GROUNDWATER SURVEY (KENYA) Ltd.

UNDP/World Bank Community Water Supply Project

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Well Siting for Low-Cost Water Supplies (Volume 1)

INVENTORY OF WELL SITING METHODS

Final Report

Hydrogeological & Geophysical Investigations

UNDP/World Bank Community Water Supply Project

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Final Report

Groundwater Survey (K) Ltd
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Summary

A comprehensive inventory of the application of hydrogeological and geophysical investigation techniques for low-cost community water supply (CWS) projects has been undertaken by Groundwater Survey (Kenya) Ltd, commissioned by the UNDP/World Bank Rural Water Supply Handpumps Project.

The objective of this study on well siting techniques is to provide information on the use and cost of various investigation methods. It presents an overview of methods, field procedures and costs, and evaluates the cost-effectiveness of well siting in light of well construction results.

Questionnaires were sent out in early 1987 to 150 governmental and non-governmental organizations, as well as to consultants involved in CWS projects, mainly in Sub-Saharan Africa, and to manufacturers of geophysical equipment worldwide. First-hand information has been acquired of nearly 40 CWS handpump projects, while additional projects were studied through project reports and other relevant literature.

Analysis of the data reveals that proper well siting can significantly increase drilling success rates. Systematic groundwater investigations are successful particularly in Basement Complex areas, with drilling success rate increases of between 10 and 40 percent using hydrogeological data inventory, aerial photo interpretation, hydrogeological fieldwork and geophysical methods. The data for volcanic and sedimentary areas is less conclusive, although significant improvements in the drilling of productive wells are reported. Hydrogeological reconnaissance was applied in most CWS projects, geophysical surveys in 76% , mostly resistivity profiling and soundings, and to a lesser extent also EM and VLF profiling. Seismic refraction surveys have been applied in only a few projects. The combination of a profiling technique with the resistivity sounding method has proven to be a powerful and cost-effective well-siting tool.

The cost of geophysics ranges for the studied projects from US $50 to $3000 with an average of $610 per site. The cost of a site investigation generally amounts to approximately 10 percent of the borehole drilling cost. It is found that the expense for well siting is justified in many cases, as the amount of 'dry' wells are reduced by more than 10%. In unconsolidated areas test drilling by hand is a cost-effective alternative method of investigation.

Given the enormous need for adequate and clean water supplies in the rural areas of the developing world, the challenge remains to take systematic hydrogeological and geophysical well siting out of the almost exclusive preserve of overseas consultants and to spend more energy and finances on the training of local hydrogeologists and geophysicists.

This Final Report (Volume I) is accompanied by a 'Well Siting Guide' (Volume II) which gives a comprehensive overview of systematic well site investigations for low-cost water supplies, based on the lessons drawn from this Study.

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1 Introduction

1.1 Background to the Study

The Community Water Supply for Low-Income Communities, previously designated as the Rural Water Supply Handpumps Project, of the UNDP and World Bank seeks to promote the reliability and cost reduction of rural and urban-fringe point-source water supply systems in order to achieve a wide-scale coverage. Such systems must be affordable to the great majority of the rural populations in order to achieve the required diffusion of improved water supplies. Groundwater wells with handpumps have proven to be among the most realistic options to meet this objective and are therefore an important component of the Community Water Supply Project.

One of the issues that has come up for further study concerns the application of hydrogeological and geophysical investigation techniques for the siting of drilled and dug wells. In addition to management and maintenance problems, deficiencies in community water supply programmes (CWS) often are caused by inappropriate location and design of the wells. According to one source: "Despite the huge investments being made in project implementation, it is common to find that no one in project management has significant training in hydrogeology, despite its obvious application in groundwater resource development" (Grey et al., 1985).

In order to better understand the need for and use of hydrogeological input in the siting and construction phase of wells, the World Bank commissioned Groundwater Survey (Kenya) Ltd. in Nairobi in January 1987 to carry out a comprehensive study of well siting methods currently in use and to prepare a handy reference booklet for all those involved in rural water supply programmes (see section 1.4).

1.2 Objectives

The aim of the study is to undertake a comprehensive inventory of the experience obtained by a large number of rural water supply programmes with the application of hydrogeological and geophysical investigation techniques for the siting of drilled and dug wells. This is supplemented by information gathered on the current state-of-the-art techniques and available equipment for well site investigations through a review of available project reports, publications and papers, as well as through an inventory of geophysical equipment.

The inventory is intended to give a general overview of the most common site investigation techniques and the circumstances under which these are applied. It provides the background for an analysis and discussion of the wider suitability of hydrogeological and geophysical investigation techniques in rural water supply programmes in a variety of hydrogeological environments. Given the financial constraints of most water development projects and the need for a wide-spread diffusion of improved water supplies, a number of basic questions have been formulated which need to be answered:

- Are hydrogeological and geophysical investigations really needed for site location?
- If so, which methods are most suitable under the given circumstances?
- How much field investigation is needed per well?
- What are the costs?
- What skills and equipment are required?

The central question is:

- Is the application of hydrogeological and geophysical site investigation techniques justified through a higher success rate of dug and drilled wells.

1.3 Approach

The study involved the following activities:

- A comprehensive inventory and review of available literature.

- Assessment of experience with well siting obtained in programmes carried out in the region at present or completed in the recent past. To this end comprehensive questionnaires were prepared and sent out to current projects.

- Field visits to CWS programmes being undertaken in Kenya at the present time.

- A comprehensive study and evaluation of available equipment, its cost, suitability and technical specifications.

- Evaluation and reporting of the results in this draft final report, which after review is to be published as a Technical Note of the Project.

Three different questionnaires were prepared (listed in Appendix 2) and were sent out to:

- those directly involved in the technical execution of well siting, primarily non-government consultancy firms and specialized government departments (questionnaire No. 1);

- bi-lateral, multi-lateral, and non-governmental organizations involved in sponsoring and sometimes execution of CWS projects (questionnaire no.1 and questionnaire No. 2);

- suppliers and manufacturers of geophysical equipment (questionnaire No. 3).

The data collected from the completed and returned questionnaires concerning the various water supply projects has been tabulated and listed in the Appendices and is analyzed in Chapter 2. Information on geophysical equipment obtained from suppliers and manufacturers of specialized equipment is presented in Chapter 3. Selected literature on the use of the most common well-siting techniques is reviewed in Chapter 4. Chapter 5 discusses the gathered data in light of the questions posed above and draws conclusions about the applicability and validity of experiences to well siting in general.

1.4 Well Siting Guide

Based on the results of this study, an accompanying 'Well Siting Guide' has been produced, introducing and rationalizing the use of well siting techniques for planners and managers of rural water supply programmes. The Guide presents a systematic approach to well siting which involves a detailed description of the various levels of investigation and suitable methods. It discusses the suitability of the various possible methods in the context of several case studies taken from the respondents to the questionnaires described above. Specific attention is given to determining the financial feasibility of applying the various levels of investigation against the potential benefits. Basic hydrogeological and geophysical principles and terminology are explained in the appendices of the Guide. Prior knowledge of these techniques is not assumed.

2 Questionnaires

2.1 Response

A total of 147 letters with attached questionnaires have been sent out to consultants, government and non-government agencies, and manufacturers and suppliers of geophysical equipment. Most of this was sent out in February 1987 with a few additional inquiries sent in the months following.

Initial response to the letters and questionnaires was slow, with only 29 replies having been received by the middle of May 1987. It was therefore decided to send out a number of letters to remind key agencies of the study's interest in their experiences in the field of well siting. By the end of May 49 form-letter reminders were sent out, while additional individual reminders have been since that date. In a number of instances questionnaires had been forwarded to third parties by the addressees and when this was indicated an individual request for completion and return of the relevant questionnaire was sent. Several follow-up letters were also sent to request clarification of particulars of the returned questionnaires, but it soon became apparent that a number of questions were liable to multiple interpretation and short of sending out a new batch of questionnaires or explanatory notes, which was not considered feasible, this could not be corrected. Table 1 below gives an overview of the total response. The complete list of respondents is given in Appendix 3.

Table 1 Response to well siting questionnaires

Type	Sent	Reminders	Replies				Completed Quest.		
			Pos	Neg	Tot	N/R	No. 1	2	3
Consultants	67	33	23	11	34	33	54	1	
Organizations	53	24	13	10	23	30	14	6	
Suppliers & Manufacturers	27	4	15	1	16	11			9
Total	147	60	51	22	73	76	68	7	9

N/R - No Reply

Nearly 50 percent of those that received a questionnaire have responded of whom 35 percent favourably. Most returned one or more completed questionnaires and/or sent along specific project documentation.

Questionnaire No 1

Most of the 68 completed No. 1 questionnaires directly concern rural water supplies with handpump abstraction. The No. 1 questionnaires can be subdivided as follows:

- 40 questionnaires concern rural water supplies with manual abstraction (mostly handpumps); this includes 2 overlaps, i.e. 2 times 2 questionnaires describe the same project; and 2 questionnaires concerning projects which at the time of the reply had not yet started with the siting process, describing expectations rather than findings.
- 1 questionnaire which does not clearly indicate what kind of project it is (but for convenience sake is include in the above category).
- 7 questionnaires concern primarily general groundwater assessment studies; the provision of rural water supplies is only indirectly involved, when test boreholes are equiped to become productive boreholes.
- 15 questionnaires concern primarily projects with high-yielding wells for urban piped-water supplies; They include 1 overlap and 3 questionnaires which describe separate areas within the same project, without any distinction in siting method, which are treated as one.
- 5 questionnaires concern geophysical applications for engineering purposes, i.e. a dam site and groundwater corrosivity studies.

The last category is not included for analysis in this study, neither are the two project descriptions based on expectations. The overlapping questionnaires has been used to complement each other. This leaves 56 projects for study, divided into three categories:

1. Well siting for low-cost rural water supplies (37)
2. General groundwater assessment studies (7)
3. Well siting for high-yielding wells (12)

The first category will receive most attention in light of the terms of reference of this study, but as relevant information can also be obtained from the other categories, these are also discussed. The projects are listed in Table 2, alphabetically according to the country in which they are located. For the first category, which falls completely within Africa, this is subdivided into three main regions in order to highlight possible trends and differences between the regions.

To avoid a continuous repetition of long project names, these projects will further be referred to by the number that is given in Table 2.

Table 2 Questionnaire No. 1 project categories, names and regions

PN	COUNTRY	PROJECT NAME	REGION
	WEST AFRICA	**CATEGORY 1**	
1	BENIN	5th EDF Project	
2	BENIN	Village Hydraulics	Atlantique, South Zou
3	BURKINA FASO	Hydraulique Villageoise - Conseil de l'Entente	Oubritenga, Burkina, Passore
4	BURKINA FASO	Hydraulique Villageoise dans l'ORD Sahel	Djibo, Aribinda, Sebba
5	BURKINA FASO	Projet d'Hydraulique Villageoise	Kossi, Mou-Houn, Sourou
6	MALI	Groundwater Drilling	
7	MALI	Projet LEAO Hydraul. Villageoise et Pastorale	Kayes, Yelimane, Niord, Nara
8	NIGER	Programme 1000 Forages	Zinder, Maradi, Liptako
9	NIGER	Sahel-Saudi Programme	Zinder
10	NIGERIA	Kaduna State Water Supply Programme	Rigachikun, Zaria, Pampeguwa
11	NIGERIA	ARDP - Rural Water Supplies	Kano
12	NIGERIA	New Capital Shallow Wells	
13	SIERRA LEONE	Wasser- und Sanitarversorgung	Bo Pujehun
14	SIERRA LEONE	Wasser- und Sanitarversorgung	Bo Pujehun
15	TOGO	Village Water Supply Project	Savanne Plateau
	EAST AFRICA		
16	ETHIOPIA	Rural Water Supply	Several
17	ETHIOPIA	Rural Water Supply	Southern Region
18	KENYA	Borehole Drilling Programme	Meru, Igembe Division
19	KENYA	German Assisted Settlement Scheme - HMSS	Lamu District
20	KENYA	German Assisted Settlement Scheme - LKSS	Lamu District
21	KENYA	Kenya-Finland Rural Water Development Project	Western and Nyanza Provinces
22	KENYA	Mutomo Soil and Water Conservation Project	Kitui District, Southern Div
23	KENYA	Rural Domestic Water Supply & San. Progr.	Nyanza
24	KENYA	Water for Africa - Water for People	Marsabit and Samburu Districts
25	TANZANIA	Implementation of Water Master Plans	Iringa, Ruvuma, Mbeya
26	TANZANIA	Rural Water Supply Project	Mtwara, Lindi
27	TANZANIA	Water Supply and Sanitation Development	Rukwa, Kigoma
28	UGANDA	Emergency Rural Water Supply Project	Luwero Triangle
29	UGANDA	New Borehole Drilling Programme	Soroti
	SOUTHERN AFRICA		
30	MADAGASCAR	Alimentation en Eau dans le Sud	Southern Province
31	MALAWI	Rural Water Supply Project	Central Region, Dowa District
32	MALAWI	Livulezi Rural Water Supply Project	Central Region Ntcheu District
33	MOZAMBIQUE	Rural Water Supply	Cabo Delgado Province
34	ZIMBABWE	Buhera Water Supply	Buhera, Manicaland
35	ZIMBABWE	Int. Rural Water Supply & San. Project	Manicaland
36	ZIMBABWE	Mashonaland Crash Programme	Mashonaland
37	ZIMBABWE	Drought Relief Programme	Victoria Province
		CATEGORY 2	
38	CAMEROUN	Groundwater Exploratory Drilling	Mbam North Basin
39	INDONESIA	Groundwater Survey	Central Java
40	KENYA	Integrated Project in Arid Lands	Marsabit District
41	KENYA	Water Resources Assessment Project	West Pokot, Kerio Valley
42	NIGERIA	Groundwater Investigation	Kaduna State
43	SUDAN	Groundwater Investigation	Kordofan, Darfur, Upper Nile
44	SWAZILAND	Groundwater Project	Low veld
		CATEGORY 3	
45	ABU DHABI	Rural Water Supply	Al Khadar, Al Ain
46	BENIN	13 Small Town Water Supply	
47	BOTSWANA	Western Transvaal Rural Development	Mefeking
48	HONDURAS	Groundwater Supply Interim Stage	Amarateca
49	HONDURAS	Groundwater Supply Interim Stage	Mateo
50	KENYA	Lake Kenyatta Settlement Scheme	Coast Province, Lamu District
51	MALAYSIA	Development of Production Wells	Kedah and Perlis
52	SAUDI ARABIA	Water Supply	Wadi Suleim, Madh Adh Dhahab
53	SOUTH AFRICA (REP)	Western Transvaal Rural Development	Ottosdal
54	YEMEN (PDR)	Dhalla Water Supply	Dhalla
55	YEMEN (PDR)	Greater Aden Water Supply	Abyan Delta, Bir Nasir, Tuban
56	ZAMBIA	Kabwe Water Supply	Kabwe

Questionnaire No 2

Only 7 of the No. 2 questionnaires were returned. In most cases the organizations, which had also received questionnaire No. 1, responded only with No. 1. In 4 of the 7 replies the No. 2 questionnaires were accompanied by the No. 1 questionnaires. The 3 remaining No. 2 questionnaires were sent singly, and have only in one case been followed up with a request for further detail, but without result. The data provided by questionnaire No. 2 does not provide adequate detail to be included in the analysis of questionnaire No. 1.

Questionnaire No 3

Questionnaire No. 3 was sent out to suppliers and manufacturers of geophysical equipment. The results are listed in Chapter 3 and discussed in conjunction with product documentation and relevant publications. While no response was received from some of the major manufacturers, it was possible to obtain product information on the most commonly used equipment from other sources such as equipment suppliers.

2.2 Method of Analysis

The No. 1 questionnaires are analyzed by dividing the 50 questions into several clusters:

-	Project Identifiers	Q1-Q10, Q13, Q14, Q50
-	Geology and Well Characteristics	Q11, Q12, Q15, Q18-Q21
-	Well Siting Procedure	Q24-Q43
-	Well Construction	Q16, Q17, Q22, Q23, Q44, Q47, Q48
-	Success of Siting	Q45, Q46, Q49

The responses to the individual questions are tabulated and compared with the other questions in the cluster. The numerical overview of the response is followed where possible by a statistical analysis comparing the data of the projects to discover possible trends and correlations. The database serving as background to the analysis of the various questions has been quantified, as much as possible, and is listed in the various appendices and referred to where appropriate. Many of the questions, however, are more suited to a qualitative analysis, because of the wide range in answers which do not always lend themselves to a useful statistical analysis. It is clear that averages have only a limited usefulness where the sample sizes drop far below the total number of projects submitted, or where the ranges are very large. However, where appropriate the sample size and standard deviation (SD) will be given as a measure of the usefulness of the data. Where this was possible the data has been complemented and clarified by information taken from the various project reports and relevant publications.

Tabulating the overall response to the individual questions shows that per questionnaire No. 1 an average of 64.1 % of the questions were answered while the remainder where either incomplete (4.3 %) or left unanswered (31.5 %). For the projects which did not use geophysical siting, a number of questions were irrelevant and if those are taken into account of the thus weighted average of answered questions is raised to 68 percent (see Appendix 4.1). The response to the individual questions is looked at in more detail below.

2.3 Project Identifiers

Country, Project Name and Region Q1, Q2, Q5

The Category 1 projects (rural water supply) are all situated in Africa. They are divided into a Western, Eastern and Southern African group, as shown in Table 2. This subdivision is useful to compare the various aspects of well siting between the three regions.

Projects 13 & 14 and 16 & 17 are each related, but differ significantly in many of the replies and are therefore treated as separate projects. Projects will be referred by the project number (PN) given in the table.

Project Objectives Q7

Most projects are primarily and directly focused on the provision of water wells fitted with handpumps. Some of the stated objectives are:

- construction of boreholes with handpumps and the setting up of pump maintenance organizations
- provision of 10, 20 or 27 liters per capita per day (lpcd)
- provision of clean, untreated groundwater within 500m walking distance
- soil and water conservation and rainwater harvesting
- improve health and living conditions through water supply, sanitation, health education and institution building
- 1 handpump per 200 people
- to provide clean protected water supplies & good sanitation
- to provide primary water supply, washing slabs, pit latrines and gardening opportunities.

Some of the objectives of the Category 2 and 3 projects are:

- Location of high-yielding fissures for urban water supply
- Wells for green farming
- Wells for rural/urban/suburban reticulated water supplies.

Executing and Sponsoring Agencies Q3 & Q4

In most of the projects a substantial amount of external expertise and finance is involved. This paragraph gives an overview of the agencies engaged in the execution and sponsoring of water supply projects and is based on the data listed in Appendix 4.2. Four types of agencies can be distinguished which each take a share of the execution of the projects, as listed in Table 3.

Table 3 Share of project execution[1]

	WA	EA	SA	TOT
Category 1 Projects:				
National Government Organizations	12%	46%	31%	29%
Bilateral Organizations	23%	8%	13%	15%
Multilateral Organizations	0%	8%	0%	3%
Consultants	65%	21%	38%	42%
Non-Government Organizations	0%	17%	19%	11%
	100%	100%	101%[2]	100%
Category 2 Projects:				
National Government Organizations				30%
Bilateral Organizations				40%
Multilateral Organizations				20%
Consultants				10%
Non-Government Organizations				0%
				100%
Category 3 Projects:				
National Government Organizations				8%
Bilateral Organizations				4%
Multilateral Organizations				0%
Consultants				88%
Non-Government Organizations				0%
				100%
All Projects:				
National Government Organizations				24%
Bilateral Organizations				15%
Multilateral Organizations				4%
Consultants				50%
Non-Government Organizations				7%
				100%

WA - West Africa; EA - East Africa; SA - Southern Africa

[1] Not always exclusive, often in combination with other agencies

[2] small rounding error

It was not possible to differentiate between the well siting process and associated project work, such as well construction. In Section 2.5 well siting and the agencies and expertise involved in it will be discussed separately. No clear indication was given of any project being executed solely by national government agencies, while the prevalent involvement of private sector (consultancy bureaus, engineering firms, etc.) is marked. It was not possible to quantify the exact division of the project execution when more than one executing agency is involved. In such a case an even division has been assumed. The consultants especially play a large role in projects requiring wells with a high yield, probably justifying the assumption that the level of technical expertise required by such projects is not yet generally available in the project countries. Execution by Bi- and Multilateral Organizations and Non-Government Organizations does not exclude subcontracting to the private sector, but where not otherwise indicated it is assumed to have been carried out by experts directly in the employ of such organizations.

The sponsoring agencies can be similarly divided into local and external agencies. They are listed in Table 4 with their respective share of the funding.

Table 4 Share of project sponsoring

	WA	EA	SA	TOT
Handpump Projects:				
National Government Organizations	15%	12%	21%	15%
Bilateral Organizations	36%	39%	38%	37%
Multilateral Organizations	49%	28%	30%	37%
Non-Government Organizations	0%	22%	11%	10%
	100%	101%[1]	100%	99%[1]
Investigation Projects:				
National Government Organizations				31%
Bilateral Organizations				69%
Multilateral Organizations				0%
Non-Government Organizations				0%
				100%
Non-Handpump Projects:				
National Government Organizations				47%
Bilateral Organizations				53%
Multilateral Organizations				0%
Non-Government Organizations				0%
				100%
All Projects:				
National Government Organizations				23%
Bilateral Organizations				43%
Multilateral Organizations				26%
Non-Government Organizations				7%
				99%[1]

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[1] small rounding errors

The distribution of funding between local and external sources is somewhat easier to quantify than the division in execution, as information concerning the local and outside component of the budget was explicitly requested in the questionnaire. 62.5% answered this question and concerning two other projects budget information could be obtained from the project reports, showing the type of donors. The budget amounts are discussed in the next paragraph. Two projects appear to have been funded with national government money only (PN 10 & PN 51), one of which was subsequently discontinued due to a lack of funds. The funding of two other projects is also stated as local (PN 42 & PN 43), but in all likelihood involved bilateral (East European) sponsorship. In one case (PN 13) funding was withdrawn before project completion, because the executing agency failed to reach agreed objectives.

Project Area, Time Period, Budget, Number of Wells Q6, Q8-Q10, Q13-Q14

The projects from which questionnaires were returned were primarily large area, large budget projects. The questionnaires of all three categories together represent a stated amount of nearly US $250 million. None of the respondents sent information about small-scale projects, i.e. concerning the siting of only a few handpump wells. Of 28 handpump projects 24 had budgets over 1 million US $ (2 of which include funds for sanitation development) with an average of $7.4 million per project (see also Appendix 4.2). Because the duration of the projects varies this amount can be divided by the average project length which then shows an expenditure of $2.2 million per project per year. Similarly, the budget amount can be compared to the number of wells planned (for ongoing projects) or constructed (for completed projects) during the particular budget period, in order to establish the expenditure per well. This yields some interesting results, as is shown in Table 5.

Table 5 Cost per well

Category/Region	Ave Budget[1]	Ave Cost/well[2]	R[3]	Sample	No/Wells
Category 1:					
West Africa	$ 8.23	$ 12 000	0.89	12	6921
East Africa	$ 9.58	$ 10 095	0.94	8	7969
Southern Africa	$ 1.27	$ 2 766	0.92	6	2751
Subaverage	$ 7.08	$ 10 903	0.88	26	17741
Category 2:	$ 4.40	$ 16 694	-	2	530
Category 3:	$ 2.23	$ 81 091	0.99	4	110

[1] Million US dollars

[2] Total project budget divided by number of wells

[3] Correlation between project budgets and number of wells (see text)

The average values given in the questionnaires and again averaged in the table hide the fact that individual well costs can va significantly, according to varying siting expenses, drilling cost depths of the individual wells, materials used and cost of handpump. Except for the cost of drilling which will be discussed later, no information to further quantify this variation is available. However, as the averages mainly concern large projects, the average values are considered useful for comparison between the different regions and categories.

The well costs for handpump projects are lower than those wells constructed in investigation projects, and significantly lower than the costs of high yield wells. More funding is generally available for wells for irrigation or large reticulation systems which require more sophisticated construction to optimize yields and reliability.

The high correlation factor for each of the three regions of Africa under Category 1 does indicate however that a clear pattern of well costs exists, which as shown in Figure 1 is clearly different for the three regions. The same budget in Southern Africa results in almost four times as many wells as in East or West Africa. The significance of this will be discussed later in relation to the economic justification for the use of well siting methods in the three regions. It is also evident that a number of projects are clearly more economical or less economical than the average of the region as shown by their respective distances above and below the median line. It should however be remembered that the given figures represent in a number of cases budgeted figures which differ from the actual programmes carried out. PN 13 for example appears very economical for the West African situation, but was in fact discontinued because it could not live up the targets set in the planning phase. PN 14, its successor, was more expensive, but in line with the regional averages and is reported to be significantly more successful. A similar explanation can be given for PN 26 in East Africa which appears to be significantly more economical than other projects in the region, but the project consists mainly of the construction of (machine) dug wells with a success rate of about 50 %. By dividing the budget over only the successful wells the project cost per well would be more in line with the regional average. Three projects are clearly less economical than their regional counterparts, i.e. PN 2 in West Africa and PN 17 and 25 in East Africa. In the case of PN 2 this is somewhat mitigated as instead of the planned 130 boreholes as shown in Figure 1 an actual 180 were drilled. No information is available to suggest why PN 17 and 25 are rather expensive (especially in the latter case the high costs are curious, since most wells are drilled by hand and very little geophysics is used, and well casing and screens are made locally).

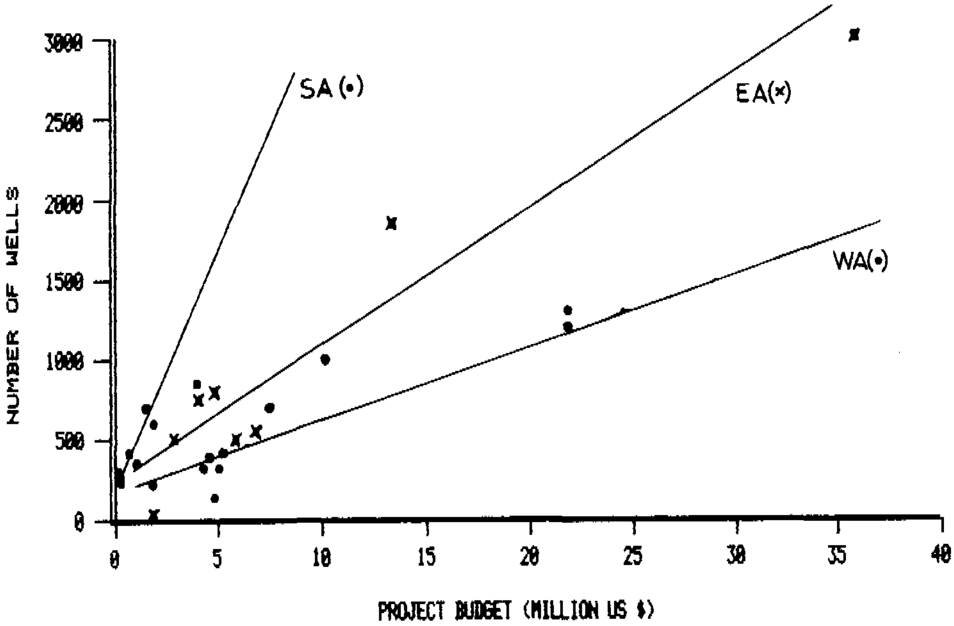

Figure 1 **Correlation between number of wells and the project budget for the different regions**

The Category 1 project areas vary in size from approximately 100 km² to nearly 180,000 km² (average 37,845km²).

Project Reports Q50

Most projects have produced reports, although it is not clear if these in all cases paid specific attention to hydrogeology and well siting. A number of project reports, individual site reports and/or publications concerning projects were sent along with the questionnaires and these will be discussed, where relevant in more detail in Chapter 3.

2.4 Geology and Well Characteristics

Q11, Q12, Q15, Q18-Q21

The questions of geology and well characteristics give an overview of the occurrence, properties and distribution of the different types of aquifers used for rural water supplies. The basic data is listed in Appendix 4.3, while Table 6 below gives an overview of average values for geology, well depths, water levels, yields and water quality for the different regions of Africa and for the different project types.

Table 6 Geology and well characteristics

	Alluvium	Sediment	Volcanics	Basement	Alluvium	Sediment	Volcanics	Basement
		(Project Average)				(Well Average)		
Geology Distribution								
West Africa	7.3%	27.3%	4.4%	61.0%	6.4%	32.2%	2.2%	59.1%
East Africa	4.1%	34.8%	14.1%	45.3%	5.7%	28.9%	7.2%	58.2%
Southern Africa	0.6%	6.3%	3.8%	89.4%	1.7%	12.2%	5.5%	80.6%
Category 1	4.7%	25.2%	7.7%	62.4%	5.3%	27.5%	4.9%	62.3%
Category 2	20.2%	36.9%	7.3%	35.6%	13.3%	30.8%	5.0%	50.9%
Category 3	4.2%	33.9%	16.7%	45.2%	12.4%	60.5%	11.2%	15.9%
Total	6.6%	28.2%	9.2%	56.1%	5.7%	28.1%	5.0%	61.2%
Well Depth (meters below ground level)								
West Africa	21.5	64.0	69.5	46.3	7.2	59.2	64.7	51.0
East Africa	31.0	70.4	80.0	54.0	18.0	32.9	117.4	60.5
Southern Africa	5.0	28.8	100.0	31.4	5.0	16.3	100.0	33.8
Category 1	21.9	62.8	79.9	44.6	7.2	47.9	103.3	49.4
Category 2	63.0	78.0	55.0	63.9	56.7	75.9	55.0	60.3
Category 3	44.0	44.3	90.0	93.3	43.4	44.4	102.9	106.0
Total	29.8	61.6	79.5	51.0	10.1	48.4	102.9	50.7
Water Level (meters below ground level)								
West Africa	5.7	20.2	10.0	15.7	3.2	21.1	10.4	14.6
East Africa	12.5	43.7	42.8	20.8	7.4	21.1	84.9	22.1
Southern Africa	3.0	10.3	20.0	10.9	3.0	7.5	20.0	14.6
Category 1	7.5	30.7	31.8	16.2	3.3	20.1	56.0	16.9
Category 2	10.0	31.0	20.0	16.3	9.0	29.1	20.0	15.2
Category 3	3.1	19.3		55.0	3.1	8.5		37.0
Total	7.3	29.0	30.4	18.9	3.3	19.2	55.7	17.0
Well Yield (cubic meters per hour)								
West Africa	1.9	5.1	3.0	2.1	0.4	4.9	2.9	2.7
East Africa	3.0	5.9	12.1	3.2	2.4	5.4	18.0	3.3
Southern Africa	2.0	1.8	4.0	1.8	2.0	1.9	4.0	2.1
Category 1	2.3	5.0	8.8	2.4	0.6	4.8	11.9	2.6
Category 2	22.0	5.9	10.0	2.6	19.8	8.3	10.0	2.9
Category 3	8.6	30.0	50.0	133.4	8.5	24.0	37.1	217.0
Total	5.5	8.8	16.4	18.8	1.3	5.8	13.0	3.9
Electrical Conductivity (uS/cm)								
West Africa	600	750	660	481	694	590	658	516
East Africa	1100	2194	700	800	1418	1664	398	678
Southern Africa				1119				948
Category 1	850	1472	690	736	710	841	494	639
Category 2	1500		1000	1400	1350		1000	1709
Category 3	160	360	550	500	158	368	571	500
Total	843	1194	694	797	676	796	517	671

The project averages are compared to averages calculated by taking the number of drilled wells per project into account, the so called weighted average or well average[1]. The results for the handpump projects are illustrated in Figures 2 - 6.

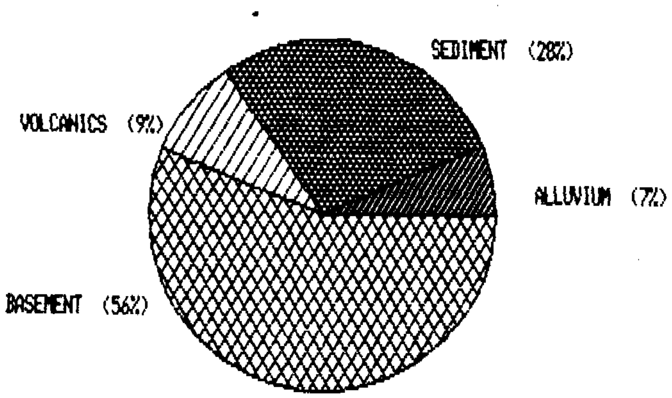

Figure 2 Occurrence of aquifer types in Category 1 projects (Well Averages)

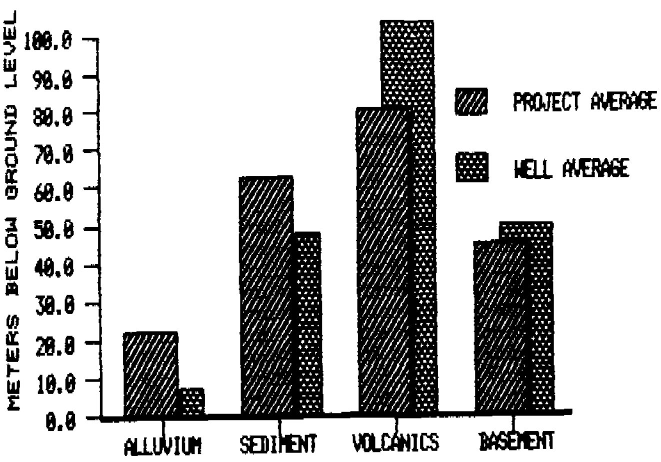

Figure 3 Average well depths

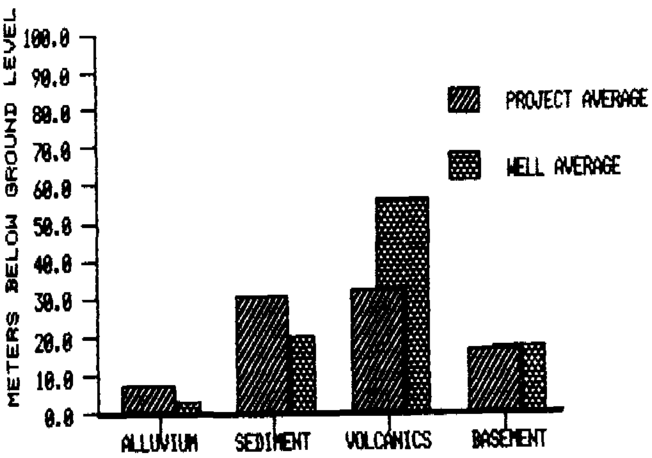

Figure 4 Average water rest levels

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[1] The figures based on project averages compare the basic values (well depth, water level, etc.) per variable (i.e. geology types) with equal weight for each project. The figures based on well or weighted averages take into account the number of wells associated with each variable and averages the values of the number of wells listed under each variable. In the latter case the projects with more wells influence the average more heavily than the smaller projects. The sample size in the first case, i.e. project average, is the number of projects, in the second case it is the number of wells.

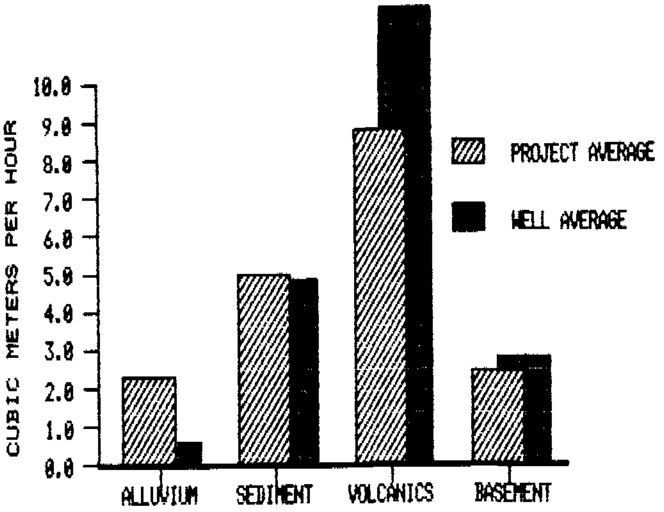

Figure 5 Average well yields

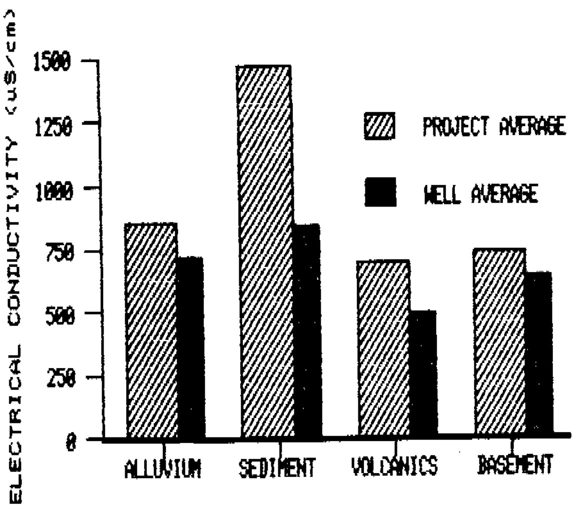

Figure 6 Average water EC

The majority of Category 1 projects (i.e. of those who answered the geology and well questions in sufficient detail and representing in this case over 7000 wells[2]) are located in Basement areas. This is followed by Sedimentary areas (over 3000 wells), with relatively few wells in Alluvial and Volcanic areas (435 and 606 wells respectively). The well depth and water level data suggests that volcanic areas require deepest drilling and high lift handpumps, especially in the East African projects. The difference between drilled depth and water rest levels is probably due to both the need to drill deeper than the level at which water is first struck, to ensure adequate yield allowing for a significant drawdown and to provide a safety margin in periods of drought. To some degree the difference may also be due to confined aquifer conditions. In practically all cases the drilling depth is 2 to 3 times greater than the depth to the water level.

The average yield in volcanic areas is significantly higher than elsewhere, although this is mainly due to the high yields in volcanics in East Africa. Sedimentary areas are characterized by relatively high yields, but significantly higher electrical conductivity (EC) values. The EC of volcanic water is the lowest, although a high fluoride content is characteristic for the volcanics in East Africa.

2.5 Well Siting Q24-Q43

The main objective of the present study on well siting techniques is to provide information on the use and cost of various investigation methods and to analyze their cost effectiveness. This section presents

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[2] It is assumed that the well characteristics given in Q18 - Q21 are representative of all wells in the project according to the geological distribution listed in Q12, unless otherwise stated. Especially regarding the question on water quality fewer than the total number of wells constructed is generally sampled or monitored unless large-scale contamination is suspected.

an overview of the methods, field procedures and costs, while a later section will evaluate the cost-effectiveness in light of well construction results.

Table 7 Use of siting methods

	NO OF	SITING METHODS																
	WELLS	NO	LK	DV	GI	AP	LS	ES	RS	RP	SR	EM	VL	GV	MG	AG	GR	OT
Category 1																		
West Africa	6014	0	3	1	10	11	1	1	11	10	1	2	4	0	1	0	0	0
East Africa	5861	1	10	5	9	4	3	4	7	2	3	1	0	0	1	0	0	2
Southern Africa	1837	0	5	0	7	6	2	1	6	4	0	1	1	0	0	0	0	1
Subtotal	13712	1	18	6	26	21	6	6	24	16	4	4	5	0	2	0	0	3
Category 2	489	0	1	0	6	5	2	2	7	3	3	3	2	2	3	1	0	1
Category 3	302	0	3	0	9	9	2	4	10	6	2	3	3	1	0	0	0	0
Total	14503	1	22	6	41	35	10	12	41	25	9	10	10	3	5	1	0	4

Legend:
NO - No Siting
LK - Local Knowledge
DV - Water Divining/Dowsing
GI - Geological Information
AP - Aerial Photo Interpretation
LS - Landsat Imagery
ES - Earlier Studies
OT - Other

RS - Resistivity Sounding
RP - Resistivity Profiling
SR - Seismic Refraction
EM - Electromagnetics
VL - Very Low Frequency EM
GV - Gravimetry
MG - Magnetometry
GR - Ground Radar
AG - Airborne Geophysics

Methods Q24

All the respondents answered the question concerning the type of siting methods used in the project by checking one or more of the listed possibilities. The graph in Figure 7 illustrates the total number of times each method is used in the different regions and categories and is based on the information in Table 7. The data for the individual projects is listed in Appendix 4.4. For most projects it was not possible to discern whether the listed investigation methods were used for all or only part of the total number of wells, nor on what basis such a distinction would be made.

No Siting

None of the projects indicated that well locations were chosen absolutely random. For 4 handpump projects local knowledge was the main siting criterion, i.e. the local population mainly determined the location of the well. It is not certain whether this was actually based on local knowledge of the area's groundwater presence or mainly on the basis of convenience (walking distance, ownership of plot, etc.).

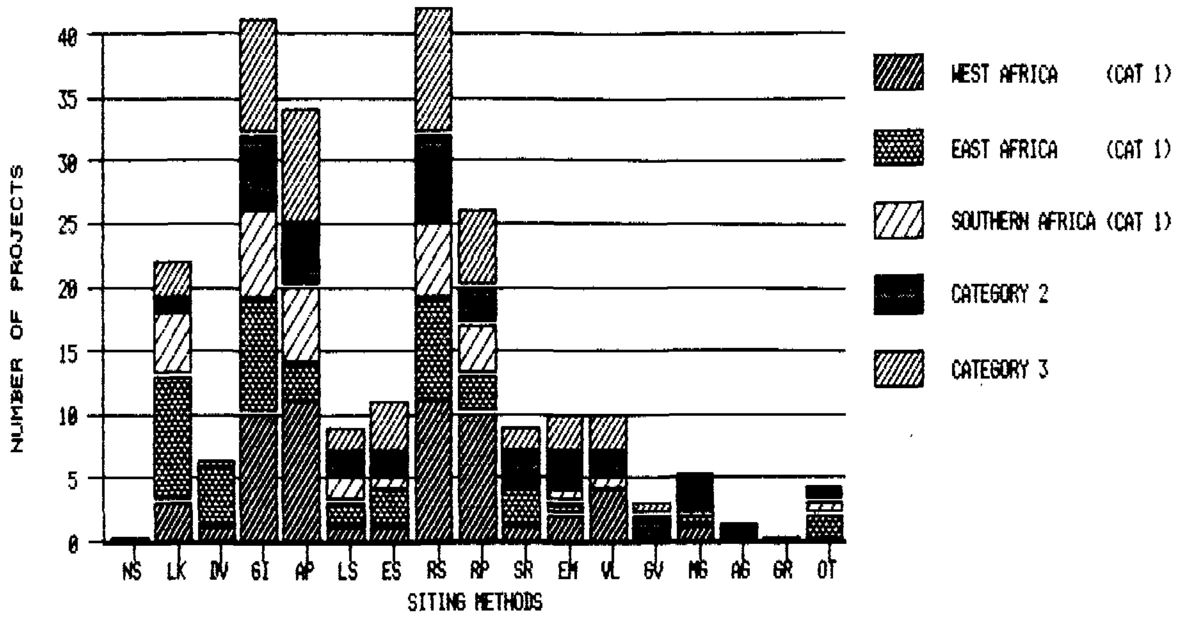

Figure 7 Application of well siting methods in different regions of Africa and for the different Categories

Hydrogeological Investigation

Many projects take the local preference and the local traditional knowledge of groundwater occurrence into consideration and complement this by hydrogeological and geophysical investigations. Ideally in such cases the site proposed by the local people is first investigated to confirm its suitability before additional investigations are carried out elsewhere.

Six projects have used water diviners (dowsers) to locate well sites. For two of these projects divining was used as the main investigative method. Three of the projects involved are executed by the same organization. The largest of these was discontinued due to insufficient successful results. A new project replaced the discontinued project and used geophysical methods.

Geological information was used in most of the Category 1 projects (27 out of 37) and in all the Category 2 and 3 projects[3]. Geological information (without geophysics) is the primarily method of well siting in only three projects. It is often used in conjunction with aerial photo interpretation (17 out of the 27 projects). Satellite (Landsat) imagery is used much less and is mentioned in only 6 projects, in all cases in combination with aerial photography. The question relating to

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[3] One Category 2 and four Category 3 questionnaires were returned by a geophysical subcontractor who only lists the geophysical methods used. It is however likely that local hydrogeological information was gathered during the fieldwork to assist in the interpretation of the measurements.

earlier studies, gave positive answers in 6 of the 37 handpump (i.e. Category 1) projects and were specified in two cases as earlier hydrogeological studies in the area. Three projects listed 'other' investigative methods. In two cases this concerned test hand drilling and in one case hand digging.

Geophysical Investigations

Geophysical investigations were used in 28 of the 37 Category 1 projects. Of these 28, 15 projects combined geophysics with the use of geological information and aerial photo interpretation, 9 combined geophysics with only geological information and 4 projects combined the geophysics with only aerial photo interpretation. As stated earlier, it can not be determined if geophysical methods are routinely applied for all or only part of the total number of wells within a project. However, it can be assumed, in line with common practice, that where hydrogeological investigation and geophysical investigation methods are listed together this implies their combined application for every site.

Table 8 shows the various combinations of geophysical techniques which were applied by the 28 Category 1 projects (see Appendix 4.4). It is clear that the resistivity method is the most popular investigation method. It can be used as a depth sounding method (known as vertical electrical soundings or VES) and as a profiling (traversing or trenching) method for identification of lateral anomalies along the measurement line.

Table 8 Application of geophysical methods in Category 1 projects

Geophysics		
Resistivity, VES only		7
Resistivity, VES and Profiling		8
Resistivity and EM		4
Resistivity and VLF		3
Resistivity and Seismic Refraction		1
Resistivity and Magnetometry		1
Resistivity and Seismic Refraction and VLF		1
Resistivity and Seismic Refraction and Magnetometry		1
Seismic Refraction only		1
VLF only		1
	Subtotal	28
No Geophysics		9
	Total	37

Equipment Q25-Q27, Q38-Q40, Q42

A wide variety of geophysical equipment is used in the all projects. Table 9 lists the various types of equipment and the number of projects in which they are used by the different agencies (see Appendix 4.5).

The question concerning the type of equipment used for geophysical measurements was not completed by all projects and many omitted the cost aspects of the equipment: 80% of all projects which used geophysics provided (some) information on equipment, but only 27% and 29% answered the 'total cost' and 'cost-per-day' questions. The cost figures shown in Appendix 4.5 are most likely country-, agency- and project-specific and should probably not be applied to other situations. More information on equipment and cost will be given in Chapter 4.

Table 9 Use of geophysical equipment

Equipment	Project Category: 1	2&3	Agencies
Resistivity			
ABEM SAS 300 Terrameter (Sweden)	13	10	20
BGS 256 Offset System* (UK)	1	4	2
Bodenseewerke GGA 30 (FRG)	1	1	2
BRGM Syscal Resistivity (France)	6	0	2
Geska (?) (Czechoslovakia)	0	2	1
Jesse (Netherlands)	1	0	1
TNO-DGV GEA 51 (Netherlands)	0	1	0
Seismic Refraction			
ABEM Trio (Sweden)	1	1	2
Bison 1550 (USA)	1	0	1
Bison 2350 B (USA)	1	0	1
EG&G Geometrics ES 125 (USA)	1	0	1
EG&G Geometrics 1210 F (USA)	0	1	1
OYO McSeis (160) (Japan)	1	1	1
Electromagnetics			
APEX Max Min (Canada)	1	1	2
Geonics EM 34 (Canada)	3	3	5
GSO Turam Enslin (RSA)	0	2	1
VLF			
BRGM Syscal VLF (France)	1	0	1
Geonics EM 16 (Canada)	2	1	3
EDA-ERA (Czechoslovakia)	0	1	1
Magnetometry			
BRGM Elsec Proton Magn. (France)	2	0	2
G 816 Proton Magn. (Canada)	0	1	1
Unspecified Proton Magn.	1	0	1
Gravity			
Worden (USA)	0	2	1
Hand drilling			
Morogoro (Tanzania/Netherlands)	1	0	1
Eykelkamp (Netherlands)	1	0	1

* The BGS Offset Sounding System is used in conjunction with a regular resistivity instrument and consists of a multicore cable adaptation for offset Wenner soundings.

Given the fact that agencies which have returned more than one questionnaire are likely to use the same equipment in the various projects they have been engaged in, a project comparison of geophysical equipment is complemented by an agency comparison of equipment. It is notable that especially the ABEM Terrameter is a popular instrument and used by 20 of the 29 agencies which used the Resistivity method. Second on the list is the Geonics EM 34 which is used by 5 of the 8 agencies that apply Electromagnetics, all five using it in combination with the Terrameter (combining Resistivity soundings with EM profiling).

A number of agencies mentioned that they were able to borrow or rent equipment instead of purchasing it. Especially for the smaller projects this alternative, where available, is a good way to avoid the high initial investment cost.

The equipment mentioned so far primarily concerns equipment to carry out geophysical fieldwork. Other types of equipment is also mentioned in the questionnaires:

- For standard stereoscopic aerial photo interpretation (and certain types of SPOT satellite imagery; not Landsat images) a pocket or desk stereoscope is required.

- For hydrogeological fieldwork in two cases hand drilling sets are mentioned. The Eykelkamp is a 70 - 100mm lightweight auger set for test drilling operations and the 'Morogoro' type which is similar (a heavy duty set also exists for well construction purposes with diameters up to 300mm or 12 inch).

- Evaluation of the geophysical measurements usually requires computation and computerization. This is discussed under Evaluation.

Field Crews Q28-Q30

Of the 25 Category 1 projects which provided information concerning the composition of geophysical field crews (see Appendix 4.6), 18 stated that either a geologist or geophysicist was part of the crew (most questionnaires did not indicated which of the two). Two other projects indicated that both were present and two had geological/geophysical supervision from the project office. Of the 10 projects which listed the training background, there were 5 MSc-s and 5 BSc-s with experience ranging from 3 to 15 years (only 4 answers). The geophysical instrument operators are mostly trained on-the-job, while labourers are basically unskilled. Average crew size amounts to 6 people (1 expert, 1 operator, 1 driver and 3 labourers) in a range from 1 (1 geophysicist with VLF equipment) to a crew of 10 (1 geologist, 1 geophysicist, 2 operators, 1 driver and 5 casuals for resistivity and magnetometric surveying). Average crew costs per day amount to $325 in a range of $20 to $1250, with no correlation between crew sizes and costs.

Geologists or geophysicists were used in all but one of the Category 2 and 3 projects, where the crews consist on average of 7 members at an average cost of $622 per day, with 3 of the 16 projects far over $1000/day.

Transport Q31, Q32

Most of the crews used one (a few two) four-wheel-drive vehicle at an average cost of $42 per day (11 samples, range $20 to $125), except for the lone VLF geophysicist who used a small motorcycle at $3/day. Profiling techniques are generally light-weight and portable, not requiring vehicle transport for movement along the measurement line.

Output Q33, Q34, Q41

The output per field crew in terms of geophysical measurements per site gives an impression of the extent of investigation per site, while the number of sites per time unit shows how quickly the field investigation is carried out (see also Appendix 4.6). Point measurements, such as resistivity soundings are relatively unambiguous and easy to compare between projects. The extent of depth penetration, mainly a function of the chosen maximum spread of the electrodes, can of course influence the amount of subsurface information obtained and the speed with which the sounding is carried out. This is, however, not considered when comparing the projects. Thus a comparison of the resistivity soundings is relatively straightforward and shows that 14 Category 1 projects averaged 3 soundings per site (2 rather ambiguous answers stated that between 20 and 25 soundings were carried out per site, these were not included in the average). Leaving out 1 extreme (200 soundings for only 1 site) and one ambiguous answer, the average Category 2 and 3 projects had a clearly higher average of 22 soundings per site (8 projects).

The profiling techniques are more difficult to compare, since some projects answered by giving the number of profile kilometers per site, others by the number of profile measurements without stating the station interval (i.e. 50 measurements at unknown intervals) and some stated the number of profiles per site without mentioning the length of each profile or the number of measurements per profile. The given lengths of the profiles vary from 120m VLF combined with 200m EM to 4km EM per site.

The number of sites investigated per time period were mostly given in sites/day and sites/week and some sites/month. Converted to number of sites per week (based on 5 working days per week and 22 per month), this yields for 21 handpump projects an average of 5.5 sites per week in a range from 1.5 to 15 s/w (SD = 3.3). For 11 non-handpump projects this is, given the more extensive investigation, about half at 2.7 s/w in a range from 0.5 to 5.5 s/w (SD = 1.7).

Evaluation Q35-Q41

In most cases the field crew geologists and/or geophysicists are the ones also to evaluate the obtained data. Of 24 answers 13 handpump projects used a geologist, 3 projects a geophysicist, 6 both and 2 projects used the services of a consulting engineer, respectively an on-the-job trained technician (see also Appendix 4.6). Most appear to be university trained (BSc and MSc). Only very little information was provided on the daily rates of these specialists. The given figures range from $10/d to $850/d for a double evaluation (initial interpretation in the project country and reinterpretation in the consultant's country). Nearly all Category 2 and 3 projects provided the daily rates which averaged at $238 and $299 respectively.

Sixteen projects used computers to interpret the data, several of which did so in the field, while others made an initial interpretation in the project country and re-evaluated the data in the consultant's country. Manual interpretation was also carried out in four cases, one of which stated that master curves for resistivity soundings were used, while the others gave the impression that only a qualitative visual check of the resistivity graphs was made. Only three handpump projects provided figures on the total cost of the computer system used, ranging from $3000 - $17187. Six non-handpump computer systems had an average price of $14500. Some projects were able to rent or obtain free computer access. Daily computer cost is relatively similar for all projects with an average of $38/day (SD = $23). Software for geophysical evaluation is discussed in Chapter 3.

The number of sites evaluated per day for 11 handpump projects is around 3 per day, for 3 investigation projects 1.2/day, and for 7 high-yield projects 2.4 sites/day (excluding one project where apparently 60 sites/day were evaluated).

Costs Q43

The total siting costs are basically made up of the items discussed above, i.e. siting equipment cost, crew cost, transportation costs, evaluation costs (personnel and equipment) and should include administrative overheads. Only a few projects provided a full breakdown of the site investigation costs (see Appendix 4.7), but 21 Category 1 projects which used geophysics provided the average total cost per site. Table 10 lists and Figure 8 illustrates the average siting cost per site for the three Category 1 regions and the averages for the two other project categories.

Table 10 Average investigation cost per site for the different regions and categories

	Project Average:	Well Average:
Category 1		
West Africa	$ 1193	$ 1053
East Africa	$ 420	$ 359
Southern Africa	$ 208	$ 182
Subaverage	$ 711	$ 608
Category 2	$ 1938	$ 2119
Category 3	$ 2123	$ 2254
Total Average	$ 1202	$ 688

Also shown in Table 10 and Figure 8 are the weighted siting costs, which are averaged per section by taking into account the total number of wells per project and thus lending more weight to the projects with the higher number of wells. Economies of scale would suggest that this would reduce the average cost, which is to a limited extent the case for the Category 1 projects (an average reduction of 14%), but not for the Category 2 & 3 projects (an average increase of 8%). A likely explanation is that the latter are less constrained by tight budgets associated with the low-cost community water supply objectives.

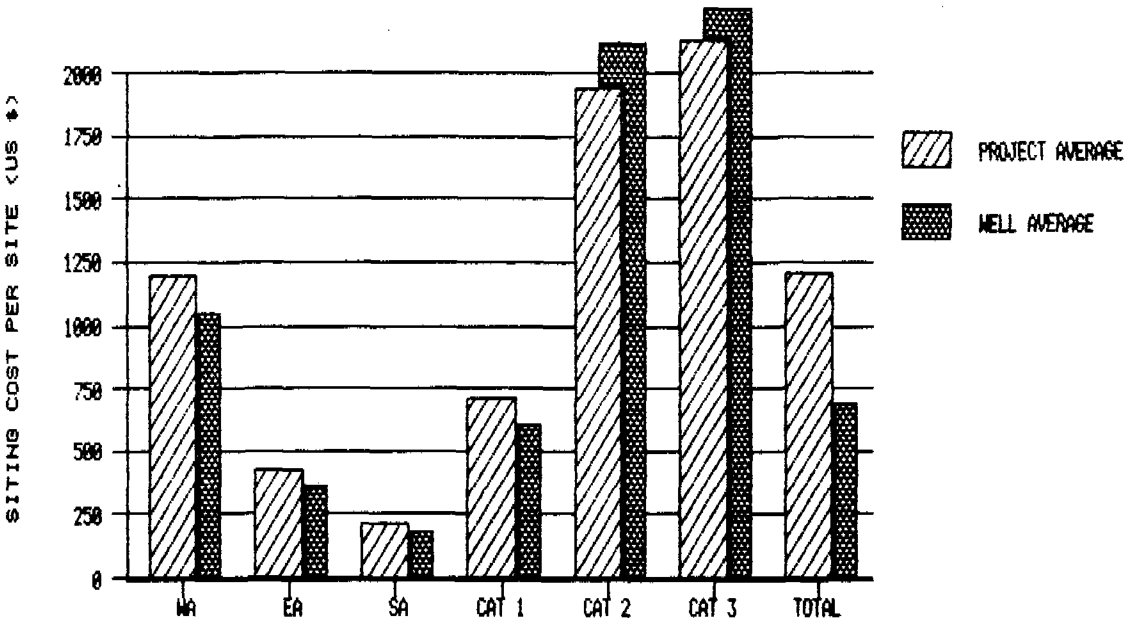

Figure 8 Average investigation cost per site

The siting costs for handpump projects in West Africa are much higher than in either Eastern or Southern Africa at an approximate ratio of 6:2:1. Of the nine projects which provided siting cost information in Western Africa in a range of $103 to $3500, 5 listed costs above $1000. The extensive involvement of expatriate personnel is the most obvious explanation for the higher costs. In Eastern and Southern Africa it appears that more local contractors have been used, thus resulting in lower personnel costs.

A representative breakdown of the total siting costs is not possible since only 2 handpump projects provided all the costing details asked for (Appendix 4.7). However, a very rough comparison of the average values, including the partial answers is shown in Figure 9 (average sample size per portion of the pie is 9 projects) for handpump projects and in Figure 10 (average portion sample size is 6 projects) for the investigation and high-yield projects. This demonstrates the weight of the crew costs (probably mainly due to expatriate services) in comparison to geophysical and computer equipment and transport cost.

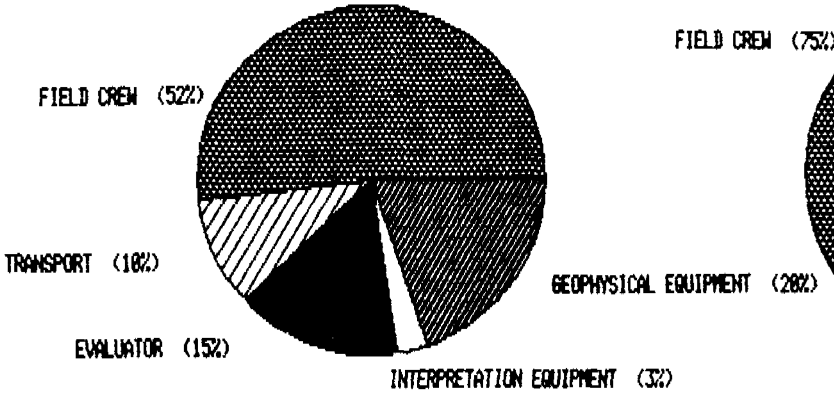

Figure 9 Siting cost breakdown for Category 1 projects

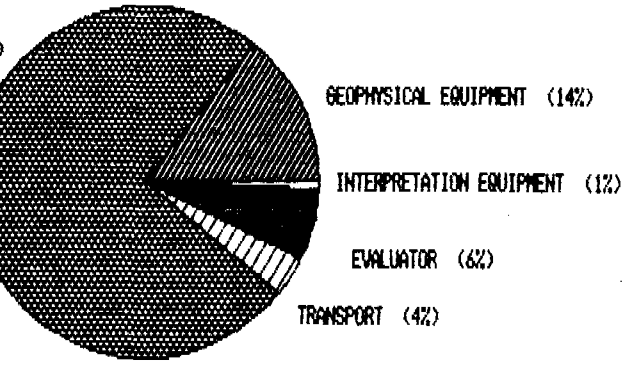

Figure 10 Siting cost breakdown for Category 2 & 3 projects

2.6 Well Construction Q16, Q17, Q22, Q23, Q44, Q47, Q48

The relatively good response to the questions concerning well construction provides an overview of the total number of constructed wells, the rate of construction, completion methods, handpump types and the costs. This data which is presented in this section will be used in the next section to discuss the success and economic justification of site investigations. The construction data is presented in Appendix 4.8. Some of the incomplete questionnaire data has been complemented where possible by information from available project reports.

The constructed wells on which information was provided by the Category 1 projects are in Appendix 4.8 divided into three sections:

Dug Wells	4912
Machine-drilled Wells	9895
Other Water Points	706 +
Total	15511

It should be noted that dug wells are not in all cases dug by hand. At least one large dug-well project mainly used a tractor mounted excavator, while jack hammers are known to be used in several others. Most of the wells were machine drilled, with percussion or rotary and down-the-hole hammer rigs. Specification of drilling methods was usually not made in the questionnaires. In two instances the use of the hand drilling methods was also mentioned, while another project included a significant amount of spring protections in their water supply programmes. The last two types of construction fall under the third ('Other') section. The total number of constructed wells listed here differs from the number listed in Appendix 4.2, where for incomplete projects the planned number of wells was used to calculate the total. In both cases however, where only partial budgets were given for continuing projects an effort was made to determine the number of wells constructed for that budget period in order to be able to give a more accurate average total cost per well figure.

Little can be said about the rate of well construction. The speed with which wells are dug or drilled depends not only on the methods used and personnel involved, but also on geology, required depth, logistics, community aspects, etc. In some projects with time constraints it may be important that well siting be carried out as fast or at a faster rate than the drilling rate of one or more rigs as the time gap between siting and drilling may be very small.

The success of a well depends not just on the initial location of adequate supplies of groundwater, but also on the method of well construction and development to ensure an adequate lifetime. This requires the proper screening and selection of pumping method. Most of the Category 1 projects used PVC screens, which as a rule are quite adequate for handpumped wells. Little information was available on the used slot sizes and the use of gravel pack to avoid siltation and rapid wearing down of the pump cylinder.

A large variety of handpumps are in use, of which the India Mark II was the most common (i.e. by 12 projects in all three regions of Africa), followed by the SWN 80/81 (6 projects, mainly in East Africa), the Vergnet (5 projects), and the ABI MN/ASM (4 projects). It could not be determined which pump was fitted on the largest number of wells, since within projects often a variety of pumps are fitted. Other types of pumps were also used in individual projects and shallow wells were sometimes fitted with bailers, i.e. bucket and rope.

The various costs for handpump well construction is given in Figure 11, where (1) the cost of drilling a dry well is compared with (2) the cost of a successful well (including casing, screens, gravel pack where necessary and in some cases testing) and (3) the overall average cost of a project well, by dividing the total budget by the number of wells constructed (the budgeted cost per well). However, it is likely that for a number of projects the costs given for a successful well also include costs for siting, the handpump and the write-off costs for the dry wells which were drilled. Appendix 4.8 lists both the given amount and a modified amount where costs for siting, handpump, dry wells, etc. have been subtracted (where possible) from the successful well cost.

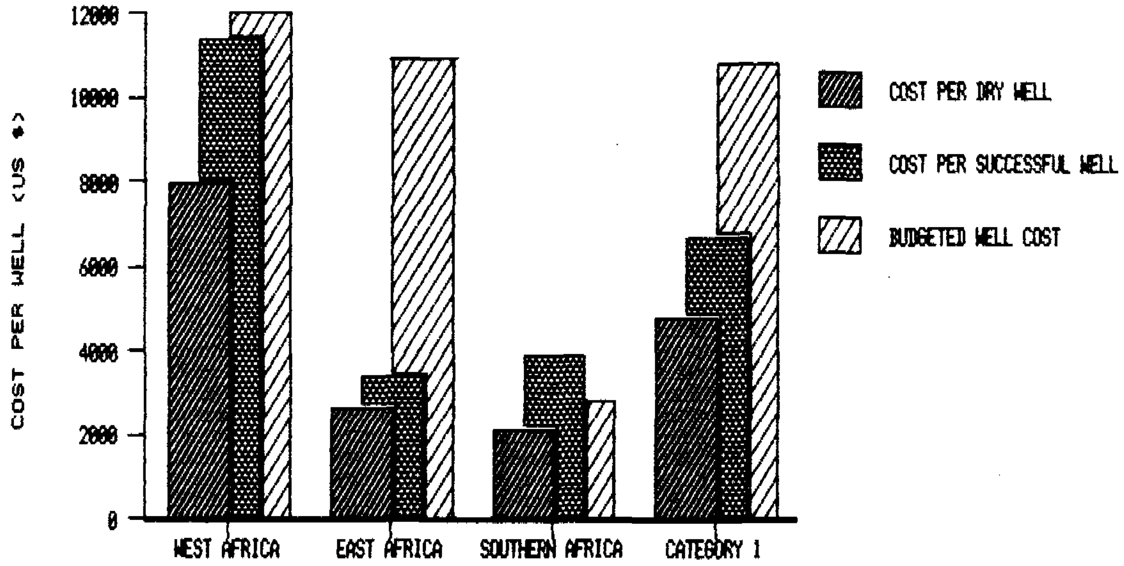

Figure 11 Drilling costs and total costs per well

The basic cost of drilling is expressed in terms of drilling the borehole without the installation of casing, screens and gravel pack and without development and test pumping. If the well appears to yield inadequate amounts of water after the basic drilling is completed, it is abandoned at this stage without further spending on casing, screens, etc. The cost incurred are the costs of drilling a dry well. This figure is used in section 2.7 to calculate the effectiveness of well siting.

The basic drilling cost are much higher in West Africa than in either East or Southern Africa, but not enough information was available to clearly indicate the reason for this difference. There is a big gap between the stated basic drilling cost and the apparent budgeted cost per well in East Africa. Two projects are basically responsible for the high budgeted cost per well PN 17 and 25. The budgets of several East African projects involve a number of other development activities (sanitation, workshops for water management, etc.). This apparently causes the comparatively high overall cost per well (i.e. budget divided by no of wells). On the other hand commercial drilling, well construction and development costs (compared to the 'in-house' drilling operations of the larger development projects) are often higher than suggested by the questionnaires for East Africa and possibly Southern Africa. Local drilling contractors in Southern Africa are plentiful, effective and competitive, thus keeping basic drilling prices relatively low. The fact that the budgeted cost per well in Southern Africa is lower than the cost for drilling and completing a successful well of 50m depth can be explained by the fact that the actual drilling depths per well are on average less than 50m (see Appendix 4.3).

The basic drilling costs of the Category 2 & 3 projects are not very different from those of Category 1. A major difference is found in the costs of well completion and development for the high-yield Category 3 (see Appendix 4.8) which is a multiple of the other categories.

2.7 Success of Site Investigation **Q45, Q46, Q49**

The justification for well site investigations is based on the argument that the application of site investigation techniques leads (should lead) to a higher percentage of successful wells, thus reducing the overall cost of the project by a decrease in the number of unsuccessful, i.e. 'dry' (or saline) wells which are drilled or dug. Or with the words of one study: "The groundwater search techniques are only justified if *they increase the chances of subsequent boreholes* being successful, such that the overall saving in drilling cost, in the long run, is greater than the cost of the search" (Farr et al., 1982).

The criteria for determining a well to be successful differ from project to project and is mostly given in terms of a certain minimum yield to be obtained from the well. For 30 handpump projects this required minimum yield ranges from 0.3 - 5.0 m³/h, with 24 of the projects at or below 1 m³/h. Two of the projects in a coastal environment used primarily salinity criteria to determine the success of the wells. This means that the comparisons discussed below should only be considered as approximations in the widest sense and not as representative statistical values.

The basic requirement for a proper evaluation of siting methods in terms of the effect on a project's success rate is the availability of comparable data for the project area concerning well construction without or with different levels of site investigation. If such data is available a basic comparison can be made yielding the difference in drilling (and/or digging) success rate. The costs of drilling a well without and with site investigations, taking into account the percentage of dry wells can then be compared to the cost of siting to see if the application of siting is economical. The relationship can be put into a simple formula:

$$S = C_r - C_s = C_d/R_{ns} - (C_d + C_s)/R_s$$

with S as the savings; C_r the overall reduction in drilling cost; C_d the basic cost of drilling to a depth of 50 meters; R_{ns} the success rate without the use of well siting; R_s the success rate with the use of well siting; and C_s the cost of the site investigation. Table 11 applies this formula to the data obtained from the various Category 1 projects representing approximately 7600 wells (Appendices 10, 11, 12).

Table 11 Comparison of basic well costs without and with site investigation

PN	C_d	R_{ns}	R_s	C_d/R_{ns}	C_d/R_s	C_r	C_s	C_s/R_s	S
4	3946	0.65	0.75	6070	5261	809	1361	1815	-1006
5	11900	0.50*	0.78	23800	15256	8544	2250	2885	5659
7	9947	0.50*	0.58	19894	17150	2744	426	734	2010
10	9000	0.80	0.95	11250	9474	1776	1300	1368	408
11	12000	0.73*	0.85	16438	14151	2287	600	706	1581
14	12180	0.60	1.00	20300	12180	8120	103	103	8017
21	1600	0.85	0.87	1887	1831	56	200	230	- 174
23	3313	0.52	0.78	6371	4247	2124	238	305	1819
27	2000	0.70	0.80	2857	2500	357**			
34	2157	0.60	0.90	3595	2397	1198	60	67	1131
35	1807	0.65	0.90	2780	2008	772	90	100	672
37	3200	0.63	0.90	5079	3555	1524	580	644	880
Average	6088	0.65	0.84	9366	7247	2119	660	786	1333

* R for hydrogeological siting where R_{ns} not available

** C_s not available, according to C_r a maximum allowable investigation cost of $C_r * R_s$ = $285

For explanation of titles see text.

Most of the twelve projects which estimated and in some cases were able to calculate the increase in drilling success with the use of geophysical methods are according to Table 11 justified in the use of geophysics. The average success rate increase of approximately 20 percent with site investigations results in an average reduction of $ 2119 in drilling costs, nearly three times the amount needed to cover the average investigation cost (per successful well) of $786.

Two projects (PN 4 and 21) have a negative savings when comparing the drilling costs without and with the use of geophysics. The comparative advantage of geophysics is evidently too small to cover the siting costs of these projects. The reliability of such a cost-benefit analysis however is very much dependent on the accuracy of the success rate estimates given by the respondents. Furthermore the formula above assumes equal drilling depth without and with siting and does not take into account the possible savings through a reduction in the required depth of drilling as a result of site investigations, which would increase the margin favouring the use of geophysics[4].

The comparisons made in Table 11, while giving a reasonable indication of the cost-effectiveness of site investigations, is not necessarily representative for well siting in all types of environments. The success of site investigations is in addition to the geology of the project area very much dependent on such local variables as climate, topography, the presence of major recharge from surface water, etc. However, the data presented by the respondents appears to support two general conclusions:

- Where groundwater is known to be present at shallow depth, such as in many alluvial aquifers (PN 9) or in areas with significant recharge from rainfall (PN 21, 28, 29) or surface water sources (PN 11), the limited abstraction needs of handpumps require only a basic hydrogeological investigation. However, in coastal environments where differentiation between fresh and saline groundwater is important (PN 19, 20), geophysics can provide a good method of distinguishing between the two (see Chapter 4.2).

- Geophysical investigation techniques are especially useful where the subsurface conditions and therefore geophysical modeling requirements relatively simple. This applies to the location of water-bearing fractures and deeper depressions in the weathered zone above solid bedrock. In complex formations the resolution provided by geophysics is often less than ideal. In practice the Basement areas, overlain by weathered material generally conform well enough to a simple (2 or 3-layer) model of the subsurface for geophysics (especially resistivity and seismics) to lead to significant improvements in the well-siting success rates (PN 23, 37), while in consolidated sediments or in volcanics the usefulness of geophysics will be limited. In the latter environment detailed hydrogeological investigations may provide enough information to locate a drilling site (PN 1, 32, 33).

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[4] The formula for calculating the savings can easily be adapted to include the expected decrease in drilling depth:

$$S = C_r - C_s = L_{ns} \times C_d/R_{ns} - L_s \times C_d/R_s - C_s/R_s$$

with L_{ns} as the average required drilling depth for a non-sited borehole, L_s as the average required depth for a sited borehole, C_d as the basic drilling cost per meter. The other variables as in the original formula.

3 Geophysical Equipment

The equipment used for site investigations discussed in this chapter concerns primarily geophysical field equipment and equipment needed for processing and evaluation of field data. The information is derived from the No. 3 questionnaires which were sent out to manufacturers and suppliers of geophysical equipment and on the documentation which was received together with the returned questionnaires or otherwise made available. A total of 15 positive replies were received with 9 completed questionnaires from the 27 requests for information which were sent out.

3.1 Questionnaire No 3

The original questionnaire is shown in Appendix 2.3 and basically consists of 11 questions. Nine of the respondents answered with a No. 3 questionnaire, others mainly sent product documentation. The data is listed in Appendix 5.

Company Q1

Six of the respondents to the questionnaire are manufacturers, one a major supplier and two are basically consultancy firms which manufacture a limited range of geophysical equipment, which is mainly used by themselves. The response represents a significant part of the total range of geophysical manufacturers and suppliers, and gives some insight into the ideas the manufacturers have on the use of their equipment.

Geophysical Equipment and Cost Q2, Q3

The only supplier in the list of respondents provides the whole range of geophysical equipment, the manufacturers and the two consultants have a more limited range. Of one of the manufacturers only one of the branches answered concerning the manufacture of borehole logging equipment, while another branch is involved in the manufacture of a wider range of equipment. In addition to the information provided by the supplier, information on resistivity equipment is provided by 6 of the questionnaires, 3 replied on borehole logging equipment, 2 on the seismic refraction and shallow reflection equipment, and one on each of the following: EM, VLF and Ground Radar. Many of the respondents provided quotations for their equipment. A comprehensive list of available geophysical products for groundwater investigation and approximate prices is given in Appendix 6 based on product documentation and quotations sent along with the questionnaires and from other sources.

Crew and Transport Q4, Q5

Most of the respondents suggest that the field crew working with their equipment should be accompanied by a university trained geophysicist or hydrogeologist with geophysical experience. For the resistivity method the additional crew members should basically consist of one operator and two or more labourers. The seismic refraction crew may need to be a bit larger with up to 2 operators and 2 to 6 labourers. EM requires a geologist/geophysicist and an operator, while ground radar and borehole logging similarly requires two operators, of which one, according to one of the two manufacturers should be a trained geologist/geophysicist. Gravity and magnetometry each can be carried out by one geologist or geophysicist; for the former when no detailed topographic maps are available the measurements stations need to be leveled by surveyors. As one of the consultant respondents points out, it may not always be necessary to employ professional geophysicists or geologists in the field crew if a well trained and experienced operator is available.

Staffing requirements suggested by the manufacturer appear often to be superseded. In actual field practice more casual, unskilled labour is used which most likely is a matter of ease rather than necessity, reflecting the predominantly low cost of such labour.

Evaluation Q6

Most of the respondents agree that for the evaluation professional skills are necessary, but two suggest that non-university trained personnel can be specially trained in the interpretation of the measurements and that this should be adequate.

Interpretation Hardware and Software Q7, Q8, Q9

For the interpretation of the resistivity measurements a computer, plotter and/or printer are listed as the main requirements. Small portable computers are quite adequate and can often be carried into the field. Master curves, i.e. model resistivity graphs calculated for a variety of layers with variable resistivities, can be used for manual interpretation, while calculator-based interpretation routines are also available. Computer interpretation is, however, the quickest and the most accurate. For the interpretation of seismic refraction results, interpretation with a small calculator is possible and relatively easy although somewhat laborious. Computer programmes can speed up the process. Data processing for profiling techniques such as EM, VLF, Magnometry and Gravity measurements is usually not as complex as the procedures for Resistivity and Seismic measurement interpretation and is easily plotted by hand unto maps or profiles. However, computer applications can assist with the plotting. The latter is also true of the interpretation of geophysical borehole logs.

A wide range of software is commonly available for the different applications and most manufacturers provide a software package to accompany their equipment (see also Appendix 6) and in some cases provide demonstration software. Some also have special arrangements with computer firms to provide computing equipment.

Reports on Equipment Q10

A few of the respondents made reports available on the application of geophysical equipment of their manufacture in various water development projects. These are discussed alongside other reports in Chapter 4.

Testing of Equipment Q11

Some of the companies indicated that they had equipment available for testing. No actual testing under controlled circumstances was however carried out, but several types of equipment were observed in use by the various projects which were visited in Kenya in the course of the study as listed in Table 12.

Table 12 Demonstrated geophysical equipment in various Kenyan projects

Model	Method	Agency, Region
ABEM Terrameter SAS 300 B	Resistivity	Groundwater Survey (K) Ltd, Embu District DHV Consulting Engineers/LBDA, Siaya District
ABEM Trio SX 12	Seismic Refraction	Kefinco, Bungoma District
ABEM Wadi	VLF	Groundwater Survey (K) Ltd, Nairobi
Geonics EM 34-3	Electromagnetics	DHV Consulting Engineers/LBDA, Siaya District Groundwater Survey (Kenya) Ltd, Embu District
APEX Max Min	Electromagnetics	Groundwater Survey (K) Ltd/MoWD, Embu District

3.2 Product Documentation

Information concerning geophysical equipment for use in well siting has been sent along with the No. 3 questionnaires by the various respondents and also obtained from other sources. This information describes, in many cases, the theoretical principles on which the instruments are based, the basic operating principles and a number of case studies of the application of the various instruments.

The equipment cost factor as supplied by the various manufacturers (Appendix 6) is a better reference than the cost figures supplied by the consultants and organizations in questionnaire No. 1 (Appendix 4.5). The actual equipment cost depends on system configuration and options and whether or not the equipment can be imported free of duty.

In most cases the equipment is technologically sophisticated and therefore expensive (in the order of $10,000 and above). Consequently, its purchase can only be justified when it can be written off against a relatively large number of sitings in order to keep the cost per site investigation low. In a few cases (in India, the Netherlands, and Thailand; documentation reached us only of the latter) cheap resistivity equipment has been developed (in the order of $500).

4 Literature Review

Many project reports, publications, informal papers, etc. which partly or wholly concern well siting for community water supplies were received together with the questionnaires and from other sources. A comprehensive list of these reports, publications and papers is included in the bibliography. The main purpose of the review of the literature is to complement the information obtained from the questionnaires on the use of site investigation methods. The literature has also been used extensively to compile the accompanying introductory volume on well siting. More insight than provided by the questionnaires into the well siting procedures commonly used, the choice of investigation methods and the economic aspects of well siting can be obtained from the various project reports.

4.1 Well Siting Procedures

Identification

Site investigation procedures and crews are usually only activated after an initial phase of project and target identification has taken place. In most of the larger projects the work is commissioned by regional or government agencies who determine the geographic layout of the project area and general project Terms of Reference for the construction of wells. Regional water master plans are often drawn up to study the availability of water and to provide a plan for the development of the resources. The next step is the preparation of a water development programme to provide every village with clean and dependable water supplies within a reasonable walking distance (Finnida, 1984). The implementation of the regional water plans within the specified criteria is then contracted out. Other commonly applied parameters include design yields, users per water point, quality standards, etc. which vary from country to country and even within countries. Such a set of 'groundrules' form for most projects the basic starting point for all further and more specific well siting activities.

Community Development

Apart from national guidelines, many projects take the suggestions of the local community concerning the preferred location of the proposed well into account. The extent of local involvement ranges from merely asking the community leaders to select a few preferred sites, which are then evaluated hydrogeologically and/or geophysically, to a more detailed sociological study of the location, involving extensive meetings not just with community leaders, but also with regular community members and in particular with the main potential users' groups. Hydrotechnica (1985), in the Victoria Province Drought Relief Programme in Zimbabwe, considers that the site should be chosen principally on hydrogeological (or related geophysical) grounds, but states also that "discussions with the local community are absolutely essential, even though they may require considerable time both as a result of trying to resolve conflicting interests within the community and as a result of lack of water at the location preferred by the community." A report from the Bubu-Tomboli Water Project in Guinea-Bissau (DGIS, 1982), a mainly participatory project of well digging and hand drilling, emphasizes the need to consult with all sections of the local community (especially minority groups and women) in addition to consultations with the community leaders, in order to ensure that the needs of all groups are met. A Malawi Manual for Integrated Projects for Rural Groundwater Supplies (Chilton et al., 1982) recommends: "Maximum involvement of the village in the selection of their own waterpoint sites, preferably through the democratic process of an elected Water Committee to assist in creating the sense of waterpoint ownership." This is also affirmed by several other projects (e.g. Finnida, 1984 and South Coast Handpumps Project, 1987). The liaison with the community is sometimes carried out by a separate 'Community Development' department which seeks to encourage the formation of a Water Committee to take charge of the proposed well (operation and maintenance) and who through its close contact with the community is able to obtain and forward the suggestions and recommendations to the siting team (Kefinco - Kakamega, DHV Consulting Engineers - Kisumu, Foster Parents Plan - Embu: personal communications, 1987-1988).

Hydrogeological Reconnaissance

The common approach to the selection of individual sites involves a preliminary desk study of available materials such as geological maps, topographic maps, climatic data, borehole records, aerial photographs and sometimes satellite imagery. This information is then used as a background for hydrogeological assessment in the field of the community proposed sites and the project location as a whole (Hydrotechnica, 1985; MacDonald, 1986; Chilton et al., 1982; Norconsult, 1983b; GSK, 1987b). When the hydrogeological data is considered inadequate for individual site selection, geophysical measurements are generally recommended and carried out.

In many large projects the hydrogeological study is divided into two separate stages. First a general hydrogeological reconnaissance of the project area before engaging in specific site investigations. Sometimes such a general investigation is directly connected to the object of rural water supply and sometimes the general regional investigative study is meant as a general basis from which other, smaller water supply projects can proceed. The investigative studies mentioned under Category 2 in Chapter 2 are basically of this nature. The government of Kenya is for example engaged in a systematic study of the water resources of in the various regions of Kenya which indicate the potential for groundwater abstraction for the local needs (WRAP, 1984a/b, 1987a/b). Norconsult (1983a) in such a study of Turkana District in Kenya produced a hydrogeological map and a groundwater 'guide', to assist in the further development of groundwater resources for individual water supplies. The guide is shown in Appendix 7. It illustrates very well the general procedures and hierarchy of data collection which are generally followed by professional consultants in site investigations. A general impression of aquifer characteristics (the right-hand column in the guide) can, even when test drilling is too expensive, often be obtained from existing boreholes in the area. Thus it is possible to gain some information on the drilling requirements and possible cost of a proposed water supply programme.

4.2 Choice of Geophysical Siting Method

No Siting

It may not always be necessary to use geophysics for the final selection of well sites. MacDonald (1986) describes how in a sedimentary area in northern Nigeria with low rainfall (<750mm) enough hydrogeological evidence was available (significant recharge from a major river system) to suggest that application of geophysics was not necessary. Alternatively, two publications (DHV, 1978 and Blankwaardt, 1984) both based on projects in Tanzania recommend the use of hand drilling as a cheaper alternative to the use of geophysics in areas where the water table is relatively shallow and the soil firm but unconsolidated. A light set of hand drilling equipment is easier to use and cheaper than most geophysical instruments, while soil sample interpretation is relatively straightforward and water capacity can be determined through pump testing. Where hand drilling is possible, hand digging or drilling for the production well is also possible, further reducing the overall cost of the well. Test hand drilling is however impossible in rocky areas.

Chilton and Smith-Carington (1983, 1984) point out that in Malawi the use of geophysics for borehole siting is quite unnecessary for handpump wells in the weathered zone of the Basement Complex where the saturated layer generally provides an adequate yield. Only when higher yields are required with a greater capital investment in the wells, such as for small urban, reticulated supplies or irrigation, is a fuller range of exploration techniques justified.

The NCA Water Project in southern Sudan (Sundness et al., 1985) is an example of a situation where very little hydrogeological and no geophysical well siting was used to the detriment of the drilling programme. In the predominantly Basement Complex and Sedimentary area about 64% of the boreholes proved unsuccessful without any siting, decreasing to 41% unsuccessful when a hydrogeologist carried out the siting (without geophysics). The financial consequences of this approach will be discussed in section 4.3.

Resistivity

An early and excellent description of the use of electrical resistivity sounding and profiling techniques for groundwater exploration in 20 projects in 10 West African countries comes from Mathiez and Hout (1968). The initial experimental, but nevertheless in most cases successful, application of the resistivity method for general water resources assessment, urban and rural water supply is described in some detail for various types of Basement, Sedimentary and Alluvial environments. The report stresses the importance of a close cooperation between the hydrogeologist and geophysicist leading to a better understanding of the uses and limitations of geophysics in groundwater investigations. Figure 12 illustrates a resistivity survey carried out in Bassari, Togo which resulted in the successful drilling of three boreholes (A, B, C) which each continued to yield more than 40 m^3/day at the end of the dry season from crushed and altered schists overlying sound rock at respectively 16, 23 and 48m below ground level.

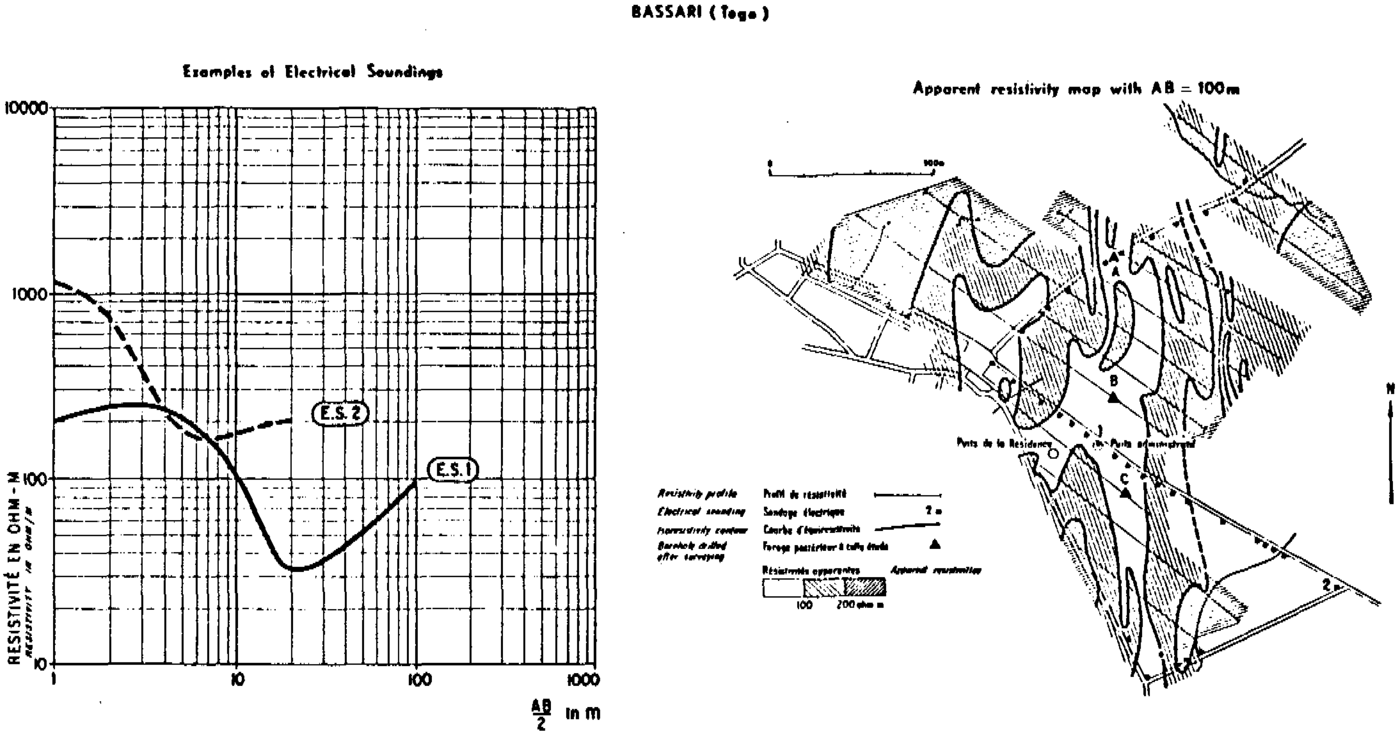

Figure 12 Resistivity survey layout and sample soundings at Bassari, Togo (Mathiez and Huot, 1968)

Another hydrogeological situation in which the resistivity method excels is where fresh/saline-water contact zones need to be mapped. Mathiez and Huot describe several cases of this nature. Figure 13 illustrates one example in Senegal, where it was possible to give an estimate of the fresh/ saline interface position.

A similar situation is described in the report of a project carried out by Groundwater Survey (K) Ltd at the Kenyan coast (GSK, 1987a, see also PN 50). Fresh water primarily concentrated in karstified fossil coral reefs provided a clear resistivity contrast with the underlying and surrounding saline groundwater. Several exploratory boreholes were drilled and geologically and geophysically logged for calibration purposes.

CAP VERT PENINSULA (Senegal)

Schematic section

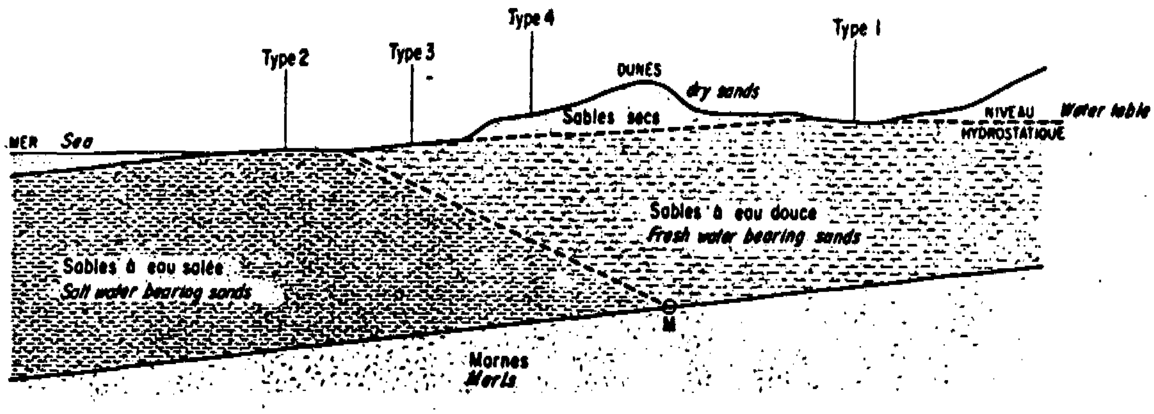

FIGURE 27b Typical Electrical Soundings

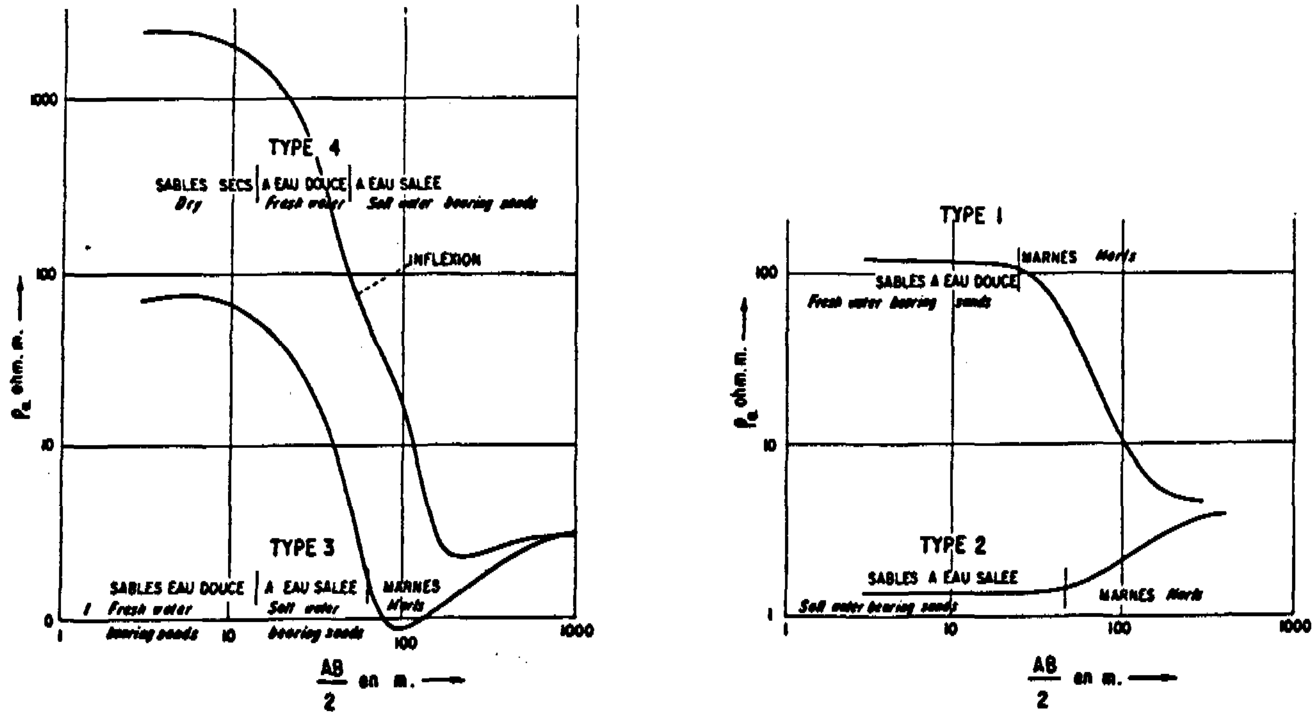

Figure 13 The resistivity method in a fresh/saline-water environment in Senegal (Mathiez and Huot, 1968)

While the Schlumberger electrode array is usually considered as the superior resistivity sounding technique, the relatively recently developed Offset Wenner technique has been used in a number of projects (Hydrotechnica, 1985; Beale, 1986) as a more accurate measuring system, being less sensitive to near surface lateral inhomogeneities, which sometimes invalidate the traditional resistivity soundings (Barker, 1981, 1985). A recently developed combined sounding/profiling technique (the Campus Multiprocessor controlled resistivity traversing

'MRT' system), with electrodes connected by a multicore cable and a microprocessor to a resistivity meter, is also based on the Wenner array and provides regular quantifiable resistivity data at almost the speed of carrying out the EM measurements (Griffiths & Turnbull, 1985). An example of such a profile is shown in Figure 14. The lack of conductance through very dry near-surface layers is the main drawback, over which the EM & VLF systems have the advantage of not requiring surface contact.

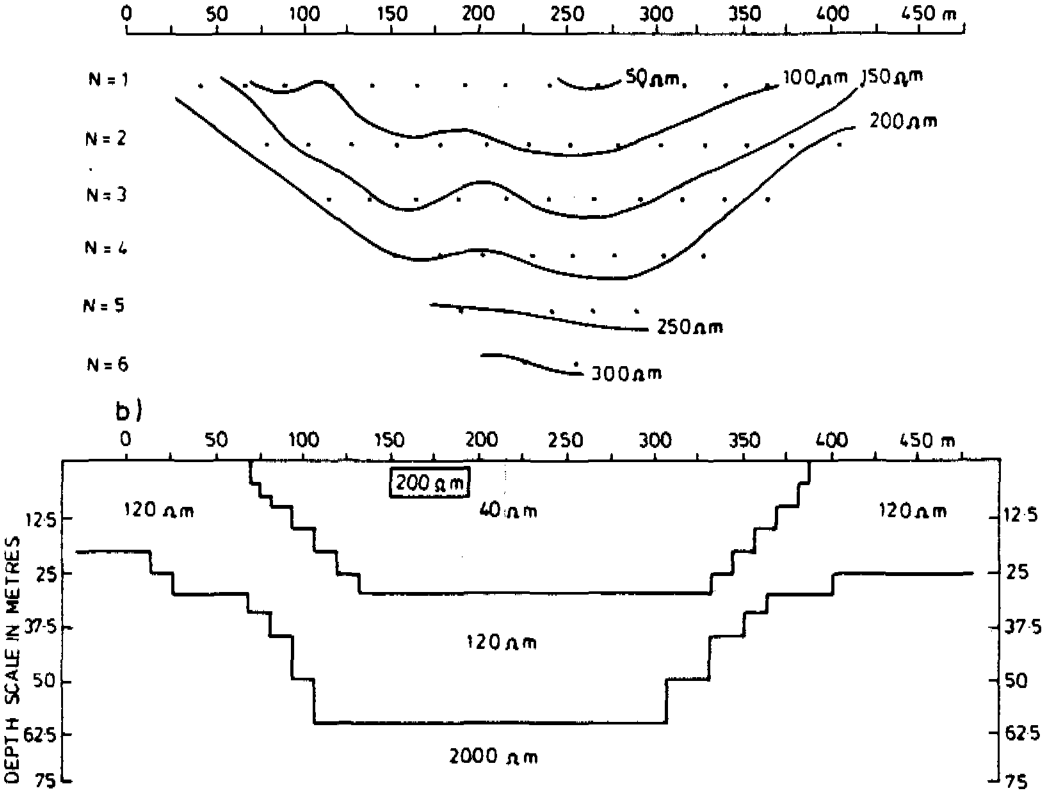

Figure 14 MRT profile with interpretation across a weathered basement channel in Zimbabwe (Griffiths and Turnbull, 1985)

Seismic Refraction

Information was available for a only few projects in which the seismic refraction is the solely used method of groundwater investigation. Kefinco in Western Kenya, one of the respondents to questionnaire no 1 (PN 21), uses seismic refraction as the only method of investigation for locating borehole sites. Ovaskainen (n.d.) rationalizes the use of the method as opposed to not using any method based on the early drilling results of the project. While the seismic refraction method is clearly useful and very effective in optimising the well location, as is pointed out earlier, there is some doubt on the current cost-effectiveness of seismic refraction under the generally favourable conditions of the project area. This is described in more detail in the chapter with case studies in Volume 2 of this study. Ovaskainen (1985) also reports on a pilot study of the seismic refraction method in Sudan to improve drilling conditions in the South Kordofan area and suggests that seismic refraction will most probably lead to larger yields and a higher success rate.

Resistivity & EM

Many different geophysical investigation techniques are available when the hydrogeological data is not considered sufficient to select a well site. However, as the responses (from questionnaire No. 1) already indicated (see Table 7 and Figure 7), the resistivity method is very popular, while the combination of resistivity soundings, profiling and electromagnetic profiling is acclaimed as a very successful geophysical tool by a number of the larger projects (WRAP, 1984a/b. 1987a/b, Sir MacDonald & Partners, 1986; Hydrotechnica, 1985; Beale, 1986; van Lissa, 1987). As Carruthers (1985) points out a better interpretation can often be made if different geophysical techniques are used simultaneously in a survey area.

Data obtained with several geophysical methods often complement each other and provide a clearer understanding of the geology. Hydrotechnica (1985) chose the resistivity/EM combination after considering a number of different options such as Magnetics, Seismic Refraction and Shear Wave Refraction. It considered the resistivity and EM techniques considerably faster and cheaper than any seismic technique, while the EM technique was found to give comparable results to a magnometer, after which the latter was cut out of the project. In combination with the resistivity technique the EM profiles are used as an initial and fast reconnaissance tool, followed by more detailed EM and resistivity profiles and soundings in areas of specific interest. The same approach was followed by MacDonald in northern Nigeria, while the systematic inventory of Kenya's groundwater resources by WRAP is also based on the application of the Resistivity/ EM combination, occasionally supplemented by other techniques, and has proven to be very useful for fast large-scale reconnaissance.

Palacky et al. (1981) for a survey area in Burkina Faso confirm the advantages of EM over resistivity profiling as a faster and cheaper method and providing "data of a quality at least equal to resistivity profiling." The VLF method was also applied and was also found to be useful, but limited by the availability of VLF stations. They suggest that the EM profiling technique should replace traditional resistivity profiling (see comparison of methods in Figure 15).

A simple VLF/Resistivity combination provided by the Geonics VLF-EM 16R instrument has also proven successful in mapping the weathered overburden for groundwater investigations in Andhra Pradesh, southern India, as documented by Poddar and Rathor (1983). However in both of the latter cases resistivity soundings or drilling of test holes were necessary to calibrate and confirm the attempt at quantitative interpretation. Another VLF instrument, the ABEM Wadi, has recently been introduced by the manufacturers of the successful ABEM Terrameter, but no results have been published to date to substantiate the claims on the instrument's sensitivity, especially in light of the weak transmitter signals in Sub-Saharan Africa.

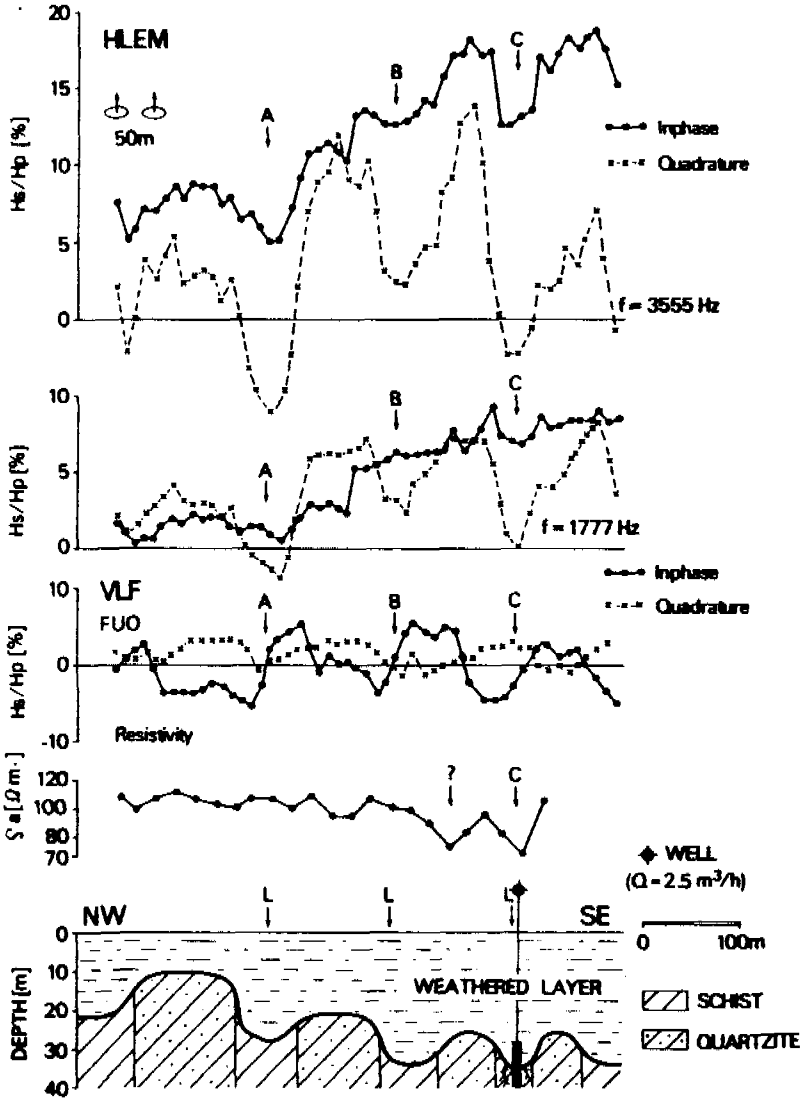

Figure 15 Comparison of EM, VLF and resistivity profiles (Palacky et al., 1981)

Resistivity and Seismic Refraction

The resistivity technique has also been combined with the seismic refraction technique for groundwater investigations in several projects in Kenya, Tanzania and Sudan (Pulawski & Klitten, 1977; Luonsi & Lappalainen, 1981; van Overmeeren, 1981). Mathiez and Huot (1968) also report the use of the seismic refraction method in some of the West African projects they describe. The Kenyan project was specifically aimed at studying the correlation in the findings between the two methods. In the second project in Tanzania a general distinction was made between the areas in which resistivity and seismics were used (sedimentary and basement, respectively), but complementary resistivity soundings were made in the seismic areas in order to obtain information on water quality. The third project used the seismic refraction technique to calibrate the resistivity soundings in order to overcome the problem of equivalent interpretations.

In the Kenyan project the resistivity curves were on purpose interpreted without taking the seismic data into account, in order to compare the individual data obtained by the two techniques in the same basement and volcanic areas. Table 13 gives a basic overview of the results. The report concludes that because the two techniques provide two different sets of information, they may supplement each other but cannot substitute each other. The lack of boreholes at most sites to confirm the results of either technique and several other limitations in the set-up of the comparisons unfortunately result in rather unsatisfactory conclusions.

Table 13 Resistivity and seismic refraction survey, comparison of results (after Pulawski & Klitten, 1977)

Accordance > Site:	Both methods indicate the same geological and hydrogeological conditions	Both methods indicate rather similar conditions from a hydrogeological point of view, but differ markedly in the quantitative results	Both methods provide contradictory results
Basement Area			
1	- - -	In many cases the resistivity survey indicates greater depth to the firm rock than does the seismic survey. Both indicate the same sites as prospective for groundwater	- - -
2 & 3	- - -	- - -	Resistivity survey: Positive groundwater conditions Seismic survey: Negative conditions
4, 5 & 6	Both methods accord in indicating a thick weathering profile	- - -	- - -
7	- - -	- - -	No accordance
8	- - -	- - -	Resistivity survey: Positive groundwater conditions Seismic survey: Negative conditions. However, wells drilled here are successful
9	Accordance in the estimate of the depth to the firm rock	- - -	- - -
Volcanic Area			
10 - 12	The seismic survey does not provide usable data The resistivity survey is indicative		

A clear case study of the usefulness of limited seismic investigations is given by the Sudan project (Van Overmeeren, 1981). In this project gravity measurements were used to provide an initial rapid overview of the basement structure in the area, which however was inadequate to provide the detailed depth-to-bedrock information. Resistivity soundings were carried out to provide additional quantitative data, while limited seismic refraction investigations provided a cost-effective way to accurately calibrate the resistivity measurements. The results were confirmed by subsequent test drilling.

Seismic Refraction and Gravity

The seismic refraction technique is on its own quite a comprehensive investigation technique which provides both qualitative and quantitative information in terms of the basic structure of the subsurface layers and the depth or thickness of the layers. Van Overmeeren (1975, 1980) and Ali (1987) describe respectively two projects in Chili (Alluvium/Basement and Volcanics) and one in Sudan (Volcanics/Sediment/Basement) where seismics were relied on for the detailed information, while gravity measurements were used as a secondary aid to trace the general structures of the areas. The gravity method proved very useful and economic in flat terrain for qualitative interpretation. Due to velocity inversion in Sudan project the seismic measurements were not able to pick up the sandstone formation underlying the basalts and Ali suggests that in such situations other methods should be use to delineate the basaltic flows.

Other Methods

A number of geophysical techniques are newcomers in the field of groundwater exploration and have not been reported on by any of the projects. However, as it is likely that some of these new developments will start to play a more prominent role in this area they are mentioned here shortly based on reports and publications from more or less experimental applications.

Seismic Reflection

Dobecki and Romig (1985) in an overview give the reason for the late entry of seismic reflection in the groundwater exploration scene as the high cost of complex data processing and tailoring to the deep penetration, necessary for oil exploration. Recently with the advent of powerful micro computers data processing has come within reach of the low-budget groundwater applications, while developments in field practice and equipment (high frequency impact with special geophones and recording equipment to minimize the lower frequencies, signal stacking and automatic gain control) make shallow reflection surveys feasible for low-cost applications.

Hunter et al. (1982, 1984), and Haeni (1986) report a number of successful experiments in shallow groundwater investigations (see Figure 16), while Birkelo (1987) describes a seismic study based on the reflection off the groundwater table during a pumping test. While Dobecki and Romig suggest that shallow reflection surveys will replace refraction surveys as the most common tool for (engineering and) groundwater studies within five years, they consider that some further testing is necessary before the technique can be accepted as a standard surveying tool. Most current seismic refraction hardware also supports the shallow reflection option.

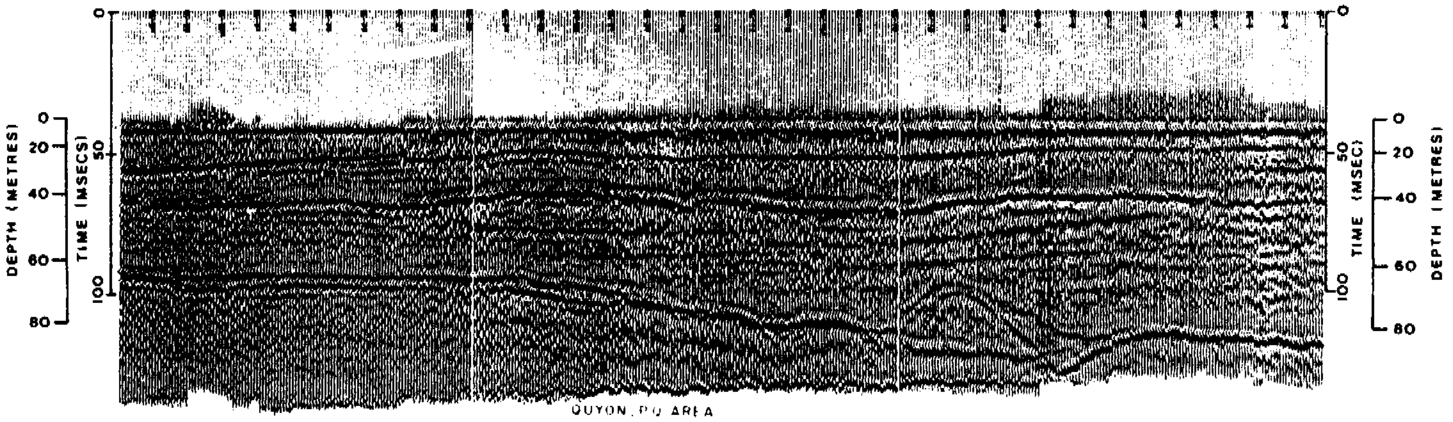

Figure 16 Reflection section showing sub-surface bedrock topography from 70 to 90m below surface and other shallow layers (Hunter et al., 1984)

Transient Electromagnetics

Another method considered to become an important tool for groundwater investigations in the near future is the transient electromagnetic (TEM) or time-domain EM (TDEM) technique. Unlike the commonly used frequency-domain EM method (such as the Geonics EM 34), the TEM can be used for carrying out quantitative depth soundings much like a resistivity sounding. There is however no need for changing the distance between the transmitter and receiver coils as with resistivity soundings to achieve deeper penetration. TEM is more sensitive to conductive zones than the resistivity method, thus has less problems with suppression of small conductive layers at depth. The method is described by Patra and Shastri (1983), Fitterman and Steward (1986) and Fitterman (1987) for shallow groundwater investigations. Some problems still limit the application of the TEM method, such as resolution problems at very shallow depths, equivalent interpretation solutions similar to resistivity interpretations, limited development of interpretation routines and rather expensive equipment.

Magnetotellurics

The magnetotelluric method (MT) is an electromagnetic technique which uses natural electrical and magnetic fields for determining the electrical properties of the earth at great depths. Bazinet and Legault (1986) describe the adaptation of this method to groundwater exploration in the form of a portable scalar audio-magnetotelluric instrument (EDA Instruments Inc.), which they claim as providing greater penetration than frequency domain EM and VLF methods and being less sensitive to near-surface effects (such as clay layers which disturb regular EM measurements), and because no transmitter has to be carried around the method is less expensive and less heavy as controlled source MT. The field examples used by Bazinet and Legault however do not include a study of groundwater sources just beyond the range of the conventional EM/VLF techniques (50-100m) which could be of interest to site investigations for CWS projects and no other publications describing the application of MT to shallow groundwater problems were available.

Ground Radar

Ground Radar is a technique also based on electromagnetic principles. It is not really a new system to shallow groundwater studies, but has not been reported on for CWS investigations. Sub-surface penetration is generally in the order of 3-10 meters and under ideal conditions up to 20m, depending on the conductivity of the soil. An experimental survey for a well-digging project, carried out in Turkana District, Kenya, proved quite successful in mapping the groundwater table and subsurface bedrock topography of sand rivers. However, in areas with a very conductive overburden, caused for example by clayey soils, the limited penetration makes ground radar virtually useless. Dobecki and Romig (1985), Fenner (1985) and Wright et al. (n.d.) describe it as a very precise and rapid site surveying method showing subsurface structures and the groundwater table. It is generally used for engineering studies and is of limited use for low-cost groundwater investigations.

A recent development, called the ARGUS, is a radar technique using a continuous wave transmission. A selected number of frequencies is swept and emitted into the ground. By recording amplitude and phase at all emitted frequencies subsurface reflectors can be detected. The system can be operated from the ground, but also from aircraft or helicopter. The manufacturer claims that penetration is an order of magnitude larger than pulsed radar systems. Still, the penetration system is severely reduced in areas where conductive soils occur. Good examples are not yet available.

Figure 17 Coastal Aquifer identified by AEM, with apparent resistivity contours in ohm.m (Geosurvey Int. Ltd)

Airborne Geophysics

The Airborne Electromagnetic Method (AEM) is the most common airborne geophysical technique and has primarily been used for mineral prospecting. Application to groundwater investigations has become possible due to recent developments and improvements in instrumentation, making detection and identification of subsurface conductive zones possible to a depth of 200 meters (Palacky, 1981; Paterson and Bosschart, 1987). Figure 17 on the previous page shows an example of an AEM investigation of the saline/fresh-water interface on the Kenya coast, where the fresh-water aquifer clearly stands out. The main drawback which presently keeps the use of AEM out of the CWS realm is the high cost of flying the surveys (e.g. Geoterrex, 1984) and the subsequent need for geophysical follow-up on the ground.

Water Divining

A perhaps rather unusual siting method to be included in this review of geophysics is Water Divining. However, it is a method that according to the questionnaires is occasionally applied in relatively large projects, while other evidence suggests that especially for the individual sitings water divining is commonly practiced. Walking with a forked stick, hand angles or other implements is probably the oldest method of well siting. As was shown in Chapter 2, divining continues to be practiced. One project report from Sri Lanka reports a nearly 100 percent success rate for the location of 600 wells and claims it is superior to the resistivity technique which was also used in the project, although the need for hydrogeological knowledge is not discounted (Schleberger, 1986):

> ...the success of a dowser does not only depend on his general ability to handle the dowsing-rod, but also on his understanding of geological and hydro-geological features of the area where surveys are conducted. The most suitable person to be trained in the water divining method would have been a hydro-geologist.

While many are skeptical of the method and the practical results in other projects often leave much to be desired (cf. projects 13 and 19 in Chapter 2), a recent article in the New Scientist (Williamson, 1987) proposes a number of scientific explanations for the dowsing technique. Like homing pigeons, bees and whales, humans may have ultra-sensitive magnetic sensors which change their orientation when changes are detected in the magnetic field of the earth. Such changes, caused for example by subsurface ore bodies, conductive fault and fracture zones, steel pipelines and electricity cables, trigger an unconscious response in a magnetically sensitive person in the form of small muscle contractions which are amplified by any implement held loosely in one's hands. Geophysical experiments carried out in the Netherlands, Saudi Arabia and the Soviet Union (Mijne, n.d.) correlated with test drilling appear to have resulted in significant and repeatable results, occasionally surpassing geophysical methods in the same area.

4.3 Cost-Effectiveness

The issue cost-effectiveness has already been discussed in section 2.7 with reference to the information given by the questionnaires. A number of project reports and publications take up the issue of the cost-effectiveness of well siting in more detail. The overall need for and the issues involved in determining the cost-effectiveness of well siting is probably most clearly put by Farr et al. (1982), who demonstrate for a commercial ranching enterprise in Botswana the criteria involved in the method and extent of borehole site investigations. The parameters involved are similar to those of many community water supply projects, whether or not the actual well construction costs are borne by the local community or, more likely, subsidized by external sources. The model used in Chapter 2.7 is based on the same principles as described by Farr et al. Carruthers (1985), however, rightly points out the difficulty in evaluating the increase in drilling success at the different levels and with the different methods of site investigation over the basic 'wildcat' success rate. In the pilot phase of large projects a number of wells may be drilled without any special investigations and some based on various types of investigation techniques in order to compare the cost-effectiveness of the alternative investigation approaches. Ovaskainen (n.d.) describes the results of the pilot phase of the large Kefinco project in western Kenya and concludes that while the survey costs are about 10% of the basic drilling costs per well the success rate is increased by 30-40%. Furthermore the investigated wells proved to be better, having a higher specific capacity and a lesser drawdown, reducing the required operating energy and wear of the pump. Comparative success rates were given by the Rural Domestic Water Supply and Sanitation Programme (van Lissa et al., 1987) using data from earlier boreholes drilled in the project area without the benefit of modern search techniques. Van Lissa demonstrates that a 26% increase in the success rate, combined with a decrease in the required drilling depth of nearly 50 percent, reduced the basic drilling cost to nearly one third of the earlier boreholes. This covers the cost of extensive siting by a large margin. White (1986) after an analysis of the cost of drilling and siting in the Victoria Drought Relief Project in Zimbabwe concludes that enough savings in drilling cost were made by the geophysical investigations to have warranted a second investigation team to carry out geophysical siting at all sites, which was not possible with one team due to time limitations. If the NCA Water Project in Sudan (Sundnes et al., 1985) would have made a similar calculation of the cost of their drilling programme and used hydrogeological siting throughout and even proper geophysical investigations, considerable savings (30-40%) could have been effected, bringing down the average cost of one well from $7000 to $6000, including pump and excluding overheads. (Note: including overheads the average cost per well was almost $20,000).

Other references to the savings effected by the use of geophysical investigation methods are often less specific. Palacky et al. (1981) compare the average cost of resistivity surveys at $911 per mile (1978) to that of EM surveys at $239 per mile. Mathiez and Huot (1968) referring to a large number of projects carried out in Western Africa state that the costs of geophysical investigations range from $400 to nearly $6000 per site, but is usually well justified given increases in drilling success rates from 20% without site investigations to as much as 90% with site investigations.

5 Conclusions

The information on well site investigations presented in the previous chapters is but a limited collection of current experiences in the realm of groundwater investigation techniques for low-cost community water supply projects. Very little information was obtained from projects outside the African continent. In a context similar to that of Sub-Saharan Africa, the experiences with well siting in for example the Indian sub-continent, where professional well siting is almost a tradition, would have been very useful and relevant to this study. However, as it is, the data collected concerns mainly Africa, but is not expected to be wholly unlike practices elsewhere in the developing world.

While the collected data cannot be considered statistically representative due to the primarily qualitative nature of the questionnaires, the data does give a wide overview of current well site investigation practice in CWS projects in Africa. Although a large variety in the application of these methods is evident, a number of common trends are visible in the approach to the survey, field techniques, cost effectiveness and applications under different geological conditions. Thus this study provides not only a range of information on current practices, but can even indicate or recommend useful approaches to well site investigations, which is undertaken in the accompanying volume to this study.

5.1 Suitability of Well Siting

Based on the findings described in the previous chapters answers can be given to the questions posed in the introduction of this report concerning the suitability of hydrogeological and geophysical investigation techniques for low-cost water supplies.

Are hydrogeological and geophysical investigations really needed for well site location?

Without doubt the answer to this question is 'Yes'. The need for a hydrogeological understanding of the project area is essential for the proper location of a well. The amount of special investigation efforts required, however, depends entirely on the local geological and climatological conditions.

Which methods are the most suitable under given circumstances?

It has become common practice to start the investigation with a basic hydrogeological reconnaissance survey, in which available topographical, geological, climatological and other relevant information is collected and aerial photos are studied. Hydrogeological fieldwork is then carried out to confirm and expand on the desk study data. The extent to which this is carried out mainly depends on the complexity of the project area and the detail of available data. The importance of carrying out a proper hydrogeological investigation is emphasized by many projects.

Whether or not the next step of geophysical investigations are necessary depends again on the prevailing hydrogeological conditions. A number of projects base the need for geophysics on the preliminary hydrogeological study and only selectively apply the chosen methods. The larger projects often base their investigation approach on a pilot phase in which the suitability of one or more geophysical methods are tested. The analysis of available hydrogeological data and hydrogeological fieldwork generally will provide adequate grounds to determine where hydrogeological investigations will suffice and where additional geophysical exploration is necessary.

In areas with unconsolidated sediments and abundant rainfall, groundwater is usually shallow. In such cases it is rather obvious that no special investigation will be necessary for determining precise well sites. A number of projects have basically followed this approach and have allowed the local population to select practically all the well sites.

Geophysical measurements are however certainly viable in unconsolidated sediments, although not always the most appropriate method of investigation as a number of projects and publications have pointed out. Test drilling with hand augers has been used by several projects and are considered more economical while at the same time providing more useful information concerning the potential aquifer through simple test pumping, soil and water-quality sampling.

Geophysical measurements are used most successfully in Basement Complex areas, where water is found in either the weathered or fissured zone above the bedrock or in fractured zones in the bedrock. Fractured zones and variations in depth to bedrock surface are traced by profiling techniques (EM, Resistivity or VLF), while depth measurements are made by resistivity or seismic refraction sounding techniques.

In volcanic and consolidated sedimentary formations, geophysical techniques can also be applied successfully. However, problems sometimes arise when encountering a complex succession of sedimentary or volcanic layers which make it difficult to identify potential aquifers. A good geological understanding of sedimentary and volcanic regions appears to be the key to determining whether or not geophysical investigations will contribute significantly to the identification of suitable aquifers.

The popularity of the resistivity method has already been noted, especially using the ABEM Terrameter. The resistivity method is one of the earliest geophysical methods to be applied for groundwater investigations and therefore more known than some of the more recently developed methods. It is also cheaper and less cumbersome in terms of safety precautions and logistics than for example the seismic refraction method with explosives. The inventory of projects revealed that the resistivity method is applied in virtually all kinds of hydrogeological environments.

In spite of a number of drawbacks (e.g. suppression and equivalence problems, contact problems in dry surface layers, 'noise' from lateral inhomogeneities), the resistivity method is a versatile geophysical tool, which when used alongside a proper hydrogeological investigation can often provide very useful additional information on potential groundwater occurrence in many different environments. An important aspect of the resistivity method is its capability to provide information on both lithology and groundwater quality. With recent developments such as the Offset Sounding System and the MRT profiling system the resistivity method will probably hold on to its popularity.

In the last 10 years the electromagnetic (EM) and VLF profiling methods have gained much in popularity, especially with the easy-to-use Geonics EM 34 equipment. These methods have proven to be extremely useful as rapid profiling techniques and are often used for initial geophysical reconnaissance, following and confirming aerial photo interpretation results and providing qualitative data about relatively shallow lateral inhomogeneities such as fractures and depressions in the fresh bedrock surface or contact zones between different types of rock. Once an interesting anomaly has been located a number of resistivity soundings are carried out to provide more quantitative information. The EM/VLF methods appear therefore most useful where lateral anomalies can be correlated to potential aquifers. Where the geological conditions primarily vary in vertical direction the EM/VLF methods are less useful than resistivity soundings. This would be the case in sedimentary basins and in volcanic areas with little tectonic disturbance.

Many projects combine a profiling/reconnaissance technique with a sounding technique (VLF or EM and Resistivity; Gravity or Magnetometry and Seismic Refraction), which has proven itself a very useful approach.

Gravity and magnetometric investigations are used in a few projects for similar reasons as the EM/VLF methods, as a preliminary reconnaissance tool to be followed by more detailed quantitative investigations. For surveying large areas such point or grid measurements are considered very useful.

The seismic refraction technique could well be a superior method for project areas with weathered basement. While like the resistivity method the interpretation is based on a simplified model of the true sub-surface situation, the interpretation itself is less complex and usually less ambiguous. The time in which the measurements can be carried out is roughly equal to resistivity soundings, but on certain conditions it provides qualitative and quantitative information along the whole geophone spread, unlike the single point data provided by a resistivity sounding. The need for explosives and the high cost of the equipment have always been the main obstacles to a wider application of the seismic refraction method. However, with low-cost seismographs such as the EG&G 1225, having the facility of signal stacking, non-explosive weight-drop methods become a suitable alternative. The seismic refraction method might well become a serious competitor for the resistivity method.

How much field investigation is needed per well?

The preparatory aerial photograph interpretation and hydrogeological fieldwork are essential to narrow down the size of the investigated area and thus the amount of geophysical fieldwork. How much profiling needs to be done and how many soundings need to be carried out depends mostly on the complexity of the local geology. The length of line profiles can range from several hundred meters to a few kilometers and the resistivity soundings or seismic spreads from 2 to 5 per proposed well site. Such geophysical fieldwork should under normal circumstances not require more than one to two days per site, usually with an extra day being allotted earlier in the schedule for the preliminary hydrogeological study. This however again depends very much on local conditions.

A number of projects have developed a standard approach or routine which is applied at practically all sites which are considered to need geophysics. This has the advantage that an initially non-skilled field crew can become familiar with the routine and after some experience proceed without the constant supervision of the expert. Occasionally this will result in extra work where it was probably not necessary, but as a whole it can speed up field operations and reduce costs considerably. The geophysicist/hydrogeologist is of course still needed initially to select the sites requiring geophysics and preferably also for the layout of the measurements, as well as for the interpretation of the data.

What are the costs?

The average cost figures as obtained by the present survey seems a reasonable indicator of approximate cost of investigation per well site in the three regions of Africa, i.e. approximately $1100, $350, $150 respectively for West, East and Southern Africa. Since these figures are primarily derived from large development projects (economies of scale) it can be expected that the investigation costs for smaller projects will lead to somewhat higher unit prices.

The major portion of the cost of site investigations are the salary costs, i.e. mainly the salary of the hydrogeologist and/or geophysicist. The second most important cost item is the geophysical equipment. The proper application of geophysical methods under practically all circumstances require the services of university trained experts. Expensive expatriates can only be replaced when local expertise is becoming available to fill the local demand, which will result in a reduction of personnel costs. Initial investment in geophysical equipment is high ranging from approximately $5000 for VLF, gravity and magnetometry to upwards of $15,000 for most resistivity, EM and seismic equipment (these will be basic costs, which can drastically increase depending on accessory options, and on the tax and duty policies of the project country). Using two systems, e.g. EM and resistivity, would cost more than $30,000. For low-cost well siting this can only be justified when written off against a large number of wells. For the smaller projects such costs will usually be prohibitive, unless the equipment can be rented. A better option is that the complete siting process be contracted out to a qualified, preferably local groundwater investigation agency to avoid the high investment costs.

What skills and equipment are required?

For the initial stage of a hydrogeological reconnaissance, which involves inventory of existing hydrogeological data of the project area, aerial photo interpretation and hydrogeological fieldwork it is necessary that a person with proven hydrogeological expertise is employed. Similarly for the application of geophysical methods it is not recommended that this be attempted without the supervision of a geophysicist or a hydrogeologist with geophysical experience.

A wide range of commercially produced equipment is available; the most current being listed in Appendix 6. It is clear that recent developments, especially the application of micro-electronics, have done much to change and simplify geophysical field practice, making the measurements, data processing and interpretation faster, more reliable and more applicable to groundwater investigations. When written off against a substantial number of surveys, groundwater investigations are in many hydrogeological environments a healthy commercial enterprise. It follows that investment in advanced equipment is warranted and that facilitating importation and making credit facilities available for the purchase of such equipment is a more viable option than to return to guesswork and accepting a high percentage of "dry" wells.

Is the application of hydrogeological and geophysical site investigation techniques justified through a higher success rate of dug and drilled wells?

This question is the financial counterpart of the first question posed above and will for many projects with limited financing be the central question. The answer is referred to in sections 2.7 and 4.3 and can be summarized as follows: When hydrogeological and geophysical site investigations are highly likely to increase the drilling success rate so that the overall cost per well is reduced beyond the cost of the investigation it makes good economic sense to engage in well siting. Determining the exact extent of investigations needed to bring about a certain increase in the drilling success rate is in most cases rather uncertain and needs to be evaluated against all available information. The information collected in the present study shows, however, that in most cases the reduction in drilling cost is significantly higher than the investigation costs.

5.2 Other Considerations

Geophysical field operations, data processing and interpretation routines are with continual technological developments becoming more and more simple to apply. However, there is a danger of putting too much emphasis on the application of sophisticated technology and too little on the insight into the underlying assumptions and principles on which the technical operations are based. Skill in operating the instruments and producing computer readouts based on mathematical and physical reductions and simplifications does not necessarily mean equal hydrogeological knowledge of the area of interest. The geophysical practice should be seen as a servant of the hydrogeological discipline.

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Abbreviations

Add	Additional
AEM	Airborne Electromagnetics
AG	Airborne Geophysics
AP	Aerial Photograph Interpretation
Asst	Assistant
AVE	Average
BHL	Borehole Logging
BL	Bilateral Agency
C	Concrete
C	Cost
C+T	Crew plus Transport (Costs)
C/D	Cost per Day
C&S	Casing and Screens
C1	Category 1
CAL	Calculator
CAT 1	Category 1
CH	Charity Organization
CM	Commercial Agency
COM	Computer
CST/D	Cost per Day
CST/KM	Cost per Kilometer
DRIV	Driver
DUG	Dug Wells
DV	Divining
EA	East Africa
EC	Electrical Conductivity
EM	Electromagnetic Profiling
EQUIP	Equipment
ES	Earlier Studies
EVAL	Evaluator/Evaluation
EVC/D	Evaluation Cost per Day
EXP	Experience
EXPAT	Expatriate
G/GP	(Hydro)Geologist or Geophysicist
GEOL	(Hydro)Geologist
GEOP	Geophysicist
GI	Geological Information
GP	Geophysical Siting
GR	Ground (Penetrating) Radar
GV	Gravimetry
H-DR	Hand Drilled
HG	Hydrogeological Siting
INCL	Including
IP	Induced Polerization
KM	Kilometer
KShs	Kenya Shillings
LAB	Labourers/Casuals
LK	Local Knowledge
LS	Landsat Imagery
M	Meter
M-DR	Machine Drilled
MAN	Manual
MG	Magnetometry
MILL	Million
MIN	Minimum
ML	Multilateral Agency
MP	Motor Pump
NAT	National Government Agency
NEG	Negative
NO	Number
NS	No Siting
O	Open Hole
O-J-T	On-the-Job Training
OPER	Operator
OT	Other
p	Portable
PLT	Plotter
PN	Project Number
POS	Positive
Prel	Preliminary
PRT	Printer
Q	Quality (in EC)
Q32	Question No 32
RIGS	Drilling Rigs
RM	Radiometrics
RP	Resistivity Profiling (Traversing)
RS	Resistivity Soundings (= VES)
RWSH	Rural Water Supply Handpumps
S	Steel
S	Site
S/D	Site per Day
S/W	Site per Week
SA	Southern Africa
SR	Seismic Refraction
SRa	Seismic Refraction
SRe	Seismic Reflection
SS	Stainless Steel
SUBAV2	Sub-Average Level 2
SUBTOT	Sub-Total
SUCC	Successful
SWL	Static (or Rest) Water Level
T-NO	Total Number
TD	Total Depth
TDEM	Time-Domain Electromagnetics
Tech	Technician
TEM	Transient Electromagnetics
TOT	Total
TOT-C	Total Cost
TOT-EV	Total Evaluation (Cost)
TRANS	Transport
TRN	Training
UNIV	University
uS/cm	micro Siemens per centimeter
VES	Vertical Electrical Soundings (= RS)
VL	Very Low Frequency EM
W*TOT	Number of Wells multipl. Total Cost
WA	West Africa
WP	Wind Pump
Y	Yield
4x4	Four Wheel Drive Vehicle

Appendices

Appendix 1 Terms of Reference

Appendix 1

Terms of Reference

1 PROJECT IDENTIFICATION

1.1 Title of Project:

Well Siting for Low-Cost Water Supplies

1.2 Implementation:

Groundwater Survey (K) Ltd,
(Pieter G.van Dongen)

1.3 Duration of Project:

6 months;
commencing: January 1987
completion: July 1987

1.4 Costs of project:

KShs 375,000/- (=Dfl.50,000)

2 OBJECTIVES

The aim of the study is to undertake a comprehensive inventory of the experience obtained by a large number of rural water supply programmes on the application of hydrogeological and geophysical investigation techniques for the siting of drilled and dug wells.

In addition, information will be gathered on the current state-of-the-art techniques and available equipment for well site investigations.

3 BACKGROUND

When planning a low-cost rural water supply programme, through development of groundwater through dug or drilled wells fitted with handpumps, the executing agency is usually faced with the following questions as far as hydrogeological site investigations are concerned:

- do we need investigations to locate sites for wells?
- if so, which method or combination of methods is the most suitable for the prevailing conditions in the area?
- how much field investigation do we need per well?
- how much does it cost per well?
- what level of skill is required?
- what kind of equipment is required and what is available in the market?
- what tools for interpretation are available?
- is the use of hydrogeological and geophysical methods justified through a higher success rate of dug and drilled wells?

4 JUSTIFICATION

At present no consensus exists on the most suitable method (if at all) for siting of a water well under given hydrogeological conditions. Seen against the background of keeping the cost of a water point as low as possible, an analysis of experience with site investigation techniques is most relevant.

The central question is: Are the costs involved with siting techniques justified through a higher success rate?

The proposed study aims to provide answers to the above questions in the form of a substantial report, which gives guidelines to planners and managers of low-cost water supply programmes. This publication will be intended for non-technical personnel and will not assume prior knowledge of these techniques.

5 ACTIVITIES

The study will involve the following activities:

1. Comprehensive inventory and review of available literature.
2. Assessment of experience with well siting obtained in programmes carried out in the region at present or completed in the recent past. To this end comprehensive questionnaires will be prepared and sent out to current projects.
3. Field visits to programmes being undertaken at present in Kenya and possibly elsewhere in the region.
4. A comprehensive study and evaluation of available equipment, their cost, suitability and technical specifications. Some field testing might be involved.
5. Evaluation and reporting. After evaluation of the collected data, a draft final report will be presented, which after review will ultimately be published as a Technical Note of the Project.

6 PLANNING

Activity	JAN	FEB	MAR	APR 1987	MAY	JUN
1. Preparation	==					
2. Inventory						
-literature	==	==				
-equipment	==	==				
3. Enquiry						
-drafting	=					
-mailing	=					
-reminders			x	x		
-prel.eval.				===		
-add.enquiries					==	
-final eval.						====
4. Field Visits		==		==		
5. Equipment						
-inventory	==					
-inquiry		=				
-field tests			===			
-analysis of data					==	
7. Evaluation & Reporting			(15/3)	(15/5)		
-Progress			=	=		(15/7)
-(Draft) Final						====

Personnel	J	F	M	A	M	J
Sr.Geoph.(9w)	2	1	2	1	1	2
Jr.Hydrog.(8w)	1	1	1	2	2	1
Assistant (7w)	1	2	1	1	1	1

(Nairobi, 16/1/87)

Appendix 2 Questionnaires

Appendix 2.1

Questionnaire No 1 UNDP/World Bank

Well Siting for Low-Cost Water Supplies

Please complete this form as complete as possible and return
to: Rural Water Supply Handpumps Project, UNDP/World Bank
P.O.Box 30577, Nairobi, Kenya
Att. Mr. Pieter G.van Dongen

Q1 Country:
Q2 Name of project:
Q3 Executing agency:
Q4 Sponsoring agency:
Q5 Region/District:
Q6 Project area (size): km^2
Q7 Objectives of project:

Q8 Year started: Year completed:
Q9 Budget (total) : US $; per year: US $ Q10
Local component: US $; per year: US $

Q11 Geology of the area: (very brief outline)

Q12 Type of aquifers: alluvial %
sedimentary %
volcanic %
basement system, weathered %
fractured %

Q13 Number of watering points planned: per year: Q14
Q15 of which Groundwater % ; and Surface water %

Q16 No. of Groundwater Wells dug: (total); and (per year) Q17
drilled: (total); and (per year)

	WELLS	alluvial	sediment	volcanic	basement
Q18	average depth (m)				
Q19	av. water rest level(m)				
Q20	average yield (m^3/hr)				
Q21	water quality (EC)				

well completion
Q22 -casing, screens
Q23 -handpumps, (type) other

Q24 Which methods are used for locating well sites?

O - none
O - local knowledge
O - divining rods
O - geological information
O - aerial photo's
O - Landsat images
O - earlier studies, if so, which
O - geophysical methods
O - other (which?)

Geophysical methods applied

O - resistivity soundings
O - resistivity profiling
O - seismic refraction
O - electromagnetic profiling (which method?)
O - VLF profiling
O - gravity
O - magnetometry

0 - airborne geophysics
0 - ground radar
0 - other (which?)

Q25 What type of equipment is used? Q26 Q27
make: ; type: ; cost: $ cost/day:
make: ; type: ; cost: cost/day:

Q28 Composition of field crew(s): (indicate level of training and experience) Q29

0 - Geologist/geophysicist
0 - Assistant/operator
0 - Driver(s)
0 - Labourers

Q30 What is the running cost/day per crew?

Q31 Means of transport:
Q32 Cost/day or /km:

Q33 How many measurements per site (average):
Q34 Output per field crew: sites per day or per week

Q35 Who does evaluation of field data ?
Q36 (indicate level of training) cost/day Q37

Q38 What aids are used for interpretation (computer, plotter, etc)

Q39 total costs cost/day Q40

Q41 How many sites are evaluated per day?
Q42 Cost of interpretation per day:

Q43 Total Cost of well site investigation,
per site (average): US $

Q44 How many wells are constructed per month?
dug: drilled:

Q45 At which yield do you consider a well successful: m^3/h.

Q46 How many are successful: %

Q47 What is the total cost of drilling a well of 50 m?
Q48 How much is the cost of drilling a dry well?

Q49 Can you indicate (or estimate) by which percentage the use of site investigation methods increases the success rate of drilling or digging of wells:

- geological info, aerial photo's %
- one geophysical method %
- combination of methods %

Q50 Have the results of the hydrogeological and geophysical site been written down in reports? Yes/No

---

* * *

We would highly appreciate if you possibly could make available (some of) these reports for the present study.

* * *

Full acknowledgement will be made to all who have contributed to the study.

* * *

Appendix 2.2

Questionnaire No 2 UNDP/World Bank

Well Siting For Low-Cost Water Supplies

Please complete this form as fully as possible and return to: Rural Water Supply Handpumps Project, UNDP/World Bank
P.O.Box 30577, Nairobi, Kenya
Att. Mr. Pieter G.van Dongen

Name of organization/agency:
Address:
Country:
Telephone: Telex:

In which countries is your organization/agency active (or has been) with the execution or sponsoring of low-cost water supply programmes?

Can you provide us with relevant background information, reports or publications on these programmes?

We are particularly interested in contacting the executing agencies who might be in a position to provide us with relevant information on the applied site investigation techniques. We would very much appreciate if you could provide us with names and addresses. (Use separate sheet if necessary)

In case you have been yourself engaged in the execution of these programmes, could you please complete attached questionnaire (one set for each programme).

Can you indicate (or estimate) by which percentage the use of site investigation methods increases the success rate of drilling or digging of wells:

- geological info, aerial photo's %
- one geophysical method %
- combination of methods %

Have the results of the hydrogeological and geophysical site investigations been written down in reports? Yes/No

* * * We would be very grateful if you could possibly make available some copies of these reports for the present study. * * *

Are you prepared to answer additional questions, if these arise from your answers to the above questions? Yes/No

---

* * *

Full acknowledgement will be made to all who have contributed to the study.

Appendix 2.3

Questionnaire No 3 UNDP/World Bank

Well Siting For Low-Cost Water Supplies

Please complete this form as fully as possible and return
to: Rural Water Supply Handpumps Project, UNDP/World Bank
P.O.Box 30577, Nairobi, Kenya
Att. Mr. Pieter G. van Dongen

Q1 Name of the Company:
Address:
Country:
Telephone: Telex:
Name of person who is completing this questionnaire:

Q2 Which types of geophysical (or other) equipment that can be used in groundwater investigations are manufactured by your company?

0 - resistivity
0 - IP
0 - seismic refraction
0 - shallow reflection
0 - electromagnetic (which method?)
0 - VLF
0 - gravity
0 - magnetometry
0 - radiometrics
0 - airborne geophysics, (which method?)
0 - ground radar
0 - borehole logging
0 - others (which?)

(please attach catalogs, technical descriptions, manuals, etc)

Q3 Could you please include quotations for the equipment that is used for groundwater drill site investigations?

Q4 What is in your opinion the necessary composition of field crew(s) for the different equipment supplied:

(indicate level of training and experience)

	Resist.	Seismic	EM	Other
- Geologist/geophysicist				
- Assistant/operator				
- others				

Q5 Means of transport required:
- resistivity
- seismic refraction
- EM/VLF
- other

Q6 What is required for the evaluation of the field data?
(indicate level of training)

Q7 What aids are necessary for interpretation (computer, plotter, etc)

Do you supply these?

Q8 Do you supply software for data interpretation?

Which programs?

Q9 * * * Is it possible to send us demonstration program(s)? * * *

Q10 Do you have results of hydrogeological and geophysical test investigations, and are these written down in reports? Yes/No

---

* * * We would highly appreciate if you possibly could make available (some of) these reports for the present study. * * *

===

Q11 * * * Is there a possibility that you could make some of your equipment available during a short period for testing under field conditions? * * *

===

Are you prepared to answer additional questions, if these arise from your answers to above questions? Yes/No

===

* * *

Full acknowledgement will be made to all who have contributed to the study.

* * *

Appendix 3 List of Respondents

Respondents:

	Q1	Q2	Q3	DOC	PN
Addison & Baxter Ltd (UK)			1	1	
Advies Bureau v Geofysica (Netherlands)			1	1	
Alta Geophysics (UK)	12				39, 52, 54, 55, 56
Atlas Copco Abem AB (Kenya)				1	
Bison Instruments Inc (USA)			1	1	
Bodenseewerk Geosystem Gmbh (W Germany)			1	1	
BRGM (France)	5				3, 4, 7, 8, 15
British Geological Survey (UK)	2			1	31, 32
Campus Geophysical Instrument Ltd (UK)			1	1	
CCKK (Denmark)	1				25
Christian Care (Zimbabwe)	1				34
COWIconsult (Denmark)	1				46
Danida (Kenya)	1				22
DHV Consulting Engineers (Kenya)	1			1	23
Diocese of Marsabit (Kenya)	1	1		1	24
Direccao Nacional de Aguas (Mozambique)	1				33
EDA Instruments Inc (USA)				1	
EE&G Geometrics Mt Sopris Division (USA)			1	1	
EWWCA (Ethiopia)	1			1	16
Foster Parents Plan (Kenya)	2	1		1	18
Geohydraulique (France)	2				1, 2
Geological Survey and Mines (Swaziland)	1			1	44
Geonics Ltd (Canada)			1	1	
Geophysical Survey Systems Inc (USA)				1	
Geotechnisches Buro (W Germany)	9			1	9, 13, 14, 30, 45, 47, 48, 49, 53
Groundwater Development Consultants (UK)	2			1	11, 51
Groundwater Survey (K) Ltd (Kenya)	1			1	50
GTZ-PAS Lamu (Kenya)	2				19, 20
Hemker (Netherlands)				1	
Hope International (Ethiopia)	1				17
Hydrotechnica (UK)	2			1	37, 56
ICCO (Netherlands)	1	1			34
Idromin SRL (Italy)	3				6, 12, 38
Interconsult A/S (Zimbabwe)	2				35, 36
Ivrea (Italy)		1		1	
Iwaco (Burkina Faso)	1			1	5
Kefinco (Kenya)	1				21
Min. dos Recursos Naturais (Guinea Bissau)				1	
Norconsult AS (Norway)	1				27
Norwegian Church Aid (Norway)		1		1	
Oyo Corporation (Japan)			1	1	
Preussag (W Germany)	1			1	10
Scintrex (Canada)				1	
Strojexport (Czechoslovakia)	2			1	42, 43
Tampere University of Technology (Finland)				1	
Terraplan Ltd (Finland)	1	1			26
TNO-DGV (Netherlands)	1		1		5
Unesco/Ipal (Kenya)	1				40
Unicef (India)		1			
Unicef (Uganda)	3			1	28, 29
WRAP (Kenya)	1			1	41
	68	7	9	32	

Appendix 3

Negative Reply:

Actionaid (Kenya), British Water International (UK), Care (Kenya), Carl Bro Int AS (Denmark), Carl Bro (Swaziland), CIDA (Kenya), Civil & Planning Partnership (Zimbabwe), Commonwealth Development Corporation (Kenya), Diocese of Lodwar (Kenya), Diocese of Machakos (Kenya), Delegate of the EEC (Kenya), Euroconsult (Netherlands), Geological Survey (Botswana), Geominco (Hungary), Groundwater Data Systems (Netherlands), Loughborough University of Technology (UK), Norad (Kenya), Regional Remote Sensing Centre (Kenya), Rwegarulira Water Resources Institute (Tanzania), TAMS (USA), UNEP (Kenya), Wapcos (India).

No Reply:

Airmag Services Inc (USA), Amref (Kenya), Androtex Ltd (Canada), Aqua Tech (Botswana), BCI Geonetics Inc (USA), Bidex (Ghana), Bish International (Kenya), BKH Consulting Engineers (Netherlands), Chidley (UK), Cowater (Canada), Department of Water Affairs (Botswana), DGIS (Kenya), DHV Consulting Engineers (Netherlands), Diocese of Kisii (Kenya), Ecosystems Ltd (Kenya), Edcon Inc (USA), EE&G Geometrics CA (USA), Enplan Group (Nigeria), FIA (Italy), Finnida (Kenya), Finnida (Tanzania), Geophysical Microcomputer Applications (Canada), Geosurvey International Ltd (UK), Geoterrex Ltd (Canada), GTZ (W Germany), Huntec Ltd (Canada), Hunting Geology & Geophysics Ltd (UK), Hunting Surveys & Consultants Ltd (USA), IRC (Netherlands), ITC (Netherlands), Iwaco (Netherlands), Kenting Earth Sciences Ltd (Canada), Kruger AS (Denmark), LaCoste & Romberg Inc (USA), Louis Berger Inc (Kenya), Louis Berger International Inc (USA), Mawa (Kenya), McPhar Geophysics (Canada), Machakos Integrated Development Programme (Kenya), Ministry of Lands, Water, Housing and Urban Development (Tanzania), Ministry of Water, Energy and Minerals, Geophysics and Exploration Section (Tanzania), Ministry of Water Development (Kenya), Ministry of Water Resources (Zimbabwe), Ministry of Works and Supplies (Malawi), Mooney (USA), Morogoro Shallow Wells Project (Tanzania), Nedeco (Netherlands), Norconsult AS (Kenya), Organization of Netherlands Volunteers (Kenya), Oxfam (Kenya), Phoenix Geophysics Ltd (USA), Prakla-Seismos AG (W Germany), Rockview (France), Sercel (USA), SIDA (Kenya), Sudan Council of Churches (Sudan), Swedish Geological Company (Sweden), Turkana Rehabilitation Programme (Kenya), UNCHS (Kenya), UNDP (Kenya), UNHCR (Kenya), UNICEF (Sudan), UNICEF (W Africa), Viak AB (Sweden), Water Resources Research Institute (Ghana), Wellfield Consulting Services (Australia), Wellfield Consulting Services (Botswana), World Bank (Ivory Coast), World Vision (Kenya), Zonge Engineering & Research Org (USA).

Appendix 4 Data Questionnaire No 1

QUESTIONS PN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Q1 COUNTRY	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q2 PROJECT NAME	+	+	+	+	+		+	+	+	+	+		+	+	+	+	+	+	+
Q3 EXECUTING AGENGY			+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+
Q4 SPONSORING AGENCY	+	+	+	+	+		+	+	+	+	+		+	+	+		+		+
Q5 REGION/DISTRICT		+	+	+	+		+	+	+	+	+	+	+	+	+		+	+	+
Q6 PROJECT AREA	+	+	+	+	+	+	+	+		+	+	+			+			+	+
Q7 OBJECTIVES	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+
Q8 YEAR STARTED/ENDED	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	
Q9 BUDGET TOTAL	+	+	+	+	+		+	+	+	+	+		+	+	+		+		
Q10 BUDGET/YEAR					+												+		
Q11 GEOLOGY	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+
Q12 AQUIFER TYPES	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q13 PLANNED POINTS	+	+	+	+	+	+	+	+	+		+	+	+	+	+		+		+
Q14 PLANNED/YEAR	+	+			+	+			+			+	+	+			+		
Q15 GROUND/SURFACE WATER			+	+	+		+	+	+		+		+	+	+		+		+
Q16 POINTS CONSTRUCTED	+	+	+	+			+	+		+	+	+	+	+	+	+	+	+	+
Q17 CONSTRUCTION/YEAR	+	+						+		+	+	+	+	+			+		
Q18 MEAN WELL DEPTH	+	+	+	+	+		+	+	+	+	+		+	+	+	+	+	+	+
Q19 MEAN SWL	+	+	+	+	+		+	+	+	+	+		+	+	+	+	+	+	+
Q20 MEAN YIELD	+	+		+	+		+	+	+	+	+		+	+	+	+	+	+	
Q21 MEAN EC				+	+		+		+		+		+	+					+
Q22 CASING/SCREENS	+	+	+	+			+	+		+	+	+			+	+	+	+	+
Q23 HANDPUMP TYPE	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+
Q24 SITING METHODS	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q25 SITING EQUIPMENT		+	+	+	+	+	+	+		+	+	+			+	+	+		
Q26 TOTAL EQUIPMENT COST										+	+						+		
Q27 EQUIP COST/DAY					+					+	+						+		
Q28 CREW COMPOSITION		+	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	
Q29 CREW TRAINING										+	+			+				+	
Q30 CREW COST/DAY		+			+		+			+	+		+	+	+	+	+		
Q31 TRANSPORT		+	+	+	+	+	+			+	+			+	+	+	+	+	
Q32 TRANSPORT COST					+		+			+	+			+	+	+	+		
Q33 MEASUREMENTS/SITE		+	+	+		+	+	+		+	+	+		+	+		+		
Q34 OUTPUT		+	+	+	+	+	+	+		+	+			+		+	+	+	
Q35 EVALUATOR		+	+	+	+	+	+	+		+	+	+	+		+	+	+	+	
Q36 TRAINING										+	+		+			+			
Q37 COST/DAY					+	+				+	+					+	+		
Q38 INTERPRETATION EQUIP			+	+		+	+	+		+	+	+			+	+	+	+	
Q39 TOTAL COST										+	+					+	+		
Q40 EQUIP COST/DAY					+					+	+					+	+		
Q41 SITE EVAL/DAY					+					+	+			+		+	+	+	
Q42 EVAL COST/DAY									+	+			+	+		+	+		
Q43 SITING COST/SITE			+	+	+	+	+		+	+	+		+	+	+	+	+	+	+
Q44 CONSTRUCTION/MONTH		+	+	+	+		+	+	+	+	+		+	+	+	+	+	+	
Q45 SUCCESSFUL YIELD		+	+	+	+		+	+	+	+	+		+	+	+	+	+	+	
Q46 SUCCESS PERCENTAGE		+	+	+	+		+	+	+	+	+		+	+	+	+	+	+	+
Q47 COST OF SUCC WELL		+	+	+	+		+	+		+	+				+	+	+	+	
Q48 COST OF DRY WELL		+		+	+		+	+		+	+						+	+	
Q49 SUCCESSRATE INCREASE			+	+			+		+	+	+			+				+	
Q50 REPORT	+		+	+	+		+	+	+	+	+		+	+	+	+	+	+	+
ANSWERED QUESTIONS:	20	32	33	36	39	18	38	33	26	45	47	20	31	36	34	31	45	31	21

PERCENTAGE ANSWERED:40.0%64.0%66.0%72.0%78.0%36.0%76.0%66.0%52.0%90.0%94.0%40.0%62.0%72.0%68.0%62.0%90.0%62.0%42.0%

WEIGHTED % ANSWERED:62.5% 78.8% 83.8% 65.6%

Appendix 4.1

QUEST	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Q1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q2	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q4	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+			+	+	+
Q5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+
Q6	+	+	+	+		+	+	+	+			+	+	+	+	+		+	+		+	+	+
Q7	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q8		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q9		+	+			+			+	+		+	+	+	+		+	+			+	+	
Q10		+				+						+	+	+	+						+	+	
Q11	+	+		+		+	+	+	+	+	+	+	+		+	+	+	+		+	+	+	+
Q12	+	+		+		+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+
Q13		+	+	+		+			+	+	+		+	+	+	+		+	+		+		+
Q14		+		+		+		+		+	+		+	+					+				+
Q15	+	+	+	+		+		+		+	+	+	+	+	+	+		+	+		+		+
Q16	+	+				+		+	+	+		+	+	+	+		+	+			+	+	+
Q17		+				+		+				+		+	+			+				+	+
Q18	+	+	+	+	+	+		+	+	+		+	+	+	+	+	+	+				+	+
Q19	+	+		+	+	+		+	+	+		+	+	+	+	+		+				+	
Q20		+		+		+		+	+	+		+	+	+	+	+		+				+	+
Q21	+			+				+				+	+					+				+	+
Q22	+		+	+		+	+	+				+	+	+	+	+		+					+
Q23	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+						+	
Q24	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Q25		+		+		+		+		+		+		+	+	+		+	+	+		+	+
Q26		+		+		+	+	+							+							+	
Q27				+			+								+	+						+	
Q28				+		+		+		+	+	+			+	+		+	+	+		+	+
Q29		+		+		+		+		+	+	+			+	+				+	+		+
Q30		+		+		+				+	+			+	+					+		+	
Q31		+		+			+	+		+	+	+			+	+		+	+	+		+	+
Q32		+		+		+	+					+			+	+						+	
Q33				+	+	+	+			+	+				+	+		+	+	+			
Q34		+		+		+	+				+			+	+	+		+	+			+	+
Q35		+	+	+		+		+			+			+	+	+		+	+	+		+	+
Q36		+		+		+		+			+				+					+		+	+
Q37				+		+									+				+	+		+	+
Q38		+		+				+		+	+				+	+		+	+	+		+	+
Q39		+		+																			+
Q40				+																		+	+
Q41		+		+											+	+		+				+	+
Q42				+		+									+							+	+
Q43		+		+	+	+					+	+	+	+	+	+		+				+	+
Q44		+	+	+		+		+	+	+		+	+	+	+	+		+				+	+
Q45		+		+	+	+	+	+	+	+	+	+	+	+	+	+		+				+	+
Q46	+	+	+	+		+	+	+	+	+		+	+	+	+	+	+	+				+	+
Q47		+		+	+			+	+	+		+	+	+	+	+		+				+	
Q48		+		+	+			+	+	+		+	+	+	+	+		+				+	
Q49		+	+	+	+			+				+	+	+	+	+		+				+	+
Q50	+		+	+	+	+	+	+	+	+	+		+	+	+	+		+		+		+	+
	19	41	20	46	17	40	21	36	24	32	26	34	31	34	46	37	14	37	19	19	17	43	39
	38.0%	82.0%	40.0%	92.0%	34.0%	80.0%	42.0%	72.0%	48.0%	64.0%	52.0%	68.0%	62.0%	68.0%	92.0%	74.0%	28.0%	74.0%	38.0%	38.0%	34.0%	86.0%	78.0%
	59.4%		60.6%						75.0%				96.9%	89.5%									

QUEST	43	44	45	46	47	48	49	50	51	52	53	54	55	56	ANSWERED	(%)	INCOMPLETE	(%)	NOT ANSWERED	(%)	TOTAL
Q1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	56	100.0%		0.0%		0.0%	56
Q2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	53	94.6%	1	1.8%	2	3.6%	56
Q3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	53	94.6%		0.0%	3	5.4%	56
Q4	+	+	+	+	+	+	+	+	+		+		+	+	48	85.7%	1	1.8%	7	12.5%	56
Q5	+	+	+		+	+	+	+	+	+	+	+	+		50	89.3%	1	1.8%	5	8.9%	56
Q6	+	+		+	+	+	+	+	+	+	+	+	+	+	45	80.4%	6	10.7%	5	8.9%	56
Q7	+	+	+	+	+	+	+	+	+	+	+	+	+	+	54	96.4%		0.0%	2	3.6%	56
Q8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	53	94.6%		0.0%	3	5.4%	56
Q9		+	+	+	+	+	+	+			+				35	62.5%	1	1.8%	20	35.7%	56
Q10		+						+							12	21.4%		0.0%	44	78.6%	56
Q11	+	+	+	+	+	+	+	+	+	+	+	+	+	+	51	91.1%	1	1.8%	4	7.1%	56
Q12	+	+	+	+	+	+	+	+	+		+			+	50	89.3%	1	1.8%	5	8.9%	56
Q13	+	+	+		+	+	+	+	+		+			+	41	73.2%		0.0%	15	26.8%	56
Q14	+	+	+		+	+		+			+				26	45.6%		0.0%	31	54.4%	57
Q15	+	+	+		+	+	+	+	+		+			+	39	69.6%		0.0%	17	30.4%	56
Q16	+	+	+		+	+	+	+	+		+			+	41	73.2%	2	3.6%	13	23.2%	56
Q17	+	+	+		+	+	+	+	+						26	46.4%	1	1.8%	29	51.8%	56
Q18		+	+		+	+	+	+	+		+			+	44	78.6%	2	3.6%	10	17.9%	56
Q19		+			+			+	+		+			+	38	67.9%	2	3.6%	16	28.6%	56
Q20		+	+	+	+	+	+	+	+		+			+	39	69.6%	3	5.4%	14	25.0%	56
Q21		+			+	+	+	+	+		+			+	24	42.9%	16	28.6%	16	28.6%	56
Q22		+			+			+	+		+			+	33	58.9%	10	17.9%	13	23.2%	56
Q23			+		+	+	+	+			+				41	73.2%	1	1.8%	14	25.0%	56
Q24	+	+	+	+	+	+	+	+	+	+	+	+	+	+	56	100.0%		0.0%		0.0%	56
Q25	+	+	+	+	+			+	+	+	+	+	+	+	39	69.6%	2	3.6%	15	26.8%	56
Q26		+		+				+							13	23.2%		0.0%	43	76.8%	56
Q27		+		+				+					+	+	14	25.0%	2	3.6%	40	71.4%	56
Q28	+	+	+	+	+	+	+	+	+	+	+	+	+	+	43	76.8%	4	7.1%	9	16.1%	56
Q29	+	+	+		+	+	+	+	+	+	+	+	+	+	29	51.8%	5	8.9%	22	39.3%	56
Q30		+	+	+	+	+	+	+			+	+	+	+	30	53.6%	6	10.7%	20	35.7%	56
Q31	+	+	+	+	+	+	+	+	+	+	+	+	+	+	41	73.2%	1	1.8%	14	25.0%	56
Q32		+	+			+	+	+							21	37.5%	5	8.9%	30	53.6%	56
Q33			+	+	+	+	+	+	+	+	+	+	+	+	35	62.5%	2	3.6%	19	33.9%	56
Q34	+		+	+	+	+		+	+		+			+	34	60.7%	1	1.8%	21	37.5%	56
Q35	+	+	+	+	+	+	+	+	+	+	+	+	+	+	43	76.8%	3	5.4%	10	17.9%	56
Q36	+	+	+		+	+	+	+	+	+	+	+	+	+	26	46.4%	4	7.1%	26	46.4%	56
Q37	+	+	+	+	+	+	+	+			+	+	+	+	25	44.6%	1	1.8%	30	53.6%	56
Q38	+	+	+	+	+	+	+	+	+	+		+	+	+	37	66.1%	1	1.8%	18	32.1%	56
Q39		+	+			+	+	+							12	21.4%	1	1.8%	43	76.8%	56
Q40			+			+	+	+							12	21.4%	1	1.8%	43	76.8%	56
Q41	+		+	+	+	+	+	+	+					+	23	41.1%	2	3.6%	31	55.4%	56
Q42	+		+			+	+	+							16	28.6%	5	8.9%	35	62.5%	56
Q43	+	+	+	+	+	+	+	+			+			+	38	67.9%	2	3.6%	16	28.6%	56
Q44	+	+	+	+		+	+		+					+	38	67.9%	3	5.4%	15	26.8%	56
Q45	+	+	+	+	+	+	+	+	+		+			+	43	76.8%	3	5.4%	10	17.9%	56
Q46	+	+	+	+	+	+	+	+	+		+			+	45	80.4%	2	3.6%	9	16.1%	56
Q47		+	+	+		+	+								30	53.6%	5	8.9%	21	37.5%	56
Q48		+	+			+	+								26	46.4%	7	12.5%	23	41.1%	56
Q49	+	+	+	+	+	+	+		+		+				30	53.6%	3	5.4%	23	41.1%	56
Q50	+	+	+	+	+	+	+	+	+	+	+	+	+	+	48	85.7%		0.0%	8	14.3%	56
	33	44	43	31	40	44	42	46	35	18	37	20	22	36	1799	64.2%	120	4.3%	882	31.5%	2801
	66.0%	88.0%	86.0%	62.0%	80.0%	88.0%	84.0%	92.0%	70.0%	36.0%	74.0%	40.0%	44.0%	72.0%		64.3%					
																68.0%					

Appendix 4.2

PR	EXECUTION					SPONSORING					BUDGET	PERIOD			WELL	AREA
NO	CM	NAT	BL	ML	CH	NAT	BL	ML	CH	AGENCY	MILL US$	START	END	LENGTH	NO	KM2
1	100%					6%		94%		EDF	5.20	1982	1985	3.0	305	39000
2	100%					20%		80%		WADB	4.95	1984	1987	3.0	130	6200
3	100%					10%		90%		CCCE, FAC	5.44	1983	1984	1.0	420	32000
4	100%						100%			FAC	2.00	1981	1983	2.0	218	30000
5	50%	50%				2%	98%			DGIS	22.00	1980	CONT	10.0	1300	36000
6												1983	1984	1.0	30	40000
7	100%					2%		98%		CCCE	4.76	1983	1985	2.0	378	70000
8	100%							100%		CCCE	10.30	1981	1983	2.0	1000	40000
9			100%			10%	90%			SAUDI ARABIA	1.20	1984	1986	2.0	350	
10		100%				100%				KADUNA STATE GOV'T	15.00	1982	NOT			45000
11	100%					25%		75%		WORLD BANK	22.00	1983	1986	3.0	1200	43000
12												1980	1981	1.0	50	5000
13			100%				100%			BMZ	2.00	1981	NOT		600	
14			100%			16%	84%			KfW	4.40	1986	CONT	2.0	320	
15	100%					3%		97%		USAID, FAC, EDF	7.70	1981	1984	3.0	700	25000
WA AVE	65%	12%	23%	0%	0%	15%	36%	49%	0%		8.23			2.7	500	34267
16		100%						100%		UNICEF						
17		100%				13%			87%	HOPE INTERNATIONAL	2.00	1986	CONT	2.0	24	
18					100%				100%	FOSTER PARENTS		1986	CONT			2572
19										BMZ			CONT		29	100
20										BMZ			CONT		169	225
21	50%	50%				11%	89%			FINNIDA	7.00	1983	CONT	2.0	550	3654
22		50%	50%			17%	83%			DANIDA	3.00	1982	CONT	6.0	500	10000
23	50%	50%				5%	95%			DGIS	4.17	1984	CONT	5.0	750	12500
24					100%	50%			50%	NORAD, CEBEMO, CELIM		1969	CONT			
25		50%	50%			1%	99%			DANIDA	36.00	1983	CONT	6.0	3000	177000
26	100%					10%	59%	31%		FINNIDA, ODA, UNICEF	13.45	1978	1984	7.0	1845	160000
27	50%	50%								NORAD		1981	CONT?			70000
28		50%		50%		10%		90%		UNICEF	6.00	1986	1987	1.0	500	12000
29		50%		50%		13%		87%		UNICEF	5.00	1983	1986	3.0	800	
EA AVE	21%	46%	8%	8%	17%	12%	39%	28%	22%		9.58			4.0	817	44805
30	100%						100%			GR DE BANQUE SUISSE		1986	CONT	3.0	150	
31		50%	50%			14%		86%		IFAD	0.43	1982	1986	4.0	233	320
32		50%	50%			18%		82%		DANIDA, ODA, UNICEF	0.42	1981	1983	3.0	244	180
33		50%			50%	100%				SWISS GOVERNMENT	4.02	1981	CONT	7.0	854	83000
34					100%	10%			90%	CHRISTIAN CARE	0.30	1985	CONT	4.0	300	4000
35	50%	50%					100%			NORAD		1984	CONT			150000
36	50%	50%					100%			NORAD	0.84	1984	1985	1.0	420	
37	100%					29%		71%		EDF	1.60	1983	1984	1.0	700	750
SA AVE	38%	31%	13%	0%	19%	21%	38%	30%	11%		1.27			3.3	414	39708
C1 TOT	1400%	950%	500%	100%	350%	495%	1197%	1181%	327%		191.18			90.0	18069	1097501
C1 AVE	42%	29%	15%	3%	11%	15%	37%	37%	10%		7.08			3.2	583	37845
38												1983	1983	1.0	60	20000
39												1980	1980	0.3		
40				100%			100%			BMZ	11.50	1976	CONT	11.0		22500
41	50%	50%					100%			DGIS	1.00	1982	1984	2.0	30	10000
42			100%							KADUNA STATE		1977	1980	3.0	200	16000
43			100%			100%				NAT WATER CORP		1970	1977	7.0	52	180000
44		100%				23%	77%			CIDA	7.80	1986	CONT	5.0	500	10000
C2 TOT	50%	150%	200%	100%	0%	123%	277%	0%	0%		20.30			29.3	842	258500
C2 AVE	10%	30%	40%	20%	0%	31%	69%	0%	0%		6.77			4.2	168	43083
45	100%					100%				M of Energy & Water	6.40	1975	1976	1.0	60	
46	50%	50%				20%	80%			DANIDA	15.00	1979	1987	8.0		1300
47	50%		50%				100%			Gov't of RSA	0.02	1972	1973	1.0		600
48	100%						100%			KfW	1.60	1977	1978	1.0	20	200
49	100%						100%			KfW	0.90	1977	1978	1.0	20	500
50	100%						100%			GTZ	0.02	1987	1987	0.5	10	500
51	100%					100%				Ministry of Works		1981	1983	2.0	200	10000
52	100%											1983	1983	0.1		40
53	50%	50%				100%				Gov't of RSA	0.03	1973	1974	1.0		100
54	100%											1987	1987	0.1		12
55	100%											1984	1985	0.7		340
56	100%					100%				Municipal Council		1980	1981	1.0	7	800
C3 TOT	1050%	100%	50%	0%	0%	420%	480%	0%	0%		23.98			17.4	317	14392
C3 AVE	88%	8%	4%	0%	0%	47%	53%	0%	0%		3.43			1.5	53	1308
TOTAL	2500%	1200%	750%	200%	350%	1038%	1954%	1181%	327%	TOTAL:	235.46			136.7	19228	1370393
AVERAGE	50%	24%	15%	4%	7%	23%	43%	26%	7%	AVERAGE:	6.36			2.9	458	30453

PROJECT AVERAGES

PN	NO OF WELLS	ALLUVIAL %	TD	SWL	Y	Q	SEDIMENTARY %	TD	SWL	Y	Q	VOLCANIC %	TD	SWL	Y	Q	BASEMENT %	TD	SWL	Y	Q
1	320						67%	79.4	26.0	3.5							33%	52.8	15.0	2.5	
2	180						100%	79.0	21.5	3.6											
3	459																100%	61.0	27.5	1.0	
4	219						1%			7.3							98%	49.7	25.0	3.0	250
5	175																100%	60.0	25.0	2.0	800
6	30																90%				
7	378	3%	29.5	12.0	3.0	500	68%	54.0	17.0	3.4	480	19%	49.0	12.0	2.4	660	7%	50.0	18.0	2.5	530
8	1079						50%	58.4	25.0	3.0							50%	60.0	14.0	1.7	
9	350	100%	5.0	3.0	0.2	700															
10	450	5%	30.0	2.0	2.4							10%	90.0	8.0	3.6		85%	60.0	8.0	1.8	
11	1120						45%	48.0	23.0	8.3	270						55%	45.6	14.5	3.9	240
12	50						50%					35%									
13	20																100%	10.0	9.0	0.2	400
14	140																100%	15.0	10.0	0.3	400
15	1044						20%	65.0	8.5	6.8	1500						80%	45.0	7.0	4.5	750
16	650						42%	60.0	45.0	10.8		35%	150.0	120.0	25.2		23%	50.0	25.0	5.4	
17	8	15%	50.0	20.0	4.0	700	15%	300.0	200.0	4.0		50%	40.0	20.0	10.0	1000	20%	60.0	40.0	4.0	1000
18	20						55%	20.0	15.0	12.0		45%	90.0	33.0	9.0						
19	29						100%	10.1	9.6		4283										
20	169						100%	9.1	7.9		1999										
21	420						23%	51.4	13.3	2.8	300	22%	55.1	21.0	2.3	300	55%	50.4	10.0	1.7	300
22	500																				
23	140	5%	12.0	5.0	2.0	1500	5%					15%	65.0	20.0	14.0	800	75%	60.0	20.0	5.0	1000
24																					
25	1350	10%					30%	12.5	8.5	2.0							60%	12.5	8.5	2.0	
26	1845	10%					40%					5%					45%				
27	300	10%					10%										80%	60.0	12.0	1.1	900
28	500																100%	69.0	25.0	3.6	
29	800						5%	100.0	50.0	3.6							95%	70.0	26.0	2.7	
30																	100%				
31	98																100%	26.0	10.2	1.2	2500
32	134																100%	23.8	7.4	2.8	325
33	854	5%	5.0	3.0	2.0		20%	7.5	5.5	2.0							75%	35.0	25.0	3.0	
34	230																100%	10.0	7.0	1.5	1000
35	450						10%	50.0	15.0	1.5		30%	100.0	20.0	4.0		60%	40.0	10.0	1.8	
36	420						20%										80%	40.0			
37	270																100%	45.0	6.0	0.7	650
38	60	60%					40%														
39																					
40	0	30%					40%					10%					20%				
41	30	15%	63.0	10.0	22.0	1500	25%	80.0	31.0	2.8		20%	55.0	20.0	10.0	1000	40%	62.0	17.5	1.4	1000
42	200						35%	76.0		9.0							65%	33.0		1.8	
43	52						85%										15%				
44	121	20%					3%					15%					80%	96.8	15.0	4.6	1800
45																	100%	60.0		20.0	
46		10%					10%										80%			3.5	
47	20						100%	60.0	40.0	50.0											
48	20											100%	120.0		20.0	600					
49	20											40%	60.0		80.0	500					
50	10	5%					95%	30.0	15.0	20.0	350										
51	153	20%	44.0	3.1	8.6	160	80%	43.0	2.8	20.1	370										
52																					
53	12																100%	120.0	100.0	350.0	
54																					
55																					
56	28																100%	100.0	10.0	160.0	500
WA	401	7.3%	21.5	5.7	1.9	600	27.3%	64.0	20.2	5.1	750	4.4%	69.5	10.0	3.0	660	61.0%	46.3	15.7	2.1	481
EA	518	4.1%	31.0	12.5	3.0	1100	34.8%	70.4	43.7	5.9	2194	14.1%	80.0	42.8	12.1	700	45.3%	54.0	20.8	3.2	800
SA	351	0.6%	5.0	3.0	2.0	0	6.3%	28.8	10.3	1.8	0	3.8%	100.0	20.0	4.0	0	89.4%	31.4	10.9	1.8	1119
CAT 1	434	4.7%	21.9	7.5	2.3	850	25.2%	62.8	30.7	5.0	1472	7.7%	79.9	31.8	8.8	690	62.4%	44.6	16.2	2.4	736
CAT 2	77	20.2%	63.0	10.0	22.0	1500	36.9%	78.0	31.0	5.9	0	7.3%	55.0	20.0	10.0	1000	35.6%	63.9	16.3	2.6	1400
CAT 3	38	4.2%	44.0	3.1	8.6	160	33.9%	44.3	19.3	30.0	360	16.7%	90.0	0.0	50.0	550	45.2%	93.3	55.0	133.4	500
TOTAL	332	6.6%	29.8	7.3	5.5	843	28.2%	61.6	29.0	8.8	1194	9.2%	79.5	30.4	16.4	694	56.1%	51.0	18.9	18.8	797

WEIGHTED (WELL) AVERAGES

PN	ALLUVIAL					SEDIMENTARY					VOLCANIC					BASEMENT				
	%	TD	SWL	Y	Q	%	TD	SWL	Y	Q	%	TD	SWL	Y	Q	%	TD	SWL	Y	Q
1						214	17023	5574	750							106	5576	1584	264	
2						180	14220	3870	648											
3																459	27999	12623	459	
4						2			16							215	10667	5366	644	53655
5																175	10500	4375	350	140000
6																27				
7	11	335	136	34	5670	257	13880	4370	874	123379	72	3519	862	172	47401	26	1323	476	66	14024
8						540	31507	13488	1619							540	32370	7553	917	
9	350	1750	1050	70	245000															
10	23	675	45	54							45	4050	360	162		383	22950	3060	689	
11						504	24192	11592	4183	136080						616	28090	8932	2402	147840
12						25					18									
13																20	200	180	4	8000
14																140	2100	1400	42	56000
15						209	13572	1775	1420	313200						835	37584	5846	3758	626400
16						273	16380	12285	2948		228	34125	27300	5733		150	7475	3738	807	
17	1	60	24	5	840	1	360	240	5		4	160	80	40	4000	2	96	64	6	1600
18						11	220	165	132		9	810	297	81						
19						29	293	278		124207										
20						169	1545	1342		337831										
21						97	4965	1285	270	28980	92	5091	1940	213	27720	231	11642	2310	393	69300
22																				
23	7	84	35	14	10500	7					21	1365	420	294	16800	105	6300	2100	525	105000
24																				
25	135					405	5063	3443	810							810	10125	6885	1620	
26	185					738					92					830				
27	30					30										240	14400	2880	264	216000
28																500	34500	12500	1800	
29						40	4000	2000	144							760	53200	19760	2052	
30																				
31																98	2548	1000	118	245000
32																134	3189	992	375	43550
33	43	214	128	85		171	1281	939	342							641	22418	16013	1922	
34																230	2300	1610	345	230000
35						45	2250	675	68		135	13500	2700	540		270	10800	2700	486	
36						84										336	13440			
37																270	12150	1620	189	175500
38	36					24														
39																				
40																				
41	5	284	45	99	6750	8	600	233	21		6	330	120	60	6000	12	744	210	17	12000
42						70	5320		630							130	4290		234	
43						44										8				
44	24					4					18					97	9370	1452	445	174240
45																				
46																				
47						20	1200	800	1000											
48											20	2400		400	12000					
49											8	480		640	4000					
50	1					10	285	143	190	3325										
51	31	1346	95	263	4896	122	5263	343	2460	45288										
52																				
53																12	1440	1200	4200	
54																				
55																				
56																28	2800	280	4480	14000
WA	6.4%	7.2	3.2	0.4	694	32.2%	59.2	21.1	4.9	590	2.2%	64.7	10.4	2.9	658	59.1%	51.0	14.6	2.7	516
EA	5.7%	18.0	7.4	2.4	1418	28.9%	32.9	21.1	5.4	1664	7.2%	117.4	84.9	18.0	398	58.2%	60.5	22.1	3.3	678
SA	1.7%	5.0	3.0	2.0		12.2%	16.3	7.5	1.9		5.5%	100.0	20.0	4.0		80.6%	33.8	14.6	2.1	948
CAT 1	5.3%	7.2	3.3	0.6	710	27.5%	47.9	20.1	4.8	841	4.9%	103.3	56.0	11.9	494	62.3%	49.4	16.9	2.8	639
CAT 2	13.3%	56.7	9.0	19.8	1350	30.8%	75.9	29.1	8.3		5.0%	55.0	20.0	10.0	1000	50.9%	60.3	15.2	2.9	1709
CAT 3	12.4%	43.4	3.1	8.5	158	60.5%	44.4	8.5	24.0	368	11.2%	102.9		37.1	571	15.9%	106.0	37.0	217.0	500
TOTAL	5.7%	10.1	3.3	1.3	676	28.1%	48.4	19.2	5.8	796	5.0%	102.9	55.7	13.0	517	61.2%	50.7	17.0	3.9	671

PN	NO OF WELLS	NS	LK	DV	GI	AP	LS	ES	RS	RP	SR	EM	VL	GV	MG	AG	GR	OT
								SITING METHODS										
1	320				+	+												
2	180				+				+	+								
3	459				+	+			+	+			+					
4	219					+	+		+	+								
5	175				+	+		+	+	+		+						
6	30				+	+			+	+								
7	378				+	+			+	+					+			
8	1079				+	+			+	+			+					
9	350		+															
10	450				+	+			+	+	+		+					
11	1120		+		+	+			+			+						
12	50					+			+	+								
13	20			+														
14	140		+		+								+					
15	1044					+			+	+								
16	650				+	+	+	+	+									
17	8		+		+				+		+				+			
18	20			+	+	+	+		+									
19	29			+														
20	169		+	+														
21	550		+		+			+			+							
22	500		+	+														+
23	140				+	+	+	+	+	+		+						
24			+	+	+				+	+	+							
25	350		+		+	+		+	+									+
26	1845		+		+				+	+								
27	300		+		+				+									
28	500		+															
29	800		+		+				+									
30	0		+		+	+	+	+	+	+			+					
31	233		+		+	+			+	+		+						
32	244		+		+	+												
33			+		+													+
34	220		+			+			+									
35	450				+	+	+		+	+								
36	420				+				+									
37	270				+	+			+	+								
38	60				+	+			+									
39									+									
40	26		+		+	+			+									
41	30				+	+	+		+	+	+					+		
42	200				+	+	+	+	+	+	+	+	+	+	+			
43	52				+			+	+	+	+	+	+	+	+			
44	121				+	+			+			+			+			+
45	60		+		+	+	+	+	+									
46					+	+	+		+	+	+		+	+				
47	20				+	+			+	+			+					
48	20		+		+	+		+	+	+	+	+						
49	20		+		+	+		+	+									
50	10				+	+		+	+									
51	153				+	+			+	+								
52												+						
53	12				+	+				+			+					
54									+									
55									+			+						
56	7				+	+			+	+								
TOT WA	6014	0	3	1	10	11	1	1	11	10	1	2	4	0	1	0	0	0
TOT EA	5211	0	10	5	9	3	2	3	8	3	3	1	0	0	1	0	0	2
TOT SA	1837	0	5	0	7	6	2	1	6	4	0	1	1	0	0	0	0	1
TOT C1	13712	0	18	6	27	21	6	6	26	17	4	4	5	0	2	0	0	3
TOT C2	489	0	1	0	6	5	2	2	7	3	3	3	2	2	3	1	0	1
TOT C3	302	0	3	0	9	9	2	4	10	6	2	3	3	1	0	0	0	0
TOTAL	14503	0	22	6	42	35	10	12	43	26	9	10	10	3	5	1	0	4

GEOPHYSICAL EQUIPMENT PN:	TOT COST US$	COST/DAY US$	1	2	3	4	5	6	7	8	9	1 0	1	2	3	4	5	6	7	8	9	2 0	1	2	3	4	5	6	7	8	9
RESISTIVITY																															
ABEM SAS 300(B) TERRAMETER	10300	26.5											+					+	+	+					+	+		+	+		+
BGS 256 MULTICORE SYSTEM																															
BODENSEEWERKE GGA 30	19000	35										+																			
BRGM SYSCAL				+	+	+			+	+							+														
GESKA (?)																															
JESSE		200					+																								
TNO GEA 51																															
UNKNOWN								+						+																	
SEISMIC REFRACTION																															
ABEM TRIO	31000	100																					+								
BISON 1550	5000																						+								
BISON 2340 B	9000	15										+																			
EG&G GEOMETRICS 1210 F	35000	150																													
EG&G GEOMETRICS ES 125																										+					
OYO MCSEIS 160?	24000	12																	+												
ELECTROMAGNETICS																															
APEX MAX MIN	20000	220					+																								
GEONICS EM 34	20000	37.5																							+						
GSO TURAM ENSLIN																															
VERY LOW FREQUENCY																															
BRGM SYSCAL					+																										
EDA-ERA																															
GEONICS EM 16	5000	8								+		+																			
MAGNETOMETRY																															
BRGM ELSEC PROTON MAGN.									+																						
G 816 PROTON MAGN.																															
UNSPECIFIED	3000																	+													
GRAVITY																															
WORDEN																															
HAND DRILLING																															
EYKELKAMP																															
MOROGORO	2000																										+				

GEOPHYSICAL EQUIPMENT	3										4										5							TOTALS						
PN:	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	WA	EA	SA	C1	C2	C3	TOT
RESISTIVITY																																		
ABEM SAS 300(B) TERRAMETER		+			+	+		+		+	+	+			+		+				+	+			+	+	+	1	8	4	13	4	6	23
BGS 256 MULTICORE SYSTEM								+		+															+	+	+	0	0	1	1	1	3	5
BODENSEEWERKE GGA 30																+												1	0	0	1	0	1	2
BRGM SYSCAL																												6	0	0	6	0	0	6
GESKA (?)													+	+														0	0	0	0	2	0	2
JESSE																												1	0	0	1	0	0	1
TNO GEA 51												+																0	0	0	0	1	0	1
UNKNOWN									+																			2	0	0	2	1	0	3
SEISMIC REFRACTION																																		
ABEM TRIO														+														0	1	0	1	1	0	2
BISON 1550																												0	1	0	1	0	0	1
BISON 2340 B																												1	0	0	1	0	0	1
EG&G GEOMETRICS 1210 F												+																0	0	0	0	1	0	1
EG&G GEOMETRICS ES 125																												0	1	0	1	0	0	1
OYO MCSEIS 160?																	+											0	1	0	1	0	1	2
ELECTROMAGNETICS																																		
APEX MAX MIN												+																1	0	0	1	1	0	2
GEONICS EM 34		+						+							+								+			+		0	1	2	3	1	2	6
GSO TURAM ENSLIN																		+						+				0	0	0	0	0	2	2
VERY LOW FREQUENCY																																		
BRGM SYSCAL																												1	0	0	1	0	0	1
EDA-ERA													+															0	0	0	0	1	0	1
GEONICS EM 16																	+											2	0	0	2	0	1	3
MAGNETOMETRY																																		
BRGM ELSEC PROTON MAGN.		+																										1	0	1	2	0	0	2
G 816 PROTON MAGN.													+															0	0	0	0	1	0	1
UNSPECIFIED																																		
GRAVITY																																		
WORDEN													+	+														0	0	0	0	2	0	2
HAND DRILLING																																		
EYKELKAMP				+																								0	0	1	1	0	0	1
MOROGORO																												0	1	0	1	0	0	1

Appendix 4.6

PN								GEOPHYSICAL FIELD CREWS								TRANSPORTATION				
	GEOL	GEOP	PhD	MSc	BSc	EXPAT	EXP	OPER	UNIV	O-T-J	EXP	DRIV	LAB	T-NO	COST	TRANS	CST/D	CST/KM	TOT-C	
1		no geophysical siting																		
2								2					4	6	200	1				
3		1				1						1	6	8		2			1000	
4		1				1						1	6	8		2			1000	
5		1				1		1		1		1	?		500	1	125	0.5	625	
6		1						1				1	2	5		1			720	INCL GEOPH
7	1	1				2		2				1	5	10	900	1	35		935	
8	1	1				2		1				1	5	9						
9		no geophysical siting						1					?		440	1				
10		1		1		1		2		1		2	3	8	650	1	70		720	
11	1			1			3					1	2	4	350	1	20		370	
12		1						1												
13		no geophysical siting						1					?		12.5					
14		1		1			15							1	428	M.C.	3		431	
15		1										1	5		300	2	35		335	
16	1							1				1	2	5	50	1	25		75	
17		1					6	2					?		100	1	50		150	
18	1				1			2				2	?		50	1				
19		no geophysical siting																		
20		no geophysical siting																		
21								?				2	?		175	2		0.3	175	
22		no geophysical siting																		
23	1				1			5		1		1	2	10	75	1	30		105	
24	1				1			1		1			2	4						
25								1				1	2	4	10	1	40		50	
26		no geophysical siting																		
27	1			1			5	2			4	1	?			1				
28		no geophysical siting																		
29	1				1	1		1				1	1	4		1			250	
30		1		1								1	3	5	1250	1				
31								1				1	4	5		1		0.45		
32		no geophysical siting																		
33		no geophysical siting																		
34								1			5		2	3	20	1	30		50	
35	1				1		3	1	1				2			1		0.35		
36																				
37	1												2	3		1				
38		1						1				1	3	6		1			670	INCL GEOPH
39	1			1				1				1	1		100	1			100	
40		1	1																	
41	1						3	2				2	4	9	100	2	50		150	
42		1	1	1			10	1	1		5	?	?			?				
43		1	1	1			10	1	1		5	?	?			?				
44	1				1			6		1		3	7	17	500	5	200		700	
45		2		2			10					2	6	10	1700	1	90		1790	
46		1				1						?	?		450	1				
47		1		1			3	1				1	4	7	95	1				
48		1		1			10	3	3		5	2	2	8	4500	1	45		4545	
49		1		1				1	1			2	2	6	2100	1	45		2145	
50	1				1			1		1		1	4	7	65	1		0.5		
51								2				1	1	4		1				
52		1		1				1								1				
53		1		1			4	1				1	4	7	130	1				
54		1		1								1	?		150	1				
55		1		1								1	3	5	150	1				
56		1		1				1				1	3	6	150					
WA	3	10	0	3	0	8	9	1	0	2	0	10	4	7	420	13	48	0.5	682	
EA	6	2	0	2	4	1	6	2	0	2	4	10	2	5	244	10	36	0.3	134	
SA	2	0	0	0	1	0	3	1	1	0	5	1	3	4	20	4	30	0.4	50	
C1	11	12	0	5	5	9	6	2	1	4	5	21	3	6	324	27	42	0.4	437	
C2	3	4	3	3	1	0	8	2	2	1	5	7	4	11	233	9	125		405	
C3	1	11	0	10	1	1	7	1	4	1	5	13	3	7	949	11	60	0.5	2827	
TL	15	27	3	18	7	10	7	2	7	6	5	41	3	6	523	47	56	0.4	743	
	SUM	SUM	SUM	SUM	SUM	SUM	AVE	AVE	SUM	SUM	AVE	SUM	AVE	AVE	AVE	SUM	AVE	AVE	AVE	

Appendix 4.6

PN			GEOPHYSICAL OUTPUT							EVALUATOR						EQUIPMENT							
	RS/S	RP/S	SR/S	EM/S	VL/S	MG/S	S/D	S/W	GEOL	GEOP	OTHER	TRN	C/D	MAN	CAL	COM	PRT	PLT	TOT C	C/D	S/D	EVC/D	SC/S
1																							
2	2	2.5						3			Eng												
3	2	1KM						4	1	1						1							1027
4	1.25	1KM						4	1	1						1							1361
5								5		1		UNIV	500			1		1		100	4		2250
6	21							1.5	1				300			1							3500
7	1	2KM				2KM	0.75	3.8 *	1	1						1							426
8	1	.2KM			.12KM		2	10 *	1	1						1							
9																							
10	15	50			50			6	1	1		MSc	850			1			14000	40	2.5	500	1300
11	1			4KM			1	5 *	1			MSc	275	1		1					3.5		600
12	27								1							1							
13																							
14					3		2	10 *	1			MSc									5		103
15		2							1	1						1							170
16							1	5 *	1			UNIV	10	1							1	10	1256
17								2	1				50	1							1	50	500
18								3	1			BSc				1					3		75
19																							
20																							
21			2				1	5 *		1		MSc							3000		1		200
22																							
23	5	1		2			1	5 *	1			BSc	19			1	1	1	17187	14	7.5	6	238
24																							781
25	2							3	1		Tech	UNIV	4										100
26																							
27									1			MSc				1							
28																							
29	4						1.5	7.5 *	1							1							
30	2						2	10 *		1		MSc		1		1		1				400	628
31																							100
32																							50
33											Tech												75
34	5						1	5 *			Asst	O-T-J	10	1								1	60
35	2							3.5	1			BSc		1							3.5		150
36																							
37	2			.5KM			3	15 *	1			MSc				1	1	1			3		580
38	23							2	1				300			1							
39	200									1		MSc	105			1							
40																							
41								2		2		M/BSc	320			1		1		30	1.5	100	1250
42								1		1		PhD	200			1			11000	20	1	200	3000
43								1		1		PhD	200			1					1	200	3000
44									2			BSc	300			1			15000				500
45	10						1	5 *	1			MSc	500			1		1	24000	30	60	30	770
46								2.5		1			400			1					1		3000
47	10						1	5 *	1			BSc	60	1							1		95
48							0.5	2.5 *	1			MSc	800			1		1	15000	40	5	700	9000
49	5								1			MSc	800			1		1	15000	40	5	700	
50	13							1	1	1		MSc	60			1	1		7500	25	0.5	85	2200
51	2.4	.5KM					1.1	5.5 *	1			MSc			1						4		
52				98KM						1		MSc				1							
53							0.5	2.5 *	1			BSc	90										120
54	75									1		MSc	80			1							
55	52			25KM						1		MSc	80			1							
56	8	8KM								1		MSc	120			1					0.2		800
								* inferred															
WA	8						1.4	5.2	10	7			481	1	0	10	0	1	14000	70	3.8	500	1193
EA	3						1.3	5.1	7	2			21	3	0	5	1	2	10094	14	2.7	117	472
SA	3						2.0	7.8	2	0			10	2	0	1	1	1	0	0	3.3	1	169
C1	6						1.5	5.5	19	9			224	6	0	16	2	4	11396	51	3.2	161	675
C2	112						0.0	1.5	3	5			238	0	0	6	0	1	13000	25	1.2	167	1938
C3	22						0.8	3.4	7	6			299	1	1	9	1	3	15375	34	9.6	379	2284
TL	19						1.3	4.6	29	20			257	7	1	31	3	8	13521	38	5.2	229	1155
	AVE						AVE	AVE	SUM	SUM			AVE	SUM	SUM	SUM	SUM	SUM	AVE	AVE	AVE	AVE	AVE

Appendix 4.7

PN	EQUIP	CREW	TRANSP	C+T	EVAL	EQUIP	TOT-EV	TOTAL	WELLS	W*TOT	
1									320		
2		200							180		
3				1300				1027	459	471393	
4				1466				1361	221	300781	
5	420	500	125		125	25		2250	1300	2925000	
6				2880				3500	30	105000	
7		890	34					426	378	161028	
8									1079		
9									350		
10	60	650	70		340	40	500	1300	450	585000	
11	55	350	20		100	0		600	1120	672000	
12									50		
13									20		(12.5)
14		214	1.5		0			103	140	14420	
15		296	37					170	1044	177480	5142
16		50	25		20	0		840	650	546000	
17		300	150		50			500	8	4000	
18		100						75	20	1500	
19									16		
20									169		
21		175						200	1200	240000	
22									150		
23	28	75	31		4	14	8	238	1000	238000	
24								780			
25		20	80		8			100	350	35000	
26									1845		
27									300		
28									500		
29		165							800		3228
30		625						628	150	94200	
31								100	233	23300	
32									244		(50)
33		60							854		(75)
34	0	20	30				1	60	230	13800	
35	75							90	900	81000	
36									420		
37								580	370	214600	1883
38				2010					60		
39											
40									26		
41	720	300	150		70	30	100	1250	30	37500	
42					200	20	200	3000	200	600000	
43					200		200	3000	52	156000	
44								500	121	60500	403
45		1700	90		80	5		770	60	46200	
46	150	2250			400			3000	65	195000	
47		95			60			95	20	1900	
48		9000	90		160	8		9000	20	180000	
49		1050	23		160	8		1000	20	20000	
50	210	390			120	50	170	2200	10	22000	
51									153		
52											
53		260						120	12	1440	
54											
55								800			
56									7		207
WA	178	443	48	1882	141	22	500	1193	476	1053	
EA	28	189	72	0	21	7	8	420	511	359	
SA	38	40	30	0	0	0	1	208	464	182	
CAT 1	106	276	55	1882	81	16	170	711	488	608	
CAT 2	720	300	150	2010	157	25	167	1938	82	2119	
CAT 3	180	2106	68	0	163	18	170	2123	41	2254	
TOTAL	191	789	64	1914	123	18	168	1202	361	688	

Appendix 4.8

	BUDGET	TOTAL CONSTR.			RATE PER MONTH				COST 50m DRILLING			COMPLETION	
PN	(mill $)	DUG	OTHER	M-DR	DUG	H-DR	M-DR	RIGS	DRY	SUCCESSF	+OTHER	C&S	PUMP
1	5.20			320			13		3850	8613	11650	PVC	ASM/ABI-MENGIN
2	4.95			180			8		4200	12225	13900	PVC	ASM/ABI-MENGIN
3	5.44			459			34	2?			15408	PVC	ABI-MN
4	2.00	2		219			27	3?	3946	5952	12075		VERGNET
5	22.00	650		650	12		22		11900	13500			VOLANTA
6													
7	4.76	8		370			13	2?	9947	11905	14210	PVC	ABI/VERGNET
8	10.30			1079			60	6	7993	8061	11565	PVC	VERGNET
9	1.20	350			15								INDIA MK II/BAILER
10	15.00			450			19		9000	15000		S/SS	MONO
11	22.00			1120			50	2	12000	18200		PVC	CONSALLEN/VERGNET
12													
13	2.00	20			1								BAILER
14	4.40	20		120	1		14		12180	13745			PREUSSAG
15	7.70			1044			24	2	4166	6542	11514	PVC	VERGNET 4C
16		400		250	40		20				24154	S/O	INDIA MK 2/MONO/MOYNO
17	2.00			8					2000	3000		S	MONO/MOYNO
18				20			5		2500	4063		S	INDIA MK 2/MONOLIFT/NILE INVESTMENTS
19		15										C/O	SWN 81
20		169										C/O	SWN 81/PREUSSAG/DEMPSTER
21	7.00	363	189	270	13		10		1600	1875		PVC	INDIA MK 2/NIRA
22	3.00	150			30							C	BAILER
23	4.17	40		100	4		8		3313	3813		PVC	SWN 80/81
24										3750			
25	36.00			350			12					PVC	SWN 80
26	13.45	1143	342	60	12	6	1			2765		C/PVC/SS	INDIA MK2/NIRA
27				300			8		2000	3000		PVC	INDIA MK 2/SWN 80/81
28	6.00			500			40		3500	4000			U2/INDIA MK 2
29	5.00			800			33	4	3500	4000			U2/INDIA MK 2
30													INDIA MK 2
31	0.43	135		98	10		7		1750	4500		PVC	MALDEV/MALAWI/WELL PUMP/MK 4
32	0.42	60		134	5		8		850	3000		PVC	CONSALLEN/INDIA MK 2/MALAWI/AFRIDEV
33	4.02	720	90	44	8	4	1		3000	4000		C/PVC	INDIA MK 2/NIRA/INALSO/NATIONAL PUMP
34	0.30	150		80	5		4		2157	2807		C	BUSH PUMP/MONO
35		600		750	16		20		1807	3313		O/PVC	BUSH PUMP
36	0.84			420									
37	1.60			370			45		3200	5800		PVC	
38													
39													
40	11.50												
41	2.00			30			2		6000	8000		S	INDIA MK2/SWN 81
42				200			6					S	
43				52			2.5						
44	7.80			121			7.5		1250			S/PVC	
45	6.40			60			8		20800	106000			MP
46	15.00			65			7			12500			MP
47	0.02			20								S	WP
48	1.60			20			5		1500		93000		MP
49	0.90			20			5		1500		37000		MP
50	0.02			5									
51				153			7					PV/SS	MP
52													
53	0.03			12								S	MP
54													
55													
56				28			1						
WA	8.23	175	0	546	7	0	26		7918	11374	12903		
EA	9.58	326	266	266	20	6	15		2630	3363	24154		
SA	1.27	333	90	271	9	4	14		2127	3903	0		
CAT 1	7.08	278	207	377	12	5	19		4798	6697	14310		
CAT 2	7.10	0	0	101	0	0	5		3625	8000	0		
CAT 3	3.43	0	0	43	0	0	6		7933	59250	65000		
TOTAL	6.39	278	207	277	12	5	15		5050	10497	24448		

Appendix 4.9

PN	MIN	ALLUVIUM			SEDIMENT			VOLCANICS			BASEMENT			SUCCESS RATE INCREASE			
	YIELD	%	METHOD	SUCCESS	%	METHOD	SUCCESS	%	METHOD	SUCCESS	%	METHOD	SUCCESS	NS	HG	1GP	COMB
1	0.7				67.0%	HG	88.5%				33.0%	HG	77.4%				
2	0.7				100.0%	HG/GP	80.0%										
3	0.6										100.0%	HG/GP	78.0%				
4	0.7				1.0%						98.0%	HG/GP	75.0%	65.0%			75.0%
5	1.0										100.0%	HG/GP	78.0%		50.0%	65.0%	78.0%
6											90.0%						
7	0.7	3.0%			68.0%	HG/GP	77.0%	19.0%	HG/GP	52.0%	7.0%	HG/GP	47.0%		50.0%		58.0%
8	0.6				50.0%	HG/GP	83.0%				50.0%	HG/GP	83.0%				
9	0.5	100.0%	NS	100.0%										100.0%			
10	0.8	5.0%						10.0%			85.0%	HG/GP	95.0%	80.0%			95.0%
11	0.6				45.0%	HG	99.2%				55.0%	HG/GP	84.8%		73.0%		84.8%
12					50.0%			35.0%									
13	5.0										100.0%	DV	50.0%				
14	5.0										100.0%	HG/GP	100.0%	30.0%	60.0%	80.0%	100.0%
15	0.8				20.0%						80.0%	HG/GP	67.0%				
16	3.6				42.0%	HG	85.0%	35.0%	HG	85.0%	23.0%	HG	85.0%				
17	2.0	15.0%			15.0%			50.0%	HG/GP	75.0%	20.0%						
18	2.5				55.0%	DV/HG/GP	75.0%	45.0%	DV/HG/GP	75.0%							
19					100.0%	DV	60.0%										
20					100.0%	NS	62.0%										
21	0.3				23.0%	GP	94.9%	22.0%	GP	79.5%	55.0%	GP	88.0%	84.8%		87.4%	
22			NS	80.0%													
23	1.0	5.0%			5.0%			15.0%	HG/GP	78.0%	75.0%	HG/GP	76.0%	52.0%			78.0%
24																	
25	1.0	10.0%			30.0%	HG	95.0%				60.0%	HG	95.0%				
26	0.3	10.0%			40.0%	HG	50.0%	5.0%			45.0%	HG	50.0%				
27	0.9	10.0%			10.0%						80.0%	HG/GP	80.0%	70.0%		80.0%	
28	1.0										100.0%	NS	95.0%				
29	1.0				5.0%						95.0%	GP	92.0%				
30	1.0										100.0%						
31	0.9										100.0%	HG/GP	89.0%				
32	0.9										100.0%	HG	92.0%				
33	1.0	5.0%			20.0%						75.0%	HG	90.0%				
34	2.0										100.0%	HG/GP	90.0%	50.0%	60.0%	75.0%	90.0%
35	1.0				10.0%			30.0%			60.0%	HG/GP	90.0%	45.0%	65.0%	85.0%	90.0%
36					20.0%						80.0%		82.0%				
37	0.7										100.0%	HG/GP	76.0%	50.0%	63.0%	84.0%	90.0%
38		60.0%			40.0%												
39																	
40		30.0%			40.0%			10.0%			20.0%						
41	1.0	15.0%			25.0%			20.0%			40.0%	HG/GP	70.0%	50.0%	60.0%	65.0%	70.0%
42	0.9				35.0%						65.0%	HG/GP	86.0%	20.0%	30.0%	60.0%	80.0%
43	0.9				85.0%	HG/GP	79.0%				15.0%			20.0%	40.0%	60.0%	80.0%
44	0.4	20.0%			3.0%			15.0%			80.0%	HG/GP	75.0%	45.0%			75.0%
45	50.0										100.0%	HG/GP	80.0%	10.0%	30.0%	70.0%	
46	2.0	10.0%			10.0%						80.0%	HG/GP	50.0%				
47	50.0				100.0%	HG/GP	100.0%							0.0%	40.0%	90.0%	
48	50.0							100.0%	HG/GP	30.0%				10.0%	10.0%	40.0%	60.0%
49	100.0	60.0%	HG/GP	70.0%				40.0%	HG/GP	70.0%				80.0%		100.0%	
50	10.0	5.0%			95.0%	HG/GP	80.0%										
51		20.0%			80.0%	HG/GP	70.0%								40.0%		75.0%
52																	
53	150.0										100.0%	HG/GP	100.0%	0.0%	20.0%	40.0%	100.0%
54																	
55																	
56	100.0										100.0%	HG/GP	86.0%				
WA	1.4	7.3%		100.0%	27.3%		85.5%	4.4%		52.0%	61.0%		75.9%	68.8%	58.3%	72.5%	81.8%
EA	1.3	4.1%		80.0%	34.8%		74.6%	14.1%		78.5%	45.3%		82.6%	68.9%	0.0%	83.7%	78.0%
SA	1.1	0.6%		0.0%	6.3%		0.0%	3.8%		0.0%	89.4%		87.0%	48.3%	62.7%	81.3%	90.0%
C 1	1.3	4.7%		90.0%	25.2%		79.1%	7.7%		74.1%	62.4%		81.0%	62.7%	60.1%	79.5%	83.9%
C 2	0.8	20.2%		0.0%	36.9%		79.0%	7.3%		0.0%	35.6%		77.0%	33.8%	43.3%	61.7%	76.3%
C 3	64.0	4.2%		70.0%	33.9%		83.3%	16.7%		50.0%	45.2%		79.0%	20.0%	28.0%	68.0%	78.3%
TOT	13.2	6.6%		83.3%	28.2%		79.9%	9.2%		68.1%	56.1%		80.4%	45.4%	46.1%	72.1%	81.1%

Appendix 5 Data Questionnaire No 3

QUESTION 1	A & B UK	ADV BUREAU NETHERLANDS	BISON USA	BODENSEE W GERMANY	CAMPUS UK	EG&G USA	GEONICS CANADA	OYO JAPAN	TNO-DGV NETHERLAND
QUESTION 2 EQUIPMENT									
RS	+	+	+	+	+			+	+
IP	+		+						
SRa	+		+					+	
SRe	+		+					+	
EM	+						+		
VLF	+						+		
GV	+								
MG	+								
RM	+								
AG	+								
GR	+							+	
BHL	+					+		+	+
OTHER									
QUESTION 3 QUOTATION									
	NO	YES	YES	YES	YES	YES	YES	YES	NO
QUESTION4/5 CREW & TRANSPORT									
RS G/GP	1		1	1	1			1	1
OPERATOR	1	1	1-2	1				1	1
LABOURERS	4-6	2			2			2	2
TRANSPORT	4x4	4x4	p	p	4x4			car/p	4x4
SRa G/GP	1		1					1	
OPERATOR	1		1-2					2	
LABOURERS	4-6							4	
TRANSPORT	4x4		p					car	
EM G/GP	1						1		
OPERATOR	1						1		
LABOURERS	0								
TRANSPORT	car/p						p		
GV G/GP	1								
OPERATOR									
LABOURERS	2 survey								
TRANSPORT									
MG G/GP	1								
OPERATOR									
LABOURERS									
TRANSPORT									
GR G/GP									
OPERATOR									
LABOURERS									
TRANSPORT									
BHL G/GP						1			
OPERATORS						1			
LABOURERS									
TRANSPORT									
QUESTION 6 EVALUATOR									
	GP	G/GP	BAS	G/GP	G/GP	GP	G	O-T-J	G/GP
QUESTION 7 EVALUATION EQUIPMENT & SUPPLY									
	COM/PL	MC/COM/PL	CALC/COM	COM	COM	CALC/COM	MAN/COM	COM/PL	COM/PR/PL
QUESTION 8 SOFTWARE & SUPPLY									
	MOST	RS/SR	RS/SR	RS	RS	NO	EM	RS/SR/GR	RS/EM
QUESTION 9 DEMONSTRATION PROGRAMMES									
	SOME	YES			NO	NO	YES	NO	YES
QUESTION 10 REPORTS OF THE USE OF EQUIPMENT									
	NO	PERHAPS	NO	NO	YES	NO	YES	NO	YES
QUESTION 11 FIELDTESTING OF EQUIPMENT									
	NO	YES	NO	YES	PERHAPS	PERHAPS	YES		

Appendix 6 Geophysical Equipment, Software & Prices

Appendix 6

Geophysical Equipment

Resistivity		cost[5]	rental[6]
ABEM Terrameter SAS 300B		10400	230
Adviesburo voor Geofysica[7]		4075	
Bison Model 2350 B		4085	
Bison Model 2390		9435	
Bison Offset Sounding System (BOSS)[8]		5170	
Bodenseewerk Geosystem GGA 30		14670	
GGA 31		22865	
Campus Geophysical Instruments BGS 256[10]		2765[9]	83
EDA Instruments R-Plus		14500	
OYO McOhm		15540	
TNO Institute of Geoscience GEA 51		9675	
Seismics			
ABEM Terraloc Mark 3	(12 Channel)	45210	
ABEM Trio SX-12	(12 Channel)	O/P	
Bison 1570 C	(1 Channel)	4875	
Bison GeoPro 8012 A	(12 Channel)		
EG&G Geometrics ES-125	(1 Channel)		182
ES-1210 F	(12 Channel)		
ES-1225	(12 Channel)	13000	367
OYO McSeis 160	(12 Channel)	16910	
Electromagnetics			
Apex Max Min		O/P	473
Geonics EM 31 DL		9450	322
EM 34-3		14500	497
EM 34-3 XL		15950	547
Swedish Geological Co SGAB Slingram			
VLF			
ABEM Wadi		4770	
EDA Instruments OMNI-VLF		8050	
Geonics EM 16		4400	146
Magnetometry			
EDA Instruments OMNI IV Magnetometer		6350	
EG&G Recording Proton Magnetometer G-846		3500	
G-856		6385	232
G-866		11320	
Swedish Geological Co GSM-8 Proton Magnetometer			
Gravity			
LaCoste & Romberg Land Gravity Meter G			976
Microgal Gravity Meter D			1361
Sodin Prospector 100			519
Prospector 200			554

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[5] Cost in US dollars ex-factory, including basic accessories; quotations early 1987 unless otherwise indicated

[6] Rental cost per month, based on 5 year term, by Addison & Baxter Ltd (UK). 1 Pound Sterling = 1.842 US Dollar.

[7] excluding cables and electrodes

[8] (excluding resistivity meter)

[9] price 1986

Appendix 6

Ground Radar

Geophysical Survey Systems SIR System-3	17900	608
OYO Georadar I	49960	

Well Logging

ABEM SAS log 200	13025	
EG&G Mount Sopris 1000 C	23000	669
OYO Geologger 3030	37760	
Swedish Geological Co Boremac A2D		

Software

Resistivity

ABEM Super-VES	1700
Adviesburo voor Geofysica (Schlumberger)	793
Bison BOSS & Resist	114
EDA Instruments Resix	650
Geosoft INRES	475
Heaker (Schlumberger)	538
Hydrotechnica Sondage (Offset Wenner)	1610
OYO Grivel-PC	714
TNO Institute for Geoscience VES	4300

Seismics

ABEM Sextette	1700
Adviesburo voor Geofysica[10]	476
Bison Refract	575
Bison $T^2 - X^2$ (Reflection)	
EG&G Geometrics Seisview	free [11]
OYO Refraction Seismic Interpretation[12]	794
OYO Reflection Velocity Analysis	794

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[10] Plus-minus method

[11] with purchase of seismic equipment

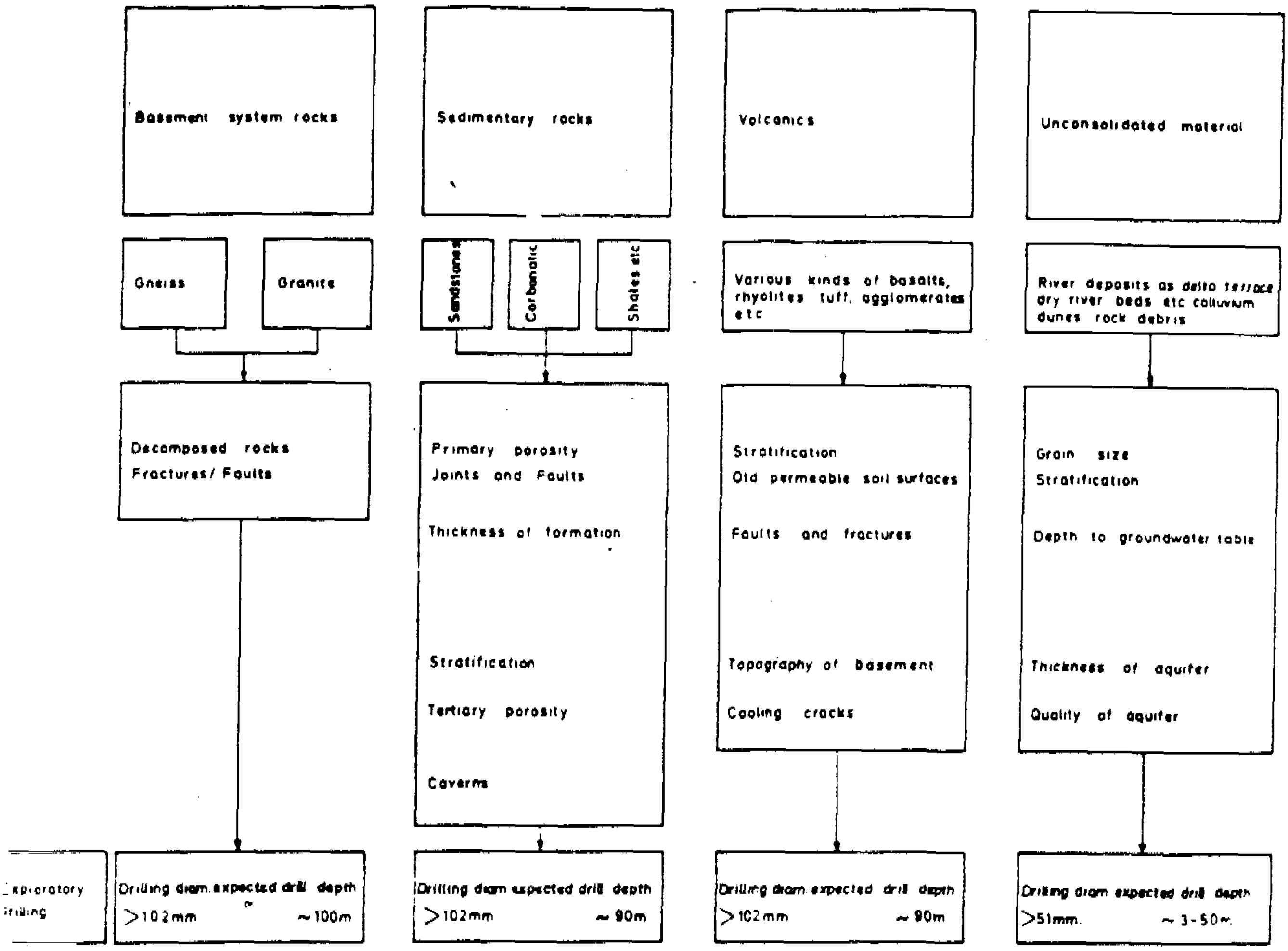
Appendix 7 Groundwater Investigation Guide

(from Norconsult, 1983b)

DATA AND INFORMATION REQUIRED

LOCATION	RECONNAISSANCE LEVEL	Satellite image 1:500,000 Topographical map. 1:250,000 Geological map. 1:500,000 Soil map. 1:500,000 Meteorological map 1:500,000	Gathering of borehole data and chemical analysis data Study hydrological features Study the tectonic pattern Look for lineaments, Geological formations and lithology Establish broadly major rainfall zones, evaporation zones etc Locate major recharge areas with stress on highly permeable soils and outcrops
SUB-LOCATION	DATA FOR HYDROGEOLOGICAL MAP	Topographical map 1:100000 - 1:50000 Geological map 1 250,000 - 1:50,000 Photo interpretation 1 30,000 Field reconnaissance Geophysical survey Exploratory drilling with test pumping	Compilation of a simplified hyrogeological map based on borehole data chemistry, geology, topography, soil map and meteorology Establish measurements of groundwater table, carry out pumping tests Register major springs, monitor discharge etc Establish the tectonic pattern of the sublocation indicate major weakness zones, faults, fractures, joins Locate barriers in dry river beds Establish knowledge of the geological history of sublocation, locate potential aquifers both in consolidated and unconsolidated material Evaluate the topography, geology tectonic pattern etc in the sublocation look for vegetation pattern check springlines etc Drilling of exploratory holes, test pumping, formation sampling, soil sampling water sampling Locate saline groundwater bodies in unconsolidated material
SITE	DETAILED FIELD INVESTIGATIONS AND WELL SITING	Geological map 1:50,000 Photo interpretation 1 10,000 Field reconnaissance Geophysical survey Site Location	Intensive use of the hydrogeological map interpretation of pumping test data to establish interesting sites or clusters of sites Study groundwater movements in river beds, determine recharge potential etc Locate fractures faults etc at the site. Locate barriers in river beds and determine volumes of shallow river aquifers Use geophysics to determine the exact whereabouts of fractures faults and weakness zones and also their extension horizontally and vertically Establish depth to groundwater table Monitor groundwater fluctuations with time. Choose best drill site according to well yield, water quality, access, pollution hazard, drillability etc

AQUIFERS OF THE MAIN GEOLOGICAL FORMATIONS IN TURKANA



AQUIFER DATA

round water struck nd rest level (m)	39/22	30/18	48/26	9/4
quifer yield (m^3/hr) ased on test pumping	2.4	1.5	9.0	17
uality tal dissolved solids D S in ppm)	Poor - Medium 425 - 5000	Poor - Good 100 - 2300	Medium - Good 300 - 8000	Good < 250
xpected range of rill depth (m)	40 - 100	30 - 90	50 - 100	7 - 20
xpected range of asing diameter (mm)	75 - 150	150 - 250	150 - 250	150-300
creen type	Louvred + Gravel pack	Continous wire wound or louvred + Gravel pack	Louvred + Gravel pack	Continous wire wound + Gravel pack

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GROUNDWATER EXPLORATION GUIDE
TURKANA DISTRICT

APPENDIX
7

Rev