passage through the aquifer (confined at top and base by impermeable beds) to the discharge zone, which may involve leakage to upper or lower beds, discharge to surface water bodies, or evaporation and evapotranspiration. In the case of unconfined aquifers, this method can still be used for approximate calculations of recharge provided the correct section is chosen for the computation.

For a confined aquifer, the throughflow in the system, such as shown in Figure 60, can be expressed by the standard form of the Darcy equation as follows:

$$Qu = KD \frac{dh}{dx} \qquad (9)$$

where Qu = groundwater flow per unit length of outcrop
K = mean lateral permeability of the aquifer
D = aquifer thickness
h = hydraulic head
x = the horizontal coordinate.

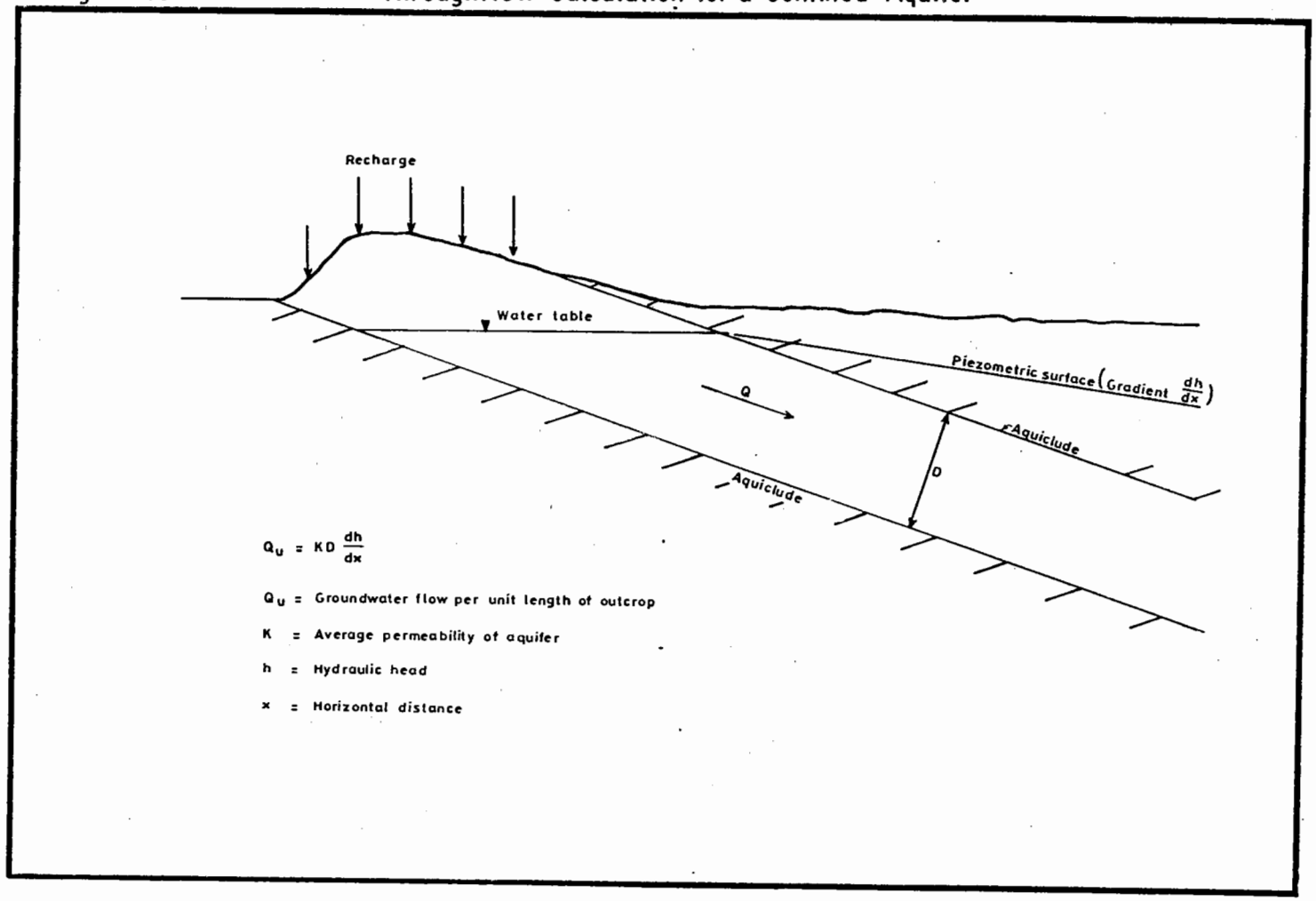
Using this method, the total recharge rate is estimated by computing throughflow for various sectors of the aquifer and then summing up the flow components for the length of outcrop within the basin considered. Annual recharge is calculated by extrapolating the estimated recharge rate to a full year.

9.5.3 Groundwater Discharge Methods

In some cases it is much easier to quantify the outflows from a groundwater reservoir than the inflows into it.

Assuming a long term equilibrium between annual inflows and outflows, groundwater discharge can be taken as equivalent to recharge. The major components of groundwater discharge normally comprise some or all of the following:

Figure 60 Throughflow Calculation for a Confined Aquifer



- spring flow;
- diffuse flow to rivers;
- evaporation from shallow watertables;
- evaporation by phreatophytes;
- pumped abstractions.

Total spring flow is normally estimated by carrying out an inventory of all springs in an area, and gauging or visually assessing the flow of each spring. It should be kept in mind that some spring discharges may vary strongly seasonally; springs may also exhibit flow variations from year to year. The best estimates are then added up to give an annual total for a groundwater basin or a project area.

Diffuse groundwater discharge to rivers is normally estimated from the records of river gauging, particularly those of the automatic recorders. The simplest method is to gauge a river at two points, one at the entrance to a particular groundwater basin, the other at the exit. Then, provided there are no surface inflows in that stretch of the river (or that these are measured), the groundwater inflow can be estimated.

However, a more common method is to study an individual hydrograph of a stream or river and to separate the base flow from the surface run-off. The methods of doing this can be found in any standardd hydrology text book. The base flow is then taken as the groundwater discharge to the river upstream of the point of measurement.

Evaporation from shallow watertables can be estimated from the calculations of potential evaporation from meteorological records, and from functions relating the intensity of evaporation and depth to watertable, such as those developed by Gardner and Fireman (1958).

Phreatophytes are plants which take the whole or part of their transpirative water use from the watertable. Such plants are usually trees or bushes with extensive root systems and are particularly common in arid or semi-arid environments. The distribution and density of phreatophytes is normally obtained from the examination of air photos. The consumptive use of individual plants, or that per unit area, is estimated on the basis of the meteorological records.

CHAPTER 10

REPORT

A groundwater investigation is useless if the results and conclusions are not written up in the form of a final report. It is important that the field data and methods of collection are included in as much detail as possible, to enable reassessments to be made of the groundwater resource by workers later on should new information come to light. Data could be tabulated in the text, included as appendices at the end of the report, or form separate volumes for ease of reference. Drilling logs and geophysical soundings/traverses should appear in full.

Illustrations, in the form of diagrams, maps and photographs, should be used wherever possible in place of lengthy verbal explanations - the saying, "a picture is worth a thousand words", is very true.

Sources of information from published and unpublished works should be referred to in the text where appropiate, and a bibliography included at the end of the report.

A suggested layout for a typical report follows below:

Chapter / Section	Contents
1 Introduction	Objectives of investigation, terms of reference (if any), brief description on form of investigations;
2 Physical Background	Geology, topography, general hydrogeology, drainage, climate, vegetation, land use, soils, etc;
3 Existing Data	Previous investigations; maps, aerial photograps, geophysical surveys and borehole logs;
4 Investigation Methods	Field programme, equipment, drilling and geophysical techniques, chemical analyses, pumping tests, data interpretation methods, constraints and problems;
5 Groundwater Occurence	Aquifers, hydrogeological setting (geometry), piezometry, groundwater movements, flow conditions (confined, unconfined etc);
6 Aquifer Properties	Transmissivity, permeability, storage coefficent, etc;

7	Groundwater Quality	Chemistry, regional variations, suitability of water for intended use;
8	Recharge	Recharge estimates, seasonal fluctuation of water levels, water balance, safe yield;
9	Development Potential	Suggested form of development, borehole designs, pumping rates;
10	Conclusions	Conclusions on investigations undertaken, and recommendations for development, further work.

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APPENDIX A

GROUNDWATER REPORTS IN NWRI LIBRARY

AND REFERENCES

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Nr	Client	Consultant/ Author	Title	Date
1	FMWR	BRGM (Nigeria) Metal and Minerals (Nigeria) Ltd.	Hydrogeological Investigations Sedimentary Basins - Areas XVIII and XIX (Coastal Plains and Niger Delta) Final Report Vol.2	1979
2	FMWR	Nippon Koei Co. Ltd and Skoup & Co. Ltd Nigeria	Anambra River Basin Project, Pre - Feasibility Study, Vol. 1, Main Report.	1977
3	NWRI	C.C. Mbachu	Design Criteria for Water Borehole in Anambra State	1983
4.	FMWR	Polservice Consulting Engineers in association with Geoconsults	Pre-Drilling Hydrogeological Investigations. Area XVII Final Report (3 vols)	1979

BAUCHI STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	OSOT Associates	Pre-Drilling Hydrogeological Investigations, Study Area V	1982
2.	"	German Consult/ GWE/Insumma/PHI	Pre-Drilling Hydrogeological Investigations, Phase 1, Area V, Report and Appendix (Data)	1978
3	"	Basil and Associates Ltd. in association with Basil Geotechnics S.A.	A Pre-Drilling Hydrogeological Investigations, Study Area XV, Benue Valley, Vols. I, II & III	1979
4	"	Probi - Nig. Engineering Consulting Services	Monitoring and Management of Hydrometric Stations, Wells and Boreholes, Upper Benue (Zone A)	1984
5	FMWR ?	Aholis Geo-Services (Nig) Ltd. Consultants.	Geophysical Survey (Lot I Extention), parts of Bauchi and Bornu States of Nigeria, Final Report, Vol. I.	?
6	FMWR	SCET International/ Charles Olumide & Co.	Pre-Drilling Hydrogeological Investigations Areas XIV and XV. Report, Appendix I, Appendix 2 and Plates.	1979
7	GSN	I.D. Carber, W. Barber and E.A. Tait.	The geology of parts of Adamawa, Bauchi and Bornu Provinces in North Eastern Nigeria. GSN Bulletin 30	1963
8	?	Conred (Nigeria)	Geophysical investigations of Gombe area.	1978
9	?	Consolint (Nigeria) Ltd.	Urban Water Supply of Gombe, Kumo, Damaturu, Geidam	1975
10	Bauchi State W/Board	Edok - Eter - Mandilas Ltd.	Hydrological and Geophysical Investigations for Groundwater in Bauchi State. 2 reports.	1976
11			Geology and water Supply of Gombe Town, Tares. GSN Report No. 765 (unpublished)	?
12	GSN	J.H. Thompson and E.A. Tait	Report on borehole siting in Gombe Town. GSN Report No. 890 (unpublished)	?
13	GSN	J.H. Thompson	The geology and hydrology of Gombe, Bauchi Province. Rec. of GSN.	1956

BENDEL STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	Dubon Project Engineering PVT LTD in association with Alolis Geo-Services (Nig) Ltd.	Studies to fill in data gaps in the Basement Complex. Pre-Drilling Hydrogeological Investigations in Areas X, XI and XII. Final Report Vols. I & II	1982
2	"	BRGM (Nigeria) Metal and Minerals (Nigeria) Ltd.	Hydrogeological Investigations in the Sedimentary Basins - Areas XVIII and XIX (Coastal Plains and Niger Delta), Final Report Vol. 2	1979
3	NWRI	O. Jackson	Groundwater Resources of Bendel State	1983
4	FMWR	Geco Engineering Company (Nig) Ltd.	Geophysical Investigations for the Location of Suitable sites for Drilling of Productive Boreholes in the Basement Complex of Nigeria, Vols IV, V and VI, Lot 2 Ogun, Ondo and Bendel State	?
5	"	Polservice Consulting Engineers in association with Geoconsults	Pre-Drilling Hydrogeological Investigations. Area XVII. Final Report (3 Vols)	1979

BENUE STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	Unik Engineers in association with Watson Hawksley Nig.	Pre-Drilling Hydrogeological Investigations, Data Gaps in the Basement Complex, Areas VI, VII, VIII and IX, Vol. I (Report and Recommendations) & Vol. II (Appendix)	1981
2	"	Basil and Associates Ltd. in Association with Basil Teotechnics S.A.	A Pre-Drilling Hydrogeological Investigations, Study AREa XVI, Benue Valley, Vols. I, II & III.	1979
3	"	Nippon Koei Co. Ltd	Anambra River Basin Project, Pre-Feasibility Study, Vol. I (Main Report)	1977
4	"	Polservices Consulting Engineers in association with Geoconsults.	Pre-Drilling Hydrogeological Investigations , Area XVII Final Report (3 vols.)	1979

BORNO STATE

Nr.	Client	Consultant/ Author	Title	Date
1	FMWR	ASOT Associates	Pre-Drilling Hydrogeological Investigations, Study Area I, Data Gap Filling	1982
2	"	Niger-Techno Ltd in association with Technosynesis Sp.A	Pre-Drilling Hydrogeological Investigations, Area I Final Design	1978
3	NWRI	D. Ifeanyi Uba	Groundwater Exploitation in Maiduguri Metropolis and Environs.	1983
4	FMWR	Acholis Geo- Services (Nig) Ltd.	Geophysical Survey (Lot I Extension), parts of Bauchi and Bornu States of Nigeria, Final Report, Vol. I.	?
5	Chad Basin and Rural Development Authority	U.S. Dept. of the Interior, Bureau of Reclamation	Land and Water Resources (Reconnaissance Study), Lake Chad Basin	1968
6	"	Agriculture, Livestock and Technical Services (Nig) Ltd.	Jere Bowl Rice Scheme Feasibility Studies Phase I, Half-Yearly Progress Report No.1, Annex 1 Hydrology - Hydrogeology and Geology	1975
7	FMWR	SCET International/ Charles Olumide & Co.	Pre-Drilling Hydrogeological Investigations Areas XIV and XV. 4 volumes - Report, Appendix !, Appendix 2 and Plates.	1979
8	GSN	W.M. Barber	Hydrology of the Garin Maji-Bela - Demshua Area, Potiskum Division, Bornu Province, GSN Report No.1152	1955
9	GSN	W. Barber	Pressure water in the Chad Formation of Bornu and Dikwa Emirates, North Eastern Nigeria GSN Bulletin No.36.	1965
10	GSN	W.M. Barber and J.D Carter	The Hydrology of the Mafada, Potiskum and Damaturu, 1:1000 000 Standard sheets, GSn Report No.1157	

Bornu State (Contd.)

11	GSN	W. Barber and B. Dousse	Rise in the water table in parts of Potiskum Division, Bornu Province further observations. GSN Report No.1523	1965
12	GSN	W. Barber and D.G. Jones	The geology and Hydrology of Maiduguri, Bornu Province. Rec. of GSN	1960
13	Land Resources Division DOS	M.G. Bawden, M.D. Carroll and P. Tuley	North East Nigeria Project, Preliminary Description of Land Systems	1968
14	USGS	S.W. Carmalt, G.S. Tibbitts	Water levels and artesian pressures in the Chad Basin of Notheastern Nigeria, 1963 - 1968, USGS open File Report	1969
15	GSN	J.D. Carler and W. Barber	The rise in the water table in parts of Potiskum Division, Bornu Province, FSN Rec. 1956 5 - 1B	1958
16	GSN	J.D. Carter, W. Barber and E.A. Tait	The geology of parts of Adamawa, Bauchi and Nornu Provinces in North Eastern Nigeria. GSN Bulletin 30	1963
17	USGS	F.E. Clark	Preliminary study of water well corrosion, Chad Basin, Nigeria, USGS open file report	1965
18	?	Consulint (Nig.) Ltd.	Urban Water Supplies, Potiskum	?
19	Govt. of North Eastern State	Consulint (Nigeria) Ltd.	Water Survey of the North-Eastern State.	1975
20	Chad Basin Commission	FAO	Groundwater Resources in Lake Chad Basin. 2 volumes	1973
21	BSWB	Hydroquest	Construction of production and piezometric boreholes. Final reports by well number	1978-79
22	Forign & Commonwealth Office, ODA	Land Resources Division (Ed. P. Tuley)	The Land Resources of North East Nigeria	1972

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BORNO STATE Contd.

23	Chad Basin DA	MMP and HTS	South Chad Irrigation Project Feasibility Study	1972
24	USGS	R.E. Miller R.H. Johnston, J.A.I Olowu & J.U. Uzoma	Groundwater hydrology of the Chad Basin in Nornu and Dikwa Emirates, North-eastern Nigeria, with special emphasis on the flow life of the artesian system, USGS Water Supply Paper.	?
25	GSN	C. Reaburn & B. Jones	The Chad Basin: Geology and Water Supply. GSN Bulletin No.15	1934

CROSS RIVER STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	Unik Engineers in association with Watson Hawksley Nig.	Pre-Drilling Hydrogeological Investigations, Data Gaps in the Basement Complex Areas VI, VII, VIII, and IX. Vol.I (Report and Recommendations), Vol.II (Appendix)	1981
2	"	BRGM (Nigeria), Metal and Minerals (Nigeria) Ltd.	HYdrogeological Investigations in the Sedimentary Basins - Areas XVIII and XIX (Coastal Plains and Niger Delta), Final Report Vol.2	1979
3	NWRI	G.A. Wokoma	Groundwater Exploration in Cross River State.	1983

FEDERAL CAPITAL TERRITORY

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	German Consult / GWE/Insumma/PHI	Pre-Drilling Hydrogeological Investigations, Phase I, Area III, Report and Appendix (Data)	1978
2	"	OSOT Associates	Pre-Drilling Hydrogeological Investigations, Area III, Report and Appendix	1976
3	"	Polservice Consulting Engineers in association with Geoconsults.	Pre-Drilling Hydrogeological Investigations, Area XVII Final Report (3 vols.)	1979

GONGOLA STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	Unik Engineers in association with Watson Hawksley Nig.	Pre-Drilling Hydrogeological Investigations, Data Gaps in the Basement Complex Areas VI, VII, VIII and IX. Reports and Recommendations, Vol.I; Vil.II (Appendix)	1981
2	"	Basil and Associates Ltd. in Association with Basil Geogechnics S.A.	Pre-Drilling Hydrogeological Investigation, Study Area XVI, Benue Valley. Vols I, II and III	1979
3	"	Probi - Nig. Engineering Consulting Services	Monitoring and Management of Hydrometric Stations, Wells and Boreholes, Upper Benue (Zone A), Second Progress Report and Appendices	1984
4	NWRI	A. Uche	Review of Hydrologic Data used in the construction of Dadinkowa Dam Project.	1983
5	FMWR	SCET International/ Charles Olumide & Co.	Pre-Drilling Hydrogeological Investigations Area XIV and XV. 4 volumes - Report, Appendix 1, Appendix 2 and Plates.	1979
6	GSN	W. Barber, E.A. Tait and J.H. Thompson	The geology of the lower Gongola. GSN Annual Report 1952 - 53.	1954
7	Uper Benue River Basin Development Authority	Diyam Consltants in association with Parkman Consultants Ltd.	Pre-Feasibility Study, Gongola River Basin.	?

IMO STATE

Nr	Clint	Consultant/ Author	Title	Date
1	FMWR	BRGM (Nigeria) Metal and Minerals (Nigeria) Ltd.	Hydrogeological Investigations in the Sedimentary Formations -- Areas XVII and XIX (Coastal Plains and Niger Delta) Final Report Vol.2	1979

KADUNA STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	OSOT Associates Consulting Engineers	Pre-Drilling Hydrogeological Investigations (Study Area I) Data Gap Filling	1982
2	"	Niger-Techno Ltd. in association with Technosynesis	Pre-Drilling Hydrogeological Investigations (Area I), Final Design	1978
3	"	German Consult, GWE, Insumma PHI	Pre-Drilling Hydrogeological Investigations. Phase 1, Area III Report and Appendix A) (Data)	1978
4	"	OSOT Associates Consulting Engineers.	Pre-Drilling Hydrogeological Investigations, Report and Appendix, Area III	1976
5	"	German Consult, GWE, Isumma, PHI	Pre-Drilling Hydrogeological Investigation, Area IV	1978
6	NWRI	A.A. Oyinlola	The Role of Geophysical Investigation in the National Borehole Programme in some parts of Southern Kaduna State	1983
7	"	F.O. Okela	Nature and Quality of Groundwater in Kaduna State.	"
8	"	D.B. Magaji	Hydrogeology of the Northern Part of Kaduna	"
9	?	MOD Land Resources Division	Land Resources of Central Nigeria, Environmental Aspects of the Kaduna Plains, Vol.1, Landforms and Soils.	1977
10	?	LRDC Central Nigeria Project Team	Land Resources of Central Nigeria, Agricultural Development Possibilities, Vol.5, The Kaduna Plains, Maps	1978
11	FMWR	Eptasa/CEC	Geophysical Investigation for the Location of Suitable sites for Drilling Productive Boreholes in the Basement Complex of Nigeria (2 reports - one for FDWR/NWRI compound, Kaduna, the other for Buruku.	1981

KADUNA STATE (Contd.)

12	"NACO" B.V.	Geoexploration (Nig) Associates	Groundwater Investigation around Kaduna International Airport (2 reports)	1980
13	FDWR	Loladson Consultants	Studies on Groundwater Pollution in Kaduna. Final Report, Vol.1, and The Appendix to Final Progress Reports Cumulative Chemical and Microbiological Data June 1983 to June 1984.	1984
14	KSWB	MRT Consulting Engineers (Nig.) Limited	Kaduna State Water Board Master Plan 1980 - 2005	1978
15	FDWR	MRT Consulting Engineers (Nig.) Ltd.	Groundwater Research Department National Water Resources Institute. Working Paper Nr.1, Experimental Catchment Area, Kaduna, Groundwater Investigations - First Phase.	1985
16	FMWR	Unecom Associates	Monitoring and Management of Hydrometric Stations and Boreholes in Sokoto - Rima Basin, Zone A, Final Report.	1984
17	-	North Central State W/Board	Water Resources Development, Master Plan of Area "A" in the Northern part of Katsina Emirate, Vol.II Present Situation and Water Balance.	1973
18	Sokoto-Rima RBDA, FMWR	Wakuti Consulting Engineers	Feasibility Study and Preliminary Design for the Karaduwa River Basin Development Project, Kaduna State.	1979
19	?	Impresit Bakolori (Nigeria)	Gagare and Bunsuru River Basin Project, Feasibility Studies, Report on Existing Hydrological and Meterological Stations	1980
20	?	Progress Engineering	Reactivation of Hydrological Stations, Sokoto-Rima Basin	1980

KANO STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	OSOT Associates	Pre-Drilling Hydrogeological Investigations, Data Gap Filling study, Area Final Report.	1982
2	"	Niger - Techno Ltd. in association with Technosynesis Geoexpert Sp. A	Pre-Drilling Hydrogeological Investigations, Area 1 - Final Design	1978
3	"	German Consult/ GWE/ Isumma/PHI	Pre-drilling Hydrogeological Investigations, Area IV	1978
4	"	OSOT Associates	Pre-Drilling Hydrogeological Investigations, Study Area V	1982
5	"	Germ Consult/ GWE/Isumma/PHI	Pre-Drilling Hydrogeological Investigations, Phase 1, Area V, Report and Appendix (Data)	1978
6	-	Diyam Consultants	Records of all boreholes drilled in Kano State are held on computer file.	-
7	KNARDA	MRT Consulting Engineers (Nigeria) Ltd.	Records of 1000 boreholes drilled for KNARDA from 1983 to 1986	-

KWARA STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	Dubon Project Engineering PVT Ltd. in association with Alolis Geo-Sciences (Nig.) Ltd.	Studies to full in data gaps in the Basement Complex Pre-Drilling Hydrogeological Investigations in Areas X, XI and XII, Final Report, Vols. I & II	1982
2	"	Niger-Techno Ltd. In association with Technosynesis.	Pre-Drilling Hydrogeological Investigation, Area XII, Final Design.	1978
3	NWRI	O. Olusola	Groundwater Exploration in Kwara State	1983
4		GSN (Jones D.G.)	Report on Water Supply in parts of Borgu Division, Ilorin Province. GSN Report No.1131	1954
5		GSN (Jones, D.G)	The Geological Aspects of the proposed Urban Water Supply for Kaiama Town, Borgu Division GSN Report N.1131	1954
6	FMWR	Polservice Consulting Engineers in association with Geoconsult	Pre-Drilling Hydrogeological Investigations Area XVII Final Report (3 vols.)	1979

LAGOS STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	BRGM (Nigeria) Metal and Minerals (Nigeria) Ltd.	Hydrogeological Investigations in the Sedimentary Basins - Areas XVIII and XIX (Coastal Plains and Niger Delta) Final Report Vol.2	1979

NIGER STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	Niger-Techno Ltd in association with Technosynesis Sp.A. and Geoexpert Sp.A.	Pre-Drilling Hydrogeological Investigations, Area II - Final Design	1978
2	"	OSOT Associates Consulting Engineers	Pre-Drilling Hydrogeological Investigations, Data Gap Filling Study Area II, Final Report (1 vol.)	1982
3	"	German Consult/ GWE/Insumma	Pre-Drilling Hydrogeological Investigations, Phase I, Area III, Report and Appendix (Data) 1 vol.	1978
4	"	OSOT Associates Consulting Engineers	Pre-Drilling Hydrogeological Investigations, Area III, Report and Appendix	1976
5	Upper Niger RB. & RDA.	ABU (Dr. P. Stenzel)	Results of Geophysical Survey for Upper Niger River Basin and Rural Development Authority	1983
6		GSN (Hazell, J.R.T.)	Water Supply in Kontangora and Bida Division. GSN Report No1149	1955
7		GSN (Szell, G.P.)	Report on the Water Supply Investigation of Zuru Town, Niger Province, North-Western State. GSN Report No.1482	1970
8		GSN (Szell, G.P.)	Report on Water Supply Kontagora Town, Niger Province, North-Western State, GSN Report No.1484	1970
9	FDWR	Polservice Consulting Engineers in association with Geoconsults	Pre-Drilling Hydrogeological Investigations Area XVII, Final Report (3 vols.)	1979

OGUN STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	Dubon-Project Engineering PVT Ltd in Association with Alolis Geo-Services (Nig) Ltd.	Studies to fill in Data Gaps in the Basement Complex. Pre-Drilling Hydrogeological Investigations in Areas X, XI and XII, Final Report, Vol I and II	1982
2	"	Niger-Techno Ltd in association with Technosynesis.	Pre-Drilling Hydrogeological Investigations, Area XII, Final Design.	1978
3	"	BRGM (Nigeria) Metal and Minerals (Nigeria) Ltd	Hydrogeological Investigations in the Sedimentary Basins - Areas XVIII and XIX (Coastal Plains and Niger Delta), Final Report Vol.2	1979
4	"	Geco Engineering Company (Nig) Ltd.	Geophysical Investigations for the location of suitable sites for drilling of prodictive boreholes in the Basement Complex of Nigeria, Vols.IV, V and VI, Lot 2 Ogun, Ondo and Bendel States.	?
5	Ogun-Oshun RBRDA	Syscon and Associates	Monitoring and Management of Hydrometric stations. Wells and BOreholes in Ogun Oshun River Basin, Region 14, Phast II Progress Report.	1984
6	"	Skoup & Co. in association with Hydronamic & NEDECO	Oshun River Basin Study, Pre-Feasibility Report.	1874

ONDO STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	Dubon -Project Engineering PVT Ltd in association with Alolis Geo-Sciences (Nig) Ltd.	Studies to illl in data gaps in the Basement Complex Pre-Drilling Hydrogeological Investigations in Areas X, XI and XII. Final Report, Vols. I and II.	1982
2	"	BRGM (Nigeria) Metals and Materials (Nigeria) Ltd.	Hydrogeological Investigations in the Sedimentary Basins - Areas XVIII and XIX (Costal Plains and Niger Delta) Final Report Vol.2	1979
3	"	Geco Engineering Co. (Nig) Ltd.	Geophysical Investigations for the Location of Suitable sites for drilling of productive boreholes in the Basement Complex of Nigeria Vols.IV, V and Vi, Lot 2 Ogun, Ondo and Bendel States.	?

OYO STATE

Nr	Cline	Consultant/ Author	Title	Date
1	FMWR	Dubon Project Engineering PVT Ltd. in Association with Alolis Geo-Services (Nig) Ltd.	Studies to fill in data gaps in the Basement Complex. Pre-Drilling Hydrogeological Investigations in Areas X, XI and XII, Final Report (Vols. I andII) and Album (Vol. III)	1982
2	"	Niger-Techno Ltd. in association with Technosynesis	Pre-Drilling Hydrogeological Investigation, Area XII, Final Design	1978
3	"	BRGM (Nigeria) Metal and Minerals (Nigeria) Ltd	Hydrogeological Investigations in the Sedimentary Basins - Areas XVIII and XIX (Coastal Plains and NIger Delta) Final Report Vol.2	1979
4	"	Eptisa	Geophysical Investigation for the Location of Suitable Site for Drilling Productive Boreholes in the Basement Complex Areas of Nigeria. Lot No.9. Oyo State, Vols. I, II & III	?
5	Ogun-Oshun RBRDA	Syscon and Associates	Monitoring and Management of Hydrometric Stations. Wells and Boreholes in Ogun-Oshun River Basin, Region 14 Phase II Progress Report	1984
6	Ogun-Oshun RBRDA	Skoup & Co Ltd. in cooperation with Hydronamic and NEDECO	Oshun River Basin Study. Pre-Feasibility Report	1974
7	-	Asseez, L.O.	Hydrogeology of South-Western Nigeria. The Nigerian Engineer Vol.7, No.1	1971
8	-	GSN (Carter, J.D)	Water Supply of the Western Region, GSN REport No.1185	1964
9	-	GSN (Jones, H.A.)	The Geology of the Part of South-Western Nigeria. GSB Bull.37	1964

PLATEAU STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	German Consult/ GWE/Insumma/PHI	Pre-Drilling Hydrogeological Investigations, Area IV	1978
2	"	OSOT Associates	Pre-Drilling Hydrogeological Investigations, Study Area V	1982
3	"	German Consult/ GWR/Insumma/PHI	Pre-Drilling Hydrogeological Investigations, Phase I, Area V, Report and Appendix (Data)	1978
4	" "	Basil and Associates Ltd. in association with Basil Geotechnics S.A.	A Pre-Drilling Hydrogeological Investigation, Study Area XVI, Benue Valley. Vols. I, II and III.	1979
5	"	Polservice Consulting Engineers in association with Geoconsults	Pre-Drilling Hydrogeological Investigations, Area XVII Final Report (3 vols.)	1979

RIVER STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	BRGM (Nigeria) Metal and Minerals (Nigeria) Ltd	Hydrogeological Investigations in the Sedimentary Basins - Areas XVIII and XIX (Coastal Plains and Niger Delta) Final Report Vol.2	1979

SOKOTO STATE

Nr	Client	Consultant/ Author	Title	Date
1	FMWR	OSOT Associates Consulting Engineers	Pre=Drilling Hydrogeological Investigations, Data Gap Filling Study, Area 1, Final Report	1982
2	"	Niger-Techno Ltd in association with Technosynesis S.p.A. and Geo-expert Sp.A.	Pre-Drilling Hydrogeological Investigations, Area I, Final Design	1978
3	"	Niger-Techno Ltd in association with Technesynesis S.p.A amd Geoexpert S.p.A.	Pre-Drilling Hydrogeological Investigations, Area II - Final Design	1978
4	"	OSOT Associates Consulting Engineers	Pre-Drilling Hydrogeological Investigations, Data Gap Filling, Study Area II, Final Report.	1982
5	"	German Consult/ GWE/Insumma/PHI	Pre-Drilling Hydrogeological Investigations, Phase I, Area III, Report and Appendix (Data)	1978
6	"	OSOT Associates Consulting Engineers	Pre-Drilling Hydrogeological Investigations, Report and Appendix, Area III	1976
7	"	Unecon A Associates	Monitoring and Management of Hydrometric Stations and Bore-Holes in Sokoto-Rima Basin, Zone A. Final Report	1984
8	?	FAO/UNDP	Soil and Water Resources Survey of the Sokoto Valley, Final Report FAO/SF.67/NIR3.	1969
9	Ministry of Natural Resources Govt. of North Western State	Dar Al Handasah Consultants/ Shair and Partners	State-side Water Resources Development: Selected Locations for Reservoirs and Boreholes	1973

SOKOTO STATE (Contd.)

10	Sokoto Rima River Basin Authority	USGA in cooperation with GSN.	Water Supply Paper 1757-L, Aquifers in the Sokoto Basin, North-Western Nigeria, with a description of the General Hydrogeology of the Region	1973
11	S. State W. Board	MRT Consulting Engineers (Nig.) Ltd.	Sokoto Water Supply Extensions.	1979
12	?	Impresit Bakolori (Nigeria)	Gagare and Bunsuru River Basin Project, Feasibility Studies Report on Existing Hydrological and Meteorological Stations	1980
13	?	Progress Engineering	Reactivation of Hydrological Stations, Sokoto - Rima Basin	1980
14	Sokoto Rima River Basin Authority	Prof. C.A. Kogbe, Dept. of Geology, A.B.U.	Geology of the South-Eastern (Sokoto) Sector of the Jullemmenden Basin	1979
15	"	Electrowatt Engineering Services Ltd.	Water and Land Resources Feasibility Study, Vol.2, Skemanker River Basin Development (Draft)	1978
16	Geological Survey of Nigeria	USGS and GSN .	Exploratory Drilling for Groundwater in Western Sokoto Province, Nigeria, with particular reference to artesian aquifers in Gwardu Formation.	?
17		GSN (Ako B.D., Onwausor E.O. & Akano N.)	Resistivity survey for groundwater near Zuru town, North-western State. GSN Report No.1510	1973
18	FMWR	Polservice Consulting Engineers in association with Geoconsults	Pre-Drilling Hydrogeological Investigations Area XIII Final Report (2 vols.)	1979