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Groundwater Exploration and Management using Geophysics: Northern Region of Ghana

Grundwassererforschung und- management mittels Geophysik in the Nordregion von Ghana

Submitted by: **Ewusi Anthony**

Matriculation No: **2116319**

Born: **31.05.1972**

in: **Ghana**

1. Supervisor

Prof. Dr. rer. nat. habil. Hans-Jürgen Voigt

2. Supervisor

Prof. Dr. rer. nat. habil. Albrecht Gnauck

3. Supervisor

Dr. rer. nat. Helfried Petzold

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DEDICATED TO MY DEAR CHILDREN KOBINA EWUSI AND EKOW HANS

Abstract

Groundwater has been identified as the best source for rural water supply in most rural communities in the Northern region of Ghana because it eliminates the problems of water borne diseases which have affected communities in the region over the years. The guinea worm disease is presently not totally eradicated in the area and there are signals that its occurrence will be increasing in the near future if adequate measures are not implemented to curtail the problem. Adequate groundwater exploration and management appears to be the key to ensure that potable and safe water is available for the entire population of the region and that its availability on a sustainable basis is guaranteed.

Groundwater facilities being provided in the area include; engineered hand dug wells, boreholes fitted with hand pumps and mechanised small towns' piped schemes. Groundwater exploration programs implemented have however resulted in low success rates of borehole drilling because of the lack of a systematic and methodological approach. The available conventional geophysical techniques; one dimensional (1-D) electrical resistivity profiling and sounding as well as the electromagnetic (EM) methods have not been able to efficiently select suitable sites for successful borehole drilling because of their inability to successfully demarcate areas which are likely aquifer potential zones for successful groundwater abstraction. Current borehole drilling success rates especially in the Voltain rock formation are very low.

The complex geological setting of groundwater systems in the area gives cause for the adoption and application of a systematic methodological approach in groundwater exploration utilising effective geophysical techniques. Available geophysical techniques which have been considered in this research work include; two dimensional (2-D) multi-electrode electrical resistivity survey, electro kinetic survey (EKS) and the radon survey.

Keywords; Groundwater, geophysical techniques, 2-D multi-electrode electrical resistivity survey, electro kinetic survey, radon survey.

Zusammenfassung:

Grundwasser hat sich als die beste Quelle für die Trinkwasserversorgung in den ländlichen Regionen im nördlichen Teil Ghanas herausgestellt, weil dadurch die durch das Trinkwasser übertragenen Krankheiten ausgeschlossen werden, die seit Jahren die Gemeinden der Region befallen. Die durch den Guineawurm verursachte Krankheit ist in der Region heutzutage noch nicht ganz ausgerottet, und es gibt Hinweise, dass ihr Auftreten in der nahen Zukunft zunehmen würde, falls keine betreffenden Maßnahmen unternommen werden. Angemessene Grundwassererkundung und Grundwassermanagement sind ein wesentlicher Faktor, um sicherzustellen, dass sicheres und trinkbares Wasser für die ganze Bevölkerung der Region zur Verfügung steht und dass die Wasserverfügbarkeit auf einer nachhaltigen Basis garantiert wird.

Die im Gebiet vorhandene Einrichtungen zur Grundwasserförderung umfassen handgeschachtete Brunnen, mit Handpumpen ausgestattete Bohrungen und Rohrleitungsinstallationen für größere Dörfer.

Bisherige Grundwassererkundungsprogrammen hatten eine niedrige Erfolgsquote (d.h. Anteil grundwasserliefernder Brunnen), weil es an den systematischen und methodologischen Ansätzen mangelte. Die verfügbaren herkömmliche geophysikalische Methoden – eindimensionale (1-D) elektrische Widerstandsprofile und -sondierungen und elektromagnetische (EM) Methoden – waren für die Ausweisung grundwasserhöflicher Bohrlokationen wenig geeignet. Die gegenwärtige Erfolgsquote von Brunnenbohrungen, besonders in der Voltain-Formation, ist sehr niedrig.

Die komplexen geologischen Verhältnisse, die die Grundwassersysteme im Untersuchungsgebiet prägen, gaben Anlass zur Entwicklung einer systematischen methodologischen Grundwassererkundung mit Einsatz effektiver geophysikalischer Methoden. Die verfügbaren geophysikalischen Verfahren, die in dieser Arbeit betrachtet wurden, sind die zweidimensionale (2-D) elektrische Widerstandskartierung, das elektrokinetische Verfahren (electro kinetic survey, EKS) und die Radon-Kartierung.

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1.0 INTRODUCTION

1.1 Background

The northern region is divided into 13 administrative districts and constitutes more than a quarter of the total land area of Ghana. Apart from Tamale township, the capital of the region which has piped borne water supply, most of the communities in the region depend on untreated surface water sources, dams, dugouts and ground water exploited by boreholes and hand dug wells. With the increasing awareness of guinea worm and other water borne infectious diseases associated with untreated surface water bodies emphasis has been placed high on the use of groundwater by drilling boreholes and engineered hand dug wells.

The Government of Ghana, in its determination to provide potable and safe drinking water for the rural communities in the region and the country as a whole, has adopted a community ownership and management (COM) concept in the provision of water supply facilities in order to ensure long-term sustainability. With this approach management and operations of the water facilities are entrusted in the care of the beneficiary communities. Groundwater based systems have been considered to be the cost-effective technologies for community management in the area since no treatment of the water is required.

Over half the world's population depends on groundwater for drinking water supplies. In the UK, about 30% of the public water supplies are derived from groundwater, in the USA about 50%, Denmark 99% (Tebbut, 1992; Mato, 2002) and Germany 70% (Trauth and Xanothopoulous, 1997 in Mato, 2002). 52% of rural inhabitants have access to potable water mainly from groundwater sources in Ghana (Gyau-Boakye and Dapaah-Siakwan, 1999). Facilities considered for groundwater supplies with respect to rural communities and small towns in the northern region of Ghana include hand-dug wells, boreholes fitted with hand pumps and borehole sources for mechanized town water supply popularly referred to as small towns' water supply schemes.

Various groundwater exploration programs that have been carried out in the area have not yielded the required results in terms of success with regards to yields of boreholes

limits classified as successful by the Community Water and Sanitation Agency (CWSA). These programs have mostly utilized the ‘conventional geophysical techniques’ in the context of this research for groundwater investigations adapted for rural supply projects in most developing countries where techniques are quite simple and inexpensive. Geophysical techniques using the one dimensional (1-D) electrical resistivity profiling and sounding with four electrodes which have been used in the area over the past years are referred to as the conventional techniques. These techniques have been applied in the area without any systematic methodological approach which has also contributed significantly to the failures of most groundwater projects. Financial considerations have played a major role in the selection of geophysical techniques for groundwater exploration in Ghana.

These conventional techniques have however not been able to efficiently demarcate geological structures indicating the presence of possible aquifers for successful borehole drilling after considering the results of various programs in the area and have therefore necessitated the need for the introduction of more advance and effective techniques. The geological groups that have been classified as very difficult in terms of successful borehole drilling and therefore need the application of advanced state-of-the-art and efficient techniques are the areas with dominant shale and/or mudstone lithologies which are noted for very low success results in groundwater exploration programs.

Available state-of-the-art techniques which have been considered in this research, with the aim of developing a methodological approach to their application in the area include the radon survey, electro-kinetic sounding (EKS) survey and the 2-D multi-electrode electrical resistivity imaging survey.

1.2 Background of groundwater exploration in the area

Apart from the cities and urban centers which have pipe borne water in Ghana, most rural communities depend on surface and ground waters. Even in the cities and urban centers many communities depend on shallow hand dug wells which are mostly private owned (Ali, 1996).

In Ghana hand dug wells are usually between 2.4-12 m. The dryer northern region usually has hand dug well depths greater than 5 m (Ali, 1996). Boreholes are normally deep and usually over 20 m deep. Borehole depths in the northern region especially in the difficult shale and mudstone region are normally at the intermediate to deeper depth horizon between 30-80 m.

As a general guide for groundwater exploration, C.W.S.A has made the following classification for borehole drilling. These classifications have therefore been used for the evaluation of the efficiency of the new techniques. Borehole yields for hand pump installation are categorized as follows;

- Yields greater than 14 litres per minute as successful
- Yields between 14 litres per minute and 5 litres per minute as marginal
- Yields less than 5 litres per minute as dry

Borehole sources for small town water supply schemes usually require a yield greater than 100 litres per minute to be considered successful.

Existing data from previous projects in the northern region indicate that the drilling success rates vary as low as 25% in the Voltain sedimentary formation to a maximum of 65% in the Birimian formations (Unihydro, 2003). The main impacts of low success rates make most groundwater exploration very expensive since these substantial amounts of dry wells add up to overall project implementation cost.

Selection of the most appropriate geophysical technique, methodology and the correct application of these methods is therefore utmost important.

1.3 Objectives of the study

From the preceding sections it may be noted that various groundwater exploration programs have failed with low borehole drilling success rates because of the lack of a systematic approach and effective geophysical techniques capable of selecting potential successful borehole drilling sites.

Project aims have therefore not been fulfilled and programs have been undertaken based on individual project guidelines without a general methodological approach to groundwater exploration with respect to peculiar geological environment.

The main objective therefore of this research is to investigate the development potential of groundwater in the problematic geological environment of the area where the demand for water for rural communities is expected to grow as a result of population growth, and to develop a systematic methodology and guidelines for groundwater exploration in the various geological environments which can be transferred to other parts of the country. Evaluations of the currently used conventional methods and ways in which they can be improved have also been considered. It is very important to consider techniques and equipments which are easy to use taking into account the education level and training of the operators. Geophysical techniques which are very sophisticated and require advanced training and special knowledge to operate might be very expensive to use since an expert has to be present before it can be used. The high temperature in the area especially during the dry season period is also another factor which has to be considered in the selection of geophysical techniques since certain equipments cannot withstand these high temperatures.

The geological evaluation of target features, methodology and guidelines for groundwater exploration will assist water practitioners in siting boreholes and interpreting geophysical data. It will also reduce the use of inappropriate geophysical methods and/or the siting of boreholes based on an incorrect geophysical interpretation. This will reduce the frequency of incorrectly sited boreholes and increase the drilling success rate of wells in the area.

The research has therefore involved:

- Investigating the general approach to groundwater exploration in the area.
- Investigating into the conventional geophysical techniques previously employed in the area and ways to make them more efficient especially with the data acquisition procedure.

- Carrying out a pilot study and calibration of the three improved state of the art techniques; two dimensional (2-D) multi-electrode electrical resistivity imaging survey, electrokinetic sounding (EKS) survey and the radon survey.
- Investigating into the suitability of the 2-D multi-electrode resistivity survey and the EKS techniques with regards to the different geological units.
- Providing a standard methodological approach and guidelines for groundwater exploration in the area with regards to the individual geological targets that could be transferred to other parts of the country with similar geology and hydrogeological conditions.

2.0 DESCRIPTION OF THE AREA

The area is a sparsely populated rural region with underdeveloped infrastructure and services and has been identified as a critical water deficit area based on the water supply coverage (Unihydro, 2000). Water supply availability is a serious problem and the area relies mostly on dugouts, dams, hand-dug wells and some boreholes. Groundwater is a preferred water supply option in the area because it is generally available even in drought situations and it has relatively good quality. Groundwater is not only feasible but also the most economic source of potable water due to the dispersed nature of the rural settlement (Gyau-Boakye and Dapaah-Siakwan, 1999).

2.1 Location and general geology

The northern region is one of the ten region administrative regions of Ghana. It is located approximately between latitudes $8^{\circ} 45'S$ and $10^{\circ} 15'N$ and Longitudes $1^{\circ} 0'W$ and $0^{\circ} 30'E$. The major parts of the region fall within the Voltaian Basin which covers more than a third of the total area of Ghana (fig. 1).

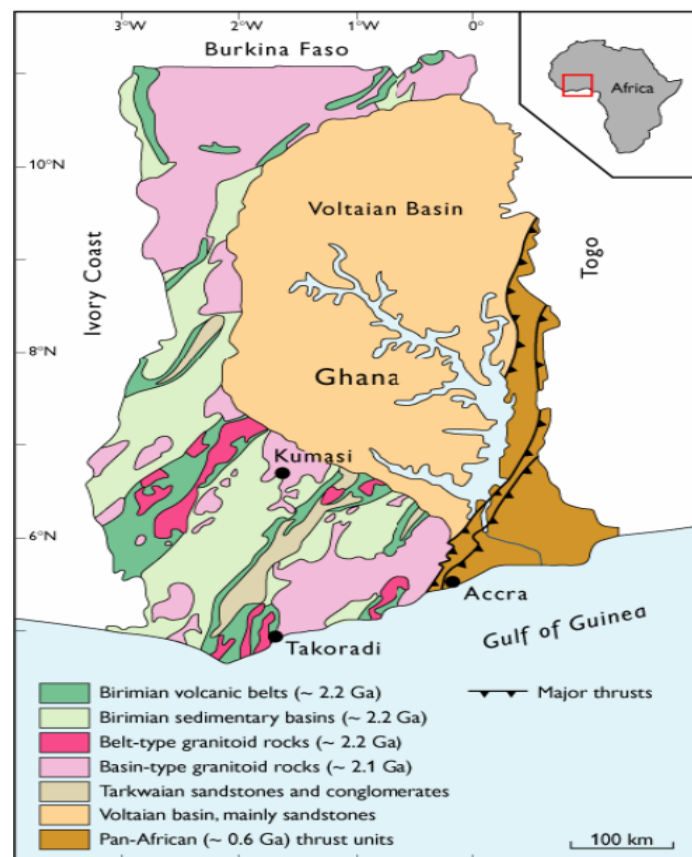


Figure 1: Simplified geological map of Ghana. (modified from Kesse, 1985 in Kalsbeek *et al*, 2003)

2.2 Topography, drainage and vegetation

The area is essentially flat and lying with a rolling terrain and a few scattered hills. Ground elevations usually range between 120 m and 180 m above mean sea level. The Oti-Daka river basin and the White Volta basin drain the area. Apart from the White Volta, Oti and Daka rivers, many of the rivers that drain the area are only seasonal and become ponded or dry up completely during the long dry season. There are two main mechanisms of groundwater recharge, generally percolation of soil water, which moves past the plants root zone and percolation from the beds of the rivers in the area. The area is basically guinea savannah woodland with the main tree species being acacia, baobab, and shea nut trees and it is thickly grassed (Unihydro, 2002).

The annual rainfall in the northern region ranges from 1016 mm to 1600 mm with evapo-transpiration averaging around 890 mm (Kwei, 1997).

There are normally seasonal flow of streams and other surface water bodies. There is a 6-month (October-April) dry period. Rainfall is relatively high during the rainy season varying from 1000 mm to 1300 mm annually with an estimated runoff coefficient of 10% of total rainfall (Todd, 1981).

A thin lateritic hard pan rests on the bedrock with practically no percolation below the hard pan resulting in extensive flooding with little runoff due to the low relief. Groundwater recharge is mainly through fractures, which have variable lateral extent and densities.

2.3 Climate

The main characteristics of the local climate are the long dry season, high temperatures and the dusty atmospheres during the hamartan. Temperatures can be as high as 43 degrees during the month of April and the annual precipitation is between 1016mm and 1143mm (Unihydro, 2002). The climatic parameters of rainfall and potential evapotranspiration as well as the plant-soil complex and general slope determine the groundwater recharge. Because of the extreme high temperatures in the area, rainfall is usually evaporated back into the atmosphere with little water percolating beyond deep depth for groundwater recharge. In some parts of the area

that is always flooded during the main raining season, percolation is the dominant groundwater recharge component.

2.4 Geological environment

A good appreciation of geology is fundamental in any groundwater development program since the geology determines where, how and what quantities and quality groundwater occurs (Unihydro, 2002). The Voltain sedimentary basin comprising horizontally bedded consolidated sedimentary rocks belonging to the Paleozoic age, which overlie unconformable by the middle Precambrian Birimian system, predominantly underlie the area (fig. 1). The Birimian system (comprising phyllites, schist, greywacke and granite intrusions) underlies the Voltain system and outcrops along the western and northwestern boundary of the area (fig. 2).

Intruded into the Birimian rocks are the large masses of granitoids known as Cape Coast and Winneba (G.1) rock types, smaller masses of granitoids called the Discover (G.2) and the Bongo potassic granitoids found mainly in the northern part of the country. The Birimian system has been folded metamorphosed and in places assimilated by granitoid bodies (fig. 2). The folding is intense with dips commonly on the order of 30-90 degrees along a NE – SW axis and of 70-90 degrees being more common than the shallower dips. Faulting tends to follow the strike of the folds and also trends perpendicular to the latter. Jointing in these rocks has many orientations but most commonly is parallel to fold and fault directions and in a north-south direction (Kesse, 1985).

The Voltain formations consist of quartzite, shale, mudstone, siltstone, sandstone and conglomerate or pebbly beds. Although there are areas of uniform lithology, interbedding of the different lithological units is a common geological feature of the basin.

The three general classifications of the Voltain formation are as follows:

- Upper Voltain that is made up of massive, cross-bedded quartzite sandstones, which in some localities are interbedded with shale and mudstone.

- Middle Voltain consisting of essentially argillaceous Obosum beds (which comprise shale, mudstone, siltstone and minor limestone and sandstone) and the arenaceous Oti beds (which comprise arkose, conglomerate, grit, shale and minor limestone).
- Lower Voltain or Basal Sandstone, which is made up of massive quartzite sandstone with minor grit (Unihydro, 2002).

According to Kesse, 1985, (Jones, 1978) proposed the following ages of the Voltain system;

Upper Voltain: Upper Ordovician- Lower Carboniferous
(450-320 million years)

Middle Voltain: Lower Vendian-Lower Ordovician
(675-480 million years)

Lower Voltain: Late Middle Rhiphaean – Upper Rhiphaean
(1,000-700 million years)

It is the view of the geological survey of Ghana that the Voltain system ranges in age from upper Proterozoic to Paleozoic; 620-1000 million years (Kesse, 1985).

A lot of geophysical investigations for groundwater have been carried out in the area using the conventional geophysical methods. Shell Company carried out an airborne magnetic survey over the entire Volta basin and the survey indicated that the maximum thickness of the sediments in the basin could be between 3,000 to 4,000 meters. The survey also indicated that the basin gradually deepens towards its eastern margin (Kesse, 1985).

The rocks in the area have joint systems oriented in the (NE-SW) directions and this was confirmed by available aerial photograph interpretation during the research work.

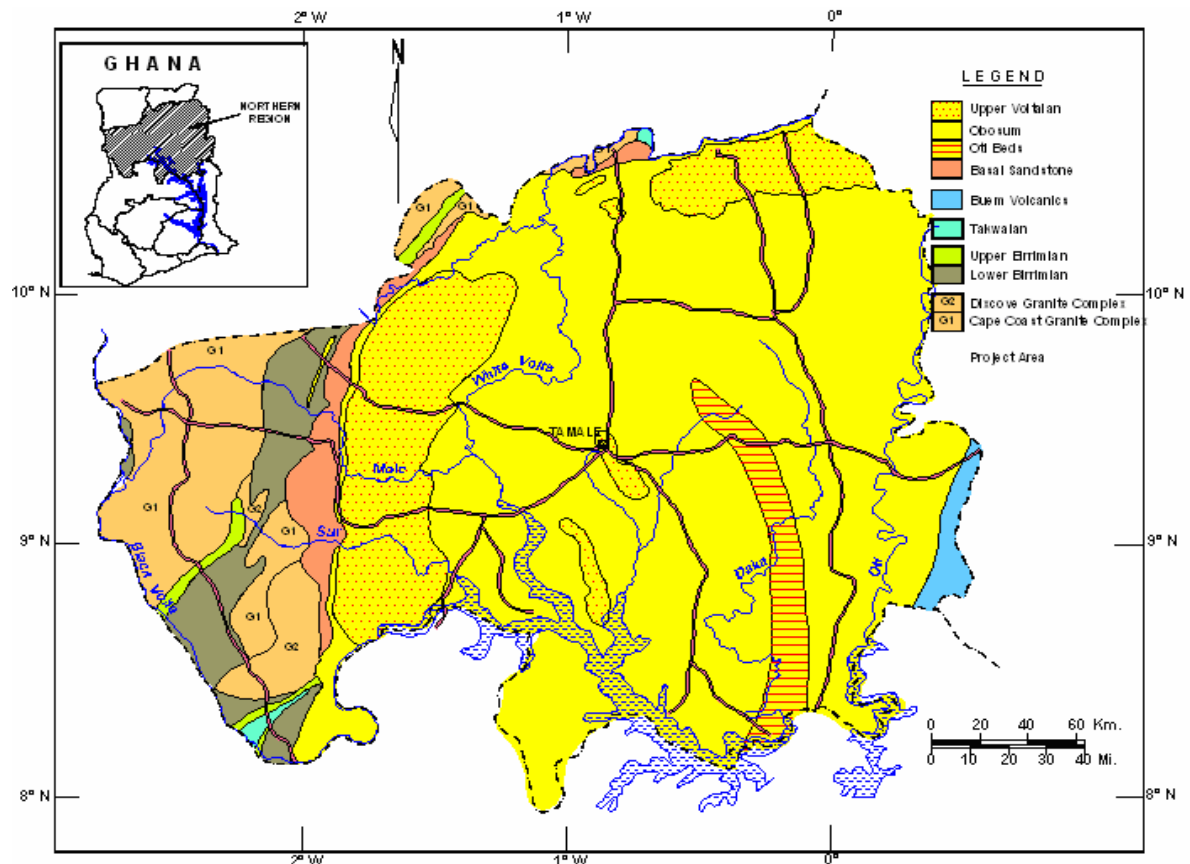


Figure 2: Simplified geology map of northern Ghana. (modified from Kesse, 1985)

2.4.1 Geologic problematic areas

Areas, which are peculiar with unsuccessful groundwater exploration programs, are the areas with dominant shale and/or mudstone lithologies. These areas have the following characteristics including;

- Impermeable bedding planes in the shale or mudstone
- Limited shear zones with non existing micro-fissures in the mudstone
- Unfractured siltstone or sandstone interbeds within the shale or mudstone(Unihydro, 2004)

2.4.2 Hydrogeology

Borehole data from community water and sanitation (CWSA) northern region and the World Vision International (WVI) have been used to evaluate the hydrogeology of the area. Data indicates low yields in the shale dominated areas of the Voltaian formation and high yields with good success rates of borehole drilling in the arenaceous Oti beds of the Voltaian formation which are fractured, permeable and have good infiltration capabilities.

The middle Voltain Obosum beds cover a greater part of the region and the stratigraphy alternates between the upper shale underlain by the mudstones and the upper mudstone underlain by meta-shale. In areas where either shale or mudstone is predominant, the rock body may be interbedded with siltstone.

Structural features associated with groundwater in the Voltain system are generally associated with bedding planes, weathering depths, joint systems and lithological boundaries (both vertical and horizontal). The siltstones, sandstones and arkoses are also well jointed. Borehole and geophysical data indicate a thin regolith in the Voltain basin with a very thin lateritic soil cover.

The lower Birimian however has a thick regolith and enough yields are obtained in this zone. However very high yields have also been obtained in fractures within the fresh rock from analysis of borehole drilling data in the area. The success rates of borehole drilling in the Birimian areas have always been better than that of the Voltain formation. The granite rocks associated with the Birimian rocks are coherently permeable but have secondary permeability or porosity developed as results of jointing, fracturing and weathering (Kesse, 1985).

2.5 Water supply

Water supply sources must be able to meet demands throughout the year as well as being able to cover future demands. Groundwater sources do not involve treatment cost, are reliable for community management and are therefore increasingly becoming the major source for domestic water supply in the area.

The extreme high temperatures resulting in high evapotranspiration make surface water body sources unsuitable in the area. Most surface water sources dry up during the long dry season periods that are normally associated with high temperatures. The additional treatment cost of surface water bodies also makes groundwater more favorable in the area. The efficient utilization of groundwater and efficient management of aquifers, hand-dug wells and boreholes therefore appear to be the solution to problems of traditional rural water supply systems (Gyau-Boakye and Dapaah-Siakwan, 1999). Groundwater sources if properly evaluated will be the most reliable water supply source in the area. There have been incidence of boreholes

drying up in the dry season but these cases have been limited to certain borehole depths and yields in particular geological environments.

Where water supply scheme has to rely on surface waters especially in areas of unsuccessful groundwater exploration, water treatment may be unavoidable. These treatment options are quite expensive in the context of rural water supply especially when it has to be operated and managed by the beneficiary community and are therefore not the best option.

2.6 Groundwater quality

The water from the Birimian rocks and associated granites on analysis has been found to be usable for all purposes. In some cases temporary hardness have been found to exceed 100 mg/l and the iron and manganese concentrations are above 0.3 mg/l. The water can be used without treatment (Kesse, 1985).

The general groundwater quality has been very satisfactory in the area according to water quality data obtained from CWSA. There have been some few cases of high iron, turbidity and chloride levels. High fluoride levels also occur but are limited to the granite rocks.

Minor occurrences of saline groundwater typically related to high sulphate concentrations have been noted in isolated boreholes in rocks of the Voltain Basin (Pelig-Ba, 1999).

2.7 Water borne disease in the area

Guinea worm disease is the main water borne disease in the area. It is a parasitic worm disease that is protracted when a person drinks standing water containing a tiny larva of the guinea worm. Over the course of a year in the human body, the immature worms pierce the intestinal wall, grow to adulthood, and mate. The males die and the females make their way through the body maturing to a length of as much as 3 feet and ending up near the surface of the skin. The worms cause swelling and painful burning blisters. To soothe the burning, sufferers tend to go into the water, where the blisters burst, allowing the worm to emerge and release a new generation of millions of larvae. In the water, small water fleas swallow the larvae, and the cycle begins

again (<http://www.astdhpphe.org/infect/guinea.html>). Infected persons usually do not have symptoms until about a year after they drink water contaminated with infected water fleas.

There is no cure for this disease after infection. The worm can however be removed by winding it around a stick and pulling it by tying at a time. It can sometimes be pulled in some days but it usually takes weeks and months. The disease is very rampant in areas of the northern region where there are no groundwater sources and as such inhabitants resort to infected surface water for drinking and have been an epidemic in parts of the study area where groundwater exploration programs have failed.

3.0 OVERVIEW OF GROUNDWATER EXPLORATION IN AREA

Several borehole projects have been carried out in the area but most of these projects have encountered difficulties in boreholes siting, resulting in very low success rates and yields lower than the minimum approved limit for borehole construction by the CWSA.

The northern region CWSA has been the main governmental organization responsible for groundwater development in the area. Most of the groundwater exploration programs have been funded by international donors notably Canadian International Development Agency (CIDA), Japan International Cooperation Agency (JICA), International Development Agency (IDA), Alliance Francoise de Development (AFD), Baptist Church, Roman Catholic Church and European Union (EU) etc. The World Vision International has also been very instrumental in the provision of groundwater facilities for most of the communities in the region for a very long period.

RCC, JICA, CIDA, BPT and WVI provided 865 borehole facilities during the period 1987-1991(Ali, 1996).

3.1 Assessment of previous geophysical techniques

Geophysical methods selected for borehole siting had been developed from recommendations made by a JICA funded project carried out during the period 1980 to 1989. The project evaluated a series of siting techniques and recommended that the target for boreholes in the geological formations of the region are the fractures and thus siting should be carried out with two different successive measurements; electrical resistivity or electromagnetic profile supposed to identify a discontinuity in the terrain, assuming that the discontinuity is representing a fracture zone and a dipole-dipole geo-electrical sounding identified as the most sensitive method for aquifer detection in the Voltain formations. Most groundwater exploration programs after these recommendations therefore adopted this procedure and practice.

Observations made from reports available on these projects indicates that most of the siting operations did not make use of aerial photographs which were either not available at the time or had such bad quality that no good, useful and reliable

information could be obtained. The main target for groundwater exploration was therefore the weak zones. Some structures identified from the air photos were also very far from the communities, which had applied for the facilities. The CWSA, the main facilitator of these projects has a guideline, which allows a maximum distance limit of 2 km distance from a community where a facility has to be sited. In this consideration therefore, interesting structures identified out of this range were not exploited.

Data on groundwater exploration projects in the area from CSWA, WVI and Unihydro ltd. have been evaluated and the following observations made as follows;

- Geophysical profiles were not specifically oriented across the general fracturing trend in the various rock formations but were set across local depressions.
- The density of measured points along the profile was very low; measurements at 10 m or sometimes 20 m space interval. This therefore led to measurements not able to pick fracturing zones probably less than 10m.
- Most of the electrical resistivity profiling used the Schlumberger configuration at two-depth horizon of 19 m and 40 m separation for the two current electrodes and 0.5 m and 5 m for the potential electrodes. This therefore gave a maximum depth investigation between 15 m and 20 m likewise for the EM profiling. These investigation depths appear to be shallow.
- Most of the profiles did not show any evidence of geological discontinuities as have been perceived. The VES sounding, which was normally carried out after the electrical resistivity profile, did not also give any additional useful information especially in the shale dominant regions.

3.2 Possible strategy for improvements with the conventional techniques

In the Volcanic sedimentary terrains, the target of the geophysical investigation should be the weathered zone and the fracture itself as well. The methodology should therefore be adapted to intercept fractures by reducing the spacing between the stations especially in situations where the fracture is sharp and discontinuous. The depth of investigations should also be increased in that the discontinuity should

appear in any competent bed from the surface to intermediate and deeper depths in the basin. The following recommendations for possible improvement using the conventional techniques can be considered as follows;

- Either measurement is taken at 5 m interval or at the usual 10 m intervals but a short profile at 2 m intervals carried out at probable fracture and weathered zones to confirm the anomaly.
- Parallel profiles on both sides of the traverse direction at about 5 m from the original traverse could also be carried out at these stations to confirm the extent of the anomalies.
- In situations without aerial photographs the general fracture and joint trends could be used to orient the traverses.

4.0 CONCEPTS OF GEOPHYSICAL TECHNIQUES

Conducting geophysical investigations include survey design, data acquisition and data analysis. These three aspects of an experiment are commonly treated independently (Stummer, 2003) and the applicability of the method under the geological conditions must be taken into account.

4.1 Electrical resistivity

The use of electrical resistivity measurements has been a favourite tool of geophysics for over 200 years because of the wide range of resistivity values found in nature. Resistivities in various geologic settings can be found ranging from less than 1ohm-meter for ore bodies to over 10000 ohm-meters for Precambrian gneiss. This represents a greater dynamic range for this technique than most of the commonly used methods (Hoover *et al*, 1999).

Electrical resistivity techniques have been used in many geological formations for characterizing the subsurface for many years. (Roman, 1951; Heather *et al*, 1999). In the earlier applications, the technique was considered to be very labour intensive. The development of the multi-electrode surveys has been able to reduce this aspect of the survey (Heather *et al*, 1999).

4.1.1 Basic principles

Groundwater, through the various dissolved salts it contains, is ionically conductive and enables electric currents to flow into the ground. By measuring the ground and subsurface resistivity therefore gives the possibility to identify conditions necessary for the presence or otherwise of water. Resistivities of rocks generally depend on the water content (porosity), the resistivity of the water, the clay content and the content of metallic minerals (Bernard, 2003). The following considerations help in the determination of the resistivity of rocks.

- A hard rock without pores or fractures is very resistive to the flow of electric current. This is generally observed in hard fresh Precambrian rocks.
- Dry sand without water is very resistive.
- Porous or fractured rock bearing free water has resistivity, which depends on the resistivity of the water and on the porosity of the rock.

- Impermeable clay layer, which is wet, has low resistivity but may not contain enough yields for successful groundwater exploitation.
- Mineral ore bodies (iron, sulphides) have very low resistivity due to their electronic conduction; usually lower or much lower than 1ohm-m (Bernard, 2003)

To identify the conditions necessary for the presence of groundwater from resistivity measurements, the absolute value of the ground resistivity must be considered. Usual target for aquifer resistivity can be between 50 ohm-m to 2000 ohm-m. (Bernard, 2003).

- In hard rock environment, which is considered very resistant to the flow of electric current, a low resistivity anomaly will be the target for groundwater.
- In a clayey or salty environment that is normally considered conductive, a comparatively high resistivity anomaly will most probably correspond to fresh water and thus will be the target in the case for groundwater exploration for domestic use.

Resistivity values of earth materials cover a wide range. The variety of resistivity has been the essential reason why the technique can be used for different applications (Loke, 2001).

In resistivity measurements, highest resistivities are associated with igneous rocks. Sedimentary rocks tend to be most conductive due to their high fluid content. Metamorphic rocks have intermediate resistivities (table 2). Granites and quartzite have high resistivities ranges; sandstone and shale have intermediate resistivity ranges (Bernard, 2003). The resistivity therefore in a particular geological environment has an influence on the aquifer resistivity. Numerical values for various types of water are outlined (table 3).

In resistivity measurements current is injected into the ground via electrodes and the resulting potential is measured also by electrodes in the ground. The outer electrodes

show the current electrodes for injecting current into the ground and the inner electrodes are the potential electrodes connected to the voltmeter (fig. 3).

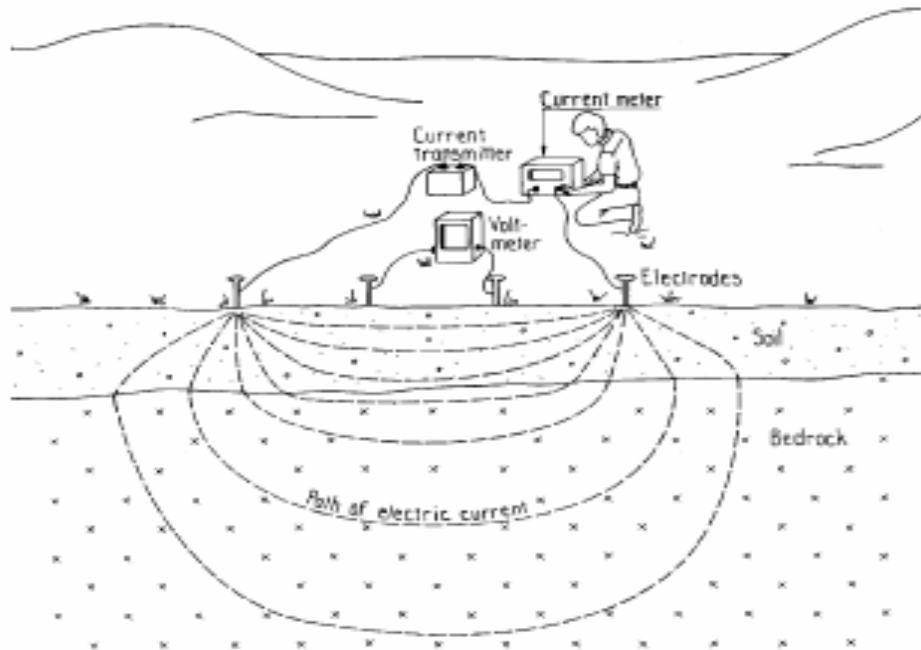


Figure 3: Sketch showing DC resistivity measurements. (Modified from Robinson and Coruh, 1988 in Sjö Dahl, 2006)

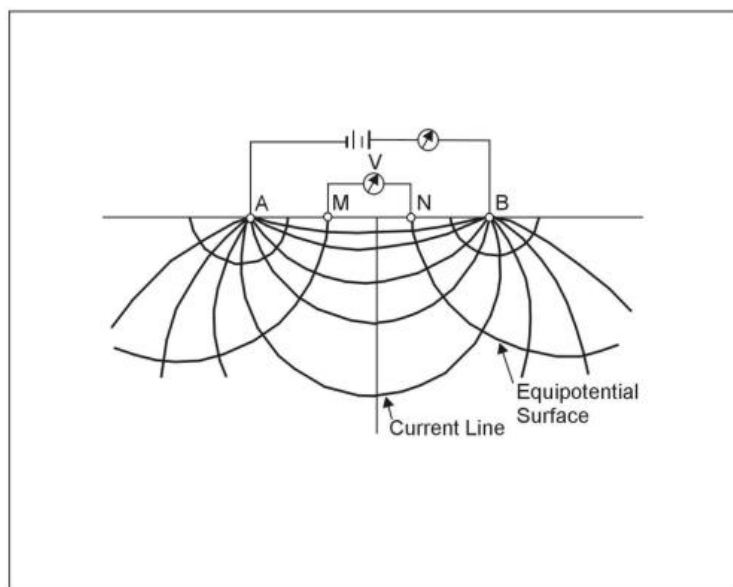


Figure 4: Equipotentials and current lines for current A, B and potentials electrode M, N. (<http://www.cflhd.gov/agm/geoApplications>)

4.1.1.1 Theory of electrical resistivity

For a geometrically ideal situation with a current through a homogenous media in a well defined uniform cross section between two potential electrodes, using the ohms law, the resistance R is given by

$$R = \frac{V}{I} \dots\dots\dots 1$$

Where R is the resistance, V is the voltage and I is the current.

The resistance is also proportional to the cross sectional area and the distance between the electrodes and the relationship is given by

$$R = \frac{\rho L}{A} \dots\dots\dots 2$$

Combining the two equations 1 and 2, $\frac{V}{I} = \frac{\rho L}{A} \dots\dots\dots 3$

Where A is the cross sectional area, V is the voltage, I is the current and L is the distance between the electrodes.

The constant of proportionality ρ is the apparent resistivity and data from resistivity surveys are represented by apparent resistivity which takes into account arrangement and spacing of electrodes. From the relationship above the potential at any point is given by

$$V = \frac{\rho I}{2\pi r}$$

V is the potential in volts, ρ is the resistivity of the medium and r is the distance from the electrode.

For an electrode pair with current I at electrode A, and -I at electrode B (fig. 4), the potential at a point is given by the algebraic sum of the individual contributions:

Therefore $V = V_A + V_B$

$$\rho I \left(\frac{1}{2\pi r_A} - \frac{1}{2\pi r_B} \right)$$

$$\frac{\rho I}{2\pi} \left(\frac{1}{r_A} - \frac{1}{r_B} \right)$$

r_A and r_B are the distance from the point between electrodes A and B.

Two pairs of electrodes M and N (fig. 4) carry no current but are used to measure the potential difference between the points M and N.

The potential V may be measured as

$$V = V_M - V_N$$

$$\frac{\rho I}{2\pi} \left(\frac{1}{AM} - \frac{1}{BM} + \frac{1}{BN} - \frac{1}{AN} \right)$$

V_M and V_N are potentials at M and N. AM is distance between A and M, AN is the distance between A and N.

The distances are the actual distances between the respective electrodes, whether or not they lie on a line.

Denoting $\frac{1}{2\pi} \left(\frac{1}{AM} - \frac{1}{BM} + \frac{1}{BN} - \frac{1}{AN} \right)$ by $\frac{1}{K}$ the equation becomes

$$V = \frac{\rho I}{K}$$

The equation gives resistivity $\rho = \frac{KV}{I}$

K is the geometric factor and only a function of the geometry of the electrode arrangement. Resistivity can be found from measuring values of V, I and K.

Table 1: Geometric factor for some common configurations (Vogelsang, 1994)

Array	Geometric factor K
Wenner	$2\pi a$
Schlumberger	$\frac{\pi}{a} \left[\left(\frac{s}{a} \right)^2 - \left(\frac{a}{2} \right)^2 \right]$
Dipole-dipole	$\pi (n+1)(n+2)a$

Table 2: Resistivity values for some common geological formations.

Material	Nominal resistivity (Ω-m)
Quartz	$3 \times 10^2 - 10^6$
Granite	$3 \times 10^2 - 10^6$
Granite (weathered)	30 – 500
Consolidated shale	$20 - 2 \times 10^3$
Sandstones	200 – 5000
Sandstone(weathered)	50-200
Clays	$1 - 10^2$
Boulder clay	15 – 35
Clay (very dry)	50 – 150
Gravel (dry)	1400
Gravel (saturated)	100
Lateritic soil	120 – 750
Dry sandy soil	80 – 1050
Sand clay/clayed sand	30 – 215
Sand and gravel(saturated)	30 – 225
Mudstone	20-120
Siltstone	20-150

Table 3: Numerical values for various types of water (modified from Bernard, 2003)

Type of Water	Resistivity (ohm-m)	Conductivity (micros/cm)	Salinity (mg/l)
Very fresh	200	50	35
Fresh	20	500	150
Salted	10	1000	700
Sea Water	0.3	30000	35000

4.1.2 Types of resistivity surveys

There are two basic types of resistivity investigations; profiling and depth sounding investigations. Resistivity profiling is used to detect lateral changes and depth sounding is used to investigate the changes in resistivity with depth. The basic difference between these two aspects of measurements is that in profiling measurements are taken at the various stations on the profile. Therefore stations are selected based on the general relative measurements along the profile. With sounding the equipment is positioned at a station and measurements are taken to a target depth. In a general principle sounding measurements are carried out after profiling.

4.1.2.1 Vertical electrical resistivity sounding

The procedure involved in vertical electrical sounding is primarily based on the assumption that the subsurface has a horizontal stratigraphy. In other words it consists of discrete, horizontal, homogeneous and isotropic layers. The measurements are taken with gradually increasing distances of the current electrodes (the potential electrodes remain constant at some stations). As the distance between current probes is increased, there is also an increase in the depth at which the current penetrates below the surface of the ground increasing the depth of investigation. In this way, an estimate of the vertical resistivity distribution below the centre of the array is determined. These are usually plotted as depth against resistivity so that the resistivities at different depths are analysed.

4.1.2.2 Electrical resistivity profiling

Profiling provides information about lateral variations, usually with some information about vertical variations. Wider electrode spacing results in deeper penetration. In profiling, readings are taken at regular intervals along a profile. The profile is usually pegged at regular interval distances. The general variations of resistivity at the individual stations are used to select anomalous stations for further investigations or drilling. Profiling results are presented as resistivity against distances corresponding to the stations. In this situation the resistivity at the stations are displayed so that anomalous stations can be observed.

4.1.3 Types of arrays

The choice of the best array for a field survey depends on the type of structure to be mapped, the sensitivity of the resistivity meter and the background noise level (Loke, 2001). Some common arrays that are commonly used for electrical resistivity measurements surveys are;

- Wenner
- Dipole-dipole
- Wenner/Schlumberger
- Pole-pole
- Pole-dipole

Among the characteristics of an array that should be considered are the sensitivity of the array to the vertical and horizontal changes in the subsurface resistivity, the depth of investigations, the horizontal data coverage and the signal strength. (Loke, 2001)

The typical methodology in conducting resistivity investigation begins by some pre-modeling to determine the type of array to be selected and electrode spacing. Choosing the type of array in investigations is not only an important factor to ensure success, it also determines the efficiency of the investigation. In resistivity profiling investigations, cables and electrodes are moved long distances and therefore the arrays chosen will be those which make movement simple and rapid as possible as well as efficient in delineating targets (Loke, 2001). Information on some common arrays (after Loke, 2001.) is enumerated below;

Wenner array is used for both resistivity profiling and depth sounding. This is a robust array that was popularized by the pioneering work carried out by the University of Birmingham research group (Griffiths and Turnbull 1985; Griffiths, Turnbull and Olayanka, 1990; Locke 2001). Many of the early 2-D multi-electrode electrical resistivity surveys were carried out with this array (Loke, 2001).

The array is relatively sensitive to vertical changes in the subsurface resistivity below the centre of the array and less sensitive to horizontal changes in the subsurface resistivity. The array is best used for horizontal structures, but is relatively poor in detecting narrow vertical structures. The Wenner array has large signal strength.

The advantage of this array is that it is popular and widely used so it has a vast amount of interpretational material. The arrays also require much smaller data than the others to construct a pseudosection (Barker, Rao and Thangarajan, 2001). However, all four electrodes are moved making it less time efficient for profiling, but since the distances between the electrodes are small mistakes are less likely (fig.5). In this array near-surface conditions differ at all four electrodes for each reading, giving a rather high noise level.

A disadvantage of this array for 2-D multi-electrode electrical resistivity survey is the relatively poor horizontal coverage as the electrode spacing is increased. This problem is normally observed in a system with relatively small number of electrodes.

Schlumberger array (where only two electrodes are moved) is appropriate for use because of speed and convenience. The plethora of interpretation material for the Schlumberger array also makes it attractive for depth sounding. Site selection is extremely important with the Schlumberger array because it is sensitive to conditions around the closely spaced inner electrodes.

Wenner-Schlumberger array is moderately sensitive to both horizontal and vertical structures. This array is a hybrid between Wenner-Schlumberger array (Pazdirck and Blaha, 1996 in Loke, 2001) arising out of a relatively recent work with electrical image surveys (Loke, 2001). This array is moderately sensitive to both horizontal and vertical structures. In arrears where both types of geological structures are expected this array may be a good compromise between the Wenner and the Dipole-dipole array. The signal strength of this array is smaller than that of the Wenner array but it is higher than that of the Dipole-dipole array. The median depth of investigation for this array is larger than that for the Wenner array for the same distance between the outer electrodes. The Wenner-Schlumberger array has a slightly better coverage compared with the Wenner array. The horizontal data coverage is slightly wider than the Wenner array but narrower than that obtained with the Dipole-dipole array.

Dipole-dipole array is suitable for vertical structures, vertical discontinuities and cavities, but less for identifying horizontal structures. The array is most sensitive to resistivity changes between the electrodes in each dipole pair. That means it is good in mapping vertical structures such as dykes and cavities but relatively poor in mapping horizontal structures such as sills or sedimentary layers. The depth of investigation is smaller than for the Wenner array. The array is mainly used in IP work where induction effects must be avoided at all costs; however it is also effective in resistivity profiling. It uses four moving electrodes (fig. 5) and it is therefore less desirable and the observed voltages tend to be rather small. The array can also be used effectively for resistivity depth sounding.

To use this array effectively, the resistivity meter should have comparatively high sensitivity and very good noise rejection circuiting and a good contact between the electrodes and the ground is necessary.

Polar-dipole array is asymmetrical and results in asymmetrical apparent resistivity anomalies in the pseudosection for surveys over symmetrical structures. This effect can be removed by repeating the measurements with the electrodes reversed. It has a higher signal strength compared with the dipole-dipole array. The array is not as sensitive to noise as the pole-pole array because the distance between the potential electrodes is not as large. The signal strength is lower compared with the Wenner and Wenner-Schlumberger arrays but higher than the Dipole-dipole array. The asymmetrical anomalies produced by this array is more difficult to interpret than those produced by symmetrical arrays.

A major problem with this array is that peaks are displaced from the centers of conductive bodies and there is no real agreement as to where the results should be plotted.

Pole-pole array is not as commonly used as the others arrays. In practice the ideal Pole-pole array with only one current and one potential electrode does not exist. To approximate the pole-pole array, the second current and potential electrodes must be placed at distances, which is more than 20 times the maximum separation between the first current and potential (C_1P_1) electrodes used in the survey.

In surveys where the electrode spacing along the line is more than a few meters there might be practical problems in finding suitable locations for the second current and potential (C_2P_2) electrodes to satisfy this requirement.

A disadvantage of this array is that because of the large distance between (P_1P_2) electrodes, it can pick up a large amount of telluric noise which can severely degrade the quality of the measurements and so it is mainly used in surveys where relatively small electrode spacing (less than 10 m) are used. This array has the widest horizontal coverage and the deepest depth of investigations.

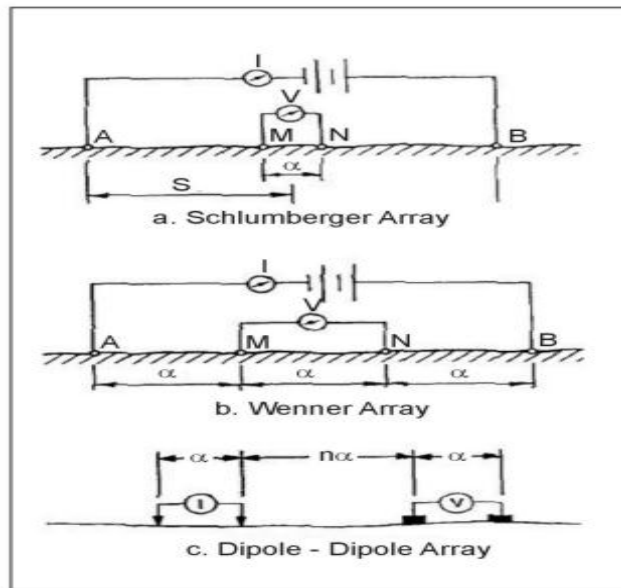


Figure 5: Common electrode array configurations for resistivity measurements.
 (<http://www.cflhd.gov/agm/geoApplications/SurfaceMethods/933ResistivityMethods.htm>)

4.1.4 Summary of effective use of common arrays

A summary of the various arrays and their effective use are illustrated below after (Loke, 2001) are as follows;

- If the survey is in a noisy area and a good vertical resolution is required with a limited survey the Wenner array will be the best option.
- When a good horizontal resolution and data coverage is important with a resistivity meter sufficiently sensitive with a good ground contact, the dipole-dipole array will be the preferred choice.
- If there is uncertainty whether both reasonably good horizontal and vertical resolution are required, the Wenner-Schlumberger array with overlapping data levels is the best option.
- Survey with a system with a limited number of electrodes the Pole-dipole array with measurements in both the forward and reverse directions might be a viable choice.
- For surveys with small electrode spacing and where good horizontal coverage is required, the Pole-pole array might be a suitable choice.

4.1.5 Data acquisition in electrical resistivity measurements

For measuring the ground resistivity, a current has to be transmitted with electrodes, while the potential created on the surface by the circulation of this current into the ground is measured with other electrodes (fig 3). Increasing progressively the distance between the transmitting and the receiving electrodes permits an increase in the depth of investigations.

The resistivity depends on hydrological-hydrogeological conditions, the chemical composition of the water, the dissolved ions in it, the porosity of the formation, the possible fractures, the temperature and pressure and the topography. Resistivity depends on many factors and it doesn't comprise a distinguishing property of specific formations, since the resistivity variability may have a large range in the same formation. Interpretation of resistivity measurements therefore must be carried out with regards to the available geologic information of the area including geologic maps, drilling information on aquifer depth, aquifer thickness and static water levels. (http://www.ims.forth.gr/rg_geophysics.html)

4.1.6 Electrical resistivity imaging (2-D multi-electrode survey)

Electrical imaging represents a re-emergence of an old technology which has been hampered by its high cost compared to other methods. With the present improvement in field equipment design capability, and the development of computer algorithms necessary to effectively and accurately reduce and present the geophysical data, electrical imaging is now cost competitive with more commonly used geophysical techniques and has attracted a lot of attention. The new and future applications for the efficient development of groundwater resources will change the way groundwater aquifers are exploited and managed. It has proven to be an effective tool for evaluating the subsurface on many sites. It appears to be a solution to pinpointing probable successful well sites on fracture locations (Hoover, 1999).

Electrical Imaging can provide information about distinct subsurface boundaries and conditions, which can indicate soil or bedrock lithology variations (Reccelli-Synder, *et al*, 1999). This aspect of the technique helps in defining weathering depths and the different rock bodies at the subsurface.

With the 2-D multi-electrode survey traversing and sounding can be combined. Measurements are carried out between current electrode pairs and potential electrode pairs. An increase in the distance between two electrode pairs gives the apparent resistivity at greater depth (fig. 6).

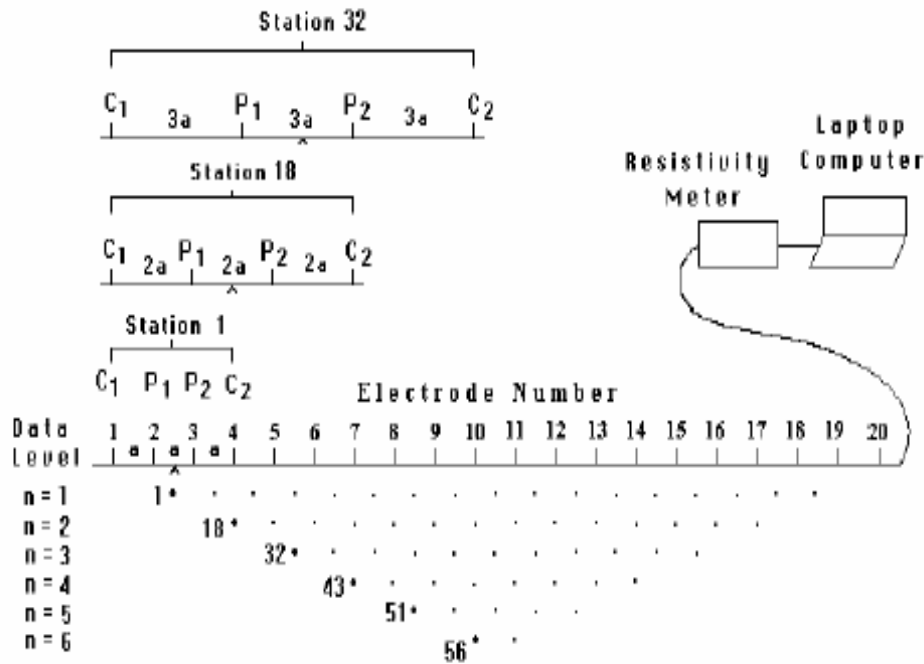


Figure 6: Arrangement used to build up a pseudosection in multi-electrode survey (Loke, 2000)

4.1.6.1 2-D Lund electrical resistivity imaging survey

The Lund resistivity imaging system is an automatic electrical imaging suited for automatic resistivity and induced polarisation (IP) profiling (ABEM, 2004). It consists of a multi-electrode system for high resolution 2-D and 3-D resistivity surveys and is used for defining geological structures. Data is obtained for the horizontal and the vertical variation of the resistivity. It involves measuring series of constant separation traverses along the same line but with the electrode spacing being increased with each successive traverse. Increasing separation of electrodes lead to greater depth penetration and therefore the measured apparent resistivities may be used to construct a vertical contoured section displaying the variation of resistivity both laterally and vertically over the section (Barker, Rao and Thangarajan, 2001).

Field systems use a multicore cable to which 50 or more electrodes are connected at takeouts moulded on at predetermined equal intervals. The cable is connected to a switching module and to an earth resistance meter and computer. With these systems, any electrodes may be switched to act as either current or potential electrodes and so within the constraints of the electrodes emplaced, any electrode arrangement can be employed (Barker, Rao and Thangarajan, 2001).

The array of electrodes is connected by the multicore cable to provide a linear depth profile, or pseudo section, of the variation in resistivity both along the survey line and with depth. This technique is usually efficient when the drilling target is a vertical discontinuity. The system consist of a basic geophysical equipment (SAS 1000/4000) unit, the electrode selector and multi conductor cables. The system can be controlled directly from the geophysical equipment unit.

4.1.6.2 Equipment for multi-electrode survey

A lot of equipments are available for data acquisition. Some of the common equipments for electrical resistivity measurements are summarised (table 4). The ABEM terrameter SAS 1000/4000 will be discussed because it was the equipment used for all the data collection for this research work. The main features include a 64 electrode unrestricted switching in a compact, battery operated unit with a robust waterproof design for reliable operation in harsh environment.

Most of the equipments (table 4) are very robust and can withstand the high temperature conditions existing in the northern region of Ghana. The ABEM was very effective in the area and generally did not encounter a lot of problems during field data collection. There were particular times when the equipment was affected by the high temperature but this was very limited. In some certain circumstances when temperatures were very high during field data acquisition, survey had to be interrupted for the ABEM terrameter to cool before data collection is continued.

Table 4: Summary of common electrical resistivity instruments (modified from Loke, 2004)

Manufacturer	Instrument Type		
	Static	Dynamic	IP
ABEM Instruments, Sweden	Yes		Yes
Advance Geophysical Instruments U.S.A	Yes		Yes
Campus Geophysical Instruments, UK	Yes		Yes
Geofyzika, Czech Republic	Yes		
GF Instruments Czech Republic	Yes		Yes
Geometrics, USA		Yes	
Geolog, Germany	Yes		
IDS Scintrex, Canada	Yes		Yes
IRIS Instruments, France	Yes		Yes
OYO Japan	Yes		
Pasi Geophysics, Italy	Yes		Yes
MAE srl, Italy	Yes		Yes
Geosys Leipzig	Yes		

**Figure 7: Arrangement for data acquisition in Lund 2-D multi-electrode resistivity survey.**

4.1.6.3 Concept and depth of investigation

The concept consists in using multi core cables, which contain arrangement of cables and electrodes one takeout every 5meters and 64 electrodes. The measuring unit includes relays, which automatically carry out the sequence of readings introduced in its internal memory. The system takes readings for many combinations of transmission and reception pairs so as to achieve some kind of mixed profiling and sounding pairs (ABEM, 2004).

The total length of the cable is the product of the electrode spacing by the number of electrodes and that determines the depth of investigations (Bernard, 2003).

The final depths of investigations of a Lund imagine survey depends on;

- Geometry of cables (type of array, number of electrodes, spacing between electrodes and the number of segments).
- The measurability of the signal by the equipment, namely the amplitudes of the signal and of the existing noise, the power specifications of the equipment and its ability of filtering the noise through the stacking process (Loke, 2001).

4.1.6.4 Data collection

The equipment set for data collection consist of the ABEM terrameter SAS 1000/4000, four set of 100m cables sets, ES-10-64 and a set of 64 standard electrodes preferably made of stainless steel (fig.7). Data is taken by automatically obtaining readings along the profile line at different electrode separations. Within the inner loop electrode spacing is limited to 5 m intervals. The electrodes are however arranged at 10 m spacing in the outer loop comprising of the first and last cables of the four set of cables (fig.8). Each cable has a length of 100 m. With this arrangement for data acquisition, probing depth is limited to about a depth of 65m using the Werner L (Werner Long) and Werner S (Werner Short) configurations.

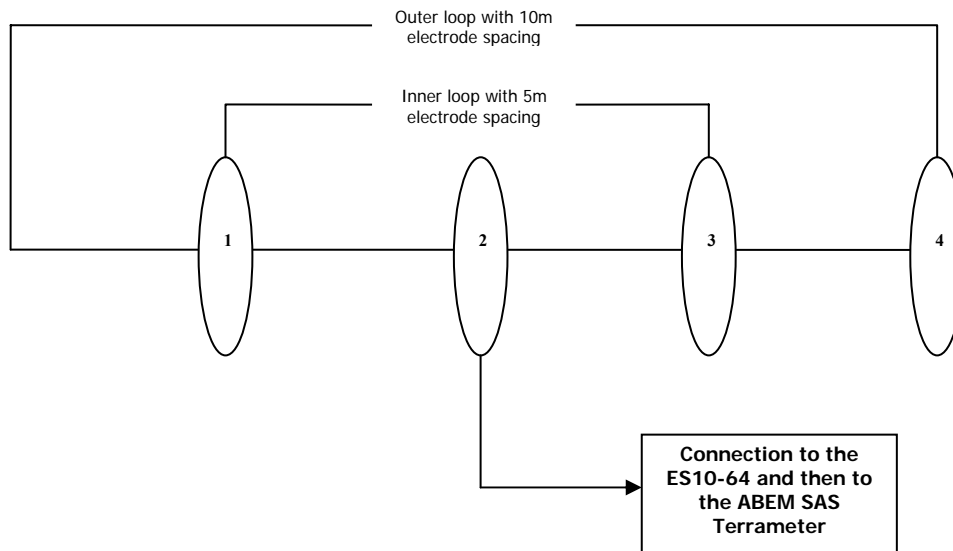


Figure 8: Diagram showing 4 sets of 100 m cables for data acquisition.

The proceeding information from methodology to processing of the resistivity data from field measurements have been summarized based on information from the ABEM Instruction manual 2004.

4.1.6.5 Methodology

The equipment is switched on after all the necessary arrangement of electrodes, cables set, selector unit and battery. External batteries are recommended for measurements during ABEM Lund Imaging survey to ensure sustainable energy during data acquisition.

In the record manager menu the Resistivity measuring mode is selected. From the submenu a display of a new record, open an existing or deleting record can be chosen. Selection of channels is important because the SAS 1000 utilizes one channel whereas the SAS4000 utilizes all the 4 channels available.

The power line frequency is important for noise reduction purposes; in countries with 60 Hz power line frequency is also set to 60 Hz. The acquisition knob is then pressed for data acquisition. In this menu, the following can be selected;

Output current; auto mode is recommended since in this mode, the current will automatically reduce if it is impossible to transmit the selected current. This is very important in areas where it is difficult to transmit higher current and so the required current can be transmitted without any problem to the operator.

Stacking Parameters; the median or the mean can be used. The median is more robust to blunders. It is the value in the middle of the ensemble of stacked values. This gives a true representation of the actual resistivities since in resistivity measurements the first measured values are always not consistent with the preceding other readings. The mean is simply the sum of individual stacked values divided by the number of stacking so that in circumstances where erratic values are obtained the mean value may not be ideal.

If the electrode test is set to YES then the system will check if it is possible to transmit current through all the electrodes. This could be tested either in pairs starting at one end or test each electrode against all the other electrodes. The program automatically continues to measure using all the four electrode cables when the contact is satisfactory. It is advisable to check that measurement have not stopped as a result of poor electrode contact even if the contact test was passed. The equipment can also be programmed so that a sound warning is given when current cannot be transmitted.

4.1.6.6 Communication between ABEM Terrameter and PC computer

The SAS ABEM terrameter communicates with PC compatible computer through the serial cable. It is set to the RS232 communication mode so that it is ready to communicate with an external PC computer. Data in the terrameter SAS 1000/4000 is displayed on the computer screen. At the import data mode in the menu, all the files in the terrameter are displayed. The specific file can be imported to the PC by marking it in the check box.

4.1.6.7 Data conversion to RES2DINV

Files in the terrameter are saved in binary formats with the file extension .s4k. This format is not compatible with the RES2DINV so it has to be converted to a convenient format. The data conversion project is used to convert to the RES2DINV

format, which is accepted for interpretation. The conversion program is automatic and readily converts the data without any inputs from the operator.

4.1.6.8 Data checking and editing

It is possible to use “the exterminate bad datum points” feature in the RES2DINV for editing and removing noisy data points. This is normally possible for one channel data but this is difficult if not impossible for 4 channel data. This is because in the data acquisition in 4-channel mode, a lot of readings are obtained for a single standard 400-meter traverse. Numerous data is obtained there extermination of bad datum points might not be appropriate and possible.

4.1.6.9 Inversion programs

There are lots of inversion programs frequently used. These include RES2DMOD, RES3DMOD, RES2DINV and RES2DINV among others. The RES12DINV program is discussed since it was the program used for the inversion. Different methods are used but the one providing the best results is by finite element forwarding (Geo-Etudes, 2003).

The inversion routine used by the program is based on the smoothness constrained least square method with the equation (Loke, 2001) as follows;

$$(JJ+\mu F) d = Jg - \mu Fr$$

In which $F = f_x * f_x + f_z * f_z$

f_x = filter from horizontal structures

f_z = filter from vertical structures

J = matrix of partial derivatives

μ = damping factor

d = model perturbation factor

g = discrepancy vector

The optimization method tries to reduce the difference between the calculated and measured apparent resistivity values by adjusting the resistivity of the model blocks. The model is considered to be appropriate when the calculated values and the measured ones are best fitted. The measure of this difference is given by the root mean square (RMS) error. The model with the lowest possible RMS error can

sometimes show large unrealistic variations in the model resistivity values and might not always be the best model from geological perspective (Loke, 1998).

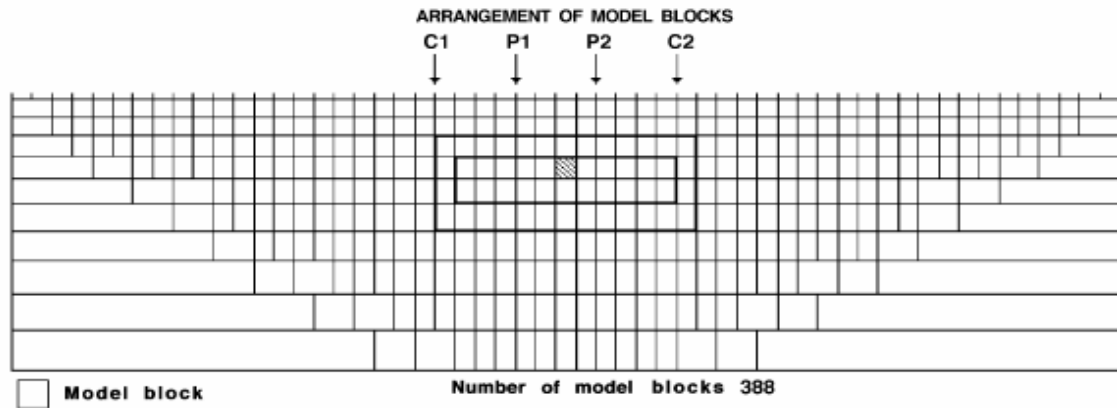


Figure 9: Subsurface model used by the inversion program. (Loke and Dahlin, 2002)

The arrangement of the cells (fig. 9) approximately follows the distribution of the data points in the apparent resistivity pseudosection. The model parameters are the resistivity values of the model blocks while the data is the apparent resistivity values. The main objective of the inversion model is to find the resistivity of the cell that will minimize the difference between the calculated and measured resistivity values. The root mean square (RMS) is calculated from the difference between the logarithms of the measured and calculated apparent resistivity values. The RMS decreases after each iteration with the largest reductions in the first three iterations.

The RES2DIN program is designed to operate as far as possible in an automatic and robust manner with minimal input from the user. It has a set of default parameters, which guides the inversion process. In most cases the default parameters give reasonable results (Loke, 2001).

The main drawback to this inversion program is that the user has a limited influence on the inversion routine. A cell based inversion model is normally applied to model complex geological structures by making a lot of assumptions. In the modeling the subsurface is divided into a lot of rectangular cells (fig. 9). The algorithm is then used to determine the resistivities of these cells. These assumptions and divisions might not always give ideal resistivities (Petzold, personal communication).

4.1.7 Limitations/problems of electrical resistivity methods

Profiling methods measure the lateral variations of apparent resistivities but do not easily provide insight into true actual resistivities. Identified electric boundaries separating layers of different resistivities may or may not coincide with boundaries separating layers of different lithologic composition. This may result in the electrostratigraphy varying from the gross geologic stratigraphy. (Hoover *et al*, 1999).

Earth resistivity measurements have been made using an array of grounded electrodes (Wenner, Schlumberger, dipole-dipole, etc) with which to inject current into the ground and to measure the potential difference. The use of grounded electrodes can sometimes give problems in areas of high surface resistivity because in such situation, obtaining useful levels of current flow can be difficult.

4.1.8 Advantages of multi-electrode over conventional resistivity survey

Data gathering in electrical resistivity imaging is less laborious compared with the conventional type where equipments and electrodes are moved from one station to the next in a straight-line traverse with more than five personnel in a survey team. With the imaging technique all the units are arranged and a command given to take all the measurements in a traverse. With electrical resistivity imaging a two-man team can successfully carry out a survey.

Interpretation of data takes time in the conventional electrical resistivity techniques. Data obtained are normally plotted either manually or by the use of Microsoft excel.

Computer interpretations of raw (apparent resistivity) data enable inversion to true resistivity, which increases the correlation to lithology (Hoover, 1999).

More information is obtained in a single profile measurement and these information are in both horizontal and vertical directions unlike the conventional techniques where only one dimensional data is obtained.

4.1.9 Advantages of conventional over multi-electrode resistivity survey

Apart from the labour intensive nature of the conventional resistivity technique, it is easy to operate and can be operated by trained technicians without any advanced training as in the case of the electrical image technique. It is also less costly since in most cases local helpers are employed which make it less expensive in terms of labour cost.

4.2 Electrokinetic sounding (EKS) technique

The interest of the electrokinetic signal as a geophysical tool had been known since the 1930s, (Peart and Beamish, 1998; Groundflow, 2004) and many authors have worked on this signal; interpretation of surface data from “sounding mode” to give information about the permeability changes beneath the sounding location. The use of the technique has gained operational recognition in recent years because a new method of acquiring electrokinetic signal has been developed.

The EKS method is somewhat controversial with some researchers claiming seismically induced Raleigh-wave signal as the main source of so-called EKS signal. (<http://www.geophysics.co.uk/mets2.html#eks>).

The British Geological Survey (BGS) carried out a research R6232 funded by the UK department for International Development (DFID) between the period 1995 to 1997 with the aim of assessing the extent to which the technique is able to map the permeability of the subsurface and to predict the presence and depth of groundwater as claimed by the manufacturer of the equipment. The following observations were made as follows:

- The largest EKS signal is generated in the dry and /or in the partially saturated zone above the water table which therefore follows that the water table is not readily observed by the technique.
- The observed EK events were generated by laterally propagating seismic disturbances and that the magnitude of the EK signal generated at depth below the shot point will typically be an order in the magnitude generated by the lateral propagation.

- Assumptions made by the suppliers of the EKS equipment, Groundflow ltd. are flawed; a vertical sounding capability had not been established in that the routine use of the 2-channel equipment is likely to provide insufficient information into the nature of the EK coupling leading to false interpretation.

The research therefore concluded that the equipment and technique would yield erroneous results and additional research was needed to confirm the claims by Groundflow ltd.

4.2.1 Basics hydrogeological parameters associated with EKS technique

Groundwater is characterized by parameters, which can be determined by geophysical measurements from the surface mostly indirectly, but sometimes directly. Some basic parameters are the porosity, the permeability and hydraulic conductivity. These parameters are therefore defined in the preceding paragraphs.

The porosity is the ratio between the volumes of the pores and that of the rock. When dealing with saturated layers (under the water level), the water content is equal to the porosity. For the exploitation of groundwater water, it is important to determine the porosity of free water (water which can move) which is characterised by the effective porosity.

The permeability (hydraulic conductivity) is the ability of a material to let fluid flow through it when a hydraulic pressure is applied. If there is no porosity or joints, the permeability is also very weak. The porosity can be high, such as in a clay layer, but with a very weak permeability. The porosity and the permeability are not two parameters independent from each other: The permeability already includes the information of the porosity for determining the volume of water that can be extracted from the ground.

Generally fine grained sediments such as clay and silts have high porosity (fig.10). Rough grained sediments such as sand and gravel have intermediate porosity and low adhesive water content. This is because with decreasing grain size the inner surface is increased, cavities between the grains will be finer, content of pore angle and capillary

water is increased. The adsorption and capillary forces between the water and mineral grains increase and the soil will be binding.

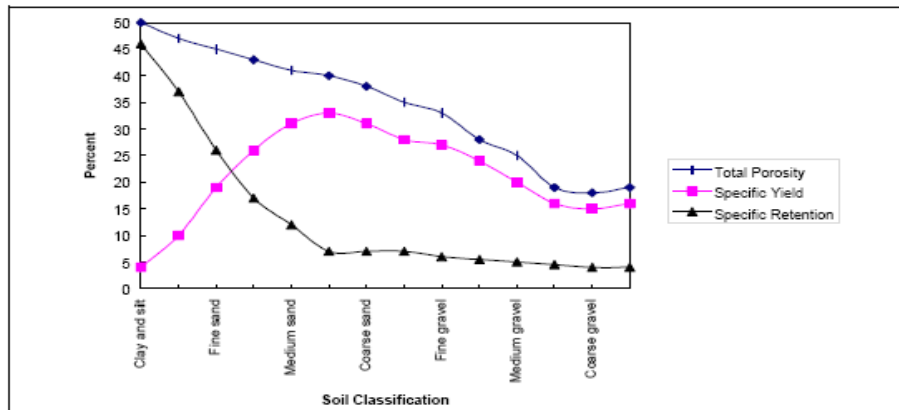


Figure 10: Correlation of porosity, specific yield, specific retention and grain size (DOK, 1999).

Table 5: Numerical values of various types of rocks (modified from Bernard, 2003)

Types of Rocks		Porosity (%)	Permeability (m/s)
Unconsolidated (Soft Sediments)	Gravel	10-30	10^{-2} - 10^{-4}
	Sand	10-25	10^{-3} - 10^{-5}
	Clay	30-50	10^{-6} - 10^{-12}
Consolidated Sandstone, limestone, granite, basalt	Massive	1	10^{-10}
	Fissured	5	10^{-8} - 10^{-10}
	Weathered	15	10^{-6}

4.2.2 Electrokinetic phenomenon

When a an electrical current or voltage is applied across a saturated soil specimen the various ions, suspended soil particles and water move in some specific direction depending upon the charge of ions and particles. This movement of particles, ions and water in the wet soil medium is known as electro-kinetics. An electrical gradient is induced apart from chemical and hydraulic gradients. Positive ions are attracted to the negatively charged cathode and negative ions move to the positively charged anode (Groundflow, 2004).

4.2.3 Basic concept and principles of the EKS

The electroseismic technique is based on the generation of electromagnetic fields in soils and rocks by seismic waves. The method measures the hydraulic conductivity which is related to permeability and therefore the possibility for groundwater flow can be extrapolated. Fig.11 and fig.12 are used to illustrate the phenomenon.

When a seismic wave encounters an interface, it creates a ge separation at the interface forming an electric dipole which can be detected by an antenna on the ground surface (fig. 11).

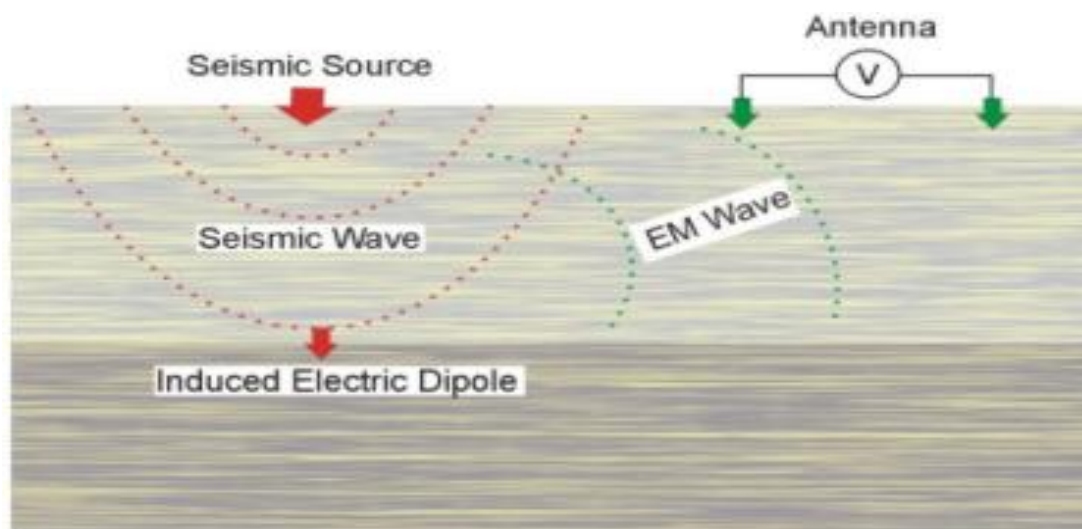


Figure 11: Seismoelectrical conversion at the interface. (Groundflow, 2004)

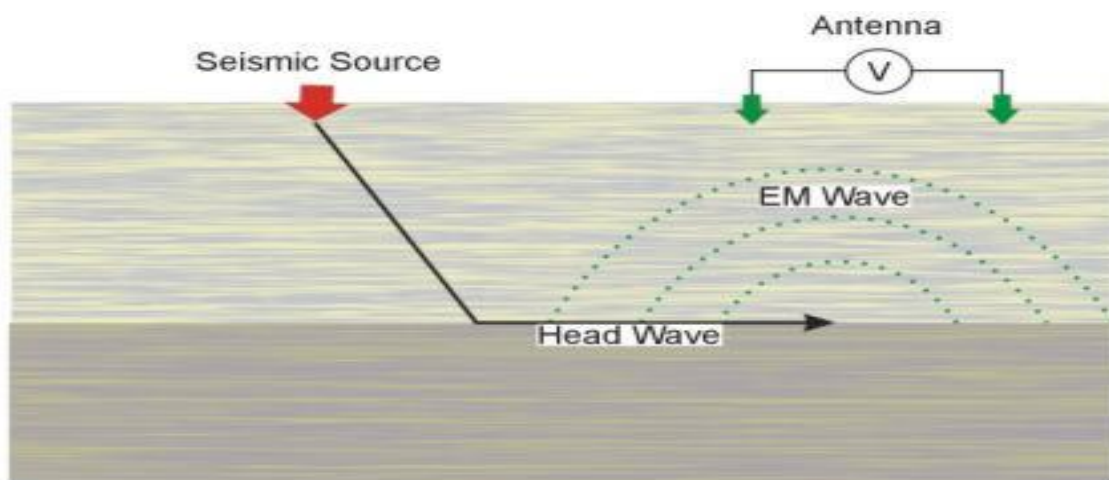


Figure 12: Generation of electric field by a head wave. (Groundflow, 2004)

In another situation, a seismic head wave traveling along an interface creates a separation across the interface which induces an electric field. EM wave emanating from the interface can also be detected at the surface by an antenna (fig. 12).

The interest of the technique is therefore to measure the electrokinetic effects which are initiated by sound waves passing through a porous rock inducing relative motion of the rock matrix and fluid. When the ionic fluid moves through the rock sample, the cations are attracted to the walls and the applied pressure and resulting fluid movement relative to the rock matrix produces an electric dipole.

In the technique of the EKS the electric dipole produced gives a signal. The rise time of the electrical signal is inversely proportional to the rock permeability. The frequency of the signal is determined by the frequency of the pressure pulse and by the permeability of the aquifer. The water can move easier and faster in a more permeable rock and generates a higher frequency response than from less permeable rocks.

The conductivity of the water also determines the amplitude of the signal. Conductive (blackish or saline) water tends to short circuit the signal generating process and reduces the amplitude of signals. Fresh water produces signals that can be several millivolts in amplitude (Groundflow, 2004)

4.2.4 How the EKS works as illustrated by Groundflow ltd.

A normal seismic source creates a sharp seismic pulse. This travels through the ground at the velocity of sound. When it enters the aquifer the water, which is less compressible, is forced to move as the rock matrix, more compressible is deformed. Water carries ionic charge with it away from the ions of the opposite charge, which are stuck to the pore surfaces. The charge separation distributes the electromagnetic field and the disturbance propagates to the surface at the speed of light (Groundflow, 2004).

The signals are strongly dependent on at least three main physical properties; porosity of the rock, permeability and fluid chemistry. In theory there is no seismic electric

response in partially or unsaturated media (Zhu & Jokossos, 2003) so the geological medium must be saturated by an electrolyte.

The permeability has a strong influence on streaming potential when the fluid is resistive and hence affects the electro kinetic response as these effects are related (Jouniaux & Pozzi, 1995; Clarke & Miller, 1996).

Furthermore electro kinetic signals are divided into two types (Burthler *et al*, 1996; Haartsen & Pride, 1997; Groundflow, 2004) .The first type of signal is a non-radiating field, which occurs in homogeneous media and is contained within and travels with the seismic P-waves. The second type of signal is raised when the P-waves passes through a boundary with contrast in elastic and /or electrokinetic's (fluid-chemistry) properties. The electric signals diffuse rapidly to the sensors with an apparent velocity that is much faster than any seismic wave. Thus the signal will arrive nearly simultaneously across the array of widely spaced dipole sensors. The second type is the signals that can be used to determine hydrogeological properties. (Goldbeck, 2002)

4.2.5 Equipment for EKS survey

The GF 2500 is the latest equipment for EKS data collection manufactured by Groundflow ltd. in the United Kingdom. The set is mounted in a vehicle for power, protection and transportation and consist of an electronic module and a computer, an antenna array and a seismic source. The equipment has standard PC controls and is powered in three ways:

- Mains power using the switch converter.
- Internal lithium ion battery
- Directly from the cigarette lighter switch in a vehicle.

A track pad is usually used instead of a mouse to ease field operations because operations with a mouse would make operations cumbersome in the field.

Surveying is carried out with the GF 2500 electro kinetic sounding set. The set consist of a computer, and antenna array and a seismic source. Two seismic sources

are possible; hammer and plate and buffalo gun. Data is recorded from both dipoles. A two-fold data stacking is achieved by averaging the two processed channels in each data file.



Figure 13: Picture of GF 2500 and hammer for data collection

4.2.6.1 Methodology for data collection

The technique relies on the collection, processing and interpretation of electro seismic survey data using a GF 2500 system. The data is collected at various stations and analyzed to selected depths. Four electrodes are arranged in a straight line with two on either side of the plate in the hammer and plate technique. The trigger is attached to the flat plane of the hammer and the other side used for the impact (fig. 13).

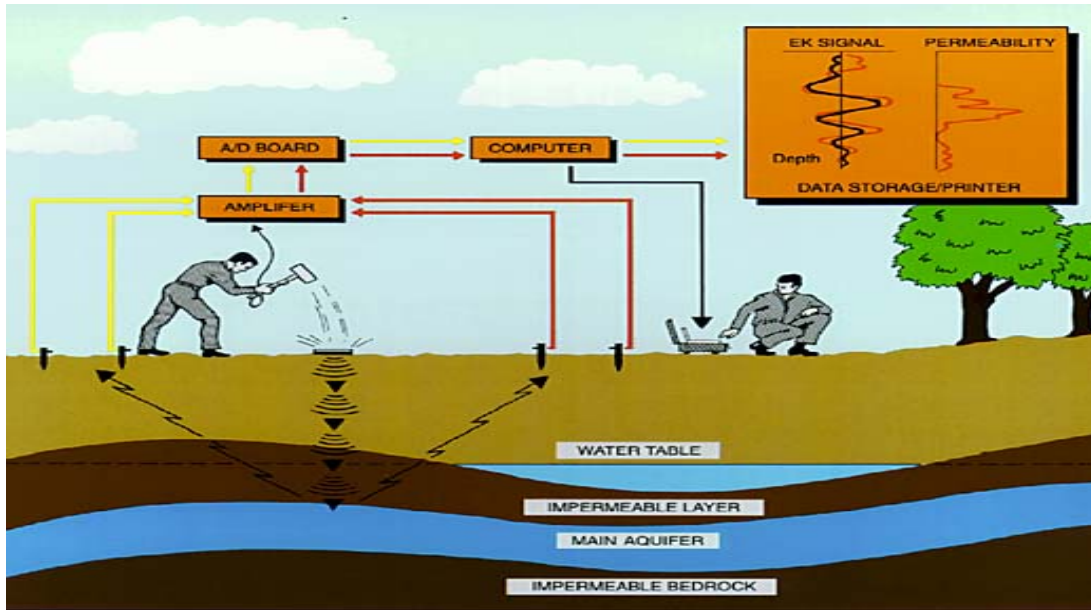


Figure 14: Illustration of data acquisition with hammer and plate method. (Groundflow, 2000)



Figure 15: Left-Hammer and plate data acquisition (fieldwork): Right- Buffalo gun data acquisition (Groundflow, 2004)

4.2.6.2 Electrostatic source

The purpose of the source is to send strong, broad-band seismic pulse into the ground. The pulse will stimulate the emissions by the electric signals from porous, permeable rock layers (fig. 14). The trigger device times the instant of the shot and signals are recorded for 0.4 s after this time (Groundflow, 2004).

The buffalo gun is recommended for all deep electroseismic surveying operations because it offers the most practical way of ensuring that the outgoing sound pulse is not attenuated by loose dry surface vegetation, soil or sand. The buffalo gun is embedded well in the weathered layer (fig. 15). The readings can however not be repeated because after the shot, the ground is totally disturbed. The disadvantage is that it cannot be shot repeatedly in one site and this makes it impossible to acquire duplicate shots from the same site.

The hammer and plate (fig. 15) is quick and easy to use but is generally a weaker source and higher frequency component of the source energy will be lost in the soil if the water table is deep or if the surface material is unconsolidated making electro seismic signals more difficult to detect.

With the hammer and plate seismic source each sounding location is prepared by the removal of the top layer so that the plate could be set firm in the ground. Three recordings are carried out at each site for making sure the readings are reproducible. Usually the second readings are used for processing because it is the reading where the plate is adequately embedded in the ground. The third measurement is not used because the ground would have been disturbed after the second measurement. The first shot always serve as a trial to embed the plate in the ground.

4.2.6.2 Setting the electrodes

Four metal rods form the electrodes of the grounded dipole antenna array. The rods are inserted at positions $0.25 \pm 0.02\text{m}$ and $2.25 \pm 0.05\text{m}$ from the center of the plate or buffalo gun (fig. 16). The rods are inserted into the ground with the help of a hammer until they are firm. 80% of the electrodes should be embedded in the ground. The hammering should be carried out along the axis of the rods to attain maximum contact with the ground.

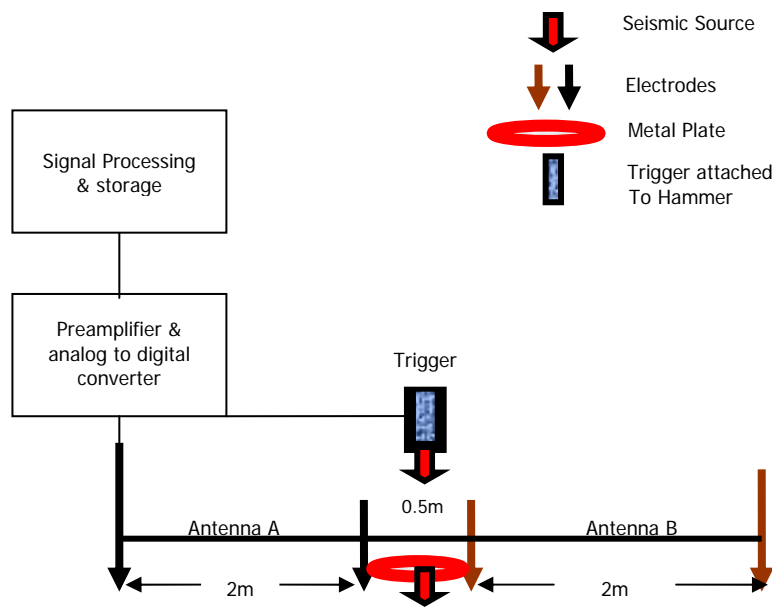


Figure 16: Schematic representation of the arrangement for data acquisition.

4.2.6.3 Setting the Trigger

The trigger is attached to the unused face of the rubber hammer with a tape and the black dot on the trigger facing downwards (fig. 13). This is applicable only in the hammer and plate method. The GF 2500 will not trigger if the switch is loosely attached or does not feel the impact of the shot. In the buffalo gun method the trigger is attached to the opening on the gun.

4.2.6.4 Parameter input choices

After the data has been obtained from the field, processing is carried out by using parameters that have been chosen using all available hydrogeological information. The following has to be considered in the selection of parameters;

- How salty is the water from nearby wells and do some layers give fresh and others salty water
- How deep is the local standing water level in pumped wells
- What types of rock occur below the surface and the type of aquifers (Groundflow, 2004).

Although there is a provision for changing several parameters in order to match aquifer properties determined from an EKS survey to actual values, in practice it is usually only the seismic velocity profile that needs detailed attention (Groundflow, 2004).

4.2.7 Presentation of the EKS results

A four-electrode array of two independent channels, records small electrical signals that are induced by the passage of a seismic pulse through water saturated porous permeable rock and unconsolidated sediments. Proprietary algorithms built into the EKS hardware and software interprets the electrical signal from each channel into a hydraulic conductivity versus depth trace (dependent on selected seismic velocities). The results are presented as a one-dimensional plot of the Electro kinetic signal in millivolt and the depth in meters of investigation on one side and hydraulic conductivity in m/d against depth. The equipment cannot predict yield of boreholes accurately because so much depends on the local variations in the rock and also the method of drilling and lining.

4.2.8 Advantages of EKS over other geophysical methods

EKS offers a number of important advantages over other geophysical methods:

If there is no EKS signal, it is certain that there is no groundwater and this was confirmed in most of the sites surveyed especially during the pilot survey.

The equipment for data collection is portability. Two people can transport the equipment and undertake surveys. It is very cost effective in that a lot of sites can be surveyed in a day and the modeling is very fast.

4.2.9 Limitations of EKS

The electroseismic method is apparently susceptible to electrical noise from nearby power lines. Typical electroseismic signals are at the microvolt level. The electroseismic signal is proportional to the pressure of the seismic wave. Thus, it would seem possible to increase the signal by using stronger seismic sources.

4.2.10 Where to use EKS

The following recommendations have been made for the use of the EKS technique. These have been made based on recommendations in the EKS Manual, 2002 and personal experience after using the technique in many different geological formations in Ghana. The EKS technique is suited for the following geological formations;

SEDIMENTARY DEPOSITS (marine, beach and river deposits, wind-blown sands, clay, sands and gravels)

BEDDED ROCKS (sandstones, Limestones with matrix permeability, bedding-confined fractured units)

CRYSTALLINE ROCKS (tropical weathered basement, layered volcanic rocks, weathered basalt)

4.2.11 Where to avoid EKS

SEDIMENTARY DEPOSITS (boulder beds, very impermeable deposits - no permeability therefore no signal)

BEDDED ROCKS (cavernous limestones - water-filled caverns are too large and permeable to image using EKS)

VERY IMPERMEABLE ROCKS - no permeability therefore no signal

CRYSTALLINE ROCKS (unweathered rocks - no permeability therefore no signal;

Rocks with few isolated fractures - negligible porosity giving little or no signal)

5.0 RESULTS OF PILOT STUDY AND CALIBRATION SURVEY

A pilot and calibration survey was carried out for the three advanced techniques considered for application in the area. The main reason of the calibration survey was to test the techniques before its use in the geological formations in the area. Three techniques were employed for this pilot survey; two dimensional (2-D) multi-electrode electrical resistivity survey, electro kinetic sounding (EKS) survey and radon survey. After the pilot study the application of the radon survey technique was abandoned because of its high cost and unavailability of the radon survey equipment. The calibration was done by selecting four categories of previously drilled borehole stations including;

- Successful high yield borehole station (yields > 100 l/m)
- Successful low yield borehole station (14 l/m < yields > 100 l/m)
- Marginal yield borehole station (5 l/m < yields > 14 l/m)
- Dry/unsuccessful borehole station (yields < 5 l/m)

All the three methods were tested at selected stations to test the ability to effectively predict these situations.

The pilot and calibration surveys gave satisfactory results for the applications of the techniques. The results demonstrated that the applications of the three geophysical techniques might be efficient for the difficult volcanic hydrogeological formation. The results from the individual techniques are summarised.

5.1 2-D Lund multi-electrode resistivity imaging survey

The 2-D Lund multi-electrode resistivity imaging survey was efficient in identifying discontinuities along a profile. It also clearly defined areas with high and low apparent resistivities. One complete profile was performed at each of the sites. The measurement was centered on the stations so that a lot of information could be obtained at these stations. The system used was as follows;

- One profile with 64 electrodes with 5m spacing.
- Measurements were carried out with the pole-pole configuration.

The pole–pole configuration was used because it allows a maximum penetration depth compared to the other configurations and it remains the best way to detect fracturing zones in bedrock (Geo-etude, 2003).

The results of the pilot field survey showed that some of the borehole stations would not have been drilled if this technique had been applied. It showed that negative boreholes were never drilled beneath an electrical resistivity anomaly although electrical anomalies are not conclusive for successful groundwater stations. Boreholes drilled beneath vertical electrical discontinuity were mostly positive. The presence of water seemed verified in areas with low resistivity anomalies in the hard rocks.

5.2 EKS survey

EKS sounding were carried out to obtain the hydraulic conductivity of discontinuities identified from the multi-electrode survey. The ability to correctly predict the yield of boreholes was not very accurate. The technique could however differentiate between a potential successful station and a potential dry or unsuccessful station. The new data collection procedure and the GF2500 equipment by ground flow ltd. were employed.

Reproducibility was excellent for most of the site locations. Two fold data stacking was achieved by averaging the two processed channels in each data file. There was a satisfactory correlation between EKS data and the existing drilling records on most of the boreholes stations tested. There were clear differences between data obtained for dry borehole sites and successful borehole sites. It was observed that no signals are obtained for dry borehole sites compared with that for successful sites. Successful borehole site locations on the other hand produced very good and quality EKS signals with high hydraulic conductivity.

It must however be emphasized that borehole yield calculated from the EKS survey were not comparable to actual borehole yields obtained on information on these existing boreholes. These could be attributed to lack of seismic data in the area resulting in using inappropriate velocities for the calculation of borehole yields.

5.3 Radon Survey

The ^{222}Rn anomaly prospecting is an efficient tool to identify the areas of important water circulation. This technique takes time and is expensive to operate.

Rn has been used over the 15 past years as tracer in hydrogeology studies especially for water well siting. Initially used in granites and metamorphic contexts, prospecting ^{222}Rn anomaly is now also used in sedimentary terrains as the presence of radon is related to that of his parents (uranium 238 and 234, thorium 232 and radium 226), which are present in practically all the rocks (AFD, 2003). There is no information of radon in the area since the method has never been tested in the research area but there is a general belief of the presence of uranium in the area.

The pilot surveys demonstrated the sensitivity of the radon technique for locating fault or fracture systems when masked by unconsolidated cover (weathered sandstone). The study also showed that at least about 200 samples are necessary in a survey for the selection of a potential borehole-drilling site.

6.0 RESULTS AND DISCUSSION

The area has been divided into three groups based on the hydrogeological characteristics in the area.

Group 1 comprise of rocks belonging to the Bririmian, Tarkwain, Basal Sandstone and Granite rock formations (table 6). This group has a thick regolith and groundwater occurrence has been predominant in the weathered depths. High yields have been obtained in the fractured zones in the bedrock although generally fractures are limited in the bedrock. There has been appreciable success rate of borehole drilling in the group especially for hand pump installation where a minimum yield of 14 l/m is required to be classified as successful.

Group 2 comprise of rocks belonging to the sandstone and conglomerate dominated arenaceous Oti beds of the voltain rock formation (table 6). In this group the beds are highly fractured and jointed with a thin regolith. High yields have been obtained in this group from the fractured and jointed beds. This group has very good groundwater potential in the area. Success rates of drilling are always above average.

Group 3 comprise of rocks belonging to the argillaceous Obosum beds and upper Voltain formation (table 6). It is dominated by the sandstone, mudstone, shale and siltstone beds. Intercalations of these beds are also present in the group. The sandstone and siltstone beds produce most of the aquifers in this group. The group has the lowest groundwater potential in the area. Very low yields are encountered in the group.

6.1 Results of geophysical investigations

The results of geophysical investigations are discussed with respect to the various groups. A summary of the communities in each group are shown in table 6. The geology of the various groups is also shown in fig 17.

Typical results showing successful or otherwise of geophysical correlation with drilling in the various groups are discussed. The full results of the geophysical investigations; 2-D multi-electrode electrical resistivity survey and electro kinetic sounding (EKS) survey in all the 15 communities where measurements were taken are

included as Annex A & B. Symbols denoting the various categories of borehole status; successful, dry, marginal and aquifer zones are summarised in fig. 18.

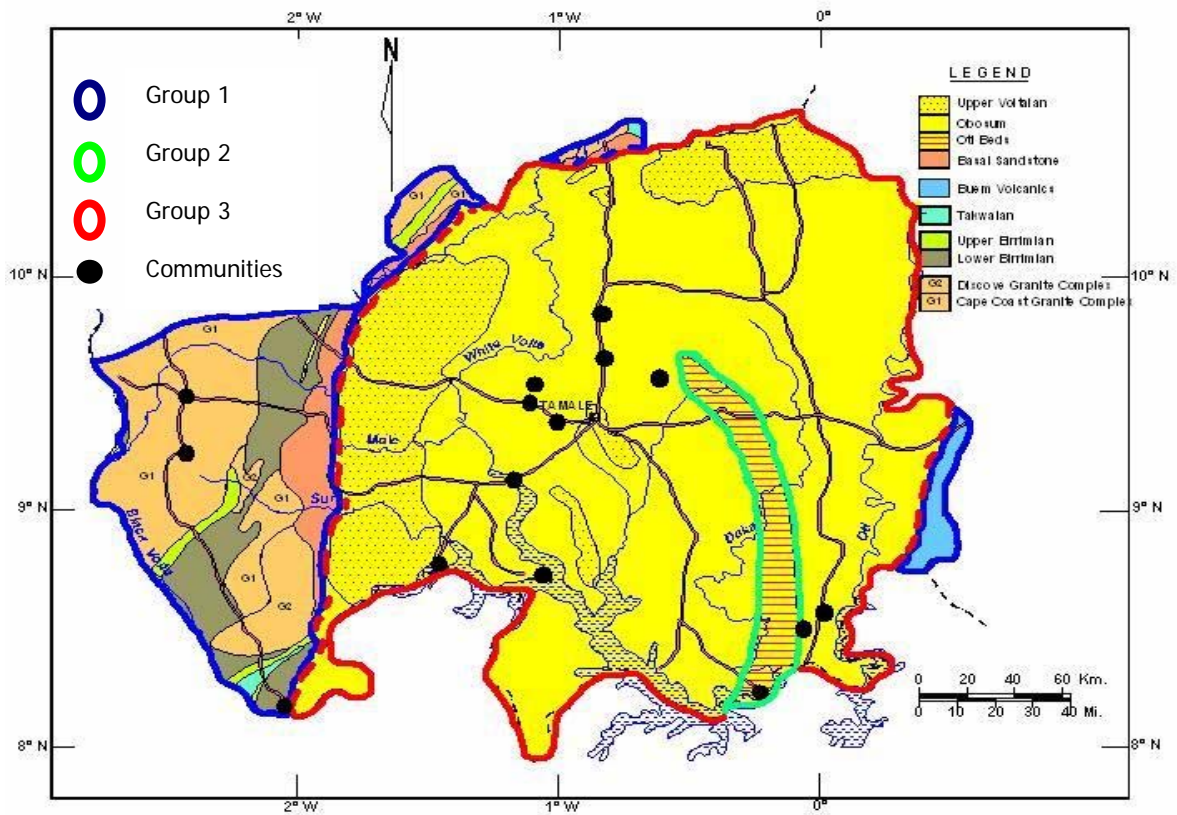


Figure 17: A map showing the geology, various groups and communities of data collection (modified from Kesse, 1985)

Successful well	Dry well	Marginal well	Water zones
■	■	▤	▤

Figure 18: Symbols denoting the various borehole status

Table 6: Summary of the various groups and traverse identification

Group	Formation	Communities	Traverse ID
Group 1	Birimain, Tarkwain, Basal Sandstone & Granites. (Precambrian)	Tuna Sawla Bamboi	A, C, E1, E2 E, F, G A, B, C
Group 2	Oti Beds. (Voltain sedimentary)	Gulubi quarters Kpandai	A, B, C C, F
Group 3	Upper Voltain & Obusom beds. (Voltain sedimentary)	Diari Pong Tamale Nanton Nyankpala Yapei Mpaha Buipe Tuna Yoggu Lonto	C1,C2,D1,D2 B,E,F F1,F2,G B,C1,C2 C,E1,E2 A,B A,C,E A,C,E1,E2 A,B,C A,B,C

6.1.1 2-D multi-electrode electrical resistivity survey results

The ABEM terrameter SAS 1000 is the equipment used with the Lund multi-electrode system. Stainless steel electrodes were used. Measurements on a traverse comprised the following;

- Profile with 64 electrodes and 5m interval spacing in the inner cable loop and 10m spacing interval in the outer two cables spreads as has been recommended in the ABEM terrameter SAS 4000/1000 instruction manual.
- Measurement configuration was the Werner long (WL) and the Werner short (WS) protocol.

The results are then displayed as resistivity model sections. The sections obtained for every traverse in each community are displayed in annex A.

The modelled results are displayed as coloured resistivity – depth pseudo sections. As a standard guide blue colours are used to represent comparative areas of low resistivity and red colours identify relatively higher resistivity on a profile.

6.1.2 Processing data in 2-D Lund multi-electrode electrical resistivity

The main aim of the data collected is to deliver a two dimensional (2-D) section of the resistivity distribution with depth. The RES2DINV software by Loke was used. It must however be noted that the 2-D model used during the inversion process also obeys the classical law of the resistivity theory and so the proposed model is one of the solutions and not the ultimate unique situation. The results therefore only help to give possibilities of analysis or interpretation of the proposed geological section.

The geo-electrical model obtained by the inversion process is generally not a geological section and so interpretation must be carried out based on the considerations of the prevailing field and geological conditions.

A model is the results of the forward modelling subroutine, which calculates the apparent resistivity values that can be compared with the actual values obtained from the fieldwork. The model is considered successful when the calculated values and the measured values are best correlated (ABEM, 2004).

6.1.3 Presentation of geophysical data

The summary of boreholes status summarised in fig. 18 has been adopted in the results presentation. It must be noted that not all the geophysical results in the communities are presented in this chapter but peculiar results in each of the groups are presented. All the results of geophysical investigation using the multi-electrode electrical resistivity survey and the EKS are included as annex A and B. Stations where these boreholes are indicated represent the actual drilled locations.

6.1.4 Selection of sites for drilling

Sites were selected for drilling based on the combined results of the multi-electrode resistivity survey and the EKS survey techniques. It must be noted that in the selection of sites for drilling, much emphasis was placed on the 2-D multi-electrode resistivity

survey because it has been used on a number of projects worldwide with good correlation results according to results on various groundwater projects which had utilized the technique.

In some of the profiles, drilling sites were selected in the absence of the author. Some of these sites resulted in dry boreholes and this confirms the need for qualified and trained personnel on the field during drilling geophysical data collection and drilling to review the concept for selection of drilling sites. In situations where drilling sites were selected without the approval of the author, alternative sites have been proposed and shown on the profile.

There was also a general project decision to make at least one drilling attempt in all the beneficiary communities on the project. In this respect some stations which were not considered to be very promising had to be drilled to satisfy project implementation rules and this also contributed to the drilling of some unsuccessful stations in the area.

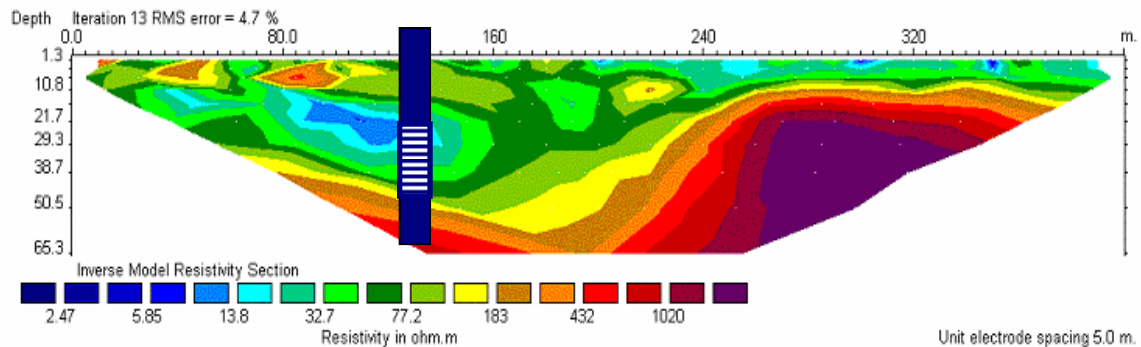
6.2 Geophysical results in group 1

This group comprise of results in Tuna, Bamboi and Sawla communities. Typical scenarios of geophysical data and the corresponding drilling results are discussed.

The geology underlying the communities in this group is the Precambrian Birimian, Tarkwain and Granite rocks (table 6). The group is characterised by deep weathering and groundwater occurrence is predominant in the weathered zones although substantial yield have been observed in fractures in the bedrock.

6.2.1 Typical 2-D multi-electrode resistivity results in group 1

Resistivity Profile 1: Bamboi Profile C

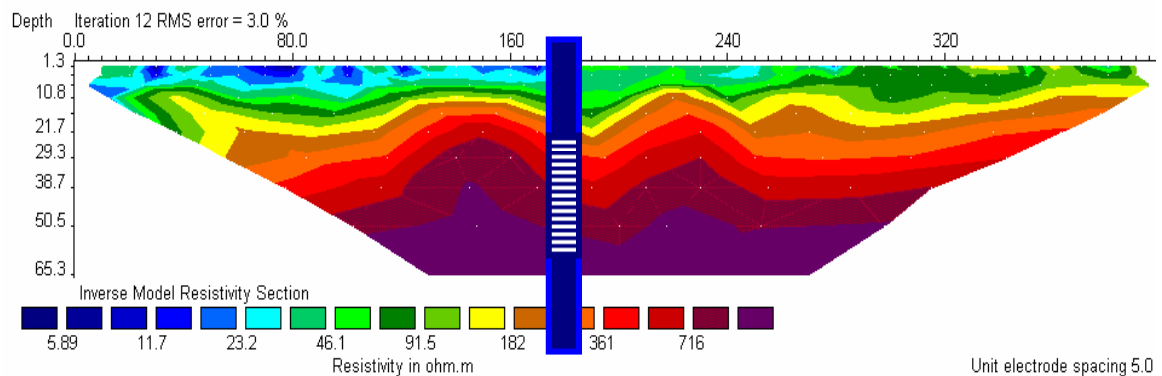


2-D multi-electrode electrical resistivity profile Bamboi C is shown above. The general structure is as follows;

A thin subsurface layer with low resistivity which extends to deeper depth in the middle of the profile and a thick layer with high resistivity (resistivity greater than 1000 ohm-m) acting as a basin at deeper depth, which is more dominant at the last quarter of the traverse where it is closer to the surface. This high resistivity layer could represent the bedrock, which is competent without any structures. A geological divide is observed at the boundary of the lower resistivity materials and that of the high resistivity material rock material at the station C 240.

In the middle of the basin at station C 125 of the profile is a very low resistivity zone, which is located between stations C 80 and C 150. This zone was interpreted to be a probable aquifer within the profile based on its lower resistivity in relation to the background resistivity on the profile and was thus selected for drilling.

A borehole drilled at the station C 125 as shown on the profile was successful with a yield of 135 litres per minute. The water strike was at a depth range (13-59 m) which coincided with the concept of interpretation of the electrical resistivity profile where the low resistivity material interpreted to be an aquifer on the profile is located. There is therefore a good correlation of the interpretation of the geophysical results with the results of the drilling.

Resistivity Profile 2: Sawla Profile G

2-D multi-electrode electrical resistivity profile G at Sawla is shown above. The profile generally shows low values of electrical resistivity rock materials at the subsurface. The profile produced three different resistivity of layered rock which are clearly defined by their different resistivity layers at the various depths as follows;

A thin subsurface layer with comparatively low resistivity values to an approximate depth of about 15 m. This layer of low resistivity is typical of weathered rock materials of the underlying rocks in the area.

An intermediate resistivity layer at the intermediate depth zone, which could represent weathered to moderately weathered rock material, is observed afterwards. This depth layer between the depth range (15-40 m) has a comparatively moderate resistivity in the range (150-300 ohm-m).

A thick layer with a comparatively high resistivity is also observed below the two layers of low to intermediate rock resistivity. This relatively high resistivity rock layer possibly representing the fresh rock material with no structural patterns gives no indication of fractures and joints which are good indications for aquifers.

The rock layers are highly sheared and show a wavy pattern. The different layers could represent different weathering profiles from the surface to intermediate depth with the fresh rock with no structures beneath. The shallow depth layers could also be interpreted to be layers of different rock material intercalations which have undergone

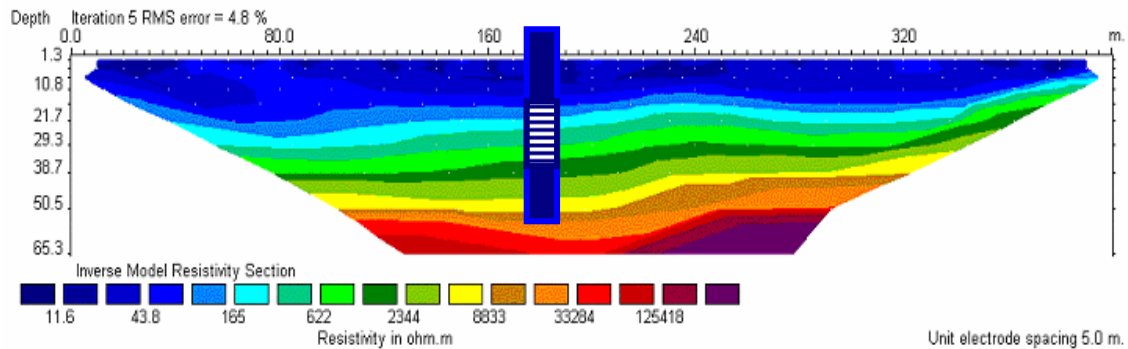
different degrees of weathering. The bedrock is interpreted as a high resistivity layer at the deeper depth horizon.

The intermediate layer rock material of resistivity in the range (180-400 ohm-m) is interpreted to be a layer which could possibly give a good aquifer. This layer is observed to have undergone some deformation at the station G 185 as observed from the wavy pattern and was therefore selected as a potential aquifer site for drilling.

Drilling was carried out at the station G 185 and information gathered from the drilling of the borehole showed that the borehole intercepted a zone of highly weathered granite after a sandy clay soil cover. The degree of weathering generally reduced with depth to a depth of about 55 m where the fresh granite rock was intercepted. The high resistivity material observed on the profile at the deeper depth therefore represented the fresh granite.

The resistivity layers of the different rock materials in the range (180-400 ohm-m) and its contact with the fresh rock observed at a depth range of about 55 m accounted for the total yield of 240 litres per minute for the borehole.

The results of the 2-D multi-electrode resistivity image and the drilling results therefore showed a good correlation. With the general concept of interpretation, the intermediate resistivity zone was the ideal target zone for groundwater exploration on the profile. This was confirmed by the presence of water at the depth range 20-54 m. No geological structures are observed in the bedrock and drilling through it did not contribute to the total yield of the borehole. The results of the drilling showed that the interpreted model is accurate with the borehole deriving its total yield of 240 l/m from the weathered granite resistivity layer at the depth range (20-54 m).

Resistivity Profile 3: Tuna Profile E

2-D multi-electrode electrical resistivity profile Tuna E is shown above. The profile shows that the area is underlain by high resistivity rock materials which are layered and boundaries of the different resistivity materials are clearly defined by the sharp change in electrical resistivity. The high resistivities observed are typical of fresh granite rocks. The general structure is as follows;

An overburden with low resistivity to a depth of about 20 m. Resistivity are in the range of (11- 45 ohm-m) approximately. This layer with the very low resistivity could be interpreted to be weathered materials derived from intense weathering of the underlying rock material.

An intermediate depth zone of comparatively high resistivity distribution in relation to the resistivity distribution on the profile in the range (2344-8833 ohm-m) which increases with depth. This intermediate depth layer shows different and sharp changes in resistivity with depth.

A very high zone of resistivity greater than 125418 ohm-m is observed from depth greater than 55 m. This layer defines the fresh rock material without any structural pattern. There is generally no structural deformation patterns on the whole profile apart from the different layering of the formation.

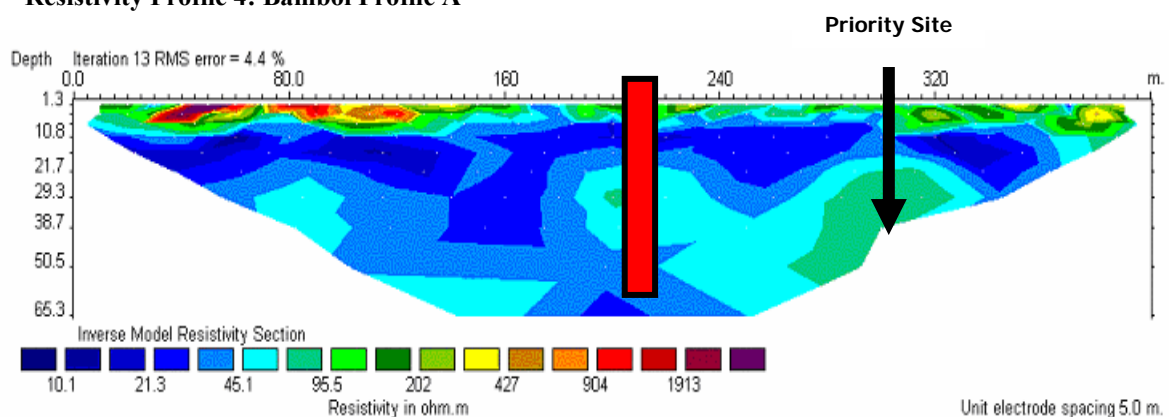
Resistivity distributions on the profile are generally high apart from the very low resistivity values observed at the surface. The profile therefore could be interpreted as showing the different layering of weathering and the different solidification and composition of the fresh electrical resistant rock materials. The layered intermediate

zone with electrical resistivity in the range (250-600 ohm-m) was therefore identified as the target for groundwater exploration. The generally high electrical resistivity on the profile at deeper depths did not give an indication of an aquifer at the deeper depth horizon.

A borehole drilled at the station E 175 intercepted a clay layer and a highly weathered granite layer underneath to a depth of about 12 m as was confirmed on the profile by the low resistivity layer. This is preceded by moderately weathered granite into a fresh granite rock at a depth of about 50 m. The borehole intercepted an aquifer in the moderate to slightly weathered granite material which conforms to the interpretation concept for such a high and resistive electrical geological formation where a lower resistivity layer is the target for drilling. A total yield of 150 l/m was obtained at this station.

The results of the interpretation of the 2-D multi-electrode resistivity survey and the drilling show that the interpreted modelling has a good correlation with the results of actual borehole drilling. The borehole derives its yield from the moderately weathered granite rocks which has a lower resistivity. Generally in a massive electrical resistant granite rock formation without any geological structures representing possible aquifers, enough yields are expected in the weathered depths.

Resistivity Profile 4: Bamboi Profile A



The traverse shows an area of typical comparative low resistivity. The high resistivity materials are only limited to the surface at the beginning of the profile and this could be a case of lateritic gravel materials at the surface. The profile shows typical

resistivity in the range (10-100 ohm-m) dominating and this very low resistivity conforms to an area of highly weathered rock materials or an indication of the presence of low resistivity rock materials in the area. In such low resistivity areas, the electrical resistivity method might not be quite efficient to demarcate a target zone for groundwater exploration since there is a low resistivity contrast between the target geological structures which is observed and the background.

With the basic concept of the electrical resistivity method on such a typical low resistivity profile, the target was therefore the area with comparatively higher resistivities within the very low electrical resistivity rocks at the subsurface. This is because the very low resistivity might be an indication of the presence of highly weathered rock material with a lot of clay.

A structure observed at the station A 300 has a resistivity in the range (95-200 ohm-m) and was interpreted to be the best potential station for drilling on the profile. The drilling however could not be carried out at the station because of the problem of land ownership. The station was located on a private property and the owner was not in favour of the location. This station has been marked as the priority site on the profile (resistivity profile 4).

A well drilled at the station A 215 was dry and logs from the borehole indicate that the area is underlain by mudstone which generally has low resistivity hence the low resistivities observed even at deeper depths. The borehole intercepted a 3 m layer of lateritic gravel from the surface confirming the high electrical resistivity materials observed at the surface after which different weathered layers of mudstone rock materials are observed to a depth of 63 m. This zone is then followed by the fresh mudstone rock material without any intrusions or intercalations.

The results of the electrical resistivity survey and the drilling generally showed a good correlation. A successful borehole could have been obtained had the borehole been drilled at the station A 300. The potential at the drilled station A 215 was not very good although an aquifer at the depths (25-40 m) was expected.

The interpretation of the electrical resistivity profile and results of actual borehole drilling gave a good correlation. From the results of the drilling at the station A 215, the station A 310 would have been able to produce a successful well with enough yield of capable of sustaining a hand pump installation borehole. The station A 215 with such a low resistivity of about 45 ohm-m had a low probability of being successful. The station was drilled in the absence of the author after an agreement between the project and the community was reached.

6.2.2 Analysis of 2-D multi-electrode resistivity and drilling in group 1

Geophysical investigations were carried out in three communities belonging to this group with a total number of 10 electrical resistivity geophysical profiles. Out of this number a total of 7 stations were drilled. A breakdown of the drilling results have been summarised in table 7.

Table 7: 2-D multi-electrode resistivity results and drilling in group 1

Total No.	Successful(mechanisation)	Successful(hand pump)	Dry
7	3	2	2

A total number of 7 stations were drilled in the three communities representing this group. The results yielded 3 successful boreholes which qualified for mechanisation, 2 drilling stations qualified for hand pump installation and 2 of the stations had yield which did not qualify for construction and therefore designated as dry/unsuccessful wells (table 7).

Analysis of the results gives a good result of the application of the technique in the formation. Distinct lithological profiles and changes within the various lithologies are accurately differentiated by the various 2-D multi-electrode electrical resistivity profiles. In most of the profiles in this group the weathering profiles are also differentiated from the fresh rock by their lower resistivity layers.

Groundwater potential in the group is closely linked with the depth of overburden and the presence of geological structures notable fractures and joints in the bedrock. The potential for obtaining groundwater in this group normally depends on the saturated thickness of the high porosity upper saprolite, and the development of a high

permeable transition zone between the regolith and the bedrock being the two key factors controlling respectively the aquifer storage capacity and well yield potential (Owen *et al*, 2005).

Table 8: Lithology and resistivity range for obtaining groundwater in group 1

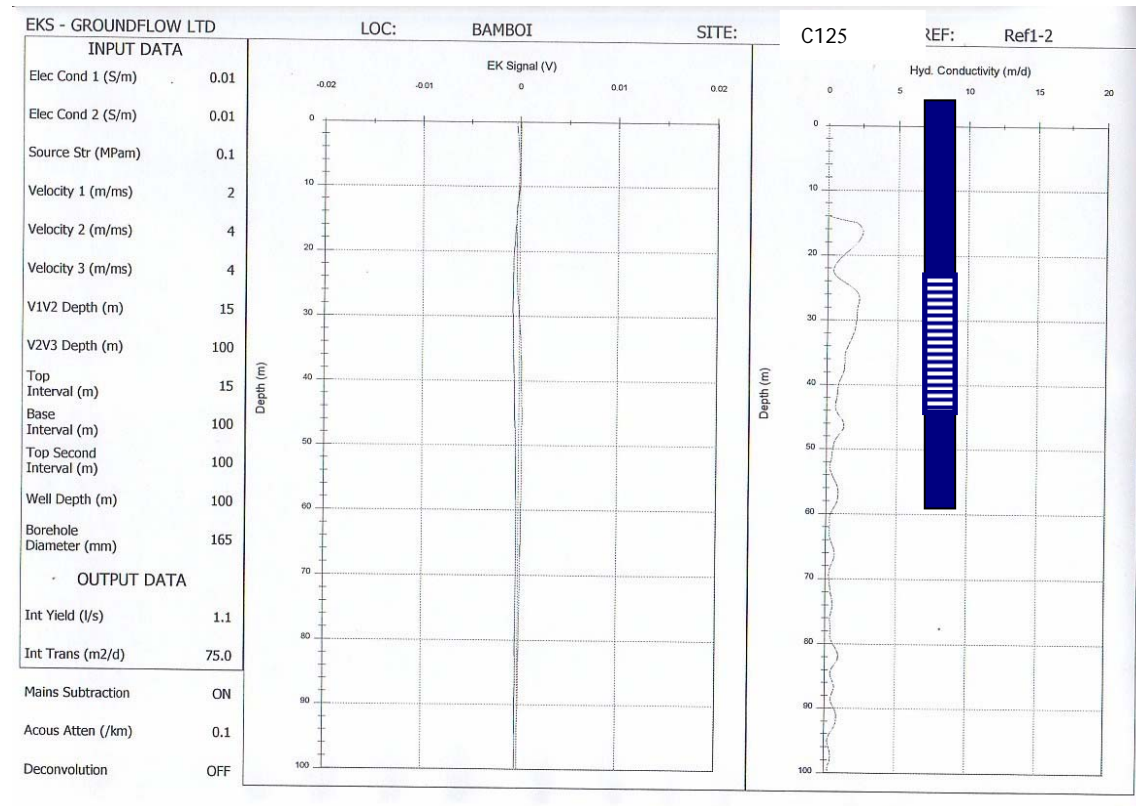
Rock Type		Resistivity (Ω -m)	Hydrogeology significance
Granite	Regolith	100-400	Good groundwater potential and main aquifer
	Jointed/fractured	150-700	Very good groundwater potential with high yields
	Consolidated	800-10000	Hard with poor groundwater potential
Sandstone	Regolith	30-100	Moderate groundwater potential
	Jointed/fractured	30-300	Very good groundwater potential with high yields
	Consolidated	200-1000	Poor groundwater potential
Mudstone	Regolith	20-80	Moderate to poor groundwater potential
	Jointed	30-100	Moderate to poor groundwater potential
	Consolidated	30-150	Poor groundwater potential

In the granite rock formation, the nature of the regolith and an approximate target resistivity between (100-700 ohm-m) mostly produce successful borehole drilling sites (table 8). Very low resistivity materials in the bedrock in very low resistivity rock formations such as mudstone and shale does not give a good indication of an aquifer. Low resistivity targets in the low resistivity rocks are not good aquifer indicators.

In the sandstone rock formation of the group a moderate resistivity range of between (32-200 ohm-m) is capable of producing a successful borehole site (table 8). Therefore the potential for obtaining groundwater in this group will depend on the lithological units, regolith and nature of bedrock (fractures and joints) and the resistivity of the target structure. Very low resistivity targets (less than 50 ohm-m) are not likely to produce successful borehole drilling sites and show the presence of clay materials in the overburden.

6.3 Typical EKS results in group 1

EKS Sounding Data 1: Bamboi C125

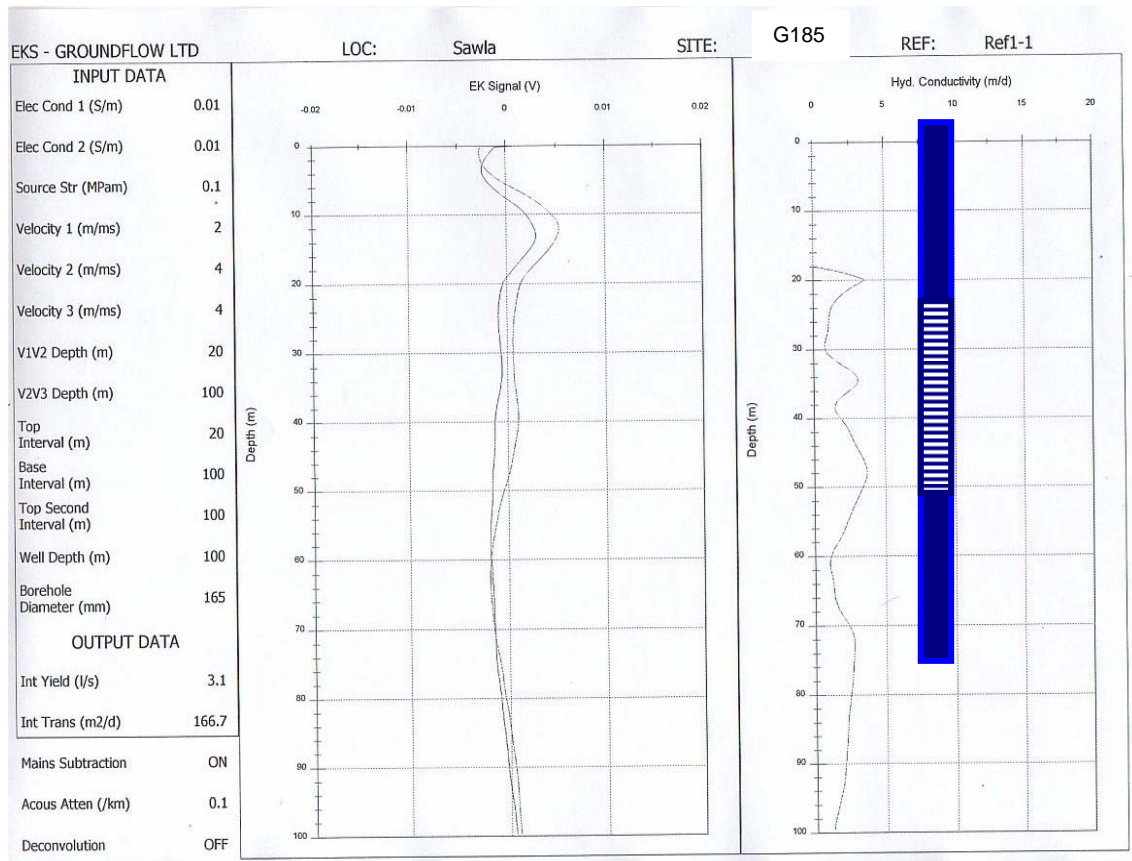


Two matched and consistent signals were obtained at this station on both channels. The hydraulic conductivity curve had higher amplitude between the depth ranges (25-45 m) and this depth zone was interpreted to be a good potential zone for groundwater exploration and hence the target for drilling. After this depth the graph shows very low amplitude which according to the concept of the EKS is an indication of the absence of an aquifer at the deeper depth.

The graph therefore was interpreted as showing an indication of the possibility of a shallow to intermediate depth aquifer at the depth horizon (25-50 m).

A borehole drilled at the station intercepted an aquifer at the depth interpreted from the EKS results with a yield of 135 l/m and this confirmed the accurate interpretation of an aquifer at the station from the EKS results. There was therefore a good correlation of EKS interpretation and actual drilling results.

EKS Sounding Data 2: Sawla G 185



EKS sounding carried out at the station G 185 is illustrated above. Two evenly matched signals were obtained at the station confirming the reliability of the data. Amplitudes of the signals were high at the shallow to intermediate depths and these signal amplitudes gradually reduced in the fresh rock at deeper depths which is normal because permeability which is related to hydraulic conductivity is generally higher in rocks at lower depths where weathered materials are encountered than at the deeper depths of fresh rock materials.

The modeling of the field data was carried out with the assumption of a static water level (SWL) of about 20 m obtained from borehole information in the area. Hydraulic conductivity was not calculated above the static water level which is part of the guidelines by Groundflow Ltd., the manufacturer of the EKS equipment. The hydraulic conductivity graph has appreciable amplitude even at deeper depths and is quite predominant at depth range (20-55 m) and (60-80 m). These depth ranges were

therefore approximately interpolated to be probable aquifer zones for groundwater accumulation and therefore a target for drilling.

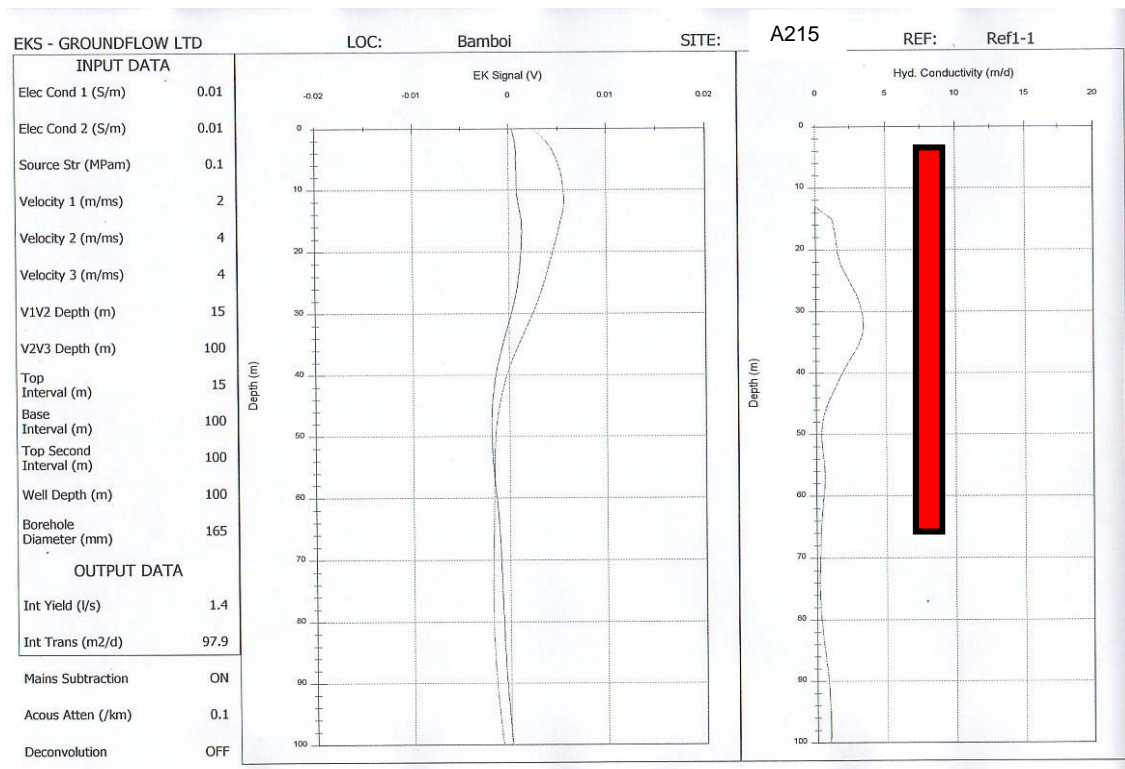
A borehole drilled at the location produced an aquifer at the depths (20-45 m) with a yield of 240 l/m. The aquifer therefore corresponded with the first aquifer zone interpreted from the results of the EKS signal and hydraulic conductivity. The drilling could not continue to exploit the total depth of the second aquifer zone because of some drilling problems. Drilling however was carried out to a depth of 75 m which was in the second interpreted aquifer zone but no contribution of the total yield of the borehole was attained as had been interpolated from the EKS model results. The second interpreted aquifer zone at the depth range (60-80 m) did not produce an aquifer although drilling could not exploit its full depth.

There was therefore a good correlation between EKS sounding and actual drilling results in the first extrapolated aquifer zone which was observed in the shallow to intermediate depth zone. The interpretation of the EKS graph at the shallow depth was therefore accurate at the station.

The second aquifer zone had a negative correlation and did not contribute to the total yield of the borehole.

It can therefore conclude that there was a good correlation with the results of drilling at the shallow depth aquifer but a negative correlation at the deeper depth aquifer.

EKS Sounding Data 3: Bamboi A 215



Two identical and evenly matched signals were observed on both channels. There was high hydraulic conductivity amplitude between the depths range (25-40 m) on the hydraulic conductivity graph and this was therefore interpreted to be a possible aquifer target at the shallow to intermediate depth horizon.

A borehole drilled at the station did not show any aquifer as has been interpreted from the results of the EKS sounding. The borehole was dry and therefore gave a bad correlation of EKS model interpretation and actual drilling results. The results therefore show that there was no correlation of actual drilling and EKS model interpretation at the station.

6.3.1 Analysis of EKS and drilling in group 1.

Amplitudes of hydraulic conductivities observed on the EKS hydraulic conductivity graphs are generally low in the group. The low amplitudes are peculiar to this geological formation of the Precambrian Birimian rocks which have low porosity in the fresh rock unless they are highly fractured and jointed. Signals produced in this group are matched and identical on both channels in the weathered rocks. With the fresh and unweathered bedrock areas in this group, signals are very haphazard confirming the non suitability of such a technique in the fresh and unfractured hard rocks of the Precambrian formation.

Actual borehole drilling yields in the group have a satisfactory correlation with calculated borehole yields from the EKS model.

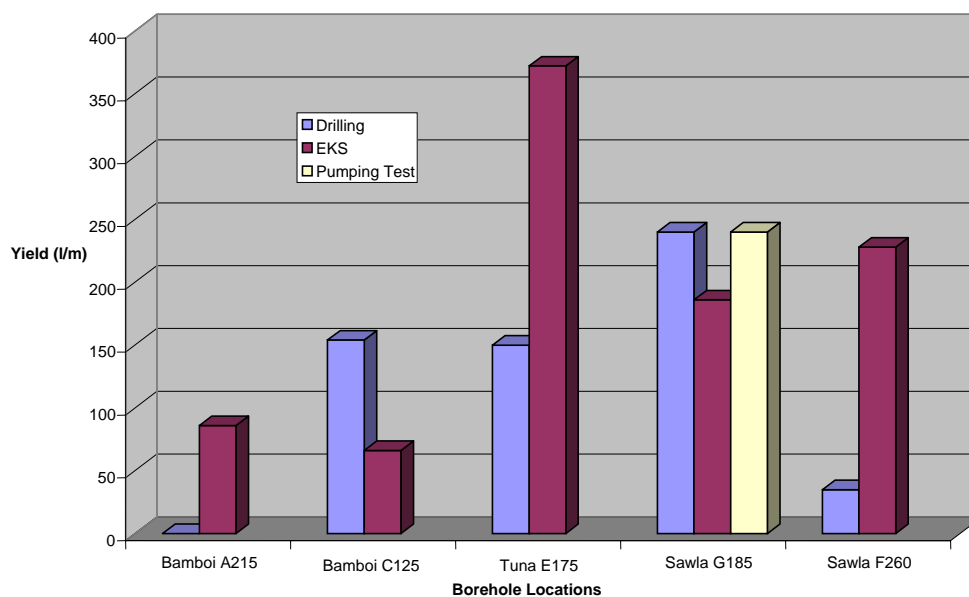


Figure 19: Comparison of borehole yield (Drilling, EKS and Pumping Test) in Group 1

NB. Drilling yield- short time pumping test during drilling to determine borehole yield.

A summary of the comparison of the yield obtained from the calculation from EKS data, drilling and pumping test is shown (fig. 19). It is observed that most of the EKS model results and actual drilling results are satisfactory correlated. In Sawla G 185 where pumping test was successfully carried out on the borehole, the EKS results, pumping test yield and drilling yield were highly correlated. In the other stations

Sawla F 260 and Tuna E 175, the predicted EKS yields were quite higher than the drilling yield. Aquifers encountered in this group were mostly in the granite rock formation apart from Bamboi A 215 in which mudstone rock was the target. Station Bamboi A 215 was dry although the EKS had predicted a successful station.

The boreholes in this group therefore gave a satisfactory correlation with the various yields in the granite rocks with the best correlation at Sawla G 185.

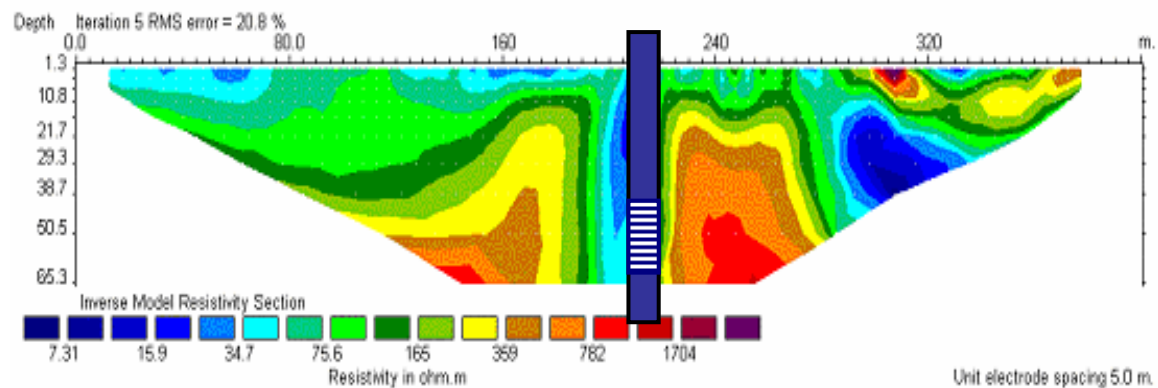
As has been stated earlier in the work, the velocity values used for the calculation as well as the Static water levels (SWL) were not very accurate since no reliable data was available and so these values were apportioned based on extrapolation from the EKS manual by Groundflow ltd. and some available data. The SWL information obtained during the drilling campaign was sometimes different from SWL information that had been obtained from the previous borehole drilling data in the area and this contributed to the disparity in calculated yields from EKS model calculation and actual drilling yields.

6.4 Geophysical results in group 2

Kpandai and Gulubi Quarters are communities belonging to this group. The major geological formation is the Voltain sedimentary rocks but with the Oti arenaceous sandstone beds quite dominant. The sandstone beds in this group are highly fractured and jointed. The group is noted for very high borehole yields and borehole drilling success rates. Groundwater quality has been very good in the group according to previous drilling results.

6.4.1 Typical 2-D multi-electrode resistivity results in group 2

Resistivity Profile 5: Gulubi Quarters Profile A



A 2-D multi-electrode resistivity profile in Gulubi Quarters profile A is shown above. Two distinct geological structural anomalies are observed on the profile. In the middle of the profile between A 100 and A 300 is a comparably very high electrical resistivity rock material which is intruded by a very low resistivity material probably a dyke at the station A 210.

Another low resistivity geological structural anomaly is observed at the station A 310 which is directly below a very high resistivity zone at the surface.

These two distinct low resistivity geological structural anomalies are interpreted to be very good aquifer zone targets for groundwater exploration considering the background resistivity rock materials on the profile.

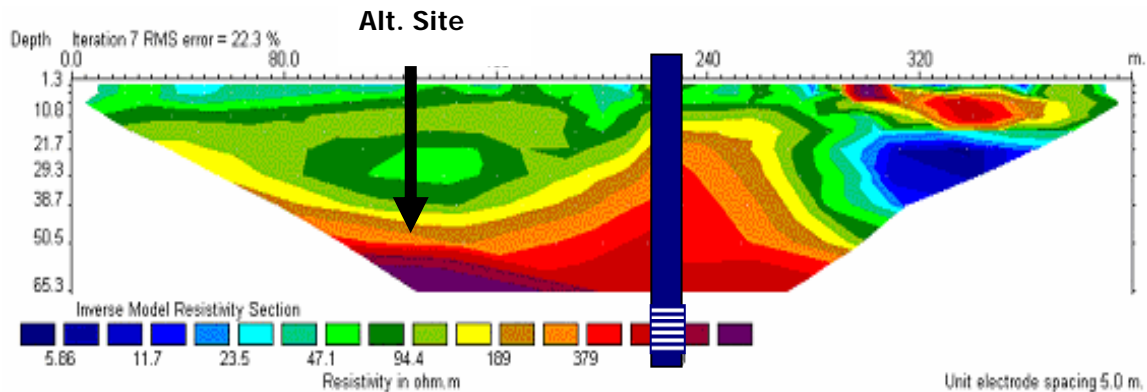
The station A 210 which has been interpreted as a probable dyke across a very high resistivity zone was therefore selected as the best possibility of intercepting an aquifer. However two scenarios were envisaged to be possible at this station as follows;

- The low resistivity zone could be a fracture zone filled with clay material thereby giving the very low resistivity observed from the results. In this situation there is the likelihood of the borehole not yielding enough for construction for mechanization but could yield enough for hand-pump installation.
- The other situation, which could be possible, is the zone representing a fracture/weak zone representing an aquifer so could produce very high yield for mechanise borehole construction.

These two possibilities are options from the interpretation of the resistivity profile at the station. The station A 210 was therefore selected as the first option for drilling based on the distinct structure observed on the profile.

The results of borehole drilling at the station A 210 encountered a clayey material up to a depth of 3 m. This was followed by highly weathered to fairly weathered sandstones to a depth of about 20 m after which the fresh grey sandstones were encountered. The first option of a clay filled fracture from the interpretation was obtained at the site. The total yield of 40 l/m obtained was at the contact zone between the clay field material and the fresh rock.

The results of the resistivity imagine and the drilling shows that the interpreted modelling is accurate. As observed from the drilling results, there was a good correlation between the geophysics and the results of drilling.

Resistivity Profile 6: Gulubi Quarters Profile B

A 2-D multi-electrode electrical resistivity profile in Gulubi Quarters profile B is shown above. General resistivities of the underlying rock materials are low. Three distinct geological structures with peculiar characteristics are observed on the profile.

- A structure with a resistivity in the range (45-300 ohm-m) between the stations B 80 to B 160.
- A structure at the station B 230 which shows an accumulation of rock materials with comparatively high resistivity in the range (94-500 ohm-m)
- A structure at the station B 320 with a very low resistivity bounded below and above by a relatively high resistivity material.

The relatively low resistivity structures observed on the profile were interpreted to be areas with dominant clay materials alternating within the sandstone beds and thus were not interpreted to be good aquifers for exploitation.

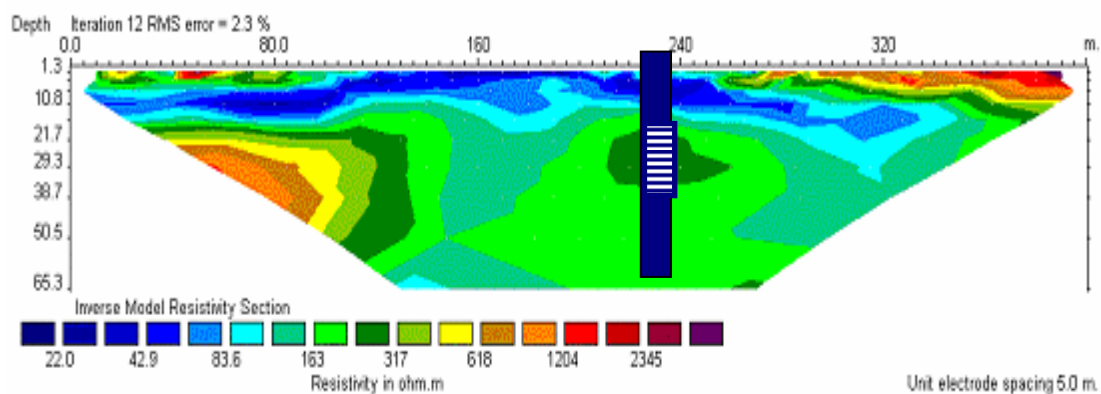
The relative high resistivity structure with resistivity in the range (180-700 ohm-m) at station B 320 was considered to be a good aquifer target. Another station which was also considered as a good aquifer potential site is station B 135 which has a resistivity layer in the range (47-700 ohm-m). However the high resistivity material under the layer was very close to the surface and so drilling could be carried out to a maximum depth of about 55m.

A borehole drilled at the station B 230 intercepted a clay layer to a depth of about 3 m followed by a highly weathered sandstone material with decreasing weathering to a depth of 20 m where the fresh sandstone material was encountered. The aquifer with a yield of 1800l/m was intercepted at the comparable intermediate resistivity zone on the profile. Resistivity of this zone was in the range (380-700 ohm-m).

The results of the resistivity image and the drilling shows that the interpreted modelling was good. As observed from the drilling results, there was a good correlation between the electrical resistivity results and that of actual drilling.

As observed on the profile, it is always important to consider the electrical resistivity values and not the colour representation. On profile A and B in Gulubi Quarters, the same colour on each of the two profiles in the same community represents different resistivity range of values.

Resistivity Profile 7: Kpandai Profile C



2-D multi-electrode electrical resistivity profile in Kpandai profile C is shown above. Generally a low resistivity rock material underlies the area. The area is generally noted for the presence of highly fractured sandstone beds. Two main geological structural anomalies are observed on the profile.

- There is a structure with a moderate resistivity in the range (163-300 ohm-m) between stations C 200 and C 250m. This resistivity range could be interpreted to be a good material for an aquifer.

- A high electrical resistivity structure is also observed on the profile beneath stations C 20 - C 90 from the beginning of the profile. The resistivity of over 1000 ohm-m was considered to be very high for the presence of an aquifer.

The profile shows an overburden with very low resistivity to a depth of about 15 m. On top of this low resistivity layers occurs high resistivity materials at the surface, which is quite visible at the last quarter and beginning of the profile. Lateritic gravel materials always represent these high resistivity materials at the surface. The intermediate resistivity structure observed at the station C 230 was interpreted as a possible aquifer zone within the profile and was therefore selected for drilling.

The results of drilling at the station C 230 showed that the very low resistivity layer to a depth of about 15 meters observed was moderately to slightly weathered shale. After this shale, moderately weathered to fresh fine grained sandstone formation was encountered. Thus the sandstone formation interpreted from the profile produced the aquifer with a yield of 1800 l/m. The structure interpreted to be an aquifer was therefore correct.

The results of the electrical resistivity profile and the actual drilling results show that the interpreted modelling is accurate with a good correlation between the 2-D multi-electrode electrical resistivity results and the results of actual drilling.

6.4.2 Analysis of 2-D multi-electrode and drilling results in group 2

Geophysical investigations were carried out in two communities Kpandai and Gulubi Quarters belonging to this group with a total number of six 2-D multi-electrode electrical resistivity geophysical profiles.

Drilling results are summarised in table 9. Very high yields were obtained from drilling in this geological formation. Distinct lithological boundaries, weak geological zones and fractures which are good indicators for groundwater availability were clearly observed on the 2-D multi-electrode profiles. Changes in resistivity of the subsurface rock materials were distinct with a sharp resistivity contrast between the layers.

Table 9: 2-D multi-electrode resistivity results and drilling in group 2

Total No.	Successful(mechanisation)	Successful(hand pump)	Dry
4	3	1	0

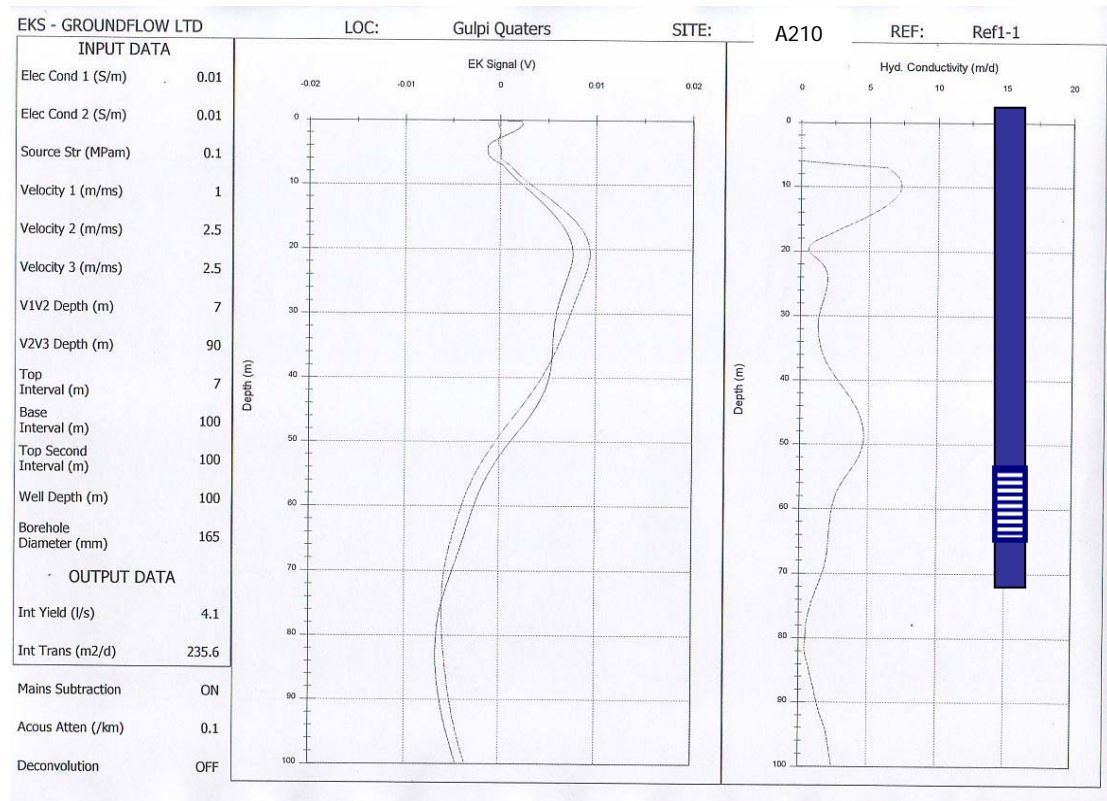
Table 10: Lithology and resistivity range for obtaining groundwater in group 2

Rock Type		Resistivity (Ω-m)	Hydrogeology significance
Sandstone	Regolith	50-150	Water bearing and very good groundwater potential
	Jointed/fractured	100-700	Very good groundwater potential, highly fractured/jointed with high yields. Main aquifer in the group.
	Consolidated	200-5000	Moderate groundwater potential.

The group generally has a very thin overburden and regolith thickness. The bedrock predominantly sandstone was observed to be highly fractured. Most aquifers in the group were intercepted in the fractured sandstone beds. Resistivity range (100-400) ohm-m is a potential aquifer zone in the group (table 10). This resistivity range accounted for high yielding borehole in the group. This resistivity range shows highly fractured bedrock saturated with potable water.

6.4.3 Typical EKS results in group 2

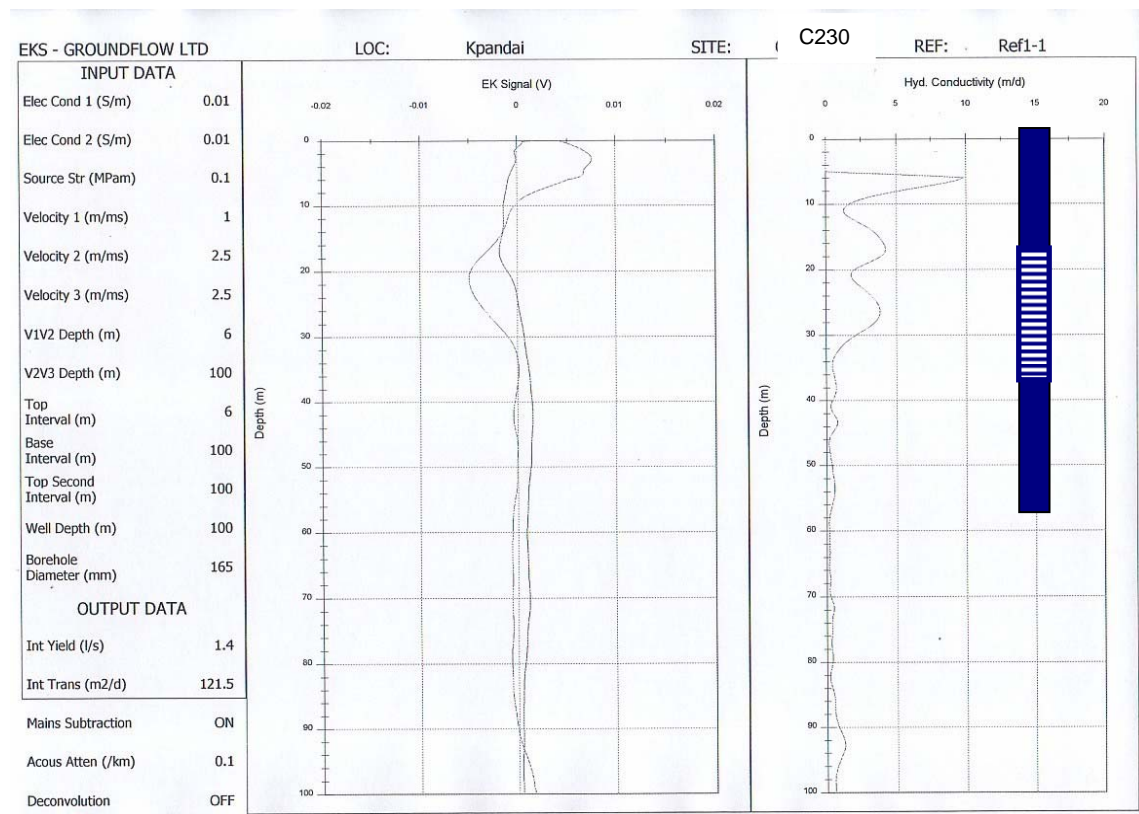
EKS Sounding Data 4: Gulubi Quarters A 210



The sounding produced matched signals which were identical on both channels. The hydraulic conductivity was high at the station. A major aquifer zone was interpreted from the hydraulic conductivity graph between the depth range (35-70 m). The shallow peak on the graph was not considered as it was very shallow for borehole construction. The interpreted aquifer zone was quite distinct and significant. Much yield was expected from this probable aquifer zone because of its big thickness.

The borehole drilled at this station produced an aquifer with a yield of 40 l/m at the depth range (54-65 m). Although the zone was within the extrapolated aquifer depth from the EKS interpretation, the expected major aquifer zone was dry. The aquifer thickness was less than had been expected from the EKS results and the yield of the borehole was less than had been expected from such a large depth aquifer zone.

There was therefore a bad correlation of the EKS and actual drilling results.

EKS Sounding Data 5: Kpandai C 230

The sounding produced two matched signals on both channels with high amplitude of hydraulic conductivity at the lower depth to a depth of about 40 m below ground level. The amplitude is very high at the depth range (15-30 m). The deeper depth signal produced no significant amplitude from the background indicating an absence of a probable aquifer. Because of the low static water level (SWL) in this area hydraulic conductivity was not calculated above a shallow depth of 6m.

The station was therefore selected to explore the possible aquifer zones extrapolated from the hydraulic conductivity curve at a depth range (15-30 m). Drilling produced a yield of 1800 l/m at the aquifer zones demarcated from the EKS model calculated results thereby giving a good correlation between EKS results and actual drilling. No aquifer was encountered after this depth and therefore the concept of interpretation of the EKS results at the station was accurate.

6.4.4 Analysis of EKS results in group 2.

This group is dominated by high hydraulic conductivity amplitudes and sometimes erratic signals on sounding stations which are not fractured. Most of these amplitudes are observed at shallow to intermediate depth horizon. Signals were reproducible and were evenly matched confirming the reliability of field data acquisition.

Very high yielding boreholes were attained in this group. As has been observed on the various EKS graphs in the zone, most of the probably aquifer zones demarcated from the EKS hydraulic conductivity graph contributed significantly to the total yields of the boreholes drilled.

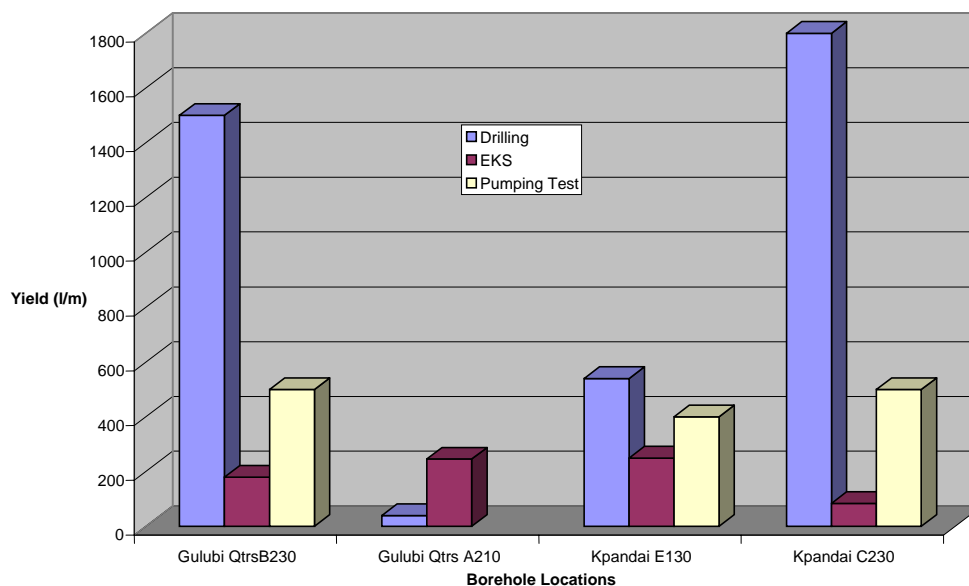


Figure 20: Comparison of borehole yields (Drilling, EKS and pumping test) in Group 2

NB. Drilling yield- short time pumping test during drilling to determine borehole yield.

Pumping test was successfully carried out on three out of the total number of four boreholes in this group. Borehole yields obtained during drilling were quite higher than that of pumping test and calculated EKS yields (fig 20). The lower yield obtained from pumping test compared to drilling is quite normal for the geological formation of fractured Oti sandstone beds. In most cases drilling yields have always been higher. EKS yield were however lower than yield obtained after pumping test in most of the designated borehole stations.

The best correlation of yields obtained from all the various activities was obtained at Kpandai E 130. At this station all the three different borehole yields were highly correlated. At the station Gulubi Quarters A 210 however the calculated EKS yield was higher than the actual drilling yield. The other stations had EKS model calculation yields lower than the actual drilling yields.

It is observed that this group is dominated by arenaceous sandstone beds which are highly fractured and therefore very porous. The technique of EKS might be quite applicable in the areas of the group known to be highly fractures with a thick overburden. It is also observed that in this group all the boreholes were successful as had been predicted by the EKS results. In the interim the EKS could be applied in the group to assess a potential successful borehole station or otherwise without considering the yield expected at the station.

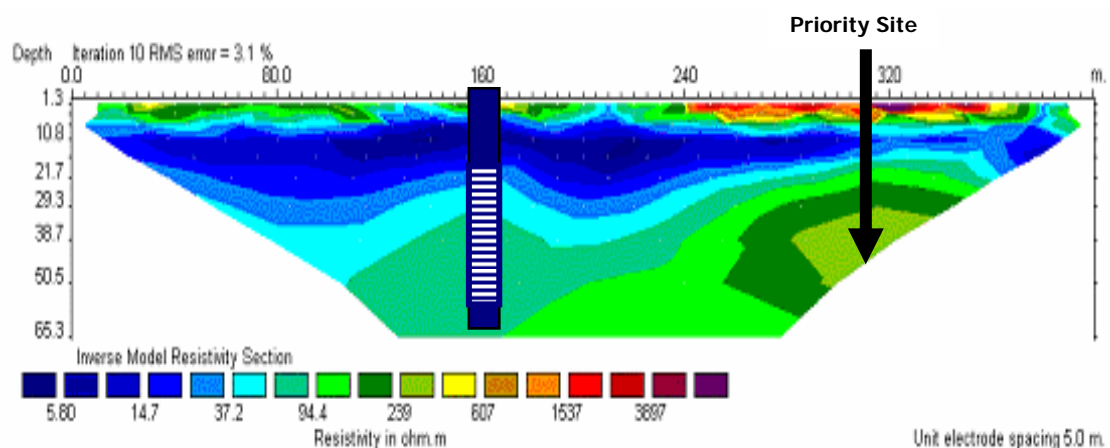
6.5 Geophysical results in group 3

This group comprise of results in the following communities; Diari, Pong Tamale, Nanton, Nyankpala, Yapei, Mpaha, Buipe, Tuna, Yoggu and Lonto and contains the largest number of communities. The geology of the group is the Voltain sediments with mainly mudstone, shale, sandstone and siltstone dominating. There are also intercalations of these rock units. This group is associated with limited groundwater resource, very low success rates of borehole drilling and low yields.

Increasing the success rates of borehole drilling in this group by utilising a systematic methodological approach and effective geophysical techniques have been one of the main objectives of the research.

6.5.1 Typical results of 2-D multi-electrode resistivity in group 3

Resistivity Profile 8: Nanton Profile F



A 2-D multi-electrode resistivity profile Nanton F is shown above. Three demarcated different resistivity layers were observed on the profile. The materials have been clearly differentiated by their different resistivity layers and the resistivities generally increase gradually with depth. A geological structure with an intermediate resistivity in the range (100-400 ohm-m) is observed beneath station F 310. Apart from this structure there are generally no structural patterns observed on the profile apart from the different layering representing groups of materials of same electrical resistivity. The general structure is as follows;

An overburden with very low resistivity distribution to a depth of about 25 m. The resistivity at the overburden is less than 50 ohm-m except the thin high resistivity material representing possible lateritic gravel material observed at the surface at the last half of the profile. This layer depth is followed by another layer with resistivities in the range of approximately (50-90 ohm-m). Two possible drilling targets were interpreted from the geophysical profile as follows;

- The layered structure with the resistivity range (95-250 ohm-m) between stations F 120 and F 180
- The geological structure beneath the station F 310 with a resistivity range (230-400 ohm-m).

The structure beneath the station F320 was interpreted to be a very good structure for groundwater exploration considering its resistivity range of about (230-400 ohm-m) and the low resistivity of the subsurface material in the area. Drilling could however not been carried out at the station because of accessibility of the drilling rig to the station.

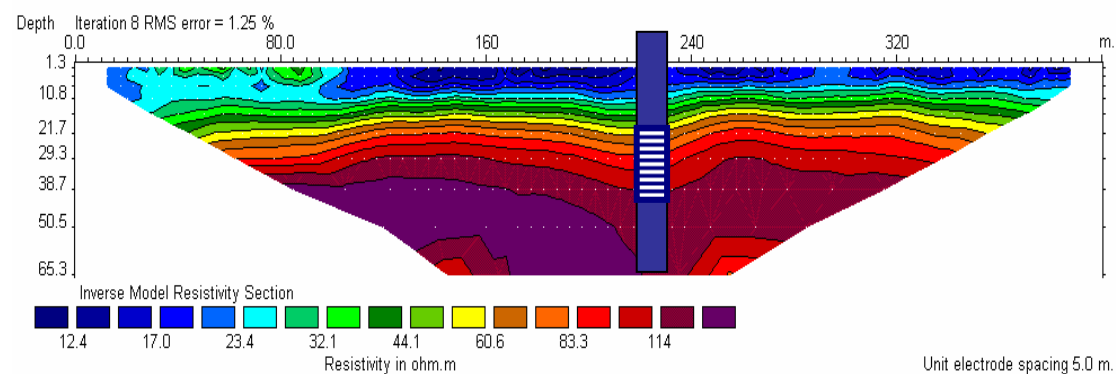
The layered structure at the station F 160 was therefore selected for drilling. The resistivity layer of about 250 ohm-m was very dominant at this station and it extended to a deeper depth horizon. Considering the value of the resistivity of the layer and the general background resistivity, it was interpreted to be a good station for groundwater exploration. The thickness of the layer was quite significant and a good aquifer was expected at the station.

Drilling at station F 160 to a depth of 60 m intercepted a highly weathered to moderately weathered sandstone material to a depth of 20 m which is observed on the profile by the low resistivity layer less than 50 ohm-m. After this depth the fresh, highly fractured/jointed sandstone rock material was intercepted and this zone contributed to the total yield of 1200 l/m for the borehole. The resistivity layer which was interpreted to be the layer for an aquifer therefore accounted for the total yield of the borehole.

The station F 310 marked as the priority site (resistivity profile 8) would have produced a higher.

The results of the 2-D multi-electrode electrical resistivity and the drilling therefore showed that the interpreted modelling and the probable aquifer zones demarcated from the profile is accurate. The drilling results confirmed the interpretation of the electrical resistivity profile. There was a good correlation between the electrical resistivity profile results and actual drilling.

Resistivity Profile 9: Diari Profile T



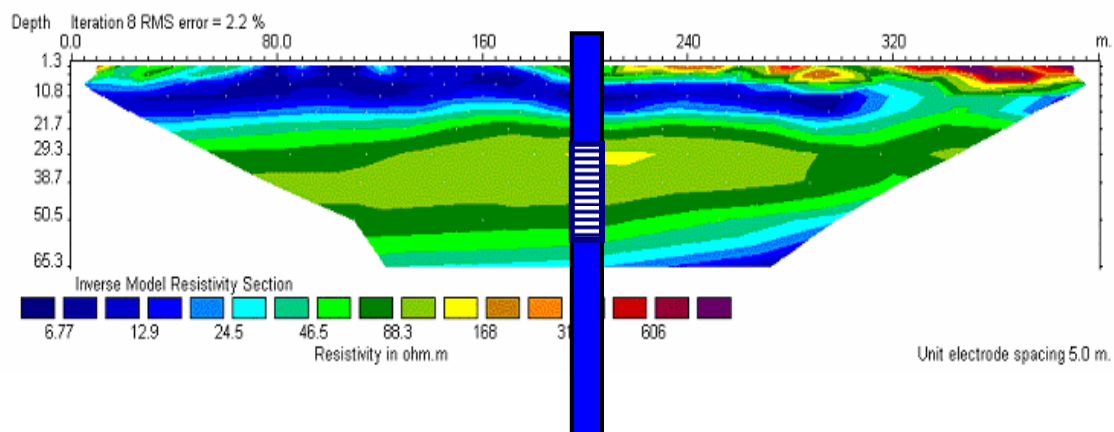
A 2-D multi-electrode resistivity profile in Diari T 230 is shown above. The profile is generally underlain by very low electrical resistivity (less than 100 ohm-m) of various rock materials. The profiles show layers of different subsurface materials with small changes in resistivity to a depth of about 35 m. These layers could also be interpreted to be intercalations of different rock materials or showing the different weathered layers of rock at the subsurface. After this depth, there is a marked increase in thickness of the individual layers.

No geological structures were observed on the profile apart from the different layers of resistivity rock materials observed. The different layers are observed to converge towards the station T 230. The moderately higher resistivity layers compared to the background resistivity is seen to elongate and the thickness of the layers also broaden at this station.

Drilling at station T 230 intercepted a lateritic clay material which was interpreted from the very low resistivity layer at the subsurface to a depth of about 6 m. After this depth different degree of weathered sandstone was intercepted. The total depth of the borehole was 60 m and no other material was intercepted apart from the different degree of weathered sandstone rock materials.

The aquifer zone was observed in the sandstone material with a yield of 420 l/m confirming the interpretation of the profile. As has been observed, in areas of very low resistivity distribution, the very low zone are not considered as target for groundwater exploration as these zone might be areas of dominant clay materials but the relative intermediate/higher resistivity zones. The results of drilling confirmed the concept of interpretation from the electrical resistivity profile results. The results showed that the interpretation was accurate.

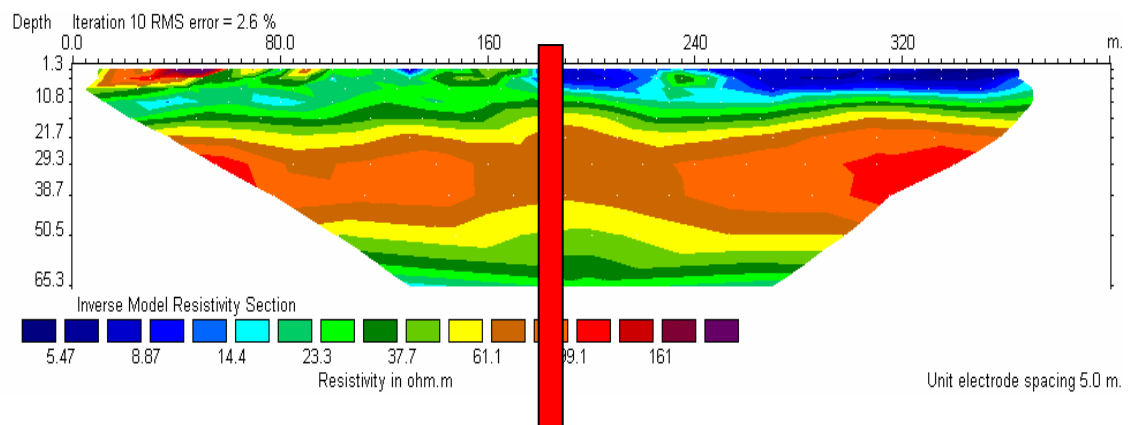
Resistivity Profile 10: Tolon Profile A



A 2-D multi-electrode resistivity profile Tolon profile A is shown. The subsurface is dominated by low electrical resistivity rock materials. The profile shows basically three different resistivity layers of subsurface materials at the shallow, intermediate and deeper depth horizons. There is a comparative intermediate resistivity layer bounded at the top and below by low resistivity materials in the middle of the profile. A geological structure observed between stations A 190 to A 220 was interpreted to be a relatively higher resistivity anomaly at the intermediate depth. The structure is very small in size. In such profiles the target is the relative higher resistivity zones within the low resistivity background rock materials.

A borehole drilled at the station A 195 to a depth of 95 m intercepted a clayey soil to a depth of 7 m. The layer at the intermediate depth which is the target for an aquifer produced highly weathered sandstone rock material and accounted for the total yield of 48 l/m for the borehole. The structure was very small and a small yield capable of sustaining hand-pump installation was expected. The borehole log indicated weathered shale material as can be seen from the low resistivity rock materials at the deeper depth layer. This layer did not contribute to the total yield of the borehole. The profile therefore shows an aquifer material bounded at the top by the clay material and below by the shale. The concept of interpretation was highly correlated with the results of drilling.

Resistivity Profile 11: Yapei Profile C



A 2-D multi-electrode electrical resistivity profile Yapei profile C is shown above. Generally three different electrical resistivity layers are observed. A very low resistivity layer to a depth of about 20 m followed by a relatively higher resistivity layer about 25 m thick in the resistivity range of about (60-160 ohm-m) and this is then followed beneath by another low resistivity layer comparable to the first and shallow resistivity layer.

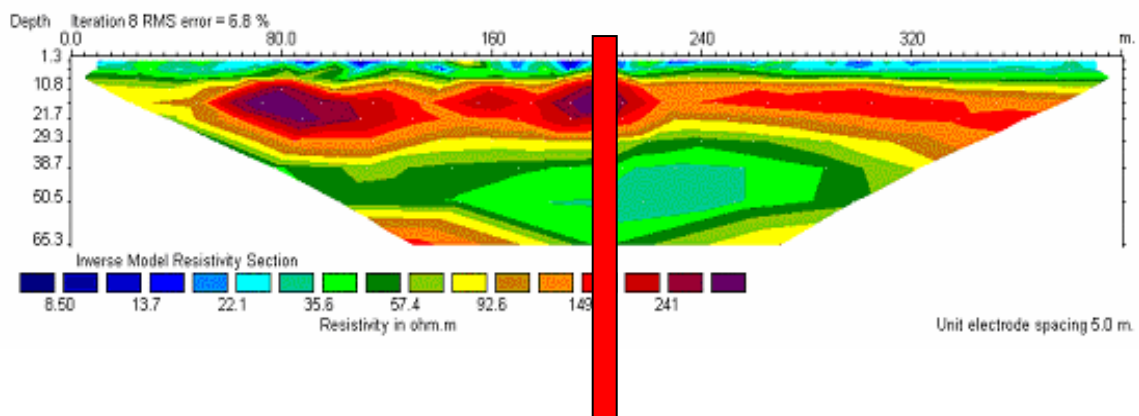
A discontinuity is observed in the intermediate comparative high resistivity layer between stations C 160 and C 240. In such a profile which is underlain by lower resistivity materials the target could be the structure formed as a result of the possible deformation at the intermediate zone.

The station C 180 has a resistivity range (60-95 ohm-m) in the discontinuity zone at the second layer. The zone was therefore interpreted to be a geological structure in the intermediate layer which could be a good aquifer target and was therefore selected for drilling.

A borehole drilled at the station C 180 was dry. The borehole intercepted clay materials which is confirmed by the very low electrical resistivity to a depth of about 7 m followed by shale/mudstone intercalations to a depth of 26 m and these two layers are followed by mudstone. The target layer was mudstone and this zone did not produce any aquifer as has been interpreted from the results of the electrical resistivity profile.

There was therefore a negative correlation with the concept of interpretation and the results of actual drilling since the designated zone from the electrical resistivity profile did not produce any aquifer as has been anticipated.

Resistivity Profile 12: Buipe Profile E



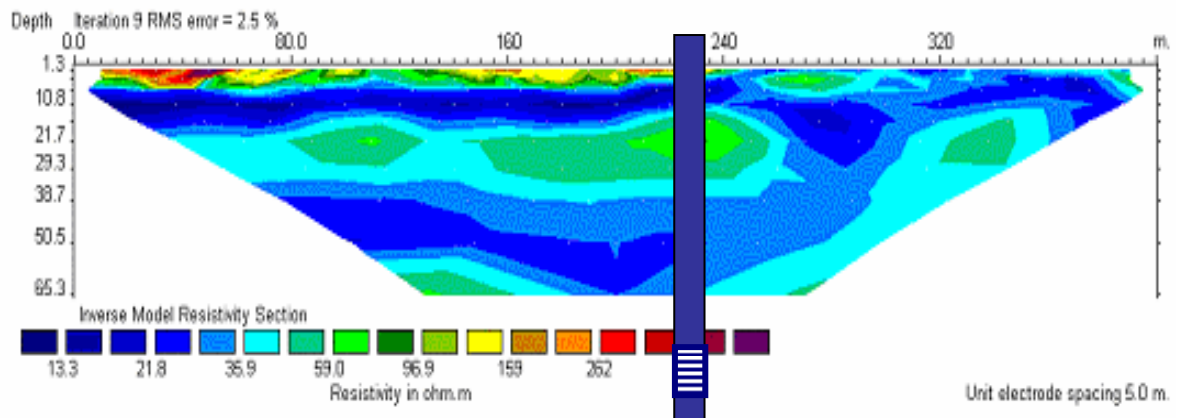
The 2-D multi-electrode electrical resistivity profile Buipe profile E is shown above. The profile is dominated by low resistivity rock materials. The general profile is as follows;

A very thin low resistivity layer at the subsurface and just limited to about 5 m. This is followed by a comparable high resistivity layer to a depth of about 25 m in the resistivity range of about 150 ohm-m. Another lower resistivity layer in the range of about (40-60 ohm-m) is then observed. A geological structure with a comparable low

resistivity is observed in this resistivity layer between stations E 160 to E 270. This structure observed at the deeper depth horizon had a relatively high resistivity compared to the background resistivity on the profile. It was envisaged that the structure could probably represent an aquifer which is bounded both at the top and bottom by the relatively higher resistivity rock materials.

A borehole drilled at the station E 200 was dry confirming the negative correlation of geophysical results and actual drilling.

Resistivity Profile 13: Lonto Profile A



The profile shows that the profile is underlain by very low resistivity materials with patches of relatively high resistivity materials at the surface. Within this low resistivity materials are structures with relatively intermediate resistivity rock materials at the intermediate depth. With the very low resistivity results observed on the profile the target was not the very low resistivity layer zones observed on the profile but the comparable intermediate resistivity zones. A structure between the stations A 200 to A 240 was observed in the second resistivity layer horizon. This layer had a comparable higher resistivity than the background low resistivity rock materials. It was therefore interpreted to be a probable aquifer and a target for borehole drilling.

A borehole drilled at the station A 230 intercepted a clay layer which can be interpreted by the low electrical resistivity at the surface to a depth of about 3 m followed by a highly weathered sandstone material with decreasing weathering to a depth of 20 m where the fresh sandstone material was encountered.

The aquifer was intercepted at a depth which had not been investigated by the multi-electrode resistivity survey. The geological structures demarcated as target from the interpretation of the profile did not produce any aquifer. There was therefore no correlation between the interpreted survey results and that of actual drilling.

6.5.1 Analysis of 2-D multi-electrode and drilling results in group 3

Geophysical investigations were carried out in ten communities representing the group. The group is dominated by low resistivities materials at the subsurface with a high resistivity layer characterising the lateritic layer observed at the surface.

Results of drilling indicate the lowest groundwater potential in all the three groups of the area. Lithological boundaries and different layering of the rocks were clearly observed on most of the profiles. The intercalations of the different rock units in the area were clearly observed on most of the profiles in this group. The intermediate electrical resistivity sandstone beds have been the target for successful borehole drilling.

Table 11: 2-D multi-electrode resistivity results and drilling in group 3

Total No.	Successful(mechanisation)	Successful(hand pump)	Dry
20	6	5	8

Drilling results in the group shows that a total number of 20 boreholes were drilled in this group resulting in 6 qualifying for mechanisation for small town construction, 8 qualifying for hand-pump installation and 8 dry boreholes (table 11).

Low resistivity on the profiles normally produced either an unsuccessful or a marginal (yields < 14 l/m) borehole in the group (table 12). Resistivity lower than 30 ohm-m were responsible for most of the unsuccessful wells in the group.

In a multi-electrode electrical resistivity survey in this group, very low resistivity rock materials beneath a profile are not potential good targets for successful groundwater exploration as these results in dry boreholes.

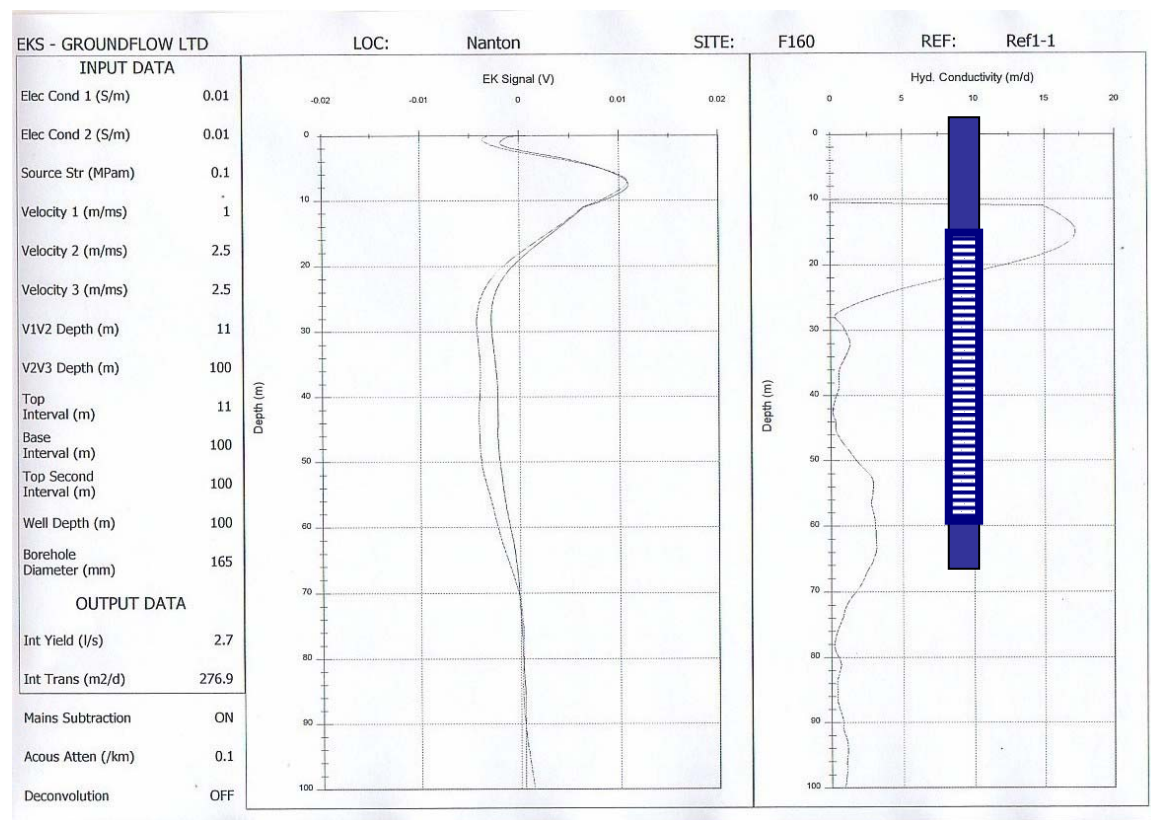
Table 12: Lithology and resistivity range for obtaining groundwater in group 3

Rock Type		Resistivity (Ω -m)	Hydrogeology significance
Sandstone	Regolith	150-500	Good groundwater potential and main aquifer
	Jointed/fractured	200-700	Very good groundwater potential with high yields
	Consolidated	1000-10000	Hard with poor groundwater potential
Shale	Regolith	2-30	Very poor groundwater potential
	Jointed/fractured	20-50	Very poor groundwater potential with dry fractures
	Consolidated	20-100	Very poor groundwater potential
Mudstone	Regolith	20-80	Moderate to poor groundwater potential
	Jointed	30-100	Moderate to poor groundwater potential
	Consolidated	30-150	Poor groundwater potential
Siltstone	Regolith	10-30	Poor to moderate groundwater potential
	Jointed	10-40	Moderate groundwater potential
	Consolidated	20-100	Moderate to poor groundwater potential
Siltstone/ Mudstone	Regolith	10-40	Poor to moderate groundwater potential
	Jointed	22-100	Moderate groundwater potential
	Consolidated	40-120	Moderate groundwater potential with aquifers at the bedding planes
Shale/ mudstone	Regolith	10-30	Poor groundwater potential
	Jointed	20-80	Poor to moderate groundwater potential. Bedding plains are responsible for marginal yields
	Consolidated	30-100	Poor groundwater potential. Bedding planes do not produce aquifers.

The sandstone rock formation was the main aquifer material in the group. Most stations drilled in the low resistivity shale formation were unsuccessful and dry.

6.5.2 Typical EKS results in group 3

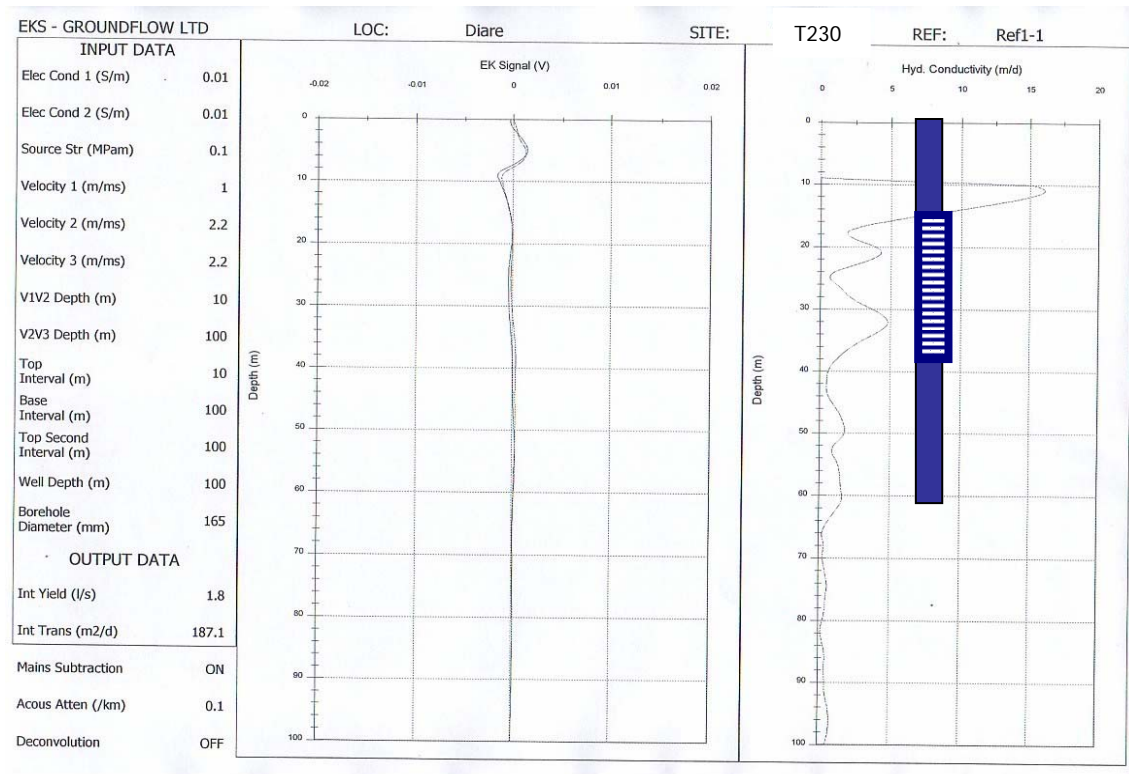
EKS Sounding Data 6: Nanton F 160



The EKS sounding result at the station F 160 in Nanton is shown. Two evenly matched and strong signals were obtained at the station. From the results two distinct aquifer zones were interpreted.

A shallow aquifer at the depth range (15-30 m) and an intermediate to deeper depth aquifer at depth range (45-65 m).

A borehole drilled at the station produced a yield of 1200 l/m at the depth range (20-58 m). The two demarcated aquifer zones contributed significantly to the total yield of the borehole thereby giving a good correlation of EKS and drilling results.

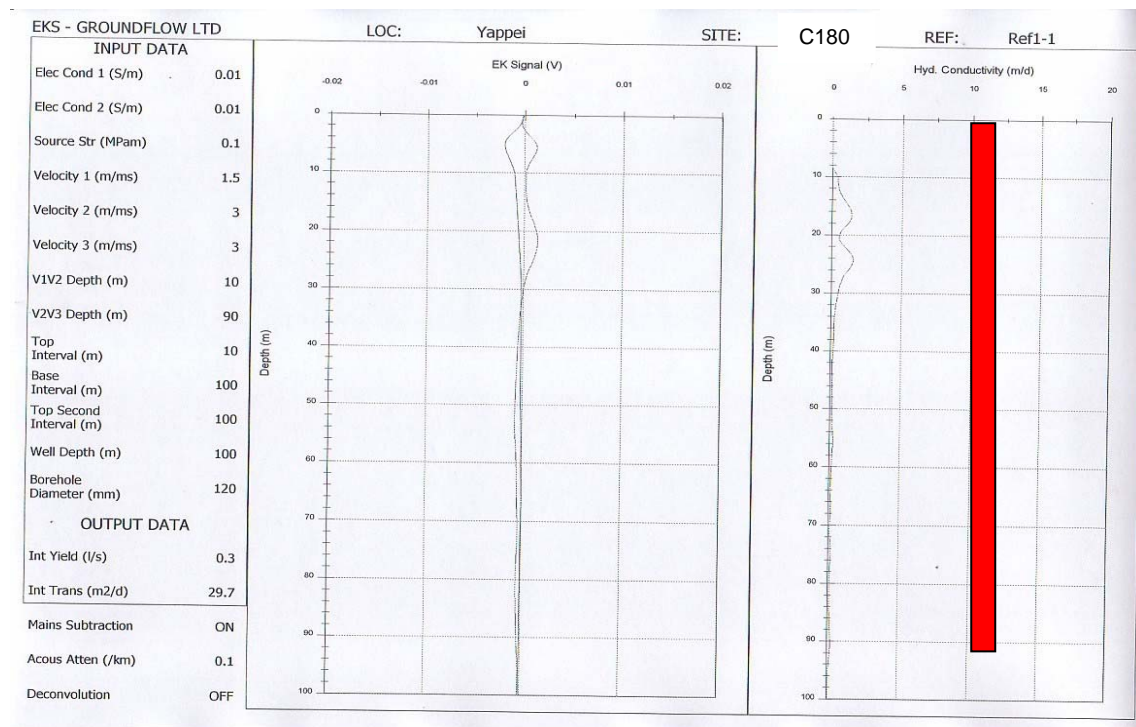
EKS Sounding Data 7: Diari T 230

EKS sounding data at the station Diari T 230 is shown above. Two identical and weak signals were obtained on both channels at the station. One main probable aquifer zone was interpreted from the EKS hydraulic conductivity graph although hydraulic conductivity was not calculated above the 10 m SWL depth.

The modelling results of the EKS data produced a probable aquifer zone at the depth range (15-40 m) as observed on the graph showing the zones with higher amplitude than the background. The station was interpreted as showing a shallow to medium depth possible aquifer and this is the observed prevailing aquifer depths in the area.

Drilling at the station however produced an aquifer in the depth range (16-40 m) which coincided with the zone interpreted from the EKS data results. The interpreted aquifer depth from the EKS results was accurate and there was a good correlation between EKS model interpretation and that of actual borehole drilling.

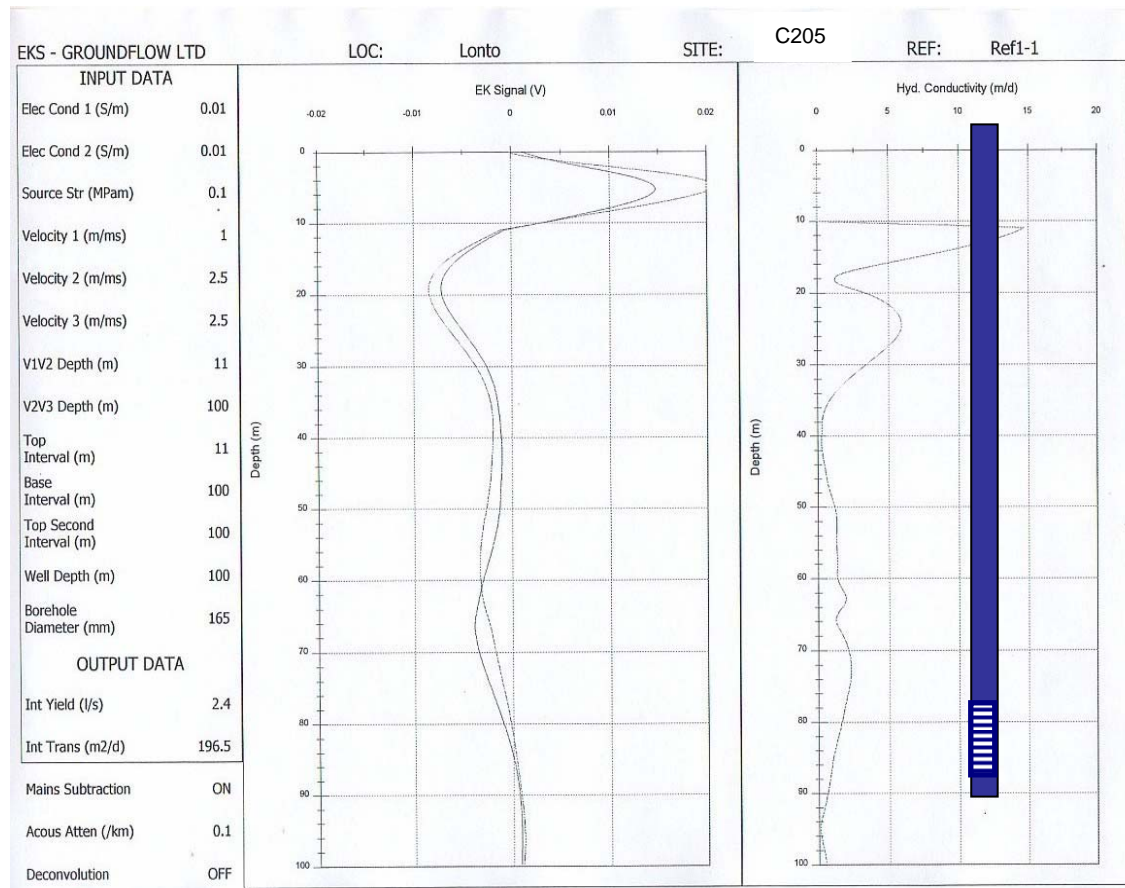
EKS Sounding Data 8: Yapei C 180



EKS sounding data at the station Yapei C 180 is shown above. Very weak EKS signals were obtained at this station. As can be observed on the hydraulic conductivity curve only a small extrapolated aquifer zone was observed at the depth range (12-30 m). The zone is shallow and has been interpreted to produce either a low yielding borehole or a dry one. The hydraulic conductivity was just similar to the background as is seen on the graph.

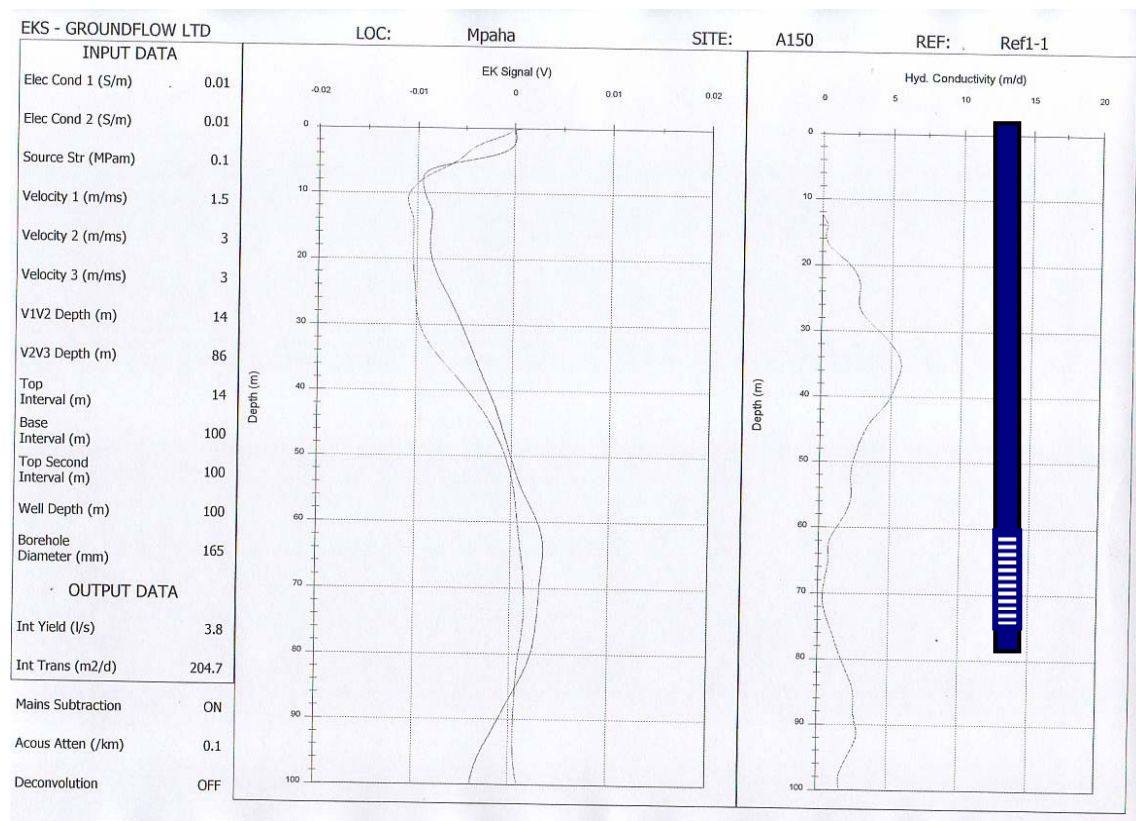
The drilling at the station was dry confirming the interpretation of the EKS results which had predicted either a low yielding or dry borehole. There was therefore a good correlation between EKS results and actual drilling.

EKS Sounding Data 9: Lonto C 205



The sounding produced two evenly matched strong signals. Two probable aquifer zones were demarcated at the shallow depth (15-35 m) and a deeper depth range (45-90 m). The shallow aquifer interpreted from the EKS results was distinct. The deeper aquifer zone although had a lower aquifer potential than the previous lower depth was also significant and could well be interpreted as an aquifer which could contribute significantly to the total yield of the borehole.

A borehole drilled at this station produced an aquifer at depth range (84-88 m). This aquifer was responsible for the total yield of the borehole and was related to the deeper zone from the EKS results. The interpretation of the EKS results considered the shallow aquifer zone to be the main aquifer however this shallow probable aquifer was dry. The results therefore implies that the main aquifer zone from the EKS results was dry and a small zone from the demarcated deeper aquifer zone was responsible for the total yield of the borehole although a very thick aquifer material had been expected. There was therefore a bad correlation of EKS results and drilling.

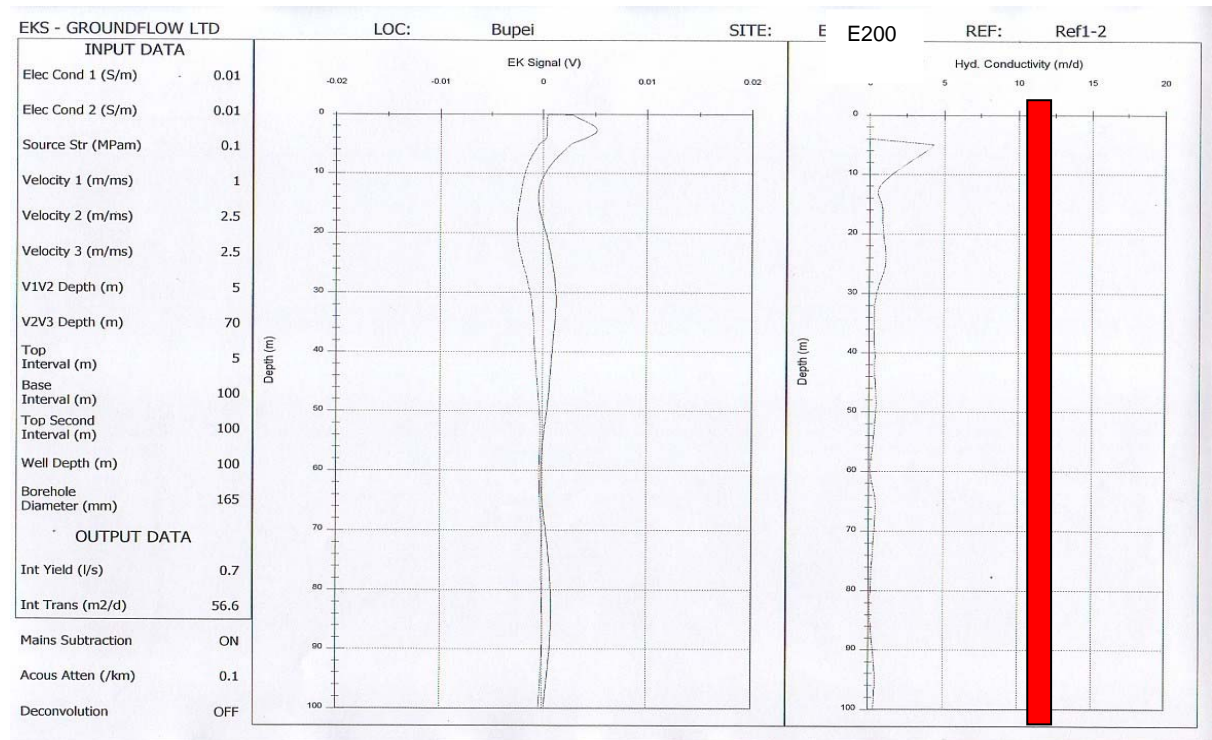
EKS Sounding Data 10: Mpaha A 150

EKS sounding model results at the station Mpaha A 150 is shown above. The signals are strong and identical to each other on the two channels. Two main probable aquifer zones were demarcated. These zones were an intermediate zone in the depth range (20-55 m) and a deeper zone between (75-100 m). The first probable aquifer zone was interpreted to be the main zone which would contribute to the total yield of the borehole.

During drilling the first interpreted aquifer zone was dry and a yield of about 14 l/m was encountered at the depth range (63-66 m) which was basically out of the second aquifer zone demarcated. The two zones demarcated from the EKS results did not contribute to the total yield of the borehole. Although the borehole was successful for hand pump installation, the various zones which had been demarcated as aquifers from the EKS results did not contribute to the total yield of the borehole

The EKS results interpretation was not accurate and therefore a negative correlation of EKS results and that of actual drilling at the station was obtained.

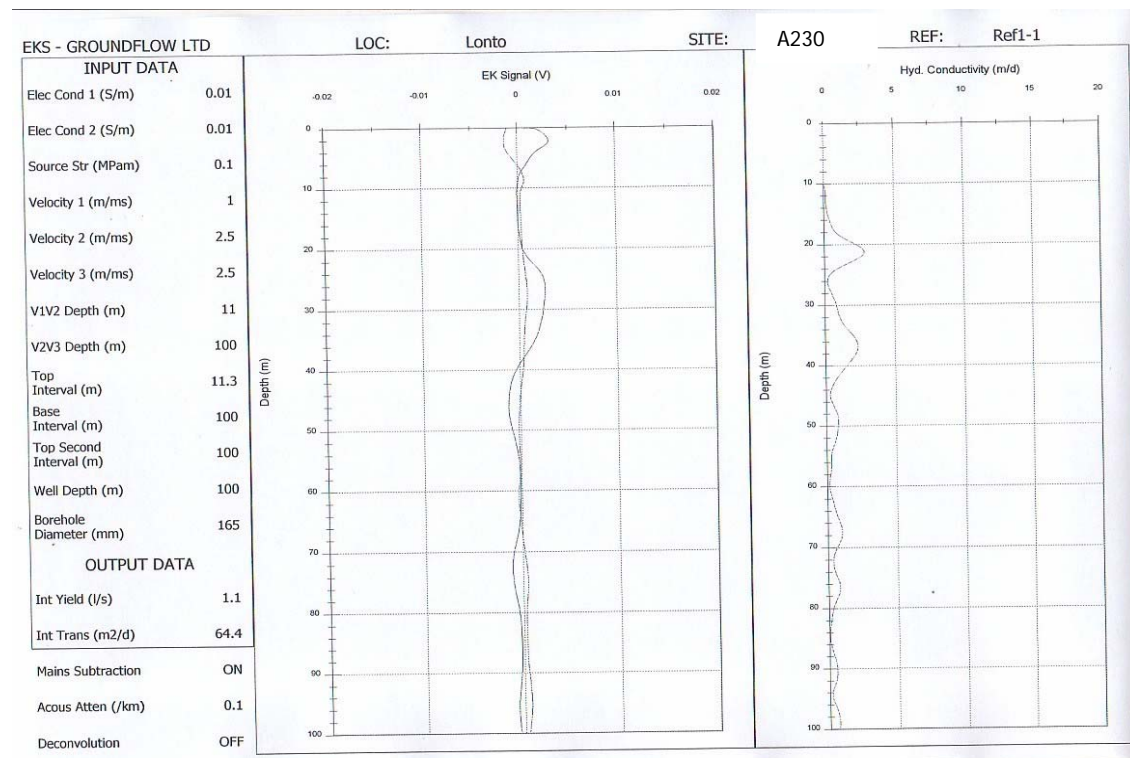
EKS Sounding Data 11: Bupei E 200



EKS sounding at Bupei E 200 is shown. Very weak signals were obtained at the station. No clearly defined aquifer zones were extrapolated from the EKS hydraulic conductivity graph.

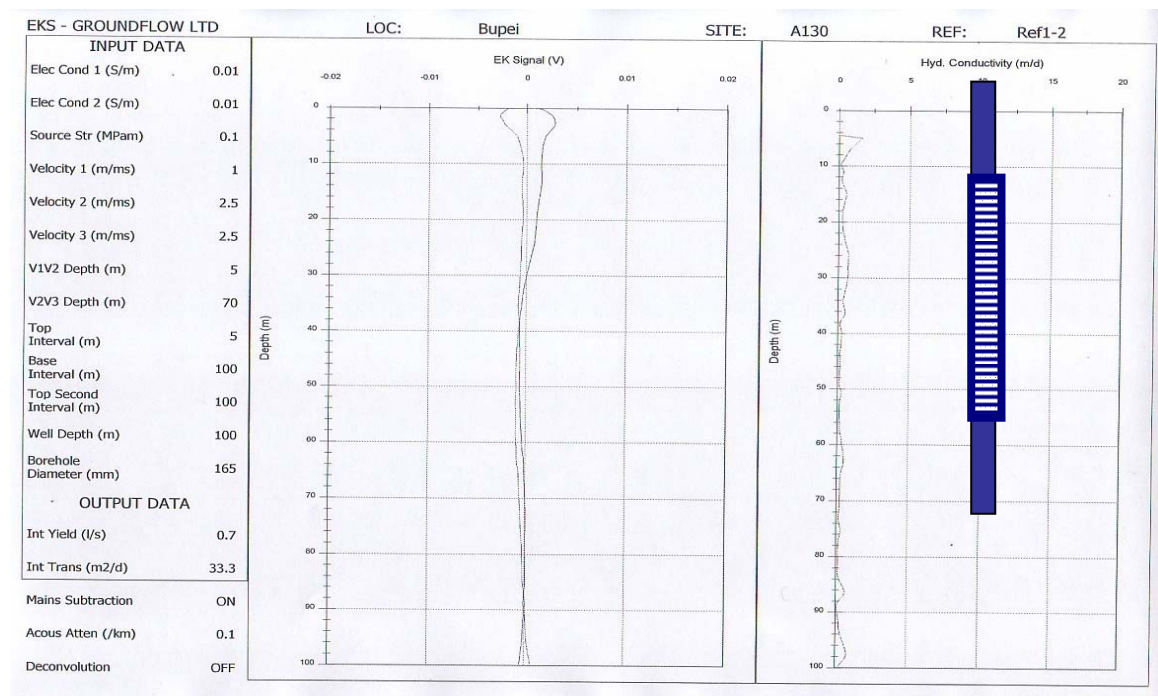
The station was selected for drilling based on the results of the 2-D multi-electrode resistivity survey results which had interpreted an aquifer potential at the station.

Drilling at the station was dry confirming the interpretation of the EKS results

EKS Sounding Data 12: Lonto A230

Signals obtained were not good. A typical signal representing the consolidation of the rock material was obtained at the station. No aquifer information could be interpreted from such sounding results as sounding results are not reliable for aquifer potential interpretation.

Drilling was however carried out at the station based on the consideration of the terrain evaluation, air photo interpretation and that of the 2-D multi-electrode resistivity profile which had interpreted the station to be a potential aquifer station.

EKS Sounding Data 13: Bupei A 130

EKS model data at the station Bupei A 130 is shown above. Two weak signals were obtained on both channels. The modelling results did not show any distinct aquifer as can be observed on the hydraulic conductivity graph. The graph shows that the hydraulic conductivity variation was just background values with no significant peak. No probable aquifer zones were therefore interpreted and demarcated on the EKS graph.

A borehole drilled at the station however produced two aquifer zones in the depth ranges (13-30 m) and (48-52 m) contrary to the interpretation. These zones however were not demarcated and recognised on the EKS hydraulic conductivity graphs. Although the borehole was successful the interpretation of the EKS results did not reveal any probable aquifer zones from interpretation. There was therefore a negative correlation of EKS data and drilling data.

The station was selected for drilling based on the 2-D multi-electrode resistivity survey results

6.5.3 Analysis of EKS and drilling results in group 3.

Varied signal strengths were observed in this group. There were localized conditions peculiar to particular communities in this group.

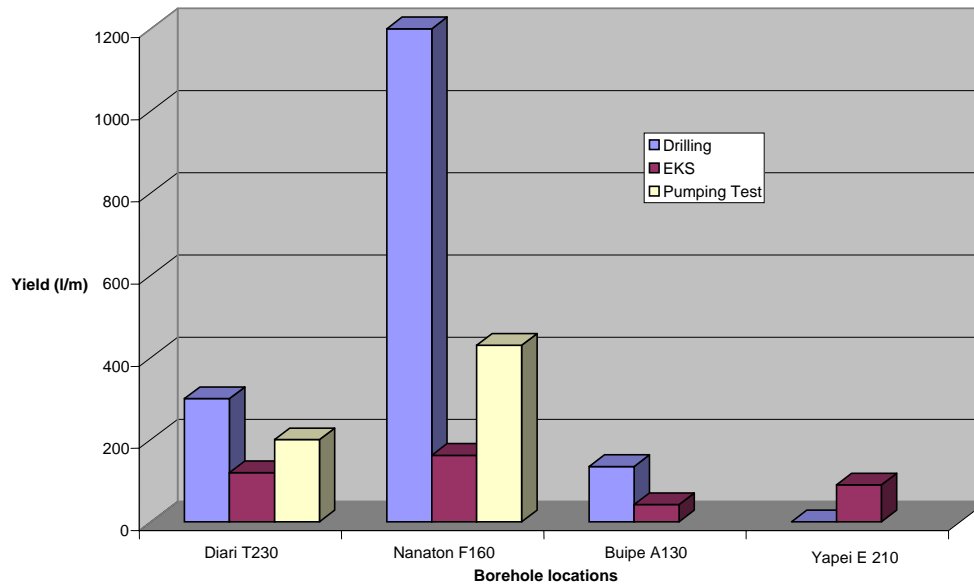


Figure 21: Comparison of yield from Drilling, EKS and pumping test in Group 3

NB. Drilling yield- short time pumping test during drilling to determine borehole yield.

It is observed that drilling yields were quite higher than yields that have been calculated from the EKS data model. At the stations Diari T 230, Nanton F 160 and Buipe A 130 yields from the actual drilling were very high compared to the anticipated EKS yield from interpretation and there was satisfactory correlation. In Yapei E 10 whereas the EKS model predicted a yield of about 90 litres per minute for the station the borehole drilled was dry. Other station results were not different with large disparities in calculated and actual yields.

Pumping test on the two stations Diari T 230 and Nanton F 160 also show that the calculated yield from the EKS data were quite lower than results calculated from the pumping test data on these boreholes. The high disparity in yield data shows that the results of yield calculation by the EKS sounding data cannot be reliable in this group.

Most of the aquifers encountered in the group were sandstone rock formation. Generally borehole yields were not correlated with calculated EKS model results in the group.

6.6 Discussions

The results of the 2-D multi-electrode electrical resistivity and the EKS survey results can be summarized for the conditions existing in the northern region. The potential aquifers materials and their resistivity range in the various rocks in the area are discussed. The sandstone aquifer is the main aquifer rock material in the groups especially the group 2 and group 3 rock formations.

6.6.1 2-D multi-electrode electrical resistivity survey

The 2-D multi-electrode electrical resistivity survey was successfully applied in the area. The least square optimisation method which is user friendly and allows the user to include information about the subsurface as constraints on the inversion procedure to produce results closest to the actual prevailing subsurface geology (Ellis and Oldenburg, 1994; Loke, 2003) was used. The method is more suitable where the true subsurface geology show smoother variation in the electrical properties (Loke, 2003).

The results of the electrical profile show that the technique is effective in differentiating the electrical resistivity of the various rock materials at the subsurface. It is very efficient for groundwater exploration when the geological structure interpreted to be a probable aquifer is vertical. It is also observed that in most cases, targets demarcated from the profiles showed clear contrast in resistivity with respect to the background resistivity. Different rock materials of different electrical resistivity on the same profile were clearly differentiated. The weathered profiles and fresh rock on most of the profiles were shown with different resistivity layers.

In some areas, especially the group 3 rock formations where intercalations of the sandstone, mudstones, siltstones and the shale are predominant, the layers of each of the individual rock materials are clearly distinguished by different layers on the profiles. As observed from most of the results in the communities, the technique was quite effective in differentiating between a clayey soil cover and a sandy one. This

aspect is also one of the main targets for groundwater recharge. Sandy soils are permeable as compared to clayey soils and therefore play a vital role in groundwater infiltration (Loke, 2001). However geological structures identified showed little resistivity contrast with the background resistivity in group 3.

Fracture zones in the area are normally associated with zones of low apparent resistivity in the fresh rock at intermediate to deeper depth horizon.

Depth limitation and resolution of the target zone should be a major consideration when applying this technique. In some cases the depth of investigation by the configuration was less than the depth of the aquifers intercepted during drilling and so the technique was ineffective in demarcating these zones. In such circumstances where aquifers are deeper than the depth which can be probed by the configuration another configuration like the Pole-pole configuration known to be able to explore deeper depth aquifers can be applied.

The survey takes a lot of data on a profile by utilising the readings for many combinations of transmission and reception to achieve a mixed profiling and sounding arrays (Bernard, 2003). For the Werner array as was used for this work, the total maximum depth of investigation is given by a factor of 0.2 multiplied by the total length of the cable which is the product of electrical spacing and the number of electrode (Bernard, 2003).

The technique should always be used with a good understanding of the on-site local geology so that the data could be interpreted correctly as most of the data cannot be interpreted correctly without an in depth knowledge of the local geological and hydrogeological conditions of the area. The profiles are always interpreted with a good background information and knowledge of the local hydrogeology.

Selection of geological anomalies has been carried out by considering the values of electrical resistivity of the layer and not the colour display by the various pseudosections. The version of the RES2DINV software used for modelling did not have the ability to apportion a range of resistivity to a particular colour. Therefore using the colour for interpretation as is seen in most of the results will be misleading

and not be efficient since the same colour representation for a particular resistivity rock material might be different on another profile. A typical example is the two profiles A and B at Gulubi Quarters (resistivity profile 5 and 6) where the same colour represented different resistivities in the same community.

6.6.2 EKS Survey

The EKS was basically used as a sounding method after the 2-D multi-electrode electrical resistivity method had been used to select a geological anomalous structure interpreted to be a probable aquifer material; weathered depths, bedding planes and discontinuities in the fresh rock representing fractures and joints. The aim of the EKS sounding was basically to investigate the hydraulic conductivities at these stations demarcated by the electrical resistivity profiles with depth.

It is observed from the EKS graphs that hydraulic conductivity in the various groups generally is observed to decrease with increasing depth of investigation. As results of this the various hydraulic conductivities in the individual sounding stations are well observed with higher amplitudes at the lower depth than in the deeper depth horizon.

6.6.2.1 Prediction of yield

A lot of disparities were observed from the yields calculated from the EKS data model and that from the actual borehole drilling and pumping test in all the groups. In most cases where high yields were obtained, the EKS model predicted a lower yield. In some other cases drilling stations were unsuccessful and dry although EKS model had calculated successful yields for these stations.

6.6.2.2 Demarcation of aquifer zones from the graph

In cases where the borehole stations were successful there was a good correlation with the depth demarcated from the EKS and actual drilling. Correlated zones were mostly at the shallow to medium depth horizon. However in some isolated cases aquifers were encountered at depth horizons which were not significant on the EKS graph.

In most cases however there is a distinction between calculated EKS model results which resulted in successful borehole drilling and that which resulted in unsuccessful boreholes.

6.6.2.3 Reproducibility of data acquisition

Reproducibility was excellent for most stations. This was basically carried out to ensure that good and reliable data is obtained and in most cases three readings were carried out at a station. The second reading was normally used for modeling.

6.6.2.4 Velocity input

The velocity input for the various depth layers were not very reliable. The values were selected primarily based on the general velocity range of values proposed by Groundflow Ltd. on similar formations in the United Kingdom. Actual velocity values for the different depth layers could not be obtained since no seismic investigation have been carried out in the area.

6.6.2.5 Equipment setup

The use of only two channels A and B at short distances from the shot point as was the case during data acquisition might not be able to give a complete description of the spatial and temporarily nature of all the electro seismic signal generated by the various wave types as well as between co-seismic energy and at the interface responses. A multi channel system will be more appropriate (Fourir, 2003) to obtain more information.

The distance between the two channels and the shot point which is about 0.5m from the centre from the plate was too small to prove to a deeper depth of about 100m. Groundflow Ltd. claims the signals are reflected back to the shot point by the Fresnel theory.

6.6.2.6 Previous research findings on EKS technique

A DFID report number R6232 by the British geological survey concluded that some important assumptions made by Ground flow Ltd; the suppliers of the EKS instrument are flawed. Their research contended that the EKS equipment does not have an effective vertical sounding capability and also the use of only two channels for data acquisition is likely to provide insufficient information into the nature of EK coupling at any site, and also it provide a false interpretation under the assumptions stated in the manual.

Observations from the field work shows that the techniques at this stage can be used to make a decision regarding a successful or dry borehole station. As observed in most of the stations drilled, yields from the EKS models were always not highly correlated with actual borehole drilling results

6.7 Problems with geological investigations for boreholes

A lot of problems were encountered during the fieldwork data collection. Some of these problems are discussed.

6.7.1 Geology and geophysical techniques

Inadequate understanding of the occurrence of groundwater and factors affecting permeability in this terrain has led to inappropriate planning in executing geophysical investigations for borehole siting. Inadequate focus on the local geological and hydro geological conditions has led to wrong alignment of geophysical profiles.

Siting of boreholes in such difficult geological terrains requires a conceptual understanding of the geological and hydrogeological framework and how it affects the geophysical response. Geophysical techniques have been applied without looking at the suitability and applicability of the technique in the terrain.

The use of only one geophysical method as used to be the case in most projects in the area sometimes gives ambiguity in geophysical anomaly interpretation. Using more than one technique give confidence in interpreted geophysical anomalies selected for drilling.

6.7.2 Deficiencies in geophysical data collection

A lot of human errors are normally encountered especially during the hot weather conditions prevailing in the area. This high temperature often results in instrument errors. There are sometimes very dry ground conditions which give electrode contact problems and water has to be applied to the ground to have a good contact of ground with electrodes.

6.7.3 Lack of quality aerial photos

Reliable and useful aerial photos are not available in the area. The few aerial photos available which are very old and have such a bad quality that no meaningful

information could be obtained. Because the air photos are very old some lineament trends observed are found at locations unsuitable for borehole construction (built up area and rubbish dump).

6.7.4 Interpretation of geophysical results

A lot of misleading interpretation of perceived geophysical anomalies are always made especially using the conventional techniques in the voltain formation. Perceived anomalies have always resulted in unsuccessful borehole drilling. These anomalies resulting in unsuccessful wells are mostly encountered in the low resistivity shale and mudstone lithologies. It is always good to have a feedback from drilling to update geophysical interpretation.

6.7.5 Community problems

Lack of access to some private properties often resulted to inadequate exploitation of lineaments observed from desk study and air photo interpretation.

Contamination and vulnerability potentials of some lineaments zones often resulted in the negligence of such areas for groundwater exploration.

Acceptability of a good site demarcated by geophysics by the beneficiary community often caused some problems since in most cases communities tend to have their preferred location of the facility especially for hand pump installation. With the education of communities this problem seems to be resolved. There is now an acceptance agreement form in which the communities and the geophysical team sign to agree on a potential borehole station. After this form has been signed by the community representatives, problems are limited.

Accessibility of drilling machine to the potential drilling site has also resulted in situations where potential successful sites have been neglected.

6.8 Groundwater quality problems

Safe water is one which is not likely to cause undesirable or adverse effects, although it may contain various contaminants (Tebbut, 1992; Mato, 2002). The quality of groundwater generally deteriorate from different activities on the land notably

urbanisation, industrialisation and agriculture etc and in most cases pollution occurs due to poor methods of waste disposal. Groundwater quality depends on the following;

- Aquifer hydrogeology
- Flow rate and direction
- Dilution characteristic
- Recharge area
- Wellhead protection
- Depth of casing
- Bulk water transport
- Whether aquifer is confined or unconfined(WHO, 2004)

Generally groundwater quality in the northern region of Ghana have been very good and well below the Ghana Water and Sewerage Corporation (GWSC) standard for drinking water.

Water quality analyses were carried out on some of the boreholes drilled in the area which were selected for mechanised piped schemes. Table (14 and 15) gives a general groundwater quality results in the various aquifers in the area and results of water quality analysis on some boreholes drilled during the research work.

Table 13: Analysis of water samples in rock formations in northern Ghana. (Kortatsi, 1994)

	Granite	Sandstone	Mudstone and shale
pH	6.99	6.95	7.64
Total dissolved salts(TDS)	387.38	211.19	424.66
Calcium(Ca)	49.3	32.09	26.10
Magnesium(Mg)	19.06	15.67	9.12
Sodium(Na)	47.99	11.67	125.39
Chloride(Cl)	73.48	9.90	42.04
Sulphate(SO ₄)	10.60	7.16	11.18
Bicarbonate(CO ₃)	81.17	104.14	189.29
Total Iron(Fe)	1.01	2.15	0.645
Manganese(Mn)	0.44	0.39	0.10
Flouride(F)	0.35	0.315	0.57
Nitrate(NO ₃)	1.605	0.59	0.135
Total Hardness	172.49	123.70	222.77

Table 14: Analysis of water samples on some boreholes in the area

	Sawla G185	Gulubi Quarters B230	Kpandae E130	Kpandae C230	Diare T230	Nanton F160	Yoggu (Wayamba)	GWSC value
pH	8.05	8.89	7.59	7.8	7.91	8.51	8.08	8.5
TDS	128	126	96	118	74	52	108	1000
Ca	66.1	38.1	48.1	72.1	58.1	14	40.1	200
Mg	61.9	87.9	47.9	45.9	15.9	38	67.9	-
Na	20.8	99.6	57.9	72	159	116	229	-
Cl	4	3	9	10	56	19	93	0-600
SO ₄	4	5.8	3.3	7.9	8.1	6.8	9.7	0-400
Total Fe	0.084	0.14	0.167	0.066	0.01	0.01	0.201	0-1.0
Mn	0.166	0.126	0.126	0.205	0.028	0.021	0.021	0-0.5
F	0.39	0.9	1	1	1.5	0.1	0.8	1.5
CO ₃	200	359	271	281	410	344	517	-
Mn	0.166	0.126	0.126	0.205	0.028	0.021	0.021	0.5
NO ₃ (N)	0.15	0.05	0.06	0.05	0.1	0.01	0.2	3.0
K	4.77	1.6	1.6	1.1	1.3	1	2.2	-
Total Hardness	128	126	96	118	74	52	108	-

NB: All values apart from pH are in mg/l

The results of water analysis on some of the boreholes drilled during the research shows that the area is devoid of serious groundwater quality problems (table 15). Most of the boreholes drilled distributed in all the three groups were quite good and well below the guideline limits by the Ghana Water and sewerage corporation. (GWSC).

It can therefore be concluded that groundwater is generally safe for drinking purposes in the area.

6.9 Cost benefit of geophysics and success rates of boreholes

The concept of success rates of boreholes and the relationship to the type and financial implications of geophysical investigations have been subjected to wide discussion but is often very misleading unless the full range of contributory effects are considered. The general knowledge about the hydrogeological conditions of an area plays an important role in the overall success of drilling in the area. In areas where aquifer is well understood, geophysics may not significantly affect the already high success rate (Carruthers & Smith, 1992) since there will be no significant change.

The contribution of geophysics to success rate of borehole drilling in the northern region of Ghana however cannot be overemphasized. Initial groundwater exploration in the voltain basin in the 1940's did not show good results with drilling success rates (Kwei, 1997). The introduction of geophysics in groundwater exploration afterwards in the mid 1970's led to a significant improvement of results of drilling. Although the conventional techniques have been applied in the area till date, a marked improvement had been made with its application over the years compared to the period when drilling was carried out without geophysics.

The discussion is focused on whether the application of the advanced methods; 2-D multi-electrode electrical resistivity profile and EKS have made significant improvement compared with the conventional techniques in each of the three groups. There has been a general improvement of the success rate of borehole drilling in the various groups in the area with the application of the advanced methods (table 15).

In the group 1 Precambrian rocks of the area, there was a general improvement in borehole success rates. A total of eight boreholes were drilled resulting in three boreholes qualifying for mechanisation, three qualifying for handpump installation and the remaining two were dry (table 6). This output results with the advanced method is better than the results which have been obtained in this area over a period of time with the conventional methods. Application of the advance method which is more expensive in this environment did not make much significant achievement as had been expected. As illustrated earlier in the recommendations for improvement with the conventional methods the conventional 1-D technique is very effective in such deep weathering and fractured basement rocks. The target of weathered rock material depth and fractured zones can be adequately demarcated by the 1-D conventional technique with some efficiency and improvement in data acquisition.

Table 15 : Comparison of borehole drilling results.

Group	Project	% Success Conventional Techniques	% Success EKS & 2-D multi- electrode (2003-2006)
Group 1	IDA (1996-2000)	65	71
Group 2	HIPIC (2003-2005)	75	100
	IDA (1996-2000)	70	
Group 3	IDA (1996-2000)	35	55
	HIPIC (2003- 2005)	15	
	CWSP Pilot 10 Bh (1999)	38	
	CIDA (2000-2005)	24	

NB. The percentage success have been calculated based on the yield of 14 litres per minute which is the minimum yield required for hand pump installation.

The application of the advanced method is quite efficient and additional information is achieved but their high comparative cost makes geophysical investigation with these techniques very expensive especially when similar comparable results are obtained with the normal conventional techniques. Although there was a slight improvement of borehole success rates in this group an overall financial gain in the application of the technique was not realised as had been expected.

There was a significant achievement in borehole yields with the advance techniques in the group 2 arenaceous Oti beds. The application of the conventional techniques in the group 2 formation has been quite impressive in the area over the years. Very few dry wells have been drilled in the area with respect to the application of the conventional geophysics techniques and so it could be argued that with some improvement in data collection the techniques could have made some good impressions.

However considering the high yields obtained, it is obvious a significant improvement has been made as very high yields were obtained in three out of the four boreholes drilled. The total number of wells which would have been drilled to obtain this number qualifying for mechanised piped schemes was greatly reduced. The various high yields obtained which are unprecedented in the area confirm the positive benefit of the application of the techniques in this group. No dry well was drilled in this group

(table 7). The number of anticipated drilling sites was less than had been expected thus saving some cost on additional drilling had the yields been less than the limit for mechanisation. The methods thus have made some gains in this group during the overall project implementation.

There was a significant success rate improvement and a gain in the application of the advance technique for project implementation in group 3 which is basically underlain by the Obosum sedimentary voltain beds. Yields of boreholes obtained were quite impressive. The success rate was more significant considering the low success rates which had been attained in the group over the years (table 6). As illustrated earlier in the discussion, a lot of high yielding boreholes were obtained in this difficult hydrogeological zone which is noted for unsuccessful and low yielding boreholes. Most of the aquifers which were demarcated by the advanced techniques would not have been observed with the conventional techniques. This was confirmed during the pilot study on the advanced techniques.

The output results from the application of the advance technique was therefore of significant improvement over the use of the conventional techniques. However much improvement is required for the general acceptability and application of the technique so as to make them economically efficient in relation to the cost of its application.

6.10 Conclusions of the Investigations

The observed low success rates and variability of yields in the development of groundwater resource in the northern region of Ghana is evident of the need to adopt a guideline and effective techniques for groundwater exploration. A detailed and systematic methodology will increase the understanding of the hydrogeological principles involved in groundwater exploration thereby helping in the selection of potential successful aquifer targets. As observed, a systematic methodological approach and utilising effective techniques capable of demarcating potential successful borehole drilling sites will increase borehole drilling success rates and reduce overall borehole drilling project cost by reducing the number of dry and unsuccessful wells.

The use of geophysics in general has led to an increase in the success rates and increased yields in boreholes in the area. Combining the 2-D multi-electrode resistivity survey and the electrokinetic sounding survey (EKS) in the selection of sites for drilling led to a marked improvement of borehole success rate and yields of boreholes (table 15). In situations where success rate improvements were not very significant, yields obtained were much higher than would have been achieved using the conventional electrical resistivity methods.

The 2-D multi-electrode resistivity survey produced significant 2-D sections with high quality in terms of structural resolution leading to significantly defined layering of different lithological units, depth to bedrock and weathering profiles and identification of structures; joints and fractures at the subsurface. These structures are quite important for groundwater exploration.

The multi-electrode electrical resistivity survey is more expensive than the conventional 1-D electrical resistivity profiling and sounding techniques but the additional cost can be justified where the demand for groundwater is relatively high such as for mechanised small towns piped schemes.

The EKS technique although may have had a lot of disparities in the calculation of borehole yields were helpful in the following situations;

- To identify sites with no permeable zones indicating possible dry holes.
- To identify sites with good permeable zones indicating possible productive boreholes
- To identify and isolate sites with variable or medium permeable zones for further decision-making regarding a marginal borehole indication.

The application of these techniques must not be carried out independently but must always be carried out in the context of the geological, hydrogeological and drilling activities. With the results from this study available, they can be used as a basis for interpretation in the near future should the techniques be applied.

The results have also shown that to improve the borehole success rate in the area an understanding of the hydrogeological framework of the area is very necessary; understanding of the structural geology and its influence of groundwater since these gives a good impression of groundwater occurrence.

In situations where aquifers required for borehole construction were not possible especially in the group 3 rock formation, hand dug well are a possible option for groundwater resource are important. These hand dug wells must be properly constructed with adequate protection to prevent surface runoff entering the well.

7.0 SUMMARY

The results of geophysical investigations carried out in the northern region of Ghana have been used to suggest recommendations for efficient and effective groundwater development practices under the individual geological conditions which can be transferred to other parts of the country with similar hydrogeological conditions.

7.1 Methodological approach to groundwater exploration

Developing a detailed systematic methodological approach to groundwater exploration and management is one of the main goals of the research. The methodology and the specific technique to be used in the various hydrogeomorphology units are important for effective groundwater exploration and management in the area. The transferability of these approaches to other parts of the country as a whole will depend on the structural, climatic, lithological and local hydrogeological factors since these factors normally depend on the local situation.

In all the three groups, the following systematic methodology has to be followed before actual ground geophysical measurements. The flow chart (fig. 22) summarises the various steps.

7.1.1 Desk study and background geological review

All background data in the area must be reviewed. Borehole data in the area including geophysics, drilling, and all hydrogeological activities which have taken place in the area must be reviewed. The depth to bedrock, static water levels and depth of water strike and expected borehole yield must be studied from this information. Hydrogeological maps in the area must also be studied critically to obtain useful information.

7.1.2 Remote sensing

The availability of useful remote sensing data, satellites images, aerial photographs and LANDSAT data is always very important. Images from LANDSAT can under certain conditions display structural information which can be interpreted in terms of present day elastic deformation and hydraulic conductivity (Boeckh, 1992).

A detailed aerial photo interpretation must be carried out. This study will help to identify structures which may be of useful and helpful hydrogeological significance. When all the available useful information has been obtained a conceptual model is built with all the available information and a plan for executing the activity is carried out. In most cases it is recommended that all the structures identified are demarcated on a topographic map so as to make them very clear and simple to identify on the field.

7.1.3 Field reconnaissance survey

Field reconnaissance visits are very important to confirm and update preliminary data assessment. All the information obtained from the desk study and remote sensing must be confirmed by visiting the site. During this visit no geophysical measurements are carried out but the structures identified are mapped out so as to have a good impression of the hydrogeological situation in the area. Information of relevance includes;

- Location of rock outcrops and their descriptions
- Location of inferred geologic structures
- Description of soil profiles
- Location of existing water supplies
- Location of potential sources of pollution to groundwater
- Depth and water levels of hand dug wells where there are no documentation

7.1.4 Potential targets

Potential targets identified from both the desk study and remote sensing activities are clearly mapped out so as to limit the area for investigation. It is recommended that these potential arrears are also mapped out clearly on the topographic base map.

7.1.5 Ground geophysical measurements

After all the above systematic processes have been carried out ground geophysical measurements can begin. As has been stated earlier these steps are very crucial to any groundwater exploration activity prior to geophysical measurements and therefore applicable in all the groups.

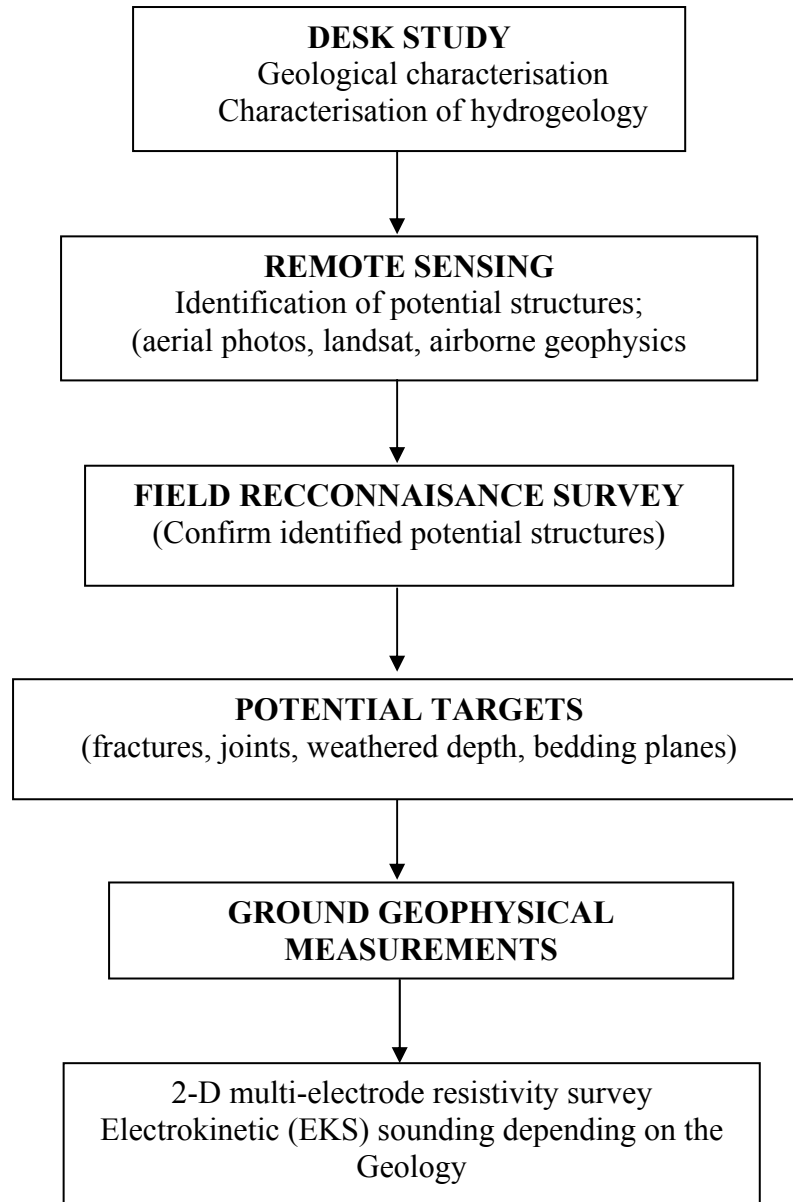


Figure 22: Flow chart showing methodology for groundwater exploration

In the group 1& 2 rock formations the application of the 2-D multi-electrode resistivity profile have been very effective in demarcating and selecting sites for successful borehole drilling. As observed on most of the resistively profiles, the various weathering depth, fractures and joints which are good indicators for an aquifer were clearly observed on the profiles. In areas where there were no structural deformations at the subsurface, the various resistivities of the layers were clearly demarcated with significant changes in resolution. The EKS was quite effective in the group 1 formation and could be used to confirm sites selected from the multi-electrode survey especially in situations where high yields are required. Shallow to

intermediate depth aquifers in the weathered and highly fractured zones are highly recommended for the application of the EKS technique in group 1. With an improvement in the technique and using the correct velocities and input parameters, the EKS might be quite efficient in the group.

In the group 2 formation of predominant arenaceous sandstone beds which are highly fractured, the 2-D multi-electrode system is very effective in defining the geological structures; fractures and joints in the bedrock. With these characteristics clearly demarcated by the technique, it could be quite appropriate to select potential successful drilling sites without any additional technique. In any case the EKS was not very effective in the group as most of the calculate yields from the EKS did not have a good correlation with pumping test and drilling yields. The ability of the 2-D multi-electrode survey to correctly and efficiently demarcate fracture zones and joints was very effective and excellent.

In group 3 however both techniques were not very effective in demarcating successful borehole stations. Although there was a marked improvement in success rates of borehole drilling, the very low resistivity distribution and the presence of clay materials in the group ensured that clearly defined anomalous structures were difficult to demarcate on most of the profiles and as a result layers with resistivity in the range 200-400 ohm-m were demarcated as targets for drilling. With the low resistivity of rock materials dominating in this group as well as the lack of clearly defined resistivity structures with a distinct contrast with the background, it is important that another technique could be employed to confirm sites from the 2-D multi-electrode survey anomalies. The EKS calculated yields were also not correlated with the results from the drilling yields and so the technique was not very effective in the group as expected. It is therefore important that another technique if proven to be very effective in the area could be employed in the area to confirm sites demarcated from these two techniques. The surface nuclear magnetic resonance (SNMR) could be an option for application in this group.

7.2 Groundwater management

Groundwater management includes the exploitation, evaluation and the protection of the resource in an effective and efficient way so as to ensure its sustainability for the present and future generations. The groundwater resource in the northern region of Ghana is currently being over exploited considering the increase in groundwater facilities and the fast population growth. The CWSA with support from donor agencies is providing a lot of groundwater facilities for rural water supply utilizing boreholes fitted with hand pump and mechanized piped schemes for small town water supply. This exploitation of the groundwater resource shall continue into the future to meet the increasing demand of the population in order to accomplish the accelerated development planned between now and the future.

There is however growing concern about the sustainability of the groundwater resource as it is being exploited. It is thought that ground water depletion could be experienced as the resource is being over exploited to meet both current and future demand. According to the Community Water and Sanitation Agency (CWSA) there have been reported cases of boreholes drilled and installed with hand pumps which are either experiencing loss of yield or declining water levels over the years. These cases seem to heighten the fear of groundwater depletion in the long term. There is therefore the need for an efficient and equitable use and an integrated management of the resource. This will be done with the background of understanding the societal need for groundwater, process involved in influencing the demand for and supply of water as well as the allocation of groundwater.

Most communities where groundwater facilities have been provided for rural water supply under the community ownership policy have obligations which include;

- Community having legal ownership and control of the groundwater facility. These include formal agreements between project and donor agencies.
- Community involvement in the location of the facility. This becomes very important in cases where hand pump installation boreholes are the facilities to be provided since people usually have to go to the borehole source to fetch water.

- Selecting a committee responsible for managing the facility with additional responsibilities for operating and maintenance of the facilities. This committee is responsible for the maintenance and repair of the groundwater facility during breakdown.
- Appointing caretakers to receive training and tolls responsible for preventive and simple corrective maintenance (Karikari, 1996)

7.2.1 Major obstacles to groundwater management

Groundwater remains a neglected and misunderstood resource because funding for management and protection has not achieved the required attention and is always considered at the bottom of the environmental table (IAH, 2006). In most cases emphasis is placed on groundwater exploitation with no official policy framework for the protection of these facilities for the sustainability of the resource.

Major obstacles for sound groundwater management in the area which have to be addressed include;

- Absence of an effective legal and regulatory framework governing groundwater abstraction and protection.

There must be a legal framework regarding abstraction of groundwater which must be enforced. The CWSA which is the main governmental agency responsible for managing groundwater must set some thresholds regarding abstraction of groundwater and issuing of groundwater permits to make sure that the resource is exploited by qualified personnel and in a sustainable way.

- Groundwater monitoring.

A low priority has been attached to groundwater monitoring in the Northern region and the whole of Ghana and as a results boreholes have been drilled without any monitoring wells in the catchments to monitor the quality over the years. Monitoring wells have to be installed in groundwater catchments to monitor the quality so as to prevent the breakdown of the system in case of pollution and contamination. The lack of monitoring wells is a serious problem and so it must be enforced with legal backing to integrate groundwater monitoring wells into the various groundwater programs in Ghana as a whole.

7.2.2 Protection of groundwater facilities

Groundwater facilities need to be protected by the implementation of guidelines as follows:

- No pit latrine, soak away or septic tank facility should be sited at distance of 40m either uphill or downhill from the groundwater facility.
- Every new borehole must be constructed with a competent lower and upper grout seal in the annulus. The upper grout seal should not be less than 5m of linear length.
- Every hand dug well facility should be provided with a competent upper grout seal of not less than 4 m of linear length.
- The superstructure of every borehole and hand dug well must be provided with a competent apron and platform to prevent spilled and contaminated water from infiltrating into the ground system around the facility.
- The siting of pit latrines or other waste disposal facilities in areas with shallow groundwater must be avoided at all cost.

These guideline are already implemented but is not enforced by the controlling authorities (Ewusi, 2003).

7.2.3 Groundwater policies

Appropriate government agencies like the district assemblies and the CWSA must be efficiently equipped to mobilize all stakeholders in the groundwater business in the management process. A formulation of a national policy must be carried out including;

- Formulating a natural groundwater policy with respect to the legal, administrative and regulatory measures with regards to the best available technologies and economic instruments. This will reduce indiscriminate drilling by obsolete equipment and machinery so as to avoid groundwater contamination.
- Outlining procedures to implement abstraction and recharge permits so that the abstraction and recharge of aquifers will be controlled taking into accounts the reserve and its replenishment. The license will include the purpose, amount, location and the technical characteristics of abstraction and the legal status of the user as is practiced in some developed nations.

- Formulation of laws governing groundwater pollution by ensuring that the drilling of boreholes is carried out by qualified and properly skilled and with appropriate personnel. The law will also make room for constant groundwater monitoring to avoid total groundwater pollution and contamination.

7.3 Establishing a groundwater data and retrieval system

There has been a lot of new information about groundwater in the northern region of Ghana especially after the many groundwater projects which have been undertaken in the area including; the GLOWA Volta project, CIDA and European union projects. Implementation of these projects has led to the general improvement in perception and importance of groundwater resource especially in the fight against the guinea worm disease.

There is therefore the need to establish a groundwater data and retrieval system to collect, store, continuously update information to enable planning and management of the resource so as to ensure its sustainability. Records of boreholes which have to be included in the database include; depth of borehole, construction details of the boreholes, water level, yield and geological descriptions of the material penetrated by the drilling and aquifer depths.

8.0 RECOMMENDATION FOR FURTHER STUDIES

The research has opened up new dimensions in the application of geophysical techniques for groundwater exploration in the northern region of Ghana. Other techniques which could contribute significantly to improving the success rates of borehole drilling are outlined.

8.1 Surface Nuclear Magnetic Resonance

Research on surface nuclear magnetic resonance (SNMR) which has successfully been applied to assess groundwater and aquifer parameters could be carried out in the area. Literature available on this technique conclude that it allows for the detection and assessing water directly by surface measurements allowing quantitative information about mobile water content leading to hydraulic conductivities. The technique is expensive but could contribute immensely to the improvement of success rate of borehole drilling in the difficult voltain formation if found applicable. The group 3 rock formation could benefit from the application of this technique if found to be very effective under the conditions of the northern region of Ghana.

The method consists in exciting the H protons of water molecules with a magnetic field at a specific frequency and measuring the magnetic field produced in return by these protons.

8.2 Radon Survey

The method has been successfully applied in locating fault structures. It can be used either as alternatively or supplementary groundwater exploration tool especially on sites where the conventional method as well as the 2-D multi-electrode and EKS techniques do not yield satisfactory results. It is based on the emission of an alpha particle by the radioactive radium to produce the gas radon. Radon is naturally produced during the radioactive decay of uranium which is present in minerals in most rocks types. The amount of radon is directly related to the porosity of the medium and the technique is used to delineate, detect and trace the porous area as a fault zone. The technique was tested during the pilot study. The results obtained from the pilot study was quite satisfactory but was abandoned because of its high cost.

8.3 Seismic Investigation

A seismic investigation is recommended in the area to determine the velocity models at the individual depths. Vertical seismic profiles (VSPs) can supply information about both velocity and subsurface interface locations. Traditional interpretation of seismic data has used a concept of layered horizons where each horizon has a seismic velocity. With these seismic information determined, a calibration with the EKS can be carried out to obtain the actual velocity for use in calculation in the model parameters for the EKS survey. The results of the seismic investigation will also be used to demarcate saline zones in the area to serve as a guide during groundwater exploration programs. A map showing the saline zones can be produced from this study to aid selection of sites for borehole drilling for potable water supply.

However the costs of seismic surveys are much greater than the cost of other types of geophysical surveys. Another option therefore is to carry out a calibration in any part of the West African province with similar geological and hydrogeological characteristics to obtain the required velocity models for the EKS survey

8.4 Aquifer vulnerability map

The production of an aquifer vulnerability map of the area to show areas where aquifers are protected by thick and low permeable cover, isolating them from contaminated sources is very important. Aquifer vulnerability maps are powerful tools in identifying appropriate short lists for site selection but are not a substitute for site investigation data.

Aquifer vulnerability map of the area will show the units having different potential for groundwater contamination and these are typically and clearly shown on the map. They are widely used by local and state officials in making environmentally sound siting decisions and hydrogeologist as a base for detailed hydrogeological studies and groundwater development.

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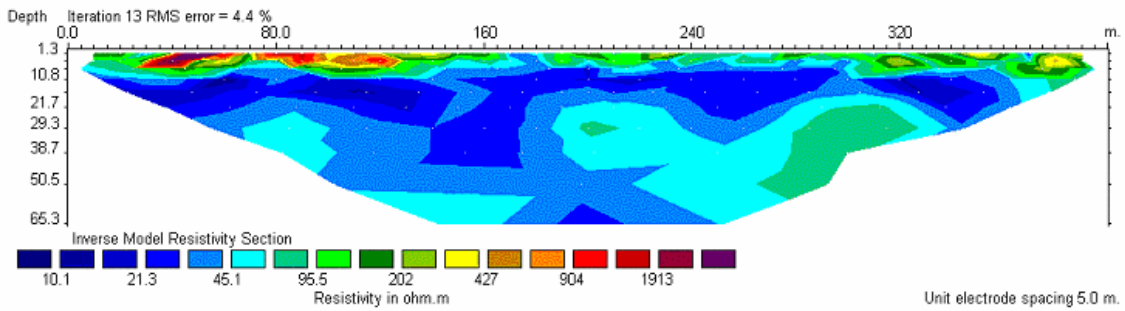
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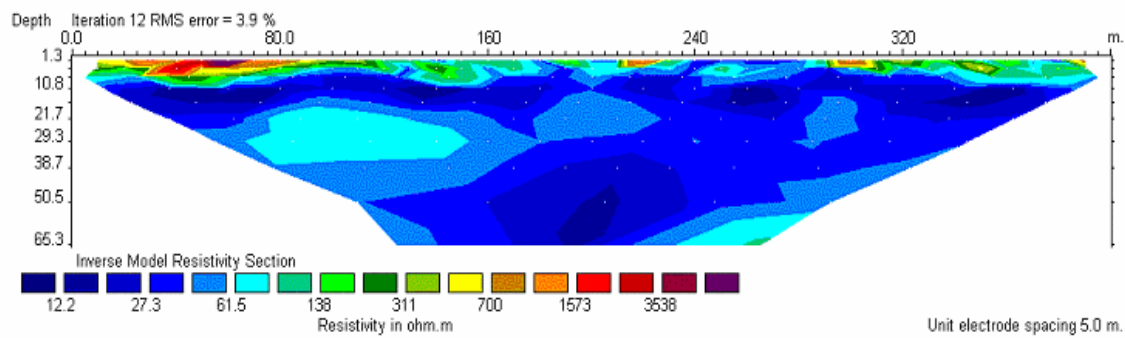
ANNEX A

2-D MULTI-ELECTRODE ELECTRICAL RESISTIVITY PROFILES

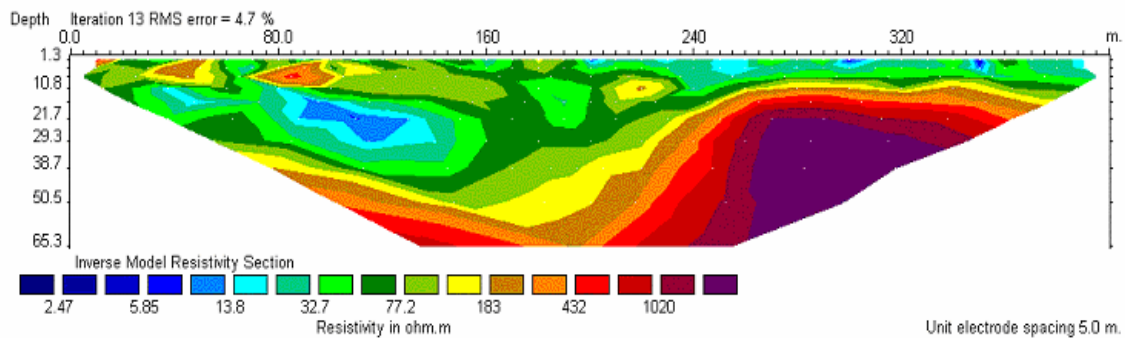
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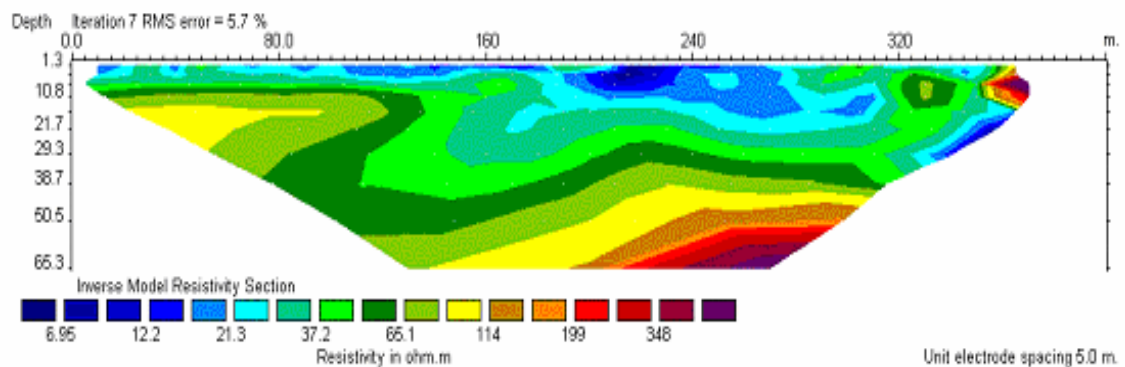
Bamboi Profile B



Bamboi Profile C

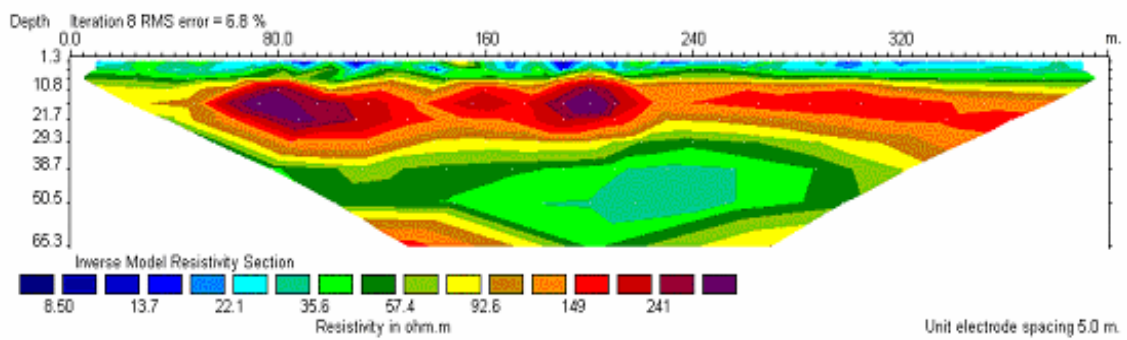
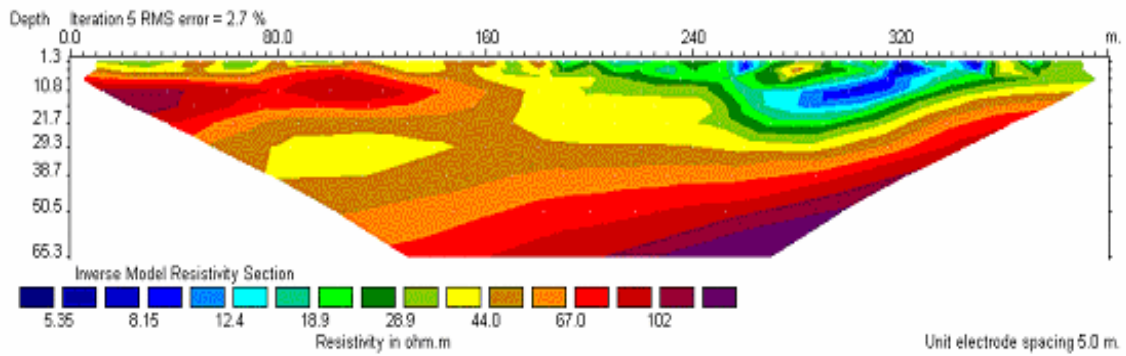


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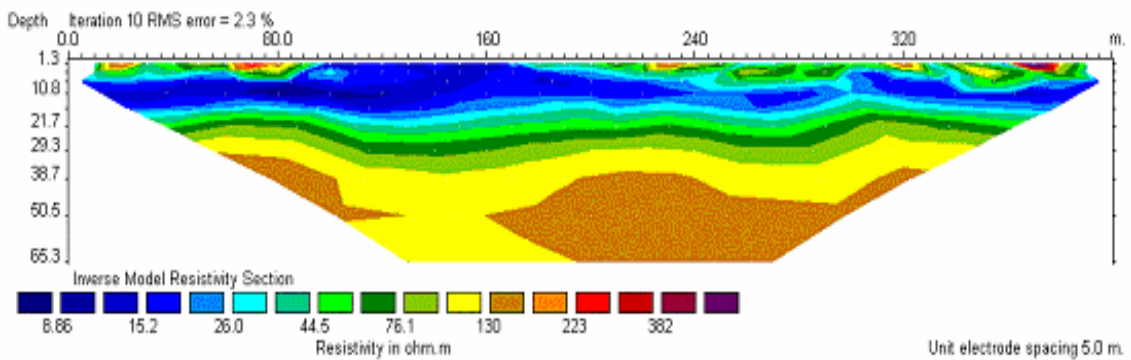


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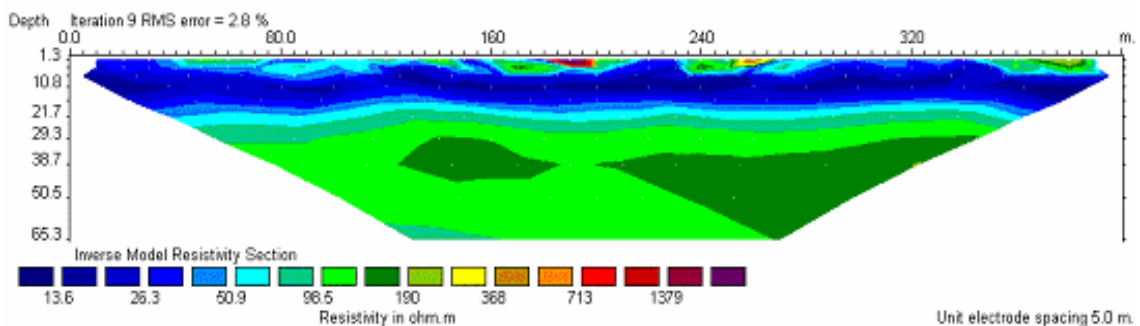
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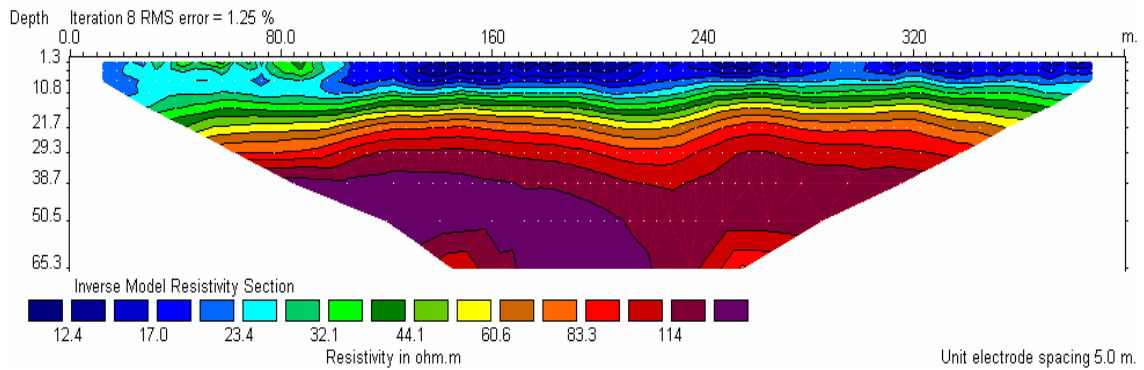
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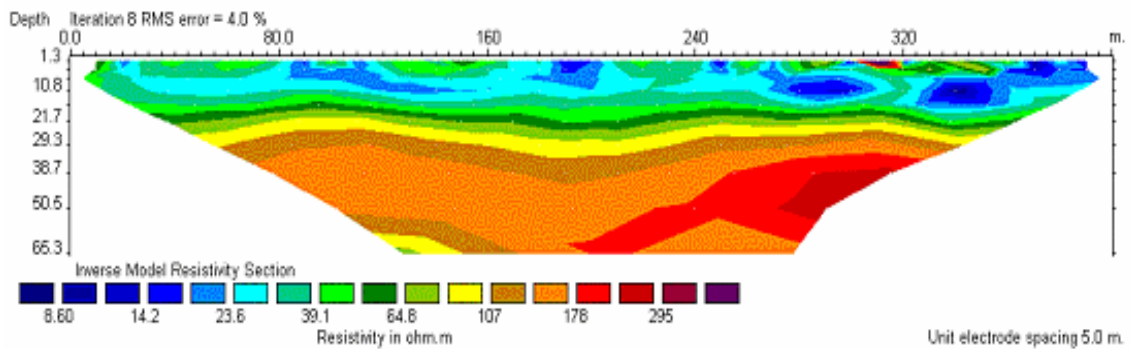
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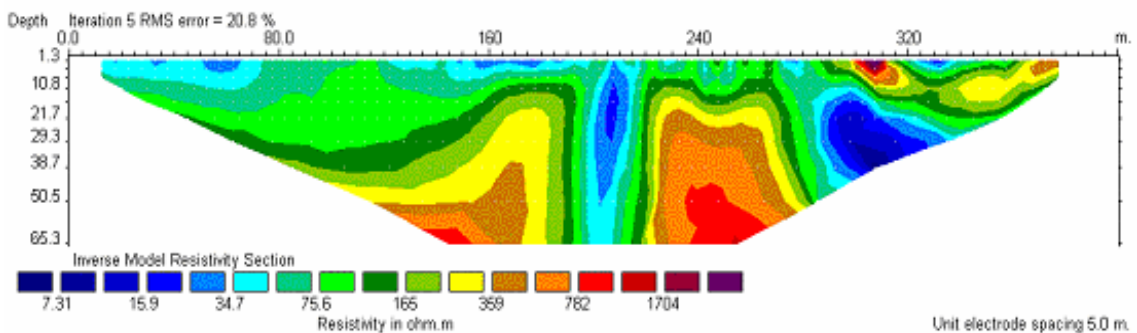
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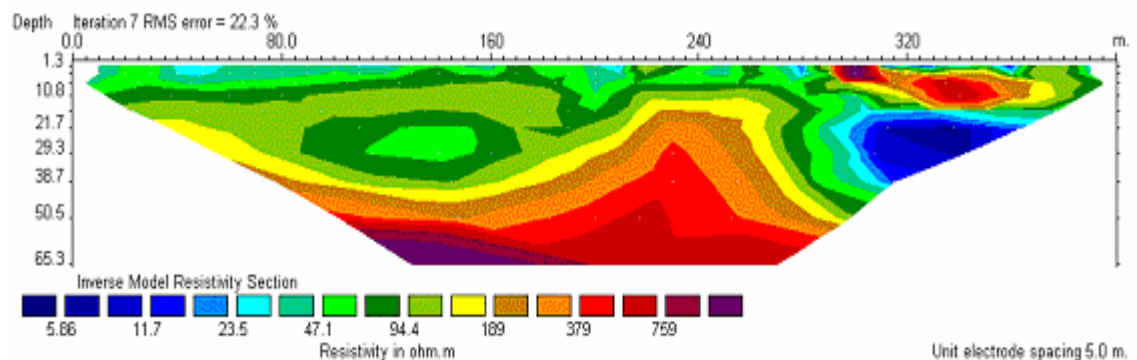
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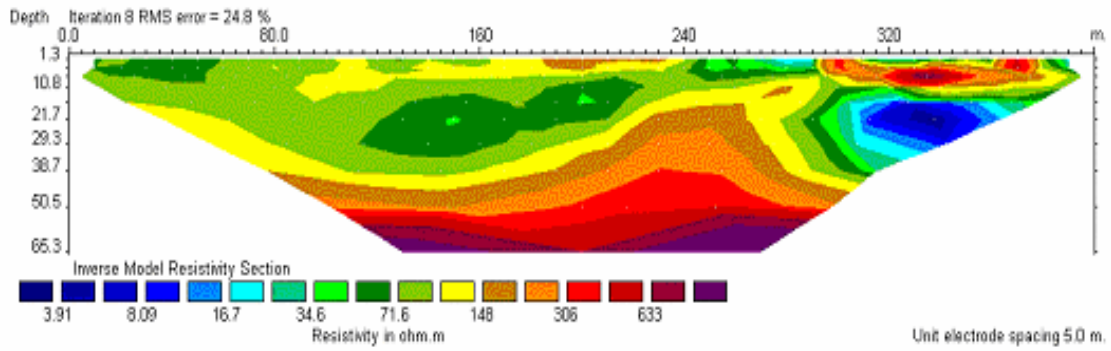
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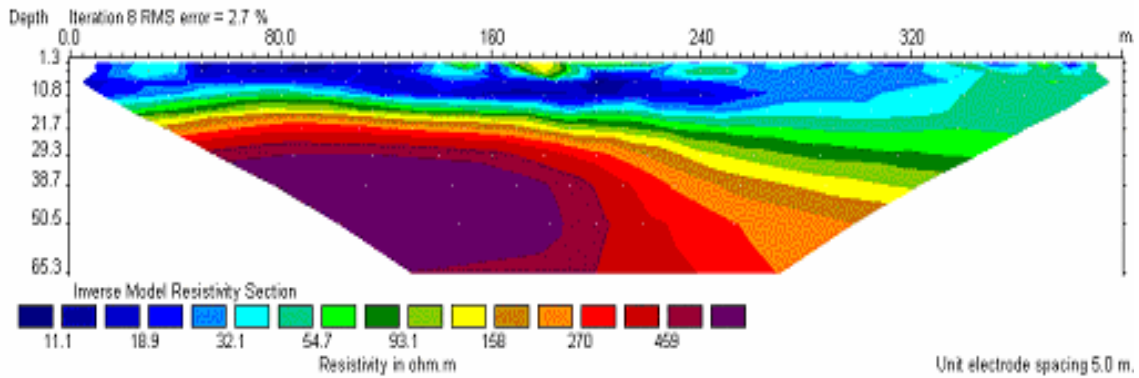
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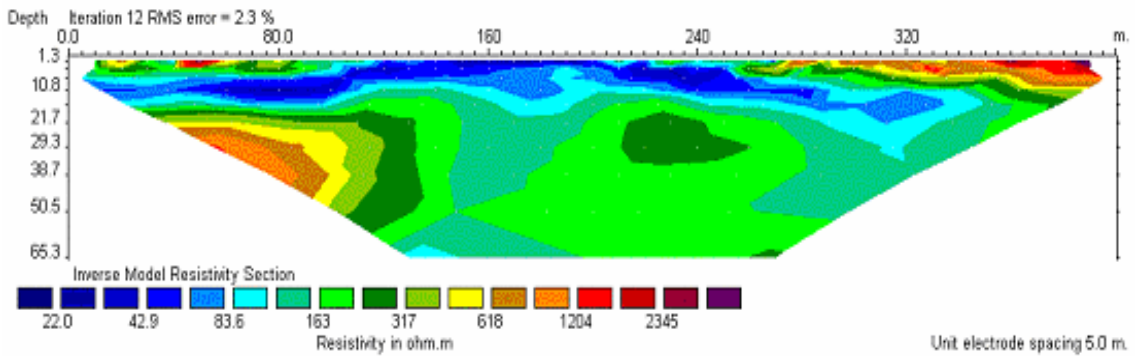
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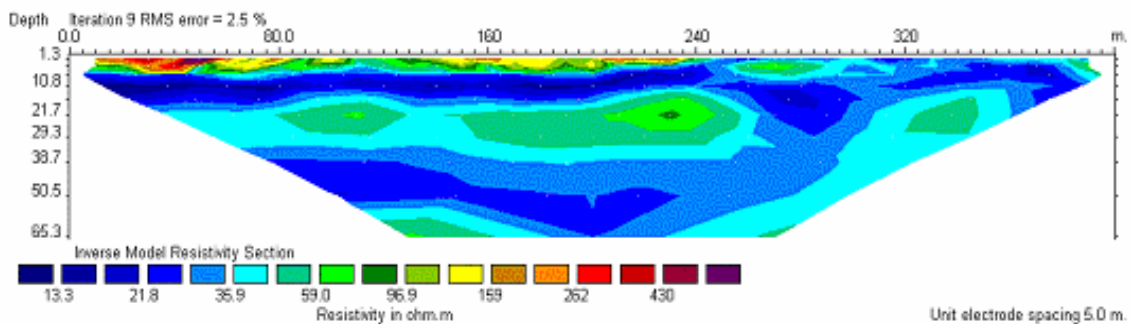
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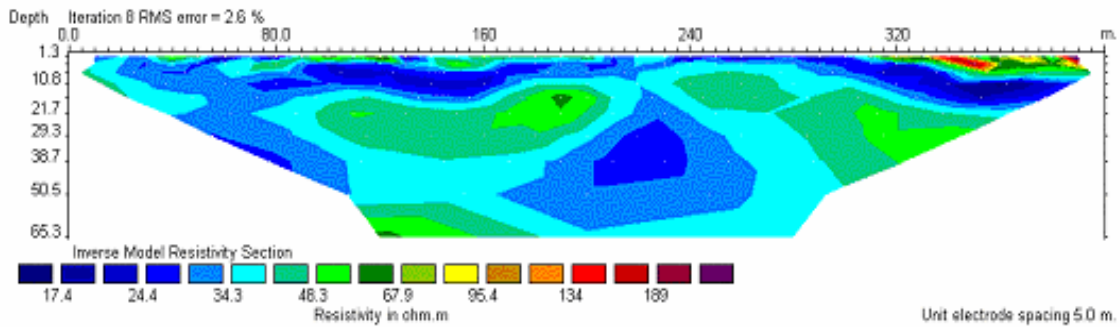
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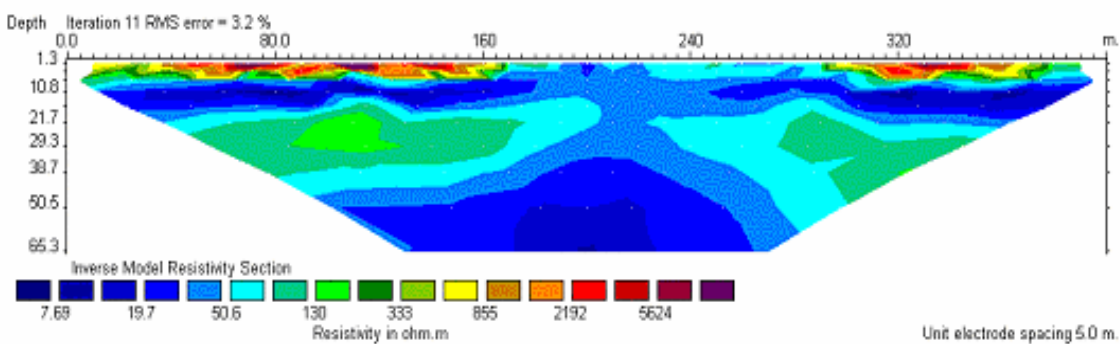
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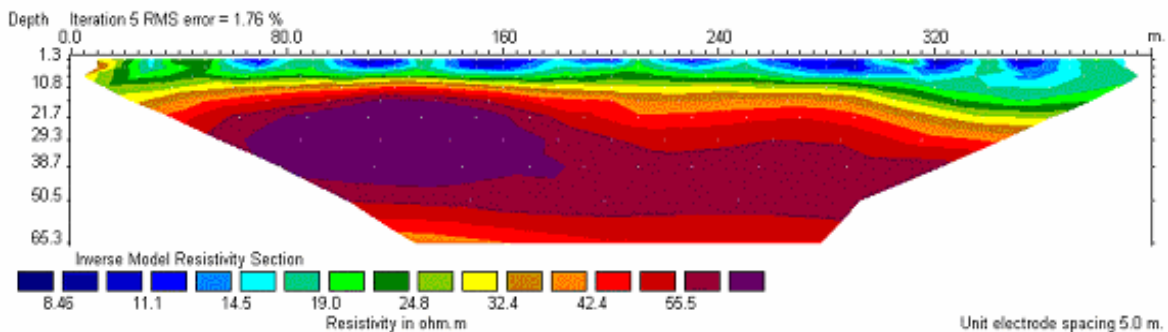
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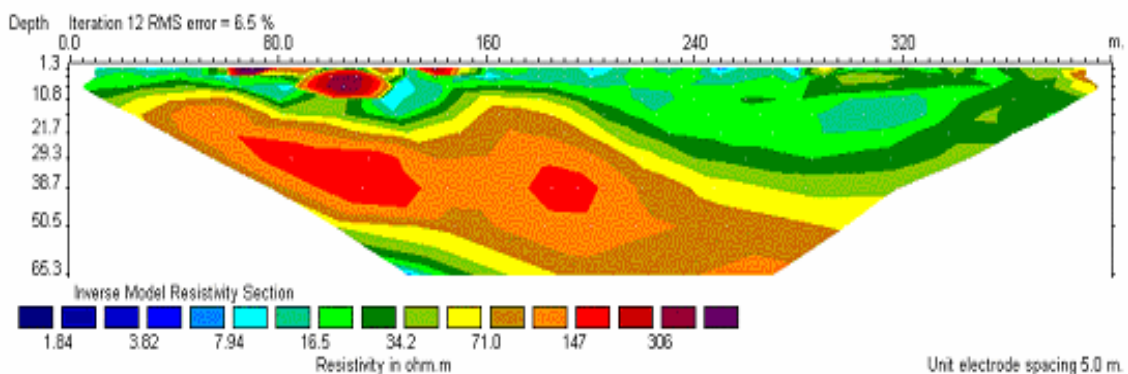
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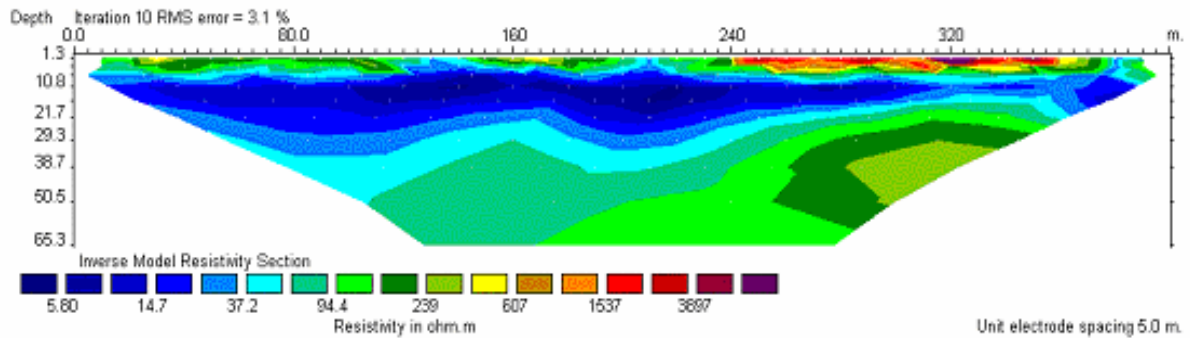
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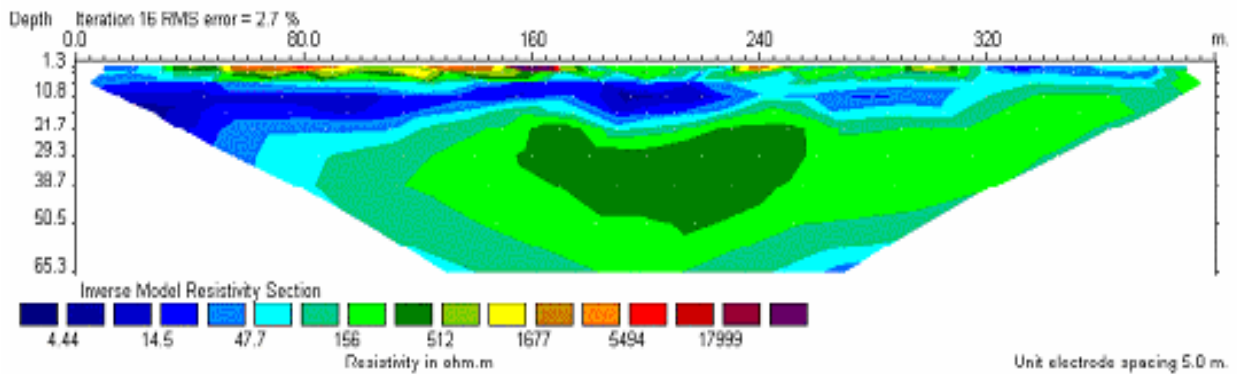
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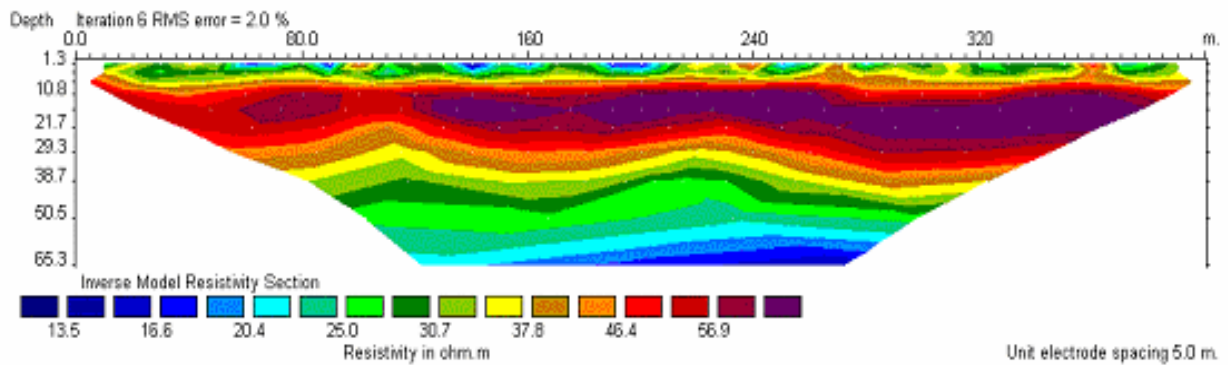
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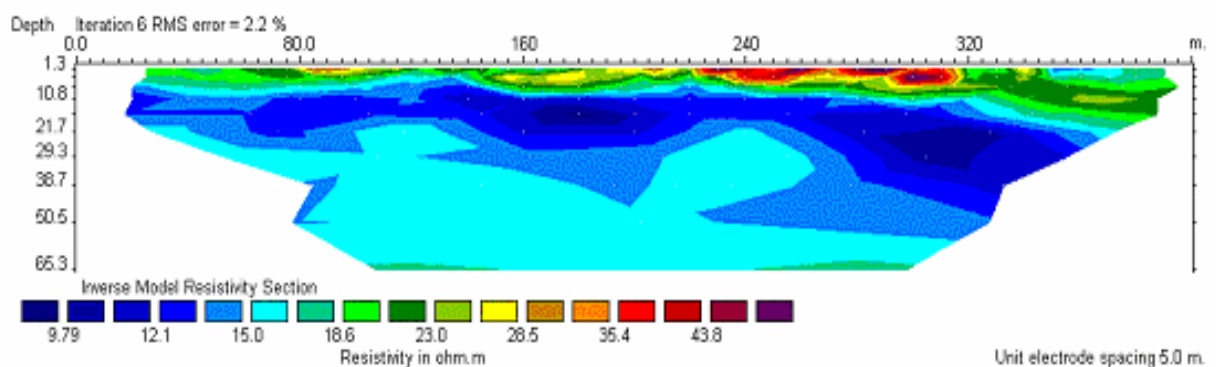
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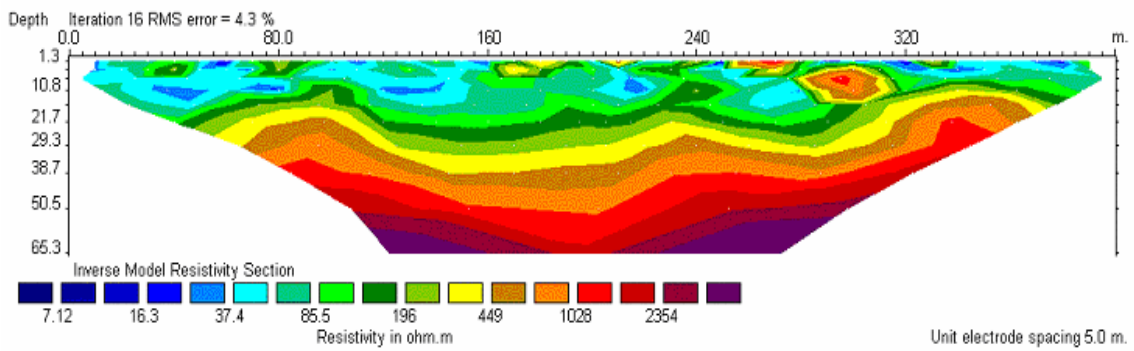
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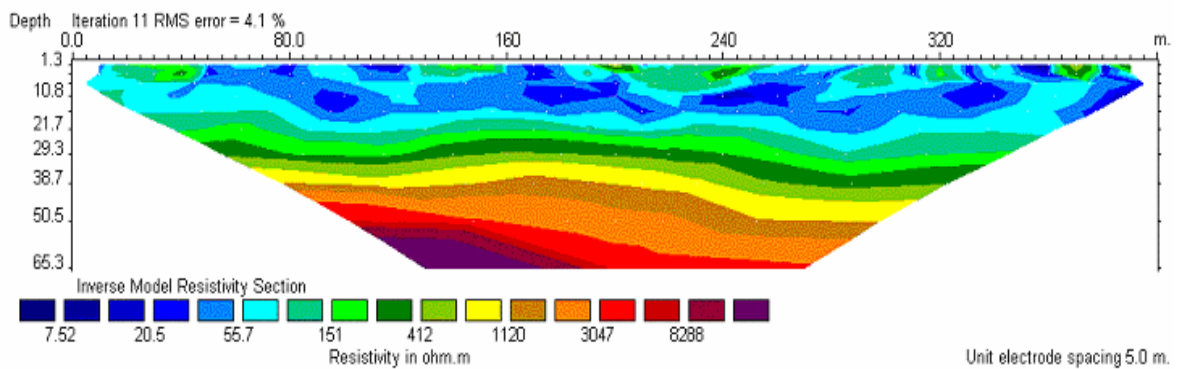
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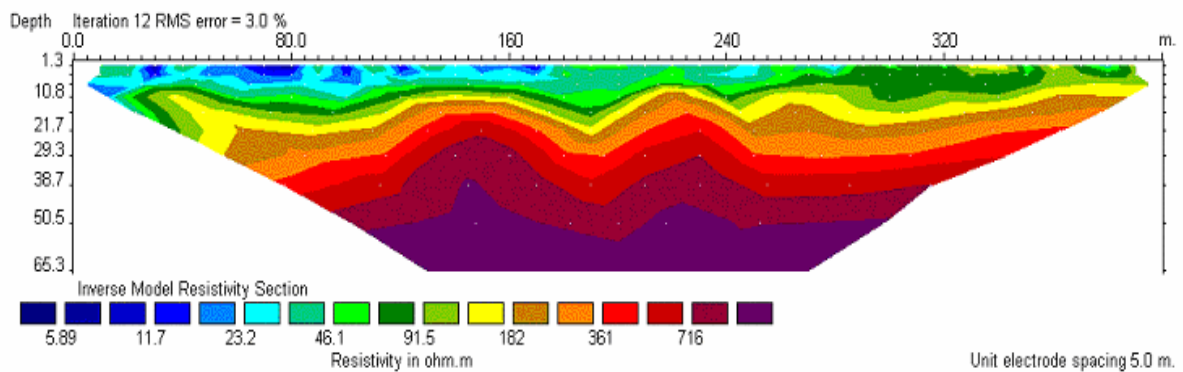
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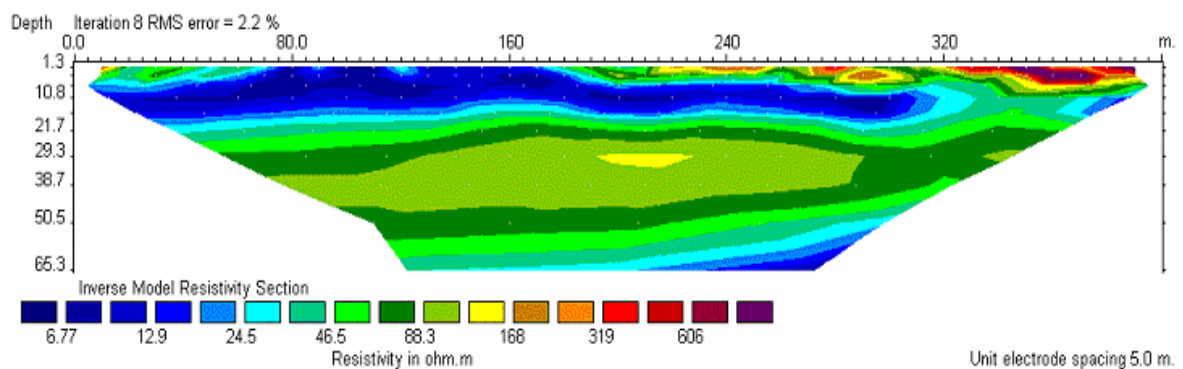
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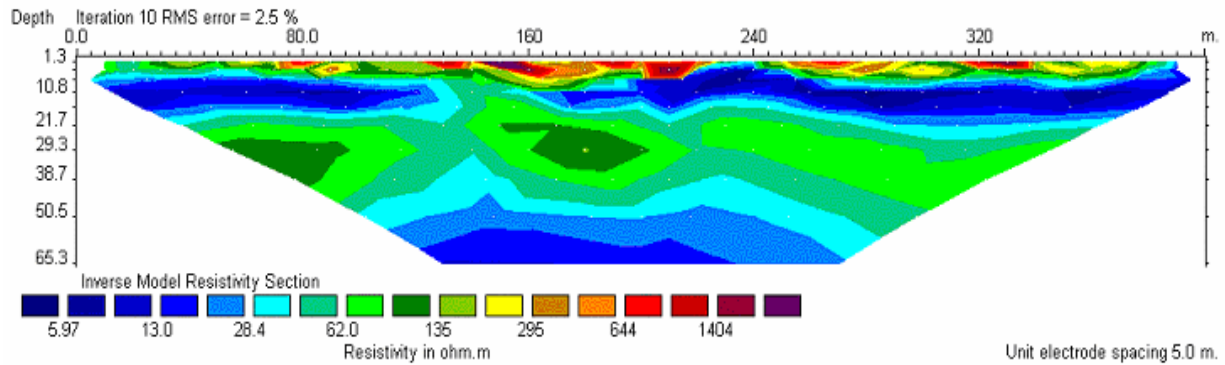
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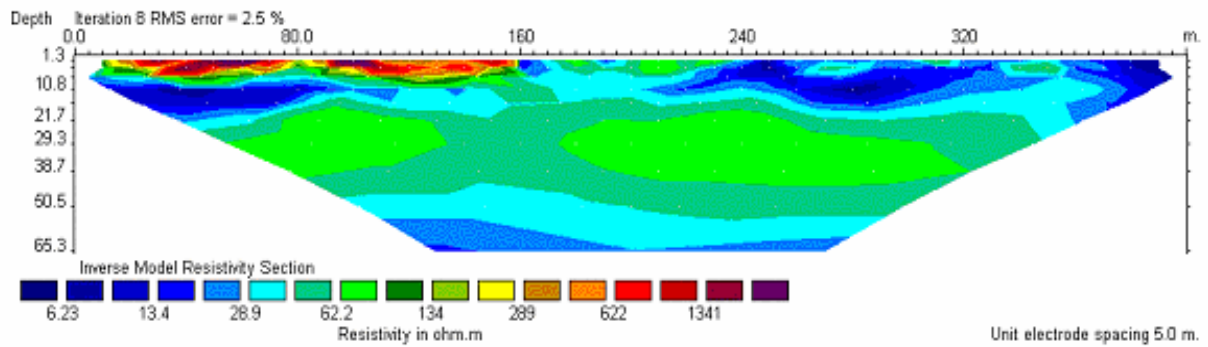
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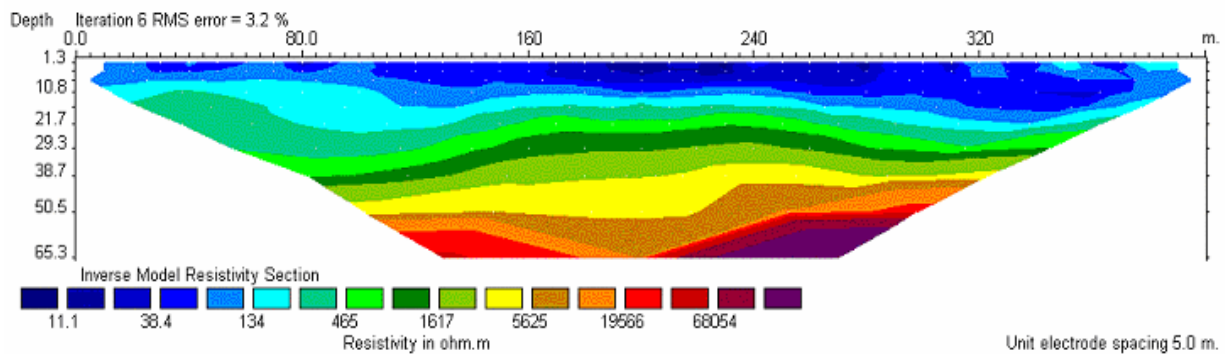
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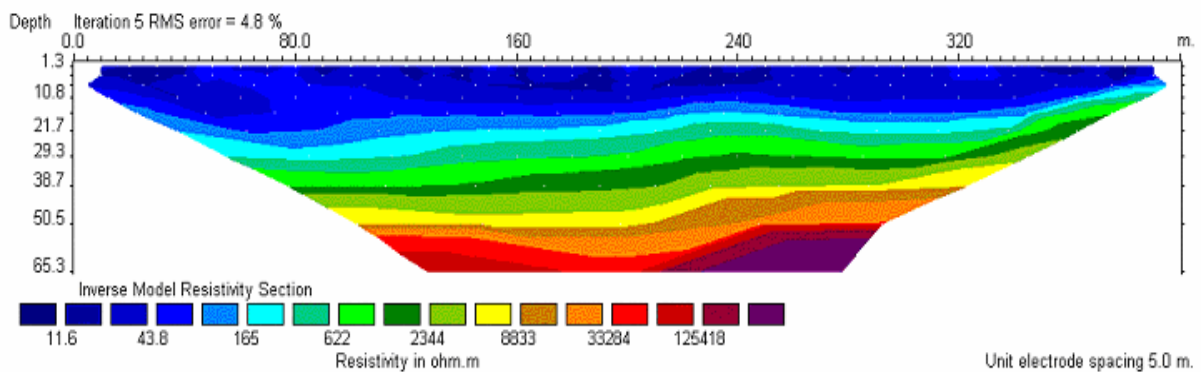
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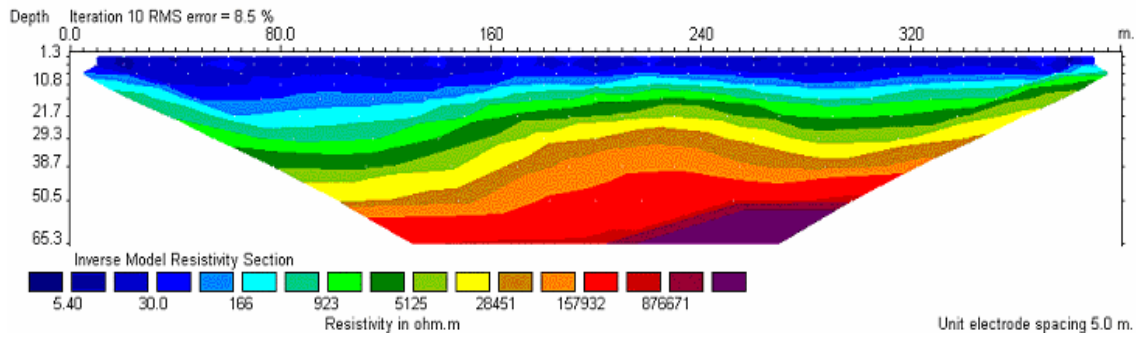
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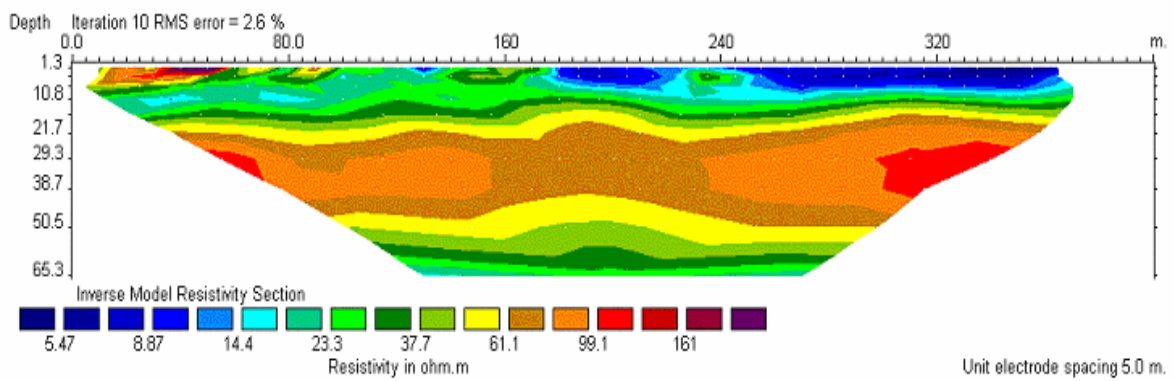
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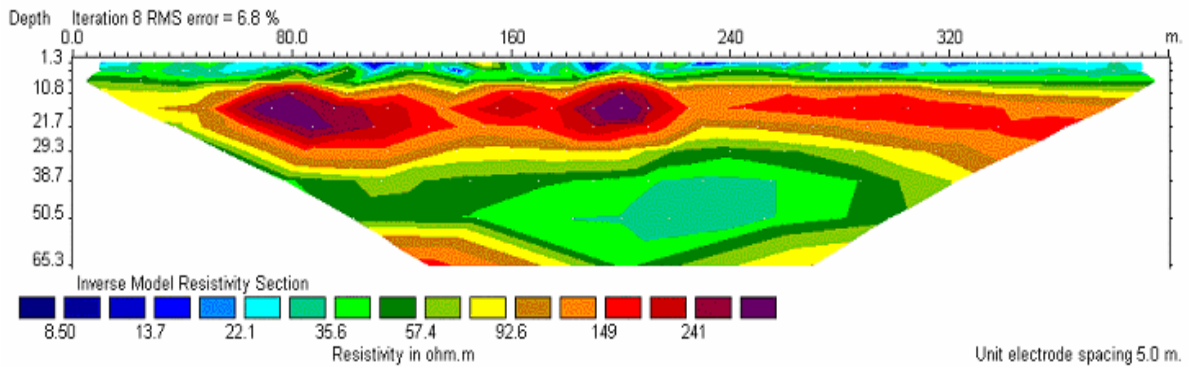
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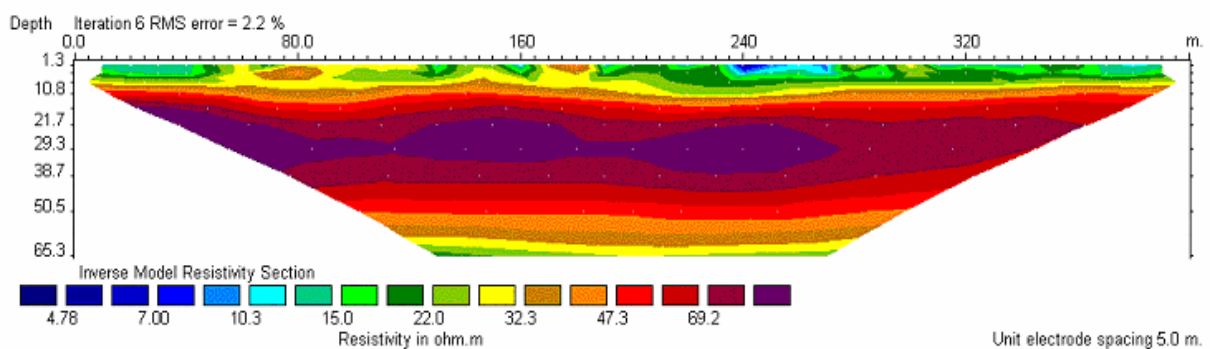
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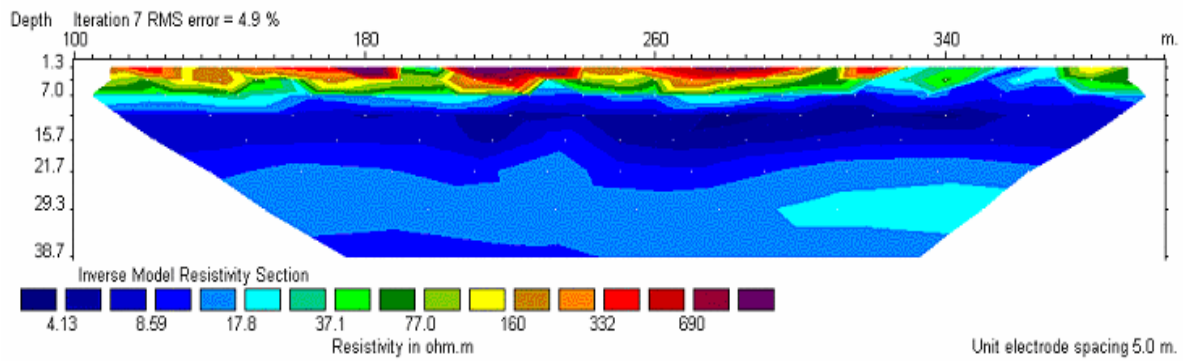
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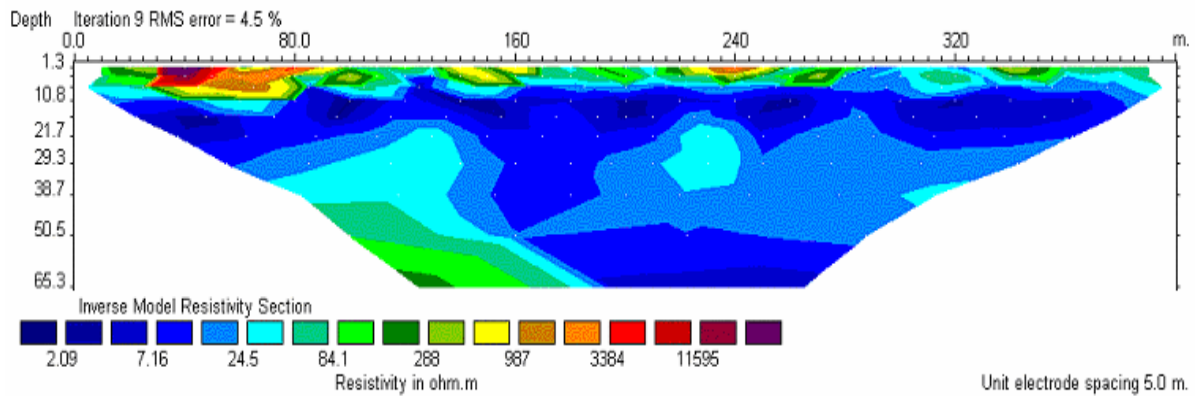
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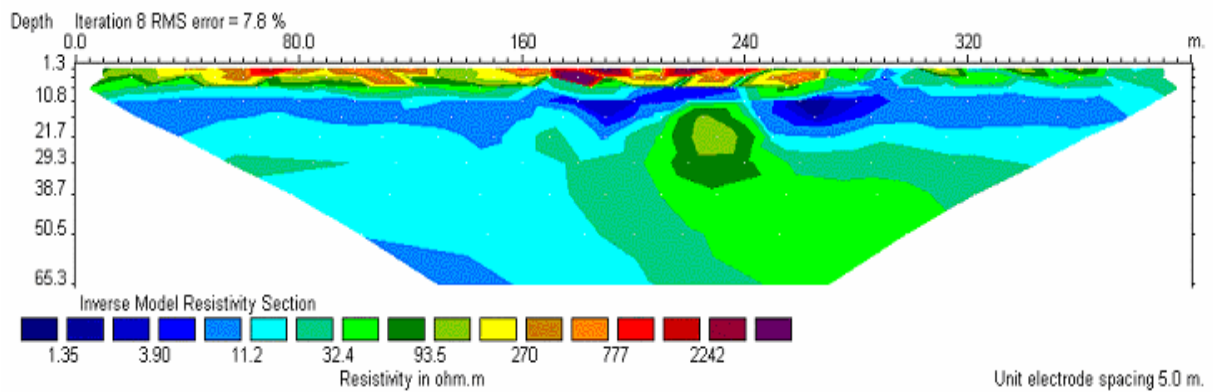
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Yoggu Profile B

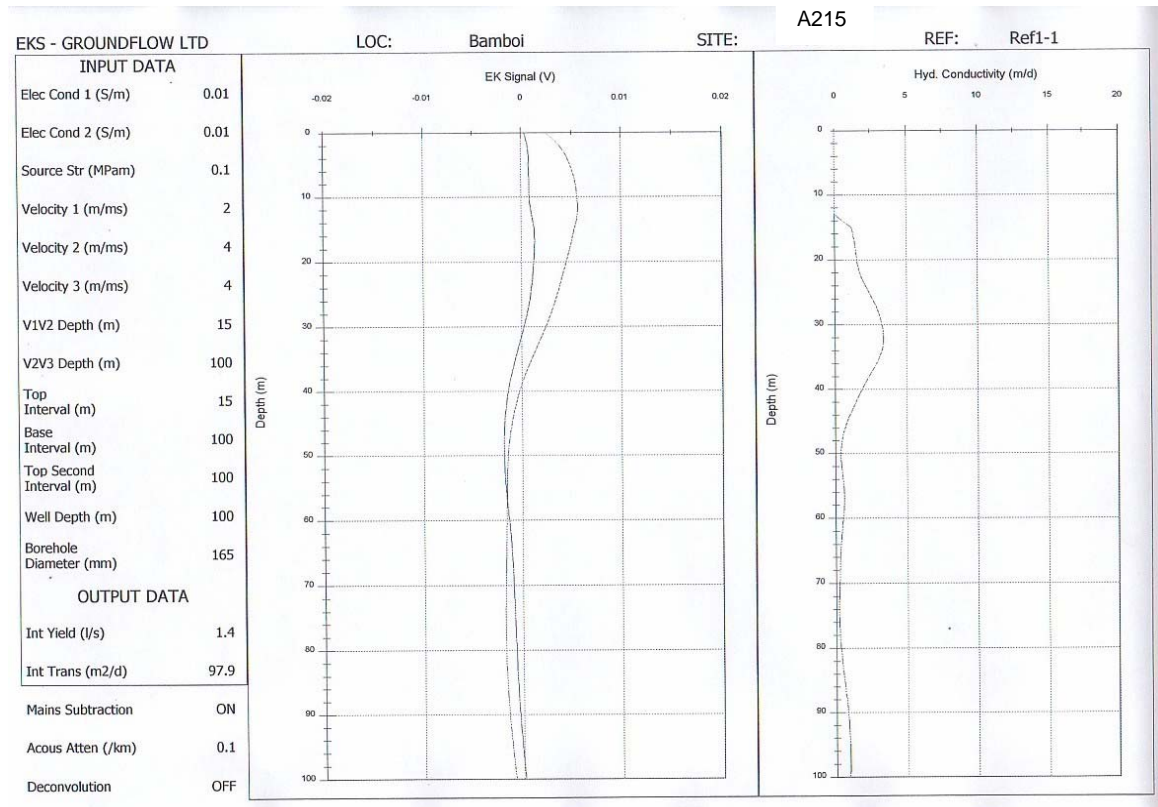


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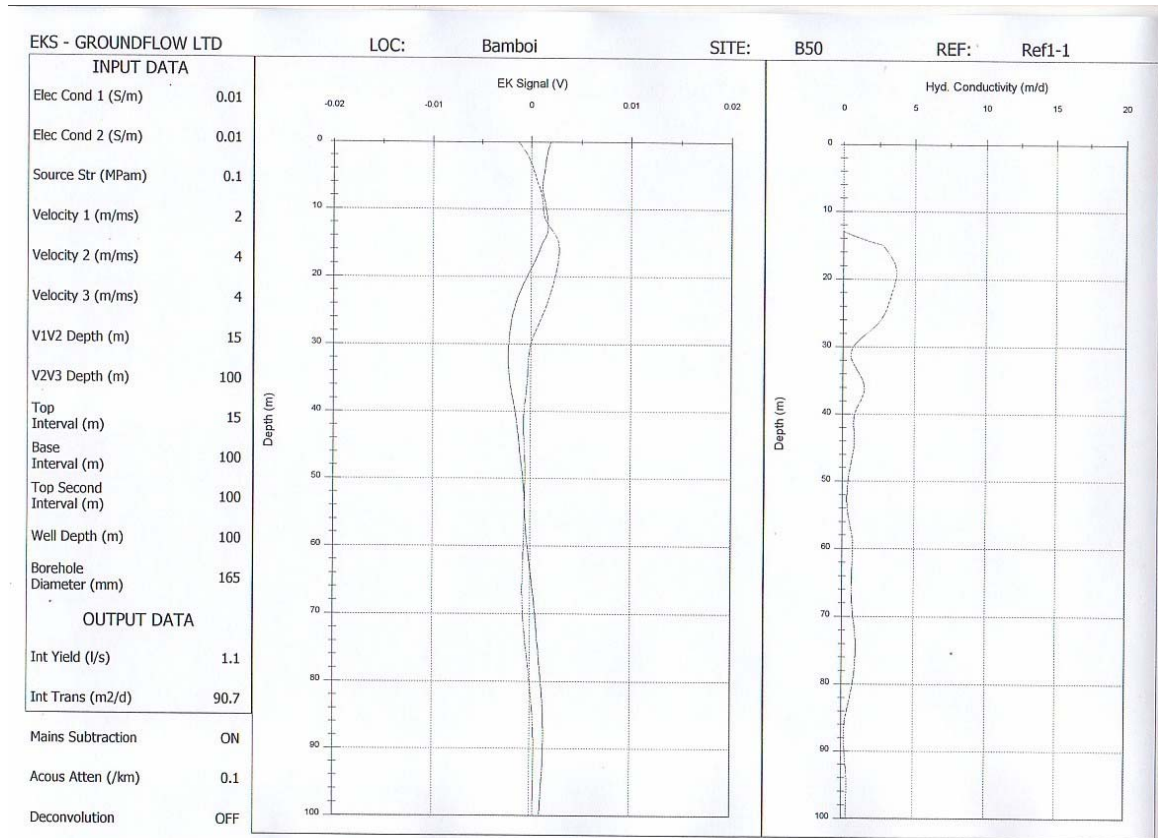


ANNEX B
ELECTROKINETIC SOUNDING (EKS) RESULTS

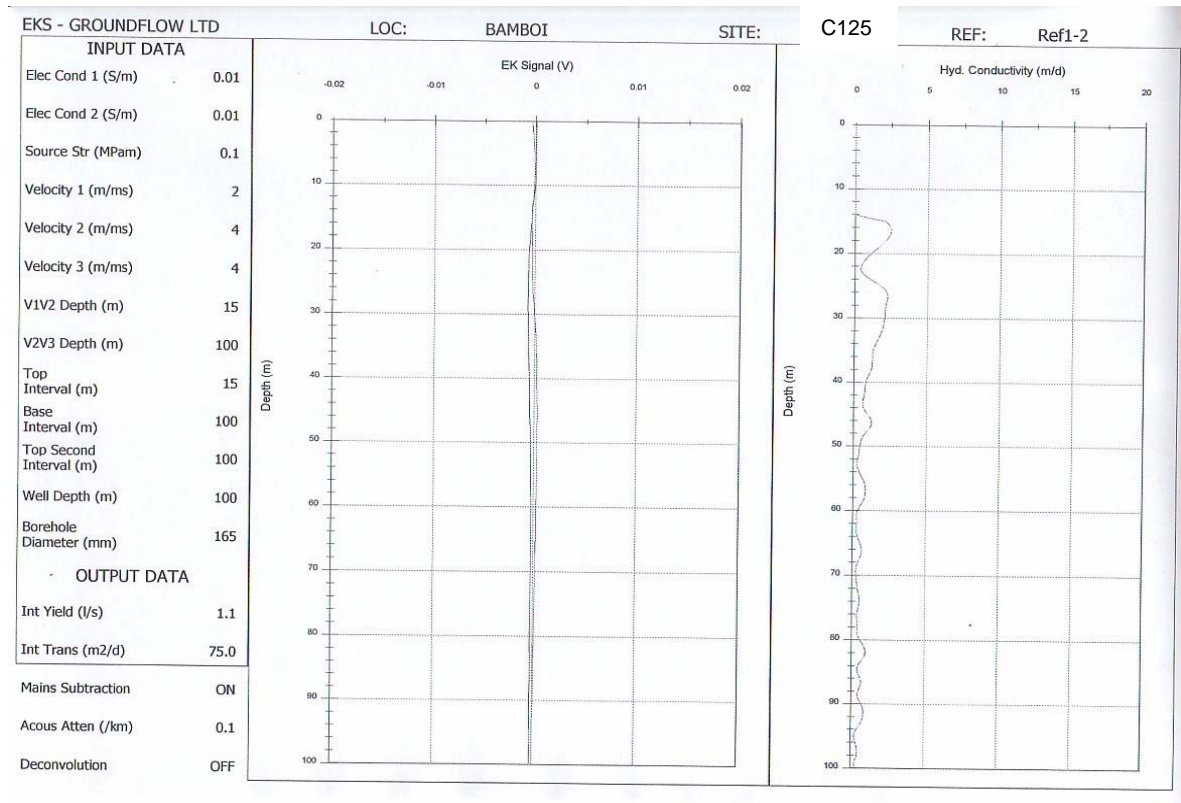
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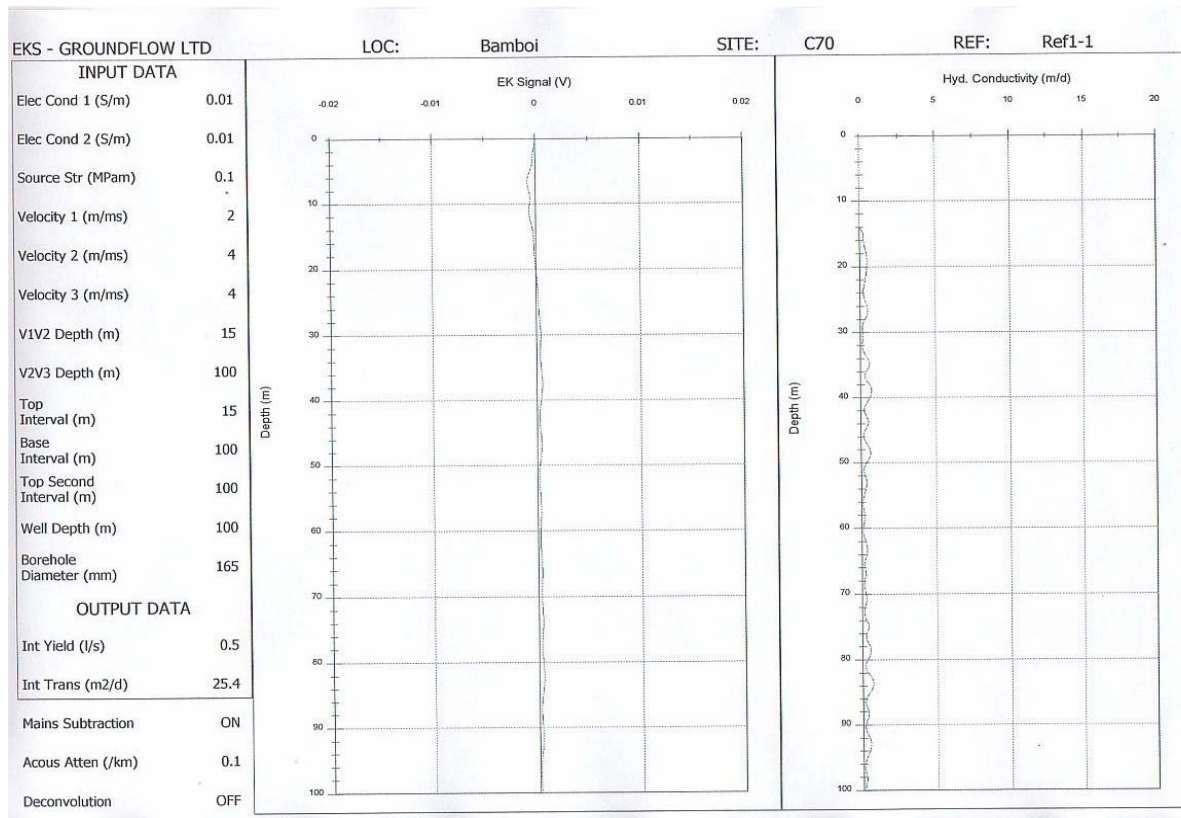
Bamboi B50



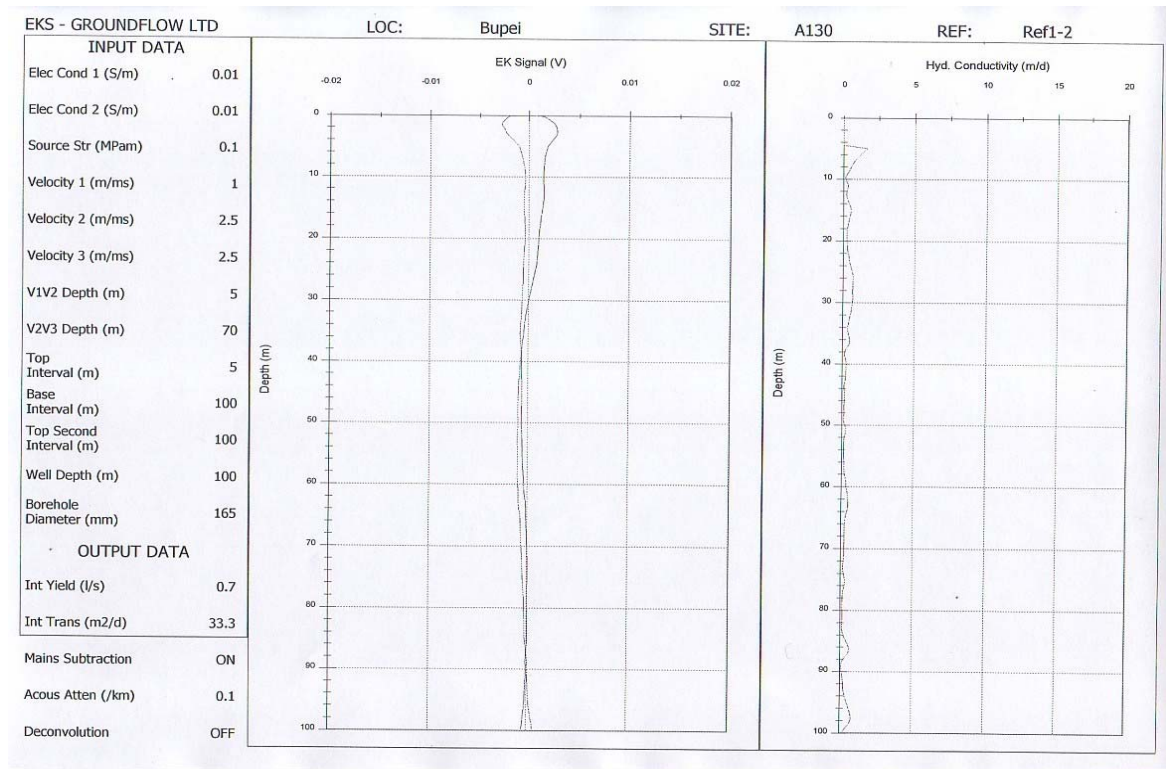
Bamboi C 125



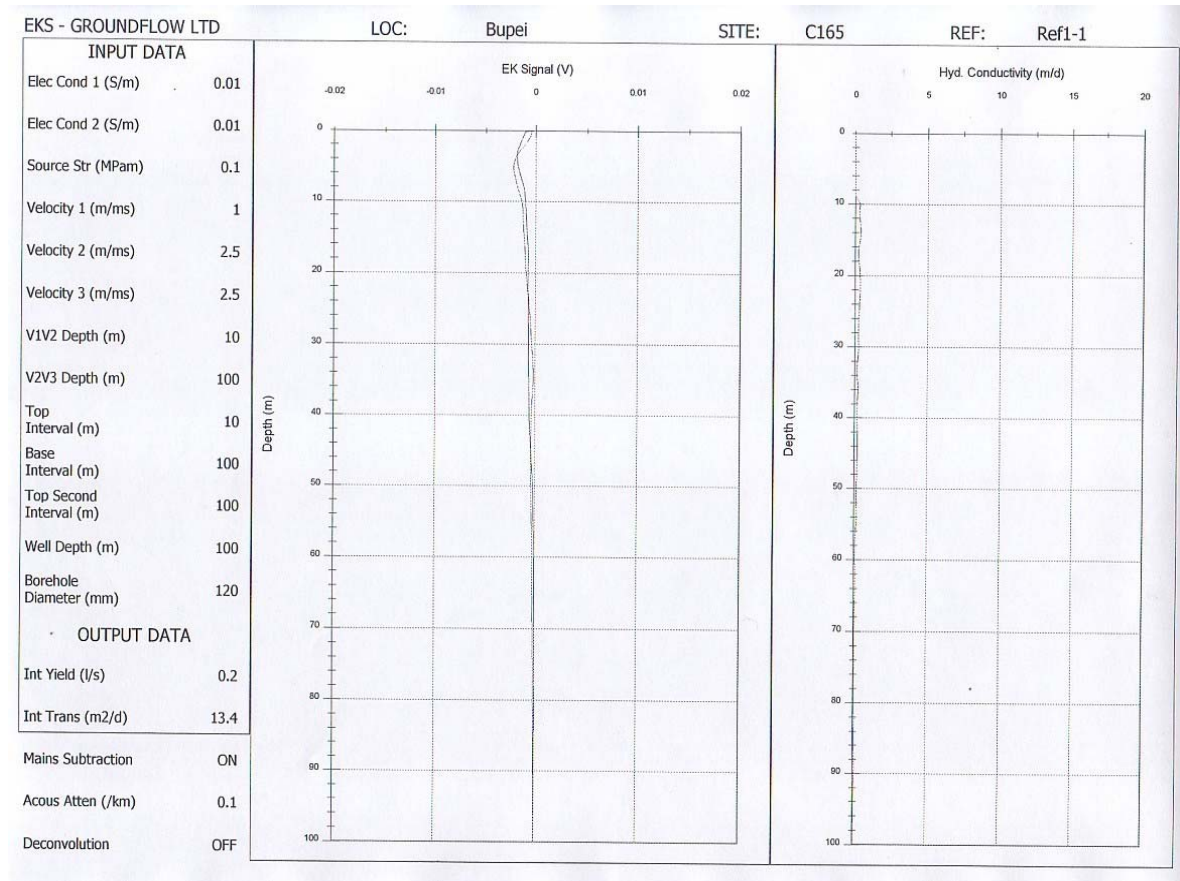
Bamboi C70



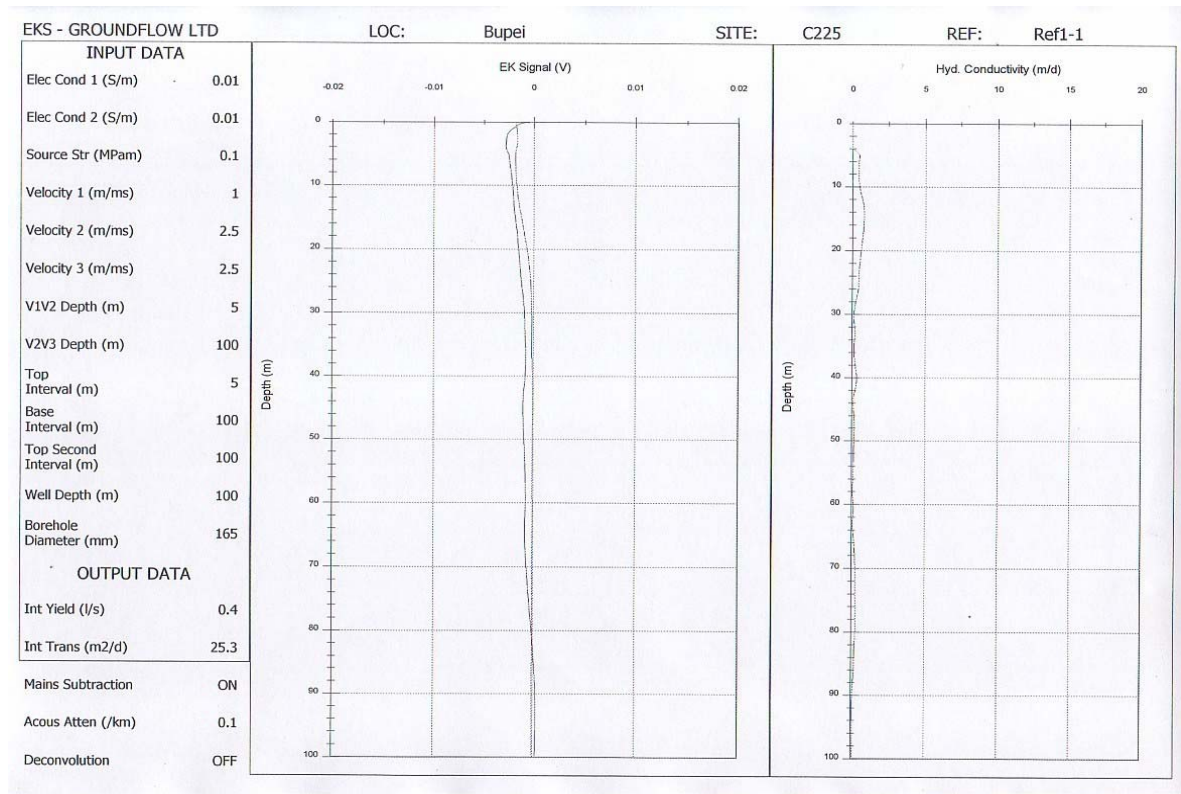
Bupei A130



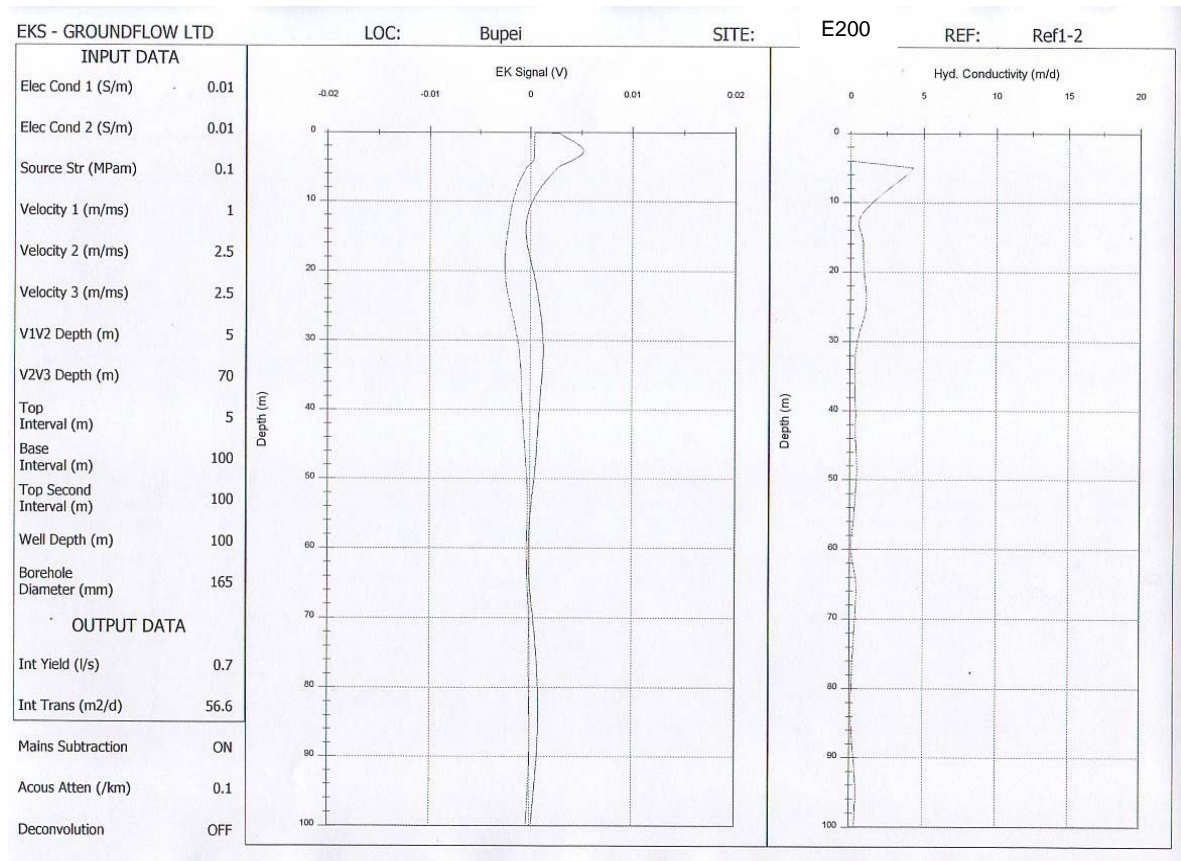
Bupei C165



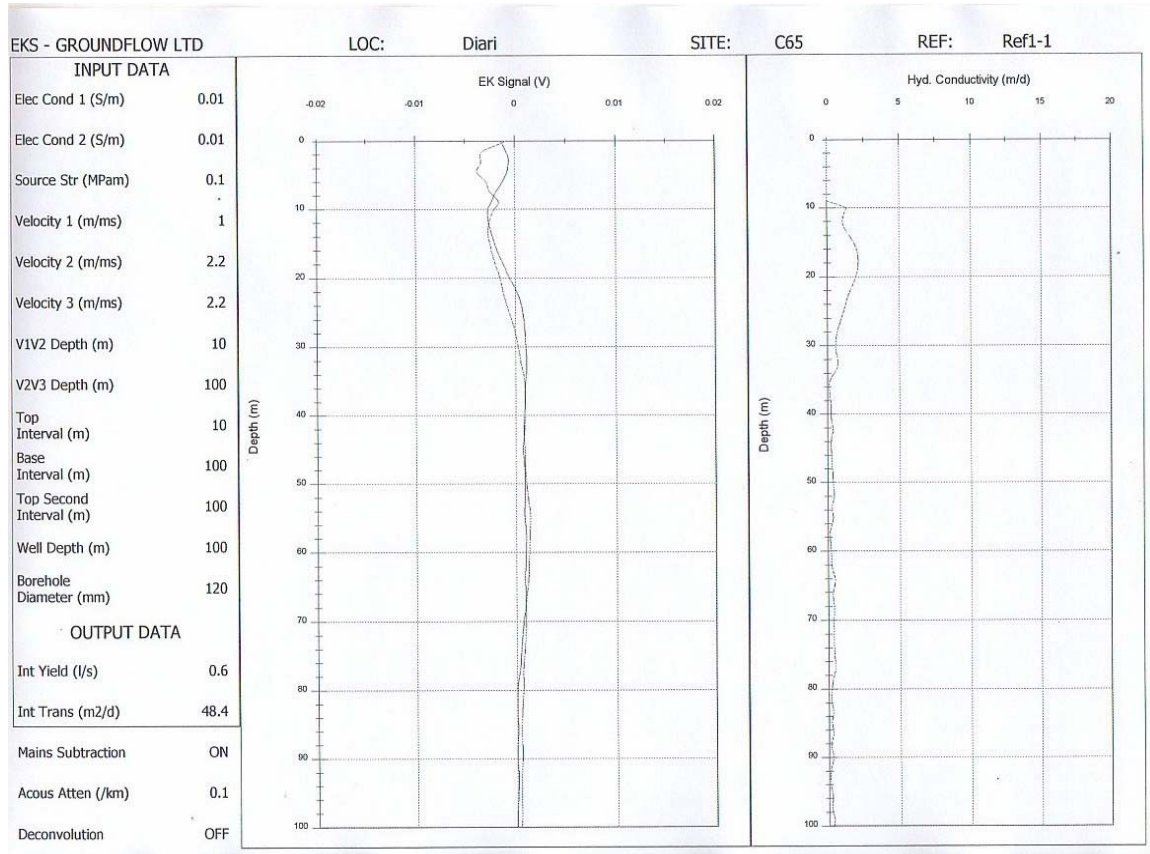
Bupei C225



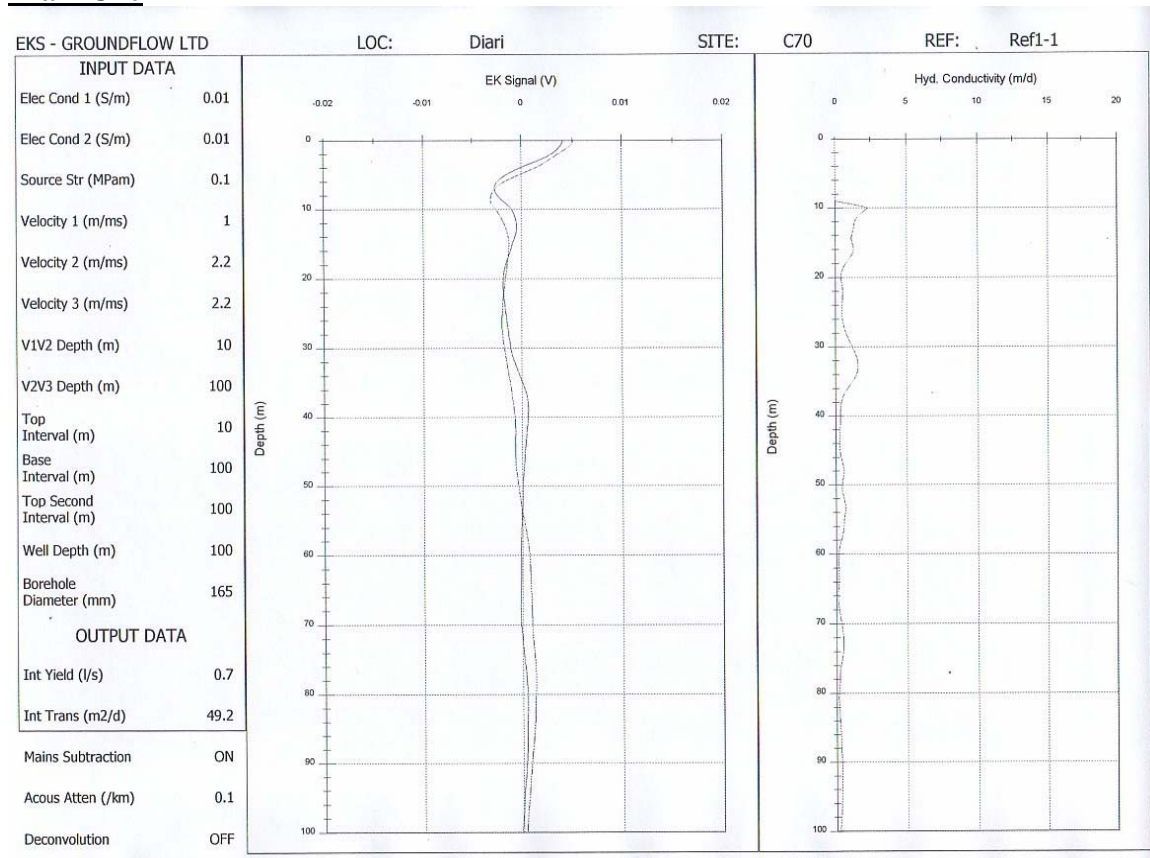
Bupei E 200



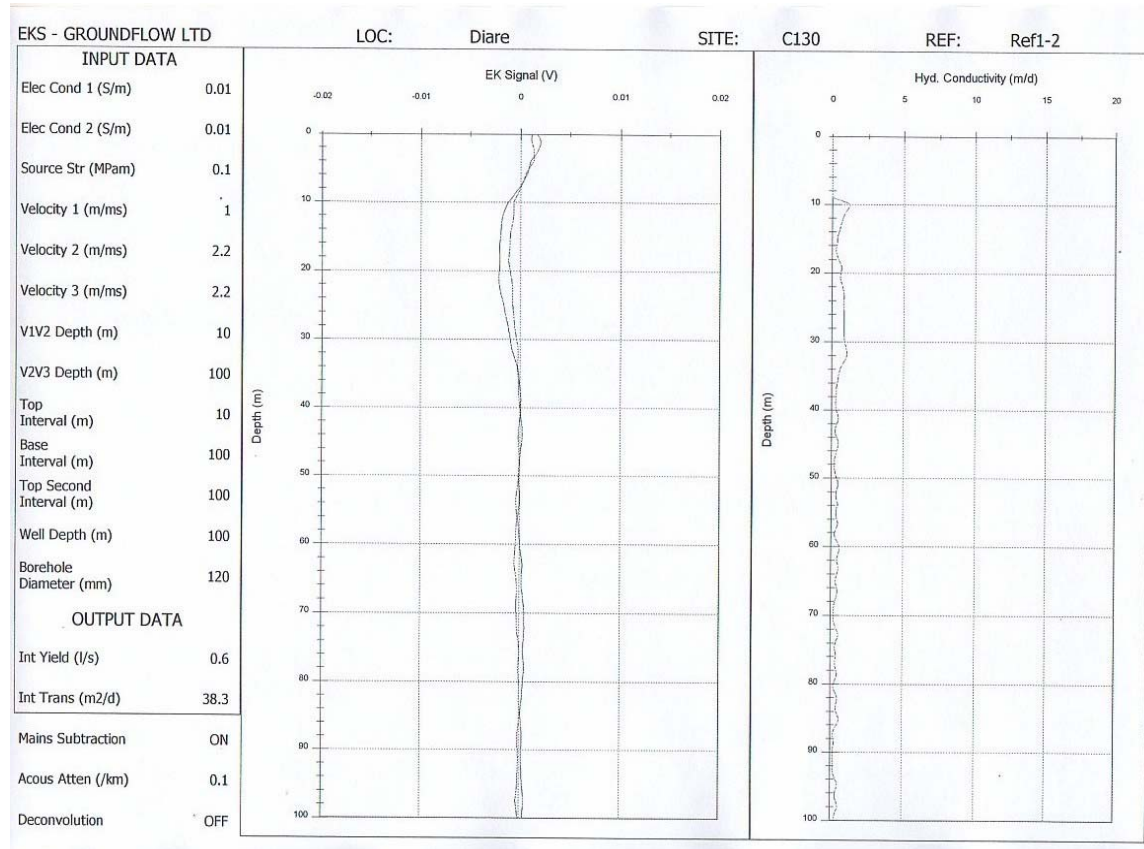
Diare C65



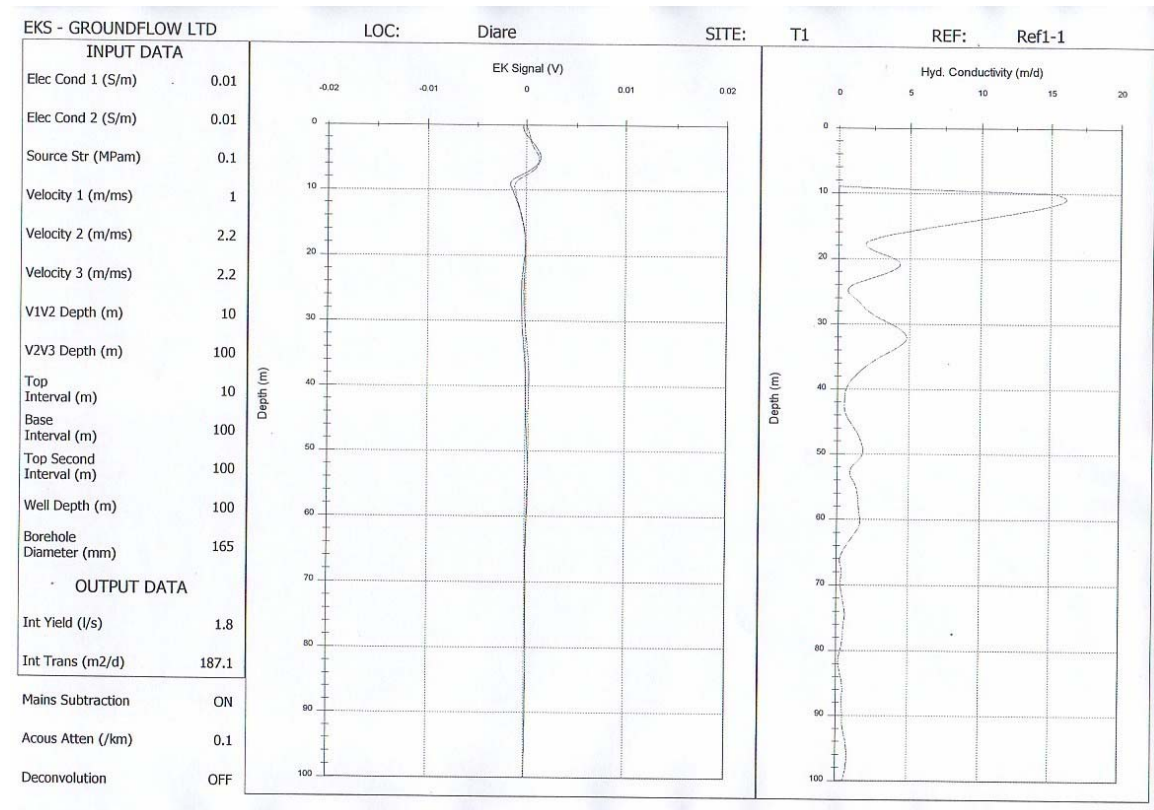
Diari C70



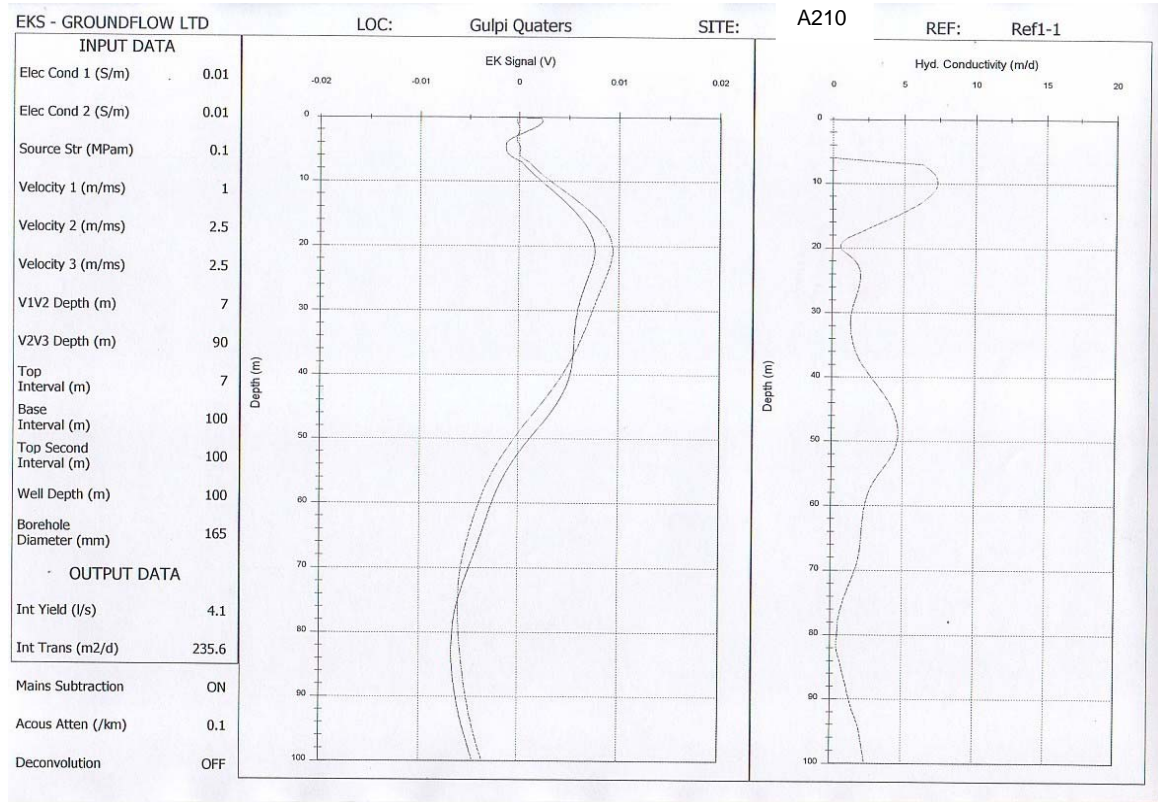
Diari C130



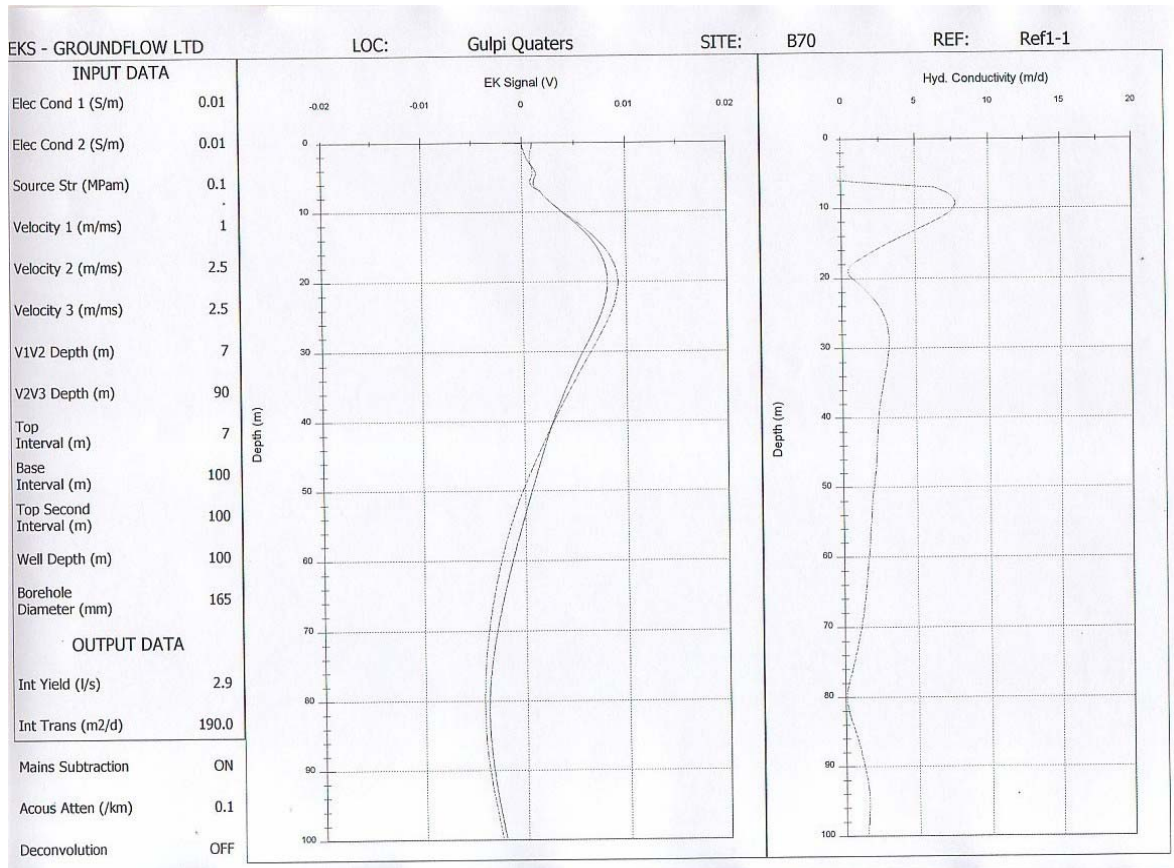
Diari T230



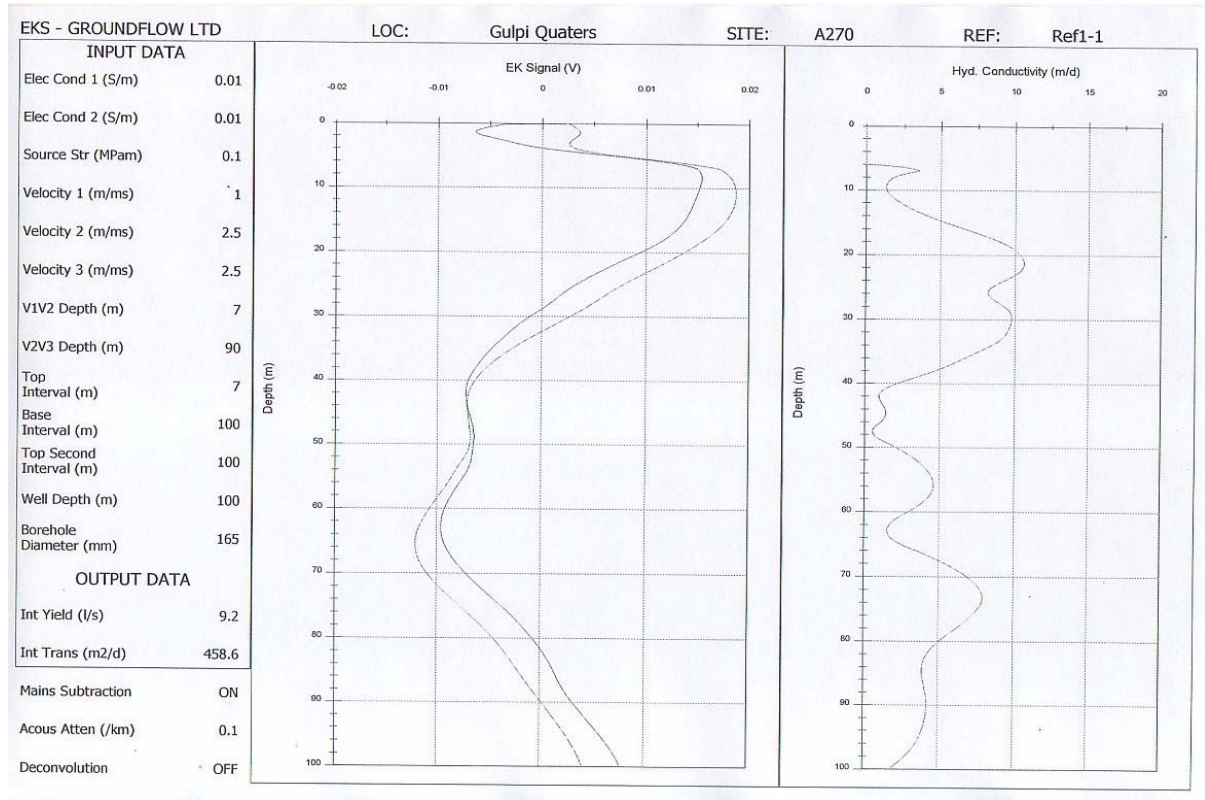
Gulubi Quarters A210



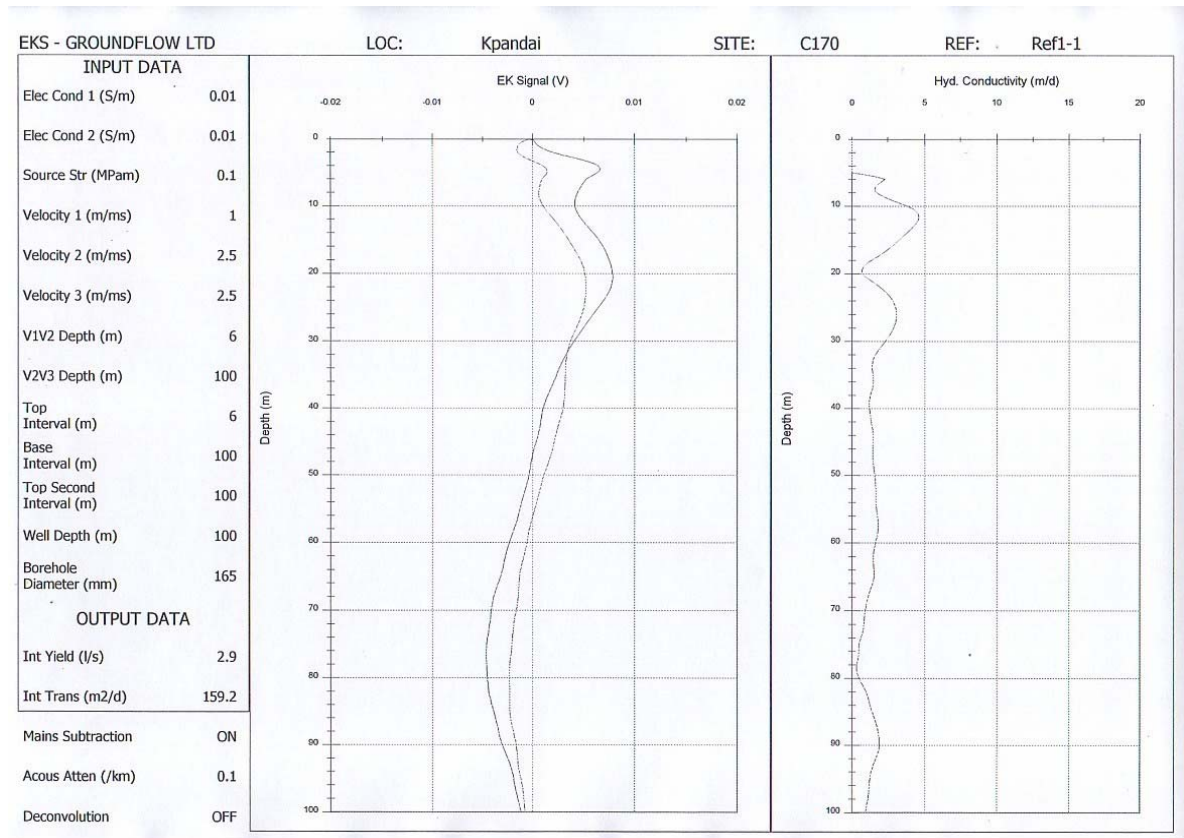
Gulubi Quarters B230



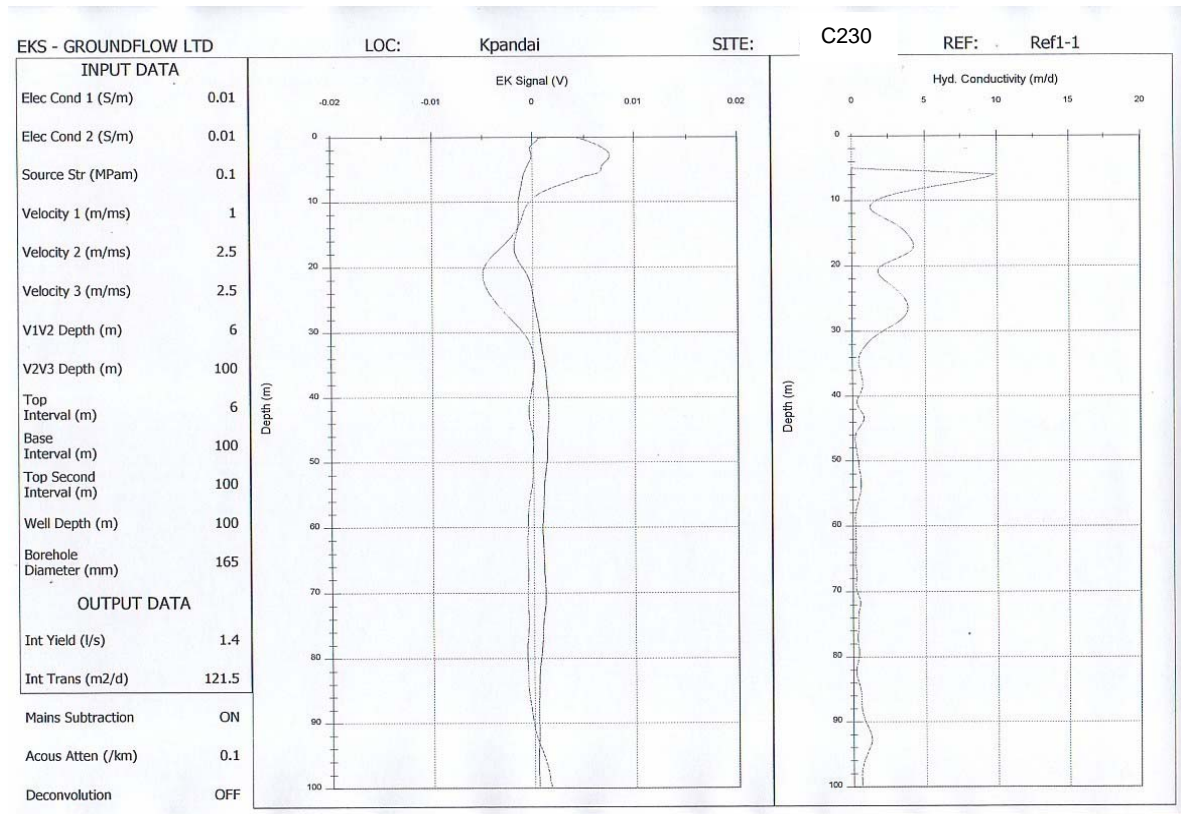
Gulubi quarters A270



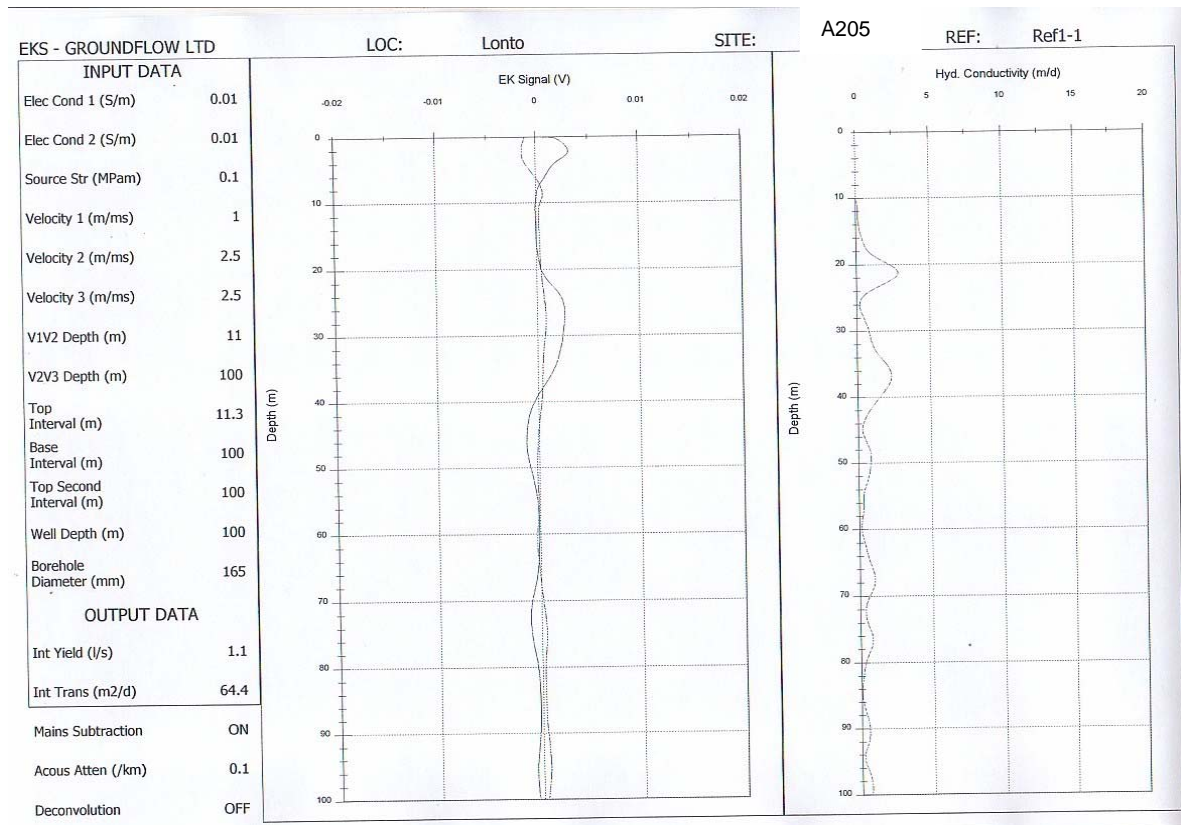
Kpandai C170



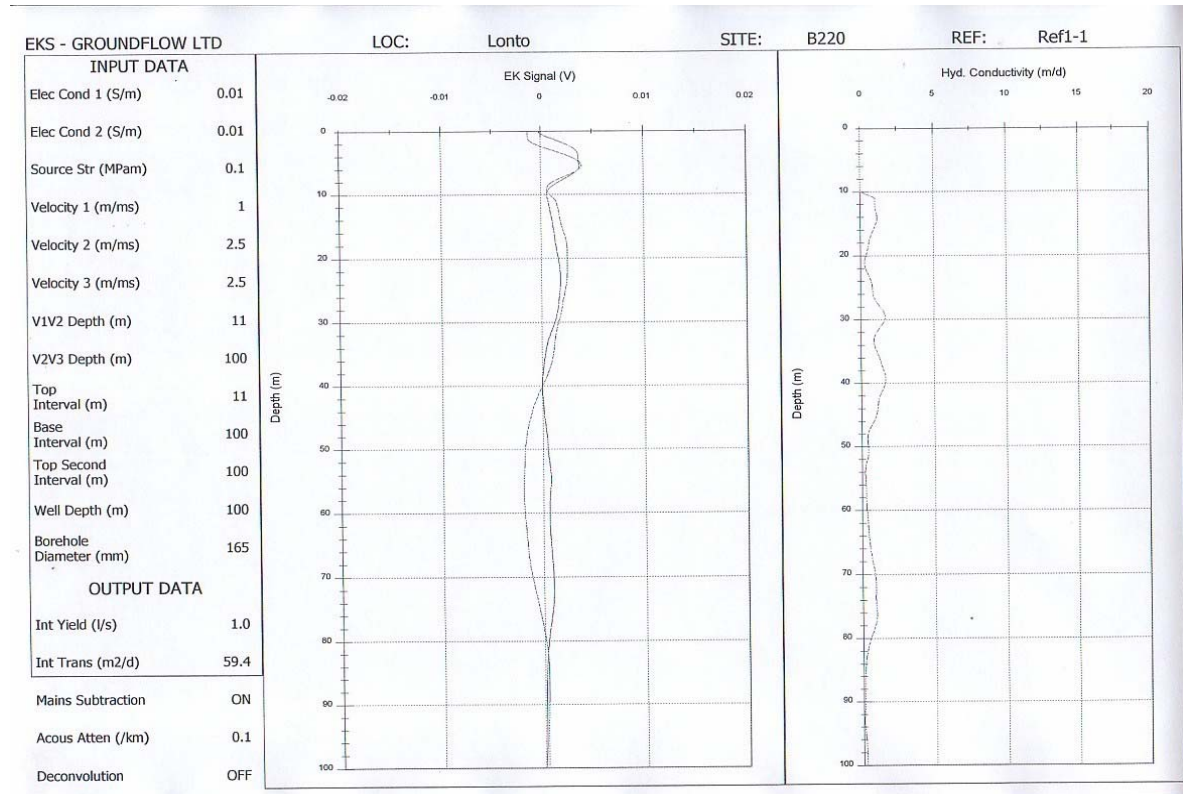
Kpandai C230



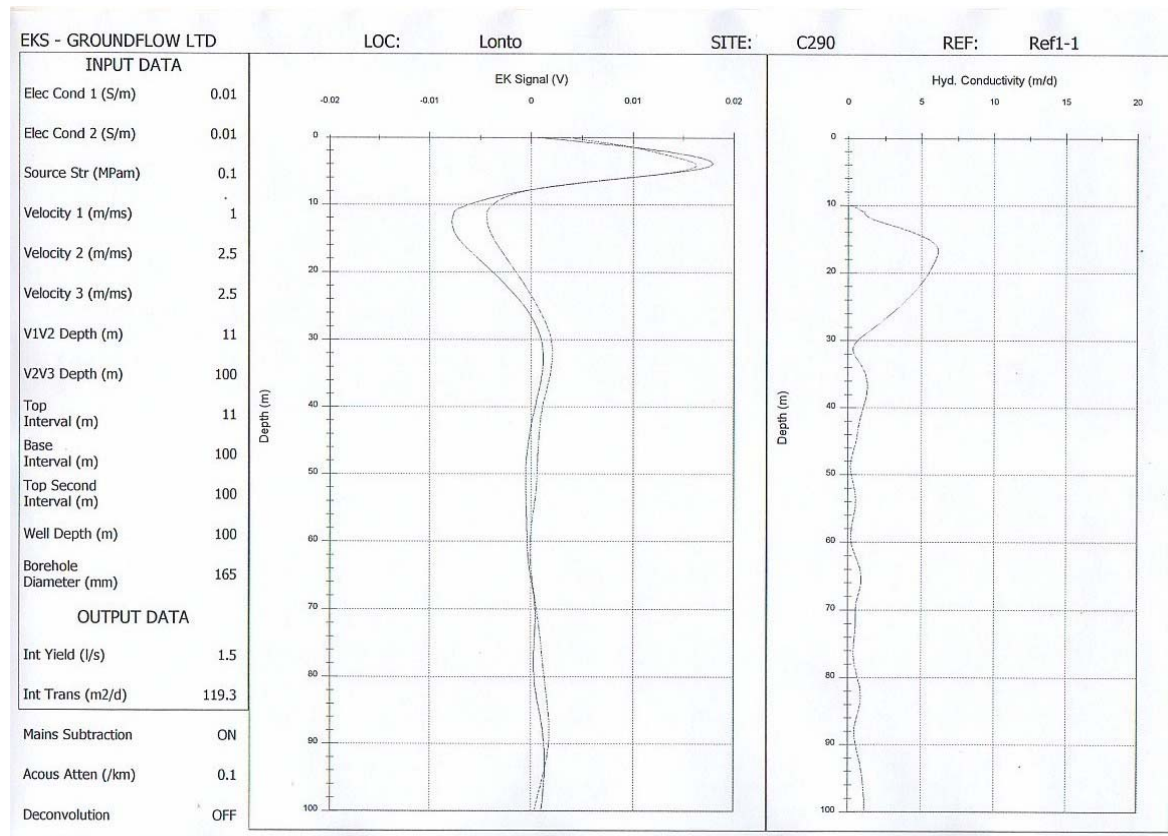
Lonto A205



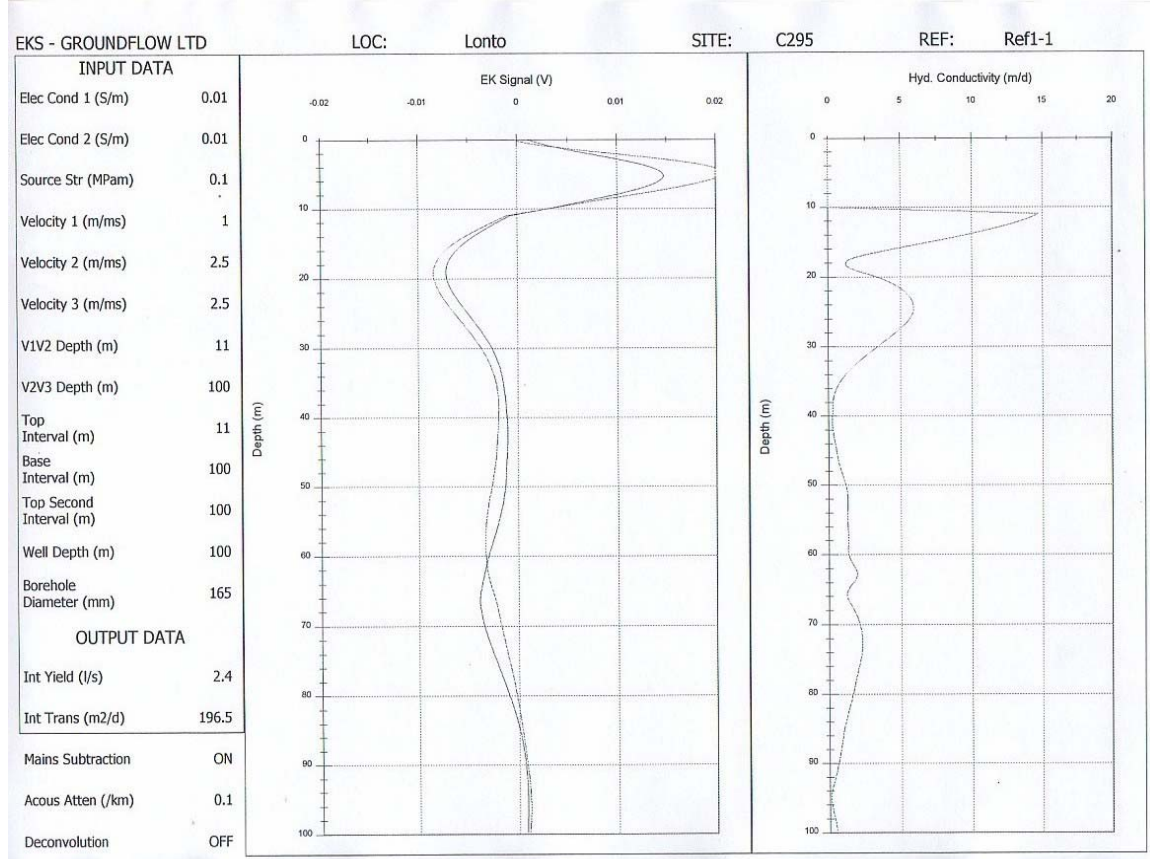
Lonto B220



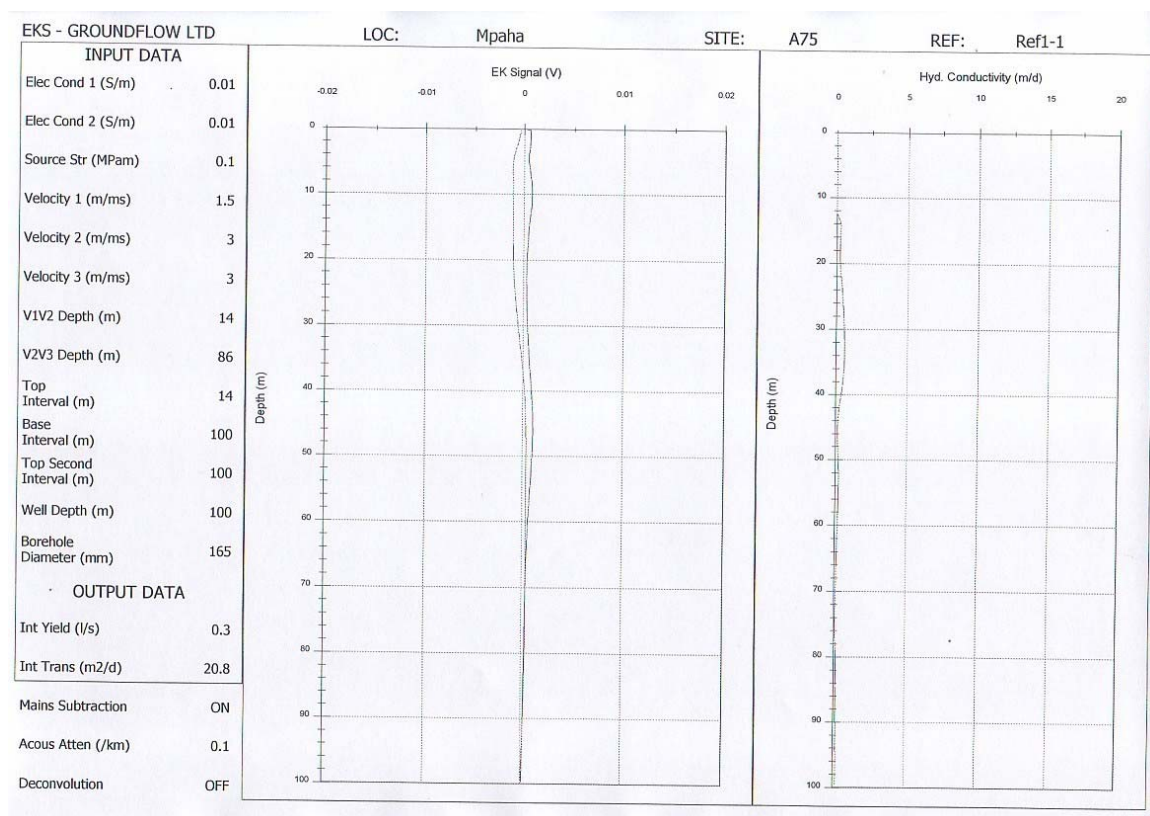
Lonto C290



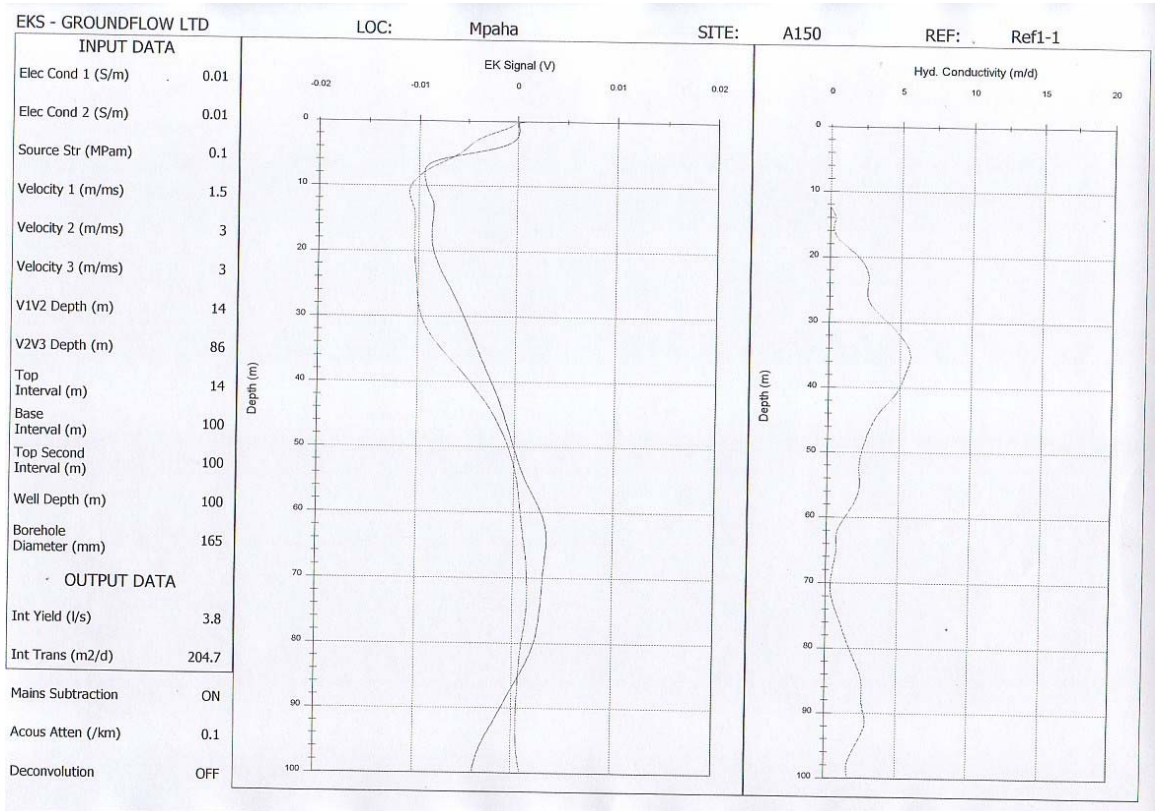
Lonto C295



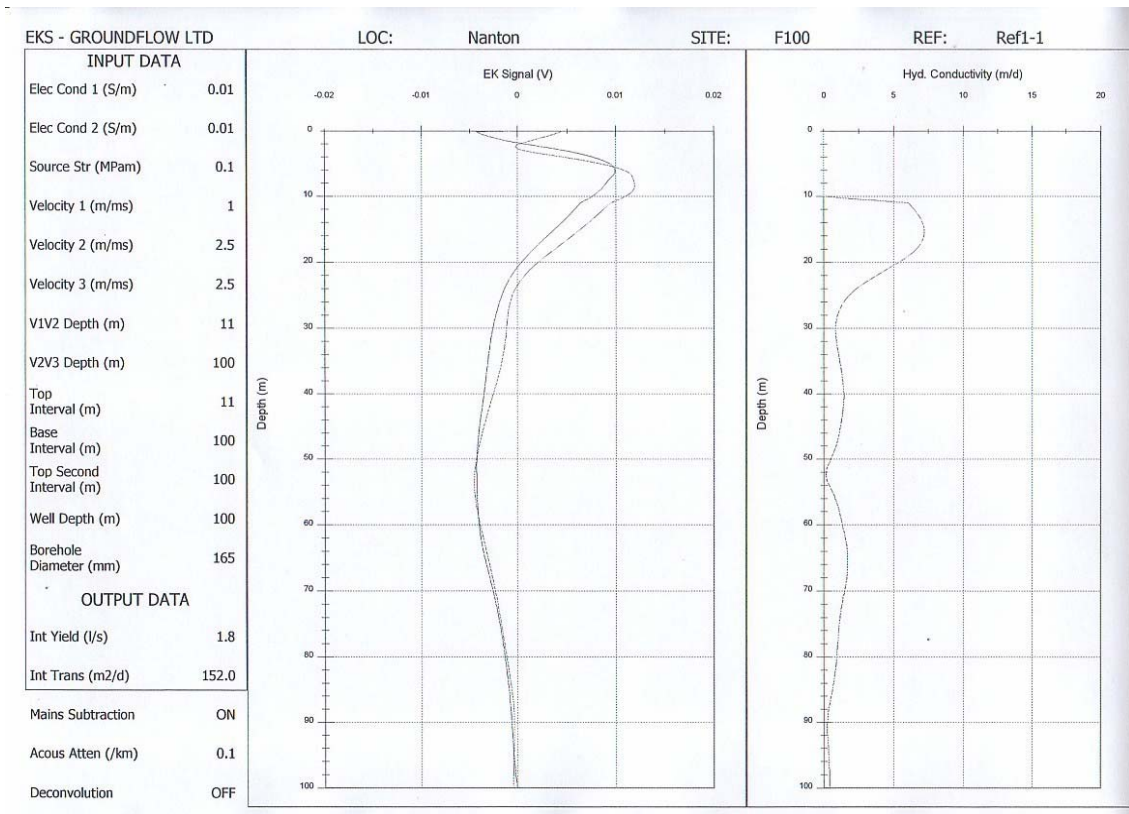
Mpaha A75



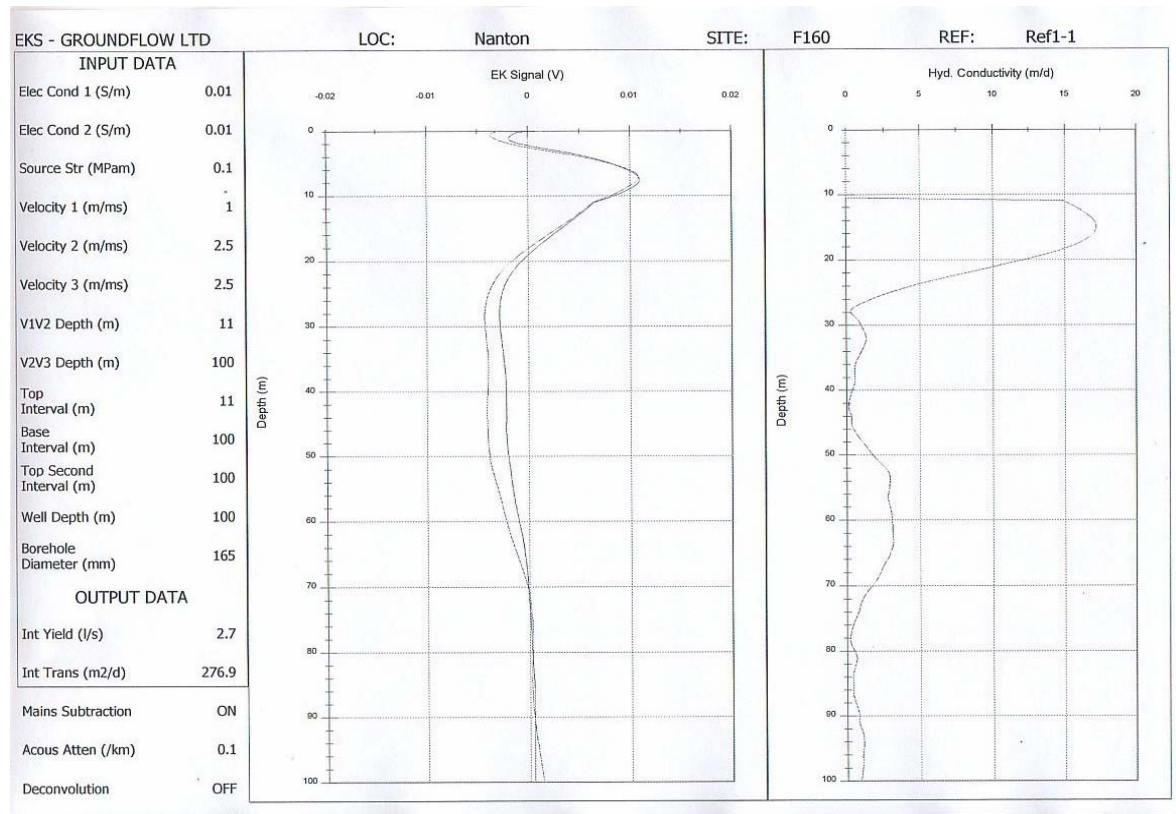
Mpaha A150



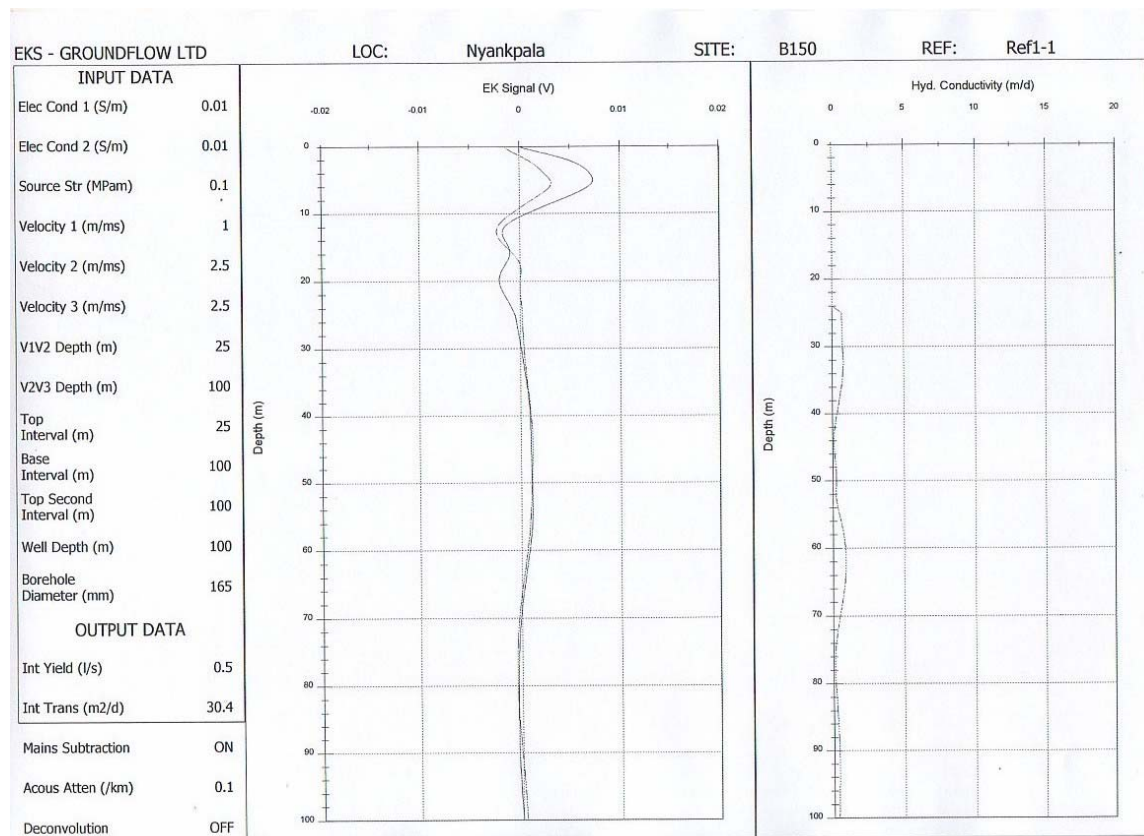
Nanton F100



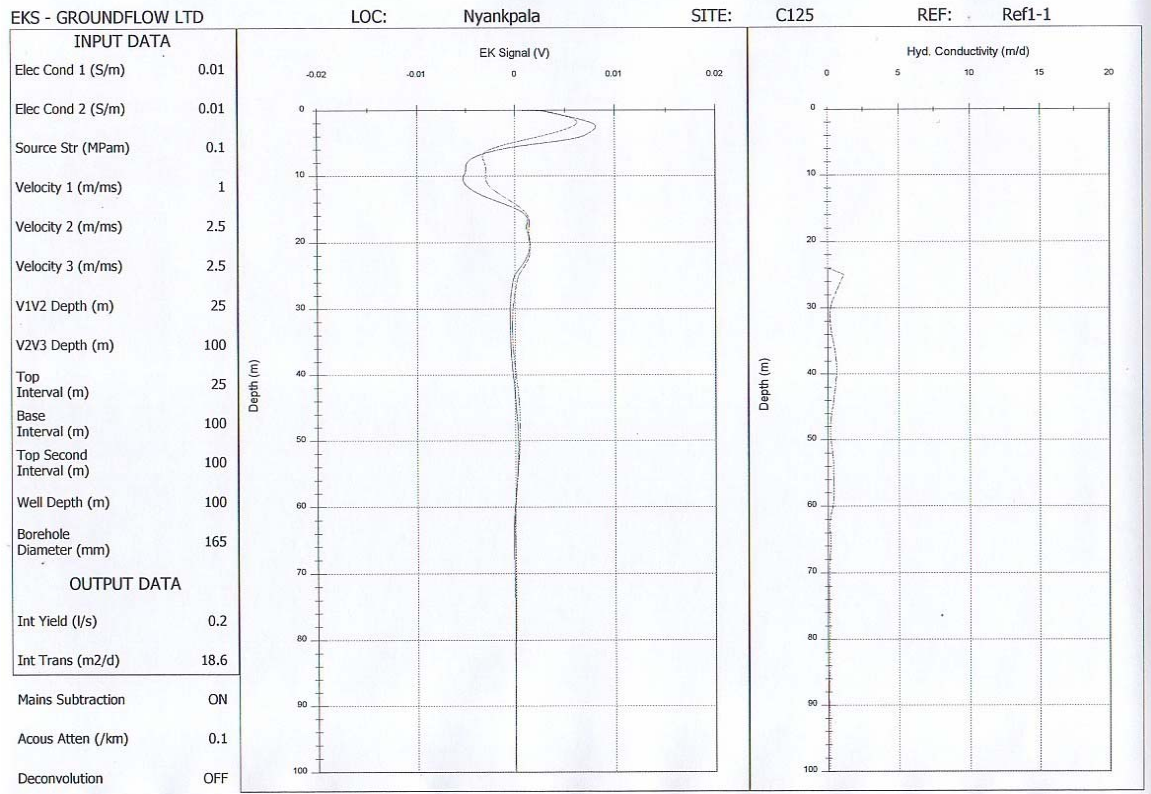
Nanton F160



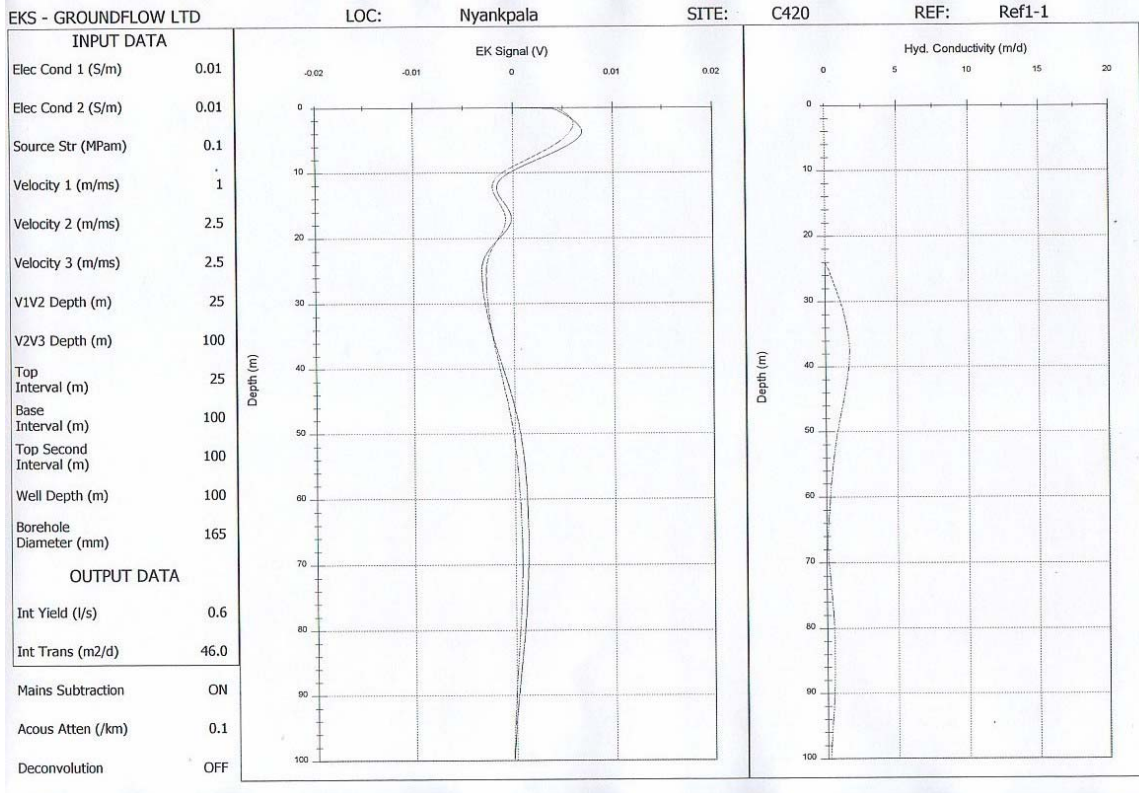
Nyankpala B150



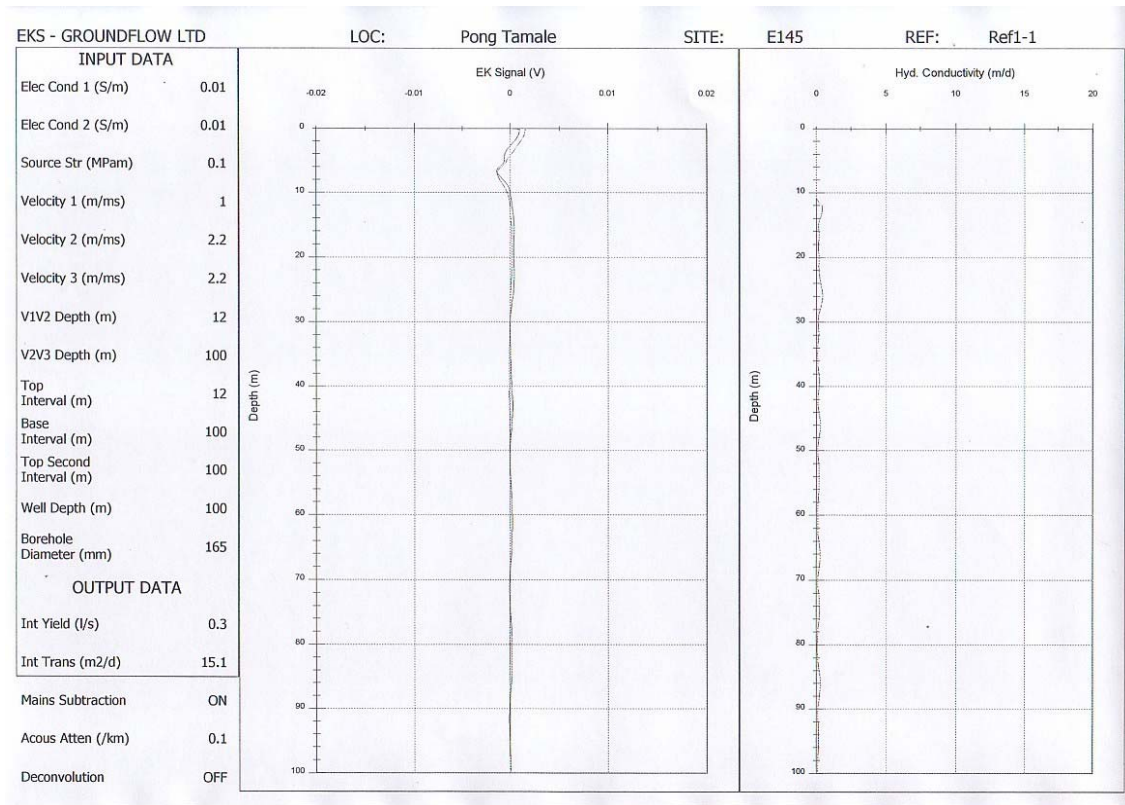
Nyankpala C125



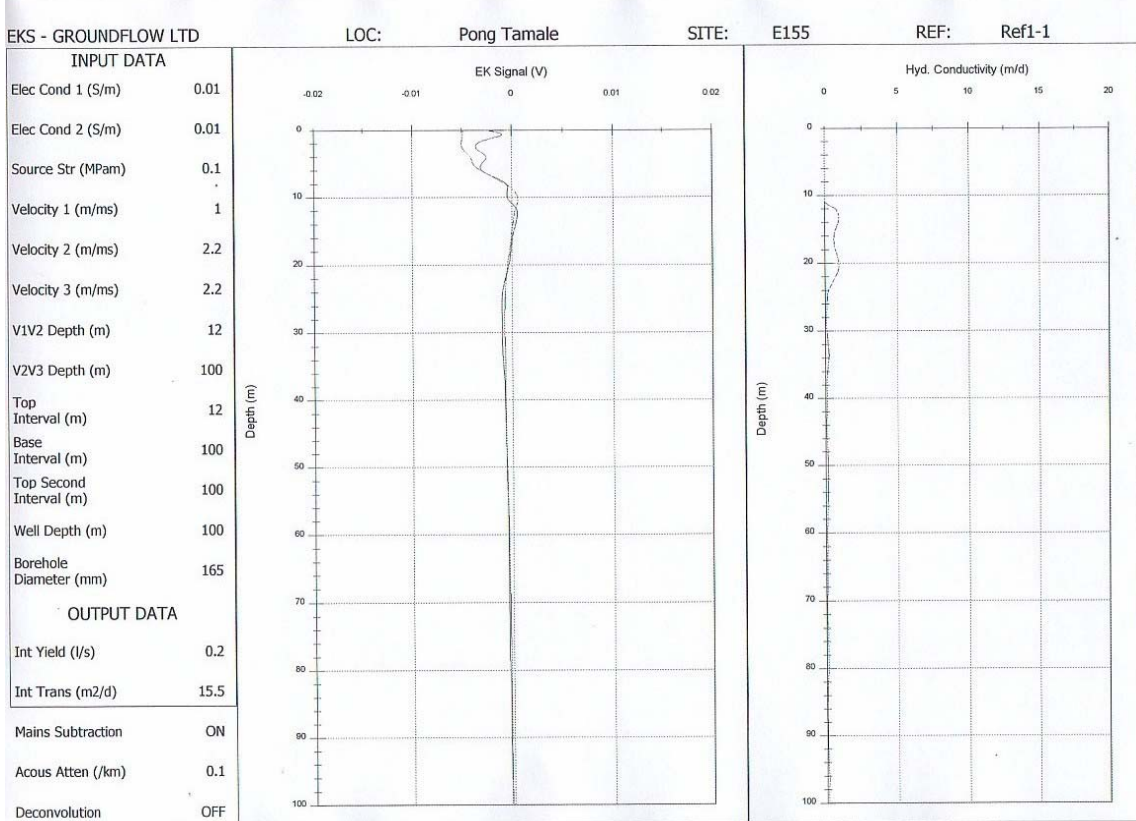
Nyankpala C420



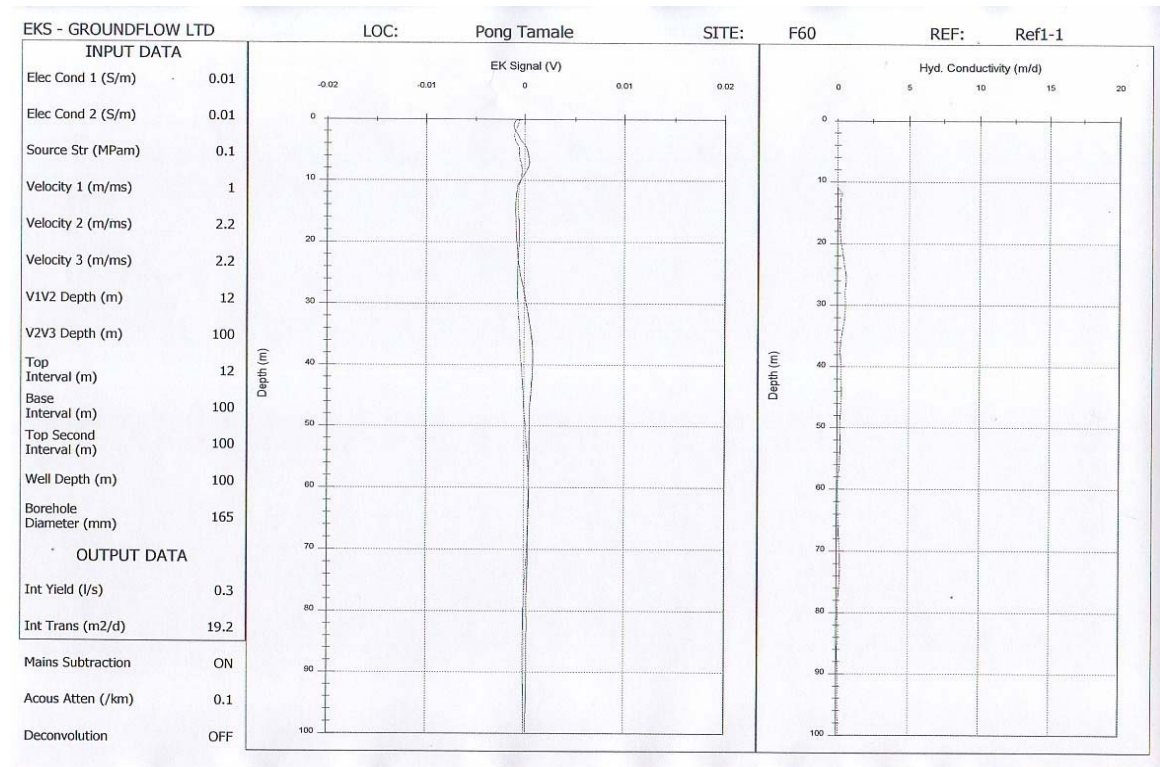
Pong Tamale E145



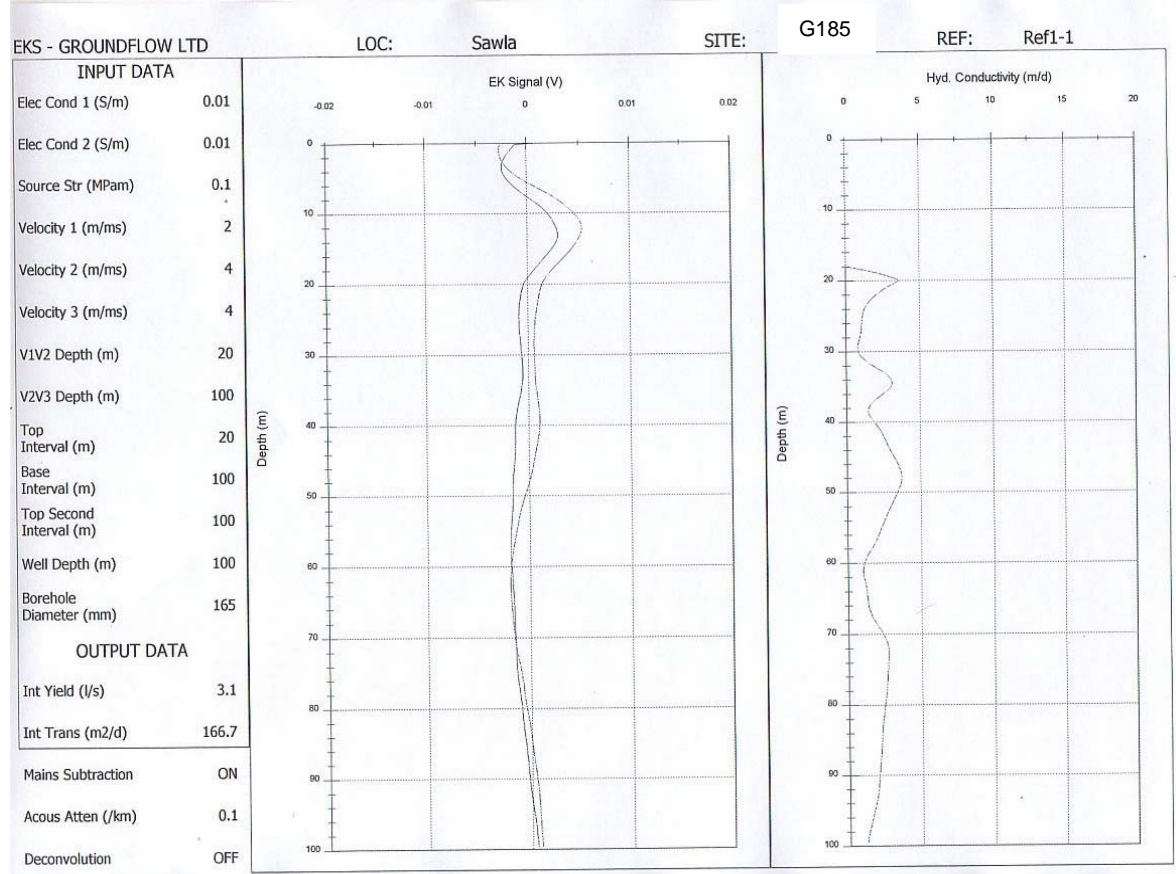
Pong Tamale E155



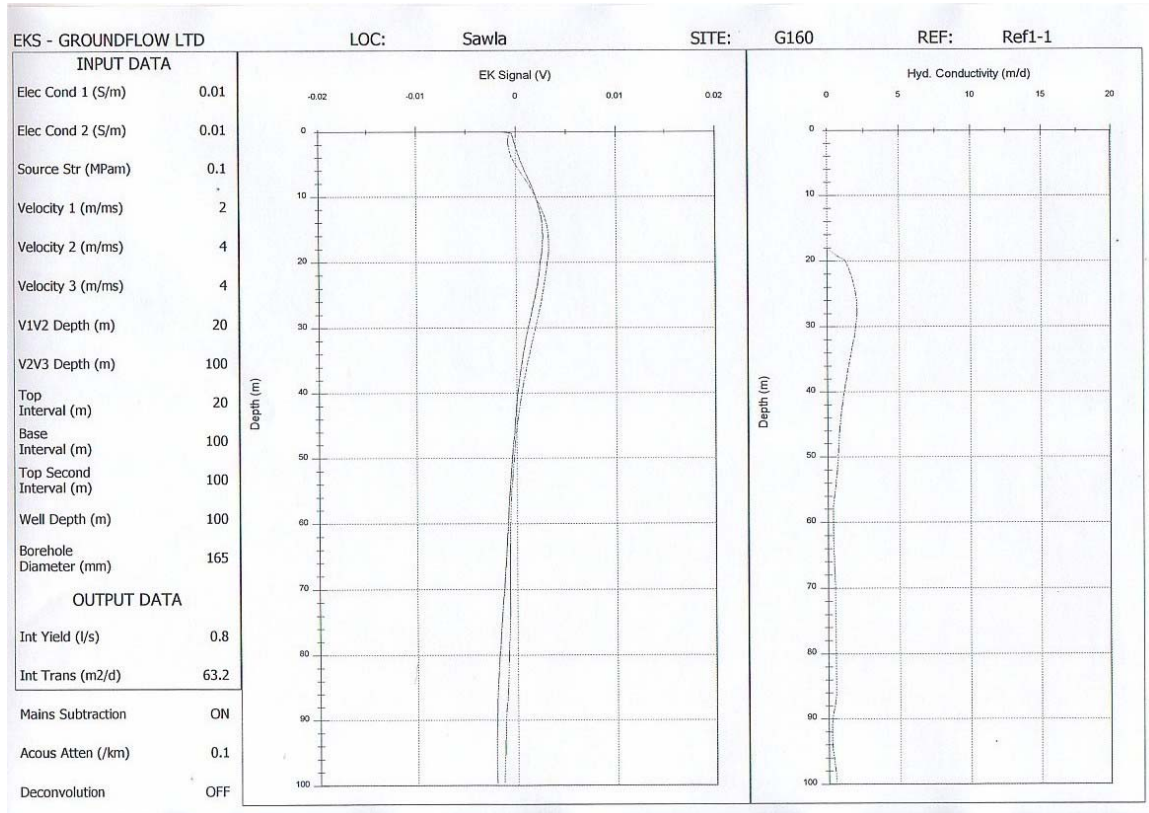
Pong Tamale F60



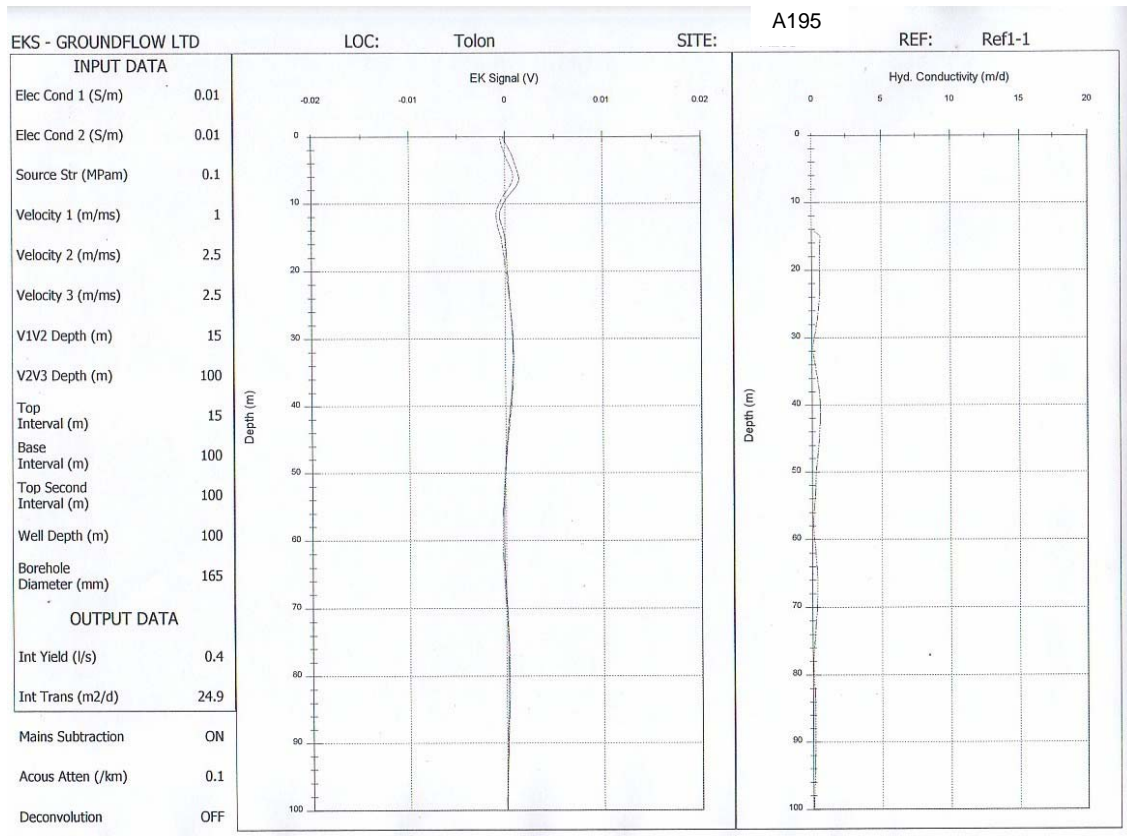
Sawla G185



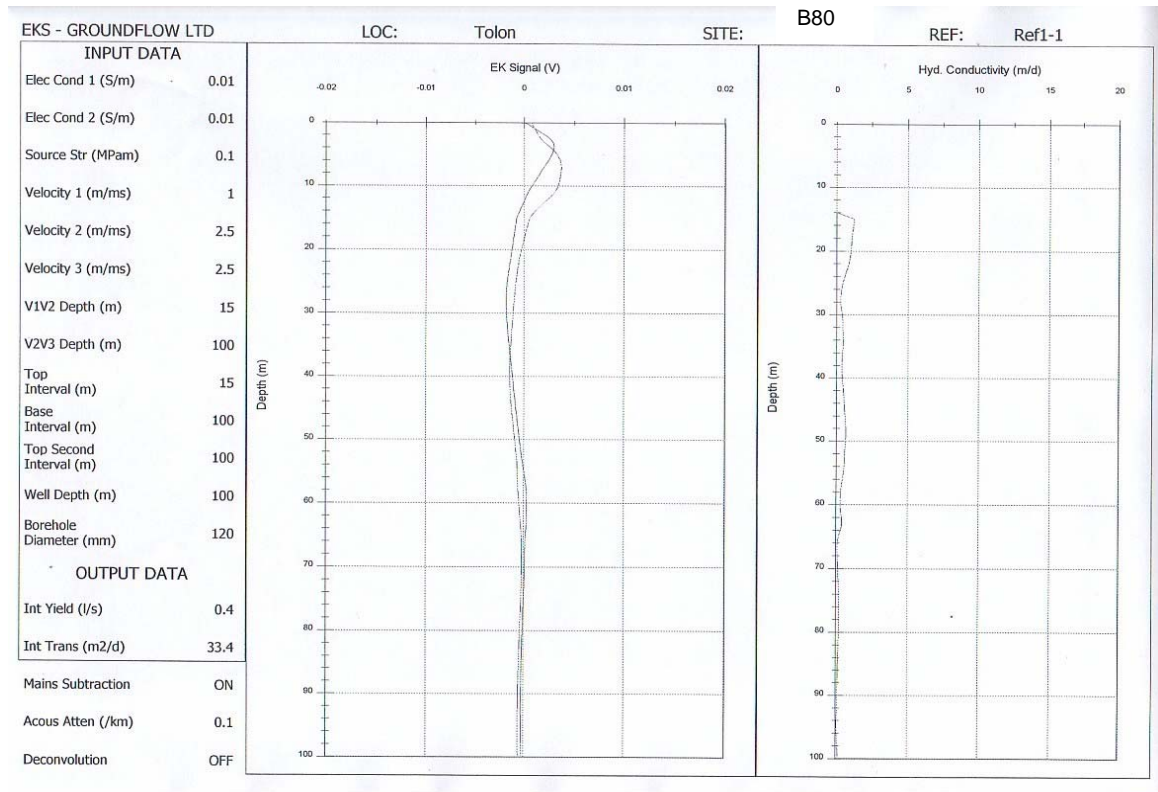
Sawla G160



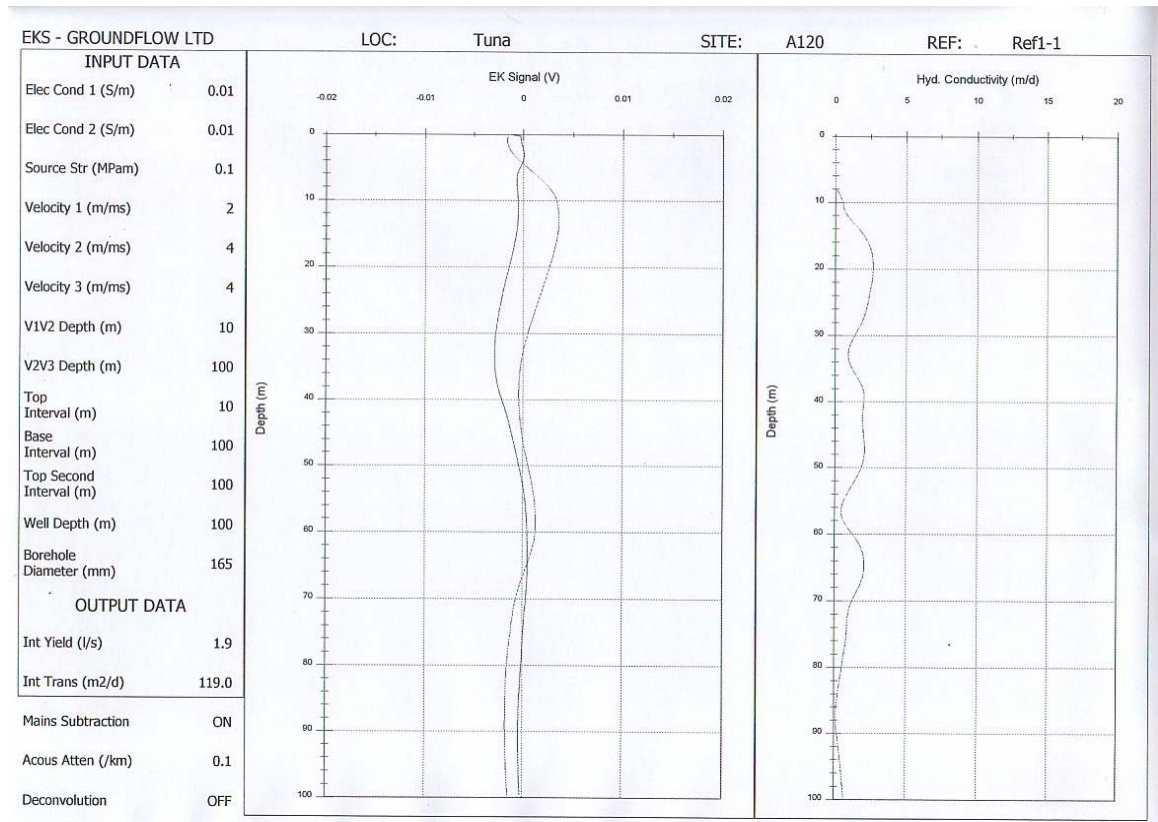
Tolon A195



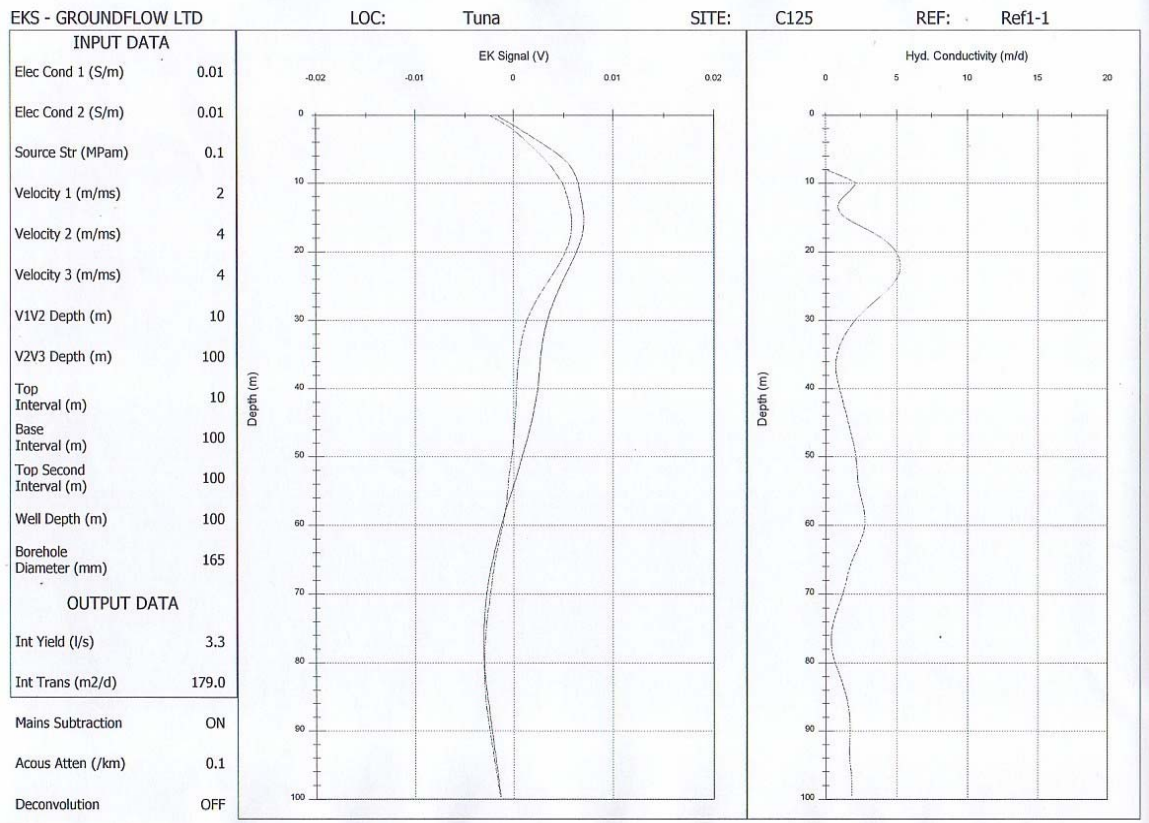
Tolon B80



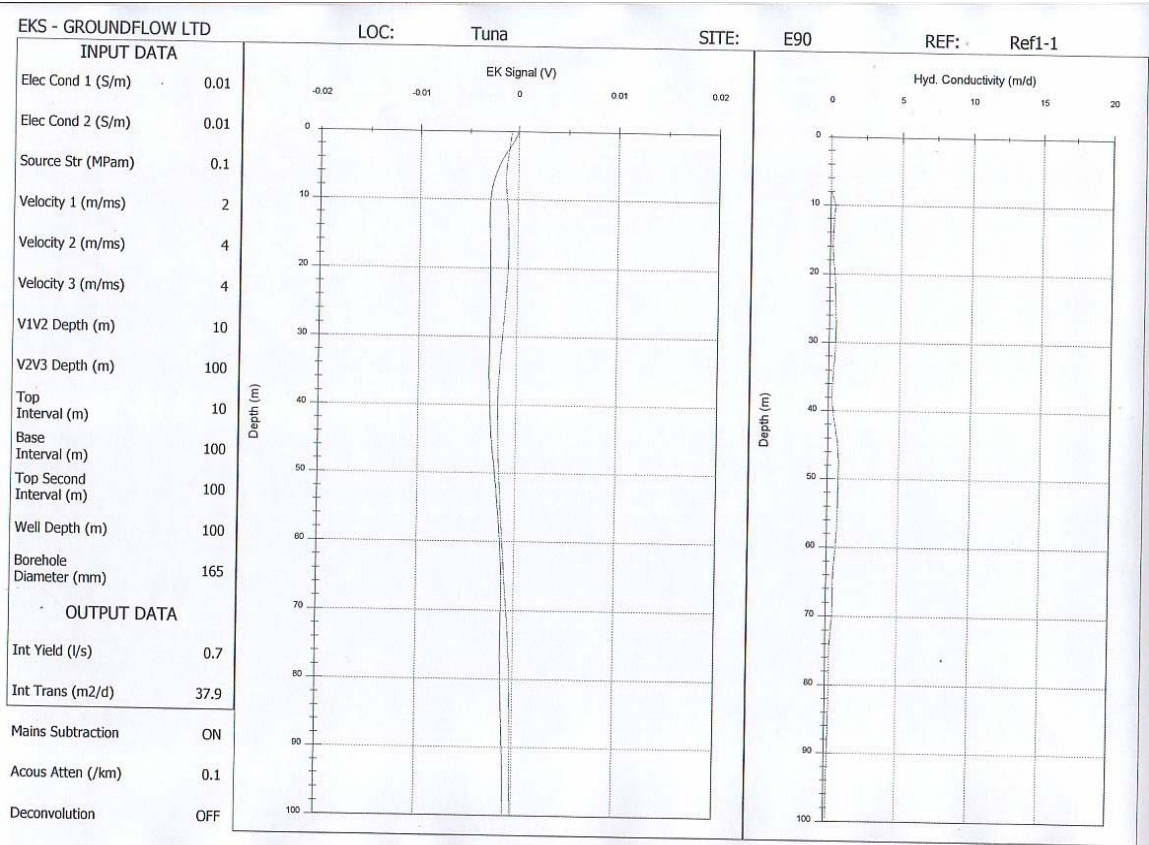
Tuna A120



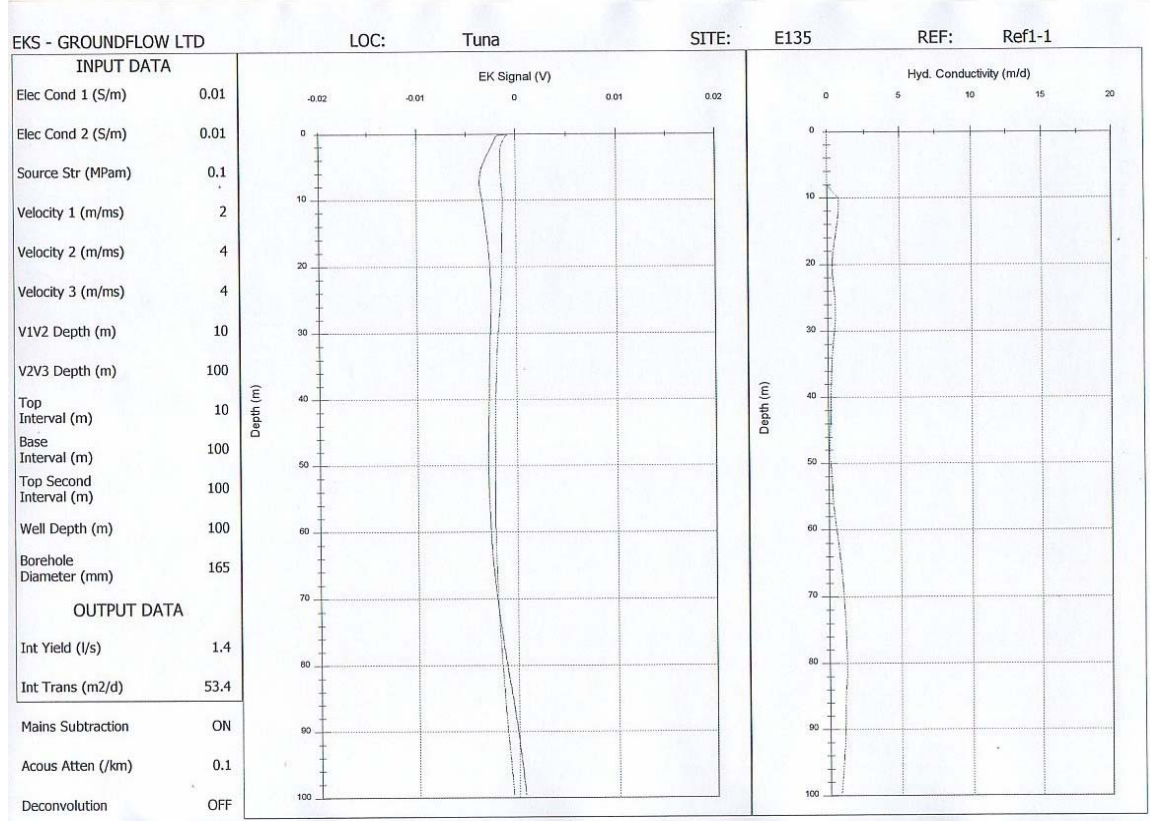
Tuna C125



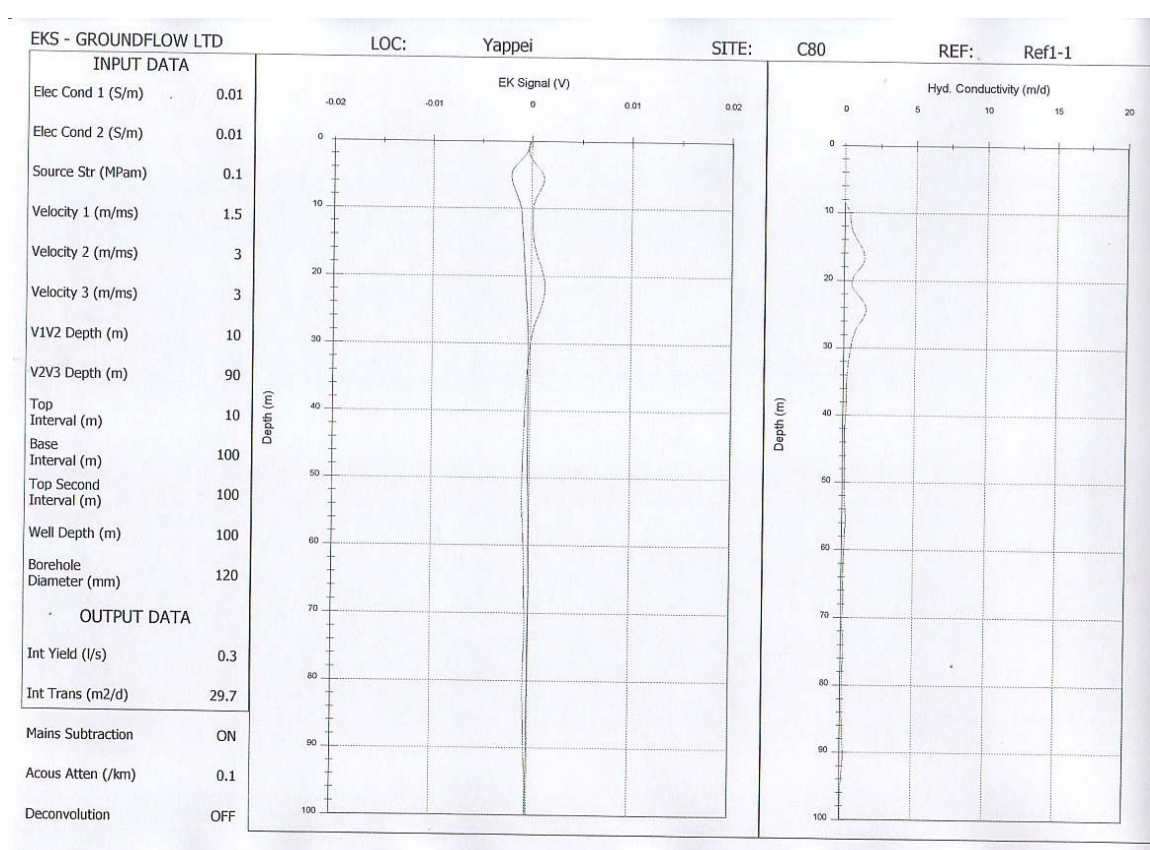
Tuna E90



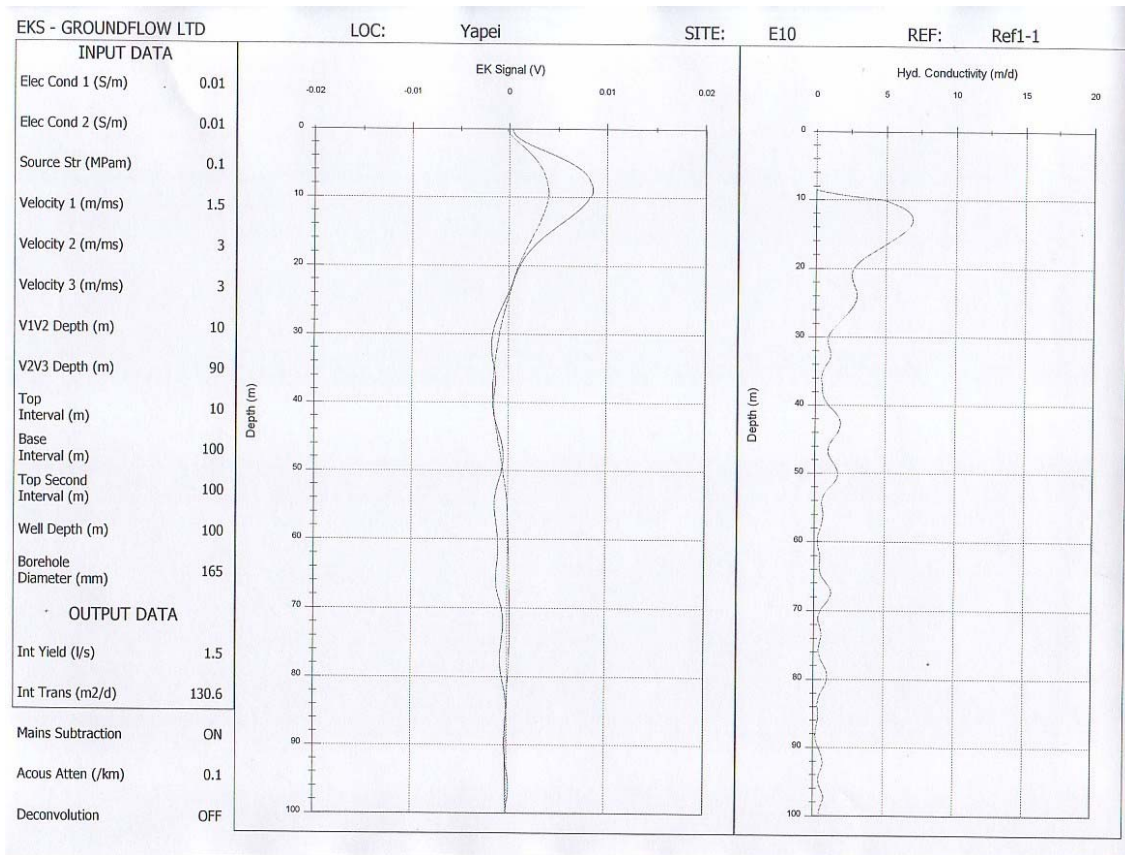
Tuna E135



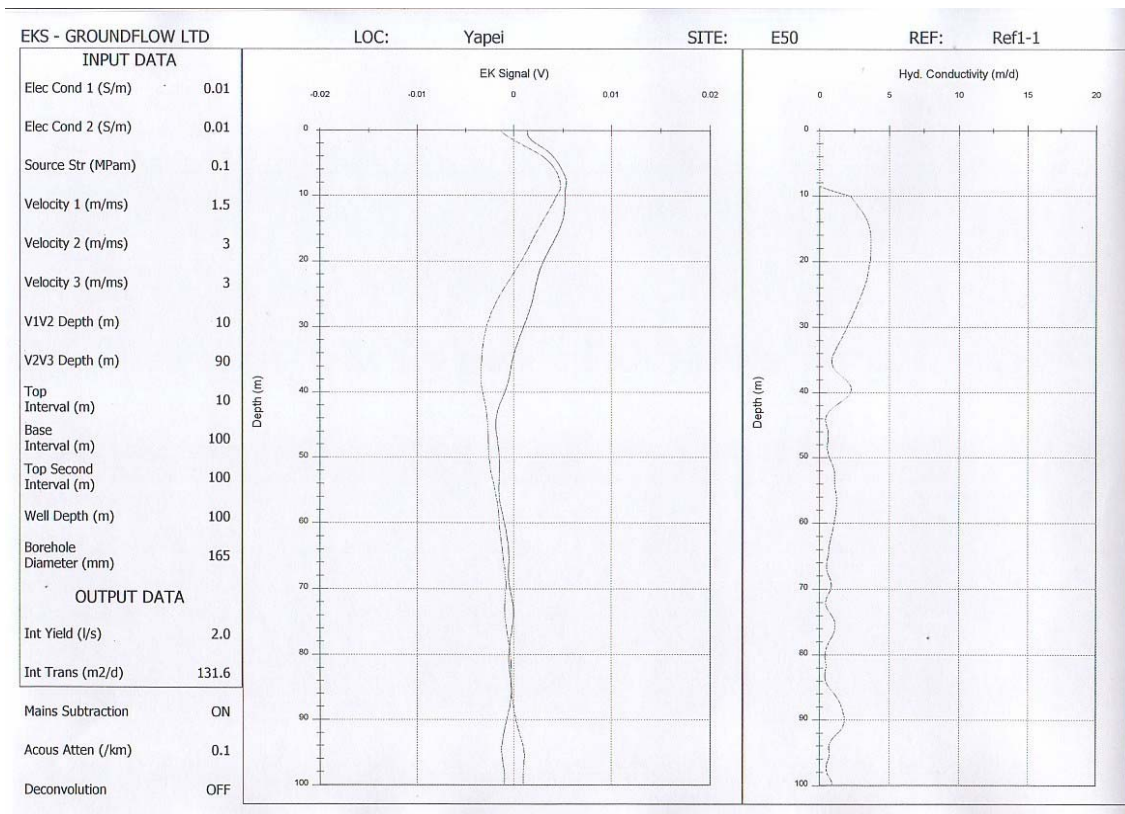
Yapei C180



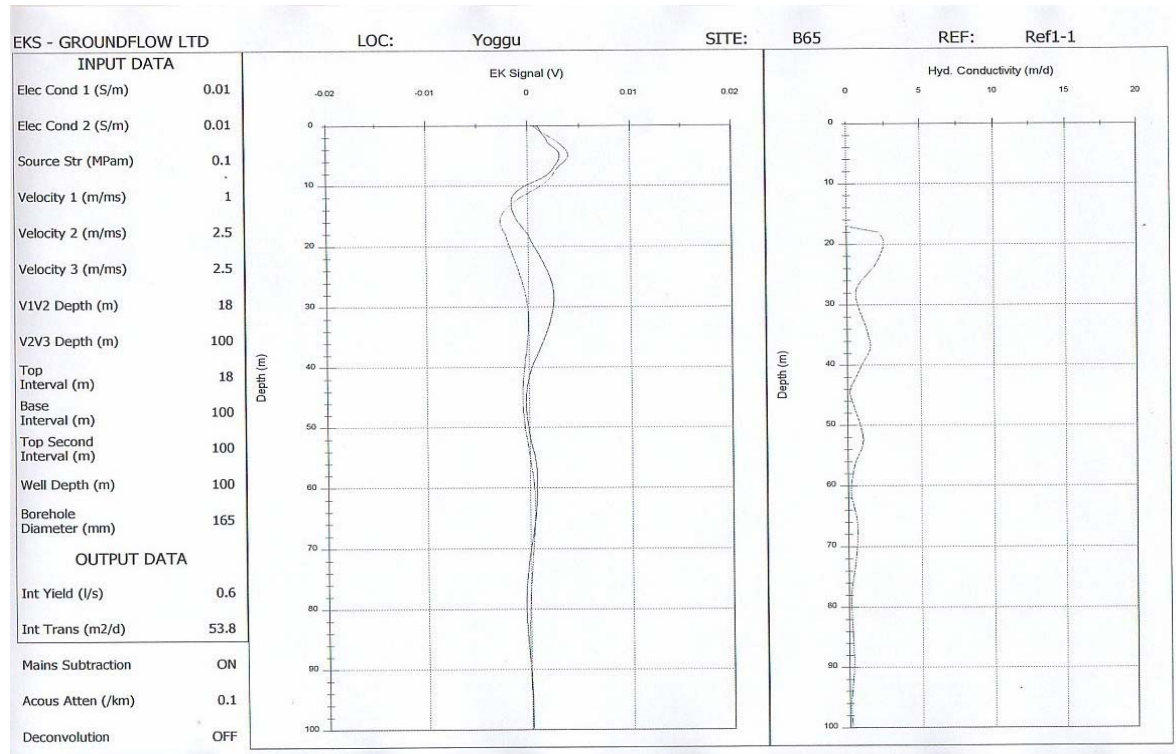
Yapei E10



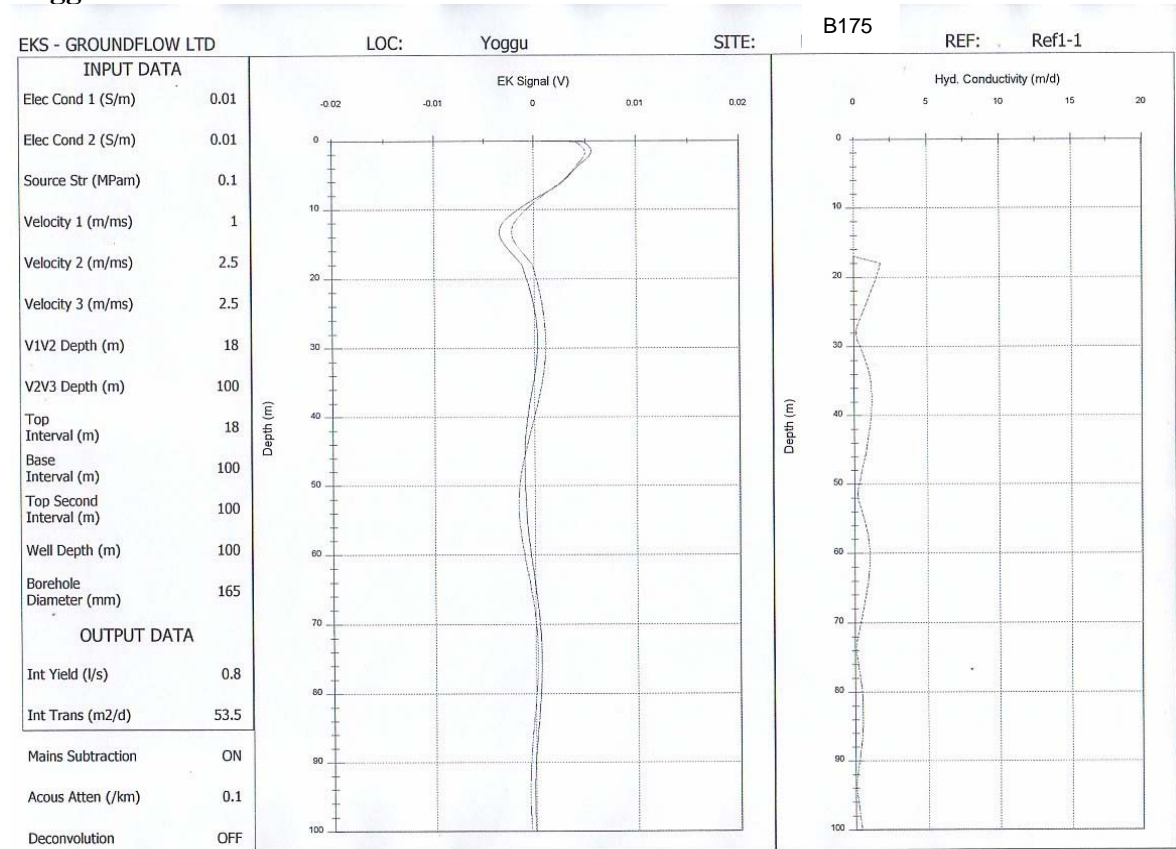
Yapei E50



Yoggu B65



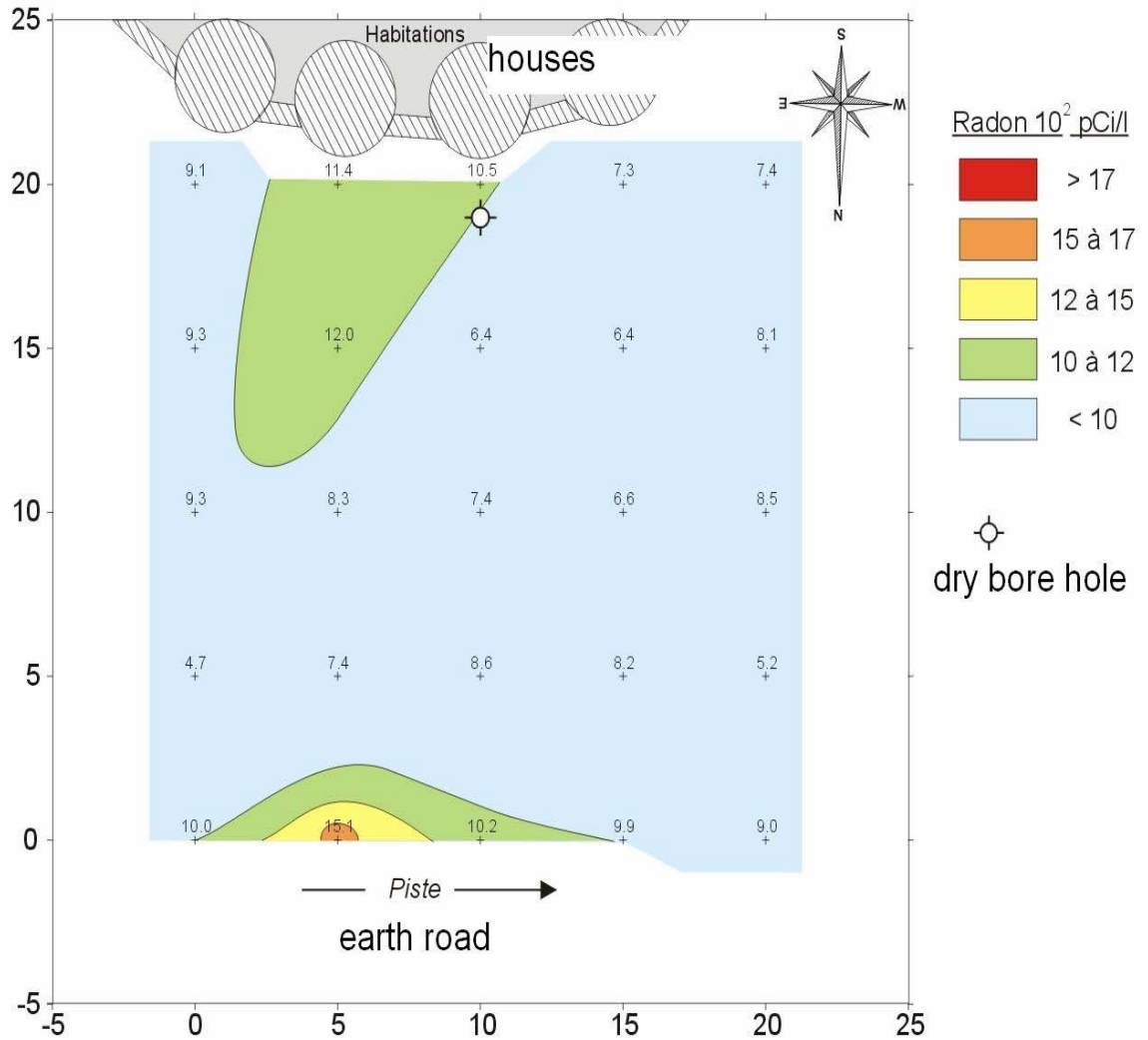
Yoggu B175

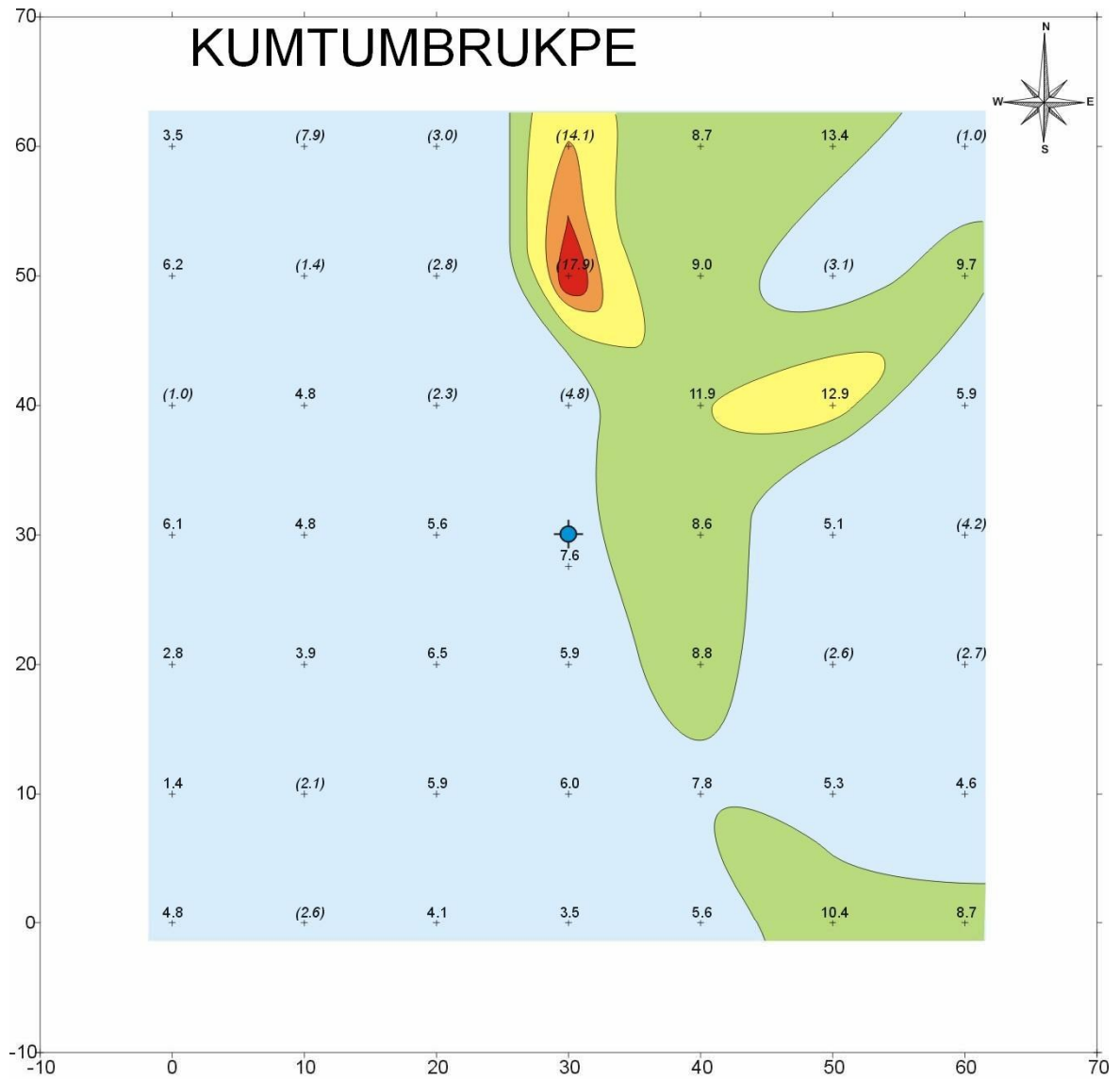


ANNEX C

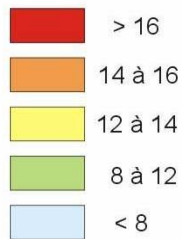
RADON PILOT STUDY RESULTS

GBANGA





Radon 10² pCi/l



(3.7) poor sampling (laterite)

wet borehole

ZOOLANYILI

