GROUNDWATER SURVEY (KENYA) Ltd.

UNDP/World Bank Community Water Supply Project

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Well Siting for Low-Cost Water Supplies (Volume 2)

WELL SITING GUIDE

Hydrogeological & Geophysical Investigations

UNDP/World Bank Community Water Supply Project

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(Final Draft)

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Preface

This document seeks to guide project planners and managers of rural water-supply projects on available cost-effective well-siting techniques suitable for numerous tropical environments. The 'Well Siting Guide' gives an overview of the hydrogeological aspects of groundwater exploration, an insight into the various levels, methods and procedures of investigation and case studies of groundwater exploration in different types of water-supply schemes in Africa.

The Guide is based on data which cover a wide range of specific project environments so as to create a more general overview of well-siting applications for different geological environments. Statistical averages, however, should not be construed as geological rules or laws. It is quite possible that in individual projects the findings will differ substantially from some of the statements made here.

This Guide is oriented towards the application of site investigations for low-cost water supplies, i.e. in general handpumped wells. In practical terms it means that the depth of the investigations can be limited to approximately 100 metres. Investigation requirements may be more extensive and costly when water is needed in regions where the water table is below the reach of handpumps. This may occur in many of the dry pastoral areas which face the need for more substantial water volumes for livestock.

A wide range of modern technologies have made possible the exploration and exploitation of groundwater sources previously unknown or judged inaccessible and unusable. In the last quarter-century, systematic groundwater exploration has been the preserve of a limited number of specialized consultancy firms, whose ranks are gradually increasing. This document will assist in bringing about a greater application and diffusion of specialized well-siting techniques towards local government agencies and local organizations in the private sector.

It is hoped that this report facilitates the decision-making concerning cost-effective implementation of groundwater exploration techniques in Community Water Supply (CWS) projects. Technical and theoretical details have been kept to a minimum since these are dealt with extensively in a great number of professional publications, the most relevant of which are listed in the Selected Literature.

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1 Introduction

It is estimated that about 1800 million people in the rural areas of the world do not have access to potable water of adequate quality and quantity[1]*. The provision of safe and reliable water for these people is the goal set for the current United Nations Water and Sanitation Decade. Given the massive financial resources which are needed for this scale of undertaking, significant progress in meeting the stated goal can only be achieved by low-cost, sustainable and replicable water development strategies.

Groundwater is one of the best sources of drinking water. It is generally free from bacteriological pollution, it has an almost constant quality and temperature and it is available in large quantities[2]. Given the limited financial and human resources a decentralized and low-cost approach to provide drinking water with handpump-equipped wells is the most suitable for wide-spread application in rural areas. In recent years pumping technologies have undergone extensive scrutiny to facilitate low-cost local manufacture, operation, and maintenance (Arlosoroff et al., 1987). Similarly, low-cost hand drilling and digging methods have been explored, with an emphasis on sustainable and replicable operating procedures (Blankwaardt 1984, DHV 1978).

One aspect of low-cost community water supplies (CWS) which has so far received little attention, but is equally important to making CWS successful and keeping their costs down, is that of groundwater exploration or 'well siting'. The proper location or siting of a well can significantly increase the success and reduce the cost of a CWS programme. A systematic hydrogeological investigation of a proposed project area should help to avoid unsuccessful wells and minimize the depth of required drilling or digging. Particularly where the only option is to use expensive machine drilling, such investigations can lead to substantial savings in the drilling cost, which more than cover the cost of the investigation procedure and thus reduces the overall cost per well.

This report proposes a systematic approach to groundwater investigations, so as to place well siting firmly within the reach of low-cost CWS applications. This study has, as a base, an inventory of approximately 40 CWS projects, mainly in Africa, and focuses on the use of well-siting techniques for low-cost rural water development. The inventory, which was carried out under the auspices of the Rural Water Supply Handpumps Project of the World Bank, consisted of sending out detailed questionnaires to numerous organizations and consultants

* Literature references found in brackets in the text are listed in Appendix 4: Selected Literature. References referred to by numbers are listed under "Notes" on page 57.

involved in rural water-supply projects. Their experience in the field demonstrated which particular methods to use and which to avoid. These lessons were further compared and contrasted with the established literature and are reported in Volume I of this study: Inventory of Well Siting Methods. The general guidelines presented here are primarily based on this inventory. Four case studies have been selected and are described in Chapter 4.

Only recently has well siting become more important to rural water-supply projects. In the past the location of well sites did not need hydrogeological investiations of groundwater occurrence. Rural communities usually settled near a known supply of surface or shallow groundwater. Many cultures also used traditional knowledge for the siting of groundwater supplies and for well digging. However, with increased population pressures, increased settlement in marginal regions, pollution of existing surface water supplies and the expansion of economic activity, available water resources in many areas have become inadequate and new, and often much deeper, potable water supplies have to be tapped.

Tens of thousands of handpumped wells have been constructed in recent years and hundreds of thousands more are planned to meet the large and growing demand for safe water. The implementation of such water-supply schemes needs to accomodate existing economic and technical constraints and opportunities which apply to groundwater development activities. This also applies to the exploration phase. Deciding on the need for and method(s) of site investigation requires careful consideration. Depending on the local circumstances, detailed groundwater exploration methods may be superfluous and costly, while in other situations the use of expensive and sophisticated equipment may lead to considerable savings for the overall project or programme in terms of time, effort, and cost per well.

Ideally, all groundwater development should be preceded by proper hydrogeological exploration to locate the optimum amount of groundwater. In many areas the construction of wells has proceeded without detailed insight into the hydrogeological conditions which determine the presence and location of groundwater and has mainly been based on user convenience (distance to site, ownership of plot, etc.). Under favourable conditions water has often been struck despite the lack of proper investigation. However, expanding water demand, especially in marginal areas, necessitates increasingly the application and proper use of groundwater investigation techniques.

Groundwater exploration is a cumulative process of gathering data on the presence of groundwater. It can be described as various levels of investigation:

- Level 1: Inventory of existing data
- Level 2: Remote sensing interpretation
- Level 3: Hydrogeological fieldwork
- Level 4: Geophysical survey
- Level 5: Exploratory drilling

Each level builds on the information obtained at the previous level and provides additional detail on the local hydrogeological situation. The level of investigation required in a proposed project area depends on the data which is obtained at the initial levels. Often the inventory of existing information can give a good impression of the amount of additional detail needed for successful well siting. Evidently, more detailed information and investigation is required in an area where previous borehole success rates have been low than where plentiful groundwater at shallow depth appears to be present.

At the same time, to determine to which level the investigation should be carried out, a cost-benefit comparison of exploration cost and the reduction in drilling costs is required. Each subsequent level of investigation naturally adds to the cost of the exploration phase and thus to the total costs of the well to be constructed. At a certain point the increase in exploration costs cannot be justified by a marginal increase in drilling success. The need for spending on groundwater exploration depends, however, not only on a project-wide technical and economical appraisal, but should also be considered in a wider regional or even national context. Socio-economic planning and political factors may also need to be taken into account.

2 The Occurrence of Groundwater

2.1 The Hydrological Cycle

The movement of water through the various stages of the hydrological cycle ie, as rainfall, evapotranspiration, runoff and groundwater flow, determines the presence and availability of groundwater. Knowledge of the movement of water above ground can often facilitate the understanding of groundwater availability and movement in investigation areas. Climate is a major factor, but other factors also play an important role in the formation of groundwater reservoirs, e.g. topography, soil conditions, vegetation and human activities. Looking at these elements in a project area provides a first impression of the likelihood of finding sufficient amounts of groundwater. Usually only a small fraction of rainwater ends up as groundwater. The complexity of the interaction of the many elements involved in this relationship is illustrated by a simplified flow diagram in Figure 1, which was used to calculate the average annual recharge from rainwater to groundwater storage for the project described by Case Study 1 (see Chapter 4). This gives not only an impression of the possible groundwater availability, but can also be used to estimate maximum allowable abstraction.

The diagram shows that rainwater first has to pass through the unsaturated soil-moisture zone, which in many of the less humid tropical environments is in a constant state of deficit, because it is continually being depleted by evaporation from the soil surface and abstraction of water through the plant roots for growth and transpiration purposes. When the rainfall in an area is less than the soil moisture deficit, recharge occurs only through the larger spaces and cracks in the soil, where the molecular forces of the soil particles are too weak to hold the water.

Runoff is naturally related to rainfall. Analysis of the relationship between the two is a useful tool to estimate the potential groundwater availability. By measuring the amount and intensity of rainfall, both temporally and spatially, the total amount of water entering a catchment can be calculated. When the measured (or estimated) losses through runoff and evapotranspiration are subtracted, an estimate of the amount of groundwater recharge can be made. Measurement of runoff at several points before the catchment outlet allows direct seepage from the stream channel to groundwater to be estimated, which can contribute substantially to groundwater recharge.

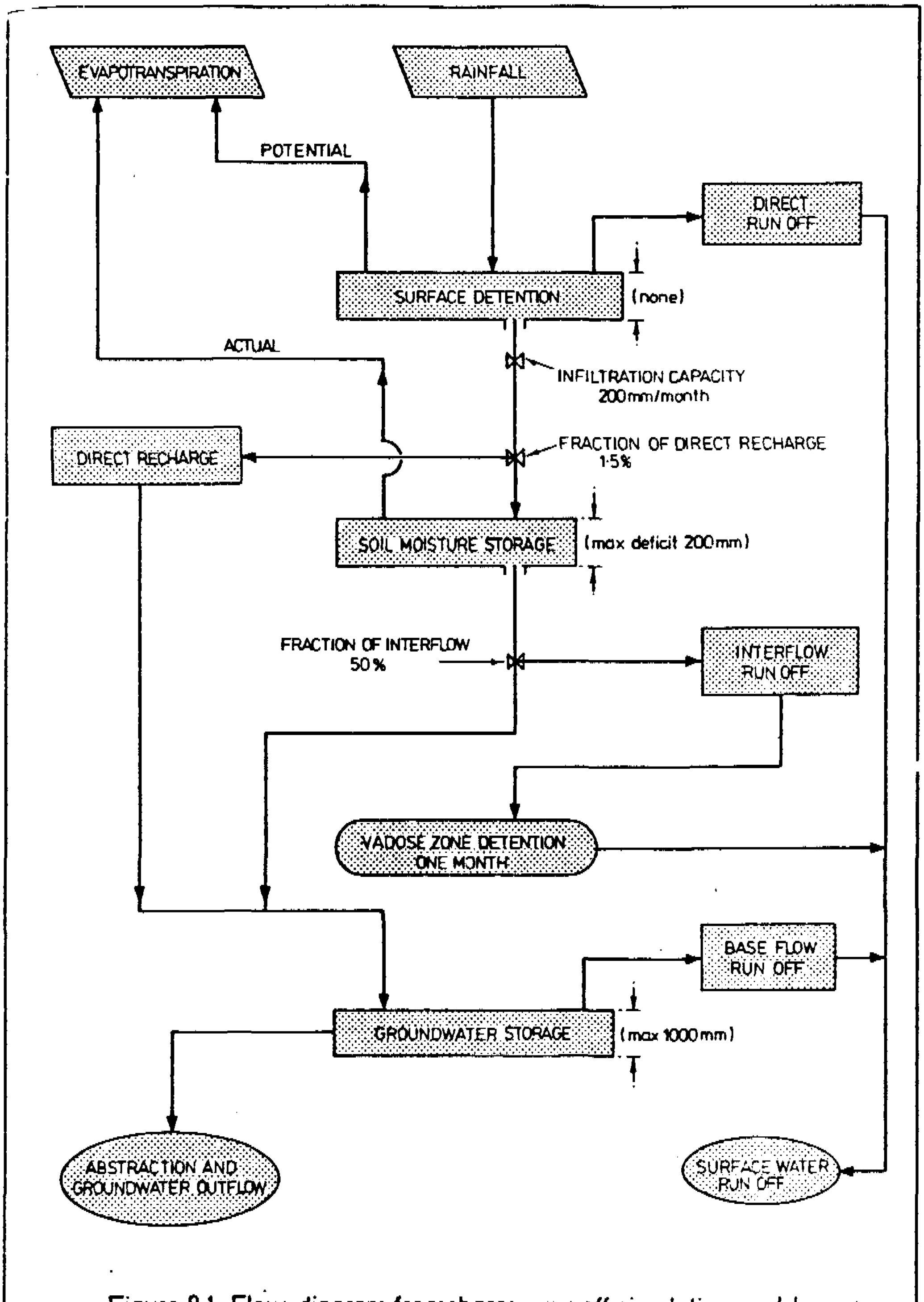


Figure 8.1 Flow diagram for recharge - run off simulation model

RUN No 11

Figure 1 Flow diagram for a calibrated recharge-runoff simulation in Zimbabwe (after Hydrotechnica, 1985)

Although potential aquifers are found in many parts of the arid and semi-arid world, recharge may not be sufficient to keep pace with growing demand. For example, in some parts of the Sahara and Sahel large groundwater resources are available which were formed during wetter climatic conditions. Significant recharge to these aquifers no longer takes place in present times. Should these resources be exploited on a large scale, water abstraction would resemble a mining operation where the resource is not renewable. Box 1 illustrates how, in theory, with limited recharge (1% of rainfall) a relative small area can provide an adequate amount of water for handpump abstraction.

Box 1

Recharge Example

Assuming a hypothetical area with average annual rainfall (P) of 500mm (0.5m) of which only 1 percent recharges (I) groundwater. A well with a handpump from which (Q) 10m³ per day is abstracted every day of the year, requires an area with a diameter (R) of approximately 500 meters to ensure adequate annual recharge:

A - annual recharge per m^2	P x I	= 0.5 x 0.01 = 0.005 m
B - annual abstraction	Q x 365	= 3650 m^3
C - area required for recharge	B / A	= 3650 / 0.005 = 730 000 m^2
D - expressed as radius of circle		R = SQR (C/PI) = $(730000/3.14)^{-0.5}$ = 482 m

In reality, however, other variables affecting the flow of groundwater are more important in determining whether or not adequate groundwater supplies are available for handpump abstraction. These variables mainly concern the structure of soils and subsurface rocks.

2.2 Aquifers

In a good aquifer the water-bearing rock or soil matrix has open spaces or pores large enough to transmit water toward the wells at the required rate of abstraction, though not all geological formations which are saturated with water are aquifers. A layer of clay with a porosity of 60 percent has a large water-holding capacity, but due to the strong bonding between the clay and water molecules, water cannot move freely through the tiny open spaces. The water yielding capacity of an aquifer is identified by three characteristics of the rock matrix: porosity, permeability, and specific yield.

Porosity

The porosity of a water-bearing formation is defined as the ratio between the volume of open space and the total volume of the rock. It serves as an index of how much groundwater theoretically can be stored in the formation under saturated conditions. For example if 1 m^3 of sand contains 0.3 m^3 of open space, its porosity is 30%. Table 1 gives an indication of the porosities of some common rock types.

Table 1 Porosities of common rocks (Driscoll, 1986)

Unconsolidated Sediments	η (%)	Consolidated Rocks	η (%)
Clay	45–55	Sandstone	5–30
Silt	35–50	Limestone/dolomite (original &	
Sand	25–40	secondary porosity	1–20
Gravel	25–40	Shale	0–10
Sand & gravel mixes	10–35	Fractured crystalline rock	0–10
Glacial till	10–25	Vesicular basalt	10–50
		Dense, solid rock	< 1

Permeability

The permeability of a soil or rock type is determined by the interconnectivity of the pore space. It is a measure for the ease at which the water can flow through the rocks. Some soil and rock types may have high porosities, but when the pores are not interconnected, they are impermeable (e.g. pumice). Similarly, clay, despite its high porosity, is quite impermeable. The transmissivity of an aquifer is an almost synonymous term which denotes the permeability (K) multiplied by the thickness (d) of the aquifer ($T = K * d$).

Specific Yield

The ease with which water is released from the pores in an aquifer depends on the transmissivity and also on the adhesion between the water molecules and the host rock. This is different for various types of rock material; for example, saturated sand and gravel will release more water than a similar volume of saturated clay, which although having a much higher porosity, binds the water more strongly. The ratio of the volume of water released per unit volume of rock is called the specific yield.

The relationship between porosity, permeability, and specific yield is illustrated for various sediment particle sizes in Figure 2. The object of groundwater investigations is to locate those formations which have the most advantageous hydraulic properties, i.e. larger porosity, good permeability and a high specific yield. The best characteristics are often encountered in recent sediments where little compaction has occurred and much of the original loose structure of deposition is still present. However, given the relatively small abstraction requirements of handpumped wells (generally less than 2 m^3/h) certain consolidated sediments, volcanics, as well as weathered and fractured bedrock zones can usually also provide suitable abstraction potential. The aquifer potential of the major rock types is described in more detail in Appendix 1.

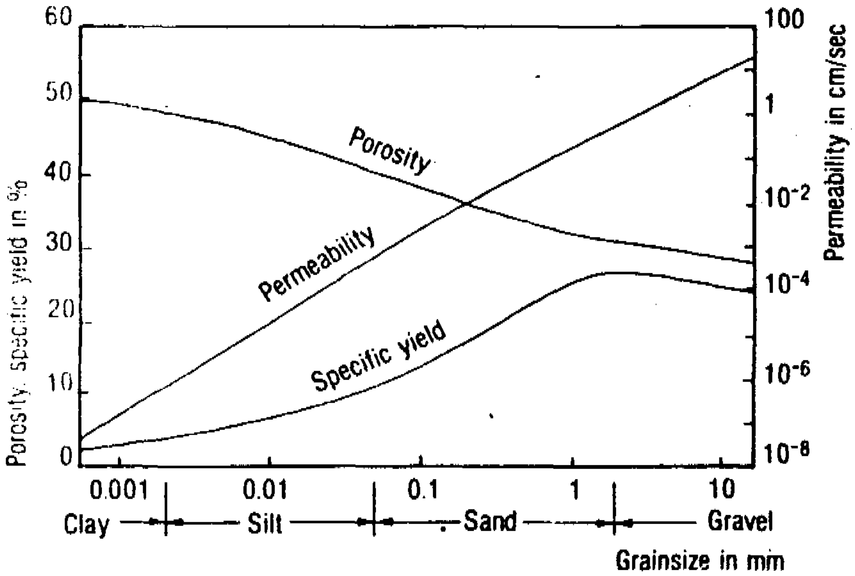


Figure 2 Porosity, permeability and specific yield as a function of grain size (Blankwaardt, 1984)

Handpumped wells usually derive their water from relatively shallow and unconfined aquifers. In some situations the hydrostatic pressure, caused by the presence of confining layers above the principal water-bearing zone, may sufficiently raise the water level above the initial struck level to a rest or static water level within the reach of a handpump. This is usually not evident from surface indications and is difficult to determine with hydrogeological and geophysical investigations.

2.3 Water Quality

A proper hydrogeological knowledge of the project region is important to understand local water quality properties and variations. The geology, type and location of an aquifer can strongly affect the groundwater quality. Groundwater may be chemically and biologically polluted by a number of geological and human factors which render it unsuitable for direct human consumption.

- Excessive mineralization is possible in volcanic and basement rock environments, where the rock material is physically and chemically unstable and dissolves easily in the available groundwater.

- Connate water is water trapped in sediments at the time of their deposition. Usually this is seawater which filled the pores of marine sediments during their deposition. Such water can over time become even more saline than seawater.

- In arid and semi-arid environments shallow aquifers may become saline due to evaporation, whereby the remaining water will contain increasing concentrations of dissolved salts.

- In areas of dense population or industrial activity, human and animal waste may contaminate shallow aquifers.

The World Health Organization has published a list of guidelines with maximum permissible concentrations of potential pollutants to which drinking water should conform for human consumption (WHO, 1984).

2.4 Well Hydraulics

Groundwater moves, in principle, just like surface water from a high energy level to a lower energy level. Where water is unconfined i.e., under atmospheric pressure conditions, the gravity difference will be the cause of such water movement. Where permeability is poor the flow velocity will be smaller than when the permeability is good.

Consider radial flow of groundwater to a pumped well: the level of the groundwater table around the well drops until it reaches a point where the gradient in the water table becomes sufficiently large, so as to increase the velocity and amount of the groundwater flow to the well, such that it reaches equilibrium with the amount abstracted by the pump. If the aquifer is limited, this equilibrium may not be achieved and the well will be pumped dry. The extent of this drop in the water level at the well (or drawdown) is significant for the choice of pump which will be installed in the well.

Success in well siting can only be determined by test pumping. This assesses whether the well will provide adequate quantities of water. By periodically measuring the drawdown while pumping at a constant rate until equilibrium is reached, the transmissivity of the aquifer can be estimated. If, in addition, measurements are taken in one or more nearby observation wells situated within the cone of depression, the calculated transmissivity becomes more reliable and the groundwater storage capacity of the aquifer can be calculated. Drawdown curves can also show if the aquifer is homogeneous (flow conditions constant throughout the aquifer) or if inhomogeneities, such as water-bearing joints and fractures or impermeable layers are encountered (Kruseman and de Ridder, 1970).

A simplified version of such testing is often sufficient for handpump abstraction and can be undertaken by fitting a suitable pump on the well and measuring the yield and the drawdown over a period of several hours of intense pumping to see the well meets the required discharge criteria (Blankwaardt, 1984).

A second criterion for a successful well is the quality of the water. This can be measured with an electrical conductivity (EC) meter by preference at the end of the test pumping. When exploring an unknown aquifer, samples should as a rule be taken and sent for a full chemical and bacteriological analysis to ensure compliance with the national standards and the WHO guidelines as described in the previous section.

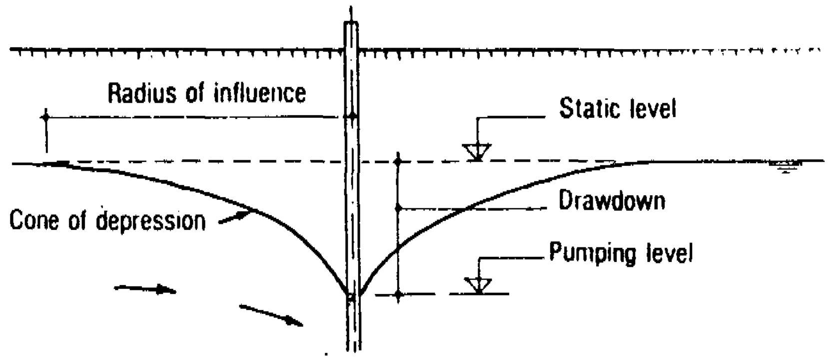


Figure 3 The groundwater table around a pumped well (Blankwaardt, 1984)

Under normal conditions the diameter of the wellbore is of much less importance to the yield of the well than the length over which the well penetrates the aquifer. However, in aquifers of poor permeability, an increase in the well diameter increases the well storage capacity. This can serve as a buffer supply which will refill when the pump is not operating.

The very basic description on the occurrence of groundwater given in this chapter is meant only to provide the layman-reader some background necessary for the discussion in the next chapters. Some further description of aquifer types and hydraulic properties is given in Appendix 1, albeit still at a very elementary level.

For any further detailed description of all groundwater related phenomena the reader is referred to the excellent handbooks which have been listed in the Selected Literature (Appendix 4), and many publications listed in the References of Volume I.

3.1 Successful Siting

The objective of a site investigation is to gain a proper understanding of the occurrence of groundwater in the project area. It is important that well sites are chosen principally on hydrogeological grounds to have the greatest chance of obtaining an adequate yield. A successful borehole is one whose yield and water quality satisfy the needs of a particular project. Compared to engine-driven pumps, handpumps have a low yield. The required lift, i.e. the height to which the water has to be pumped to the surface also affects the maximum possible yield. The achievable rate of discharge will be less when the required lift is greater, as illustrated in the graph below. Given the limited discharge possible with handpumps, groundwater investigations should focus not only on locating adequate quantities of water, but also on finding sites with minimum lift requirements and with sufficient permeability to minimize water table drawdown. In general, and as illustrated in Figure 4, a range of 2.0 cubic meters per hour (m^3/h) from shallow aquifers to 0.5 m^3/h for high lifts are reasonable yields for handpump abstraction, although in arid environments users may consider less than 0.5 m^3/h even acceptable.

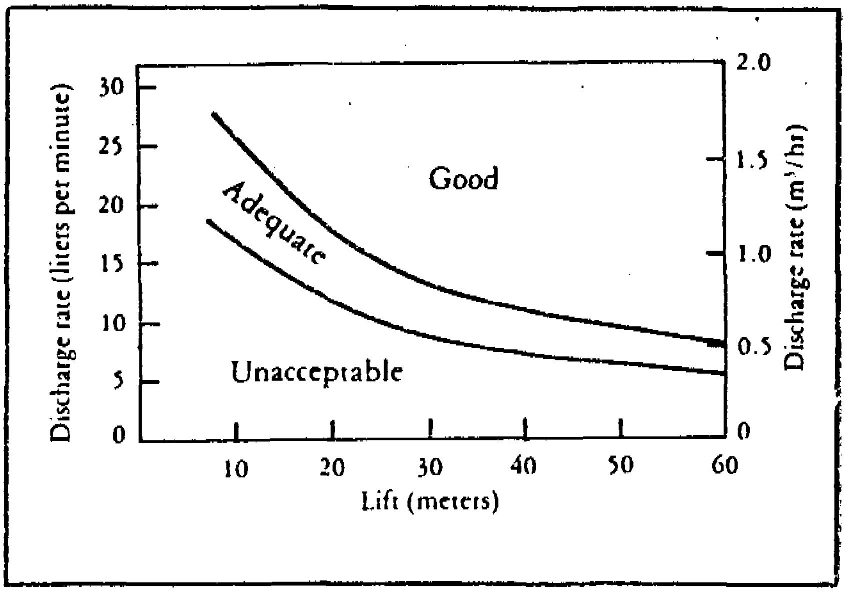


Figure 4 Relation between pumping lift and discharge rates (Arlosoroff et al., 1987)

Proper well sites should be:

- free from pollution of animal and human waste;
- protected from the risk of flooding;
- protected from erosion caused by animals;
- within easy access to the local community (and for the drilling rig).

Since the well will usually be under the care of the local community, the users' full agreement should be sought for the site location. This requires proper communication with the local community on the well-investiation process to avoid potential conflicts regarding ownership, operation and maintenance of the new well(s).[3]

3.2 Well-Siting Techniques

Groundwater exploration has several levels of investigation. Each level is further divided into several activities which complement and sometimes overlap each other. Each successive level of investigation adds more detailed information on the subsurface situation, but this gain in knowledge increases the complexity and cost of the investigation.

Depending on the findings of each previous level, the hydrogeologist has to evaluate whether he has enough information on which to decide on a well site or if he needs more information. To keep the investigation cost as low as possible, the hydrogeologist should avoid unnecessary detail in the investigation. At the same time, quite often, expenditure on proper groundwater investigations can reduce the total cost per well due to a higher success rate and a reduction in the required depth of drilling. This aspect will be discussed in more detail in section 3.3.

A logical and low-cost approach to well siting involves the following consecutive levels of investigation:

Level 1: Inventory of Existing Data
- Geological Data
- Hydrological and Climatic Data Analysis
- Analysis of Existing Well Data

Level 2: Remote Sensing Interpretation
- Satellite Imagery
- Aerial Photography

Level 3: Hydrogeological Fieldwork
- Geomorphological Analysis
- Water Points Inventory and Monitoring
- Hydro-Climatic Monitoring

Level 4: Geophysical Surveying
- Electrical Resistivity
- Seismic Refraction
- Electromagnetic Profiling (EM)
- VLF profiling

Level 5: Exploratory Drilling
- Hand Drilling
- Machine Drilling
- Geological Logging
- Geophysical Logging
- Test Pumping
- Water Sampling

A systematic step-by-step approach to well siting furnishes the most relevant information at the lowest cost and minimizes drilling expenses. When the investigation phase is skipped altogether and so-called 'wildcat' (i.e. random) drilling is carried out (either due to unfamiliarity with the investigation process or because investigations are considered too expensive), the chances of drilling a successful well are usually smaller than with proper hydrogeological investigations in the project area.

Alternatively, because of unfamiliarity of project managers with basic hydrogeological principles, all too often a high-tech approach is chosen in which much of the first three levels of investigation is skipped or inadequately utilized and only geophysical techniques are employed. This means that very useful and inexpensive information is neglected, unnecessarily increasing the cost of well siting.

A general overview of the purpose of each level of investigation and their applicability to particular geological environments is discussed below. The decision concerning the extent to which the investigation needs to be carried out i.e., to how many levels and what methods are most suitable, depends on specific project parameters and finance. Further technical information on the most common geophysical methods can be found in Appendix 2 and in the literature.

Inventory of existing data

A substantial amount of highly useful data concerning the proposed CWS project area may be available from previous studies carried out in the area by various government departments or private companies. <u>Therefore, it is often worth the effort to track down past geological studies, hydrological and climatic monitoring data, and borehole record files.</u> The acquisition of such information may involve some bureaucratic hurdles. In most countries water-supply projects require government permission; once this has been obtained permission to use existing government data is usually readily given and at low cost. Verification of existing data in the field is cheaper and requires less time than having to start from the beginning. One simple example is the need for proper topographical information.

In medium to large projects, target populations, infrastructure and access routes, as well as existing water supplies and proposed new well sites should be properly identified. This is essential for the success of a water-supply scheme. For this purpose available topographic maps at an appropriate scale can often be obtained from the relevant government department.

Data from existing boreholes in the proposed project area are of special interest as they may supply much useful information on the geology and groundwater characteristics, for example where the aquifers are located, what the yield and the water quality is, how much the drawdown is during pumping and how the groundwater levels fluctuate over the year. If the data indicate relatively uniform and promising hydrogeological characteristics in the project area, further detailed investigations may not even be necessary.

Climatic and hydrological data give an impression of the amount of recharge which can be expected in the project area. Even if no information is available from boreholes in the area, the chances of striking water in high rainfall areas (>1000 mm per year) are much better than in dry areas, so that often investigation levels 1 - 3 are sufficient for borehole location in those areas.

The available data can usually be collected by an insistent and persuasive member of the project team. The evaluation of the data requires insight into the hydrogeological significance of such data. Reference can be made to the collected data throughout the investigation; for example, geological maps may be of help during the aerial photograph and satellite imagery interpretation, and existing borehole data help calibrate geophysical measurements.

Remote Sensing Interpretation

Remote Sensing in well siting is a method of collecting indirect information concerning the occurrence of groundwater from aircraft or satellites. It concerns recording surface features of the earth in the visible and near visible electromagnetic wave ranges. The presence of groundwater can be inferred from the interpretation of topographical, vegetational and geomorphological features. The advantage of remote sensing lies in the relatively cheap and quick overview which can be obtained of a large area, by which main features of interest to the occurrence of groundwater can be identified.

Satellite imagery is ideal for obtaining a general overview of the topographic and geomorphological characteristics of a (large) project area at the beginning of the investigation process, the principal objective of which is to define smaller areas as priority targets for more localized follow-up studies. The satellite images, which cover large areas, are especially useful in highlighting regional structures such as major faults, which are often more difficult to recognize on aerial photographs.

Satellite images can be obtained as prints, film (positive or negative), or computer compatible tapes (CCT). The latter is the most expensive format and only used by highly specialized agencies with sophisticated professional computer and printing equipment. However, prints, negatives, or slides are quite adequate in most groundwater investigation projects. Imagery can be ordered from catalogues from several distribution centres[4]. Interpretation of the satellite images is carried out with transparency overlays on the images, on which the significant features are hand drawn and later transferred to project area maps. Data interpretation will need to be carried out by an experienced hydrogeologist.

However, satellite image interpretation should never be the sole basis for well siting in groundwater exploration, since resolution is too poor for the indication of specific sites. Further detail can be provided by aerial photography. Such desk studies should always be verified by hydrogeological fieldwork.

Compared to satellite imagery, aerial photography is carried out at relatively low altitudes, providing larger-scale images (usually greater than 1:60 000 and preferably in the order of 1:25 000 to 1:12 500). Vertical aerial photographs are taken in overlapping series along a flight line, allowing adjacent images to be viewed stereoscopically (i.e. three dimensionally), which greatly improves the ease of interpretation. As with satellite imagery, the features of interest are drawn on a transparent overlay by the hydrogeologist. This creates an interpretive map of the project area which highlights regions favourable to groundwater occurrence.

Aerial photography in the context of groundwater exploration can serve two purposes. Primarily it is used for the identification of features of significance in occurrence of groundwater. Through an analysis of the elements of photo interpretation (topography, lineation, drainage pattern, texture, erosion, tonal variation, vegetation and land use), different terrain conditions and their boundaries can be identified. Each element should be considered individually and in combination to identify likely signs of groundwater occurrence. Faults and associated fracture zones, for example, form narrow elongated areas of weakness with the more solid parent rock and are common areas of preferential groundwater accumulation. Erosion and weathering penetrate more deeply into these zones, forming long, straight valleys. From aerial photographs, fault systems can be identified by their accompanying valleys as dark lineations, due to increased soil moisture and vegetation density or through sharp discontinuities in the surface geology.

Secondly, aerial photography may provide much needed topographic and demographic information concerning the project area and the distribution of the target population of the planned water-supply system, especially if no appropriate topographic maps are available. This will help to locate the well in a suitable place for the local community. In the latter case, it is important that relatively recent pictures be obtained, since demographic patterns may be subject to rapid change. For geomorphological information the age of the photographs is generally not significant. For larger projects it may be beneficial and cost-effective to engage the services of a local company to acquire a new series of aerial photographs covering the project area.

Aerial photographs are widely available, comparatively cheap and can be used for hydrogeological interpretations without the need for expensive and sophisticated equipment. Rough, but generally adequate mapping can be done by hand. Detailed ortho-topographic mapping requires professional expertise.

Hydrogeological Fieldwork

The objective of hydrogeological field work is to assess the potential presence of groundwater in the underlying rock by an evaluation of ground surface characteristics. A number of useful characteristics may already have become evident from the two earlier levels of investigation described above. The hydrogeological fieldwork provides the opportunity, where possible, to check the findings of the inventory of existing data and of the remote sensing interpretation in the field. Based upon the field investigation and the previous levels of investigation, the project area can be divided into water availability zones (high, medium and low potential) according to the expected availability of groundwater.

When no inventory of existing data can be made and no remote sensing material is available, the hydrogeological field check should be undertaken on its own. In such a case, fieldwork needs to be more extensive since a general overview obtained from the previous levels of investigation is absent.

The basic elements to be checked during fieldwork are:

Geomorphology Identification and confirmation (i.e. with regard to remote sensing interpretation) of rock and soil types, geometry of layers, depth and extent of weathering and faulting and fracturing, to identify potential aquifers and zones of preferential groundwater flow. Where possible hand drilling and test pumping are carried out to assess shallow groundwater occurrence. The topography should be taken into account, as groundwater flow generally follows surface topography - significant storage is more likely in valleys than on steep slopes or hill tops - Vegetation cover often provides important clues concerning geology and (shallow) groundwater. Erosion material will accumulate in lower areas, weathering will be more significant and surface runoff will flow toward depressions where more infiltration can be expected than on steep slopes.

Water Availability This should be seen as a complement to the inventory of existing water sources carried out under investigation level 1. Field verification of water levels, yield and quality of wells, springs, seepages and surface water sources are strongly recommended for more precise and up-to-date information. In addition, local drainage and vegetation characteristics can provide more detail on potential shallow groundwater occurrence. In the case of a large project or on-going programme with many planned wells it is recommended that a monitoring network of existing wells be set up. Regular checking of water level and quality fluctuations will improve the understanding of the presence and movement of groundwater.

Human Resources The local population is likely to know details of local surface and spring-water occurrence and regime. settlement patterns, water requirements, present and alternative sources, available inputs and preferred well sites. If this is the first visit by the siting team to the project area, it is vital that special attention be paid to making contacts within the target population, involving them in the well siting procedure and decision-making process.

Hydrogeological fieldwork should be carried out by or under the auspices of a trained hydrogeologist. If enough evidence is found of high potential groundwater areas a well site may be selected without the need for additional investigations. If primarily unconsolidated material is encountered (such as river or hill-side deposits) hand drilling is recommended to locate the optimal well site (DHV, 1978; Blankwaardt, 1984). In situations where additional investigations are required, hydrogeological fieldwork serves as the basis for selection of sites for detailed geophysical surveys. It is generally too time consuming and expensive to cover the whole project area systematically with geophysical measurements.

Geophysical Fieldwork

With geophysical methods, physical properties of subsurface rocks are measured. The principal aim of geophysical fieldwork is to investigate subsurface geological conditions by means of observations of physical variables at the earth's surface. Indirectly this provides information on geology and structure of the underground.

A large number of different techniques are available for geophysical investigations, each of which has specific advantages and disadvantages. Commonly-used methods for groundwater investigations are the Electrical Resistivity, Seismic Refraction, Electromagnetic (EM) and the Very Low Frequency (VLF) EM methods. For investigations covering large regions Gravimetric and Airborne Geophysical methods can be applied. Regional geophysical coverage can provide a good background understanding against which areas for more detailed investigations are selected. However, an airborne survey is generally too expensive for CWS projects to undertake, and on its own lacks the resolution required for determining individual well sites. More information on individual techniques is given in Appendix 2.

Geophysical methods provide at best only indirect information concerning the presence of groundwater. The gathered data needs to be evaluated carefully and where possible correlated with other available hydrogeological information to ensure the correct interpretation of measurements. The need for calibration of the geophysical data can be a major reason for proceeding to the exploratory drilling level of the investigation, as described in the next section.

Two basic geophysical techniques can be distinguished:

- the sounding technique which provides quantitative depth information below the station of measurement, such as the thicknesses and depths below ground level of the individual layers;

- the profiling technique which provides qualitative information on lateral changes in the subsurface rock types and structures, without much detail on depths and thicknesses.

The electrical and electromagnetic methods are based on measurements of natural or induced electric fields. Usually variations in electrical conductivity either vertically or horizontally can be correlated to variations in layering or structure of the underground. It provides indications for the type of rock and the presence of groundwater.

Resistivity Soundings and the Seismic Refraction method are commonly used for quantitative data acquisition in groundwater investigations. Both methods can, with certain adaptations in technique and field layout, provide both depth and lateral information. The resistivity method has the added advantage that the resistivity values observed provide information on lithology and groundwater quality. However, the interpretation of resistivity field data can be subject to different equivalent solutions if no additional data are available to correlate layer depths and thicknesses.

A recent innovation of the resistivity sounding method involves the use of two multi-core cables and a microprocessor controlled switchbox (the Offset-Wenner technique[5]), which has increased the accuracy and speed of fieldwork. More advanced techniques suitable for quantitative information are Shallow Seismic Reflection and Transient or Time-Domain Electromagnetics (TEM/TDEM). As these methods are still in the experimental phase as far as their application for hydrogeological investigations is concerned, their use for relatively shallow groundwater prospecting for handpumped wells is not expected in the near future.

The strength of EM and VLF profiling methods is their capacity to map qualitative contrasts i.e., conductive versus resistive zones, which can be pin-pointed with good lateral accuracy. This combines with the advantage that they are very fast in their application in the field. Conductive zones, such as faults and fractured zones, buried river channels and contact zones between different rock types are often the best places to find water. The depth of penetration of the EM equipment which carries its own transmitter is generally much better than that of a VLF instrument, because it operates at much lower frequencies and can therefore penetrate deeper. The VLF receiver is, moreover, dependent on the availability of a strong external long-wave radio transmitter.

To carry out a quick reconnaissance of an area of interest, a combination of a profiling technique with depth sounding method is most likely to provide sufficient information for locating a well. From the Inventory Study on Well Siting Techniques it appears that in practice the choice and application of different geophysical techniques is often made irrespective of the geological environment encountered. However, certain techniques may yield better results than others depending on the geological situation. A general overview of comparative advantages is given in Table 2.

Table 2 Suitability of common geophysical methods in different hydrogeological environments

Hydrogeological Environment	Resistivity Sounding	Resistivity Profiling	Seismic Refraction	Electro-magnetics	VLF
Unconsolidated Sediments	++	+	+	o	+
Consolidated Sediments	+	+	+	o	o
Sediments fresh/salt water	++	+	o	+	o
Volcanics	+	o	o	+	o
Basement depth to bedrock	++	+	++	+	+
Basement faults/fractures	+	++	++	++	++

++ very suitable   + suitable   o not very suitable

Given the relatively simple operation of modern geophysical equipment, field practice does not necessarily require the daily supervision of a geophysicist. Geophysical fieldwork should, however, be preceded by a hydrogeological reconnaissance of the area to determine where the geophysical measurements are to be carried out. Further preparations involve the proper selection of the geophysical method to be used to prepare a proper layout for the geophysical fieldwork and, where necessary, the training of a field team in the use of the equipment. For projects where a large number of wells are planned it may prove efficient to decide on a standardized geophysical layout and field practice. An example is described in Case Study 2 in the next chapter. This does, however, increase the need for proper hydrogeological site selection in advance to make sure that the geophysical survey takes into account the individual characteristics of each site.

Interpretation of the field data is also a specialized job, which needs an experienced geophysicist or hydrogeologist. Interpretation of Resistivity and Seismic Refraction is nowadays usually carried out with the help of a computer. With the current generation of small portable computers, it can be completed in the field, thus speeding up geophysical investigations considerably. Depending on the accessibility of the site for the geophysical work and the complexity of the geology, one team can often carry out one or more sitings per day.

Dowsing or Water Divining may also be considered an exploration method, although its role in groundwater exploration remains controversial to many hydrogeologists and geophysicists. Recent scientific appraisal of dowsing suggests that it might be based on a human response to changes in the earth's magnetic field, similar to the principles of navigation applied by whales and homing pigeons[6]. The method itself is certainly low-cost, requiring only a forked stick or hand angles and a human operator sensitive to magnetic anomalies. In many places dowsing has been used as the sole investigating method without any of the preceding levels of investigation. This may explain its frequently inadequate performance. If applied along the lines suggested by a few hydrogeologists as a biophysical profiling method, it somewhat resembles the magnetometric method in field practice. Perhaps on this basis dowsing could play a scientifically-acceptable role in the well siting process as a profiling technique. If this is the case, just as with any geophysical method, interpretation of the 'measurements' should be carried out within the context of the larger hydrogeological investigation.

Exploratory Drilling

The purpose of exploratory drilling is to gather data from a test borehole to evaluate the potential for production wells in the area. Two basic levels of drilling can be considered, hand drilling (as an adjunct to hydrogeological fieldwork) and machine drilling. Although millions of boreholes have been drilled by hand in South East Asia, in Africa hand drilling has been limited in its application to relatively shallow groundwater in unconsolidated or relatively soft rock such as decomposed regolith.

Various procedures are commonly used to gather information from a test hole:

Geological logging During the drilling operation the drilling supervisor or hydrogeologist regularly collects rock samples which are brought to the surface, to determine the rock types, sequence and thickness of the various layers. The depth(s) at which water is encountered is also noted ('logged').

Geophysical logging	Directly after the hole is drilled, and before any casing and screen are installed, the hole can be logged geophysically (e.g. resistivity, SP, gamma ray and temperature measurements are made, either continuously and written on a recorder, or stepwise whereby readings are taken at regular intervals). This is used to accurately determine geological boundaries, thicknesses of layers, lithology, porosity and water quality. It is often vital for proper well construction.
Test pumping	Pumping tests are conducted to determine the performance characteristics of the well and the hydraulic parameters of the aquifer. For the former the yield and drawdown are recorded over a certain time period to measure the productive capacity of the well. The latter requires careful monitoring of the drawdown at set rates of discharge in the pumped well and nearby observation wells and provides information on the transmissivity and storage capacity of the aquifer. Aquifer tests, whereby observations are done also in nearby piezometers, are particularly important where large scale abstraction from the aquifer is envisaged.
Water sampling	Borehole water should be sampled and tested for chemical and biological constituents. Excessive mineralization and contamination may require treatment or, where this is not possible, may prohibit abstraction from the aquifer. Biological contamination from human and animal waste is a particular risk when shallow aquifers are used. The use of such aquifers should be avoided in densely populated areas.

It is recommended that also production wells be geologically and geophysically logged and pumping and water quality tests be carried out. This optimizes well construction and provides data for any additional wells to be drilled in the area (see Appendix 3).

In case the information can be acquired by exploratory hand drilling in relatively soft rock, geophysical investigations are usually not necessary. Several hand drilled holes can be easily and cheaply made to determine the best site for a production well, which will be dug or drilled by hand as well. Whether or not hand drilling is possible depends on local geological conditions and will be made in the hydrogeological investigation phase, when information is obtained on the local geology and confirmation is sought on shallow water levels and water quality. Particle size analysis of drill samples is relatively simple and provides an indication of the clay content. Based on the pumping test, the calculation of aquifer permeability and storage capacity will determine whether a hand-dug or hand-drilled well will be more suitable (hand-dug for greater well storage in low-permeability aquifers). A well siting flow chart with test hand drilling used in a CWS project in Tanzania is shown in Figure 5. A well siting flow chart for a CWS project in Zimbabwe (Case Study 1) where geophysics was used is shown in Figure 6.

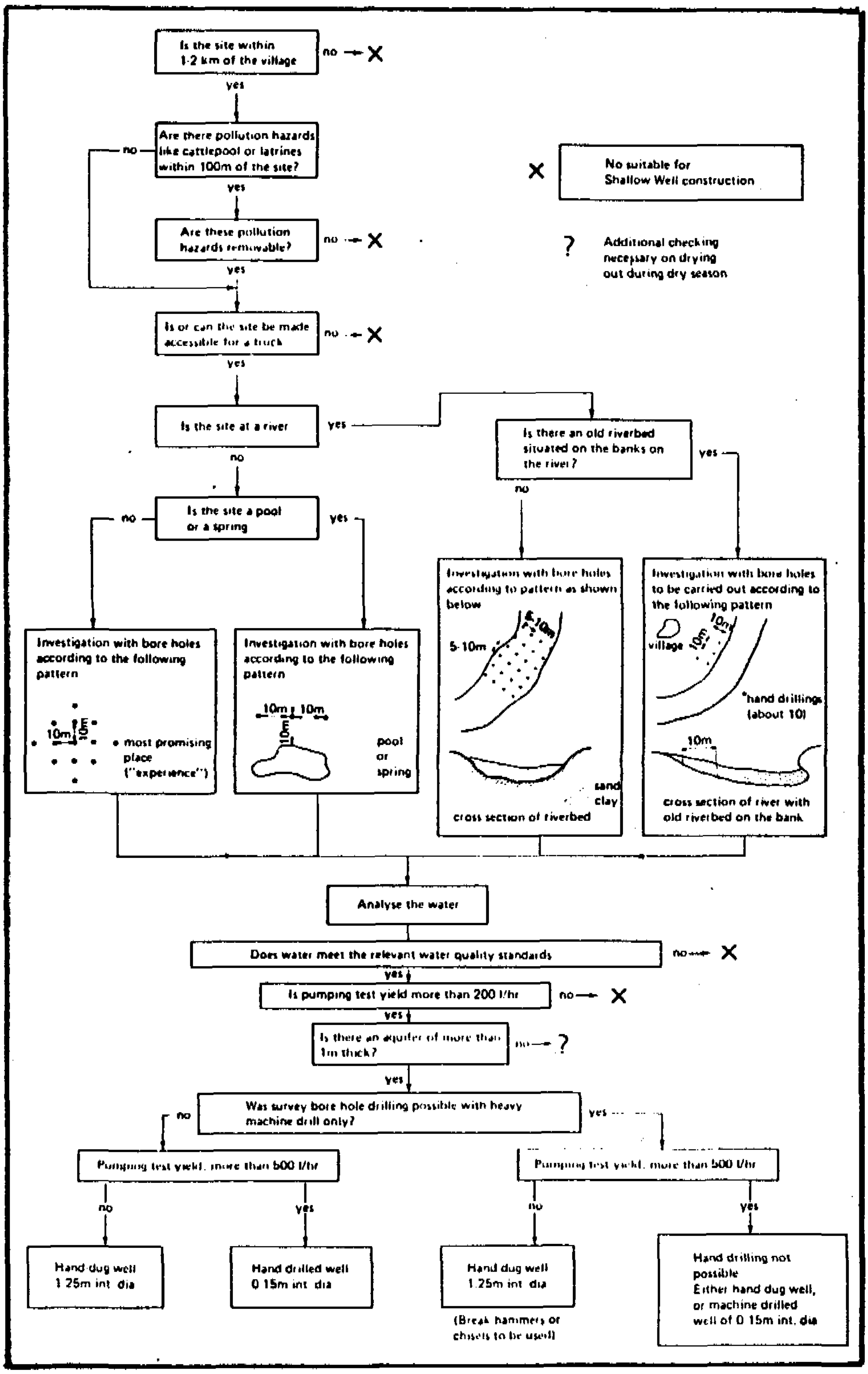


Figure 5 Well siting flow chart with hand drilling (DHV, 1978)

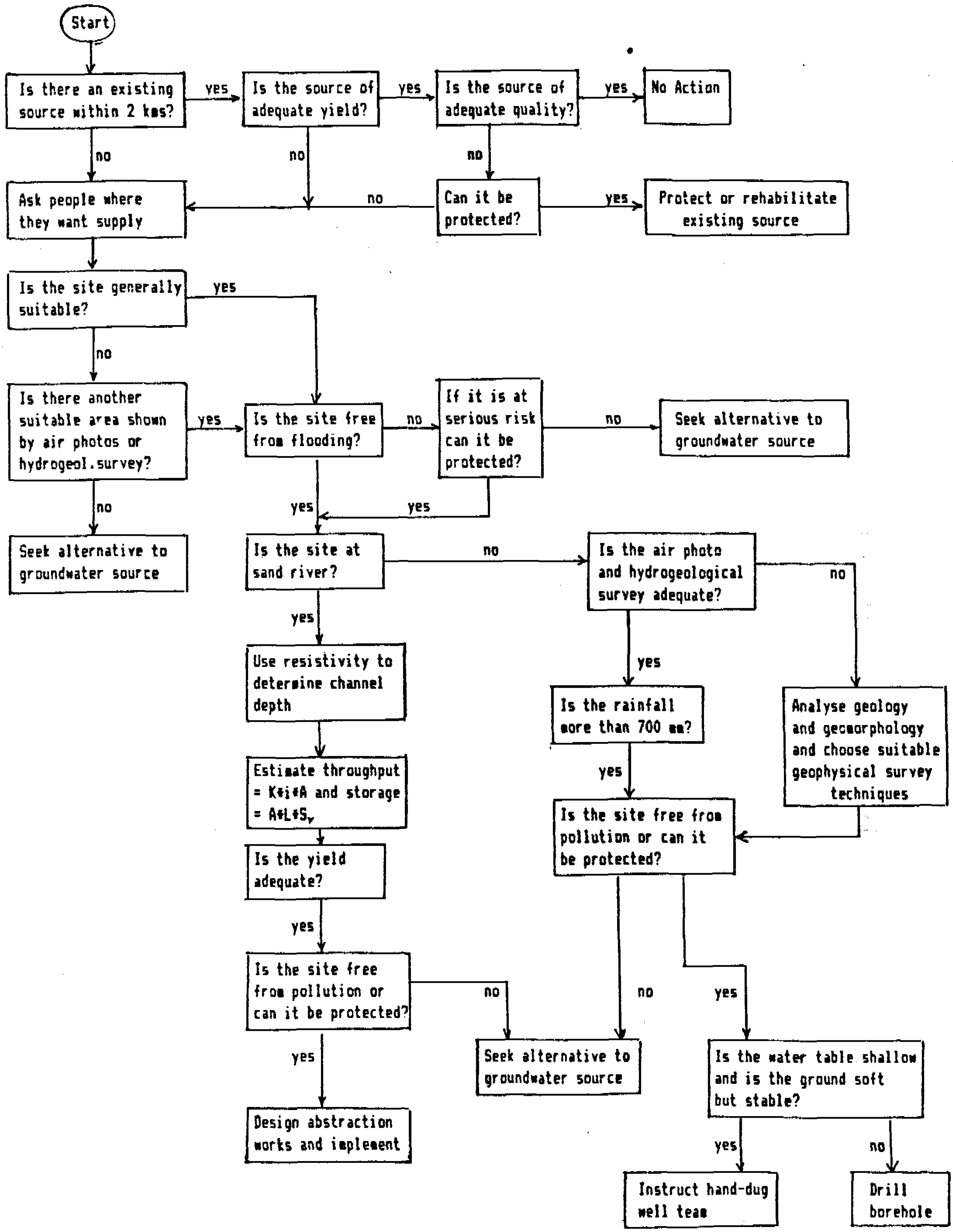


Figure 6 Well siting flow chart with geophysics (Hydrotechnica, 1985)

3.3 Feasibility of Well Siting

In most cases financial considerations determine whether or not groundwater investigations should be carried out before constructing a well[7]. The financial and economical aspects of the siting procedure have to be considered carefully and a decision reached on whether the investigation is cost-effective or not. Well siting is not just carried out to make each well yield more water, but in particular to reduce the overall cost of well construction by increasing the success rate for all the wells constructed.

Box 2

Feasibility Example 1

If in area A the chance of encountering adequate water supplies by drilling to a depth (D) of 50 meters (R_A) is 90 percent and in area B this (R_B) is 50 percent, the average cost of drilling a successful well in area B (C_B) will be nearly twice as high as in A (C_A), assuming basic drilling costs (C_d) are the same i.e, \$100/m:

$$C_A = (C_d * D)/R_A = 5000/0.90 = \$\ 5555$$

$$C_B = (C_d * D)/R_B = 5000/0.50 = \$10000$$

Well siting is needed especially in area B to increase the success rate of drilling to lower the average cost of a well. If a full hydrogeological and geophysical investigation is able to raise the success rate in area B by 25% to 75% (R_B') at a cost (C_s) of \$1000 per site, the overall reduction in well costs becomes apparent:

$$C_B = (C_d * D + C_s)/R_B' = (5000 + 1000)/0.75 = \$\ 8000$$

The use of well siting represents a saving of 20 percent, including the cost of siting. It is evident that in area A a similar siting expense to raise the success rate to 100 percent (R_A') would not be justified as the overall cost per well would actually increase due to the cost of siting:

$$C_A' = (C_d * D + C_s)/R_A' = (5000 + 1000)/1.00 = \$\ 6000$$

Case Study 2 in Chapter 4 suggests that savings through siting may also be effected because hydrogeological and geophysical investigations often locate water at shallower depths, thus reducing the required drilling depth and costs. If the required drilling depth is reduced by 30 percent (D'), well siting also becomes cost-effective in area A:

$$C_A = (C_d * D' + C_s)/R_A' = (3500 + 1000)/0.90 = \$\ 5000$$

In areas of limited rainfall the chance of striking water without proper hydrogeological investigations is usually limited. This may be expressed as the success rate of well construction in that region under those particular circumstances. The simple example presented in Box 2 illustrates the effect this has on the cost of well construction.

The example above shows that the financial rationale for the use of well site investigations is directly related to the cost of well construction in an area. If the well construction programme is a local community initiative without external funding, the funds are likely to be very limited and the hand drilling or digging option will often be the only alternative. Consequently, as construction costs decrease, expenditure on well siting will need to be justified by higher increases in the rate of success, as illustrated in Box 3.

Box 3

Feasibility Example 2

In area X the funds for well construction are limited and hand digging is considered the only feasible option. The cost of digging (C_d) is estimated at $20 per meter, the expected rate of success (R_x) at finding water at 25 meters below ground level (D) without well siting is 50 percent and the cost of a simple site investigation (C_s) $400. To warrant the use of well siting, the cost of construction including the cost of siting should be less than the construction cost without siting. The minimum improvement in rate of success required can then be calculated as follows:

$$(C_d * D' + C_s)/R_x' < (C_d * D)/R_x$$

If the depth (D') remains the same, then the success rate with siting (R_x') needs to be:

$$R_x' > \frac{(C_d * D' + C_s)}{(C_d * D)/R_x} = \frac{(20 * 25 + 400)}{(20 * 25)/0.50} = 0.90$$

The increase in the success rate ($R_x' - R_x$) has to be greater than 40 percent. It is obvious that when the construction cost and required depth are low, the siting cost should be low as well.

These examples show that the financial feasibility of well siting is closely tied to a number of variables i.e, the cost of constructing the well, the cost of well siting and the higher success rate achieveable through well siting. Proper accounting requires that the cost of a successful well should include the cost of any unsuccessful digging or drilling attempts. If the cost of siting a well is taken as a fixed percentage of the total cots of well construction (say 10%), it follows that where the construction costs are low the margin for investment in well siting is narrower than where the construction costs are high. Similarly, where siting can improve the success rate significantly (expressed as a reduction in the required depth of drilling or digging per well[a]) the margin for investment in well siting is widened. The cost of well siting is naturally also an important variable. When the siting costs are high the comparative advantage of siting is reduced, if they are low, the advantage is greater.

The evaluation of actual costs and benefits to determine the extent of investigation necessary, depends very much on local circumstances. Information on the existing success rate of drilling without any siting and the possible increase in success rate using various levels of investigation will need to be acquired from available data from earlier projects in the same area or from areas with comparable conditions.

The case studies presented in this report illustrate some of the basic variables involved in this evaluation. It should be noted that the rainfall regime of the project area can significantly influence the success rate. In high rainfall areas (e.g. >1000 mm) the wildcat success rate (i.e. without siting) is usually much higher than in low rainfall areas, and the expected increase in the success rate will subsequently be much smaller, allowing for less expenditure on the siting process.

In general it can be said that the cost of investigation increases with the level of investigation. The first three levels of investigation (data inventory, remote sensing, and hydrogeological fieldwork) involve relatively little expense in terms of equipment and probably less than one day of expert hydrogeological advice per site. The inventory of well siting in CWS in Africa (see Volume 1 of this study) would cost in the order of $100 to $200 per level, depending on the degree of detail (somewhat higher in West Africa and lower in Southern Africa).

The cost of the fourth level of investigation is generally significantly higher due to the high capital cost of the geophysical equipment and the need for a professional supervisor (basic, duty free cost of Resistivity and EM equipment US $10000 - $20000; VLF $5000; Seismics upward of $15000). The cost of a geophysical survey per site is difficult to assess and depends on the type of geophysics, the intensity of the survey, logistics, etc. The inventory of well siting practices (Volume 1) reveals average investigation costs of $650 per site (for large projects), with a maximum reported cost of $3000 for a combination of Resistivity, Seismics, EM, VLF, Gravity and Magnometry, and minimum reported cost of $50 per site for Resistivity only. It is clear however, that for the siting of a few wells it is needlessly expensive to purchase geophysical equipment. Rental of equipment, or hiring the services of a local geophysical consultant is usually a cheaper option for small projects. The use of professional geophysical equipment without the services of a geophysicist or hydrogeologist familiar with geophysics may lead to an ineffective use of the equipment and unreliable data interpretation.

Assuming geophysical services are available, an investigation including geophysics (a number of resistivity soundings and a few hundred meters of resistivity, EM or VLF profile; or 3 or 4 seismic spreads) is likely to be in the order of $1000 per site for small projects involving only a few sites and may drop below that for larger projects.

Level 5 of the investigation, (machine) test drilling, is very expensive due to the high operating costs of a modern drilling rig (see Appendix 3). Depending on the type of drilling, (hand drilling not included) the basic drilling cost may be estimated at $50 - $200 per metre (low in Southern Africa, high in West Africa), excluding casing, screens, developing, testing, and handpump. Only the largest projects where the cost of drilling exploratory holes can be written off against a large number of production holes will it be financially attractive to engage in such test drilling. When more than one well is needed in a certain area, the first few can be considered test holes, to be sited and used to provide information about the aquifer and to calibrate geophysical soundings, before a decision is made concerning the location of the remaining holes. When water is struck in adequate quantities such test holes can subsequently be turned into production wells.

The decision concerning the feasibility of well siting may also depend on economic variables such as government sponsoring of, for example, the acquisition of hydrogeological information, on the local availability of equipment and skilled personnel and/or the availability of foreign exchange to purchase the required services and equipment on the international market.

4 Case Studies

4.1 Accelerated Drought Relief Programme, Zimbabwe[9]

A community water supply programme in Victoria Province, Zimbabwe was carried out during 1983 and 1984 to help alleviate the effects of a three year-long drought in the area. Hydrotechnica, a UK groundwater consultant, surveyed a total of 331 sites over an eight month period. The geology of the project area consists primarily of granite and gneiss Basement, with the presence of significant dykes and faults. By the end of the project 282 successful boreholes had been completed with an overall success rate of 76 % . A rapid survey approach was developed and carried out by an experienced geophysicist/hydrogeologist assisted by two unskilled labourers. The survey routine included aerial photographic interpretation, reconnaissance field investigations and geophysics when necessary (in areas with more than 700mm annual rainfall, geophysics was considered unnecessary). Three sites were investigated per day. If a suitable site could be located on a hydrogeological or air photo basis only, no additional time was spent on further investigation with geophysical methods.

Two geophysical techniques were used, electromagnetic profiling with a Geonics EM 34 and electrical resistivity soundings with an ABEM SAS 300 terrameter and a BGS 256 multicore cable using the Offset Wenner technique. Interpretation of the resistivity data was speeded up by using a microcomputer in the field with software especially developed for this project[10]. The average siting cost worked out at US $580 per site with two resistivity soundings and 0.5 km of EM profiling and amounted to about 10 % of the total borehole cost. An analysis of the siting methods shows increasing success rates with each additional investigation level (Table 3):

Table 3 Success rates for siting techniques

Technique	Percentage of Successful Boreholes
Social/Logistical	50
Air Photo Interpretation	61
Hydrogeology	66
EM	82
Resistivity	85
EM and Resistivity	90

Geophysical investigations include the previous levels

The average success rate of 76 % for the whole project could in fact have been improved by applying the two geophysical methods at all sites thus increase the siting success rate to 90%. As Figure 7 shows, this would have resulted in an additional saving of Z$ 1350 (=US $800) per borehole, which would have made it cost-effective to employ an additional siting team at US $580 per site to complete the investigation within the same time period.

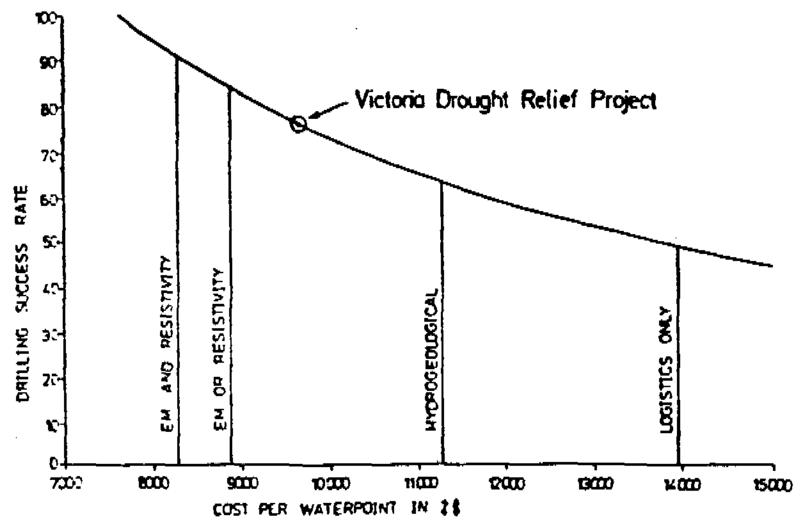


Figure 7 Effective cost of a successful borehole using different siting techniques

A discussion of three of the site investigations, as an example of typical siting situations and taken from the Programme's main report is presented below and refers respectively to a detailed account of siting based on aerial photograph interpretation, a siting with resistivity, and a combined siting with EM and resistivity.

Mapuvire School

The initial assessment of this area was carried out using aerial photographs. The photographs were used in determining the most likely areas for a borehole site and for an assessment of the potential resources. The relevant details identified from the aerial photographs are shown in Figure 8 and their interpretation in Figure 9.

Geomorphology

The variety of landforms in the area is diverse and this results in a large number of possible borehole sites. Figure 9 shows a selection of sites that could be considered for further investigations in the field. They include sites in fault zones, at the base of Basement outcrops, associated with dykes and a variety of locations within the valley systems. The original air photo reconnaissance of the area was conducted to site a borehole for Mapuvire school.

The air photograph can be divided into two distinct areas with a northeast - southwest boundary line running from corner to corner of the photograph. In the southeast part of the air photo, the area is dominated by highland terrain and straight narrow valley systems. To the northwest there is a dramatic change in the landscape where a wide plain is dissected by meandering rivers. There is also a complete contrast in the aerial distribution of exposed bedrock. In the southeast approximately 80% of the area is outcrop. In the northwest however the photograph indicates that outcrop may be present in less than 50% of the area. The contrast is typical of a change in basement geology with granite in the southeast and gneiss in the northwest. The boundary between the two is located along the base of granite hills.

Basic intrusives in the form of dykes can be identified within the gneiss as dark bands orientated east-west in the extreme north of the photograph. To the south of the main dyke, a second dyke is not so clearly defined and would need verifying in the field, using the EM profiling technique.

The first impression from a consideration of the geomorphology suggest that the gneiss is more favourable in this area for groundwater development because the regolith cover is more extensive, and therefore probably thicker.

One of the major distinguishing features identifying the change in geology in this photograph is geological structure. The granite highland is deeply dissected by joint and fault systems. There are two sets of joints present, the main set oriented at 320° and the second oriented at close to the regional mean. The joints end abruptly at the granite/gneiss boundary. The only valley present in this section of the granite is characteristically narrow and straight and coincides with a major joint, or perhaps a fault. This valley provides the only area where any significant thickness of regolith is present. The remaining joints identified from the photo show little development in terms of weathering. In the gneiss, evidence of a joint system is much less developed. One fault can be identified, oriented at 20°, from the displacement of the most northerly dyke. The eastern extremity of the southern dyke also appears to end at the fault.

Hydrology

The two rock types show distinctive drainage patterns. The geological structure dominating the granite landscape has also a profound effect on the hydrology and hydrogeology. The joints form the biggest line of weakness in an otherwise massive, resistant intrusion. Consequently the rivers and drainage channels occur along the joints and it is the erosion along the joints that makes the geological structure such a dominant landscape feature. The drainage system therefore exhibits a parallel or trellis pattern. The drainage density is also uneven, with a very low density occurring towards the centre of the intrusion and a very high density near the granite/gneiss boundary. The high density relates to the greater rate of runoff experienced on the steeper slopes along the boundary of the granite intrusion. This has also resulted in the development of a braided channel system at the base of the granite hills where sediment deposition is high, compelling the channels to become wider and shallower.

In the gneiss the drainage density is high and fairly even across the area. The lack of structural control and the relatively flat topography has produced a dendritic drainage pattern, with the main river following a meandering course towards the southwest. Tributaries joining from the south are still influenced by the granite highland and are sub-parallel. The southern intrusive dyke may have diverted the river from the fault.

Conclusions

The extensive cover of regolith over the gneiss is apparent from the vegetation. Large portions of the area shows evidence of arable land with a well developed field system. Village vegetable gardens can also be easily located and are associated with the most fertile areas where water supplies from springs or shallow wells are available. Uncultivated areas are present mostly along the valley centres, which are probably prone to flooding from the rivers and where steep gradients leading to high rates of erosion occur making them unsuitable for boreholes.

The final site chosen for the Mapuvire School borehole is ideal in many respects. From a logistical point of view it could not have been nearer to the requested site being only 30-40m from the school buildings. Secondly the site is readily accessible for large drilling rigs without difficulty. Geomorphologically the borehole is sited at the head of a tributary valley. The heads of valleys are often indicative of potentially thick regolith development. The weathered material transported from the granite mountains towards the gneiss plain also increases the development of thick regolith and probably enhances permeability.

If the site near the school had been inadequate there were several alternatives available. The first options available were those where groundwater flow was known to be utilized throughout the year. These can be identified by the dark patches on the air photograph (vleis) and by the presence of small village gardens each surrounded by fences of thorn bush. Hand-dug wells are often present in these areas. Secondly, the centre and sides of a tributary valley or even the interfluves between two valleys could be investigated near the school. Further options could be investigated in relation to the dykes. The faulted dyke at the northern edge of the air photo shows particular promise in offering a suitable borehole site. In certain areas of Victoria Province a dyke offered the only suitable place for locating a groundwater supply. Had this been the case at Mapuvire School, the site may have been less then ideal for the school children because of the longer walking distance incurred. It would still have been widely accessible to the community as a whole, however, and would have provided a permanent and clean water supply in the absence of a suitable alternative.

The lack of suitable water supplies within the granite is reflected by the lack of cultivable soil and by the marked decrease in population. The area is generally inhospitable with only the narrow valleys offering any chance of cultivation. It was generally found that such valley soils were very clayey and when investigated using EM methods, exhibited very high conductivity values. This greatly hampered the location of the associated fault zones because the electrical contrast between the clay soils and the bedrock is so great that little else can be distinguished. It was also thought that the joint zones in this area are poorly developed, offering little potential for a groundwater supply. In many cases the bedrock is massive and the thickness of clay regolith less than 7m. A more suitable alternative to a borehole in these areas may be a hand-dug well.

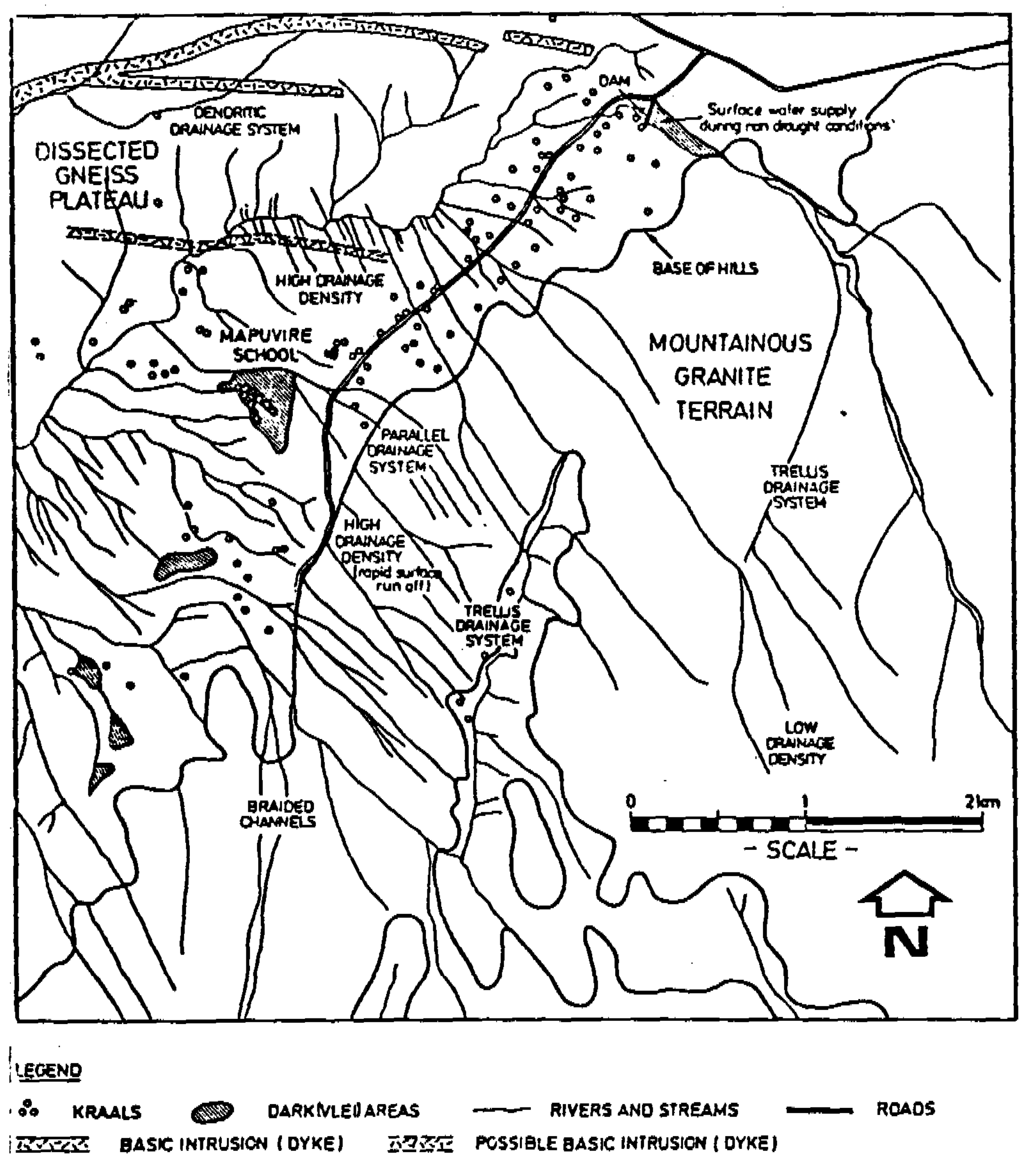


Figure 8 Aerial photograph interpretation 1: General details present on the air photo

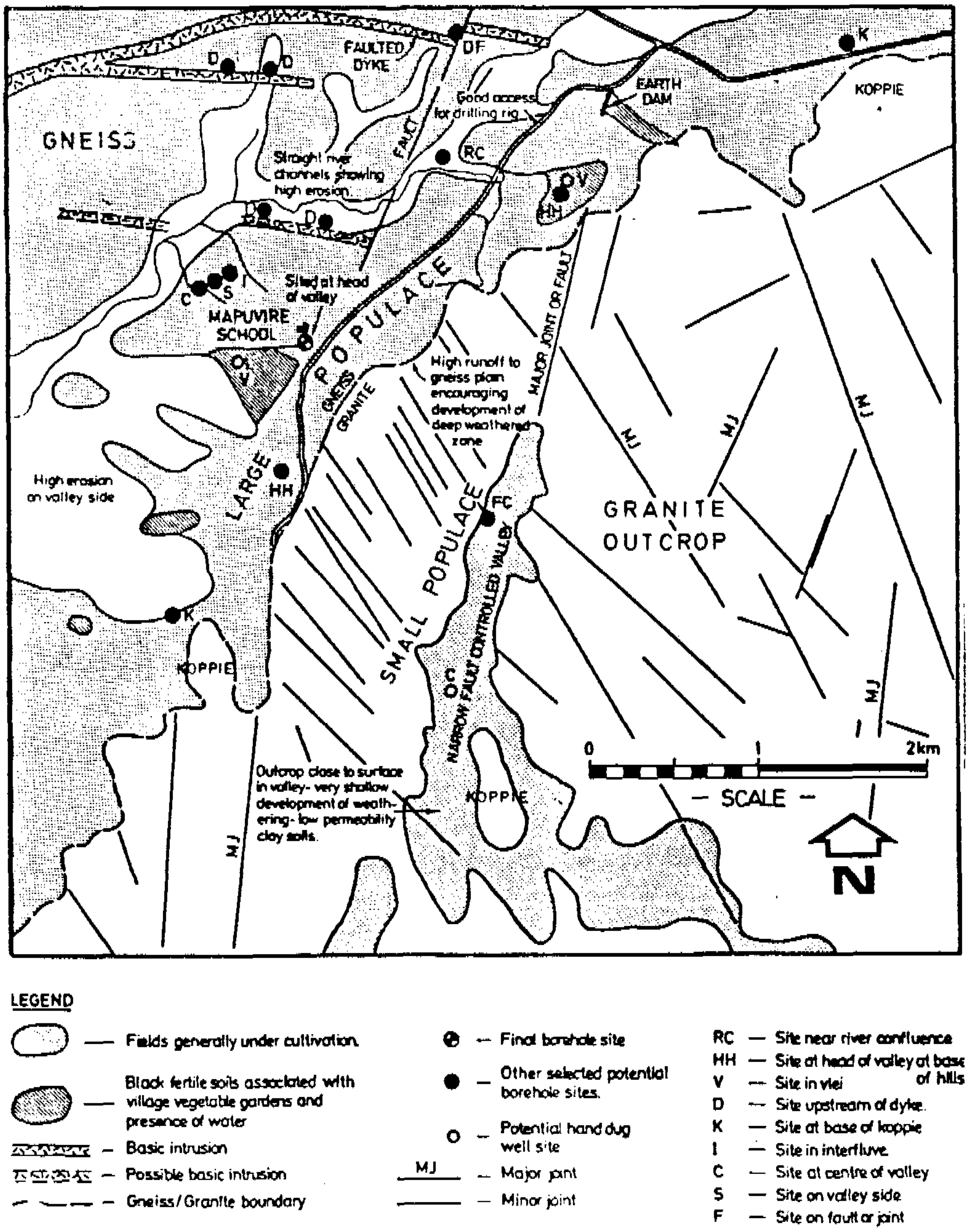


Figure 9 Aerial photograph interpretation 2: Potential borehole sites

The aerial photographs are thus used at two levels. The first level provides an overall picture of the groundwater potential in the area. A second level of interpretation in greater detail is, however, required around the proposed site. Finally, it is likely that appropriate geophysical techniques are necessary to confirm the exact location and viability of drilling a borehole. The decision concerning what geophysical technique to use can be illustrated by the following table:

Table 4 Appropriate geophysical siting techniques for different geomorphological Basement environments

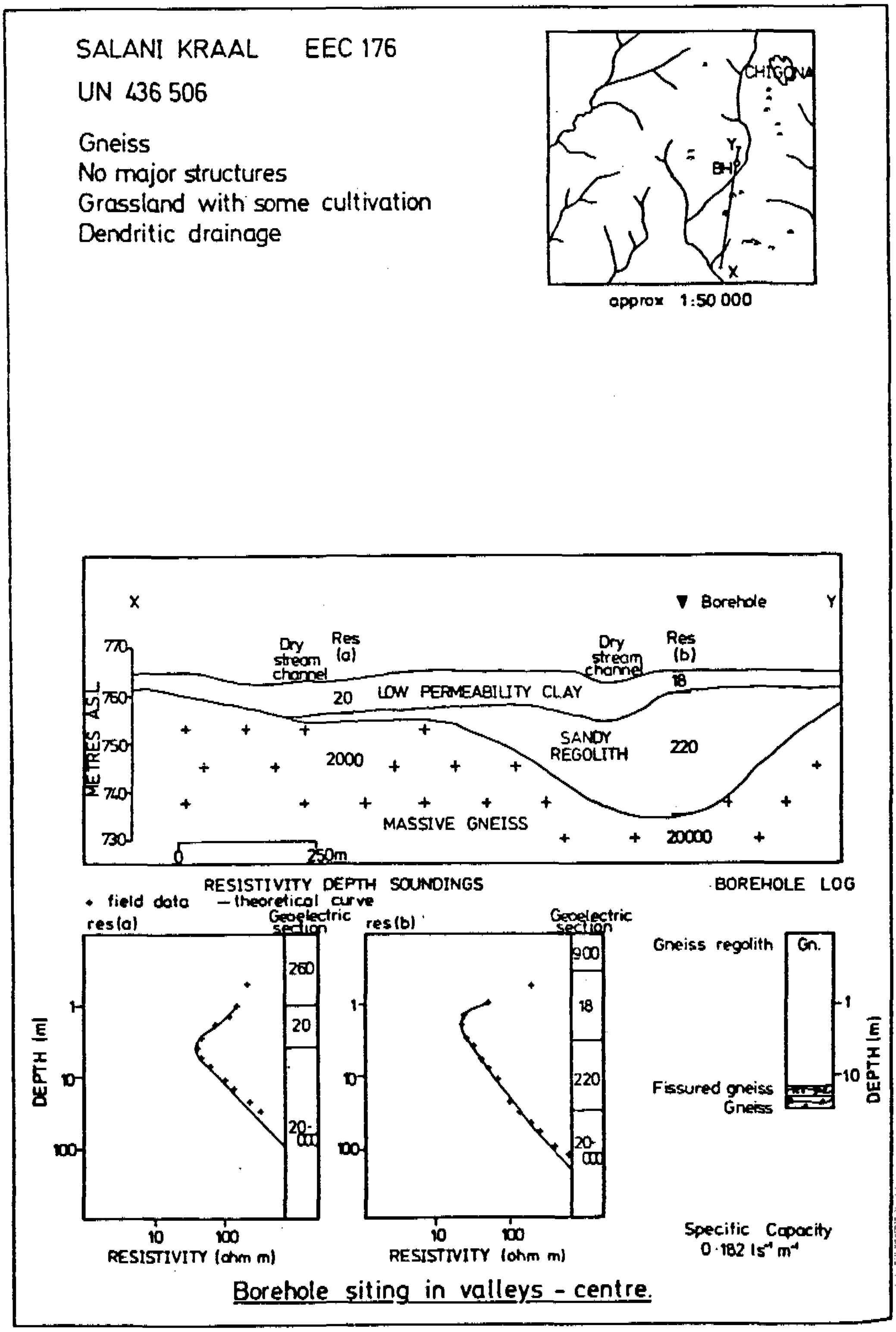
Landform	Method	Landform	Method
V shaped valley		Watershed	EM & R
(head, sides and centre)	R	Flat Plain	EM & R
Basin shaped valley		Outcrop	EM / R
(head)	R	Dyke	EM
(side and centre)	EM & R	Fault or Joint	EM

Salani Kraal

Borehole EEC 176 shown in Figure 10 is sited in the centre of a broad shallow valley, where it was anticipated that deep regolith would be found. The first sounding at A showed massive bedrock at only 4m with an overlying clayey regolith, clearly unsatisfactory. The second sounding at B indicated a sandy regolith with 30m depth to bedrock. Drilling at this site actually proved 23m of gneiss regolith above fissured gneiss resulting in a good specific capacity of 0.182 l/s/m.

Magudu School

Magudu school (Figure 11) is an example of deep regolith associated with the base of a Basement outcrop. The area surrounding the outcrop is flat with sparse vegetation and little hydrogeological evidence to aid the borehole siting. An EM profile was initially conducted from the base of the outcrop northward towards the centre of the valley. The profile revealed three distinct anomalies and two resistivity soundings revealed that the second site had a considerable depth of regolith which was confirmed by the borehole. A specific capacity of 0.051 l/s/m was obtained.



Borehole siting in valleys - centre.

Figure 10 Borehole siting with Resistivity

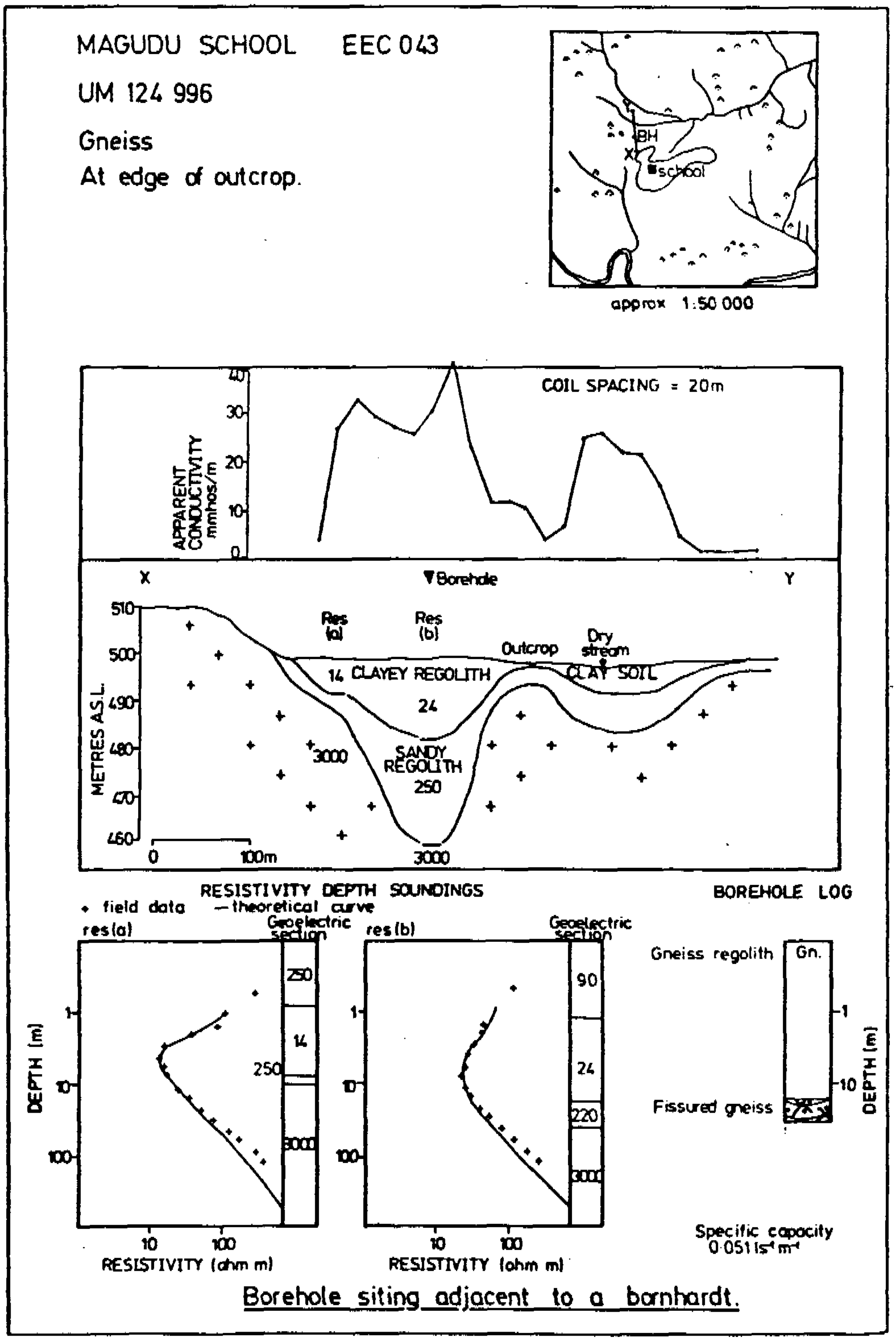


Figure 11 Borehole siting with EM and Resistivity

4.2 Rural Domestic Water Supply and Sanitation Programme, Kenya[11]

The Lake Basin Development Authority (LBDA) has initiated a CWS programme in Nyanza Province in Western Kenya with the aim of improving the generally poor water supply situation through the development of handpumped water supplies. In 75% of the province very few permanent surface water resources are found. Whenever the groundwater table can be found at less than 20 meters below ground level hand dug wells are considered. In the western part of the province the water table is lower and machine drilled boreholes have to be constructed. The province is mainly underlain by volcanic rocks of Precambrian and Tertiary age and about 15% Precambrian granites and dolerites and some Pleistocene sediments. The area has been subject to extensive tectonic activity since late Tertiary times. Based on the assumption that the most productive aquifers in hard rock usually occur in faults and fracture zones, a survey method has been developed for the programme by DHV Consulting Engineers of the Netherlands to accurately locate prospective borehole sites in the field. This comprises of the following two components:

- Mapping of faults and fracture zones by means of remote sensing;

- Geophysical surveys carried out along profiles across the most promising of the interpreted faults and fracture zones.

Regional structures and major faults show up clearly on satellite images. On aerial photographs fault systems can be identified as dark lineations due to increased soil moisture and vegetation density. So far in about half the area (6000km²) over 3000 fault structures have been identified. **It has proven essential that such features be accurately located in the field, as a location error of 10m can result in a dry hole.** The standard field survey per site consists of 2 electromagnetic profiles of about 400 to 600 meters length, 1 resistivity profile (Wenner array) and 3 to 5 resistivity soundings (Schlumberger array) evenly spread and generally perpendicular to the profiles (see Figure 12).

The equipment consists of an ABEM SAS 300B Terrameter and a Geonics EM 34-3. The latter proved especially sensitive to narrow anomalies caused by fault and fracture zones. The spool separation varies according to local conditions. The resistivity data are interpreted on a micro-computer with a special curve-fitting software package and evaluated together with the plotted profiling data in terms of:

- the presence and depth of different zones of weathering;
- the depth to the unweathered bedrock;
- the thickness of aquifers;
- the presence and accurate location of (sub)vertical discontinuities as faults, intrusive dykes and lithological boundaries;
- the salinity of the groundwater.

Based on this evaluation the most suitable well location and well type (hand dug or drilled) is selected. Figure 12 shows the Resistivity/EM survey layout for Omboga Secondary School site to illustrate the importance and accuracy of this standard survey approach.

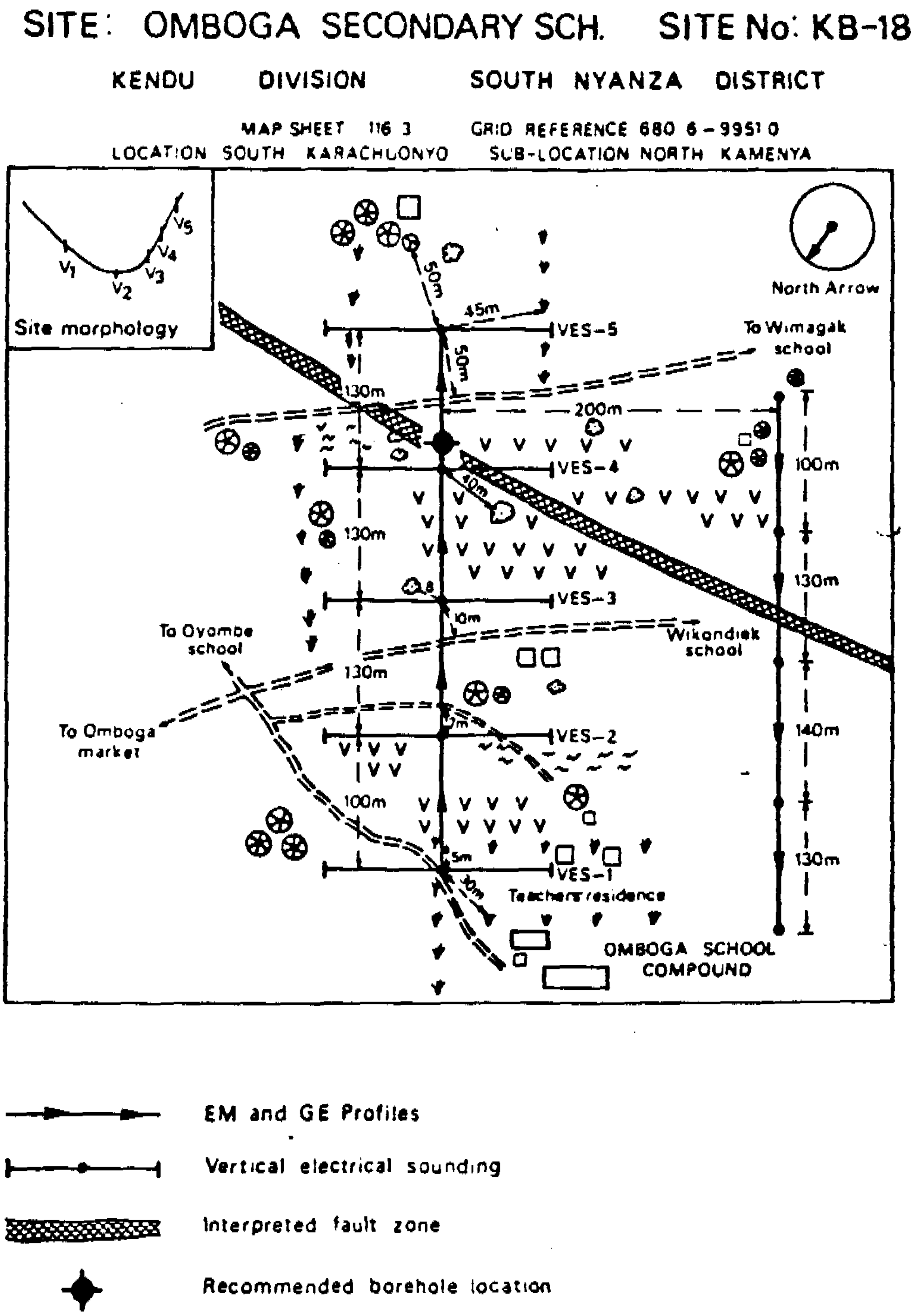


Figure 12 Schematic layout of the geophysical survey at Omboga Secondary School

The Omboga Secondary School is situated in a dry area and the nearest perennial water sources are a well and a river at 4 and 6 kilometres distance respectively. The study of aerial photographs revealed the possible existence of a fault just south of the school and a detailed geophysical survey was carried out to locate this structure. The resistivity soundings revealed the existence of a narrow dolerite dyke in this mainly granitic area. The EM profiles in particular indicated the occurrence of a pronounced fractured zone along the granite/dolerite contact (see Figure 13). The location and slope of this sub-vertical zone was assessed and a borehole location selected near VES-4 (see Figure 14). The borehole drilled at this location to a depth of 52 meters struck water at various levels with a static water level of 24 meters below ground level. A subsequent pumping test resulted in only 2.5 meters drawdown at a discharge of 12 m^3/h (or 1.33 l/s/m).

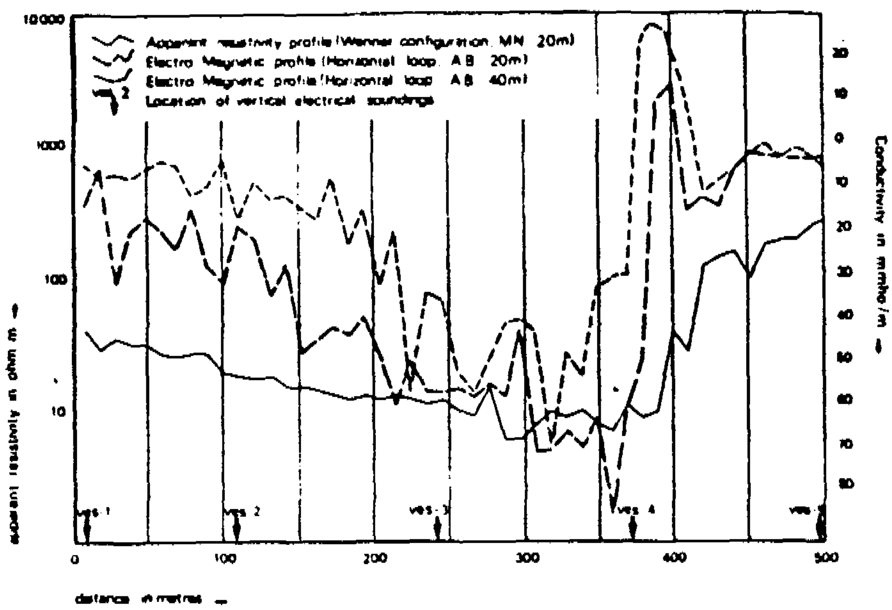


Figure 13 Resistivity and EM profiles at Omboga School

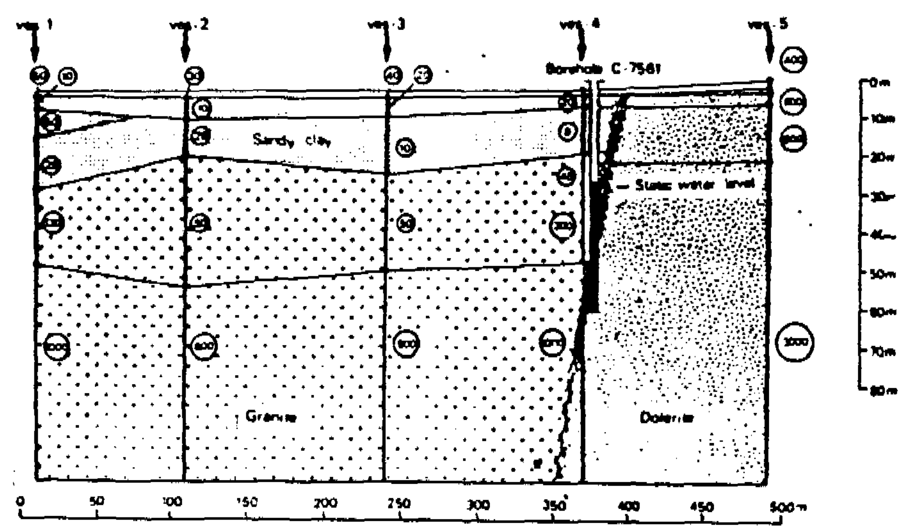


Figure 14 Resistivity soundings interpretation and borehole location at Omboga School

A fault structure was also interpreted for the following two sites located at 2 kilometers distance from each other in Tertiary Basalts. At the God Bim school a successful borehole was drilled exactly on a fault with a maximum yield of 24 m^3/h. At the Otati school the 85m deep borehole was erroneously drilled 30 metres away from the interpreted fault structure and was dry, while a later borehole relocated on the fault proved successful (see Figure 15).

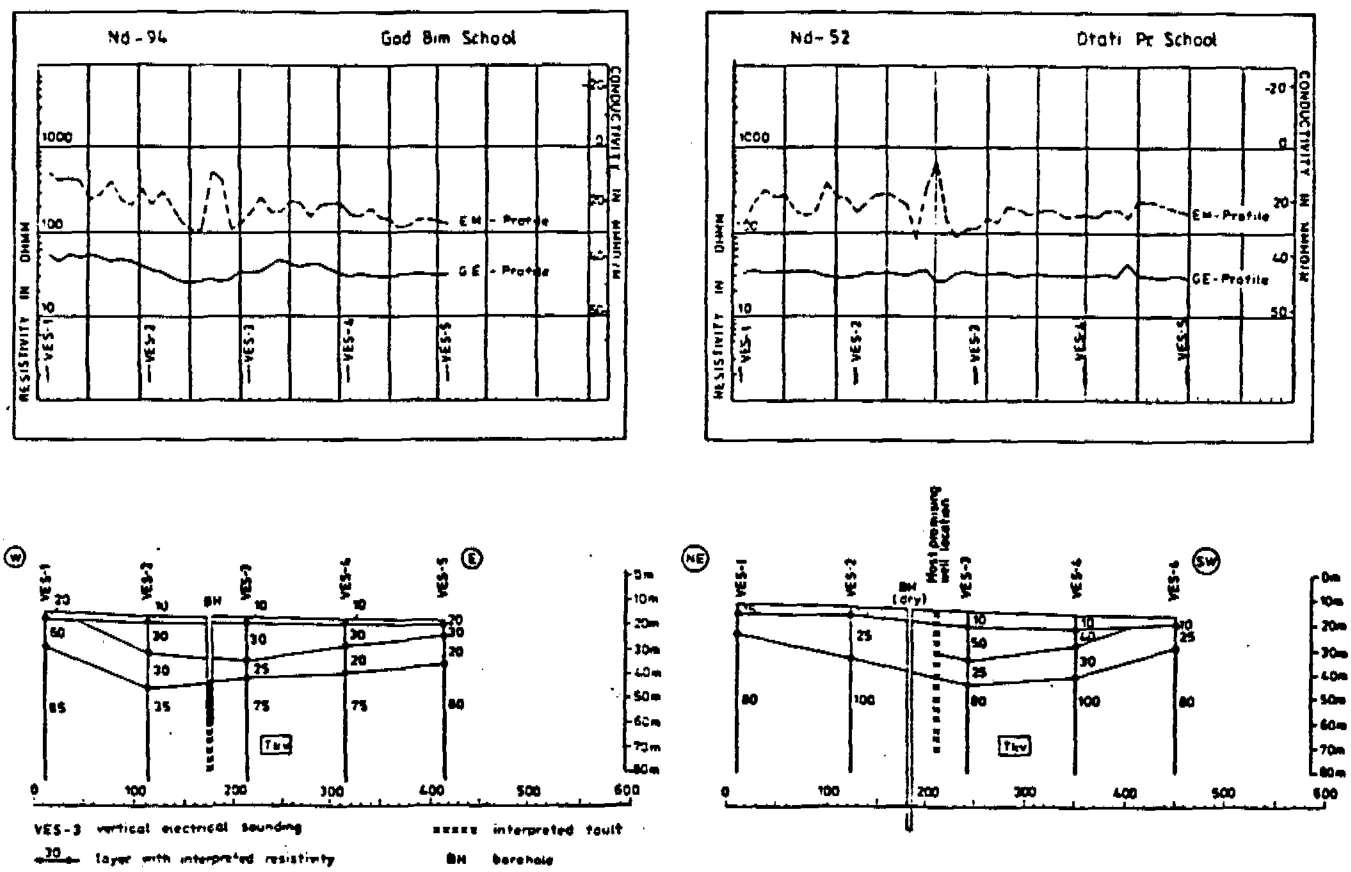


Figure 15 Hydrogeological cross sections interpreted from the geophysical data for God Bim School and Otati Primary School in Tertiary volcanics

These examples illustrate how the standard survey approach of the Rural Domestic Water Supply and Sanitation Programme has led to a significant increase in the drilling success rate (26%) and a similarly significant reduction in the depth of drilling (44%), both factors strongly reducing the cost of drilling per well (by 63%) as Table 5 shows. It should be noted that for 14 of the 18 dry holes listed in the table the geophysical survey showed no positive evidence of a fault or fracture zone, but in most of these cases the decision to go ahead with drilling in spite of this was based on socio-economic criteria.

Table 5 Comparison of results and drilling cost (US $) of existing and programme boreholes

Rock types	Number of boreholes	Success Rate (%)	Mean Depth (mbgl)	Mean Yield (m^3/d)	Drilling cost per productive well
Existing Boreholes:					
Tertiary Volcanics	36	44	126	140	17700
Nyanzian Volcanics	19	68	116	95	10600
Granites	7	43	70	48	10200
Sub Total	62	52	117	113	226700
Programme Boreholes:					
Tertiary Volcanics	60	78	68	340	5400
Nyanzian Volcanics	11	91	54	94	3700
Granites	10	60	61	140	6350
Sub Total	81	78	65	270	5200

The Programme gives a somewhat optimistic breakdown of the siting costs which is shown in Table 6. Depreciation time is relatively long and the expatriate involvement in the programme, office costs and overheads are not included. However, even when including these additional siting costs (increasing drilling cost by about 18 %) total siting and drilling costs per well remain significantly less than for the non-programme boreholes. The use of remote sensing and geophysics appears therefore to be well justified and cost-effective.

Table 6 Breakdown of cost for groundwater surveys (US $)

Description	Total Cost	Depreciation Time	Annual Cost	Cost/site (250 s/year)
Equipment (duty free):				
1 ABEM SAS 300 Terrameter	12500	60 months	2500	10
1 Geonics EM 34	22000	60	4400	18
1 computer + printer + plotter + software	17200	60	3440	14
1 4x4 car	18750	60	3750	15
6 camping sets	5000	24	2500	10
1 stereoscope + aerial & satellite photos	1500	60	320	1
Personnel (Kenyan):				
1 geologist			7500	30
1 field teamleader			3750	15
4 surveyors			7500	30
2 casual labourers			1250	5
Running Cost:				
petrol + maintenance car			7500	30
materials			2500	10
Total:	76950		46910	188

4.3 Rural Water Supply Programme, Nigeria[12]

An estimated 60% of the population of approximately 9 million in Kano State in northern Nigeria live in small rural villages dispersed throughout the State. Historically they were served by approximately 7500 hand-dug wells, many of which fell into disrepair or needed deepening. A considerable number fall dry in the dry season. In 1982 a Rural Water Supplies Programme was started by the Kano State Agricultural and Rural Development Authority (KNARDA) to provide villages with less than 2000 inhabitants with handpumped groundwater supplies. Through the widespread drilling of 1000 small diameter boreholes and the installation of handpumps in these and in rehabilitated open wells it planned to bring clean, potable water to between 0.8 and 1 million rural dwellers. Sir M. MacDonald and Partners of the UK were contracted for a period of four years to prepare and manage the overall rural water provision and to carry out the site investigations and the preparation and supervision of the drilling and pump-installation contracts.

Kano State covers an area of 43 070 square kilometers and can be divided into two distinct geological provinces, the Basement Complex consisting primarily of granites underlying three-quarters of the State and the sedimentary Chad Formation comprised of gravel, sands and clays in the northeastern quarter. Mean annual rainfall in the south is 1000mm concentrated from May to October and in the north 635mm from June to September.

Applications for well sites were provided by KNARDA and forwarded to the Consultant (Groundwater Development Consultants (Int) Ltd, UK, for Sir M. MacDonald & P.) who then paid a preliminary visit to the sites to identify, locate and assess the situation. The initial assessment was influenced by the following non-hydrogeological factors:

- the views of the Village and/or Ward Head;
- the location of existing open wells;
- potential sources of pollution; a minimum distance of 25 meters from any compound was adopted and 'salty' water areas avoided;
- the availability of suitable land (particularly relevant in the crop-growing season);
- topography - low lying areas may be subject to water-logging in the wet season while high areas result in deep water levels;
- access for drilling equipment and pump maintenance teams.

In the Chad Formation and the transition zone where shallow sediments overlie the Basement Complex a field visit was considered adequate for siting an appropriate borehole location, without the use of geophysics. Figure 16 shows the forms used to report the findings of the field visit and the drilling recommendation sent to KNARDA.

KANO STATE AGRICULTURAL AND RURAL DEVELOPMENT AUTHORITY
RURAL WATER SUPPLIES PROJECT

ZONE:

REFERENCE NUMBER:

LOCAL GOVERNMENT AREA:

DISTRICT:

VILLAGE NAME:

MAP NUMBER:

GRID REFERENCE:

AIR PHOTO NUMBER:

EXISTING SITUATION:

POPULATION:

HYDROGEOLOGICAL ASSESSI

ACCESS FOR DRILLING CONT

RECOMMENDATION:

DATE OF VISIT:

Ref. Nr: Full Name: Date:

Local Government Area:

Those Present: Who Meet With:

Access Road:

Settlement Pattern:

Geomorphology:

Background Questions:

Nr. of concrete wells:		Dead concrete?
Nr. of self dug wells:		Dead self dug?
Depth all same:	Yes/No	How many spans?
Taste all same:	Yes/No	Taste is?
Dry season yield all same:	Yes/No	Perennial/intermittent/dry?
Bottom material all same:	Yes/No	
Bottom material described as:		
Are wells on oneside of the settlement better than elsewhere?	Yes/No	Where?

Other Sources

Fetch from outside village	Yes/No	Where?
Previous investigation?	Yes/No	By whom?

Well Inspection

Chosen well is Public/Private/Concrete/Unlined/in use/almost dead/recently cleaned.

Chosen well has a dry season yield which is perennial/intermittent/dry?

SWL is m(from datum at) = m(G.L.)

Soil description:

REMARKS

OFFICE: Map Sheet Nr:
Air Photograph:
Approximate Grid Ref:
Population :

SKETCH OVER

Figure 16 Preliminary Site Investigation Report and Site Recommendation Form

The more detailed site investigation process in the Basement area involved two stages. Firstly a study of available borehole records from which a picture emerged showing that aquifers were often narrow, discontinuous and more difficult to find than originally anticipated. Secondly, interpretation of aerial photographs and remote sensing imagery provided basic information on the overall geomorphology at a scale of 1:250 000. Features at the individual village level, however, could not be distinguished. Full recent (1982) aerial photography of Kano State was available on a 1:25000 scale, and used as an aid to village location, since access tracks, official buildings and even some individual compounds were visible and an evaluation concerning the distribution and acceptable size of the local population could be made. However, stereoscopic interpretation showed little of the structural features of the Basement Complex, since it was mostly covered by regolith. In practice the interpreted fracture intersections and lineaments rarely contained features that appeared favourable when carefully examined by geophysics [in contrast to Case Study 2]. The structural analysis of the geology therefore played a very limited role in the location of borehole sites.

The third step in the investigation process involved the combined use of the electromagnetic traversing (EMT) method with vertical electrical soundings (VES) with a Geonics EM 34 and an ABEM SAS 300 Terrameter respectively. In areas with a thick weathered layer covering the Basement the resistivity soundings provided enough information to define a borehole site. This involved up to ten soundings evenly spaced over the area or specially located to examine features identified by the aerial photo interpretation. An acceptable site should have a minimum saturated thickness of 10 metres, indicated by resistivities of between 15 and 350 Ohm.m (depending on the electrical conductivity of groundwater). A typical example is shown in Figure 17 for Tanagar, predicting a suitable water-bearing layer from 6 to 30 meters below ground level. The 36m borehole drilled at the site and screened from 22 to 32 mbgl had a specific capacity of 0.53 l/s/m.

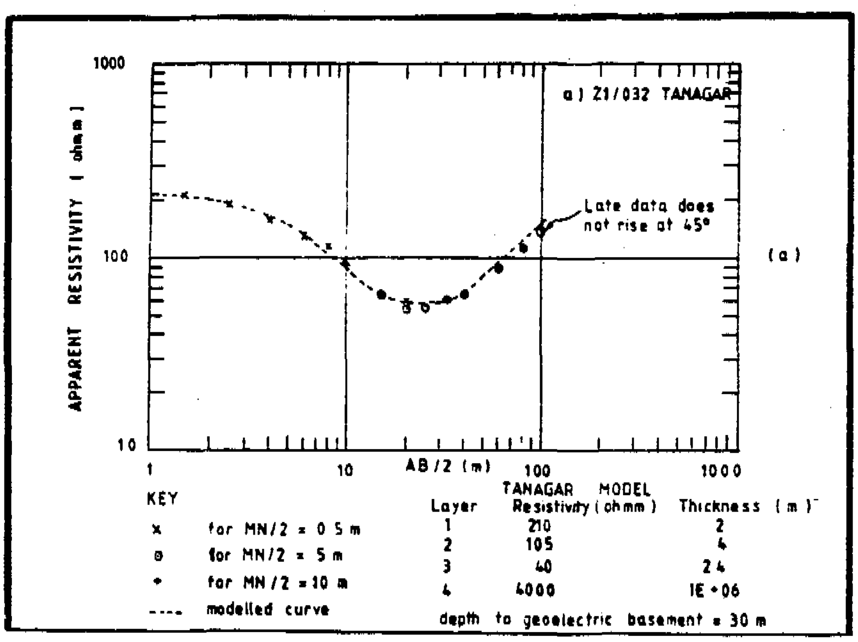


Figure 17 Example of a Resistivity sounding

In areas with thin weathered layers and many roc... rops a combined resistivity and electromagnetic approach was c... which exploited the different operating characteristics of the t... truments. With the EM 34 it is possible to either measure with ... is horizontally and coplanar on the ground (vertical dipole) or ... standing on the rim and coplanar (horizontal dipole). The verti... ole measurement has greater penetration depth than the horizontal ... nd a comparison of the two can determine which anomalies are ... d by deep-seated conductors. Thus when the conductance reading of ... vertical dipole exceeds the horizontal reading, then the ma... tribution to the apparent conductivity derives from conductors dee... an about 40% of the coil spacing.

The field procedure was as follows:

- The location and direction of the EM trav... line was selected based upon community preference, local ... ogy, groundwater quality and other information from shallow w... n the area.
- Coil spacing was selected, based on known ... to groundwater. Where the depth to static water level is ... than 15 m, a 20 m coil spacing was used, but where greater ... 15 m, the coil spacing was 40 m.
- The distance between stations was usuall... osen to be 20 m, being sufficient to detect water-bearing zon... narrow as 5 m.
- The traverses were carried out with the r... ver ahead of the transmitter, in order that the distance mete... the receiver can be used to set out the correct spacings for ... raverse.
- At every station two readings were taken. ... of the vertical dipole (horizontal coils) and one of the hori... l dipole.
- The objective of the traverse was to ... rch for adequate conductance at depth; this is normally indic... y values of the vertical dipole being greater than those of ... rizontal dipole.
- When a feature was located, its centr... int midway on a straight line between the two coils was car... located to the nearest 5 m or even 2.5 m if the feature ... ery narrow. This centre point was marked and a short orthogo... traverse was made to locate the two dimensional centre point.
- Having located the two-dimensional cen... point, a VES was carried out, either parallel to the main tra... line, or in case of marked anisotropy parallel to the structu... trike.
- The VES was extended until there were suf... data to define the rising limb on the apparent resis... curve. The resistivity sounding was carried out to che... e suitability of the feature and to predict the thickness ... ny water-bearing layer and the depth to bedrock. The latter i... important factor in cost control since drilled depths could b... dicted to within 6 metres.

This combined method is illustrated in Figure 18 f... e Masaya site.

A preliminary survey at Masaya had shown the main ... ement to be in a problem area: several dug wells had ended in ha... ck at 10 metres depth. Granite outcrops occur around the villa... d six preliminary VES had confirmed the poor prognosis. Subsequen... n EM profile of 550 metres long was made from the northern side ... e village towards the floodplain of the Dogwalo River, one kilometr... way, with a coil separation of 20 meters and a station interval ... 0m. A feature of approximately 30m long was found, centered on ... ation 48+5. The sounding carried out at that location predicted ... to bedrock with the main prebasement layer having a resistivity of 55 Ohm.m. Upon drilling a high yielding zone was found between 18 and 26 meters in weathered and pink granite with a specific capacity of 0.15 l/s/m. A sketch of the area and a summary of the geophysical results are given in the accompanying first two pages of the borehole completion record in Figure 19.

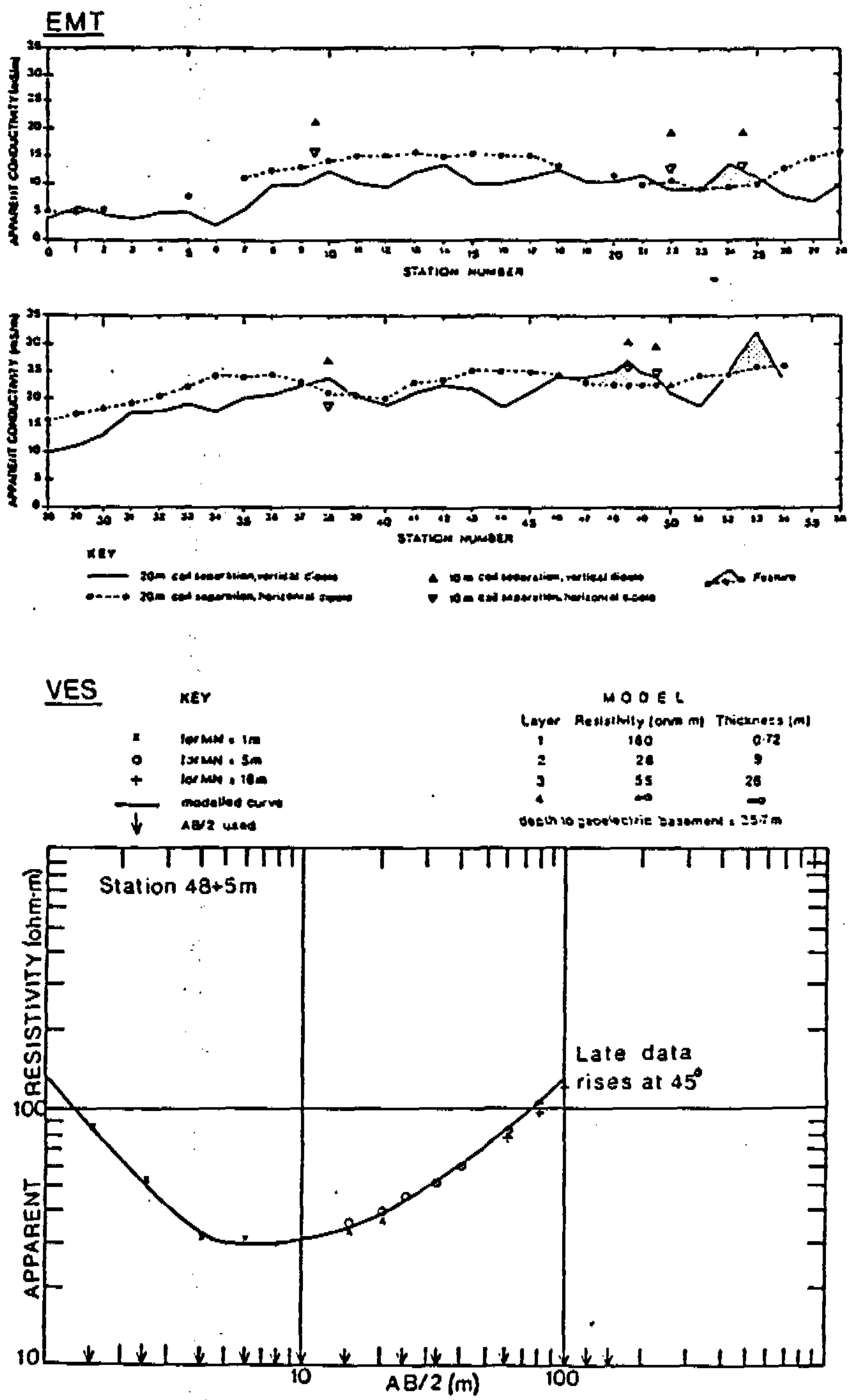
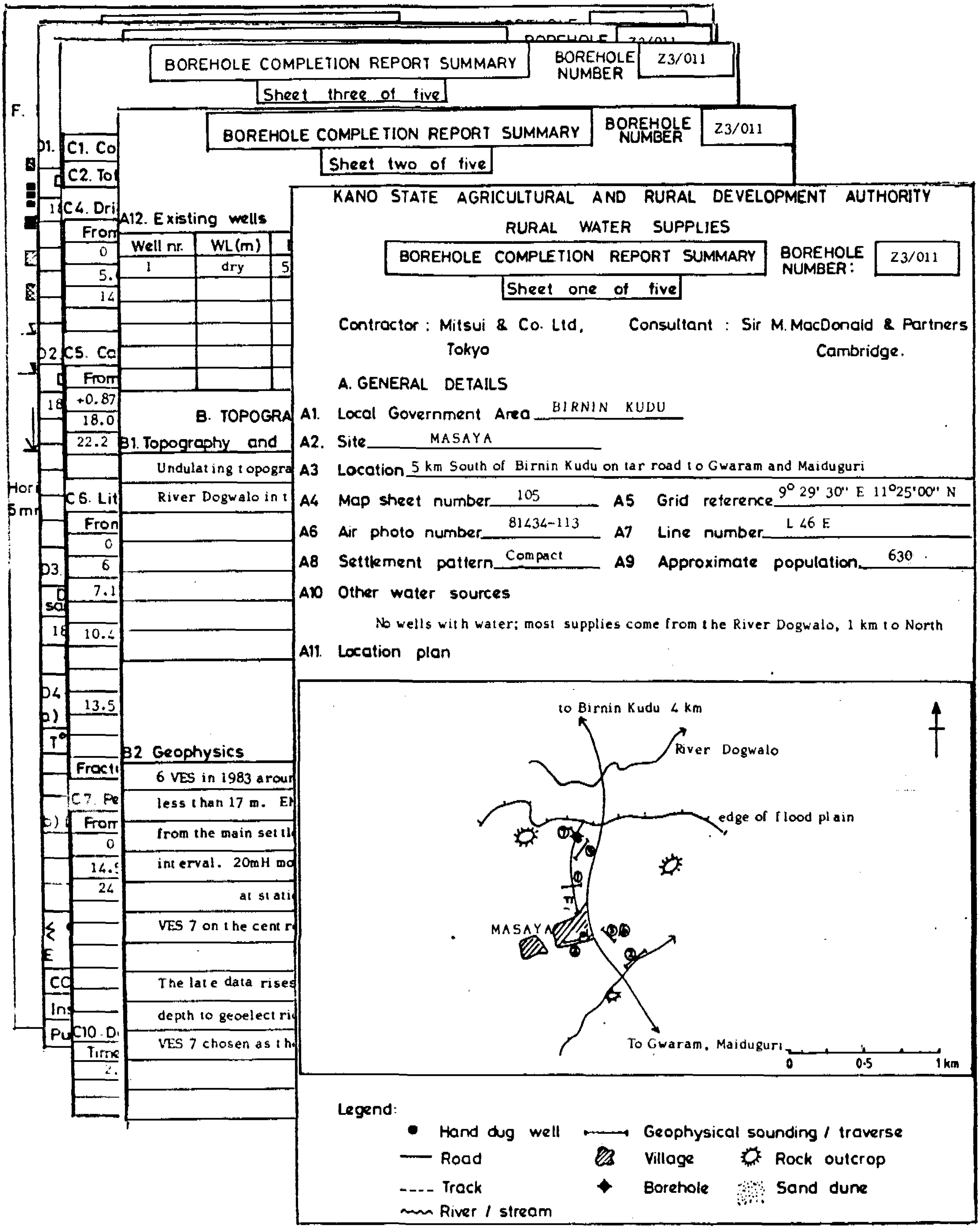


Figure 18 Example of EM/RS data for Masaya, Nigeria



KANO STATE AGRICULTURAL AND RURAL DEVELOPMENT AUTHORITY

RURAL WATER SUPPLIES

BOREHOLE COMPLETION REPORT SUMMARY | BOREHOLE NUMBER: Z3/011

Sheet one of five

Contractor : Mitsui & Co. Ltd, Tokyo

Consultant : Sir M. MacDonald & Partners Cambridge.

A. GENERAL DETAILS

A1. Local Government Area BIRNIN KUDU

A2. Site MASAYA

A3 Location 5 km South of Birnin Kudu on tar road to Gwaram and Maiduguri

A4 Map sheet number 105 A5 Grid reference 9° 29' 30" E 11°25'00" N

A6 Air photo number 81434-113 A7 Line number L 46 E

A8 Settlement pattern Compact A9 Approximate population 630

A10 Other water sources

No wells with water; most supplies come from the River Dogwalo, 1 km to North

A11. Location plan

Figure 19 Site description based on geophysical survey in Borehole Completion Report for Masaya, Nigeria

The overall success rate of this Rural Water Supplies Programme can be seen in Table 7 below.

Table 7 Drilling results for the Rural Water Supplies Programme, Kano State

Geology	Number of Boreholes	Abandoned Boreholes	Static Water Level (mbgl)	Mean Depth (mbgl)	Specific Capacity (l/s/m)	Success Rate (%)
Basement Complex:						
w/ geophysics	429	65	15.1	*	0.17	84.8
w/o geophysics	185	50	19.1	*	0.16	73.0
subtotal	614	115	16.2	42.3	0.17	81.2
Sedimentary Formation:						
w/o geophysics	506	5	21.4	48.9	0.97	99.0

* No distinction between the depth of geophysically sited and other boreholes was given in the Report

Out of 1120 boreholes 429 were geophysically investigated using the EM/RS method, while an additional 97 sites were rejected on geophysical grounds. Geophysical siting methods were only used in the Basement Complex. However, as pointed out in Box 4, the overall success rate in Basement could probably have been improved by applying geophysics for all Basement sites. The data shows that the decision not to use geophysics in the sedimentary formations was justified since the success rate is nearly 100%.

Box 4

Success Increase

The difference of nearly 12% in success rates between siting with and without geophysics in the Basement Complex suggests that geophysical siting would have been justified for all Basement boreholes. At $240 per meter of drilling and 185 boreholes of an average 42.3 meters depth the present drilling costs were $ 1 878 120.
With a success rate of 84.8% with the use of geophysics only 160 boreholes would have had to be drilled to get the same number of 135 successful wells. The savings in drilling cost would then have amounted to 185 - 160 = 25 holes x 42.3 meters x $240 = $253 800. Subtracting siting costs of $600 per site, the total savings would amount to $253 800 -(160 * $600) = $157 800, which is $1170 per successful well or a reduction of 11.5% on the original drilling cost per borehole.

4.4 Rural Water Supplies Development Project, Kenya[13]

In Western Kenya, KEFINCO, a joint venture of two Finnish engineering firms in cooperation with the Kenyan Ministry of Water Development, has been engaged since 1980 in a CWS project primarily funded by Finnish development aid. The second phase, from 1983 - 1988, aims at the construction of approximately 1650 water supply points comprising 800 protected springs, 730 hand-dug wells and 720 boreholes (the latter two equiped with handpumps).

The provision of adequate and safe water supplies in the first place involves suggestions from the local community for sites for wells and spring protection according to the local needs (approximately 200 people per water point). A basic inventory of existing water resources at the proposed site is carried out by the Community Development Team. On the basis of these findings and in consultation with the local population a decision is made whether to construct a spring protection, a hand dug well or a borehole. If springs prove inadequate or not present in the area, dug wells are considered as the next option. The community members make recommendations concerning the feasibility of digging in light of their knowledge of local groundwater levels and participate in the financing and construction of the wells. If little information is available concerning the subsurface conditions a single-channel Bison 1550 seismograph and hammer can be used to investigate a limited area (average of 50m profile) operated by the well-digging department, but usually the case is handed over to the special seismic survey team to investigate the area for the location of a machine-drilled borehole. Selection of an appropriate location for the seismic soundings is mainly based on the availability of a relatively flat piece of land near the target community. Aerial photographs are not analysed and no hydrogeological fieldwork is carried out.

The seismic refraction method, using an Abem Trio 12 channel seismograph, is used for locating deeply weathered zones and fractures in the predominantly Basement rocks as the most promising sites for boreholes in the project. Routinely each seismic profile is 200m long, involving two spreads of 100m with a geophone spacing of 10 meters, and two profiles are made at each investigation site. For one spread one or two near shots, located between geophones 1 - 2 and 11 - 12, and two far shots 100m from the near shots along the profile are used. The shock waves are generated by explosives. The fieldwork routine is carried out by a crew of about 4 to 8 unskilled (but experienced) workers supervised by several project-trained technicians. Each has an appointed task and one 200m profile can be completed within 1 - 2 hours. The photographic prints of the data (see example in Figure 20) are sent to the head office for interpretation, while the profiles are marked in the field with wooden or bamboo stakes and on a field sketch.

The 100m seismic spread gives information concerning the overburden to a maximum depth of 70 meters. Where the overburden is less than 40m thick the above described shot and geophone configuration makes it possible to calculate the rock velocities and layer thicknesses at every geophone location (this is a distinct advantage over a resistivity sounding which provides only information on one location, i.e. the array center, for each sounding). A small computer, plotter and uncomplicated software make the interpretation of the field records a simple matter. The interpretation is based on a simplified three-layer geological model comprising a low-velocity, dry weathered zone, an intermediate-velocity, saturated weathered/fractured zone and a high-velocity, fresh-rock base layer. The velocities of the seismic pulses vary according to the density of the layer and the presence or absence of groundwater. A simple graphical/mathematical analysis of the arrival times of the seismic pulses at the various geophone locations allows the layer velocities to be calculated[14]. Data acquisition and processing is fully carried out by a project-trained team, but data interpretation is done by a Finnish geophysicist in the project office.

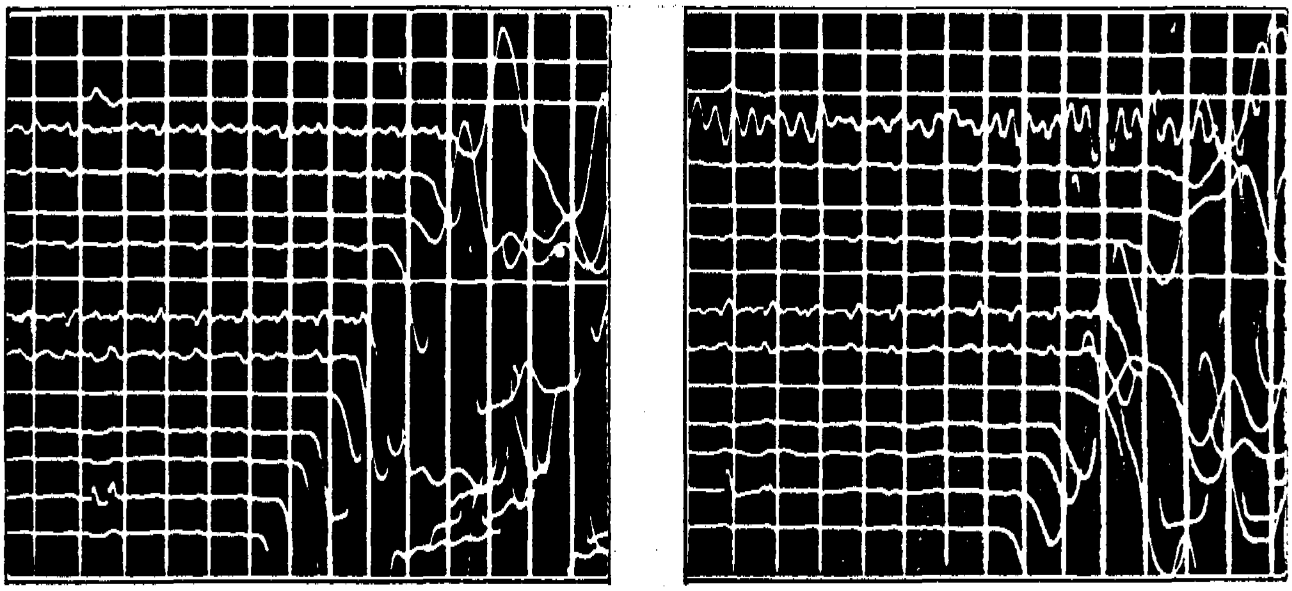


Figure 20 Two sample seismograms

Figure 21 shows the results of a 100m spread at Sega locality. Between geophones 6 - 7 and 10 - 11 reduced velocities were observed and interpreted as a fractured zones in the bedrock. Drilling in between geophones 6 and 7 resulted in a high capacity artesian well.

This case also illustrates very well the major advantage of the seismic refraction method over the resistivity method, in that a complete profile of the subsurface is obtained, showing the layering under each geophone position. With a resistivity sounding at the same location only the position of the layers near the center of the spread would be known, and it would be impossible to pinpoint the fractured zone.

Interpreting the seismic profile depicted in Figure 22 the geophysicist reported that the recording did not give any evidence of a water-bearing zone at the Kalalami Primary School. Since water was urgently needed drilling proceeded at the location on the profile where the overburden was the thickest, but resulted in a dry borehole.

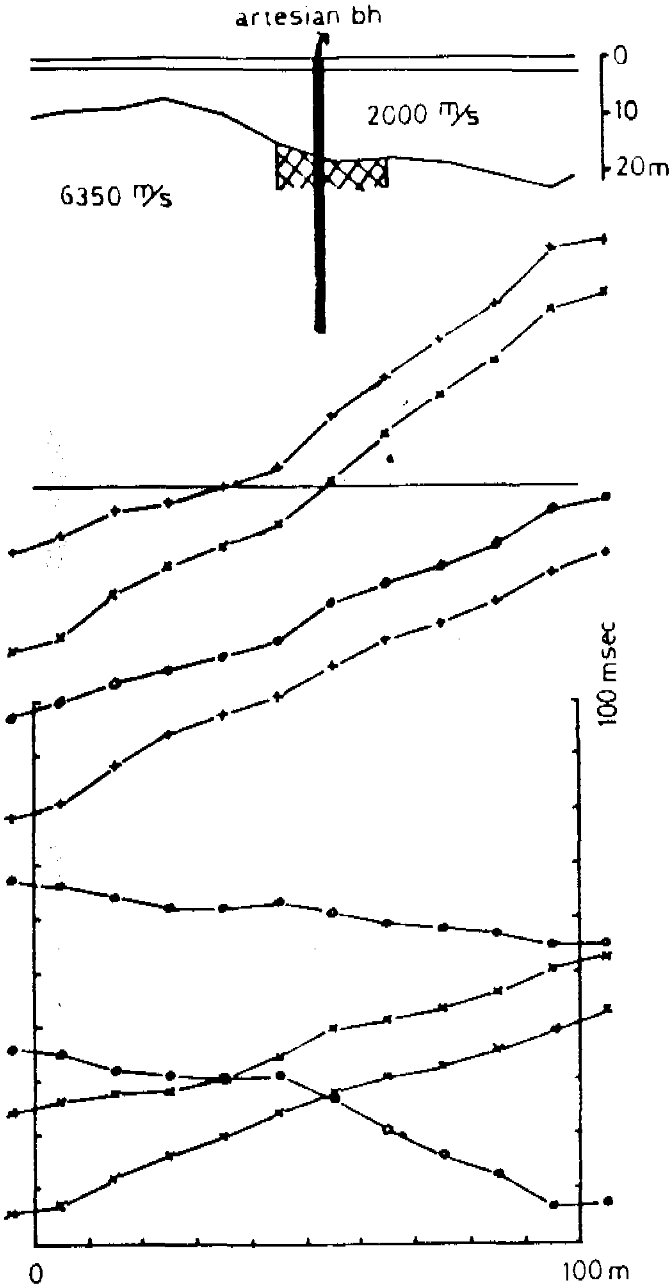


Figure 21 Seismic record for Sega Village water supply

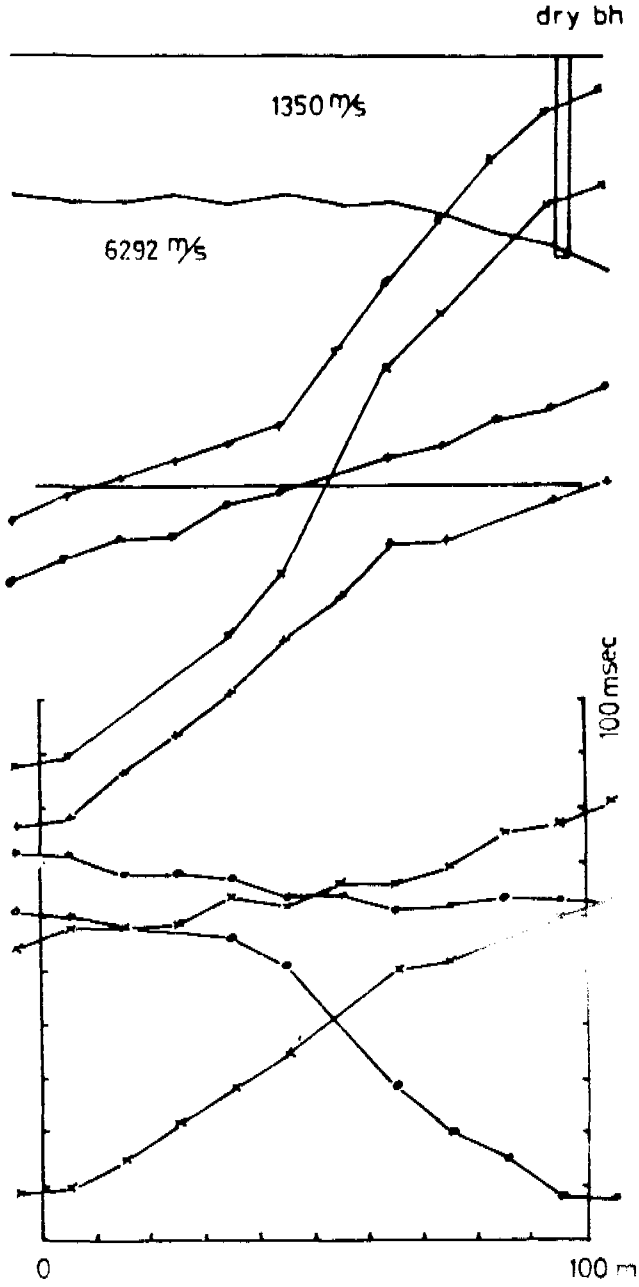


Figure 22 Seismic record at Kalalami Primary School

Table 8 gives an overview of the overall drilling results achieved by the project from 1983 - 1986 and compares the seismically selected sites with the non-seismic sites.

Table 8 Borehole characteristics sited with and without Seismic Refraction

Geology	Total no. of b/h S	Total no. of b/h N/S	No. dry b/h S	No. dry b/h N/S	Success rate (%) S	Success rate (%) N/S	Mean depth good b/h S	Mean depth good b/h N/S	Mean depth dry b/h S	Mean depth dry b/h N/S	Mean S.W.L. S	Mean S.W.L. N/S	Specific capacity (*) (l/s/m) S	Specific capacity (*) (l/s/m) N/S
Basement	207	23	25	4	88.0	81.8	51.2	43.2	59.0	71.3	10.1	8.7	.106 (89)	.150 (9)
Volcanics**	88	7	18	2	79.5	71.4	54.8	58.6	76.1	67.5	20.6	25.5	.125 (14)	.219 (1)
Sediments	79	16	4	1	94.9	93.7	51.0	53.1	63.5	100	14.0	10.0	.236 (43)	.186 (13)
Total***	374	46	47	7	87.4	84.8	51.9	49.1	65.9	74.3	13.2	13.0	.146 (146)	.173 (23)

S: With seismic investigations N/S: Without seismic investigations b/h: borehole
* (sample size) ** including dolerite dykes *** excluding boreholes abandoned for technical reasons

While the Table shows that well siting with the seismic refraction method is very successful (average 87.4% drilling success rate), it is noteworthy that without seismics drilling is on average 84.8% successful (only 2.6% less than with siting). The question arises whether under such circumstances it is really necessary to use geophysical methods at all, since the small decrease in drilling costs due to the higher success rate does not cover the costs of the investigation cost per well (see Box 5).

Box 5

Drilling versus Siting Cost

With a basic drilling cost of $40 per meter and an average well depth of 50 meters (little distinction between sited and non-sited boreholes), the drilling cost per seismically investigated well amount to:

$$C_s = \$40 \times 50m / 0.874 = \$2288$$

For a borehole drilled without a seismic survey the costs are:

$$C_{n/s} = \$40 \times 50m / 0.848 = \$2358$$

The difference is only $70, not enough to cover the approximately $400 cost of seismic investigations per site (which includes transport, equipment write-off, explosives, local and expatriate salaries and overheads). In 1987 seismic surveys were used for all new borehole sites with a success rate of 90.1 percent. The increase of 5.3 % over non-seismic sites is however still inadequate for a cost-effective justification of geophysics:

$$C_s = \$40 \times 50m / 0.901 = \$2220$$

This means that boreholes drilled on the basis of a seismic survey are more expensive than boreholes without.

It could be argued that the nearness in success rates with and without seismic survey is an indication of the correct distinction between the need for just a hydrogeological survey and an additional seismic survey. However, the absence of a detailed hydrogeological study and the relatively random (i.e. logistical) approach to the location of the seismic surveys suggests that the comparative advantage provided by seismics is in this case only marginal. The decision to use geophysics was primarily based on the results of a pilot study carried out at the start of the official project which showed a much better comparative advantage of seismic surveys[15]. Given the fact that the region receives a substantial amount of rainfall (for most of the project area more than 1500mm per year), a 1000mm maximum annual rainfall limit could probably be applied as a rule-of-thumb below which the application of geophysical investigation techniques would be useful.

While it is clear that under these particular circumstances the need for the application of seismic investigation techniques is doubtful, this case illustrates very well the simplicity, good resolution and speed of fieldwork.

Notes

1. D R C Grey et al., 1985. 'The expanding role of the hydrogeologist in the provision of village water supplies: an African perspective.' *Quarterly Journal of Engineering Geology*, 18, 13-24.

2. S S D Foster, 1984. 'African Groundwater Development - The Challenges for Hydrogeological Science.' In: Walling et al. eds., 1984, 3-12 (see Appendix 4).

3. C van Wijk and J T Visscher, May 1987. 'Handpump Projects: Avoiding Neglect.' World Water, 10, 4, 44-46.

4. EROS Data Center, User Services: Sioux Falls, SD 57198 USA
   European Space Agency, Earthnet User Services: Via Galileo Galilei, 000 44 Frascati ITALY
   Regional Centre for Services in Surveying, Mapping & Remote Sensing, Box 18118, Nairobi, KENYA
   Spot Image: 16 bis, Avenue Edouard-Benin, B.P. 4359, 31030 Toulouse cedex, FRANCE

5. R D Barker, 1981. 'The Offset System of Electrical Resistivity Sounding and its Use with a Multicore Cable.' Geophysical Prospecting, 29, 128-143.
   ibid, 1985. 'Offset Spacing Aids Resistivity Work.' World Water, 8, 9, 47-48.

6. T Williamson, 19 March 1987. 'A Sense of Direction for Dowsers?'. New Scientist.

7. J L Farr, P R Spray and S S D Foster, 1982. 'Groundwater Supply Exploration in Semi-Arid Regions for Livestock Extension - A Technical and Economic Appraisal.' Water Supply and Management, 6, 343-353.

8. Total success rate increase can be expressed as a function of R_x and a possible reduction in drilling depth as:

$$dR = \frac{D/R - D'/R'}{D/R} * 100 \qquad (\%)$$

9. Based on: Accelerated Drought Relief Programme Victoria Province. Government of the Republic of Zimbabwe. European Economic Community. Hydrotechnica (UK) and B Colquhoun, H O'Donnell and Partners (Zimbabwe). 1985.
   'Improved borehole siting using integrated geophysical techniques' by CC White. Water Services, June 1986.

10. 'Sondage' for Offset Wenner system, Hydrotechnica UK

11. Based on: The Use of Remote Sensing and Geophysics for Groundwater Exploration in Nyanza Province - Kenya. RV van Lissa, HRJ van Maanen and FW Odera. Lake Basin Development Authority, Kenya. DHV Consulting Engineers, the Netherlands. 1987.

12. Based on: Rural Water Supplies, Final Report. Federal Republic of Nigeria, Kano State Agricultural and Rural Development Authority. Sir M MacDonald & Partners Ltd. 1986.
   and: The Combined EMT/VES Geophysical Method for Siting Boreholes - 1988, by S. Beeson and C.R.C. Jones. GROUND WATER, Vol. 26, No.1, p.54-63.

13. Based on: Rural Water Supply Development Project in Western Province of Kenya: First Implementation Phase, Final Report. Kefinco, 1985. Ministry of Water Development, Kenya. Ministry of Foreign Affairs, Finland.
Boreholes Drilled in 1986. Ibid.
Finnida, 1987. Kenya: Finland - Rural Water Supply Development Project in Western Province. Report of the Review Mission. Ministry of Water Development; Finnida; UNDP/World Bank.

14. R A van Overmeeren, 1987. 'The Plus-Minus Method for Rapid Field Processing by Portable Computer of Seismic Refraction Data in Multi-Layer Groundwater Studies.' First Break, 5, 3, 83-94.
B R Redpath, 1973. Seismic Refraction Exploration for Engineering Site Investigations. Springfield, VA: National Technical Information Service, US Department of Commerce.

15. During the investigation and planning phase of the project (1982-1983) a comparison of 49 boreholes drilled without seismic surveys and 64 boreholes with seismic investigations showed drilling success rates of respectively 69.1 and 96.7 percent, a difference of 27.6 percent. On the basis of these figures and the above-mentioned cost-parameters the use of geophysical investigation techniques would be justified: C_s = $2068 and $C_{n/s}$ = $2894, a savings in basic drilling cost of $826 which would easily cover the seismic investigation cost (Ovaskainen E, n.d. Case Study of the Use of Refraction Seismic Surveys for the Siting of Boreholes for Handpumped Supplies in Western Province, Kenya).

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Appendices

Appendix 1: Aquifer Types and Properties

1.1 Unconsolidated Sediments

Origin and Composition

Unconsolidated sediments can be roughly divided into three groups according to the method of transportion prior to deposition: Alluvium, transported by water; colluvium, transported by gravity; and eolian deposits, transported by wind. The force of moving water erodes the bed and sides of the gully through which water flows, especially where water velocities are high, and moves the erosional debris downstream. When the transport capacity of the river is superseded, excess material is deposited by the river; the heaviest material, i.e. sand and gravel is deposited first within the channel; the lightest i.e., clay and silt, further downstream on the flood plains. The greatest erosion and transportation of sediments takes place under flood conditions. High water velocities and great water volumes result in an increase in both the size and volume of materials that can be transported. When a steep river valley suddenly widens, as at the foot of a mountain range, the speed of the water suddenly decreases and much of the sediment load is deposited in a typical cone or fan shape, called alluvial fans: these are usually excellent aquifers. Floodplains are also common alluvial landforms which occur in the lower (downstream) reaches of rivers and larger streams. Deposition of sediments occurs on the inside of the bends as sand-bars: erosion occurs on the outside of bends. Abandoned meanders (oxbow lakes) slowly silt up with very fine grained material. The coarse materials of the stream beds and sand bars are most favourable as aquifers, with high natural porosities. Former stream channels often form elaborate systems below the surface of a present floodplain, and can yield substantial amounts of potable water. Colluvium is the name given to erosional material, such as rockfalls, landslides and other debris from mountain and hill slopes, mainly transported to the place of deposition by gravity. Water, but also temperature, gravity, vegetation, tectonic and chemical factors break down the original parent material into loose particles which subsequently roll down and accumulate as scree or talus slopes at the foot of hills, mountains or escarpments. The mineralogical composition of colluvium depends on the parent rock material. Dunes are common wind-borne (eolian) deposits which accumulate along seashores and in deserts, and are mainly composed of quartz sands of coarse texture and good permeability.

Hydraulic Properties

The porosity of alluvium is usually very high, ranging commonly from 25 to 65 % and depends on the type, sorting, and packing of the constituent materials. Non-clayey river deposits are usually well rounded, with high porosities and good permeability. Where such deposits are mixed with clay the porosity and permeability is sharply reduced. The specific yield of unconsolidated sediments is generally higher than that of other material. Colluvium usually has high porosity and is very permeable, resulting in high potential infiltration rates. Given the relatively large size of the particles compared with alluvium, little water is retained as soil moisture and most percolates to the groundwater. Wind-borne sand particles are well sorted with porosities between 35 and 40 %. Permeability is also good, provided that little cementation has taken place.

Recharge

Recharge to alluvial deposits is often substantial due to the permanent or intermittent flow of nearby streams or rivers, where significant amounts of water percolate into the river banks and bed.

The groundwater flow also tends to follow the topography and accumulate in alluvial sediments in valleys. Direct recharge to buried river channels may be less significant due to overlying clays and silts. Deposits at the foot of hills and mountains often benefit from steep catchment areas from which most water runs off and infiltrates into the colluvium at the foot of the slope. The yield of such aquifers can be substantial, in particular if underlain by an impermeable base, and springs may occur on the down-slope side of the colluvial deposits. The availability of fresh groundwater in eolian deposits will depend on the amount of rainfall the area receives (minimal in desert regions), the depth to the groundwater table, and evaporation. Coastal streams may also be a source of recharge to fresh groundwater bodies below the dunes. Significant groundwater bodies in arid regions may be due to infiltration under previous, more humid climatic conditions.

Water Quality

The poor biological quality of river water is often a major reason for seeking alternative water sources from groundwater. Where the distance from a river to a well constructed in the river bank is small and the permeability good, groundwater quality will be similar to that of the river. However, sand has a good filtration capacity, so locating a well at some distance from the river channel can effect natural filtration of the groundwater. Biological contamination from human and animal sources is a significant danger in most unconsolidated environments, since the groundwater table is often near to the surface. With a shallow groundwater table and little recharge, evaporation may cause significant salinization of the groundwater. Groundwater abstraction from coastal dunes presents a particular challenge in maintaining adequate quality, since the fresh water floats on saline seawater. Well construction and abstraction rates need to be carefully regulated to avoid upconing of saline water with the subsequent deterioration of water quality.

Groundwater Investigation

Unconsolidated sediments can generally be identified relatively easily on aerial photos and in the field. Due to their low topographic position aquifers are often near to the surface in soft material, where test drilling is easily and cheaply carried out by hand. In arid areas lines of denser vegetation are indicative of near-surface groundwater in dry riverbeds. When hand-drilling equipment is available, geophysics are generally not necessary. However, in complicated floodplain areas or with alluvial fans geophysical profiling methods help establish the extent of the alluvial deposits and the location of buried river channels. Seismic and resistivity techniques are useful (but more burdensome in their application) where quantitative information is sought concerning the thickness of unconsolidated sediments and the topography of underlying formations.

1.2 Consolidated Sediments

Origin and Composition

Consolidated sedimentary rocks are formed from material eroded from pre-existing rocks, transported and deposited elsewhere, which over time and with the pressure of overlying layers have been hardened into consolidated rocks. Sandstones and limestones are important as aquifers. Sandstone, as the name indicates, is a consolidated product of sedimented sands. The sediments were laid down in beds which vary in thickness from a few centimeters to many meters. Extended sandstone beds are most commonly of marine origin. The original layering is often disturbed by tectonic activity, folding and fracturing it. Limestone and Dolomite have a high calcium and magnesium carbonate content and are mostly formed by chemical or biochemical processes in a warm fresh water or marine environment.

Hydraulic Properties

The porosity of the various types of sandstone ranges from a high 30 % to a low 1 % . This is a function of sorting, grain shape, packing, and the degree of cementation. The last factor is the most important, as it not only cements the individual particles together but also reduces the porosity by filling the pores. Cementation may be caused by clay minerals present in the original deposits. Silica or carbonate cement may be present in the connate porewater, or be introduced as precipitates by circulating groundwater originating from elsewhere. Secondary porosity, i.e. fissures and solution cavities, account for sometimes excellent aquifer characteristics if significantly developed by tectonic activity or weathering. The main feature which makes groundwater abstraction from limestone attractive is the development of secondary porosity through fissuring (mostly along bedding planes) and dissolution (karstification). When groundwater, which is undersaturated with $CaCO_3$, comes in contact with limestone, it will dissolve the rock until equilibrium is reached. The more groundwater flowing through joints and bedding planes, the stronger the dissolving action. This can eventually result in large caverns and underground channels in the limestone, suitable for high capacity groundwater abstraction. In humid tropical regions, limestones may weather very rapidly because of the increased acidity derived from the rapid decay of overlying vegetation.

Recharge

Recharge by fresh water is essential to replace the connate saline water of marine sediments. Where adequate rainfall and percolation occurs (or has occurred in the past), a significant body of fresh water may be found floating on the fossil saline water in a similar manner to that described for fresh-water lenses in dunes. Recharge to a limestone aquifer depends on the infiltration capacity of the surface soils. However, in the case of karst terrain, surface depressions (sinkholes) may concentrate recharge along joints and fractures. The flow of such water will be strongly controlled by the joints and fracture systems, with little recharge to primary pores.

Water Quality

The chemical quality of groundwater in sedimentary rocks can vary from highly concentrated brines to fresh water with less than 100 ppm of total dissolved solids (TDS). Solution of limestone results in 'hardness' of water, but acceptable levels are relatively high (WHO: 500 ppm). A more severe problem can occur where limestone is exposed at the surface with a highly developed network of joints and fractures: recharge will be rapid and surface pollution can be a major hazard which spreads rapidly and is difficult to control.

Groundwater Investigation

Typically, sedimentary rocks are layered as a result of the deposition process. This layering (stratification or bedding) is often recognizable on aerial photographs and on the ground, as successive layers with different characteristics. Sandstone, usually hard and resisting erosion, will form ridges in the terrain, while interbedded shale is softer and erodes more easily. Jointing perpendicular to the bedding planes when well developed may also be visible. The absence of drainage channels is a common feature and indicates high rainwater infiltration. Identification of a sandstone layer through geophysical methods is possible when it is thick enough. Strong jointing can be identified with EM or seismic equipment, while the presence of water and the presence of and distinction between fresh and saline water can usually be identified with resistivity soundings. Small confining layers of shale at considerable depth, however, are often undistinguishable with all methods except test drilling. With strong jointing and tectonic activity, such beds can become permeable. When not saturated with saline water, sandstone is highly suited to groundwater development. Easy to recognize in the field and on aerial photographs is a karstified limestone terrain with its many roughly circular sinkholes. Drainage will mostly be through sinkholes with few surface streams present. Non-karstified limestone and dolomite are more difficult to identify and geological fieldwork will be necessary. Geophysical recognition will be based on contrasting characteristics with other formations. The resistivity method will be the most useful in distinguishing the depth and extent of such contrasting formations. EM and VLF profiling methods are of limited use, except when fracture zones or major water-bearing cavities are present.

1.3 Volcanics

Origin and Composition

Volcanic rocks are associated with a number of geological phenomena. Most obvious is the association with volcanoes. Lava flows and ash layers can cover large areas, depending on magma composition and nature of the eruption, often in a typically radial manner. A second type, perhaps not as easily recognizable, evolves from the extrusion of magma along fissures, often resulting in very thick plateau basalts, so-called because of their relatively flat appearance and their composition, being fine-grained (sometimes glassy) igneous, basic rock. A third type somewhat similar to the plateau basalt consists of dykes and sills. These are bodies of magma which penetrate fissures and bedding planes (the first primarily vertical, the second more horizontal), but do not flow out at the surface. Crystallization results in medium-grained dolerite; therefore dykes and sills are not classified as volcanic, but as intrusive rocks.

Hydraulic Properties

Volcanic rocks have a wide range of hydraulic properties depending on the method of formation, composition and to some degree, age. The porosity of unfractured volcanic rock can vary from less than 1 % in dense basalt to more than 85 % in pumice (rock with large, but not interconnected openings due to trapped volcanic gasses). Dykes and sills usually have less than 5 % porosity. However, although porosities may be relatively high the permeability, which is most important to groundwater flow, is mainly a function of secondary structures. Most important of these are joints which have developed due to cooling and subsequent shrinkage of the lava, lava tubes (which passed, but did not fill up with lava), fractures caused by movement in partly-solidified lava flows and voids left in between successive lava flows. Weathering may also increase porosity and permeability. Of specific importance are buried soils (also known as 'old land surfaces') where significant weathering occurred between successive lava flows. Often these buried soils become routes for preferential groundwater flow, but it is also possible that through the formation of clay layers the overlying volcanic rock is the more permeable of the two and perched groundwater flow occurs above such buried soils. In thick tectonized volcanic sequences, significant faulting can cause high vertical permeability, which can lead to very deep groundwater levels often beyond the reach of handpumps. However, in most cases horizontal permeability is significantly larger than vertical permeability and a series of confined aquifers is formed. Thus, even when the water struck level is far below the reach of handpump abstraction, high pressure heads can reduce the depth to static water level by more than 50 % . In many volcanic environments this has resulted in artesian wells (free-flowing water at ground level). Decomposed volcanic ash layers are likely to form confining layers as their permeability is limited and dykes and sills often act as groundwater barriers. The solidified magma (dolerite) itself is often very dense and impermeable, but in the process of intruding can alter the surrounding rock, making it more liable to fracturing and deep weathering in the contact zone, and thus forming a potential aquifer.

Recharge

The amount of recharge in volcanic areas depends primarily on the climatic regime. The size of the surplus in rainfall over the soil water deficit can roughly indicate the likelihood of significant recharge. Topographic features may also contribute to recharge as high volcanoes are likely to attract more rain than the plains and up-slope infiltration into the various lava flows can support a significant amount of groundwater flow down-dip. Flat features such as plateau basalts and dyke outcrops in arid plains will have much less recharge and depend mostly on the infiltration of local rainfall along fractures and faults, unless significant surface water is present which can percolate down to the groundwater table.

Water Quality

In high rainfall areas water from volcanic rocks is usually of good chemical quality. Near hot springs and in the more arid regions, where there is less fresh water recharge, groundwater tends to be more mineralized due to its age and the dissolution of volcanic rock. High fluoride concentrations are quite often a particular problem. Shallow groundwater levels and high evaporation rates or sea water penetration in coastal environments may lead to salt water contamination. Where the volcanic rock is very permeable biological pollution is possible in areas of dense population and animal concentrations. However, groundwater in the volcanics is found usually quite deep and thick overlying layers of tuff (volcanic ash) and soil will prove to be an adequate barrier to such contamination of deeper aquifers.

Groundwater Investigation

The most important element in well siting in volcanic areas is to be able to reconstruct the geomorphological history of the area as an aid to determining the approximate thicknesses, composition and ages of the various lava flows, the position of the paleo-topography (ancient valleys, lakes, drainage patterns, etc.) and buried soils. As volcanic features are usually relatively large, many of them will have been previously studied from a geological point of view and collecting existing maps and reports may provide a substantial amount of the needed information, requiring only field correlation at the project site. Satellite imagery, but especially aerial photography of a suitable large scale (e.g. 1:12500) will provide a good overview of the often complex volcanic sequences. Geophysical investigation techniques are of limited use in areas of many successive lava flows. The resolution of an aquifer zone between individual lava flows is often insignificant and, for resistivity measurements depends largely on the depth, thickness and contrast of interbedded buried soils. If the latter are too thin they may not show up on the measurement, even though it might function as an adequate aquifer. Seismic refraction measurements will also have great difficulty in picking up such 'hidden layers', due to a reverse in the energy velocity sequence. Profiling methods, such as EM and VLF, can be very useful to locate lateral anomalies such as dykes or fracture zones, but are almost useless with a complex of lava flows.

1.4 Basement Complex

Origin and Composition

Basement Shield or Basement Complex is the name given to areas where hard rock (basically igneous and metamorphic) of Precambrian age is exposed at the surface or covered with a very thin layer of sediments. 'In situ' weathering at the surface means that the Basement is usually covered by a layer of unconsolidated material, the regolith, and broken rock. In terms of water-bearing layers, aquifers in a basement area can be divided into two components which may be present together or independently of each other, the weathered layer and the fissured and jointed zone in the fresh rock. Faulting due to tectonic activity may result in a third aquifer type in which groundwater flow is primarily restricted to the deep and narrow fracture zones in the fresh rock associated with such faulting.

Hydraulic Properties

The regolith consists of fine-grained and clayey material characterized by high porosity and low permeability. The highest groundwater potential in the weathered layer will be where the depth to bedrock is greatest and the deepest penetration of the regolith can be achieved. The joints and fractures which form the onset of the weathering process in the fresh rock may give rise to zones of high permeability, but usually with limited storage. However, for handpump abstraction, tiny fissures are often enough to provide a constant supply of water. Especially when such a fractured bedrock layer is overlain by saturated regolith, adequate storage will be provided for larger abstractions. Faults are usually narrow, elongated and form deep fracture zones in the fresh rock, which are characterized by high permeabilities and more substantial storage. Shallow subsurface depressions in the bedrock may suffer from high evaporation rates through capillary action, leaving little and poor quality groundwater for abstraction. Clay layers in the weathered zone may lead to (semi-)confined conditions in which the water level is raised above the initial water struck level. If the water table is relatively shallow (<25m bgl), wide diameter hand-dug wells may be a good option for low permeability regolith, especially where machine drilling is expensive and the yield of hand drilling, due to the small diameter, too low[16].

Recharge

Recharge of the regolith will be limited by the soil moisture deficit, which will bind most of the infiltrating water to the top soil layers. Direct infiltration through the larger pores and secondary openings and where the fracture zone is connected to surface outcrops, will provide more significant recharge. As the subsurface bedrock topography does not necessarily follow the surface topography, rainfall catchment areas should not be assumed indicative of local recharge.

Water Quality

The quality of groundwater depends basically on two factors: the speed of recharge and the nearness to the ground surface. When recharge is little and water stays in the ground for a long time, mineral dissolution of the surrounding rock particles can significantly alter the chemical composition of groundwater. Iron may achieve undesirably high concentrations in many basement areas. Excessive levels of fluoride, sulphate and metals are primarily a function of the parent rock chemistry. Another source of quality deterioration may stem from high evaporation rates of near-surface groundwater. Evaporites form at and near the surface which during rainfall will be dissolved and infiltrated in the lower groundwater, causing increased salinity. This should be expected especially in the more arid regions. Pollution caused by people and animal waste is also a distinct possibility where wells are located near population centres and animal watering places, especially where groundwater levels are shallow.

Groundwater Investigation

Surface information does usually not account for the variability of subsurface conditions in basement areas. The major exception is in the case of faulting, where lineations may be visible on satellite imagery, aerial photography and in the field. Depending on the hardness of the regolith, hand drilling will probably be the cheapest and most comprehensive method of identifying aquifers of the first type, situated in the deepest sections of the weathered material. But it will not be possible to penetrate the more compact fractured zone. Pumping tests carried out in the hand drilled holes can then be used to calculate maximum yield.

Geophysical investigation methods have proven to be very effective in discerning the two features of most interest to the location of adequate quantities of groundwater: deep valleys in the subsurface bedrock and deep (sub-)vertical faultlines and associated fracture zones. The horizontal fracture zone on the boundary between regolith and fresh rock is, because of its relative thinness, less easily detected. Qualitative profiling methods such as EM, VLF, and (though more cumbersome) Resistivity are very useful in pin-pointing lateral changes in the subsurface which are caused by undulating bedrock and faultlines. However, they are less useful in determining, for example, the depth of such anomalies. For such quantitative data seismic refraction or resistivity soundings have to be used. These last two methods take more time than the profiling methods, but give a better indication of whether water is present and at what depth it may be encountered.

2.1 Electrical Resistivity Soundings

When carrying out a resistivity sounding, also called vertical electrical sounding (VES), an electrical current (I) is passed into the ground through two metal stakes, the current electrodes. Subsurface variations in electrical conductivity determine the pattern of current flow in the ground and thus the distribution of electrical potential. A measure of this is obtained in terms of the voltage drop (dV) between a second pair of metal stakes, the potential electrodes. The ratio (dV/I) provides a direct measurement of the ground resistance and from this, and the electrode spacing, the apparent resistivity of the ground can be calculated (see Figure 23).

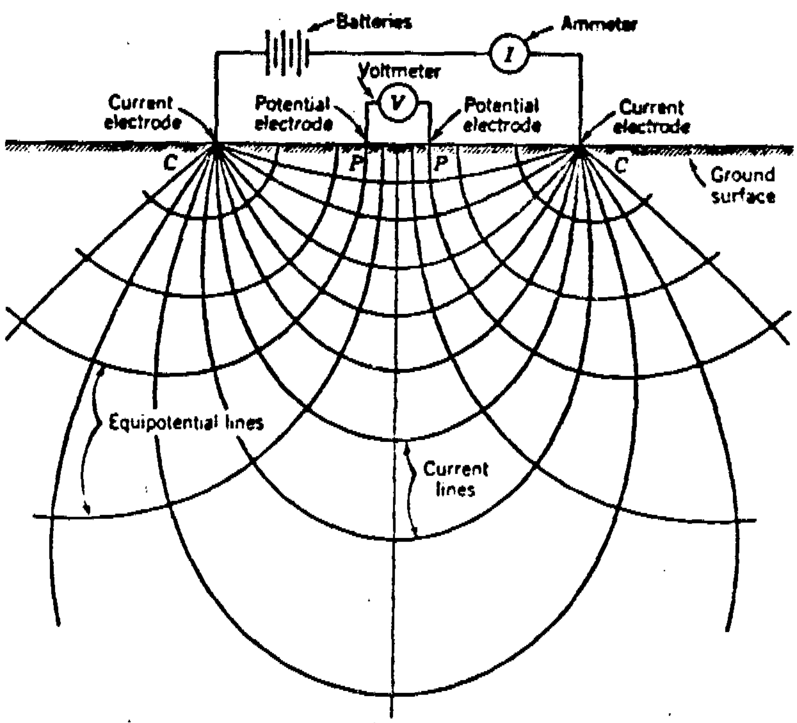

Figure 23 Schematic diagram of a Resistivity Sounding

A series of measurements made with an expanding array of current electrodes provides information on the vertical variation in resistivity. The measured apparent resistivity curves versus current electrode half-separation yields a layered earth model composed of individual layers of specific thickness and resistivity. Interpretation of the sounding graph is based upon the convolution method of Ghosh, a mathematical curve-fitting procedure. Without additional data for correlation it can easily lead to a fitting solution that does not quite correspond to reality. The layered earth model is actually very much a simplification of the many different layers which may be present. The various equivalent solutions which can be generated by the computer should therefore be carefully analyzed.

2.2 Seismic Refraction

The Seismic Refraction method consists of measuring (at known points along the surface of the ground) the travel times of compressional waves generated by an impulsive energy source. The energy source is usually a small explosive charge, or a weight dropping device. The energy pulse is detected, amplified and recorded by special equipment. The signals are picked up by detectors at the ground surface, called geophones. From the detectors the signals are transmitted along multi-conductor cables to a recording instrument, or seismograph. The instant of explosion or "zero-time" is recorded on the same record which contains the other arriving pulses. The raw data therefore consists of travel times and distances and this time-distance information is then manipulated to convert it into the format of velocity variations with depth.

Seismic Refraction is one of the methods suited to low-cost groundwater investigation projects at medium to large scale, since the method is rapid and provides a comprehensive amount of information of the project area at a reasonable cost. One or more sites can be investigated per day, providing reliable information on the types of underlying rock and their depth below the surface, as well as on the likely occurrence of groundwater.

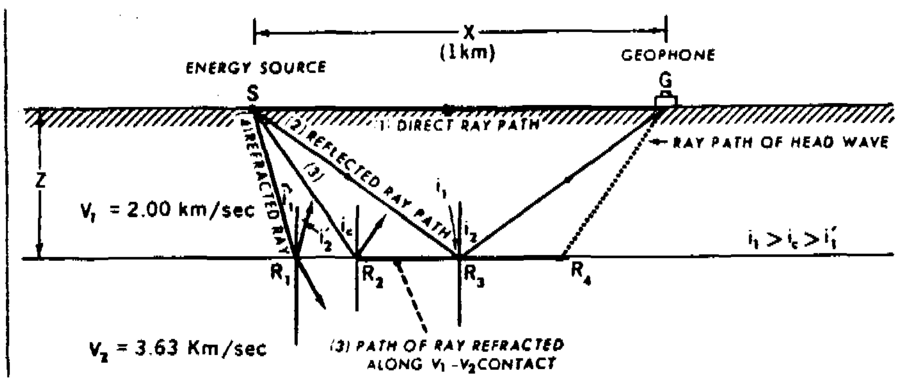

Figure 24 Schematic diagram of Seismic Refraction Method
Traveltimes for the various paths are: t_1 = 0.500 sec; t_2 = 0.630 sec; t_3 = 0.588 sec. (Zohdy, 1974)

The refraction method makes use of compressional waves travelling along the ground surface and the ones returning to ground surface after being refracted by underlying more compact layers with the higher velocities. Close to the point where the energy is released the ground surface waves are the first to arrive at the geophones. At a certain distance depending on the depth to the first refractor, waves following longer but faster paths in the subsurface layers overtake the surface waves. The time it takes for the refracted waves to travel from the impact point to the geophones, where they are recorded as first arrivals, is a function of the layer velocities and depths below surface.

By positioning the geophones in line with various shot points a continuous profile may be obtained over a large area. A second measurement line perpendicular to the first can give a three-dimensional subsurface picture of the site. It is important that the site be relatively flat.

A small programmable calculator or portable computer can be carried in the field to obtain fast interpretations. As with the resistivity method, the measurement locations should be determined by a hydrogeologist, while careful data evaluation should be carried out by a geophysicist-cum-hydrogeologist.

2.3 Electromagnetic method (EM)

Electromagnetic techniques measure the apparent conductivity of the sub-surface. A magnetic field is produced by passing an alternating current through a transmitter coil on the ground surface. This primary field generates an electric current in the ground, the strength of which depends on the conductivity of the sub-surface. The strength of the induced secondary field is measured by a receiver coil at a fixed distance. Since no direct contact with the ground surface is necessary, measurements can be made rapidly and are not hampered by bad contacts in dry surface layers. It is often utilised as an initial reconnaissance tool, giving a quick impression of subsurface conductivities. It can also be used to accurately locate specific anomalies, such as faulted zones, dykes or buried channels.

Electromagnetic measurements are usually carried out along profile lines, thus obtaining a cross-section through a certain area. Depth of penetration below ground surface depends on the frequency of the transmitted current, surface layer conductivity, coil position and the separation between the coils. With most equipment used penetration is commonly in the order of 10 to 60 meters.

A qualitative interpretation of the measurements is obtained by mapping the positions of the recorded anomalies on the survey lines, and the observed values of the conductivity of such features. Some knowledge of the local hydrogeology is necessary to identify the nature of the anomalies. Simple interpretations for two or three-layered models can calculated by hand or with computer software, but the reliability of such models depends largely upon available correlation data; for example, from borehole logs or seismic or resistivity soundings.

Two people are required to operate the system; one person at the transmitter and one at the receiver. The operators require little background knowledge and experience and can be trained on the job. The location and direction of the survey lines should be decided by a hydrogeologist, who should also interpret the data.

The time required for measuring a traverse depends on the number of readings which are taken at each station along the profile. Usually several kilometers a day can be measured. This is more than adequate for one or even two potential borehole sites.

The electromagnetic survey method is a quick method of obtaining a qualitative impression of a relatively large area. It is fool-proof and simple to operate in the field, and because it does not require electrical contact with the ground, it can be applied in any place where profiling with the electrical resistivity method does not work properly. Although its quantitative interpretation capacities are limited, the method is suitable for locating narrow conductive zones such as faults or contact zones, which are potential aquifers in any geological environment. EM can also be used to establish changes in the thickness of the regolith above basement areas.

2.4 Very Low Frequency EM

The VLF (Very Low Frequency) method of investigation is based on the same principles as the electromagnetic method, but consists only of a small light-weight receiving instrument. The signals of strong VLF (10 - 30 kHz) radio transmitters induce locally weak secondary electromagnetic fields in conductive structures below the earth's surface. The VLF receiver measures the secondary field strength and phase shift near the conductive zone in the underground. In spite of its name, the frequency of the signal is much higher than conventional EM techniques. This implies that much less penetration is achieved, especially where conductive layers are present at ground surface. At least two transmitters, in different directions, should cover the project area. A local VLF station may also be used. The depth of penetration for the VLF method depends on the signal strength, which depends on the power of transmitter and the distance to it, and the strength of the reaction by the conductor. It is usually of the order of 5 to 30 metres depth. Some manufacturers also provide a small portable field VLF transmitter, to be stationed in the survey area.

The VLF method of groundwater investigation is based on the profiling technique. Survey lines are walked (the instrument can be carried by one person), preferably perpendicular to the main terrain trends or suspected strike of the geological structures. At regular intervals (e.g. 5 or 10 meters) a reading is taken and the result written down or automatically recorded by the instrument. The operator should have some insight into the structural features of the terrain, unless the survey lines are predetermined or based on preliminary studies. Several kilometres can be surveyed daily and on-the-job training is easy. Interpretation should be carried out by a hydrogeologist with knowledge of the local geology.

A qualitative interpretation of the measurements can be obtained by plotting the observed values along profiles or on a map. The position and the strike of anomalies thus become apparent. Knowledge of the local hydrogeology is necessary to identify the nature of the anomalies. A basic quantitative interpretation of the anomaly (depth to conductive zone and its conductivity) can be obtained through a comparison of the intensity of the anomaly with the readings for the non-anomalous terrain. Some instruments have an in-built interpretation capacity. Graphs for calculation by hand, and computer software are also available. Reliability of interpretation is increased when calibrated with other quantitative data.

At present there is still some uncertainty concerning whether the signals produced by the main VLF stations sufficiently cover all parts of Africa in adequate strength to allow this method to be used in every country on the continent. In the past results with groundwater surveys in West Africa have not been encouraging. Also tests in East Africa with the new generation of VLF equipment (ABEM Wadi), recently entered into the market, have been disappointing.

2.5 Gravimetry

The Gravimetric method is based on measurements of the gravitational field at various locations over an area of interest. The objective in exploration work is to associate variations with differences in the distribution of densities and hence of rock types and structural features. Based on the measurements, gravity contour lines are drawn to give an impression of qualitative lateral variations in subsurface density of a project area.

The measurements are carried out with a gravimeter, a highly sensitive spring balance which weighs a small internal mass suspended from a spring. The points of measurements are usually predetermined along survey lines, a grid, or according to topographic features. The measurement points need to be levelled, or the elevation determined on the basis of detailed (and accurate) topographical maps (e.g. 1:5000). The spacing between the measurements depends on the size of the project area and the level of detail required. Each measurement takes approximately 5 to 10 minutes. Every one or two hours a reading must be taken at a base station to calibrate the zero value.

Qualitative interpretation of the reduced readings is basically a matter of analysis in the light of suspected differences in rock densities and the variable thicknesses of contrasting rock formations. This requires a good knowledge of the local geology. Also a comparison with other geophysical methods may assist in the evaluation. Gravity data may well be used to extrapolate depth information obtained by seismic or resistivity soundings. A quantitative analysis is, however, only possible with adequate quantitative information for calibration, such as depths to rock interfaces and densities of rock types.

Field operation needs very precise adjustments of screws, careful reading of the measured values and patience. The variations in observations are very small and the range of erroneous readings can easily invalidate the data. When correct operation is mastered, a geophysicist is only required for the initial layout of the survey and interpretation of the measured values. The observation stations need to be levelled to compensate for topographical variations. The method can provide useful geological background information for large projects, but is not suitable for well siting by itself.

2.6 Magnetometry

Magnetometry involves measurements of the direction and gradient or intensity of the earth's magnetic field. Magnetic surveys can be made on the land surface, from the air or from a ship. Measurements are made of either the relative or absolute intensity of the magnetic field. The intensity of the measured field depends on the location of the observation point with reference to the variable magnetic field of the earth and on the local or regional concentration of magnetic material in the subsurface. Magnetometry is most useful with basaltic volcanics and in Basement areas because the igneous and metamorphic rocks contain a larger proportion of magnetic minerals than most sedimentary formations (excepting certain magnetic gravels and sands), and can therefore be used to map aquifers in Basalts and above fresh bedrock in Basement areas. Quantitative interpretation is often ambiguous, but a general lateral qualitative interpretation similar to a gravimetric survey and resulting in a magnetic contour map can help locate lateral anomalies, revealing differences in rock types according to their magnetic properties. Field work is relatively simple and fast, but to be significant for individual well siting a dense network of measurements is needed and in practice EM methods are often preferred as earth conductivity is easier to interpret than earth magnetics and because EM is far superior in sedimentary environments. Magnetometric surveys have been applied successfully in several African countries (e.g. RSA, Zimbabwe, Zambia, Botswana and Tanzania) to locate water-bearing zones associated with intrusives (dolerite dykes) in Basement rock.

2.7 Seismic Reflection

By far the most common method applied in oil exploration is the Seismic Reflection Method. Based on the observation of the propagation of compressional waves through the underground, it provides detailed information on layering and structure. With the development of high resolution digital recording equipment it has only recently become suitable for shallow depth studies and as such has become a potential tool for groundwater exploration. The method is based on the measurement of the elapsed time from the impact of an explosion at the surface to the arrival of the energy pulse back to geophones at the earth's surface. The signal is reflected at every layer boundary which has sufficient acoustic contrast. By recording the arrival times of the primary reflections the depth of the reflectors can be determined and thus the geological structure and stratigraphy inferred. The fieldwork and instrumentation utilized for shallow reflection is more or less similar to that used in seismic refraction surveys, although digital recording equipment is required. Processing of data is highly specialised work for which powerful computers and expensive software are needed. The amount of detail provided makes this method, which is still in the development phase for shallow exploration purposes, potentially a promising tool for groundwater investigations.

2.8 Transient Electromagnetics

Another method which might, in the near future, become a useful tool for groundwater investigations is the transient electromagnetic method (TEM), also called the time-domain EM (TDEM) technique. Unlike the more commonly used frequency-domain EM method described above, the TEM can be used to carry out quantitative depth soundings much like resistivity soundings, except that there is no need to change the distance between the transmitter and receiver coils 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. Some problems still limit the application of the TEM method to relatively shallow groundwater investigations. For example, resolution at very shallow depths, equivalent interpretation alternatives similar to resistivity interpretations, limited development and distribution of interpretation routines and the rather expensive equipment.

2.9 Airborne Geophysics

The application of Airborne Geophysics in groundwater exploration is similar in principle to the use of surface geophysics. It utilizes geophysical methods which do not require contact with the ground surface. The most commonly used methods are electromagnetics and magnetometry, but VLF, gravimetric, radiometric, and even radar measurements can be applied. Carrying out such observations from the air allows relatively large areas to be surveyed quickly. The data thus obtained are suitable primarily for qualitative interpretation of lateral variations in the conductivity, magnetic field strength, or whatever variable has been recorded. From simultaneous multi-channel AEM (Airborne EM) recordings, a (limited) quantitative interpretation is possible. Depending on the resolution required a survey is usually flown in parallel lines of 0.5 to 2 km distance from each other. The airborne survey is generally preceded by an initial geological inventory of the area to select the required resolution and pinpoint areas of specific interest. The airborne data recording is followed by data processing, interpretation and integration with the existing geological knowledge of the project area. High-potential areas can be selected for ground follow-up with surface hydrogeological and geophysical investigations and drilling operations. Airborne geophysics gives a comprehensive regional overview.

For airborne geophysics (including data interpretation) costs are in the range of $100 - $500 per line-kilometre and depends on the total length of the required flight lines. It usually covers areas upwards of several thousand square kilometres. Only very large scale rural water supply programmes justify this type of groundwater reconnaissance.

2.10 Dowsing

> "Finding sources of water has long been considered a subtle art. Forked sticks called divining rods have been used since ancient times to detect the presence of water. (...) The divining rod will probably retain its ancient appeal. With regard to mysticism and romance, it's definitely more alluring than the scientific method. Pricewise, there's no way to beat a forked stick, and the diviner can announce his findings clearly right on the spot with mystical conviction." (A manufacturer of geophysical instruments)

Scientists have long been skeptical of dowsing (also known as divining, water witching, or the biophysical method). Many consider it to be nothing more than self-deception, resulting from autosuggestion, some relegate it to the realm of the paranormal, but others believe it is a low-cost and often highly successful method to locate potential well sites. One recent report in the latter category, concerning a rural water-supply project in Sri Lanka[17], claims that it was the most effective method (near 100 % success rate) of locating well sites in terms of:

* general location of possible well sites
* pin-pointing the site with accuracy of down to 10 cm
* detailing specifications on the width of aquifers
* pin-pointing intersecting points of aquifers
* determination of flow direction of underground water
* establishing the depth of the static water level at points where two or more aquifers intersected
* determination of the expected yield of water
* general information on the water quality (salt content etc.)
* information on the geological profile to provide a guideline for the drilling crew.

There are some grounds for a scientific explanation of the dowsing method. Just as many animals have a sense of magnetism to help them to navigate in the absence of other clues (e.g. homing pigeons, bees and whales), the human body may also have ultra-sensitive sensors of this kind. Magnetic (or other earth-potential) anomalies, caused by conductors in the subsurface, may trigger a muscle reflex, which is accentuated in a simple movement of any implement held lightly in the dowsers hand. If dowsing is treated as a profiling method, the results will primarily indicate subsurface anomalies and additional data will be needed to confirm the exact nature of the anomaly.

A number of dowsers claim, however, that they can predict the groundwater level, quality, and the potential yield, but there seems to be little scientific evidence that these claims can be substantiated. Reports of controlled experiments into the actual application of the dowsing method, while occasionally showing substantial successes, as in the example mentioned above, have also indicated expensive failures, suggesting that some dowsers are less successful than they would like to believe.

Appendix 3: Well Construction and Completion

The largest single cost item in a handpump-based community water supply (CWS) programme is almost invariably the well construction. The correct choice of construction method can have a considerable impact on overall costs and thus on the number of water points which can be provided within budget limitations.

The main well construction options which are available are hand-dug or machine-dug wells, and hand-drilled or machine-drilled boreholes. Hand digging and drilling is almost inevitably cheaper than machine construction, but also more limited in application because manpower is used. A brief description of these methods is given below, along with some comments on the hydrogeological significance of proper well completion.

3.1 Hand Drilling

One of the simplest and cheapest methods for site investigation is by drilling small test boreholes with hand augers in the immediate surroundings of a proposed well site. The equipment is uncomplicated and its operation easy to master. The hand drilling method is only feasible where the subsurface is soft enough to be penetrated by hand augers. The depth to which a hand drill can go is very limited in comparison to machine drilling, approximately in the range of 10 to 15 metres below the surface. Unconfined aquifers and shallow confined aquifers in alluvium, hill-side debris, and weathered surface material in different geological environments may be investigated with hand drills. With hand drilling the potential borehole site is investigated along conventional hydrogeological lines, by taking samples of the subsurface layers at selected intervals and testing the characteristics of any groundwater which is encountered. Depending on the suitability of the area for hand drilling, this investigation method should be conducted as an element of the hydrogeological investigation stage. If the gathered data provides clear evidence of sufficient groundwater quantity and of adequate quality, the geophysical investigation stage may be omitted. Successful testholes can be reamed into production holes without the need for machine drilling.

3.2 Hand and Machine Digging

Hand-dug wells are relatively shallow to medium depth, wide-diameter (>0.75 m) wells which continue to be relevant to CWS projects because their construction generally requires only simple tools and unskilled labour. Another advantage over boreholes is, that because of the wide diameter the wells have a large storage and can therefore be dug successfully in aquifers of poor permeability. Pumping is basically done from the water stored inside the well and not directly from the aquifer as with the small-diameter boreholes which have little well storage. In loose material the wells are generally lined with concrete rings to prevent caving in of the sides. Mechanized digging equipment can also be used, for example tractor-mounted back hoes and pneumatic chisels. Below the water table in conditions of excessive recharge dewatering pumps may be needed to remove the water during digging. Because dug wells are often cheaper than machine-drilled wells the amount of money which can be spent on well siting is also less. Only when economies of scale can be achieved, when a larger number of wells need to be dug, is the use of the more expensive geophysical techniques justified. In most situations, however, near-surface aquifers suitable for well digging are known to the local population, while additional information can often be obtained through manual test drilling as illustrated in Figure 5 in the main text.

3.3 Machine Drilling

A range of drilling equipment and services is usually available in most countries, from the $1000 set of hand drilling equipment to a $500 000 multi-purpose rotary rig. Some projects operate their own rig, while others find it more cost-effective and less cumbersome to engage the services of local or international contractors. Selection of drilling equipment should be closely tied to the anticipated geological conditions of the project area, such as rock type (especially hardness) and expected drilling depths. In addition, care should be taken to ensure that the operational requirements of the equipment are suited to available skills and support services.

Table 9 Comparison of different drilling techniques (Arlosoroff et al., 1987)

	Hand digging	Hand drilling	Percussion	Small Rotary	Large Rotary
Approx Capital Cost	$1000	$1000-$5000	$20000-$100000	$100000-$250000	> $250000
Running Cost	very low	very low	low	medium	very high
Operating Skills	very low	very low	medium	high	very high
Repair Skills	very low	low	medium	high	very high
Back-up Support	very low	low	medium	high	very high
Approx Penetration Rate per 8hr Day	0.1 - 2.0m	1 - 15m	1 - 15m	20 - 100m	20 - 100m
200mm** Hole to 15m in Unconsolidated Rock	-	fast	fast	very fast*	very fast*
200mm** Hole to 50m in Unconsolidated Rock	-	slow & difficult	fairly fast	very fast*	very fast*
200mm** Hole to 50m in Semi-consolidated Rock	-	impossible	fairly fast	very fast*	very fast*
100mm Hole to 50m in Consolidated Rock	-	impossible	very slow	very fast*	very fast*

*Constrained by logistical support **100mm finished well after screening and gravel packing

Drilling rigs can be classified under percussion and rotary rigs. Percussion rigs have been used for many decades in water well drilling and have a relatively simple design which has changed little over the years. They are durable and easy to service, require only minimally trained operators and are effective in both hardrock (Basement and volcanics) and unconsolidated sediments. They are less suitable for semi-consolidated clayey sediments. Rotary rigs are more complex and use basically two drilling methods: mud-flush drilling and compressed air down-the-hole hammer (DTH). Mud drilling requires a mud pump to circulate the mud down the hole and bring up the rock chippings to the surface, while DTH requires a powerful air compressor to drive the hammer and blow the rock chips out of the hole. The DTH technique is excellent for hard rock, but less suitable for unconsolidated and semi-consolidated materials, while mud drilling is very useful and fast in less hard rock. The size of the rotary rigs determines basically their possible depth and diameter of drilling. For CWS projects in hard rock areas the smaller multi-purpose rotary rigs (such as the Dando 220) are usually more than adequate. Table 9 gives a basic overview of the various drilling techniques and requirements in different geological environments. Inevitably, this table gives a rather simplified classification. Everyone familiar with drilling will realize that a large variation is possible and depends on local geological conditions, technical expertise available and even the availability of spare parts (which depends quite often on foreign currency regulations).

3.4 Well Completion

A well site investigation increases the chance of obtaining a good yielding well at the least expense. This is not only achieved by careful selection of the drilling location. Other factors such as the well construction determine whether an effective abstraction of groundwater and increased well life is possible.

During drilling a careful record of the various geological formations which are encountered at various depths must be kept, as well as a record of the depths at which water is encountered in the hole. In unconsolidated and semi-consolidated rocks the installation of casing and screens prevents the hole from caving in. The screens allow the water from the formation to enter the borehole where the pump is located and should be installed at the correct depth, i.e. exactly opposite the water-bearing layers, to facilitate the greatest possible inflow of groundwater. In cases where aquifer positions are difficult to ascertain from the driller's logbook (e.g. where mud drilling is used), several down-the-hole geophysical logging methods can be applied which can pinpoint aquifer depth and thickness.

In most cases, even in fractured zones in bedrock, it is advisable to install casing and screens and around the screen a gravel pack; the latter to avoid the influx of small particles into the well bore. Such particles carried by the inflowing water can silt up a well, and severely shorten the pump's life through abrasion. Screens, and a proper gravel pack, followed by well development virtually solves the siltation problem. A gravel pack is an artificial filter made of well-sorted gravel or sand particles between the screen and the water-bearing formation which acts as a barrier to fines in the formation. Well development involves over-pumping, surging and jetting of water or air in the well bore. This agitates the gravel pack and surrounding water-bearing formation into a stable position, increasing the porosity, permeability and hydraulic radius, and flushes out all particles smaller than the screen slot openings. Above and below the gravel pack an impermeable seal of clay or cement should be installed to avoid infiltration of contaminated water from the surface or from less-suitable aquifers.

A final important step in the construction of the well is the execution of a proper pumping test. Test pumping provides information on the specific yield of a well and the drawdown of the water level in the well at specific abstraction rates. Depending on the discharge which can be achieved with the test, a decision can be made as to the type of pump to be installed, the depth of the intake (cylinder) and its capacity.

Appendix 4: Selected Literature

4.1 Hydrogeology

Davis S N and R J M DeWiest, 1966. Hydrogeology. New York: John Wiley & Sons, Inc. 463 pp.

General handbook on hydrogeology, with chapters on groundwater quality, hydraulics, exploration and groundwater in different hydrogeological environments. Not specifically oriented towards the tropics.

Freeze R A and J A Cherry, 1979. Groundwater. Prentice-Hall Inc. Englewoods Cliffs, New Jersey 07632. 604 pp.

Comprehensive treatment on hydrogeology giving a broad interdisciplinary coverage of groundwater principles. Specific attention is given to groundwater chemistry and contamination problems.

Heij G J and C R Meinardi, 1984(?). A Groundwater Primer. Technical Paper No. 21. Rijswijk NL: IRC. 119 pp.

A basic introduction to the principles of occurrence and movement of groundwater and well hydraulics. Oriented towards CWS projects. Part of a series of hydrogeology related papers. International Reference Centre for Community Water Supply and Sanitation, PO Box 93190, 2509 AD The Hague, the Netherlands.

Larsson I et al., 1984. Ground Water in Hard Rocks. Project 8.6 of the International Hydrological Programme. Paris: UNESCO. 228 pp.

Comprehensive and detailed treatment of the hydrogeology of hard rock areas. Includes treatment of remote sensing and geophysical techniques and is particularly oriented towards water development in the Third World. UNESCO, 7, Place de Fontenoy, 75700 Paris, France.

Walling D E, S S D Foster and P Wurzel, 1984. Challenges in African Hydrology and Water Resources (Proceedings of the Harare Symposium, July 1984). Wallingford: IAHS Press, Institute of Hydrology.

Compilation of case studies concerning well siting and other aspects of CWS projects in Africa. International Association of Hydrological Sciences, Institute of Hydrology, Wallingford, Oxon OX10 8BB, UK.

4.2 Remote Sensing

Greenbaum D, 1985. Review of Remote Sensing Applications to Groundwater Exploration in Basement and Regolith. Nottingham: British Geological Survey. 36 pp.

Based on applications in tropical Basement areas. Part of a series of papers on Basement hydrogeology. British Geological Survey, Nicker Hill, Keyworth, Nottingham NG12 5GG, UK.

Lillesand T M and T W Kiefer, 1979. Remote Sensing and Image Interpretation. New York: John Wiley & Sons. 612 pp.

Standard textbook on Remote Sensing. Includes a helpful treatment on the interpretation of aerial photographs in different geological environments, but is not specifically oriented towards the tropics.

4.3 Geophysics

Carruthers R M, 1985. Review of Geophysical Techniques for Groundwater Exploration in Crystalline Basement Terrain. Report RGRG 85/3. Nottingham: British Geological Survey. 30 pp.

Comprehensive overview of most common geophysical exploration techniques. Primarily based on applications in tropical Basement areas. British Geological Survey, Nicker Hill, Keyworth, Nottingham NG12 5GG, UK.

Telford W M et al., 1976. Applied Geophysics. Cambridge: Cambridge University Press. 780pp.

Detailed theoretic treatment of most geophysical exploration techniques.

Zohdy A A R, G P Eaton, D R Mabey, 1974. Application of Surface Geophysics to Ground-Water Investigations. Washington: US Department of the Interior, Geological Survey. 116 pp.

Practical and comprehensive treatment of the Resistivity, Seismic Refraction, Gravity and Magnetic techniques with some case studies. Primarily based on the North American situation. US Government Printing Office, Washington DC, 20402, USA.

4.4 Well Construction

Blankwaardt B, 1984. Hand Drilled Wells. A Manual on Siting, Design, Construction and Maintenance. Dar es Salaam: Rwegarulila Water Resources Institute. 132 pp.

Detailed manual on the siting and construction of hand-drilled wells for low-cost water development, based on a CWS project in Tanzania. TOOL Foundation, Entrepotdok 68A/69A, 1018 AD Amsterdam, the Netherlands.

DHV, 1978. Shallow Wells. Amersfoort NL: DHV Consulting Engineers. 190 pp.

Detailed manual on the siting and construction of hand-dug wells especially for low-cost water development, based on a CWS project in Tanzania.
DHV, PO Box 85, 3800 AB Amersfoort, the Netherlands.

Driscoll F G, 1986. Groundwater and Wells (2nd edition). St Paul USA: Johnson Division. 1089 pp.

The well-known Johnson handbook on drilling and water wells. Exhaustively revised 2nd edition, describing all machine drilling methods, modern well construction, development and completion. Includes basic information on hydrogeology and geophysics. Johnson Division, St Paul, Minnesota 55112, USA.

4.5 Test Pumping

Kruseman G P and N A de Ridder, 1970. Analysis and Evaluation of Pumping Test Data (3d edition). Wageningen NL: ILRI. 200 pp.

Standard reference book on pumping tests. International Institute for Land Reclamation and Improvement, Wageningen, the Netherlands.

4.6 Water Quality

WHO, 1984. Guidelines for Drinking-Water Quality (Volumes 1 & 2). Geneva: World Health Organization.

Recommended values for water quality determination, information on the selection of suitable water sources and explanation of the criteria for constituents in water. - WHO Publications, Geneva, Switzerland.

4.7 Handpumps

Arlosoroff S, et al., 1987. Community Water Supply. The Handpump Option. Washington DC: The World Bank. 202 pp.

Rationalization of the use of handpumps in CWS projects and a detailed review of most of the available handpump types based on laboratory and field tests. Publication Sales Unit, The World Bank, Washington DC 20433, USA.

4.8 Management

Grover B, 1983. Water Supply and Sanitation Project Preparation Handbook. Technical Paper No 12 (3 volumes). Washington DC: The World Bank.

Manual on the preparation and management of water supply projects in Third World countries according to World Bank criteria, including several case studies.
Publication Sales Unit, The World Bank, Washington DC 20433, USA.