Finding Groundwater

A Project Manager's Guide to Techniques and How to Use Them

Pieter van Dongen
and
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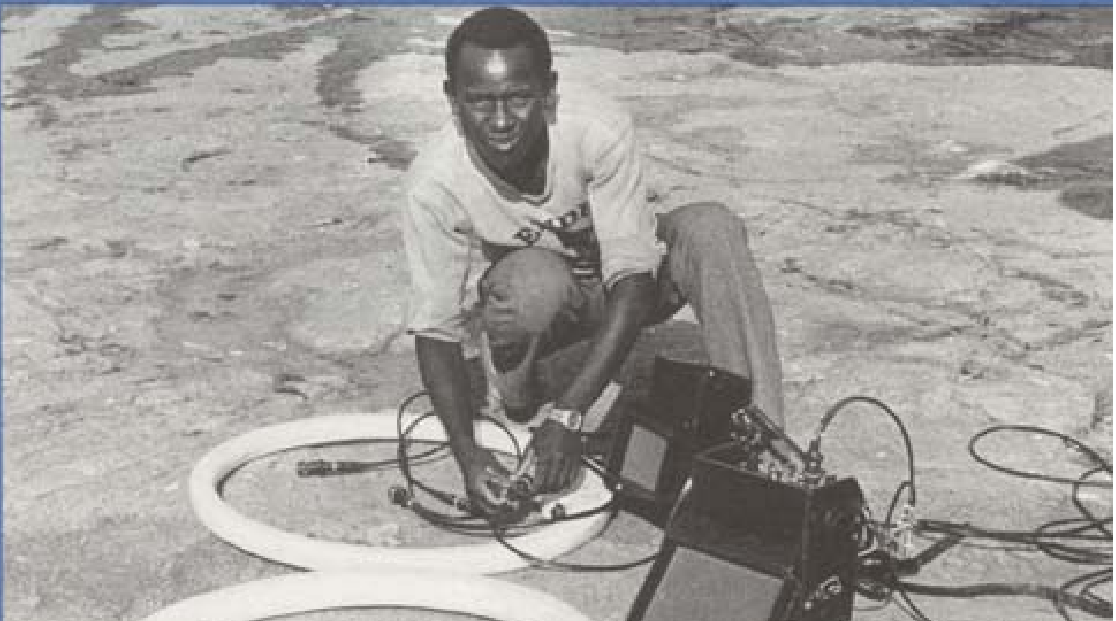
Technical
Report



UNDP-World Bank
Water and Sanitation
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UNDP–World Bank
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Introduction

More than one billion people, mostly living in rural areas of the developing world, do not have access to potable water of adequate quality and quantity. There is a growing consensus that these numbers can only be reduced significantly through approaches that are low-cost and that involve communities or individual households in their planning, financing and maintenance.

In many places, the only safe and reliable water resources are those under ground. Groundwater is generally free from bacteriological pollution; it has an almost constant quality and temperature; and it is available in large quantities (Foster, 1984). Given limited financial and human resources, handpump-equipped wells appear to be the most suitable, decentralized and low-cost approach to providing drinking water 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 that has received less attention is groundwater exploration or 'well siting'. The proper location or siting of a well can significantly increase the success and reduce the cost of a program. A systematic hydrogeological investigation of a proposed project area can help to avoid unsuccessful wells and minimize the depth of required drilling or digging. 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 reduce the overall cost per well.

To explore this aspect further a comprehensive inventory of the application of hydrogeological and geophysical investigation techniques for low-cost community water supply projects was undertaken by Groundwater Survey (Kenya) Ltd., commissioned by the UNDP/World Bank Rural Water Supply Handpump Project. The report was printed as two volumes in 1988 and gives a thorough account of its findings. However it was found to be more detailed than necessary for the purposes of planners and managers. This summary has been prepared to meet their needs. It focuses on the application of site investigations for low-cost water supplies, generally for the construction of handpump wells where well depths are less than 100 meters.

The original survey was based upon questionnaires sent out in early 1987 to 150 governmental and nongovernmental organizations, as well as to consultants involved in CWS projects, mainly in sub-Saharan Africa, and to manufacturers of geophysical equipment worldwide. Firsthand information was acquired from nearly 40 handpump projects, while additional projects were studied through project reports and other relevant literature. Costs indicated in this volume are those reported in questionnaires in 1987.

Analysis of these data reveal that proper well siting can significantly increase drilling success rates. Success rates have been increased between 10 and 40 percent, and the expense of well siting is justified in many cases when the number of 'dry' wells was reduced by more than 10 percent. Average costs per site in West Africa were $1,100, in East Africa $350 and in Southern Africa $150. As these figures are primarily derived from large development projects, it can be expected that the investigative costs for smaller projects will lead to somewhat higher unit price.

It is clear from the survey that:

- In most cases a more logical approach to groundwater siting is called for in which the more costly and sophisticated techniques are only employed after initial investigations using readily available information indicate their necessity.
- If planners and managers are more familiar with such a logical approach and have a basic knowledge of some of the techniques they will be able to appraise the economic suitability of improved well siting for their projects. Good siting could reduce the number of dry wells dug, increase well yields and reduce the depth of wells.
- Investing in well siting early in the project history and considering subcontracting well siting services to suitable local specialists may significantly reduce the cost of well siting.

When planners and managers are more familiar with groundwater survey techniques they are better able to use specialized technical services. By using a logical step-by-step approach to their investigations, they benefit from making an adequate investment at the start of a project thus reducing project costs and improving success rates.

The purpose of this publication is to increase managers' and planners' awareness of groundwater siting techniques within the framework of a step-by-step approach, and to give guidance in determining what level of investigation can economically be carried out. Part one deals with the technical approach to well siting; part two presents guidelines on appraising the cost and success of investigations. In part three, a case study is presented in which drilling costs were reduced by two thirds (improved well siting having increased success rates by 26 percent and reduced drilling depths by 50 percent). A technical appendix gives further information on techniques and equipment.

Part I

A Logical Approach to Groundwater Siting

It is important that well sites are chosen principally on hydrogeological grounds to have the greatest chance of obtaining an adequate yield. A borehole is deemed successful when the yield and water quality satisfy the needs of a particular household or community. 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, 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 acceptable.

Because many wells are under the care of local communities, the users should be consulted and in agreement with the site location. This requires proper communication with the local community to avoid potential conflicts regarding ownership, operation and maintenance of the new wells (van Wijk, 1987). In addition, the final choice of a site should consider risks associated with pollution, erosion, flooding, ease of access, and future developments planned for the area.

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

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

Geophysical investigation techniques are especially useful where the subsurface conditions are relatively simple, for example in areas of solid bedrock overlain by a weathered zone. But in complex formations the resolution provided by geophysics is often less than ideal.

In consolidated sediments or in volcanics, the usefulness of geophysics will be limited, but detailed hydrogeological investigations may provide enough information to locate a drilling site.

Investigations using simple hand drilling equipment have also proven to be very successful particularly in alluvial areas, yet it remains a much underused technique.

Projects in Africa reported that a range of siting techniques were currently in use.

A logical approach to groundwater exploration has five levels of investigation. The initial levels use

Table 1: Siting Methods in Use

Siting method	*West Africa*	*East Africa*	*Southern Africa*	*Subtotal*	*General studies*	*High-yield studies*
Number of wells	6,014	5,861	1,837	13,712	489	302
Number of sitings	0	1	0	1	0	0
Local knowledge	3	10	5	18	1	3
Divining/dowsing	1	5	0	6	0	0
Geological information	10	9	7	26	6	9
Aerial photographs	11	4	6	21	5	9
Landsat imagery	1	3	2	6	2	2
Earlier studies	1	4	1	6	2	4
Resistivity sounding	11	7	6	24	7	10
Resistivity profiling	10	2	4	16	3	6
Seismic refraction	1	3	0	4	3	2
Electromagnetics	2	1	1	4	3	3
VLF EM	4	0	1	5	2	3
Gravimetry	0	0	0	0	2	1
Magnetometry	1	1	0	2	3	0
Airborne geophysics	0	0	0	0	1	0
Ground radar	0	0	0	0	0	0
Other	0	2	1	3	1	4

information which is readily available or of low cost. Each successive level of investigation adds more detailed information on the subsurface situation until the point is reached where the certainty of drilling a successful well is ascertained, thus no unnecessary investigations are carried out. All too often the more expensive techniques are employed during the initial stages of an investigation which unnecessarily increases the cost per site. When techniques are planned as an integral part of a project, the success rate be significantly improved and project costs can also be reduced.

A logical and low-cost approach to well siting should have the following sequential levels of investigation:

LEVEL 1: INVENTORY OF EXISTING DATA
Geological Data
Hydrological and Climatic Data
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 step-by-step approach to well siting furnishes the most relevant information at the lowest cost and minimizes drilling expenses. When an investigation phase is skipped altogether and 'wildcat' or random drilling is carried out, the chances of drilling a successful well are usually smaller than with proper hydrogeological investigations in the project area.

In an approach using only geophysical techniques (where the first three levels of investigation are skipped or inadequately utilized) very useful and inexpensive information is neglected, unnecessarily increasing the cost of well siting.

In situations where expertise is locally available, projects should always compare the relative advantages of subcontracting well siting versus building a well siting facility into the project.

If it is necessary to continue beyond the third level of investigation in which geophysical field work is necessary, the selection of a suitable technique and an estimation of its costs and potential benefits will be required. Again, the benefits of an "in house" versus a subcontracted approach should be considered.

Level 1: Inventory of Existing Data

A substantial amount of useful data concerning the proposed project area may be available from previous studies carried out by various government departments or private companies. It is often worth the effort to track down past geological studies, hydrological and climatic monitoring data, and borehole record files. The acquisition of such information may involve some bureaucratic hurdles. In most countries water-supply projects require government approval. 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.

In medium to large scale 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 topographic maps at an appropriate scale are very useful.

Data from existing boreholes in the proposed project area are of special interest as they can contribute information about the geology and groundwater characteristics, aquifer location, well yield and water quality, what drawdowns are experienced during pumping, and what groundwater level fluctuations have been observed. If the data indicate relatively uniform and promising hydrogeological characteristics, further detailed investigations may not be necessary. It is often not possible to adopt a higher level of investigation without information from previous levels.

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

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 at later stages of the investigation; for example, geological maps may be of help during the aerial photograph and satellite imagery interpretation, and existing borehole data will help calibrate geophysical measurements.

The analysis of available hydrogeological data and hydrogeological fieldwork will provide adequate grounds to determine where hydrogeological investigations will suffice and where additional geophysical exploration is necessary.

Level 2: Remote Sensing Interpretation

Remote Sensing in well siting is a method of collecting information concerning the occurrence of groundwater indirectly from aircraft or satellite-borne observation systems. Surface features of the earth are recorded in a variety of electromagnetic wavelengths including visible light. The presence of groundwater can be inferred from images of the topography, geomorphology and vegetation. Through remote sensing an overview of the main features indicating the occurrence of groundwater can be obtained quickly and cheaply for a large area.

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 investigative 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 are the most expensive format and are used by specialized agencies with the necessary sophisticated 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 centers. Interpretation of the satellite images or aerial photographs is carried out by placing transparent overlays on top of the images, the significant features are hand drawn onto the overlays and later transferred to project area maps. Data must be interpreted by an experienced hydrogeologist.

Satellite image interpretation should never, however, be the sole basis for well siting in groundwater exploration, since resolution is too poor to indicate 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 favorable to groundwater occurrence.

Aerial photography in the context of groundwater exploration can serve two purposes. Firstly, it is used to identify features indicative of the presense of groundwater. Through an analysis of topography, lineation, drainage pattern, texture, erosion, tonal variation, vegetation and land use, different terrain conditions and their boundaries can be identified. For example, faults and fracture zones form narrow elongated areas of weakness within the parent rock and are areas of groundwater accumulation. Since erosion and weathering penetrate more deeply into these zones, they form long straight valleys. Fault systems are identified from aerial photographs as the accompanying valleys appear as dark lineations due to increased soil moisture and vegetation density, or are seen as sharp discontinuities in the surface topography.

Secondly, aerial photography can provide useful topographic and demographic information showing the distribution of the target population of the planned water-supply system. This will help to locate the well in a suitable place for the local community. However, 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.

The preparatory aerial photograph interpretation and hydrogeological fieldwork are essential to narrow down the size of the investigated area and the amount of geophysical fieldwork.

Standard stereoscopic aerial photo interpretation (and certain types of satellite imagery) merely requires a pocket or desk stereoscope is required. However, most types of satellite image interpretation require sophisticated equipment and expertise and is thus best contracted out.

Level 3: 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. Hydrogeological fieldwork provides the opportunity 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 groundwater availability zones of high, medium and low potential.

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 must be more extensive since a general overview obtained from the previous levels of investigation is absent.

The basic elements of hydrogeological fieldwork are:

Geomorphology

Ground contact enables the inferences of the previous levels of investigation to be confirmed. It may be possible to assess shallow groundwater occurrence by hand drilling and test pumping. As groundwater flow generally follows surface topography (and significant storage more likely in valleys than on steep slopes or hill tops), field observations of topography are important.

Similarly, observations of erosion material are useful as they accumulate in low lying areas where weathering will be more significant. As surface runoff will flow toward these depressions, more infiltration can be expected than on steep slopes. Vegetation cover can provide important information concerning geology and the presence of shallow groundwater.

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 and surface water sources is 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 program with many planned wells, it is recommended that a network to monitor 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 the history of local rivers, springs, settlement patterns, water requirements, and alternative sources. If this is the first visit by the siting team to the project area, it is vital to make contacts within the target population and involve them in the well siting procedure and decision-making process.

Hydrogeological fieldwork should be conducted 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 hillside 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.

The success of the first three levels of investigation, using existing data, remote sensing and hydrogeological field work, depends more upon the availability of suitable personnel than upon equipment. By contrast, geophysical field work and exploratory drilling require access to suitable equipment.

If qualified personnel are available and affordable to a project, then the first three levels of investigation will not require any major outlay for equipment. The field staff will require transport and perhaps some computer equipment.

Level 4: Geophysical Fieldwork

Geophysical methods indirectly characterize subsurface geology and underground structures by measuring some of their physical properties by means of observations at the earth's surface. Such physical properties include electrical resistivity, density, and travel time for compression waves. A brief description of common techniques is given in appendix I.

A large number of different techniques are available for geophysical investigations, each with its 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. But geophysical methods provide only indirect information concerning the presence of groundwater. The data gathered must be evaluated and correlated with other hydrogeological information to ensure correct interpretation. The need for calibration of the geophysical data can be a major reason for proceeding to the exploratory drilling level of the investigation (see Figure 1).

For investigations covering large regions, gravimetric and airborne geophysical methods can be applied. Such regional geophysical coverage can provide a good basis upon which areas for more detailed investigations are selected. However, an airborne survey is generally too expensive for CWS projects to undertake, and lacks the resolution required for determining individual well sites.

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. Equipment is moved over the terrain and readings taken.

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

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

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

If it is decided that geophysical surveying is required, then a specialist's advice may be sought to advise upon the techniques and applications of geophysics required.

Considerable research and development of geophysical techniques continues to be conducted. Thus it is important to have access to up-to-date product information.

During the last decade the EM and VLF profiling methods have gained popularity as rapid profiling techniques for initial geophysical reconnaissance, following and confirming aerial photo interpretation results and providing qualitative data about fractures and depressions in the fresh bedrock surface or contact zones between different types of rock. Where the geological conditions vary primarily in vertical direction, such as sedimentary basins or in volcanic areas with little tectonic disturbance, the EM/VLF methods are less useful than resistivity sounding.

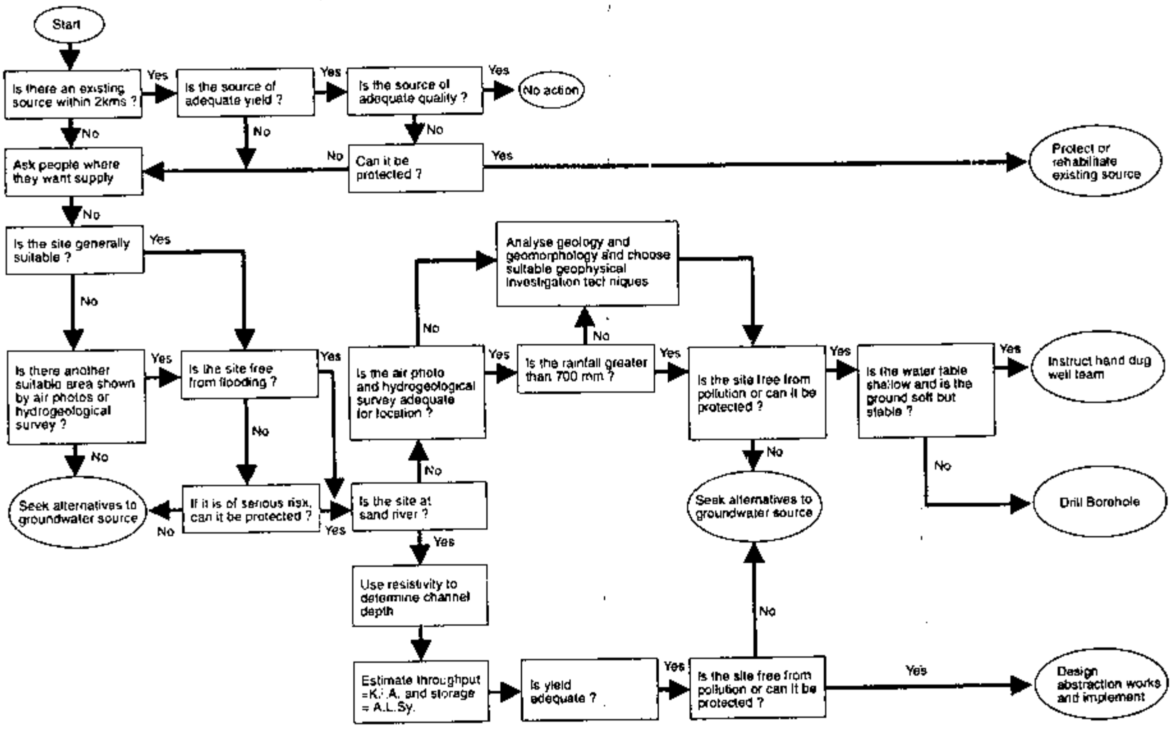
The strength and increasing popularity of EM and VLF profiling methods is due to their capacity to map qualitative contrasts i.e., conductive versus resistive zones, which can be pinpointed with good lateral accuracy. Further, they are very fast in their field application. The depth of penetration of the EM equipment which carries its own transmitter is generally much better than that of a VLF instrument. The VLF receiver is, moreover, dependent on the availability of a strong external long-wave radio transmitter.

Many projects combine a profiling/reconnaissance technique with a sounding technique (VLF or EM and resistivity; gravity or magnetometery and seismic refraction), which has proven itself a very useful approach.

The resistivity method is also very popular, being one of the earliest geophysical methods to be applied to groundwater investigations. It is better understood than more recently developed methods, and is cheaper and less cumbersome in terms of safety precautions and logistics than, for example, the seismic refraction method requiring explosives. It is a versatile geophysical tool, which when used alongside a proper hydrogeological investigation can provide useful information on potential groundwater occurrence, lithology and groundwater quality in many different environments. The inventory of projects revealed that resistivity is applied in virtually all kinds of hydrogeological environments. With recent developments such as the Offset Sounding System, the resistivity method will probably maintain its popularity.

The seismic refraction technique could well become a superior method for project areas with weathered basement. Its interpretation is less complex and usually less ambiguous than resistivity sounding. Measurement time is roughly equal to that for resistivity sounding, but in certain conditions it provides qualitative and quantitative information along the whole geophonic spread, unlike the single point data provided by a resistivity

Figure 1 Well Siting Flow Chart with Geophysics
(Hydrotechnica, 1985)



sounding. The need for explosives and the high cost of the equipment have always been the main obstacles. However, with the development of low-cost seismographs, nonexplosive weight-drop methods become a suitable alternative. The seismic refraction method might well become a serious competitor for the resistivity method.

A number of projects have developed a standard investigative routine which is applied at almost all sites needing geophysics. This has the advantage that a non-skilled field crew can become familiar with the routine and in due course can work without the supervision of an expert. Occasionally this will result in extra work, but it can accelerate field operations and reduce costs considerably. The geophysicist/hydrogeologist is still needed initially to select the sites requiring geophysics and preferably also for the layout of the measurements, as well as for the interpretation of the data.

A number of projects in Africa based the need for using geophysics on a preliminary hydrogeological study and only selectively applied chosen methods. Larger projects often base their investigation approach on a pilot phase in which the suitability of one or more geophysical methods are tested.

The "Inventory Study on Well Siting Techniques" indicates that in practice, the choice and application of different geophysical techniques is often made without regard to the geological environment encountered. However, certain techniques may yield better results than others depending on the geological situation. To carry out a quick reconnaissance of an area, the combination of a profiling technique with depth sounding method will probably provide sufficient information for locating a well. A general overview of comparative advantages is given in Table 2.

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

Given the relatively simple operation of modern geophysical equipment, fieldwork 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 selection of the geophysical method, procuring any necessary transport, designing the geophysical fieldwork, and training the field team.

Interpretation of the field data is carried out by an experienced geophysicist or hydrogeologist. Interpretation of resistivity and seismic refraction is currently carried out with the help of a portable computer 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 conduct one or more sitings per day.

Dowsing or water divining may also be considered a geophysical exploration method, although its role in groundwater exploration remains controversial. A 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 (Williamson, 1987). The method itself is certainly low-cost, requiring only a forked stick rods or a pendulum. In many places dowsing has been used as the sole method. 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.

It is recommended that the application of geophysical methods be attempted with the supervision of a geophysicist or a hydrogeologist with geophysical experience.

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

Of the 25 low-cost rural water supply projects that provided information concerning the composition of geophysical field crews, 18 reported that

Table 2: Suitability of Common Geophysical Methods in Different Hydrogeological Environments

Hydrogeological environment	*Resistivity*		*Seismic refraction*	*Electro-magnetics*	*VLF*
	Sounding	*Profiling*			
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.

either a geologist or geophysicist was part of the crew. Information from two other projects indicated that both were present, and two had geological/geophysical supervision from the project office. Of the 10 projects that listed the training background, there were 5 MSc-s and 5 BSc-s with experience ranging from 3 to 15 years. The geophysical instrument operators are mostly trained on-the-job, while labourers are basically unskilled. The average crew size is six people comprised of one expert, one operator, one driver and three labourers). But crews can vary from just one (a geophysicist with VLF equipment) to 10 (one geologist, one geophysicist, two operators, one driver and five casuals for resistivity and magnetometric surveying). Average crew costs per day amount to $325 and range from $20 to $1,250, with no correlation between crew sizes and costs. Profiling crews were able to investigate on average 5.5 sites per week, while sounding crews averaged three soundings per site.

Geologists or geophysicists were used in all but one of the projects dealing with general groundwater assessment or the siting of high yielding wells. The crews consist on average of seven members at an average cost of $622 per day. With three of the 16 projects far over $1000 per day, their resistivity teams were able, on average, to make 22 sounding per site, and their profiling teams able to investigate 2.7 sites per week.

Most of the respondents suggest that geophysical field crews should be accompanied by a university trained geophysicist or hydrogeologist with geophysical experience. For the resistivity method the additional crew members should consist of one operator and two or more laborers. These crews averaged three soundings per site. The seismic refraction crew may need up to two operators and two to six labourers. EM requires a geologist/geophysicist and an operator, while ground radar and borehole logging similarly requires two operators, of which one, according to one of the two manufacturers, should be a trained geologist/geophysicist. Gravity and magnetometery each can be carried out by one geologist or geophysicist. For the former, when no detailed topographic maps are available, the measurement stations must be levelled by surveyors. As one of the consultant respondents points out, it may not always be necessary to employ professional geophysicists or geologists in the field crew if a well trained and experienced operator is available.

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

Assuming geophysical services are available, an investigation including geophysics (a number of resistivity sounding and a few hundred meters of resistivity, EM or VLF profile, or three or four seismic spreads) is likely to be about $1,000 per site for small projects involving only a few sites and may drop below that for larger projects.

Again the survey mainly sought information on the composition, costs and outputs of geophysical data interpretation teams. Of 24 the answers, 13 handpump projects used a geologist, three projects employed a geophysicist, six used both specialists, and two used the services of a consulting engineer for data interpretation. Daily rates of these specialists range from $10 per day to $850 per day for a double evaluation (initial interpretation in the project country and reinterpretation in the consultant's country). General groundwater assessment project daily rates averaged $238, and projects siting high yielding wells averaged $299.

For the interpretation of the resistivity measurements a computer, plotter and/or printer are listed as the main requirements. Small portable computers are quite adequate and can often be carried into the field. Manual interpretation is also possible using a set of master curves, while calculator-based interpretation routines are also available. Computer interpretation is, however, the quickest and the most accurate. For the interpretation of seismic refraction results, interpretation with a small calculator is possible and relatively easy although somewhat laborious. Computer programs can speed up the process. Data processing for profiling techniques such as EM, VLF, magnetometery and gravity measurements is usually not as complex as the procedures for resistivity and seismic measurement interpretation and is easily plotted by hand onto maps or profiles. However, computer applications can assist with the plotting.

The latter is also true of the interpretation of geophysical borehole logs.

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

Sixteen projects used computers to interpret the data, several of which did so in the field, while others made an initial interpretation in the project country and reevaluated the data in the consultant's country. Manual interpretation was also carried out in four cases. Only three handpump projects provided figures on the total cost of the computer system used, ranging from $3,000 to $17,187. Six non-handpump project computer systems had an average price of $14,500. Some projects were able to rent or obtain free computer access. Daily computer cost is relatively similar for all projects with an average of $38 per day.

On average, handpump projects were able to interpret the results from three sites per day, groundwater investigation projects 1.2 sites per day and the high-yield well siting projects 2.4 sites per day.

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

Level 5: 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 and to confirm the inferences of previous investigations. It is the ultimate proof that all previous levels of investigation were accurate. Two 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.

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 at which water is struck is also logged.

Geophysical Logging

Directly after the hole is drilled, and before any casing and screen are installed, the hole can be logged geophysically. Down the hole equipment can be used to monitor a wide range of parameters which can be continuously sent to a recording device. This information 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 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 and recovery 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 made 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. A chemical analysis of the water can also yield further hydrological information.

It is recommended that production wells be geologically and geophysically logged, and pumping and water quality tests be conducted. This optimizes well construction and provides data for planned wells.

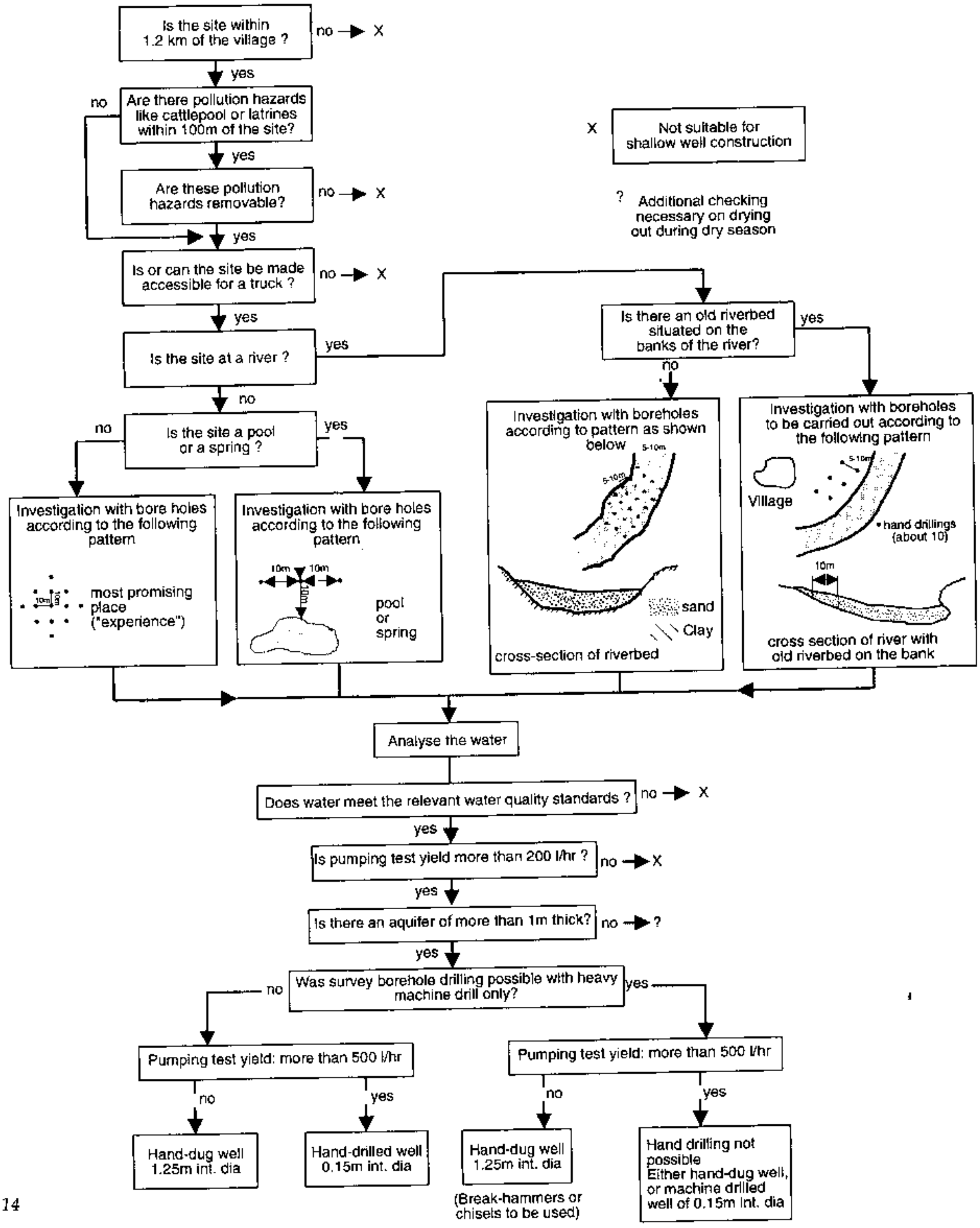
In relatively soft rock, the information can be acquired by exploratory hand drilling, and geophysical investigations are usually unnecessary. Several hand drilled holes can be easily and cheaply made to determine the best site for a production well, which will be dug or drilled by hand as well. Whether or not hand drilling is possible depends on local geological conditions and will be determined in the hydrogeological investigation phase. 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 2.

If the fifth and final level of investigation, exploratory drilling, is called for, a considerable financial outlay may be required on behalf of the project. Hopefully this will be justified by an increase in success rates and a lower mean drilling depth. In cases where the project intends to drill boreholes, it is assumed that there is access to a drilling rig, which will be used for the exploratory holes. Otherwise it will almost certainly be necessary to contract this work out. Contractors may have a variety of rigs from large rotary equipment to light portable survey rigs; their fees will vary accordingly.

The use of light and heavy hand drilling equipment has been very successful in unconsolidated rock. Two projects reported using hand drilling as part of their siting procedure. In suitable geological conditions, hand drilling offers a quick and sure siting technique which does not rely upon expert assistance and, in certain cases, can be used to drill the final production wells.

Level 5 of the investigation, (machine) test drilling, is very expensive due to the high operating costs of a modern drilling rig. Depending on the type of drilling, (hand drilling not included) the cost may be estimated at \$50 - \$200 per meter (low in Southern Africa, high in West Africa), excluding casing, screens, developing, testing, and handpump. Only the largest projects in which 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 sounding, 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.

Figure 2: Well Siting Flow Chart with Hand Drilling
(DHV, 1978)



Part II

Success and Cost

Most water supply projects operate within fixed financial constraints. Thus, the costs of groundwater investigations are a determinant in which methods are applied.

Table 3 shows the costs for well construction and siting in Africa, as determined by the well-siting survey.

The total siting costs include the costs of siting equipment, crews, transportation and evaluation; administrative overheads also need to be considered.

Economies of scale would suggest that constructing more wells would reduce the average cost of siting. A comparison of the project average costs and the well average costs from Table 3 shows that for low cost rural supplies an average reduction in siting cost of 14 percent was reported. But for the ground water investigation and high yield siting projects there was an average increase in cost of 8 percent. A likely explanation is that the latter are less constrained by tight budgets associated with the low-cost community water supply objectives.

A representative breakdown of the total siting costs is not possible since only two handpump projects provided all the costing details asked for. However, a very rough comparison of the average values is shown in Figure 3 (average sample size per portion of the pie is nine projects) for handpump

Table 3: Cost per Well

	Total construction costs					*Investigation costs per site*	
Category/region	*Average budget ($ millions)*	*Average cost/well[a] ($)*	*R[b]*	*Sample*	*Number of wells*	*Project average ($)*	*Well average ($)*
Low cost rural water supplies							
West Africa	8.23	12,000	0.89	12	6,921	1,193	1,053
East Africa	9.58	10,095	0.94	8	7,969	420	359
Southern Africa	1.27	2,766	0.92	6	2,751	208	182
Subaverage	7.08	10,903	0.88	26	17,741	711	608
Ground water assessment studies	4.40	16,694	—	2	530	1,938	2,119
Siting high yield wells	2.23	81,091	0.99	4	110	2,123	2,254
Total average						1,202	688

a. Total project budget divided by number of wells.
b. Correlation between project budgets and number of wells.

projects and in Figure 4 (average portion sample size is six projects) for the investigation and high-yield projects. This demonstrates the weight of the crew costs (probably mainly due to expatriate services) in comparison to geophysical and computer equipment and transport cost.

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

The siting costs for handpump projects in West Africa are much higher than in either Eastern or Southern Africa at an approximate ratio of 6:2:1. Of the nine projects that provided siting cost information in Western Africa in a range of $103 to $3,500, five listed costs above $1000. The extensive involvement of expatriate personnel is the most obvious explanation for the higher costs. In Eastern and Southern Africa it appears that more local contractors have been used, thus resulting in lower personnel costs.

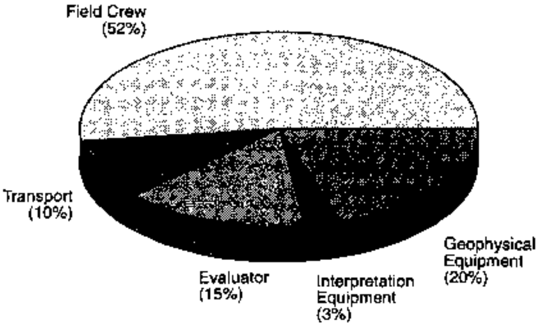
The basic cost of drilling is expressed in terms of drilling the borehole without the installation of casing, screens and gravel pack, and without development and test pumping. If the well appears to yield inadequate amounts of water after the basic drilling is completed, it is abandoned at this stage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

Basic drilling costs are much higher in West Africa than in either East or Southern Africa, but not enough information was available to clearly indicate the reason for this difference. There is a big gap between the stated basic drilling cost and the apparent budgeted cost per well in East Africa. The budgets of several East African projects involve a number of other development activities such as sanitation and workshops for water management. This apparently causes the comparatively high overall cost per well. Commercial drilling, well construction and development costs are often higher than the in-house drilling operations of the larger development projects reported in the survey for East Africa and Southern Africa. Local drilling contractors in Southern Africa are plentiful, effective and competitive, thus keeping basic drilling prices relatively low. The fact that the budgeted cost per well in Southern Africa is lower than the cost for drilling and completing a successful well of 50 m depth can be explained by the fact that the actual drilling depths per well are on average less than 50 m.

The average costs obtained by the present survey seem a reasonable indicator of approximate cost of investigation per well site in the three regions of Africa, i.e. approximately $1,100, $350, $150 respectively for West, East and Southern Africa. Since these figures are primarily derived from large development projects it can be expected that the investigative costs for smaller projects will lead to somewhat higher unit prices.

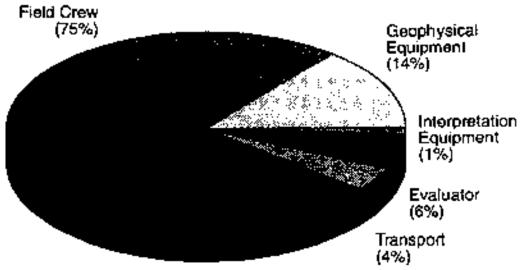
Salary costs account for the major portion of the cost of site investigations, mainly the salary of the

Figure 3: Siting Cost Breakdown for Low-Cost Rural Projects



Siting cost breakdown
for Category 1 projects

Figure 4: Siting Cost Breakdown for General Groundwater Investigations and High Yield Investigations



Siting cost breakdown
for Category 2 & 3 projects

hydrogeologist and/or geophysicist. The second most important cost item is the geophysical equipment. The proper application of geophysical methods under practically all circumstances require the services of university trained experts. Expensive expatriates can only be replaced when local expertise is available. Initial investment in geophysical equipment is high, ranging from approximately \$5,000 for VLF, gravity, and magnetometery to nearly \$15,000 for most resistivity, EM, and seismic equipment. A better option is contracting the complete siting process to a qualified, preferably local, groundwater investigation agency to avoid the high investment costs.

In order to determine at which level the investigation should proceed, a cost-benefit analysis of exploration costs 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 not only on a project-wide technical and economical appraisal but also on wider regional and national factors. Socioeconomic planning and political factors may also need to be taken into account.

As noted in Farr et al., "The groundwater search techniques are only justified if they increase the chances of subsequent boreholes being successful, such that the overall saving in drilling cost, in the long run, is greater than the cost of the search."

The criteria for determining whether a well is successful differs from project to project and are mostly given in terms of a minimum yield to be obtained from the well. For the 30 handpump projects surveyed, this minimum yield ranged from 0.3 - 5.0 m^3/h, with 24 of the projects at or below 1 m^3/h. Two of the projects in a coastal environment primarily used salinity criteria to determine success. Success may also be considered in terms of a reduction in the average drilling or digging depth. This means that the comparisons discussed below should only be considered as approximations in the widest sense and not as representative statistical values.

The basic requirement for an evaluation of the success of siting methods is the availability of comparable data for the project area concerning well construction with different levels of site investigation. If such data are available, a basic comparison can determine the difference in drilling or digging success rates. The costs of drilling a well with and without site investigations, taking into account the percentage of dry wells, can then be compared to the cost of siting to see if the application of siting is economical. The relationship can be put into a simple formula:

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

S = the savings
C_r = the overall reduction in drilling cost
C_d = the basic cost of drilling to a depth of 50 meters
R_{ns} = the success rate without the use of well siting
R_s = the success rate with the use of well siting
C_s = the cost of the site investigation.

Table 4 applies this formula to data obtained from various low-cost rural water supply projects, representing approximately 7,600 wells.

Ten of the 12 projects which estimated and, in some cases, were able to calculate the increase in drilling success using geophysical methods are (according to Table 4) justified in the use of geophysics. The average success rate increase of approximately 20 percent with site investigations results in an average reduction of \$2,119 in drilling costs, nearly three times the amount needed to cover the average investigation cost, per successful well of \$786.

Two projects have a negative savings when comparing the drilling costs without and with the use of geophysics. The comparative advantage of geophysics is evidently too small to cover the siting costs of these projects. The reliability of such a cost-benefit analysis however is very much dependent on the accuracy of the success rate estimates given by the respondents. Furthermore, the formula above assumes equal drilling depth with and without siting and does not take into account the possible savings through a reduction in the required depth of drilling as a result of site investigations, which would increase the margin favoring the use of geophysics.[1]

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

Table 4: Comparison of Basic Well Costs with and without Site Investigation

Project	C_d	R_{ns}	R_s	C_d/R_{ns}	C_d/R_s	C_r	C_s	C_s/R_s	S
A	3,946	0.65	0.75	6,070	5,261	809	1,361	1,815	-1,006
B	11,900	0.50[a]	0.78	23,800	15,256	8,544	2,250	2,885	5,659
C	9,947	0.50[a]	0.58	19,894	17,150	2,744	426	734	2,010
D	9,000	0.80	0.95	11,250	9,474	1,776	1,300	1,368	408
E	12,000	0.73[a]	0.85	16,438	14,151	2,287	600	706	1,581
F	12,180	0.60	1.00	20,300	12,180	8,120	103	103	8,017
G	1,600	0.85	0.87	1,887	1,831	56	200	230	-174
H	3,313	0.52	0.78	6,371	4,247	2,124	238	305	1,819
I	2,000	0.70	0.80	2,857	2,500	357[b]			
J	2,157	0.60	0.90	3,595	2,397	1,198	60	67	1,131
K	1,807	0.65	0.90	2,780	2,008	772	90	100	672
L	3,200	0.63	0.90	5,079	3,555	1,524	580	644	880
Average	6,088	0.65	0.84	9,366	7,247	2,119	660	786	1,333

a. R for hydrogeological siting where R_{ns} not available.
b. C_s not available, according to C_r a maximum allowable investigation cost of $C_r * R_s$ = $285.

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

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

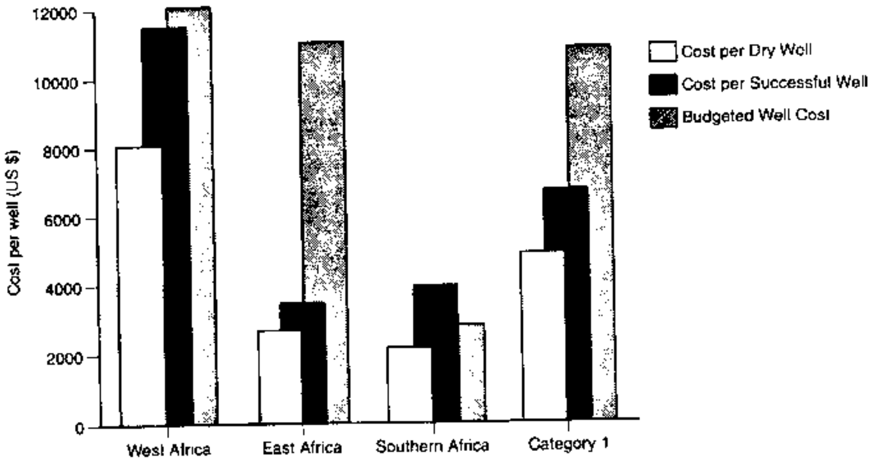
The comparisons made in Table 4, while giving a reasonable indication of the cost-effectiveness of site investigations, is not necessarily representative for well siting in all types of environments. The success of site investigations is, in addition to the geology of the project area, very much dependent on local variables such as climate, topography, and the presence of major recharge from surface water.

The evaluation of actual costs and benefits to determine the extent of investigation also depends 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 earlier projects in the same area or from areas with comparable conditions.

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

In considering the feasibility of well siting tech-

Figure 5: Drilling Costs and Total Costs per Well



niques, the survey not only studied the incidence of successful siting but also its financial implications to the overall project. Examples of determining the feasibility upon this basis were presented.

Feasibility Example 1

If in area A the chance (R_A) of encountering adequate water supplies by drilling to a depth (D) of 50 meters is 90 percent, and in area B the chance (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 at \$100/m:

$$C_A = (C_d * D)/R_A = 5{,}000/0.90 = \$5{,}555$$
$$C_B = (C_d * D)/R_B = 5{,}000/0.50 = \$10{,}000$$

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 percent to 75 percent (R_B') at a cost (C_s) of \$1000 per site, the overall reduction in well costs becomes apparent:

$$C_B = (C_d * D + C_s)/R_B' = (5{,}000 + 1{,}000)/0.75$$
$$= \$8{,}000$$

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:

$$C_A = (C_d * D + C_s)/R_A' = (5{,}000 + 1{,}000)/1.00$$
$$= \$6{,}000$$

If the required drilling depth is reduced by 30 percent (D′), well siting also becomes cost-effective in area A:

$$C_A = (C_d * D' + C_s)/R_A' = (3{,}500 + 1{,}000)/0.90$$
$$= \$5{,}000$$

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. Example 2 illustrates the effect this has on the cost of well construction.

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.

The examples show that the financial feasibility of well siting is closely tied to a number of variables, including the cost of constructing the well, the cost of well siting and the higher success rate achievable 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 costs of well construction (say 10 percent), 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 by a reduction in the required depth of drilling or digging per well, the margin for investment in well siting is widened. Total success rate increase can be expressed as a function of R_X and a possible reduction in drilling depth as:

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

The cost of well siting is 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.

If the well construction program 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.

Note

1. The formula for calculating the savings can easily be adapted to include the expected decrease in drilling depth:

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

where L_{ns} is the average required drilling depth for a nonsited borehole, L_s is the average required depth for a sited borehole, and C_d^* is the basic drilling cost per meter. The other variables remain as in the original formula.

Case Study

The Lake Basin Development Authority (LBDA) has initiated a community water supply program in Nyanza Province in Western Kenya with the aim of improving the generally poor water supply through the development of hand-pumped water supplies. In 75 percent of the province, 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 where the water table is deeper, machine drilled boreholes have to be constructed. The province is mainly underlain by volcanic rocks of Precambrian and Tertiary age, with some Pleistocene sediments present. 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 standard survey method was developed for the program by DHV Consulting Engineers of the Netherlands to accurately locate prospective borehole sites in the field. This is comprised of 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.

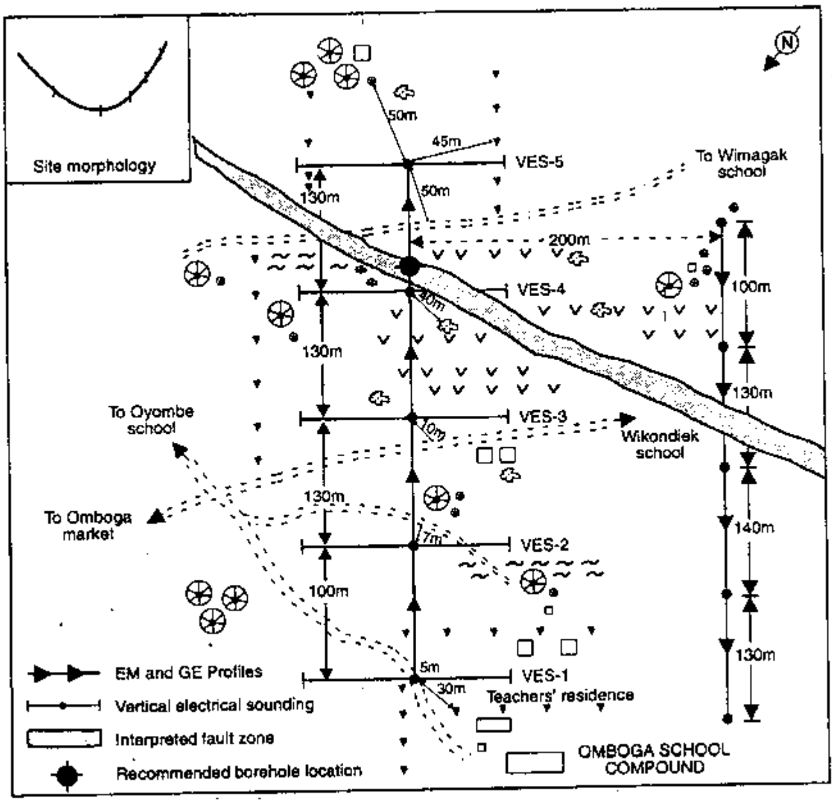
Regional structures and major faults show up clearly on satellite images. On aerial photographs fault systems can be identified as dark lineations due to increased soil moisture and vegetation density. In roughly half the area (some 6,000 km^2) over 3,000 fault structures have been identified. It has proven essential that such features be accurately located in the field, as a location error of 10 meters can result in a dry hole. The standard field survey per site consists of two electromagnetic profiles of about 400 to 600 meters length, one resistivity profile (Wenner array) and three to five resistivity soundings (Schlumberger array) evenly spread and generally perpendicular to the electromagnetic profiles as shown in Figure 6.

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 resistivity data are interpreted on a microcomputer 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, accurate location and angle of near vertical discontinuities such 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 6: Schematic Layout of Geophysical Survey at Omboga Secondary School



The importance of a standard survey technique can be illustrated by several practical examples. At Omboga Secondary School, situated in a dry area, the nearest perennial water sources were 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 sounding 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. The location and slope of this sub-vertical zone was assessed and a borehole location selected. 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. A typical relationship between the geology and geophysical soundings at such a site is shown in Figure 7.

At God Bim school a successful borehole was drilled exactly on a fault with a maximum yield of 24 m^3/h whilst at Otati school. An 85 m deep borehole was erroneously drilled 30 meters away from the interpreted fault structure and was dry. However a later borehole relocated on the fault proved successful. Field data from these two sites are shown in Figure 8.

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 percent) and a similarly significant reduction in the depth of drilling (44 percent), both factors strongly reducing the cost of drilling per well (by 63 percent) 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 socioeconomic criteria.

The Programme gives a somewhat optimistic breakdown of the siting costs (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 percent) 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 5: Comparison of Results and Drilling Cost of Existing and Programme Boreholes
(US dollars)

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	17,700
Nyanzian volcanics	19	68	116	95	10,600
Granites	7	43	70	48	10,200
Subtotal	62	52	117	113	226,700
Programme boreholes					
Tertiary volcanics	60	78	68	340	5,400
Nyanzian volcanics	11	91	54	94	3,700
Granites	10	60	61	140	6,350
Subtotal	81	78	65	270	5,200

Table 6: Breakdown of Cost for Groundwater Surveys
(US dollars)

Description	*Total cost*	*Depreciation period (months)*	*Annual cost*	*Cost per site (250s/year)*
Equipment (duty free)				
ABEM SAS 300 Terrameter	12,500	60	2,500	10
Geonics EM 34	22,000	60	4,400	18
Computer, printer, plotter, and software	17,200	60	3,440	14
4x4 car	18,750	60	3,750	15
Camping sets (6)	5,000	24	2,500	10
Stereoscope, aerial, and satellite photos	1,500	60	320	1
Personnel (Kenyan)				
Geologist			7,500	30
Field team leader			3,750	15
Surveyors (4)			7,500	30
Casual laborers (2)			1,250	5
Running cost				
Auto fuel and maintenance	7,500	30		
Materials	2,500	10		
Total	76,950		46,910	188

Figure 7: Schematic Section through Precambrian Granite with Corresponding GE and EM Profiles

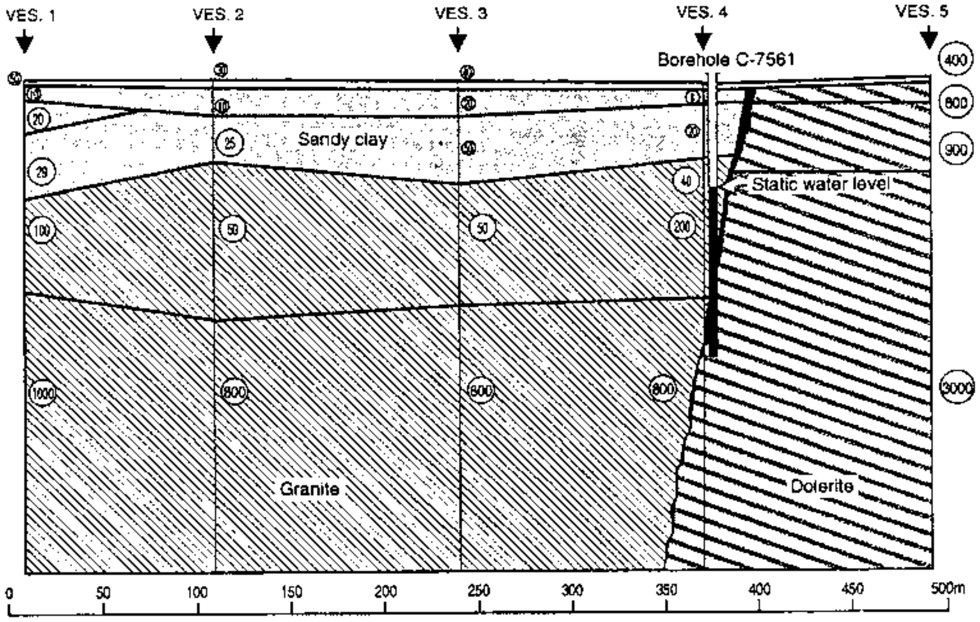
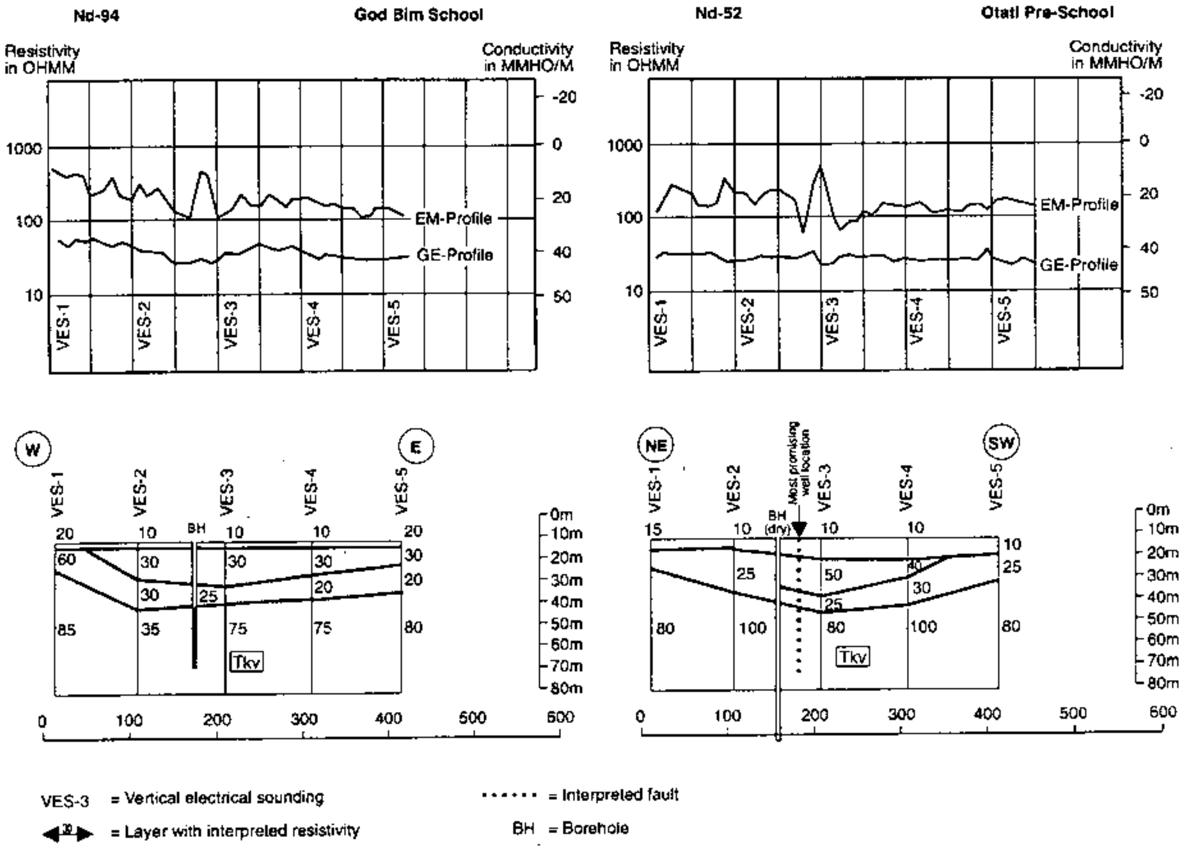


Figure 8: Hydrogeological Cross Sections Interpreted from the Geophysical Data for God Bim School and Otati Primary School in Tertiary Volcanics



Appendix I

Well Siting Techniques

1. Electrical Resistivity Sounding

The principle of the electrical resistivity method, or vertical electrical sounding (VES), is the measurement of the earth's electrical resistance by passing low frequency current into the ground through two metal "current electrodes" and measuring the potential difference resulting across two "potential electrodes." If the distance between the four electrodes is known then a resistivity of the earth may be calculated. Increasing the distance between electrodes effectively increases the depth of penetration of the sounding.

Electricity can be conducted through rocks in two ways. Electronic conduction occurs when the mineral grains themselves are conductive, for example if magnetite is present. However, most mineral grains such as quartz and feldspar are nonconductive, and in such cases conduction is ionic or through ions in the interstitial fluid. By knowing the expected resisitivities of the rock encountered, anomalies can be investigated to infer the presence of groundwater.

Resistivity equipment is light and easily carried in a vehicle. It does take some time to set up, but several sites may be investigated in one day.

2. Seismic Refraction

In the seismic refraction method an explosive charge, weight drop, or hammer blow is used to generate a shock wave (called the "shot") at the earth's surface. The radiating energy travels by several paths through the subsurface medium. It is refracted along boundaries and returns to the surface, where it can be recorded by an array of detectors or geophones. The time lapse between the shot and the first arrival of the refracted wave is plotted onto a curve. This provides information on depths to the refracting boundary and the seismic velocity of the underground layer.

Seismic refraction is suitable for low-cost groundwater investigation projects of a medium or large scale, since the method is rapid and provides a comprehensive amount of information at a reasonable cost. One or more sites can be investigated per day, providing reliable information on the types of underlying rock, their depth below the surface, and the likely occurrence of groundwater.

Seismic refraction has been successfully used in conjunction with resistivity and gravity techniques. A further modification is seismic reflection surveys in which waves reflected from boundary layers are recorded at the earth's surface using high resolution recording equipment. This method is popular for oil exploration, and recent advances have modified it for shallow-depth surveys so that it may become a promising tool for groundwater investigations.

3. Electromagnetic Method (EM)

This technique studies subsurface conductivity by generating a time varying magnetic field in a transmitter coil. This field induces a small current which in turn generates a secondary magnetic field. This is detected by a receiver coil placed a short distance away. There is no need to make an electrical connection with the earth, which makes the instrument very mobile, hence its ability to measure several hundreds of meters of profile per day. Increasing the distance between the transmitter and receiver effectively increases the depth of penetration.

Interpretation of the readings can be done by plotting graphs or using computer programs. The equipment is usually very light and operated by one or two technicians.

A current development of the EM technique is the transient electromagnetic method (TEM), or time-domain EM (TDEM) technique, which may become more popular since it can be used to carry out quantitative depth sounding much like resistivity sounding, except that there is no need to change the distance between the transmitter and receiver coils to achieve deeper penetration.

4. Very Low Frequency EM

This technique operates on the same physical principle as EM, but uses the signals of existing VLF radio transmitters rather than generate its own signal. The equipment usually consists of a small receiver set that can be carried by one person, enabling several kilometers to be traversed and profiled in a day. Interpretation is accomplished with graph plotting or the use of computer programmes.

The technique requires that the area being surveyed be covered by a strong VLF transmitter, preferably two. Manufacturers also produce small portable transmitters that are light, easy to use, and less expensive than other options. But their penetration depth is restricted to about 30 meters.

5. Gravimetry

The earth's gravitational field measured on the surface is influenced by the density of the rock beneath the measuring station. Thus, it is possible to measure small variations in the earth's magnetic field at a number of stations and thus infer the nature of subsurface geological structures. The instrument used, a gravimeter, is basically a very sensitive spring balance, in fact so sensitive that it is common to routinely check its reading against a base station several times a day. A range of corrections must be made to adjust the field reading to a standard value known as the Bougler anomaly, these include having to determine the elevation and latitude of each station. The gravity contours are then plotted onto a map from which geological features are inferred.

Gravimetric information is particulary useful when used in conjunction with seismic or resistivity information, however, on its own is more suited to large scale regional studies.

6. Magnetometery

Magnetometery involves measurements of the direction and intensity of the earth's magnetic field. Magnetic surveys can be made on the land surface, from the air or from a ship. Magnetometery is most useful with basaltic volcanics and in basement areas as these rocks contain a larger proportion of magnetic minerals than most sedimentary formations. Quantitative interpretation is often ambiguous and in practice EM methods are often preferred in these situations. However, magnetometric surveys have been applied successfully in several African countries to locate water bearing zones associated with intrusions into basement rock.

7. 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 sceptical 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 used to locate potential well sites. One recent report concerning a rural water-supply project in Sri Lanka claims that it was the most effective method, siting 600 wells with an almost 100 percent success rate in terms of overall accuracy, the amount of information obtained, water quality, and guidance for drilling crews (Schleberger, 1986).

There are some grounds for a scientific explanation of the dowsing method. Geophysical experiments carried out in the Netherlands, Saudi Arabia and the Soviet Union (Mijne, n.d.) correlated with test drilling appear to have resulted in significant and repeatable results, occasionally surpassing geophysical methods in the same area.

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, have also indicated expensive failures, suggesting that some dowsers are less successful than they would like to believe.

8. Magnetotellurics

The magnetotelluric method (MT) is an electromagnetic technique which uses natural electrical and magnetic fields for determining the electrical properties of the earth at great depths, thus no transmitter is required. Its applications to groundwater survey so far have been limited.

9. Ground Radar

Subsurface penetration by ground radar is in the order of 3 to 10 meters and under ideal conditions up to 20 m, there are a few examples where it has been used with success for groundwater survey. In areas with limited penetration of radar the technique is virtually useless.

10. Airborne Geophysics

The Airborne Electromagnetic Method (AEM) is the most common airborne geophysical technique. Its use in groundwater survey has become possible due to developments in instrumentation making identification of subsurface conductive zones possible to a depth of 200 meters (Palacky, 1981; Paterson and Bosschart, 1987). The main drawbacks that keep the use of AEM out of the CWS realm are the high cost of flying the surveys and the subsequent need for geophysical follow-up on the ground.

Appendix II

Reported Use of Geophysical Equipment in Africa

	Low-cost rural supplies	*General groundwater investigations*	*High-yield well siting*
Resistivity			
ABEM SAS 300 Terrameter (Sweden)	13	10	20
BGS 256 Offset System[a] (UK)	1	4	2
Bodenseewerke GGA 30(FRG)	1	1	2
BRGM Syscal Resistivity (France)	6	0	2
Geska (?) (Czechoslovakia)	0	2	1
Jesse (Netherlands)	1	0	1
TNO-DGV GEA 51 (Netherlands)	0	1	0
Seismic refraction			
ABEM Trio (Sweden)	1	1	2
Bison 1550 (USA)	1	0	1
Bison 2350 B(USA)	1	0	1
EG&G Geometrics ES 125(USA)	1	0	1
EG&G Geometrics 1210 F(USA)	0	1	1
OYO McSeis (160) (Japan)	1	1	1
Electromagnetics			
APEX Max Min (Canada)	1	1	2
Geonics EM 34 (Canada)	3	3	5
GSO Turam Enslin (RSA)	0	2	1
VLF			
BRGM Syscal VLF (France)	1	0	1
Geonics EM 16 (Canada)	2	1	3
EDA-ERA (Czechoslovakia)	0	1	1
Magnetometery			
BRGM Elsec Proton Magn. (France)	2	0	2
G 816 Proton Magn. (Canada)	0	1	1
Unspecified Proton Magn.	1	0	1
Gravity			
Worden (USA)	0	2	1
Hand drilling			
Morogoro (Tanzania/Netherlands)	1	0	1
Eykelkamp (Netherlands)	1	0	1

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

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

Source: Questionnaire responses from 54 consultants and 14 organizations (1987).

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