EVALUATION OF AQUIFER HYDRAULIC PROPERTIES FROM RESISTIVITY AND PUMPING TEST DATA IN PARTS OF GWAGWALADA, NORTHCENTRAL NIGERIA

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MTech/SPS/2021/12375

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FEDERAL UNIVERSITY OF TECHNOLOGY MINNA

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL
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ABSTRACT

Population upsurge in Gwagwalada increased water demand in the area, thereby stressing water resources in the area. Aquifer properties in parts of Gwagwalada in North-Central Nigeria were therefore investigated using surface geological mapping data combined with resistivity and pumping test data. The geological mapping revealed that the study area is underlain by granite-gneiss. The joint direction measurements showed two conspicuous joint directions namely the major NE-SW direction followed by the SE-NW direction. Static water level measurements of hand dug wells were used to determine the groundwater flow direction for the area which coincides with the NE-SW joint direction. Ten VES was carried out on the area. The geoelectric sections revealed 4 to 5 layers and the longitudinal conductance varied from 0.11 Ohm^{-1} to 0.37 Ohm^{-1}. Constant rate pumping test was adopted for the research and 10 boreholes were pumped test. Static water level, discharge rate and drawdown range respectively from 1.2 m to 19.4 m, 82.08 m^3/d to 319.68 m^3/d and 6.57 m to 84.6 m. The weathered/fractured basement range from 7.5 m to 56.7 m. The transmissivity values in the area ranged from 0.35 m^2/day to 3.63 m^2/day while the hydraulic conductivity range from 0.045 m/day to 0.18 m/day. The investigation results revealed areas with low and moderate groundwater potential, as well as areas with weak and moderate aquifer protective capacity. The efficacy of resistivity and pumping test data in quantifying aquifer properties has been established in this research. It is recommended that a qualitative analysis of this water be carried out in view of water demand analysis in Gwagwalada for a proper planning and management of water resources.

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LIST OF ABBREVIATION/ACRONYMS AND SYMBOLS

APC	Aquifer protective capacity
BH	Borehole
COD	Chemical oxygen demand
EPA	Environmental Protection Agency
FCT	Federal Capital Territory
FEPA	Federal Environmental Protection Agency
GPS	Global Positioning System
kVA	Kilo-volt-amperes
NIHSA	Nigeria Hydrological Service Agency
NNPC	Nigerian National Petroleum Corporation
NSDWQ	Nigerian Standard for Drinking Water Quality
pH	Hydrogen potentials
SWL	Static water level
TDS	Total dissolved solids
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
VES	Vertival Electrical Sounding
WHO	World Health Organization
WQI	Water quality index

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Water is the elixir of the life. No living thing can survive without water. People use water daily and indispensably for drinking, domestic, agricultural and industrial purposes. To maintain the essential fluids of the body, a person requires about three liters of potable water per day (Gleick, 1996). In arid lands, people existed with little more than this amount as their total daily consumption. On average, 200 liters of water can be used daily for domestic purposes. Agriculture and industry require greater volumes of water. A correct harnessing and utilization of water can turn out to be a boon and an immense value for mankind, otherwise it can become a curse and a cause of misery for humanity (Okoro *et al.*, 2016).

Freshwater, made up of surface water (rivers, streams and lakes) and groundwater, is the main source providing water for various human activities. Normally, surface water resources are the most efficient way to meet water demand. However, this freshwater resource is not readily available to all because it is unevenly distributed around the world (Nazario, 2020; Kasidi, 2017). About one-third of the world's population live in countries suffering from moderate-to-high water stress, where water consumption is more than 10 per cent of renewable freshwater resources (Abimiku *et al.*, 2019). According to UN Water 2007 estimates, by 2025 about 1.8 billion people worldwide will not have access to safe drinking water and about two-thirds will not have sufficient water for domestic use. Moreover, with the increase in population and economy of metropolitan cities in developing countries including Federal Capital Territory (FCT) Abuja, water resources' need also increases on the

one hand (Nugraha *et al.*, 2022) and on the other hand the continuous contamination of surface waters and shallow aquifers (Nnamdi *et al.*, 2019).

Measures have been taken to investigate the possibilities of providing alternative sources of water (Nazario, 2020) to supplement the non-availability of surface water (Sunkari, *et al.*, 2021). Groundwater has proven to be a suitable alternative both for water supply mainly because of its abundance, stable quality and also because it is inexpensive to exploit (Ijeh, 2014).

Federal Capital Territory (FCT) Abuja is underlain by the basement complex where surface sources of water supply are either inadequate, intermittent or polluted. Thus, groundwater plays an important role, since domestic and industrial supplies depend on it (Kasidi, 2017). Unfortunately groundwater does not occur everywhere on the Earth (Kasidi, 2017) and it is obvious that groundwater exploitation in the basement complex does not always have a good yield (Nazario, 2020; Hamidu *et al.*, 2013). Therefore, it is important to understand the aquifer potentials from which groundwater is sourced in the area to ensure living thing survival.

There are several techniques and methods to assess groundwater, such as geophysical, geological, geospatial, pumping test methods. This research evaluates aquifer hydraulic properties in parts of Gwagwalada through resistivity method by computing Dar-Zarrouk parameters and pumping tests. Vertical Electrical Sounding (VES) techniques are widely used to obtain Aquifer parameters (Nugraha *et al.*, 2022). Dar-Zarrouk parameters consists of longitudinal conductance, S (Ω-1) and Transverse resistance, T (Ωm2) and are derived from resistivity values. Aquifer test is the most suitable means for estimating hydraulic characteristics because it digests field data that reflects not only the point behavior of well

location but a certain volume of aquifer material around the well within the cone of depression (Şen, 2014).

1.2 Statement of the Research Problem

In Abuja, groundwater is the main source of potable water supply, thus supplementing the surface water which had become inadequate in both quality and quantity (Okogbue & Omonona, 2013). Nevertheless, this water source does not occur everywhere in in FCT (Sunkari *et al.*, 2021) and on one hand many folks are in dire need of this scare resources (Asije & Igwe, 2014, Sunkari *et al.*, 2021), and on the other, the yields of boreholes within the geological zones is low (Olasehinde *et al.*, 2016).

Beside these natural challenges relating to the geological nature of the area, potable water supply in Abuja is compounded by the exponential increase in population. According to the United Nations report on world population growth, by 2050, Nigeria will be one of the eight (8) countries in the world to have more than half of the projected increase in global population (United Nations, 2022), (Figure 1.1).

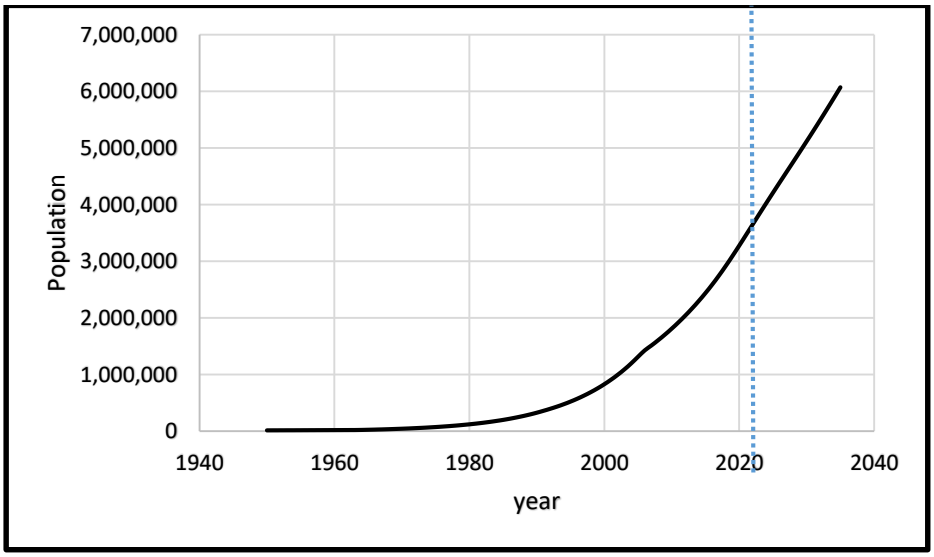

Figure 1.1: Population growth in Abuja (United Nations, 2022)

FCT, Abuja has a population of 3,652,029 with growing rate of 5.42 percent per year, that means in the next ten years, the population is expected to increase by fifty percent (United Nations, 2022). Gwagwalada area of Abuja is at the centre of the upsurge in population because it is the federal capital and due to presence of the University and Teaching Hospital as well as mining, agricultural and industrial activities. Consequently, this has led to increase in the demand for groundwater in order to meet the water need of the people.

Therefore, the need to evaluate the aquifer hydraulic properties have become imperative so as to have a good knowledge of aquifer systems from the groundwater sources and protective capacity of the overburden material. This is essential in ensuring the availability of potable water for the city.

1.3 Justification for the Study

The increasing demand for groundwater for various human activities has given great importance to water science and management practices worldwide (Amadi *et al.*, 2020). The exponential increase in the population of Abuja has led to the increase in water demand in the area. It has been established that domestic and industrial supply in Abuja depends on groundwater (Okogbue & Omonona, 2013). Due to the continuous growth of water demand accompanying population growth in Gwagwalada area, it becomes imperative to understand the aquifer systems and their properties in order to ensure that this precious resource does not get depleted.

1.4 Scope and Limitation of the Research

Assessment of the hydraulic properties of the aquifer systems in Gwagwalada area was determined in this research through hydrogeological and geophysics approaches. Two components of the hydrogeological approach was used in the research, namely depth to water

measurements and pumping tests. Static water level of hand-dug wells and topographic elevations above the sea were measured and computed to establish the hydraulic head which was computed to establish the groundwater flow direction. Pumping tests was conducted to determine the aquifer parameters in terms of hydraulic conductivity, transmissivity and specific capacity.

Geophysical survey was conducted and data generated in the field and was interpreted to determine the subsurface condition and the Dar Zarrouk parameters. The number of layers, their thickness, resistivity and depth was determined through the vertical electrical sounding (VES) using the Schlumberger array configuration which was employed in this research and computed through curve matching and the computer iteration using WINRESIST software. Longitudinal conductance, $S\ (\Omega^{-1})$ and transverse resistance, $T\ (\Omega m^2)$ (Dar-Zarrouk parameters) and the coefficient of anisotropy, λ, was obtained in combination of the thickness and resistivity of each geoelectric layers. The total longitudinal conductance (S) value was used to estimate the aquifer protective capacity in the study area. The transverse resistance value is directly related with transmissivity (Yusuf & Abiye, 2019; Nugraha *et al.*, 2022).

1.5 Description of the Study Area

1.5.1 Location and accessibility

The study area is situated in the South-West of Gwagwalada, which is a part of FCT Abuja in Nigeria, lying between latitude 8°54′00″ to 9°00′00″ N and longitude 7°00′00″ to 07°06′00″ E, The communities within the study area include Dukpa, Deshi Paiko, Paiko, Passu, Korokola, Kaida, Checheyi, Bako and Gwagwalada. The area is easily accessible due to a good road network.

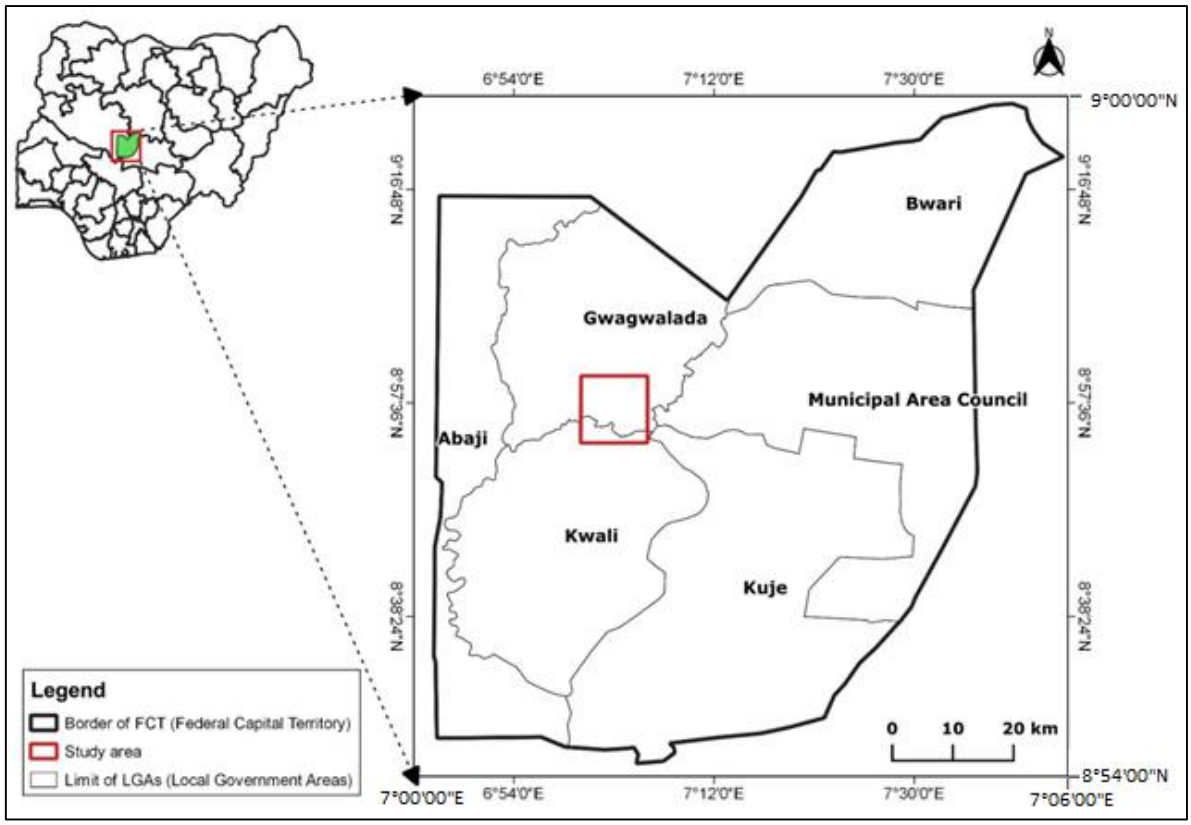

Figure 1.2. Location map of the study area (modified from Elimian *et al*., 2020)

1.5.2 Climate and vegetation

Abuja is characterized by a well-defined dry and rainy season, the rainy season falls between April and October while the dry season is between Novembers to March. The rainy season is characterized by rise in water table and most streams have water while during the dry season, most of these streams are dried up. The area falls within the Savanah Grassland vegetation belt of Nigeria. It is characterized by moderately tall grasses, shrubs and scattered tall trees especially along the river channels.

1.5.3 Relief and drainage

Hills occur as clusters and long chains throughout the Federal Capital Territory. The topography of the study area is varied, falling between 348m and 452m in altitude.

1.5.4 Local geology

Federal Capital Territory (FCT), Abuja consists of 85% igneous and high-grade metamorphic rocks of the Nigerian basement complex and Cretaceous sedimentary rocks of the Bida Basin, which cover the remaining 15%. These rocks consist of gneiss, granite-gneiss and granites and are generally oriented NNE-SSW. The belt broadens towards the south and south-eastern part of the region where the topography is rugged and the relief high. In general, the rocks are strongly sheared (Kogbe, 1989). The three major lithologic units in Abuja are: Undifferentiated Migmatite-Gneiss Complex of Proterozoic to Archean age, metavolcano-sedimentary rocks (mainly schist, phyllite and quartzite) and Bida sandstones of late Proterozoic age and Older Granite complex of late Precambrian - Lower Paleozoic age, also known as Pan-African granites (Dan-Hassan *et al*., 2012). All these rocks were subjected and deformed by the Pan-African thermo-tectonic event. In most cases the rocks have weathered into reddish sandy clay to clay materials capped by laterite with lots of mica flakes (Offodile, 1992). In the study area, Migmatite- Gneiss are well represented among the three major rock categories mentioned above.

1.6 Aim and Objectives of the Research

This research is aimed at evaluating the hydraulic properties of the aquifer systems in Gwagwalada using Dar-Zarrouk parameters and Pumping test data.

Specifically, the objectives to be achieved were:

1. To carry out geological mapping of the area in order to know the rock types in the area.
2. To determine the groundwater flow direction by measuring static water level from existing hand dug wells in the area.

3. To establish the nature of the subsurface geology using electrical resistivity method.
4. To evaluate the aquifer protective capacity and homogeneity of the area by computing Dar Zarrouk parameters from the obtained resistivity data.
5. To quantify the hydraulic properties of the aquifer in the area using pumping test data.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Nigerian Basement Complex

Precambrian crystalline rocks that outcrop in Nigeria are mostly gneisses, Migmatites, gneissose, Granites and Schist (Umeji, 1988). These form the Basement Complex on which sediments were deposited and into which igneous rocks where intruded. Major folds observed in the basement and younger metasupracrustal schist trend north-south and might have been a product of more than one tectonic event but the last imprint is considered to be of Pan African age. The western part of the country, where schists predominate was described as 'marking the trough of a synclinorium' (Truswell & Cope, 1963). This is in contrast with the eastern part where schist belts are not abundant and folds are comparatively simple.

The rocks which intrude both the basement and the metasupracrustal cover vary widely in structure and composition. These rocks include granites, granodiorites, syenites, adamellites, quartz-monzonites and tonalites which have been termed Older Granites (Falconer & Woods, 1911). They are syn-and -late tectonic plutons which are of Pan African age. The groups of lithology of the Basement Complex of Nigeria are usually distinguished into three broad categories namely, a poly-metamorphic Migmatites-gneiss Complex, low-grade sediments subjugated schists and Syntectonics to Late tectonics granitic rocks.

(A) A poly-metamorphic Migmatites-gneiss Complex that is largely made up of Migmatites and Gneiss of assorted constitutions and Amphibolite. Metasedimentary rock relicts which are represented by fine to medium grained calcareous pelitic and quarzitic rocks crop up inside the Migmatites and Gneisses. These have been expressed as "primordial

metasediments" (Oyawoye, 1972). The Migmatite-gneiss Complex is thought to have an age of isotope that varied from Liberian to Pan African.

(B) Low-grade sediment dictated Schist that reduce belts in the western half of the nation (Figure 2.1) assert description as "Younger Metasediment" (McCurry, 1976), "unmigmatised Schist" (Rahaman, 1976) and "newer metasediments" (Oyawoye, 1964). Russ (1957); McCurry (1973), described these Schists belts as remains of a supercrustal cover that was infolded into the Migmatite-gneiss Complex. The Pan African granitoids intruded into the Schist belts.

(C) Granitic rocks of syntectonic to late tectonism that intruded together the Schist belts and the Migmatite-gneiss Complex. The rocks of granitoids consist of rocks which vary in constituent from charnockite to tonalite and granite with lesser quantities of gabbro and syenite. From radiometric dating the granitoids age ranges from 750 to 500 million years (Ma) which lies in the spectrum age of Pan African. These granitoids of Pan African are in Nigeria refers to as the Older Granites so as to differentiate them from the tin influencing Mesozoic Complexes of Granites in central Nigeria that is represented as the Nigerian Younger granites.

These three broad lithologic groups of the Nigerian Basement Complex consist of six major rock types which include Complex of Migmatite-Gneiss-quartzite, non-migmatised to a little migmatised metasedimentary and meta-igneous rocks that are frequently denoted as younger or newer metasediments, charnockitic, dioritic and gabbroic rocks, members of the suite of the Older granite, unmetamorphosed to metamorphosed calc-alkaline hypabyssal and volcanics rocks, and calc-alkaline to unmetamorphosed hypabyssal and volcanics rocks, and unmetamorphosed dolerites dykes, basic dykes and syenites (Berger *et al.*, 1983).

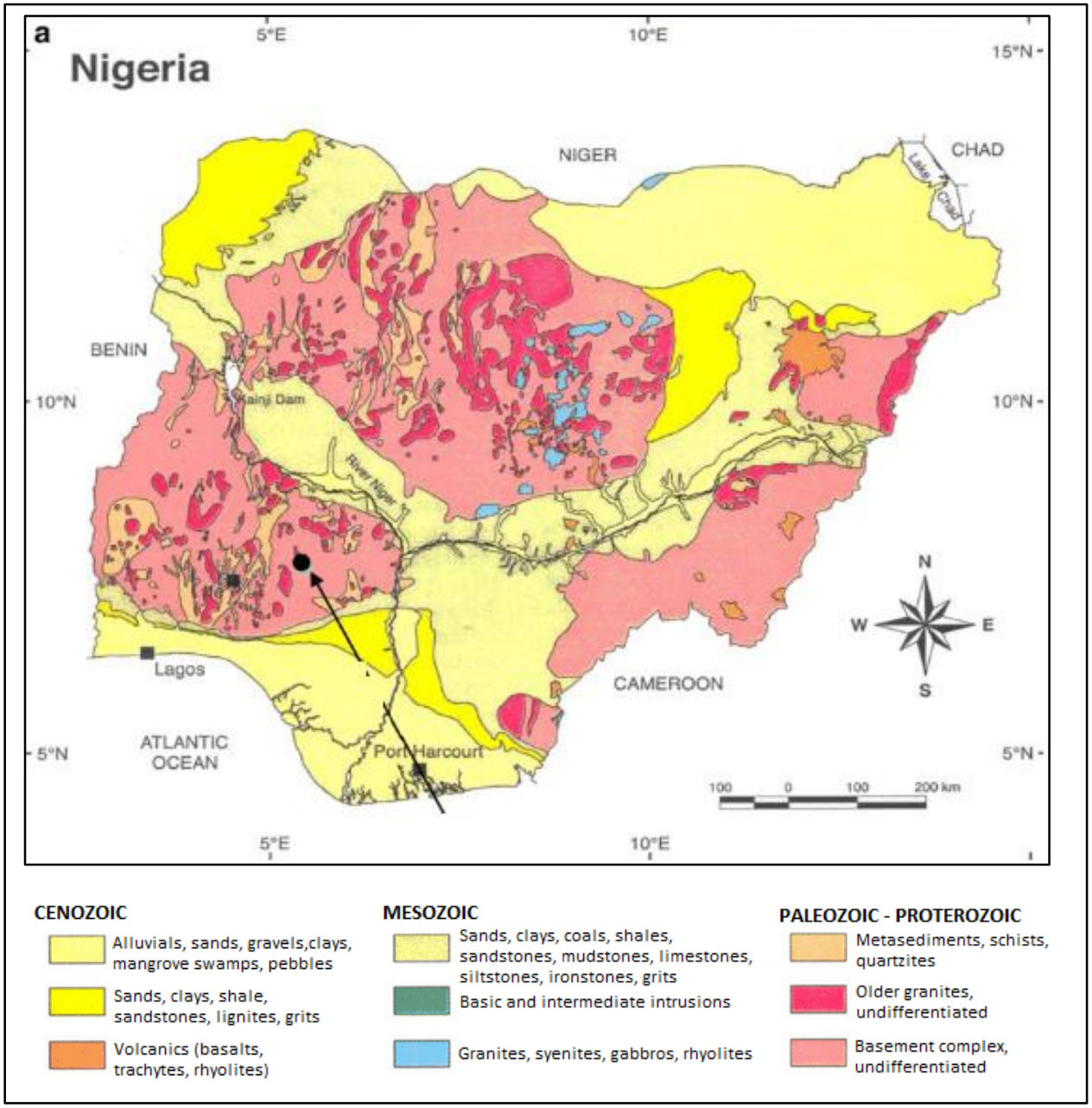

Figure 2.1: Geological map of Nigeria (Source: Rahaman, 1988)

2.1.1 The Migmatite-gneiss-quartzite complex

This Migmatite-gneiss-quartzite Complex in comparison with other rock groups that constitute the Nigerian Basement Complex is on the whole prevalent. It covers approximately 30% of the overall land of Nigeria. These rock groups are heterogenous and contains

basically of Granitic and Migmatitic Gneisses, basic Schists and Gneiss and relict metasedimentary calcareous quartzite and granulitic rocks. When compared to its large quantity, this rock group maybe the studied slightest of the main groups of rock. Majority of researchers on the Nigeria Basement Complex are of the opinion that the Migmatite-gneiss-quartzite Complex rocks encompass mainly a sedimentary sequence with related small igneous rocks that has been erratically transformed by the Granitic, Migmatitic and metamorphic developments. The metasedimentary and basic rocks are referred to as relict (resisters to the migmatisation and granitization processes). Geochronologically, the Migmatite-gneiss-quartzite Complex of the basement Complex have been interpreted by a number of authors (Grant, 1978; Ajibade, 1980; Ogezi, 1977) to be polycyclic in nature with organic events through the Pan African (600 ± 150ma), Kibaran (1100 ± 200ma) and Liberian (2800 ± 200ma).

2.1.2 Non-migmatised to slightly migmatised meta-igneous and meta-sedimentary rocks

This rock group represent the Nigerian Schist belts. They show similarities in lithology to the Schist belt of other sections of the earth (Anhaeusser *et al*., 1969) which are known to harbour important economic mineral deposits. The Schist Belts encompass low grade, metasediment-controlled belts that trends North–South that are superlatively formed in the Nigerian western half. The belts are believed to be supracrustal rocks of Upper Proterozoic age that have been infolded into the Complex of Migmatite-gneiss-quartzite. The variations in the Schist belts lithology consist of fine to coarse grained pelitic, clastics Schists, Banded Iron Formation, phyllites, mafic metavolcanics (Amphibolites) and carbonate rocks (dolomitic marbles / marbles). A few number can comprise remains of ocean floor matters from little back-arc basins. Grant (1978) and Rahaman (1976) for instance propose that there were numerous

depositional basins but McCurry (1976) and Oyawoye (1972) believe the Schists belts as a single supracrustal cover relicts. Olade & Elueze (1979) believe the Schist belts to be fault-dictated rift-like forms. Turner (1983), Holt (1982) and Grant (1978), on the bases of associations of lithology and structures, propose that there are diverse sediments ages. Conversely, Ajibade *et al*. (1979) differ with this deduction and illustrate that the two series have indistinguishable histories of deformation. The interaction of structures between the basement and the Schist belts were thought by Truswell & Cope (1963) to be metamorphic fronts that are conformable and it was Ajibade *et al.* (1979) who initially mapped a break in structure.

The Schist belts geochronology continues to be difficult even though the ages of the invasive cross-cutting Older Granites gives a lower limit of ca 750 Ma. An age of Rb/Sr of 1,040 ± 25 Ma for the phyllites of Maru Belt has been received as an age of metamorphism by Ogezi (1977). The rocks of the Schist belt are in general termed to be Upper Proterozoic. Inside the Schist belts, the amphibolite Complexes geochemistry has also guard to disagreement. Klemm *et al*. (1984) have summated that the Ilesha belt might be a belt of Archaean greenstone. Ogezi (1977), Olade & Elueze (1979) and Ajibade (1980) have preferred prevailing processes of ensialic in the development of the Schist belts even as Ajayi (1980), Rahaman (1988) and Egbuniwe (1982) have emphasized that a few contain oceanic resources having tholeiitic similarities. Some features of metallogenetic of the Schist belts are pertinent to these exertions; the obvious nonexistence of subduction linked deposits of mineral might be suggestive of an incomplete function for the processes of ensimatic; the circulation of principal gold episodes in some belts but its discern nonexistence in others and could signify that they do not characterize a particular supracrustal succession. The Schist belts are most

excellent formed in the Nigerian western section, west of 8◦E longitude, although minor incidences are establish to the east but only periodically. The belts are restricted to a zone of NNE-trend of roughly 300 km thick. The region to the west of this zone is constituted of Migmatites and gneisses that represent the Dahomeyan (Burke & Dewey, 1972). To the east likewise, there are no known Schist belts for an expanse of 700 km till Cameroun where a quantity of Schist belts, believed to be Upper Proterozoic, take place in the terrain of the Pan-African granite-Migmatite north of the Congo Craton.

2.1.3 The Pan african granitoids (older granites)

The phrase "Older Granite" was instituted by Falconer & Woods (1911) in distinguishing the deep-seated, frequently semi-concordant or concordant granites of the Basement Complex from the sophisticated, extremely discordant Northern Nigeria tin-producing granites. The Older Granites are understood to be pre-, syn- and post-tectonic rocks that sever the two of Schist belts and the Migmatite-gneiss-quartzite Complex. They extend extensively in age (750–450 Ma) and constituent. They stand for a diverse and enduring (750–450 Ma) cycle of magma coupled with the Pan-African orogeny. This suite rocks vary in constituent from diorites and tonalites to granodiorites and to syenites and true granites. Charnockites produce an essential group of rock emplaced in this episode. They are in general complex incursion and anataxes has performed a vital function (Rahaman, 1988). The suite of the Older Granites is noteworthy for its common lack of related mineralization though thermal consequences might perform a part in the remobilization of fluids of mineralization. The Older Granites are the largely evident sign of the Pan-African orogeny and stand for significant additions of material (up to 70% in certain areas) to the crust (Rahaman, 1988). Efforts in classifying the Older Granites with regards to timing through an event of orogeny are suitable over only

small expanses. Contact characteristics between components of the suite of the Older Granites indicate the coexistence of numerous magmas. Compositionally, the plots of the granites in the domain of calc-alkaline rocks on the diagram of AFM and even though they have considerable quantity of alkalis, are as well frequently a little corundum normative. Dada (2008) has the view that the name "Pan African Granitoids" be applied to the Older Granites not just on the advantage of age that was not obtainable at the time they were assigned Older Granites, but for the reason that it covers quite a lot of vital petrologic groups produced at the equivalent time.

The granitoids that outcrop together with the Schist belts in Nigeria south-western and north-western areas comprise Biotites Granites, biotite-muscovite Granites, Syenites, Charnockites, Anorthosites and Serpentinites.

In Nigerian northern section, the large quantity of Pan-African Granites seems to spread eastward. In the region west of Zaria these arise as remote intrusions (McCurry, 1973), but in the area between Rahama and the Mesozoic-Cenozoic cover the invasive granites and associated rocks cover remains of Migmatites. McCurry (1973) investigating mostly in west of Zaria, separated the granites into two major units in consistent with their relationships in the field. The initial group of syntectonic contained extended sheets of batholithic that are concordant partially, and foliated. The next group "late tectonic" are comprised of discordant bodies that are inadequately foliated, abundant in mafic xenoliths and with a lower amount of potash feldspar. The late granites are thought to be the results of extensive reactivation and mobilisation of Older basement rocks throughout the Pan-African orogeny. The Older Granites appear elaborately connected with the Schist Belts and the Migmatite-Gneiss Complex into which they usually intruded. Rocks of the Older Granite hence appear in most

areas everywhere the Schist Belt or Migmatite-Gneiss Complex rocks are found. Nevertheless, Older Granites are predominantly striking in and in the vicinity of Wusasa (Zaria), Akwanga, Bauchi, Abuja, Obudu and Ado-Ekiti areas. In areas within Bauchi and some sections of Nigerian southwest, the majority of the rocks of the Older Granite appear as dark, greenish-grey Granites having considerable amounts of olivine (fayalite) and pyroxene which occurs with Micas, Feldspars and Quartz. For this strange constitution, the Older Granites in these regions are referred to as Bauchite (in Bauchi locale) and Oyawoyite (after Professor Oyawoye who initially mapped them) in Nigerian southwest. For consistency of expressions, the two of the Bauchites and Oyawoyites represent the Basement Complex charnockitic rocks (Charnockites).

Magmas of granite are intruded as thick fluids into the lithosphere, discontinuing when the cooling of the magma and volatiles loss raises their viscosity across the threshold of flow (Zheng & Gao, 2021). Throughout the sequence of the magma cooling, a nonstop transform is created in the shape of the intrusive body. The quantity of the melted mobile part differs, growing, provided that the introduction of novel magma persists and the external solid section becomes progressively rigid and thick. As earlier stated, the composition is only produced in its previously consolidated region whose outline and magnitude endlessly differ for the period of the process of intrusion/cooling (Zheng & Gao, 2021).

2.1.4 Dioritic and charnockitic gabbroic rocks

In the view of Dada (1989), it was at Toro that charnockite was initially depicted in the basement of Nigeria by Falconer & Woods (1911), where it was at that time denoted as a quartz diorite porphyrite. It was presumed to exhibit a definite attraction with the basic constituents of the Ivory Coast charnockitic sequence. Wright (1970), illustrated it as an

annular Complex having hypersthene diorite at the middle of three rounds, concentric granites. He regarded the hypersthene diorite to be older than the granites from contact associations. Cooray (1975), in his reassessment of Nigerian charnockitic rocks arrived at identical deduction, utilising for reason the existence of veins of granites in the diorite, of xenoliths of diorite in granites and microcline porphyroblasts in the diorite. A research in the field of the same mix rocks directed Rahaman (1988) to reflect on both the charnockites and the granites as either contemporary or the latter emplaced soon behind the former. The Toro area basement is made up of Migmatites and gneisses into which the Toro Charnockitic Complex is imposed Dada (1989); Older Granites and charnockites that make up the Complex suitably; and undeformed basic (doleritic) dykes believed to be after the Granites of Pan-Africa. Dada (1989) described the Toro charnockite to be naturally greenish black, medium to fine-grained, massive and equigranular, occasionally porphyritic. The granites contain from the margin of the Complex (contacting the migmatitic gneiss) towards the middle (contacting the hypersthene diorite) of: a medium to fine grained biotite-muscovite granite, a granite of equigranular biotite-hornblende and a granite of porphyritic biotite-hornblende. Generally, these granites in addition to the diorites are not impinged on by a penetrative deformation, but undulatory extinction of the quartz and feldspar crystals fractures point to limited brittle deformation. The Older Granites are documented to be of the age of Pan-Africa. In spite of the marked relationship and field associations with the Older Granites, older ages have been recommended for these charnockites. The ages are in disagreement with the confirmation of mix reactions at the contact linking the Older Granites and the charnockites evolved by Rahaman (1988). Van Breemen *et al.*, (1977) acquired the inexact ages of 663 ± 164 Ma and 668 ± 128 Ma on the bauchites in the regions within Bauchi. Tubosun *et al.*, (1984) utilizing U-Pb technique on zircons ascribed exact Pan-

African ages of 620 ± 20 Ma and 634 ± 21 Ma to the charnockites of Akure and Ikere correspondingly. For the Idanre Complex they achieved ages of Late Pan-African of 580 ± 10 Ma and 593 ± 11 Ma thus corroborating exact ages of Pan-African for the charnockitic Complexes of Nigerian Southwest. Charnockitic rocks represent one of the significant units of petrology inside the Nigerian Precambrian Basement Complex. They are in general characterized by their greenish grey to dark greenish emergence which brand them to be effortlessly recognized in hand specimen. They frequently include quartz + alkali feldspar + plagioclase + hornblende + orthopyroxene + clinopyroxene ± fayalite ± biotite. Accessory minerals are regularly iron ores, apatite and zircon (Olarewaju, 2006). With the exception of Toro, other zones of occurrence of charnockite consist of Ado-Ekiti, Akure, Bauchi, Idanre, Ikere (Ekiti) and in the Obudu Plateau.

2.1.5 Hypabyssal and volcanic rocks

This rock group possibly of the age of late Pan African appear in various areas inside a 2000 km by 30 km linear district connected with the belt of Anka Metasediment in Nigerian Northwest. These rocks are often frequented with faults that governed their emplacement. Sills and Dykes of Felsic-mafic rocks with may vary from a some centimetres (cm) to above 500 m in depth appear in Kabba-Jakura and Igarra belt of Metasediment of the Nigerian South-west. The larger bodies are often composite intrusions with mafic-alkali syenites to quartz syenite and tonalite- granodiorite compositions present. Lamprophyre dykes are also wide spread in the area, McCurry (1976), recounted that the Maradum Volcanics comprise of unmetamorphosed aggregates of volcanic, tuffs, rhyolitics and rhyodacitics rocks in a zone of 16 km by 2 km. These unmetamorphosed volcanic are intrusive into the Maiinchi granodiorite and are in turn cut by very late pegmatites, around Kesemi which is about 90

km Southwest of Maradum occurs partly deformed porphyritic and non-porphyritic dacites. Metamorphosed sheared dacite lavas cut by dykes and sills of intermediate opus occur around Binkasau.

McCurry (1976), has stated that these rocks are divided into two series, one older and one younger, since metamorphosed and unmetamorphosed kinds form a continuous unit. K/Ar whole rock minimum age of 507 ± 20 Ma was recounted by McCurry (1976), for the porphyritic Kesemi dacites. Rb-Sr biotite whole rockpairs bore ages in the range of 480 – 509 Ma for the Igarra potassic Syenite. These ages are similar to the 478 ± 19 Ma whole rock K/Ar age opined by Grant (1978) on an unmetamorphosed dolerite dyke from Ibadan. Hence, they represent the latest Pan African intrusions in the basement Complex. The volcanic and hypabyssal rocks from Nigerian Northwest are comparable to hypabyssal and high K-calc-alkaline volcanic rocks at present which occurs at the boundaries of the belts of pacific orogeny. They enjoy similar features of ratios of elevated K/Na, elevated SiO_2, lithophile trace elements and LREE innards (McCurry & Wright, 1977). These researchers proposed that the rocks produced are a product of subduction of a Benioff zone plummeting westward in the time of the Late Pan African.

2.2 General Hydrogeology of Nigeria

Groundwater which can be extracted by boreholes and hand-dug wells occurs in permeable geological formations known as aquifers which have properties that allow storage and movement of water through them. The geological structure of Nigeria gave rise to two types of groundwater pore-type water in sedimentary cover and fissure-type water found in crystalline rocks (Adewumi & Anifowose, 2017). Fissure-type water occurs in precambrian

crystalline rocks while pore-type water in sedimentary deposits and superficial deposits (Adewumi & Anifowose, 2017).

The availability of groundwater in areas underlain by crystalline basement rocks depends on the development of thick soil overburden (overburden aquifers) or the presence of fractures that are capable of holding water (fractured crystalline aquifers). The storage of groundwater is confined to fractures and fissures in the weathered zone of igneous, metamorphic and volcanic rocks, the thickness of which range from <10-60m in arid and humid rain forest (Eduvie, 2003). The groundwater resources here are usually limited. The groundwater found in sedimentary deposits is mainly the pore-type, so also the one found in alluvial deposits where Aeolian and fluvial sediments are found. These collectively formed primary aquifers because the water is contained in their primary pore spaces.

The several sedimentary formations of variable age, mineralogical and geochemical character found in Nigerian basins, affect the quantity and quality of water found in them. These basins include Chad, Sokoto and Benue Trough, among others. Among the biggest water bearing units in Nigeria, the following should be mentioned: Chad, Kerri Kerri, Nsukka, Benin and Abeokuta Formations. This is because they are largely formed from sandstones, alluvial deposits and other related arenaceous sedimentary rocks. Shales, clays, limestones are generally poor aquifers due to their argillaceous nature. There is little groundwater in them, the one found is only confined to their fracture and weathered zones. These rocks only help to confine an aquifer. Groundwater tapped from confined aquifers is sometimes artesian in nature. Occurrence of groundwater varies with the geology of the area. In the Basement Complex terrain, groundwater occurs in the weathered regolith and in fractures in the fresh crystalline rocks. Figure 2.3 is a map of Nigeria showing eight (8) hydrogeological Areas obtained from Nigeria Hydrological Services Agency (NIHSA). Where thick weathered

zones or fractures in fresh rocks occur, wells and boreholes tap the groundwater for water supply.

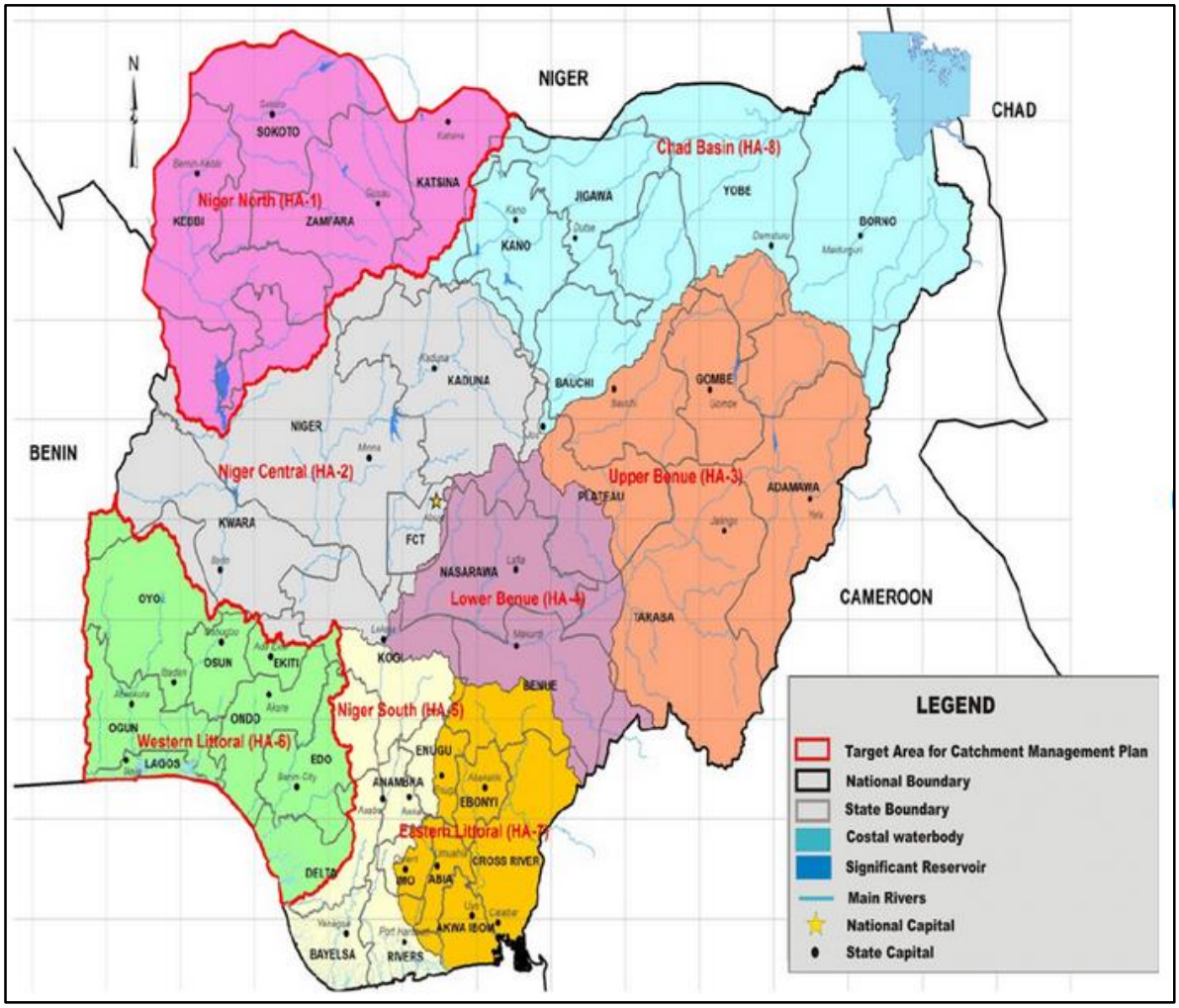

Figure 2.4: Map of Nigeria showing 8 Hydrological Areas (Source: Fasipe & Izinyon, 2021)

2.3 Hydrogeochemistry

Etu-Efeotor (1998) carried out the hydrochemical analysis of surface and groundwater of Gwagwalada area of central Nigeria. A survey of both the surface and groundwater was carried out over a period of one year observing different climatic seasons. The result shows that the surface water and groundwater meet Federal Environmental Protection Agency

(FEPA, 1991) requirements for both domestic and industrial uses except for the high silt and Fe content of the surface water. The high concentration of nitrates, phosphates and sulphates in surface water are believed to have resulted from the human and agricultural activities in the area. The concentrations of these parameters are also seasonally controlled.

Adakole *et al*. (2010) research on quality characteristics of water in Samaru area showed that all the physical parameters considered conform to the (WHO, 2002) standards, while some of the chemical parameters like total hardness, nitrate, chloride and sulphate of the samples do not conform to the standard. Aremu *et al.* (2011) evaluated the physiochemical properties of groundwater from hand-dug wells, boreholes and stream water in Bwari and its environs. The result showed that all the parameters determined fall within the World Health Organisation (WHO, 2002) standard for drinking water quality, except for pH. The result showed that the water are slightly acidic, soft, fresh, have low to moderate chemical ions values and are classified as Ca-Na-HCO_3, Ca-K-HCO_3, Mg-Ca-HCO_3, and Na-K- HCO_3 water types.

Muhammad *et al.* (2015) reported that over 90% of the water samples analysed from parts of Kaduna Metropolis is in conformity with the Nigerian Standard for Drinking Water Quality standard in term of physico-chemical quality (NSDWQ, 2007). However, over 65% of the samples were contaminated by coliform. This confirms anthropogenic contamination of some of the groundwater in the study area. It also indicated that the borehole water is more potable than the shallow wells. Nur & Ayuni (2004) research on the water quality characteristics of groundwater in Jalingo metropolis showed that some of the water samples do not conform to WHO (2006) permissible standard in terms of pH, iron, magnesium and coliform count. It further stated that the water samples have generally low concentration of anions and cations and classified the dominant water type in the area as Na+K - Cl- SO_4

water type.

Yusuf & Sonibore (2004) research on the characteristics and the pollution implications of the effluents from the textile industry on the water resources, human health and environment of Kaduna Metropolis indicated that the qualities of the effluent were grossly below the set limits of FEPA (1991) in majority of the textile mills. It also suggested that the air quality of the area covered by the Kaduna River basin to be likely negatively affected by both the gaseous emissions and particulates from the effluents and that meteorological condition are strong influencing factors to this situation.

In their various work on the groundwater quality and hydrogeochemical assessment of the water resources elsewhere in Nigeria and outside Nigeria, both British Geological Survey (2003) regional assessment and reviews of the groundwater quality of Nigeria noted that the Nigerian shallow aquifers are potentially vulnerable to pollution from human activities. Agriculture (fertilizers), domestic (waste dumps, latrines) and industrial sources, except where surface layers are of poor permeability and offered some protection of the underlying aquifers, are sources of pollution.

Adesida & Omosuyi (2005) analysed groundwater chemistry of weathered zone aquifers of an area underlain by basement complex rocks, Akure, Nigeria. The results show that there is a human activity imprint on the groundwater chemistry, which overshadows the normal expected influence of' weathering and bedrock geology. Ako *et al*., (1990) assessed the chemical quality of shallow groundwater from a metamorphic terrain of part of Southwest Nigeria. The research concluded that the pattern of nutrient concentration between surface and groundwater investigated show that the chemistry of the groundwater is dependent to a

large extent on the host bedrock. Okoli & Odaibo (1999) evaluated the bacteriological, chemical and lithologic controls on the water quality in southwest Nigeria and concluded that anthropogenic influence is the major critical factor in respect to the water quality, instead of the lithology. Adekunle *et al.* (2007) evaluated the physico-chemical and biological quality of water sources in south-western Nigeria. They attributed the contamination/ pollution of some of the water analysed to both geogenic and anthropogenic factors.

Yenika *et al*. (2003) determined the impact of human activities on groundwater quality of shallow aquifers in Jimeta- Yola. The research revealed elevated concentration for contamination/ pollution tracers (NO_3^-, Cl^-, SO_4^{2-}) and electrical conductivity. They suggested that the contamination/pollution is due to human activities. Olobaniyi & Owoyemi (2004) determined the groundwater quality in the Deltaic plain sand aquifer of Warri area. They reported saltwater contamination in some of the samples based on high chloride content, low Ca/Mg and Na/Cl ratio. They stated that the water is suitable for domestic and industrial purposes in terms of its physico-chemical attributes. However, the presence of heterothrophic and coliform bacteria compromise this quality. Edet *et al*. (2004) assessed the contamination risk of coastal plain aquifers in Calabar by some potentially toxic elements. They concluded that the small scale mining activities, low concentration of elements, immobility of mineral species under the prevailing Eh-pH conditions, dilution and precipitation of mineral phases make contamination risk of the coastal plain sand very low.

Dan-Hassan (2013) worked on some aspect of hydrogeology of FCT, Abuja. In addition, the groundwater quality of Benin City was determined using statistical correlation and multivariate analyses (Akujieze & Oteze, 2007). The result showed positive correlation between lead (Pb) and other pollution indicators like magnesium (Mg^{2+}), sodium (Na^+),

nitrate (NO_3^-), phosphate (PO_4^-) and chloride (Cl^-) and they concluded common sources for them. Momodu and Anyakora (2010) studied the groundwater quality of the Southwest based on their seasonal variations and proximity to pollution sources. The result revealed higher concentration of most of the parameters during the rainy season over the dry season period. They stated that the distance from pollution sources was more pronounced on faecal coliform count, which decreases with increasing distance from the waste dump.

Dan Hassan *et al.* (2012) worked on the spatial and temporal distribution of nitrate pollution in groundwater of Abuja, Nigeria and Aiyegbusi & Akujieze (2010) determined the groundwater quality of shallow aquifer in Ilesha area. The result showed elevated concentration of some of the parameters above the WHO (2006) standard and presence of coliform in majority of the water analysed. This revealed anthropogenic imprint on groundwater quality. They classified the water as Ca-Mg-HCO_3^-, Ca-Mg-Cl-SO_4^{2-} , Ca-Mg-Na-K-HCO_3^- , Ca-Mg-Na-K-Cl-SO_4^{2-}-HCO_3^- and Na-K-HCO_3^-. Ishaku and Ezeigbo (2010) monitored the groundwater quality of Jimeta-Yola area to determine its seasonal variation. The result revealed higher mean concentration of the chemical parameters and coliform counts during the wet season. They reported higher concentration of nitrate and coliform above the WHO (2006) limits for both seasons and linked the distribution to anthropogenic sources. Akpah and Ezeigbo (2010) investigated the hydrochemical and quality characteristics of groundwater in Itakpe and they reported that majority of the water have salty taste, high electrical conductivity and lower pH values.

Aremu *et al*. (2011) evaluated the physico-chemical quality of water resources in Eggan area. They reported that the groundwater samples are moderately acidic to strongly alkaline, while the surface water is neutral to moderately alkaline in nature. They revealed that some

parameters as pH, iron, TDS, potassium and chloride do not conform to the WHO (2006) and NSDWQ (2007). They concluded that the groundwater is more potable and safer for domestic purposes than the surface water. Taiwo et al (2011) determined the groundwater quality of hand dug wells in Obantoko, Abeokuta and revealed high concentration of some parameters above WHO standards. Some regulatory agency standards concluded that groundwater quality in the wells was compromised and unfit for safe consumption unless thoroughly treated.

Oyeku & Eludoyin (2010) used water quality index (WQI) method to evaluate the water qualities of surface and subsurface water of the Oluyole Industrial estate. They classified the surface water dominantly under bad quality category, while that of subsurface water is dominantly of medium quality category based on WQI scheme. Edet & Okereke (2003) studied the trace element hydrochemistry of the Calabar Coastal Plain aquifer using statistical methods. The research concluded that the sources of the trace elements in the aquifer of the area were due to geogenic processes and not anthropogenic processes. Mahanad *et al*. (2010), did a preliminary assessment of the groundwater quality of the Baghdad district, Oriss. The research noted that the high number of indicator micro-organisms counts in the groundwater in the area to be a reflection of the poor quality of water in the area. It linked the sources of the contaminations to human activities.

Mishra & Bhatt (2008) determined the quality of underground water in Nagar and nearby place of Anand district, Gujarat, India. They reported that the majority of the parameters determined were within the (WHO, 2002) standard, except for chloride, chemical oxygen demand (COD) and E-coli that exceeded the permissible limits in some samples. Sayyed and Arjun (2011) determined the concentration of chloride, sodium and potassium in

groundwater samples of Nanded City in Mahabharata, India and concluded that groundwater quality of the area is controlled by agriculture activities, geological formation and local environmental conditions. Rani and Babu (2008) reported that the major-ion chemistry of groundwater in Tamil Nada river basins, southern India is greatly influenced by mineral dissolution, anthropogenic activities and water level fluctuations in different geological formations.

2.3.1 Groundwater occurrences in basement complex

The crystalline basement rocks lack primary porosity and permeability when fresh but can store and transmit groundwater after the development of regolith and discontinuities in their rock mass due to weathering and fracturing. The ancient land, when exposed to prolonged weathering could result in the formation of a mantle of alteration products. This regolith includes both the residual soil and the saprolite (Chilton and Forester, 1993). The occurrence, distribution, movement, recharge-discharge and quality of groundwater in these aquifers vary largely from place to place and in some cases in boreholes located at only a few metres apart in the same rock types (Banks *et al*., 1994). These differences are caused by a combination of both independent and inter-related factors on regional and local scales (MacDonald *et al*., 2005). Gustafson & Krasny (1994), Chilton and Forester (1993) and Dash (2003) have listed these factors as geomorphological, lithological, climatological, hydrogeological and hydrogeochemical.

Preliminary assessment of geophysical and borehole drilling data collected, so far indicate that the weathered regolith varies in thickness from 2m or less to as deep as about 45m in places (Eduvie, 2003). Similar characteristics have been pointed out by other workers (Hazell *et al*.,1992; Olasehinde, 1999; Olayinka, 1990; Dan-Hassan & Olorunfemi, 1999; Bala &

Onugba, 2001; Dan-Hassan, 2001; Edet & Okereke, 2003) in other parts of the country and Key (1992), Carruthers & Smith (1992), Yadav & Singh (2008) and Ganyaglo *et al*. (2010) in other parts of the world.

The lower aquifer horizon provides a more prolific yield due to its interconnected fracture systems, which serve as water transmission avenues on a regional scale. Consequently, the fractured bedrock remains the ultimate target for drilling of boreholes in basement terrains (Vandenberghe, 1982; Olorunfemi *et al.*, 1986; Olasehinde, 1989; Annor *et al*., 1990; Olorunfemi & Fasuyi, 1993; Olorunfemi *et al*., 2005; Dan-Hassan & Yaya, 2007; Diop & Tijani, 2008).

From analysis of data from 98 boreholes, the thickness of the weathered zone varies from 5 to 36 m and borehole yields range between 0.8 and 7.2 m^3/h (Eduvie, 2003). Similarly, a range of yields between 0.7 and 3.2 m^3/h was obtained from 184 boreholes during a rural water supply drilling programme under the China - Nigeria co-operation (China-FGN, 2006).

2.4 Review of Hydrogeophysical Investigations

A number of investigations have been carried out in the study area as discussed below. The Geological Survey of Nigeria commenced hydrogeological investigations in Northern Nigeria with emphasis placed on the actual exploitation of groundwater for rural communities (Du Preez & Barber, 1965). They research reported the presence of well-developed steeply dipping joints in some granite outcrops in parts of the study area. They postulated that these joints contain water but did not give their exact location.

Truswell & Cope (1963) reported the presence of substantial late and post orogenic transcurrent faulting in parts of the study area. Kogbe (1978) conducted geological and

geotechnical investigations of the then site of the Federal Capital City, giving technical inputs into the decision-making process at the planning stage of the creation of the Federal Capital Territory. The emphasis was on the development of the surface water and construction of treatment plant to serve the city.

Hazell *et al*. (1992) carried out geological and geophysical investigations for groundwater development in various parts of Northern Nigeria, including the present study area, using combined electromagnetic and electrical resistivity methods. They concluded that thorough geological and geophysical investigations are required to locate feasible borehole sites that will yield economic quantities of water. Offodile (1992) used electrical resistivity techniques to locate successful borehole sites within the premises of Nicon Hilton Hotel. The boreholes were drilled to depths of about 100 m into the basement rock and intercepted the fracture systems, which had been identified by iso-resistivity mapping.

The electrical resistivity method is the most popular of all the geophysical methods that are used in groundwater investigation in Nigeria. It is also the most versatile. The method is relevant in depth to bedrock estimation, aquifer delineation and structural mapping (Idornigie & Olorunfemi, 1992; Olorunfemi & Fasuyi, 1993; Dan-hassan and Olorunfemi, 1995; Nwankwo *et al*., 2004; Olorunfemi *et al*., 2005).

CHAPTER THREE

3.0 RESEARCH METHODOLOGY

3.1 Stage of Investigation

The methodology adopted for this research comprises field data, which consists of in situ sampling, and lithological data acquisition, which consists of borehole lithological logs. Field data consisted of three approaches, namely geological, hydrogeological and geophysical. Two components composed the hydrogeological approach such as static water level measurements from existing hand dug wells and pumping test (Figure 3.1).

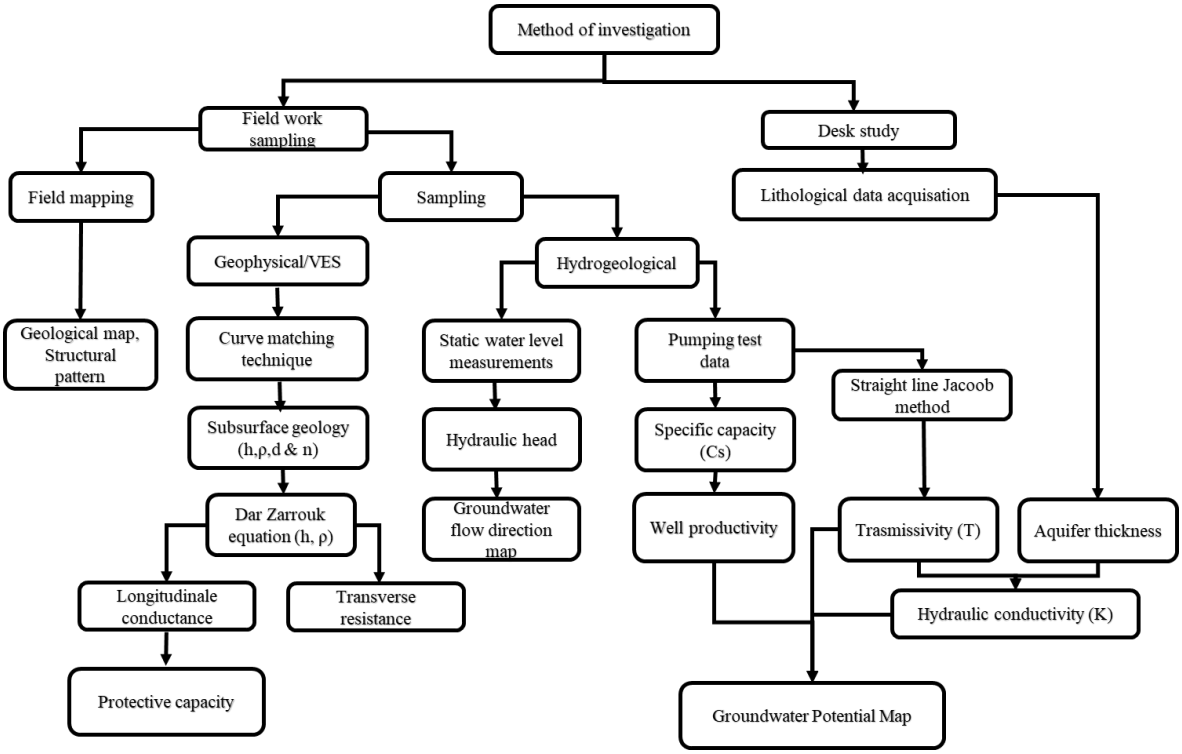

Figure 3.1: A schematic chart showing methods of investigation

3.2 Desk Study

Maps, reports and academic papers on geological and hydrogeological conditions of the study area were gathered and exanimated for understanding of the groundwater resources of the area.

3.3 Field Work

As mentioned in the section 3.1, the field work was classified in three units which included Field geological mapping, geophysical survey and hydrogeological investigation.

3.3.1 Geological mapping

The fundamental basis of any groundwater study is geology. The geological mapping was the first field stage of this research, carried out in the period from 6th to 11th June 2022. During the mapping exercise, emphasis was laid on structural features such as joints and folds. Thus, the geological mapping of the area was undertaken using the traverse method on available foot paths and minor roads leading to the production of geology map of the study area. Rock samples were collected from exposed rocks in the study area while joint direction were collected with the aid of the compass clinometer. The topographic map of Kuje 207 NW was used in the mapping on a scale of 1:12,500.

3.3.2 Geophysical investigation

Electrical resistivity surveying involving vertical electrical soundings (VES) was carried out in this research. Ten VES measurements were employed within the study area using the Schlumberger array configuration, chosen preferably by the side of the boreholes subject to pumping test. Four electrodes were placed systematically along a straight line, with the two

electrodes on the outside (A, B) and inside (M, N) respectively serving as current and potential or voltage electrodes (Figure 3.2). The current was injected into the ground through the current electrodes (A and B) and then the resultant potential difference was measured between the two potential electrodes (M and N).

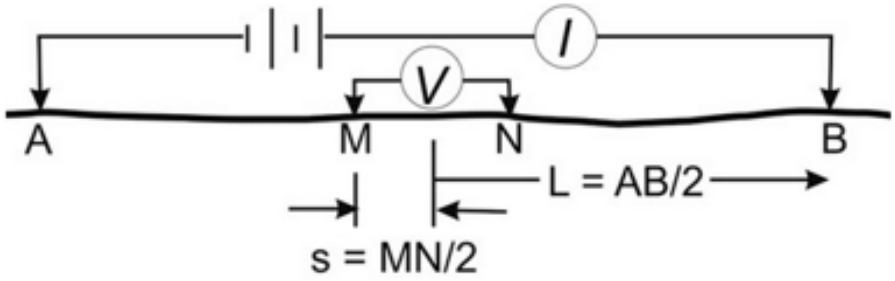

Figure 3.2: Schlumberger array configurations
(Vertical electric sounding (VES): Schlumberger and Wenner method, 16th December 2022, https://steemit.com/steemstem/@derm10/vertical-electric-sounding-ves-schlumberger-and-wenner-methods)

Field equipment employed was the ABEM SAS Terrameter 1000 for the electrical resistivity measurements, which was powered by 12V D.C power source, 4 cable wheels and 4 electrodes for current injection and voltage record, 4 hammers for fixing the electrodes and a measuring tape.

The resistivity survey helped to determine the subsurface conditions in terms of apparent resistivity (ρ_a), depth (d), thickness (h) and number of layers and deducing the Dar-Zarrouk parameters by computing the apparent resistivity and thickness in order to determine the aquifer protective capacity (APC) in the area.

Current electrode separation AB/2 was ranged from 1meter to a minimum of 100 meters at VES 9 and 160 meters as maximum at VES 3, VES 4, VES 6, VES 7 and VES 8. AB/2 was 140 meters for VES 2 while it was 160 meters for VES 1, VES 5 and VES 10. The potential electrode MN/2 was ranged from 0.5m to 20m. With Schlumberger configuration, the

potential electrodes M, N are closely spaced and centrally fixed at a distance normally less than one fifth between the current electrodes A, B and are held constant while the latter are moved outwards, enabling a good resolution and a better depth of penetration to be achieved. Hereby, the arrangement between the current and the potential electrodes was done according to the model described in Table 3.1.

Table 3.1. Field sheet for recording of VES

SCHLUMBERGER SOUNDING DATA SHEET			
Location…… VES n°: …… Date……..			
Coordinates……E ……N Altitude……			
AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5		
2.0	0.5		
3.0	0.5		
4.0	0.5		
6.0	0.5		
8.0	0.5		
12	0.5		
15	0.5		
20	0.5		
25	0.5		
32	5.0		
40	5.0		
50	5.0		
60	5.0		
70	10		
80	10		
90	10		
100	10		
120	10		
140	10		
160	20		
180	20		
200	20		

3.3.3 Measurement of static water levels

The determination of the groundwater flow direction involved the measurement of static water level (SWL) from existing hand dug wells, their topographic elevations and coordinates in nearby communities within the study area. Depth to water of 30 hand-dug wells were taken with a 250 metre long weighted measuring tape graduated to the centimetre, made of plastic and fibreglass. A total of nine locations were taken in Dukpa, one in Gwagwalada, six in Passo, four in Paikon Kore, five in Kaida and five in Koroko. The weighted tape was lowered into the wells and as it touches the water, the depth to water level was read out on the ground surface and recorded. The elevations and topographic coordinates were determined with a Geographic Positioning System (GPS). The measurements were carried out during the rain season, in June, when the SWL is at its highest.

3.3.4 Pumping test

To carry out pumping test, it involved applying a stress to aquifers by extracting groundwater from a pumping well and measuring the aquifer response to that stress by monitoring drawdown as a function of time. Pumping tests were carried out for 10 boreholes between 28th June to 10th July 2022 within the study area in order to determine the aquifer hydraulic properties such as transmissivity and hydraulic conductivity. A constant rate and recovery test was used for this research to achieve this purpose. Single-well aquifer test was used: the pumping test and the drawdown measurements were made in the same borehole.

Well information were measured before and during pumping test exercise. The discharge rate of the well and the changes in water levels (drawdown and recovery) in the well were the two measurements done during the aquifer test. All information about the well such as the

depth, the radius, the static water level, and the pump setting depth were taken before pumping started.

Field equipment used consist of a submersible pump type U.S.K model 4SDM310, 30 liters bucket was used as container to measure the discharge rate, an electronic dip meter to take water-level readings, 3.5 kVA generator used as source of power, field sheet for recording of water level fluctuation, notebook, pen, calculator, toolkit, protective clothing, mobile phone, chronometer and Geographical Positioning System (GPS).

The pump was installed deep enough for each well at an average depth of 92% of the water column, in order to maintain it under water despite the drawdown. The pumping duration was ranged between 180 to 360 minutes, according to when the steady state was reached. Water-level measurements were done very frequently at the beginning, and then gradually lengthened as pumping continues. The measuring interval used was 1 minute for the first ten minutes, 5 minutes for the period from 10 to 60 minutes of pumping, 10 minutes from 60 to 120 minutes and finally 30 minutes from 120 minutes until pumping was exhausted (Table 3.2). As the pumping test was going on, the steady state condition was reached for all the ten boreholes. Indeed, after a certain period of pumping, there was no further drawdown with the time. The time required to fill the 30 liters of the bucket used as container was recorded, so by a simple equation, the discharge rate was deduced by dividing the time to the volume. To avoid water to soak into the ground and to flow back to the well after been pumped out of it, a pipe was used to run it at a distance more than 100 meters away to a ditch, so the risk of having false optimistic yield, hydraulic conductivity and storage was moved apart.

Table 3.2 Field sheet for recording of water level fluctuation (drawdown and recovery) in a pumped borehole

PUMPING TEST FIELD SHEET					
Location…… Borehole n°: …… Date……					
Coordinates……E ……N Altitude……					
Depth:……. Pump setting:……			SWL:…… Yield:……..		
Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recovery water level (m)	Residual drawdown (m)
0			0		
1			1		
2			2		
3			3		
4			4		
5			5		
6			6		
7			7		
8			8		
9			9		
10			10		
15			15		
20			20		
25			25		
30			30		
35			35		
40			40		
45			45		
50			50		
55			55		
60			60		
70			70		
80			80		
90			90		
100			100		
120			120		
150			150		
180			180		
210			210		
240			240		
300			300		

3.4 Data Analysis and Interpretation

3.4.1 Geophysical investigation and Dar-Zarrouk computation

Vertical electrical sounding (VES) data were interpreted using the curve matching technique. The curves were obtained by plotting the apparent resistivity data (ρa) as ordinates against the electrode AB spacing as abscissa in the log-log plot. The subsurface conditions were deduced from a measured sounding curve in terms of the number of layers, their resistivities and thicknesses.

Resistivities and thicknesses of each geoelectric layers are combine together to obtain the Dar Zarrouk parameters (Yusuf *et al.*, 2021; Egbai & Iserhien-Emekeme, 2015). Maillet (1947) introduced into electrical prospecting the term Dar-Zarrouk for describing a relationship between the longitudinal unit conductance and the transverse unit resistance (Zohdy *et al.*, 1974; Nugraha *et a.l*, 2022). Dar-Zarrouk parameters consists of Longitudinal conductance, S (Ω-1) and Transverse resistance, T (Ωm2) (Egbai & Iserhien-Emekeme, 2015).

For a sequence of n layers of resistivity ρ_i and thickness h_i, the longitudinal unit conductance, S, the transverse unit resistance, T, and the coefficient of anisotropy λ are defined by:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \qquad (\Omega^{-1}) \qquad \text{Equation 3.1}$$

$$T = \sum_{i=1}^{n} h_i \rho_i \qquad (\Omega m^2) \qquad \text{Equation 3.2}$$

$$\lambda = \sqrt{\frac{\rho_T}{\rho_L}} \qquad \text{Equation 3.3}$$

Where ρ_T and ρ_L are respectively the average transverse resistivity and average longitudinal resistivity.

$$\rho_T = \frac{T}{H} \quad (\Omega m) \qquad \text{Equation 3.4}$$

$$\rho_L = \frac{H}{S} \quad (\Omega m) \qquad \text{Equation 3.5}$$

Where

$$H = \sum_{i=1}^{n} h_i \quad (m) \qquad \text{Equation 3.6}$$

The protective capacity and longitudinal unit conductance are considered to have a proportional relationship. Longitudinal unit conductance, S can be used directly in the protective capacity evaluation of aquifers to signify the regulation of percolation of contaminants into the aquifer. The transverse unit resistance, T, may be of use in assessing the hydrological properties of aquifers (Henriet, 1976, Yusuf & Abiye, 2019). There is physical correlation between Transverse resistance and Transmissivity (Henriet, 1976). Increases in Transverse resistance values are associated with regions of high transmissivity (Yusuf & Abiye, 2019).

3.4.2 Groundwater level measurement

Four parameters were measured on the field, such as the depth of hand-dug wells, depth to water, their topographic elevations and coordinates. The data generated from water level measurements were applied to the determination of depth to water contour and hydraulic head maps. By subtracting the depth to water measured of each well from its topographic elevation above mean sea level, the hydraulic head of each well was obtained (Equation 3.7).

$$h = Z - d \qquad \text{Equation 3.7}$$

Where

h is the Hydraulic Head (meter)

d: Depth to water (meter)

Z is the Topographic Elevation above mean sea level (meter)

In practice, the height to which water can rise in a well relative to a datum defines the hydraulic head. The depth to water measured and hydraulic head values generated combined to their coordinates were computed through Surfer to construct respectively the depth to water contour and hydraulic head maps. The direction of flow was read from the hydraulic head map, flow occurs from high toward low hydraulic head.

3.4.3 Pumping test

The data generated from aquifer tests was used to calculate the aquifer hydraulic properties such as transmissivity, T and hydraulic conductivity, K by being incorporated into appropriate well-flow equations.

3.4.3.1 Transmissivity (T)

In this research, where the abstraction wells were used as observation wells, Cooper-Jacob method was found suitable (Abimiku *et al.*, 2019). The method gives a simpler algebraic solution to the Theis equation and permited to determine the drawdown without the use of well functions (Okogbue & Omonona, 2013). On the basis of the analogy between flow of water in an aquifer and flow of heat in a thermal conductor, Theis stated the flow equation for confined aquifer (Fetter, 2001). The solution that Theis developed is given as:

$$T = \frac{Q}{4\pi(h_0 - h)}\left[-0.5772 - \ln u + u - \frac{u^2}{2 \bullet 2!} + \frac{u^3}{3 \bullet 3!} - \frac{u^4}{4 \bullet 4!} + \cdots\right] \qquad \text{Equation 3-8}$$

The infinite-series term in equation 3-8 has been called the well function and is generally designated as $W(u)$.

$$T = \frac{Q}{4\pi(h_0 - h)} W(u) \qquad \text{Equation 3.9}$$

Cooper and Jacob (1946) observed that after a long pumping period, the higher values of the infinite series can be neglected, and the non-equilibrium formula could be closely approximated by:

$$T = (\frac{2.3Q}{4\pi s}) log_{10} \frac{2.25Tt}{Sr^2} \qquad \text{Equation 3.10}$$

or

$$s = (\frac{2.3Q}{4\pi T}) log_{10} \frac{2.25Tt}{Sr^2} \qquad \text{Equation 3.11}$$

Where
T is transmissivity (m^2/day)
S is the storativity (dimensionless)
Q is the steady pumping rate (m^3/day)
s is drawdown (metres)
t is time since pumping began (minutes)
r is the distance to the observation well (metres)

Therefore, a plot of drawdow, symbolized by s versus the logarithm of t forms a straight line figure 3.1, projectig this line to $s = 0$, where $t = t_0$ (see figure 3.1), we have

$$0 = (\frac{2.303Q}{4\pi T}) log \frac{2.25Tt_0}{Sr^2}$$

$$0 = log_{10} \frac{2.25Tt_0}{Sr^2} \text{ ; with } 0 = \log 1$$

$$\frac{2.25Tt_0}{Sr^2} = 1$$

$$S = \frac{2.25Tt_0}{r^2}$$

A value of T can be obtained by noting that if $^{t}/_{t_0} = 10$, then $\log {}^{t}/_{t_0} = 1$, therfore replacig s by Δs, the equation becomes

$$T = \frac{2.303Q}{4\pi\Delta s} \qquad \text{Equation 3.12}$$

Q is the steady pumping rate (volume per unit time) measured during pumping test, Δs is the drawdown difference per log cycle (meter), obtained by plotting the time against the drawdown in the semilogarithmic plot (see Figure 3_1).

3.4.3.2 Transmissivity index (Y)

The relationship between the transmissivity and the transmissivity index, Y was founded in 1968 by Jetal and Krasny (Asfahani, 2021):

$$T = 10^{(Y-8.96)} * 86400 \qquad \text{Equation 3.13}$$

The Equation 3-13 can be modified into:

$$Y = \log({}^{T}/_{86400}) + 8.96 \qquad \text{Equation 3.14}$$

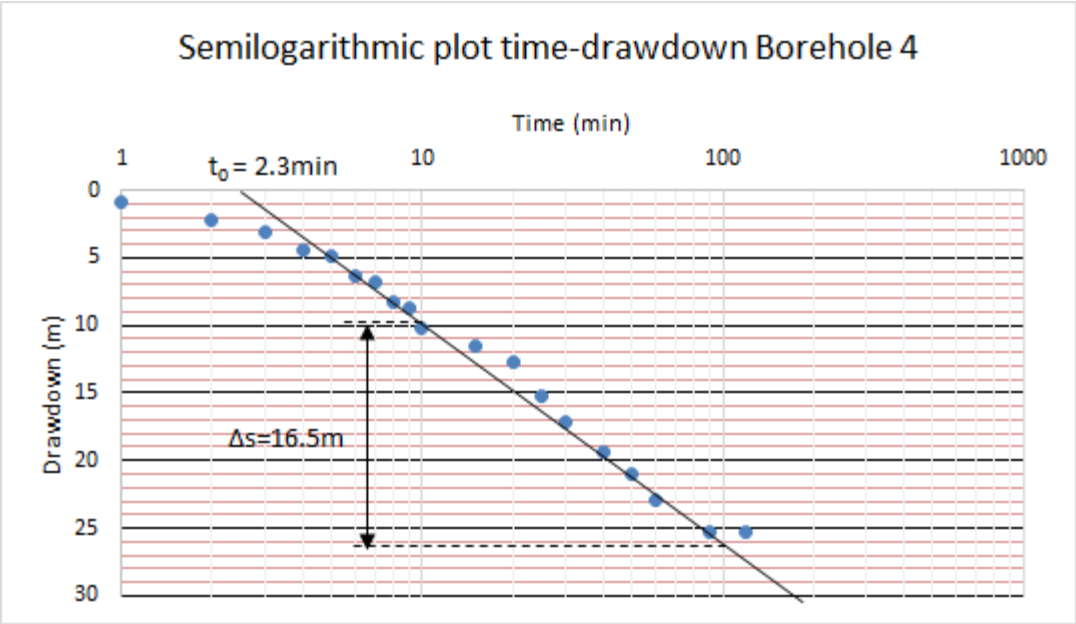

Figure 3.1. Semilogarithmic plot time-drawdown (Borehole 1)

3.4.3.3 Hydraulic conductivity (K)

A medium has a unit hydraulic conductivity if it can transmit a unit volume of groundwater through a cross-section of a unit area, measured perpendicular to the direction of flow, under a unit hydraulic gradient in one unit of time (Mays & Todd, 2005).

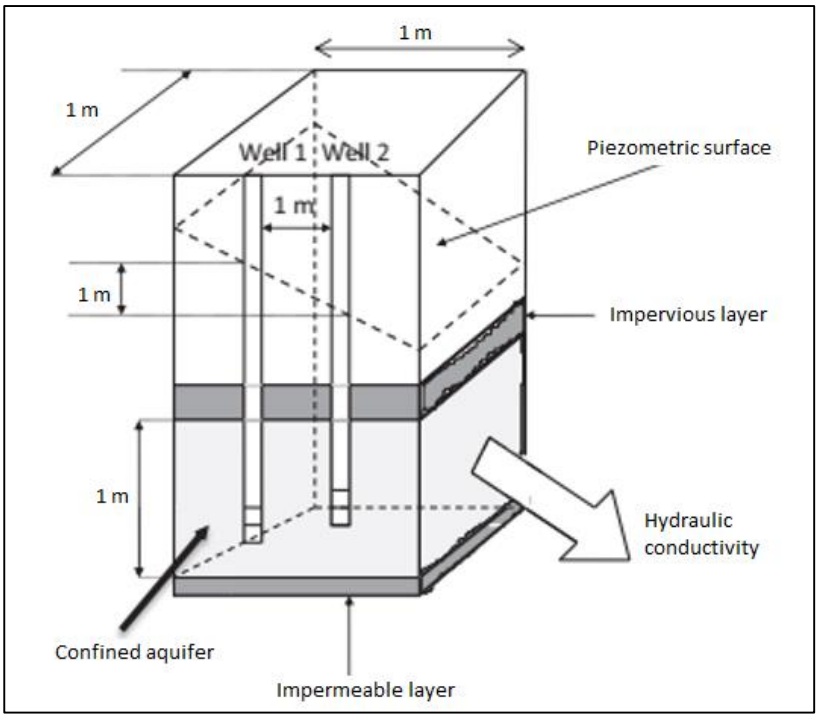

Figure 3.2: Hydraulic conductivity sketch

It follows that hydraulic conductivity is the ratio of transmissivity to the Aquifer thickness (Equation 3-15).

$$K = T/b \ \ (m/day) \qquad \text{(Equation 3.15)}$$

K is the hydraulic conductivity (m/day)

T is transmissivity (m^2/day)

b is the aquifer thickness (meter)

The transmissivity values were obtained from pumping test data while the aquifer thicknesses were deduced from the borehole lithologic logs.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Summary of Findings

This chapter presents the results from the analysis with respect to the different objectives set out at the beginning of the research. The geological mapping of the area was carried out using the traverse method on the available footpaths and secondary roads. The structural pattern was determined through the joint direction measurements. Single-well pumping tests was carried out on 10 boreholes within the study area using constant pumping rate method. The static water level (SWL), yield, drawdown and recovery of the borehole was determined and used to quantify the aquifer properties in the area. The SWL of 30 hand dug wells in the surrounding communities including their topographic elevations and coordinates were measured and converted to hydraulic head values used to produce the groundwater flow direction map of the area. The longitude, latitude, elevation of the borehole, hand dug wells and outcrops mapped were recorded in hardcover field notebook. Photographs of the sampled hand dug wells, boreholes and structural elements such fold, fault, joint and fractures were taken with digital camera.

4.2 Local Geology of the Study Area

Detailed mapping of the area on scale 1:12,500 was undertaken using the traverse method. Most of the outcrops occur in the north eastern part of the study area. The study area is underlain by granite-gneiss (Figure 4.1) and were studied at mesoscopic scale (outcrop level).

The granite-gneiss form low-lying exposures which are generally elongated along strike of the foliation in the rocks while in some cases occur in form of a ridge. The granite-gneiss is

generally pinkish-grey, coarse-grained and in hand specimen consists of feldspar, quartz and biotite. Gneissic foliation of alternating felsic (light minerals) and biotite (dark minerals) characterize the alignment in the rocks (Plate i).

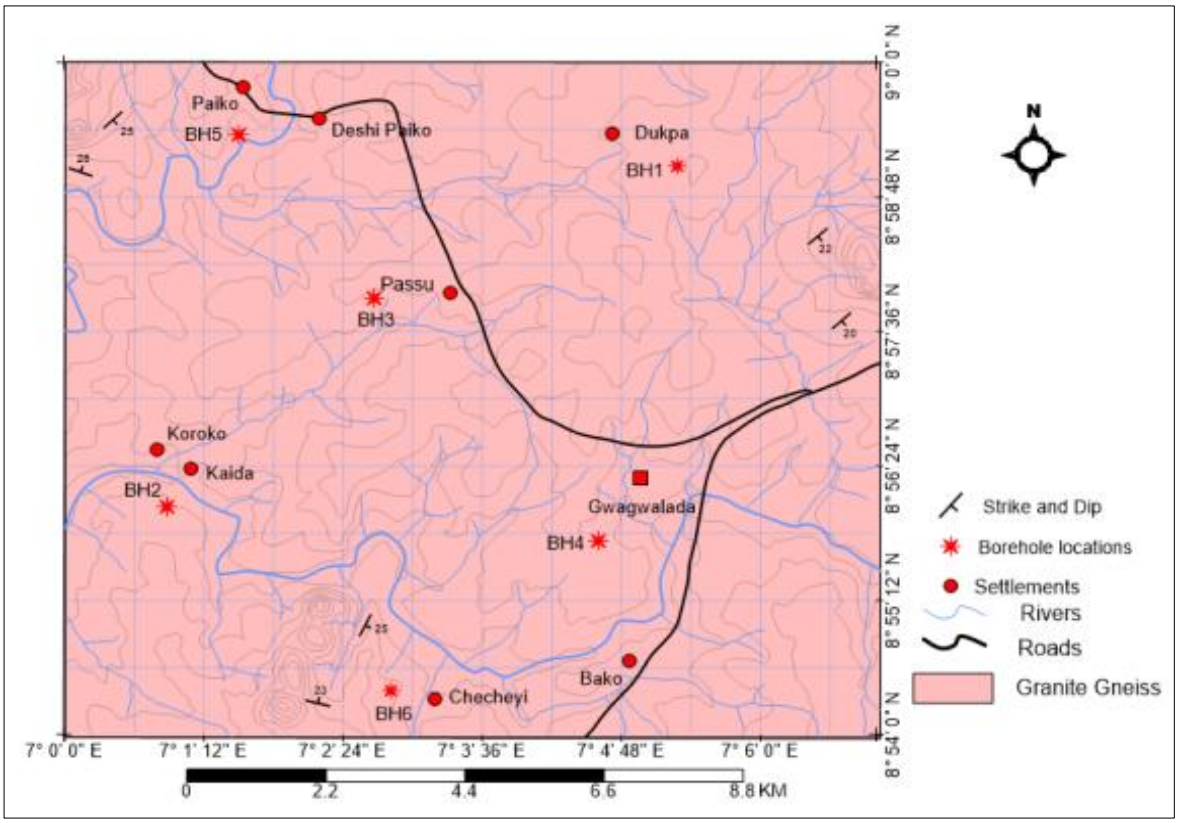

Figure 4.1: Geological map of the Study Area

During the mapping exercise, emphasis were made on structural features such as foliations, joints (Plate ii) and folds (Plate iii). Pegmatite veins cut across the granite-gneiss outcrops in several locations (Plate iv). The joint direction values measured in the field were used to plot the Rosset diagram (Figure 4.2) which shows the structural pattern in the area. The Rosset diagram of the area showed two joint directions namely: the major NE-SW direction followed by the SE-NW direction (Figure 4.2, Plate ii). The NE-SW joint direction is more dominant and widespread compared to the SW-NE joint direction. It implies that the area has witnessed two orogenic events that are different in time and direction. Economically, these are the

preferred direction for deposition and occurrence of economic minerals such as gold while structurally, foundations need to be reinforced along these directions to avoid cracks and possible failure arising from differential settlements along these axis.

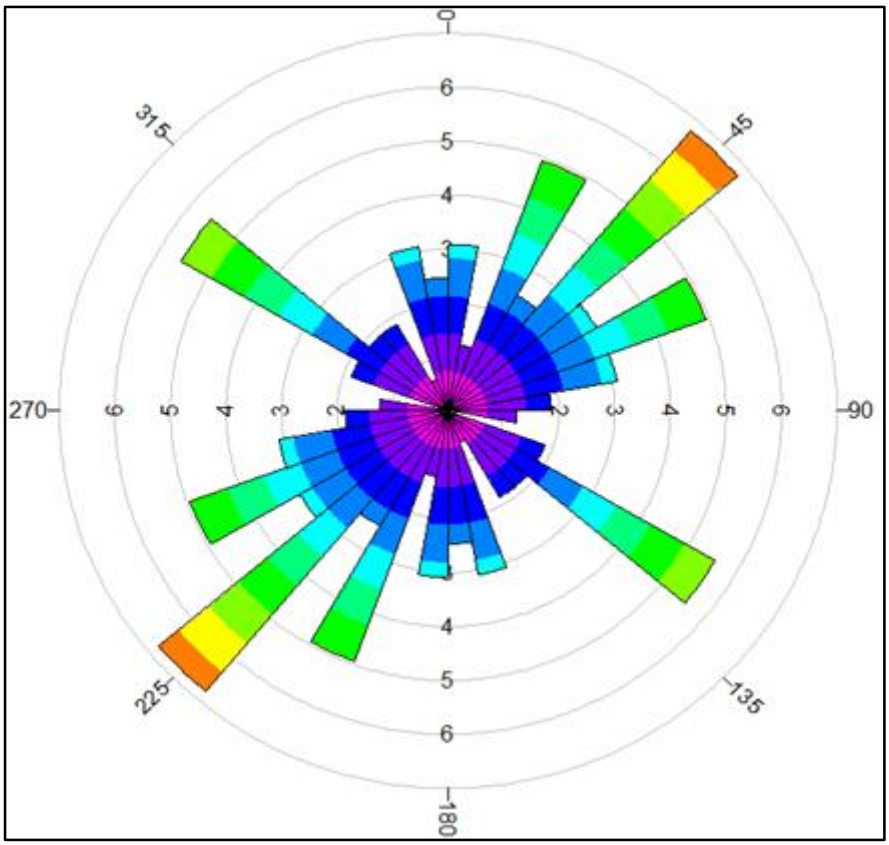

Figure 4.2: Rose plot showing joint directions (trend of fractures) within the study area



Plate i: Rock sample showing the Luecosomes (light minerals) and Melanosomes (dark minerals) of granite-gneiss within the study area (N 08° 59' 59.1", E 07°00' 24.8")



Plate ii: A system of joints in the granite-gneiss of the study area (N 08°59'45.1", E 07°00'32")



Plate iii: Evidence of ptygmatic folds on the granite-gneiss (N 08° 59' 45.1", E 07°00' 32")



Plate iv: Pegmatitic dyke intruding the migmatites of the study area (N 08° 59' 59.1", E 07° 00' 24.8")

4.3 Groundwater Flow Determination

Hydrogeology deals with the occurrence, exploration, exploitation, movement, utilization, quality and management of groundwater resources (Rizwan, 2018). It also studies the interaction between surface water and groundwater system. Groundwater is the water found below the water table (zone of saturation), where the pores spaces (voids) are completely filled with water (Amadi *et al.*, 2020). Groundwater is hosted by aquifers, which are geological formation that stores and transmits water economically to a well (borehole). Aquifers are characterized by high porosity and permeability (hydraulic conductivity). Groundwater moves from areas of high hydraulic head to regions of low hydraulic head (due to hydraulic gradient) obeying Darcy's Law, in a laminar flow.

The water table measurement is one of the widely used techniques used to estimate groundwater recharge apart from pumping test. The use of this method requires knowledge of the borehole yield and changes in water levels over time and these parameters has been determined through pumping test method. The determination of the groundwater flow direction involves the measurement of static water level (SWL) nearby communities and their corresponding elevation values above sea level.

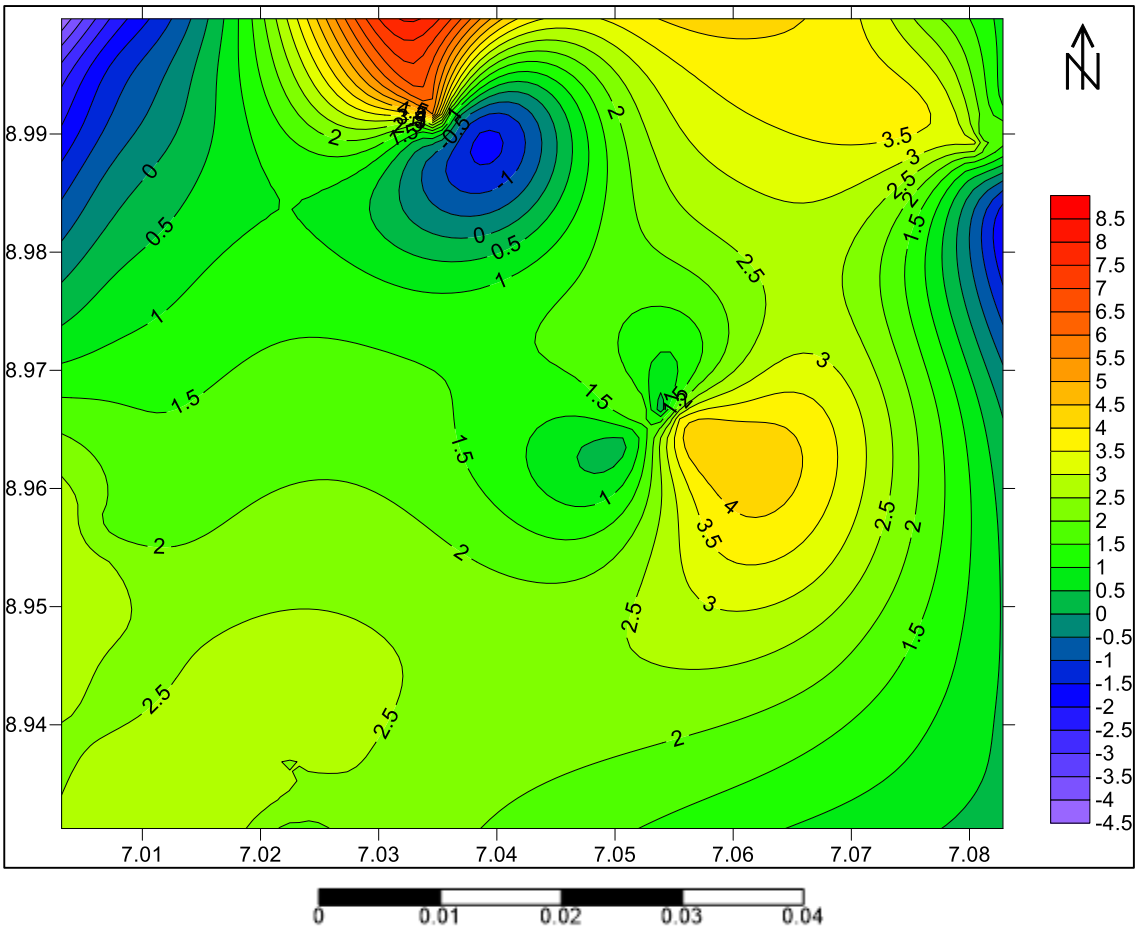

Figure 4.3: Static water level depth map for the study area

The hydraulic head values were obtained by subtracting the static water level values of each hand dug well from their corresponding elevation values above sea level. At Dukpa, the hydraulic head values vary from 135.9 to 281.5 m, with an average value of 212.53 m, at Passo an average hydraulic head value of 190.1 m was recorded ranging between 177.5 and 201.8 m, an average of 175 m in Paikon Kore, 171.8 in Kaida and 158.9 in Koroko (Table 4.1).

The groundwater flow direction map was modeled by using the hydraulic head values and corresponding coordinates through Surfer 10 software (Figure 4.3).

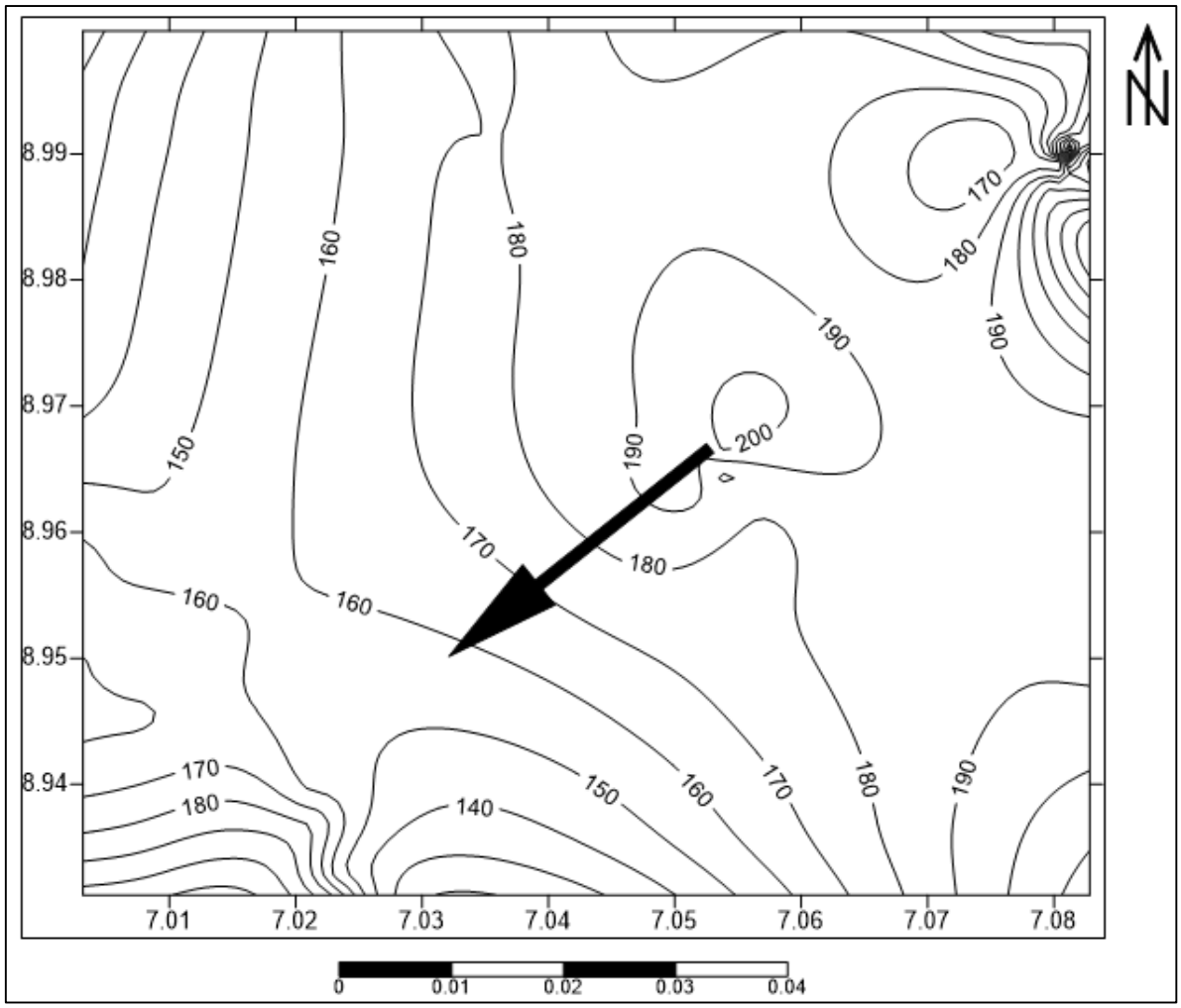

Figure 4.4: Groundwater flow direction map of the area

The groundwater flow map indicates that the groundwater in the area flows from northeast to southwest direction. The NE-SW groundwater flow direction coincides with the major principal joint direction (Figure 4.2), a confirmation that the groundwater flow direction in the area is structurally controlled. This further explains the overlapping and interwoven nature of geology, structural geology and hydrogeology in relation to groundwater studies.

Table 4.1: Data obtained from measured hand dug wells within the Study Area

No.	Location	Latitude	Longitude	Elevation (m)	Static water level (m)	Depth of well (m)	Hydraulic Head
1	Dukpa	08° 59' 22"	07°04' 50.8"	139	3.1	5.5	135.9
2	Dukpa	08° 59' 22"	07°04' 50.7"	215	3.1	4.2	211.9
3	Dukpa	08° 59' 24.6"	07°04' 53.7"	220	1.5	4.9	281.5
4	Dukpa	08° 59' 24.5"	07°04' 54.9"	216	1.8	6.9	214.2
5	Dukpa	08° 59' 28.4"	07°04' 58.2"	224	1.6	5.1	222.4
6	Dukpa	08° 59' 31.9"	07°04' 55.9"	217	1.3	4	215.7
7	Dukpa	08° 59' 30.7"	07°04' 52.7"	214	1.8	7	212.2
8	Dukpa	08° 59' 15.8"	07°04' 47.0"	207	1.6	5.5	205.4
9	Dukpa	08° 59' 14"	07°04' 48.1"	214	0.8	5.5	213.2
10	Gwagwalada	08° 59' 59.1"	07°04' 35.8"	214	2.2	5.5	211.8
11	Passo	08° 57' 55.8"	07°03' 19.0"	196	3.5	5.7	192.5
12	Passo	08° 57' 59.8"	07°03' 14.8"	202	0.2	4.1	201.8
13	Passo	08° 57' 58.9"	07°03' 7.0"	193	2.0	5.5	191.0
14	Passo	08° 57' 52.8"	07°03' 6.6"	194	0.6	4.7	193.4
15	Passo	08° 57' 49.8"	07°03' 12.5"	187	2.6	5.5	184.4
16	Passo	08° 57' 51.5"	07°03' 14.9"	180	2.5	4.5	177.5
17	Paikon Kore	08° 59' 31.5"	07°02' 5.5"	175	5.5	6	169.5
18	Paikon Kore	08° 59' 31.3"	07°02' 9.6"	184	0.0	6.2	183.9
19	Paikon Kore	08° 59' 30.1"	07°02' 10.8"	177	2.2	3.2	174.8
20	Paikon Kore	08° 59' 27.3"	07°02' 1.4"	174	2.0	4.1	172.0
21	Kaida	08° 56' 03,3"	07°01' 13"	192	2.7	5.7	189.3
22	Kaida	08° 56' 12.7"	07°01' 18.4"	180	2.5	4.4	177.5
23	Kaida	08° 55' 58.1"	07°01' 23.8"	158	2.3	4.6	155.7
24	Kaida	08° 56' 22.2"	07°01' 15.1"	164	2.7	5.1	161.3
25	Kaida	08° 55' 52.4"	07°01' 22.4"	177	1.9	4.6	175.1
26	Koroko	08° 56' 58.7"	7° 0' 11.4"	162	2.8	4.9	159.2
27	Koroko	08° 57' 12,3"	7° 0' 25.2"	170	2.5	4.5	167.5
28	Koroko	08° 57' 28,1"	7° 0' 25.2"	154	1.8	3.0	152.2
29	Koroko	08° 57' 31,9"	7° 0' 22"	158	2.2	3.5	155.8
30	Koroko	08° 56' 42,7"	7° 0' 29.3"	162	2.4	4.0	159.6

4.4 Geo-electrical Characterization

The electrical resistivity method was used to determine the subsurface conditions in terms of the number of layers in the substrate, the thickness of each layer and the ratio of the resistivity of the layers are presented in Table 4.2. This is based on the shape of the VES Curve which is a consequence of these parameters. The results of the quantitative interpretation revealed that typical 4- and 5- geoelectrical subsurface layers characterize the area, generating eight types of resistivity curves. The type curves include 2-KH ($\rho_1 < \rho_2 > \rho_3 < \rho_4$), 2-HK ($\rho_1 > \rho_2 < \rho_3 > \rho_4$), 1-HKH ($\rho_1 > \rho_2 < \rho_3 > \rho_4 < \rho_5$), 1-AA (, $\rho_1 < \rho_2 < \rho_3 < \rho_4$), 1-HA $\rho_1 > \rho_2 < \rho_3 < \rho_4$), 1-KQH ($\rho_1 < \rho_2 > \rho_3 > \rho_4 < \rho_5$), 1-HAK ($\rho_1 > \rho_2 < \rho_3 < \rho_4 > \rho_5$) and 1-KHK ($\rho_1 < \rho_2 > \rho_3 < \rho_4 > \rho_5$) (Figure 4.5).

The surface layer, averaging 0.98m thick and ranging from 0.5m to 1.8m, is observed in all VES locations. It exhibits a wide variation in resistivity ranging from 45.0 to 1194.4 Ωm with an average of 281.23 Ωm and is identified as laterite by correlation with the general lithological log of the area. Underlying the laterite is a layer correlated to reddish brown, sandy clay and clayey sands, ranging in thickness from1.4 to 8.4 m with an average of 4.68 m, and of resistivity between 13.1 to 531.1 Ωm with an average of 168.94 Ωm. The weathered and/or fractured bedrock in the study area occurs in the third and fourth geoelectric layers. In the third geoelectric layer, these units have a range of resistivity between 33.7 Ωm and 1414.1 Ωm with an average value of 499.78 Ωm, a thickness of between 10.7 m and 69.5 m with an average of 29.93 m. In the fourth layer, the weathered/fractured zones have a resistivity ranging from 72.7 Ωm to 5378 Ωm and an averaged resistivity value of 1969.36 Ωm with a thickness ranging from 12.7 m to 92.2 m and an average thickness of 42.68 m.

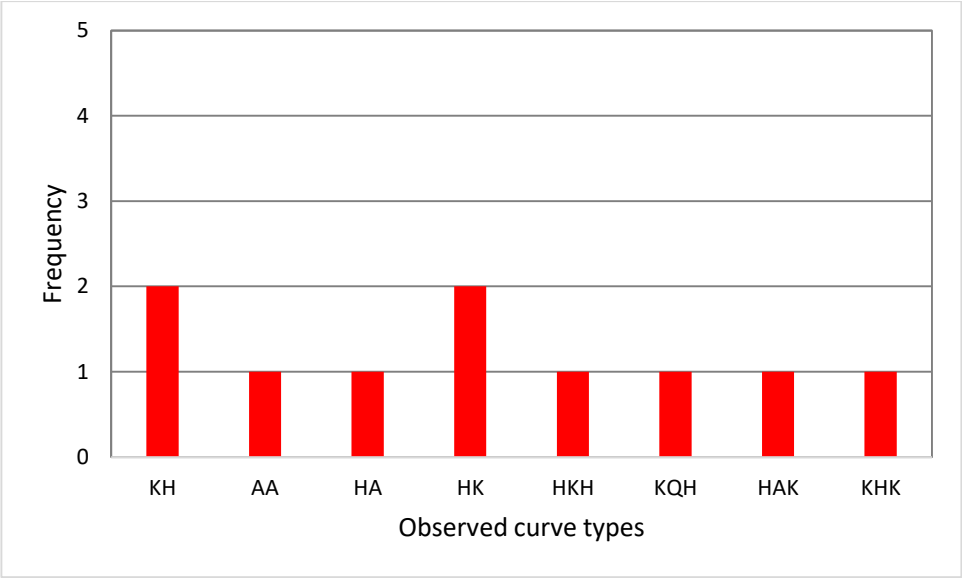

Figure 4.5 Frequency distribution of the observed curve types in the study area

Table 4.2 Results of resistivity, layer thickness surveys and classification of curve types

S/N	Lat.	Long.	location	1st layer		2nd layer		3rd layer		4th layer		5th layer		Curve type	Layer's resistivity relationship
				h_1 (m)	ρ_1 (Ωm)	h_2 (m)	ρ_2 (Ωm)	h_3 (m)	ρ_3 (Ωm)	h_4 (m)	ρ_4 (Ωm)	h_5 (m)	ρ_5 (Ωm)		
VES 1	8.9839	7.0881	Dukpa	0.5	1194.4	8.4	96.5	69.9	446.9	∞	341.0	-	-	HK	$\rho_1 > \rho_2 < \rho_3 > \rho_4$
VES 2	8.9321	7.017	Kaida	0.5	367.5	2.7	118.6	13.4	166.4	29.7	771.3	∞	83.7	HAK	$\rho_1 > \rho_2 < \rho_3 < \rho_4 > \rho_5$
VES 3	8.9618	7.0517	Passu	0.8	404.3	4.7	48.4	15.4	1414.1	∞	5044.1	-	-	HA	$\rho_1 > \rho_2 < \rho_3 < \rho_4$
VES 4	8.9322	7.0758	Gwagwalada	1.8	131.0	5.2	13.1	59.2	818.9	∞	265.1	-	-	HK	$\rho_1 > \rho_2 < \rho_3 > \rho_4$
VES 5	8.989	7.0268	Paiko	1.4	59.0	2.0	80.5	10.7	33.7	∞	5378.0	-	-	KH	$\rho_1 < \rho_2 > \rho_3 < \rho_4$
VES 6	8.9119	7.0528	Checheyi	1.0	252.2	6.7	469.6	25.6	157.1	92.2	632.7	∞	365.1	KHK	$\rho_1 < \rho_2 > \rho_3 < \rho_4 > \rho_5$
VES 7	8.9751	7.0645	NNPC Gas Plant	1.3	77.0	3.8	531.1	2.7	159.4	12.7	72.7	∞	8846.5	KQH	$\rho_1 < \rho_2 > \rho_3 > \rho_4 < \rho_5$
VES 8	8.9789	7.0673	NNPC Gas Plant	0.9	128.8	6.8	151.5	31.1	139.5	∞	1734.7	-	-	KH	$\rho_1 < \rho_2 > \rho_3 < \rho_4$
VES 9	8.971	7.0762	NNPC Gas Plant	0.6	153.8	1.4	21.5	12.9	513.4	36.1	163.6	∞	1204.7	HKH	$\rho_1 > \rho_2 < \rho_3 > \rho_4 < \rho_5$
VES 10	8.9723	7.0677	NNPC Gas Plant	1.0	45.0	5.1	138.6	32.5	630.2	∞	5290.4	-	-	AA	$\rho_1 < \rho_2 < \rho_3 < \rho_4$

4.5 Groundwater Potentials

4.5.1 Pumping test data

Pumping test analyses provide useful platform to assess the yield and potential of the aquifer system. The Table 4.3 presents the boreholes parameters measured before and during the pumping test. Borehole depth values are ranged between 124 meters and 200 meters, the SWL values are ranged from 1.2 meters to 19.4 meters having an average value of 6.8 meters. The boreholes were pumped at a constant discharge ranged from 82.08 m^3 to 319.68 m^3 per day. The consequent drawdowns in the boreholes are highly variable, ranging from 6.57 meters to 84.6 meters, with an average value of 38.7 meters.

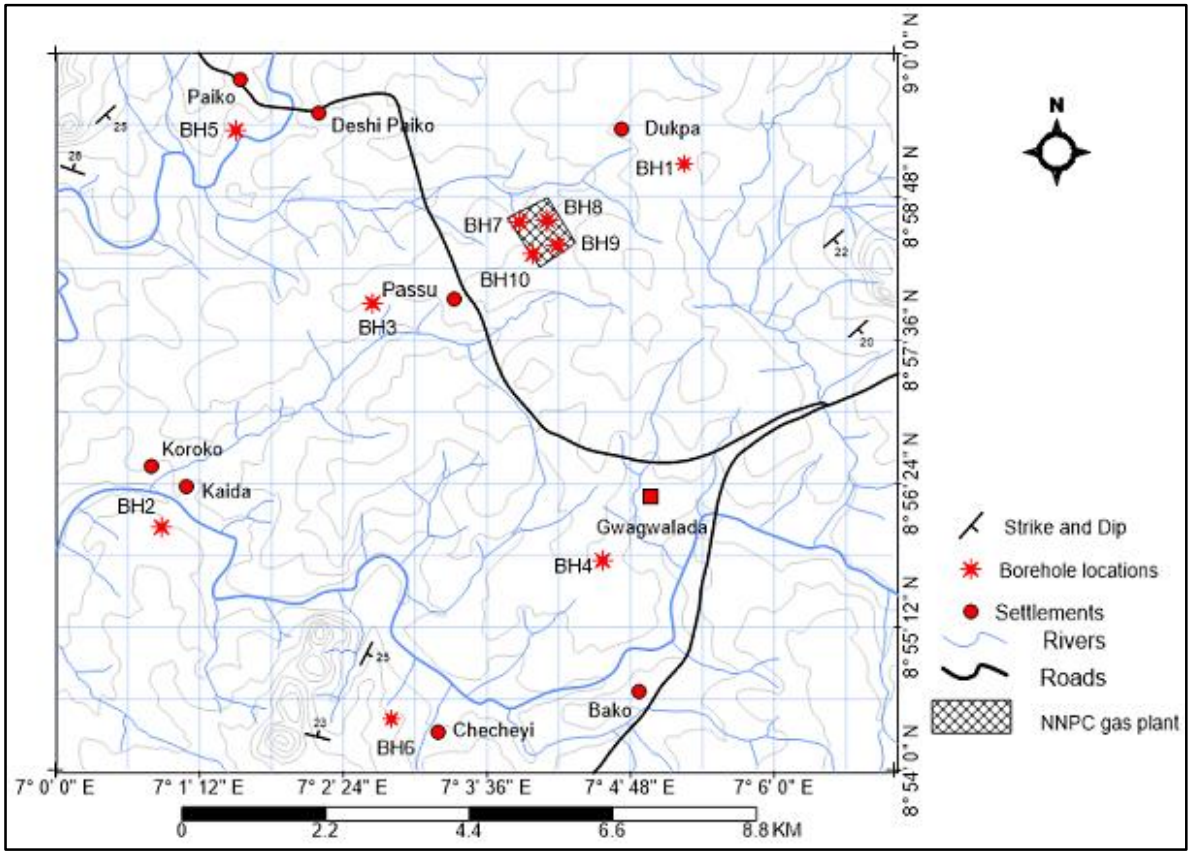

Figure 4.6: Borehole locations map

4.5.2 Lithology log

Both the general borehole lithologic log of the area and the weathered/fractured layer thicknesses were obtained from the borehole driller, Pionner GeoServices LTD. Generally, the subsurface in the study area is made up of lateritic soil, sandy clay or clayey sand, weathered basement, fractured and fresh bedrock (Figure 4.7).

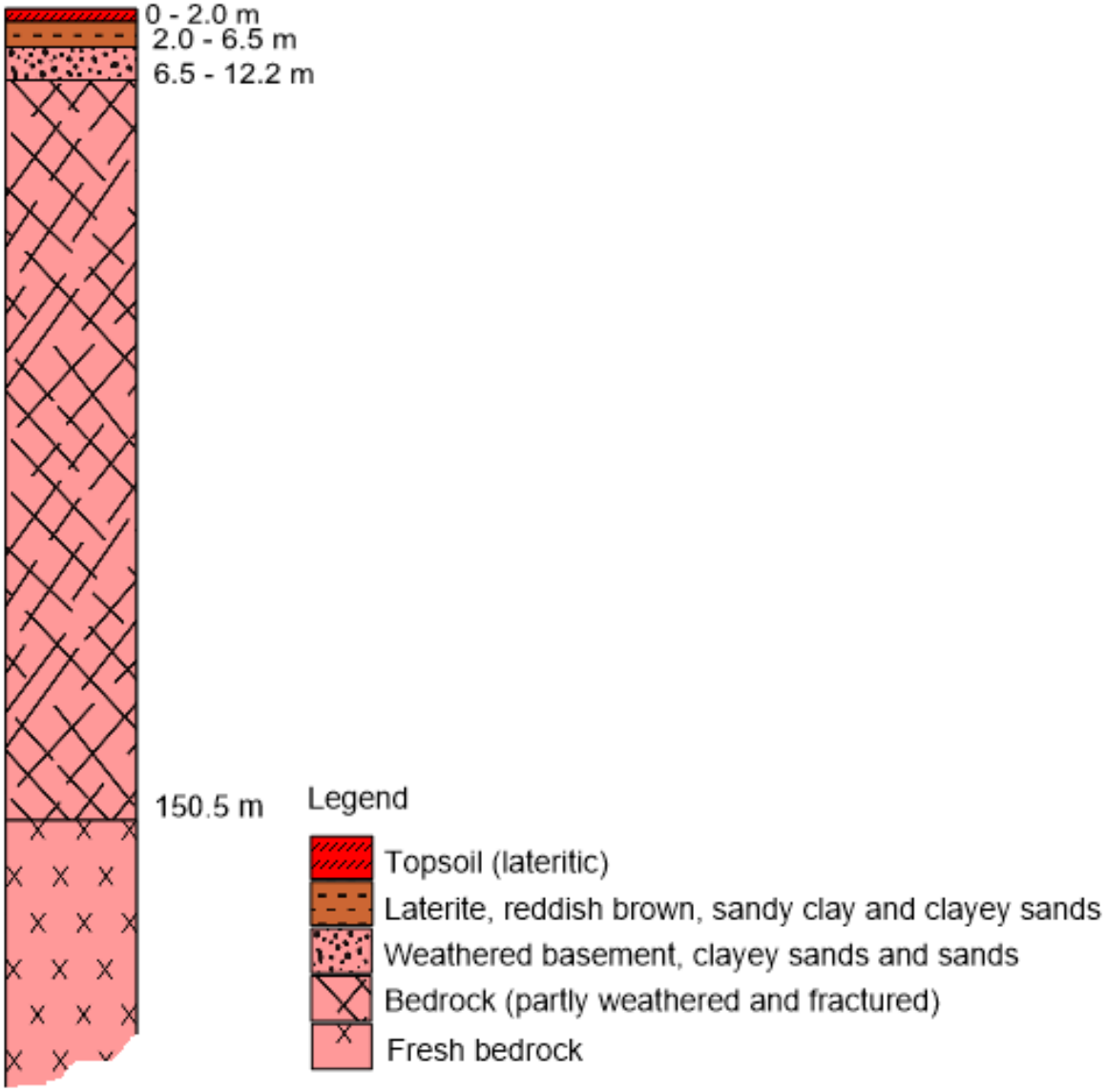

Figure 4.7: General borehole lithologic log of the area

The aquifers in the area are located within the weathered and/or fractured layer of the bedrock. The weathered/fractured layer thicknesses are ranged from 7.5 meters (borehole 5) to 56.7 meters (borehole 10) with an average value of 18.81 meters (Table 4.4).

4.5.3 Groundwater potentials evaluation

The results of pumping test interpretation and groundwater potential rating are shown in Table 4.3. The groundwater potential was established through comparison of following parameters: transmissivity and hydraulic conductivity values deduced from pumping test data (Figure 4.10).

The transmissivity values ranged from a minimum of 0.35 m²/day to a maximum of 3.63 m²/day at respectively BH5 and BH2, with an average value of 1.36 m²/day. Base on the Kransy's transmissivity standards classification (proposed by Kransy, 1993 for appraisal groundwater supply potential. The aquifers in the study area are categorized into two: very low and low (Table 4.5) and qualified to be sustained for small withdrawal for local water supply. The Kransy transmissivity classification, based on the standard deviation of transmissivity index (Table 4.5) computed according to Equation 3.14 reveal an extremely large variation of transmissivity and an extremely heterogeneous hydrogeological environment in the study area. A contour map of transmissivity in the study area is shown in Figure 4.8.

Table 4.3: Pumping test data for boreholes in the area of study and results of their interpretation

S/N	Location	Lat.	Long.	Depth (m)	SWL (m)	Discharge (m3/d)	Drawdown (m)	Weathered/ fractured layer thickness (m)	Transmissivity (m^2/day)	Standard deviation of T index "Y"	Hydraulic conductivity (m/d)
BH1	Dukpa	8.985	7.0875	155	19.4	82.08	25.35	20.2	0.910	3.98	0.045
BH2	Kaida	8.9342	7.015	130	9.3	95.04	6.57	20.1	3.623	4.58	0.180
BH3	Passu	8.9658	7.0438	124	11.4	155.52	22.81	18.9	1.654	4.24	0.087
BH4	Gwagwalada	8.9296	7.0765	172	7.8	95.04	34.32	11.5	0.836	3.95	0.073
BH5	Paiko	8.9892	7.0251	138	3.1	86.4	48.15	7.5	0.351	3.57	0.047
BH6	Checheyi	8.968	7.0472	193	5.5	120.96	43.32	11.6	0.606	3.81	0.052
BH7	NNPC Gas Plant	8.9761	7.063	138	5.3	155.52	21.81	14.8	1.186	4.10	0.080
BH8	NNPC Gas Plant	8.9782	7.068	200	2.3	216	64.7	13.9	0.898	4.0	0.064
BH9	NNPC Gas Plant	8.9733	7.072	150.8	1.2	259.2	84.6	12.7	0.847	3.95	0.067
BH10	NNPC Gas Plant	8.9717	7.066	149	2.8	319.68	35.24	56.7	2.720	4.46	0.048

Table 4.4: Magnitude and variation transmissivity of Krasny classification. (Source: Asfahani, 2021)

Classification of T Magnitude Coefficient				Classification of T Variation The			
Coefficient of T (m2/day)	**T magnitude Class**	**Designation of T magnitude**	**Groundwater supply potential >1000**	**The standard deviation of T index "Y**	**Class of T variation**	**Designation of T variation**	**Hydrogeological environment**
> 1000	I	Very high	Withdrawals of great regional importance	< 0.2	a	Insignificant	Homogeneous
1000 - 100	II	High	Withdrawals of lesser regional importance	0.2 – 0.4	b	Small	Slightly heterogeneous
100 - 10	III	intermediate	withdrawal for local water supply	0.4 – 0.6	c	Moderate	Fairly heterogeneous
10 - 1	IV	Low	Smaller withdrawal for local water supply	0.6 – 0.8	d	large Very	Considerably heterogeneous
1 - 0.1	V	Very low	withdrawal for local water supply with limited consumption	0.8 – 1	e	large	Extremely heterogeneous
< 0.1	VI	Imperceptible	Source for local water supply is difficult	> 1	f	Extremely large	Extremely heterogeneous

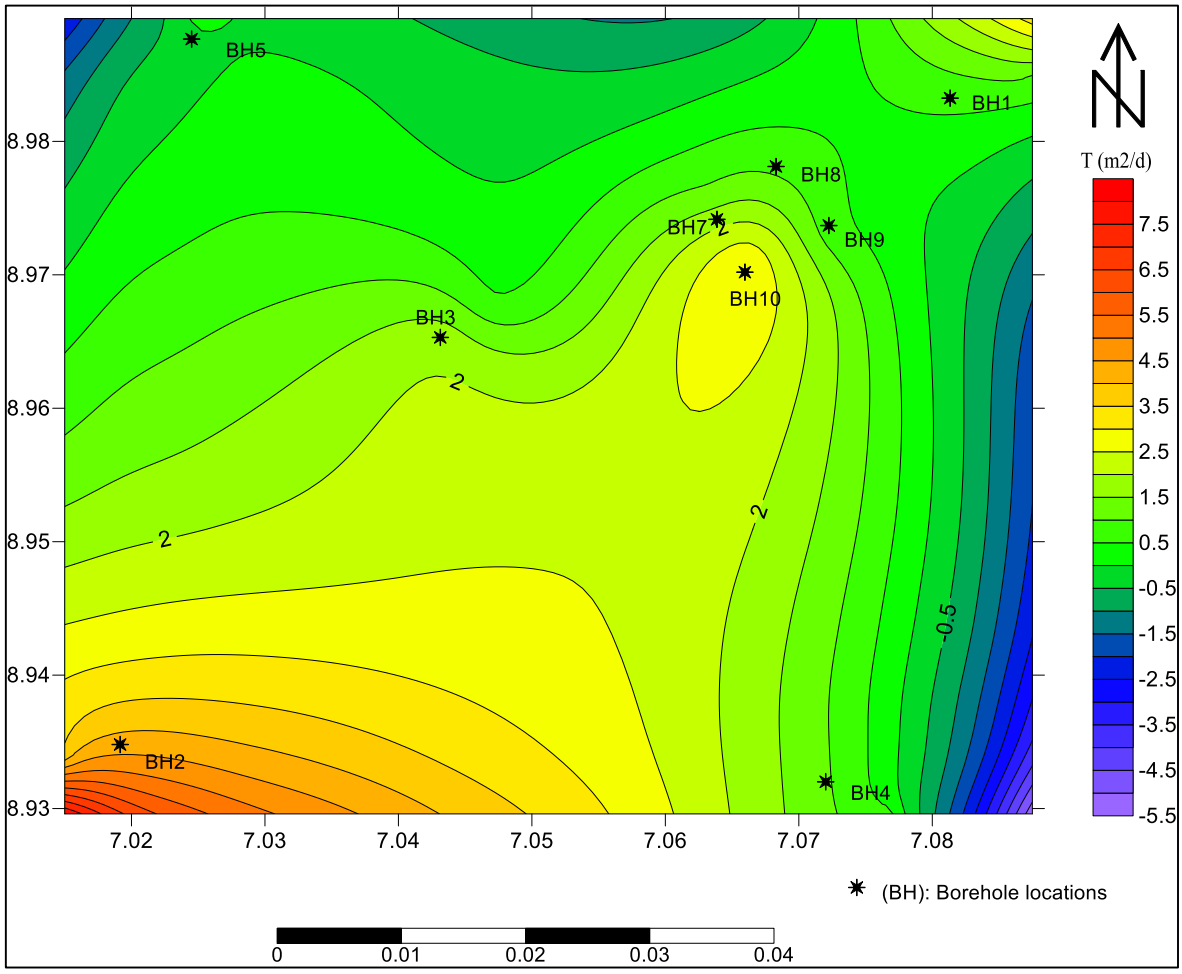

Figure 4.8. Transmissivity-*T* (m^2/d) contour map for the study area

The transmissivity map shows that the area of very low productivity occur in the Northern, North-western Eastern and South-eastern regions of the study area. The area of low productivity includes the North-East, Central, South, South-east and East of the study area.

Hydraulic conductivity values are ranged from 0.045 m/day to 0.18 m/day, thus characterizing the relative permeability in the entire study area of semi-pervious (Table 4.6). The hydraulic conductivity contour map (Figure 4.9) indicates an emphasis of K values in the south-western part of the study area, which means that the permeability is somewhat more pronounced in this part of the study area.

Table 4.5: Hydraulic Conductivity Classifications (Source: Şen, 2014)

K (×864 m/day)	10^{2}	10^{1}	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
Relative permeability	Pervious				Semi-pervious				Impervious				
Aquifer	Good				Poor				None				
Consolidated rock	Highly fracturated				Oil reservoir rock			Fresh sandstone			Fresh limestone, dolomite		Fresh granite

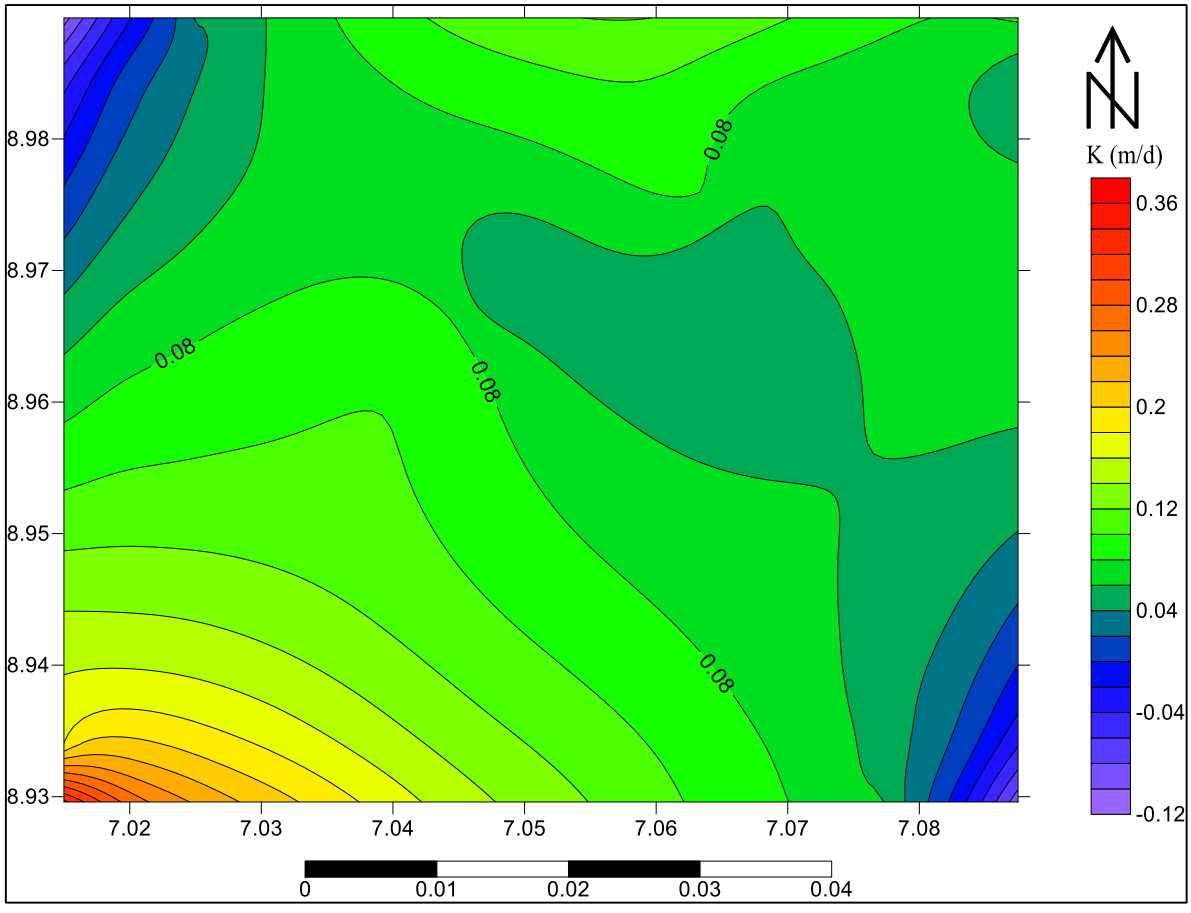

Figure 4.9. Hydraulic conductivity-*K* (m/d) contour map for the study area

Furthermore, the high variability in the hydraulic properties, namely transmissivity and hydraulic conductivity from place to place in the area can be due to the degree of

weathering/fracturing of the geological materials. Table 4.7 presents the relative errors obtained from pair-wise of transmissivity values. According to ± 5% relative error defining the homogeneity of an area, only 2 cases (BH1 versus BH8 and BH4 versus BH9) are revealed to be less than 5% over 45. This situation involves that the study area does not have regional transmissivity homogeneity.

Table 4.6: Relative Errors from pair-wise of transmissivity values

Transmissivity	**BH2**	**BH3**	**BH4**	**BH5**	**BH6**	**BH7**	**BH8**	**BH9**	**BH10**
BH1	74.9	45	8.1	61.4	33.4	23.2	1.3	7	66.5
BH2		54.3	77	90.3	83.3	67.3	75.2	76.6	24.9
BH3			49.5	78.8	63.3	28.3	45.7	48.8	39.2
BH4				58	27.5	29.5	6.9	1.3	69.3
BH5					42.1	70.4	60.9	58.5	87.1
BH6						48.9	32.5	28.4	77.7
BH7							24.2	28.6	56.4
BH8								5.7	67
BH9									68.9

Figure 4.10 shows the spatial distribution of groundwater potential, established on the basis of comparing transmissivity and hydraulic conductivity values. Approximately 70% of the study area are characterized as area of moderate groundwater potential, predominantly located within the south-western portion of the study area. The remaining 30 % having low groundwater potential are localized in the north and the south-East.

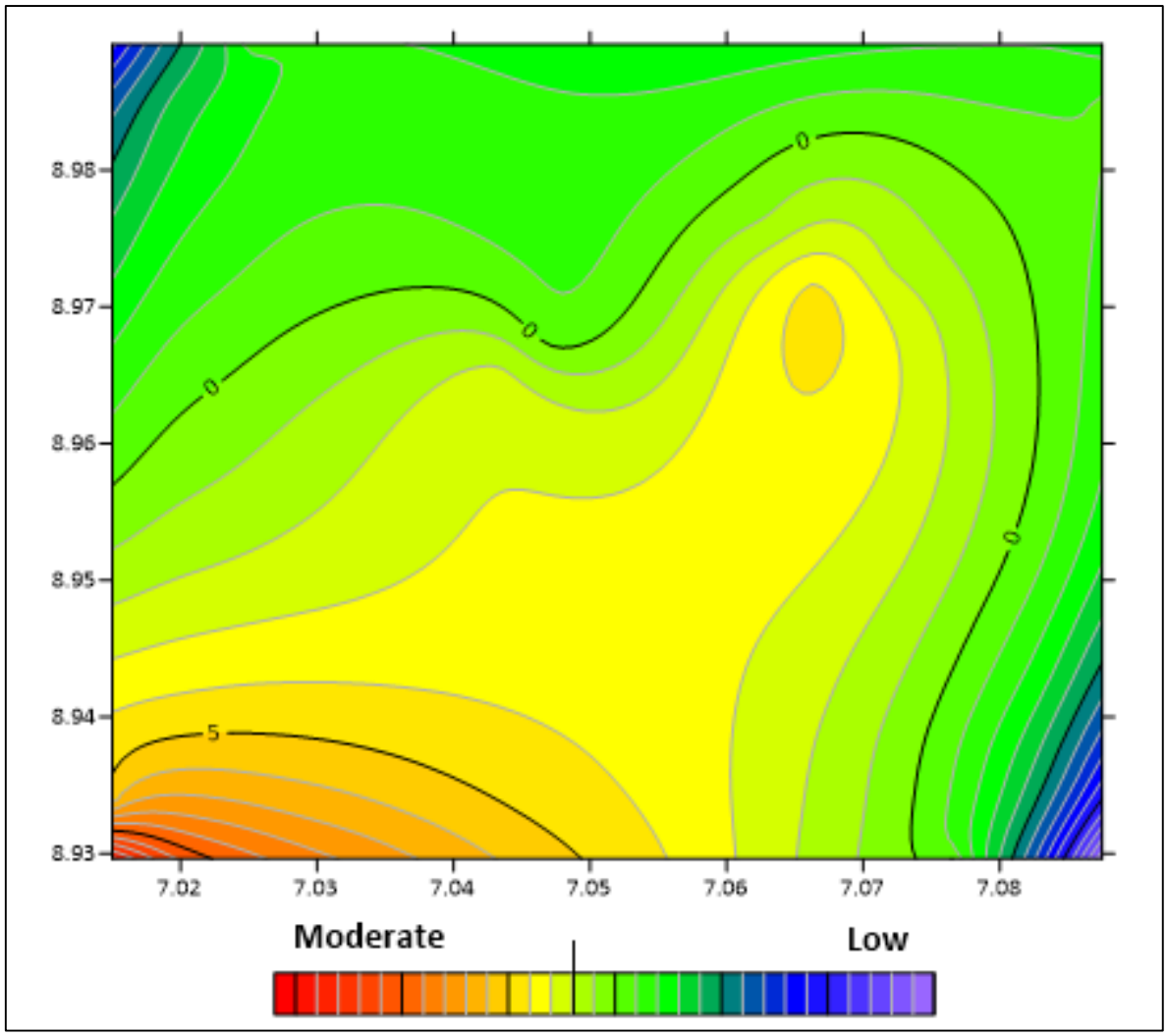

Figure 4.10: Groundwater potential map for the study area

4.6 Aquifer Protective capacity

Table 4.7 contains the results of the calculated longitudinal conductance and the corresponding aquifer protective capacity for the 10 vertical electrical sounding measuring points. Longitudinal conductance values vary from $0.11\Omega^{-1}$ to $0.37\Omega^{-1}$, with an average value of $0.243\Omega^{-1}$. Based on criteria from the Table 4.8, protective capacity for aquifer in the study area can be categorized into two parameters: Weak and Moderate.

Table 4.7: Longitudinal conductance values and aquifer protective capacity

S/N	Longitudinal conductance (Ohm^{-1})	Protective capacity
VES 1	0.242981	Moderate
VES 2	0.143161	Weak
VES 3	0.109976	Weak
VES 4	0.326328	Moderate
VES 5	0.366081	Moderate
VES 6	0.326328	Moderate
VES 7	0.215667	Moderate
VES 8	0.274811	Moderate
VES 9	0.314822	Moderate
VES 10	0.11059	Weak

VES_2, VES_3 and VES_10 have the lowest longitudinal conductance values containing in the interval between 0.1 and 0.19Ω^{-1}, thus categorizing the area to which these three VES stations belong as area of weak aquifer protective capacity (Table 4.8). Longitudinal conductance values computed from VES 1, VES 4, VES 5, VES 6, VES 7, VES 8 and VES 9 are included in the bracket ranging from 0.2 to 0.69Ω^{-1} : the area to which belong these seven VES stations is categorized as area of moderate aquifer protective capacity (Table 4.8).

Table 4.8: Aquifer protective capacity rating (Source: Nugraha *et al*., 2022)

Longitudinal conductance ($\boldsymbol{\Omega^{-1}}$)	**Protective capacity**
> 10	Excellent
5 – 10	Very good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak
< 0.1	Poor

The longitudinal conductance values were computed through Surfer 10 software to model the aquifer protective capacity pattern in the study area (Figure 4.10). The Aquifer protective capacity map shows that approximately 70% of the study area are characterized as area of low protective capacity and tended to be oriented in a NE-SW direction, including the north-eastern, central, eastern and south-eastern (purple, blue and dark green colors). The remaining 30% are characterized as moderate protective capacity and are located in the following areas: west, south-west and north-Est (yellow, light green and red colors).

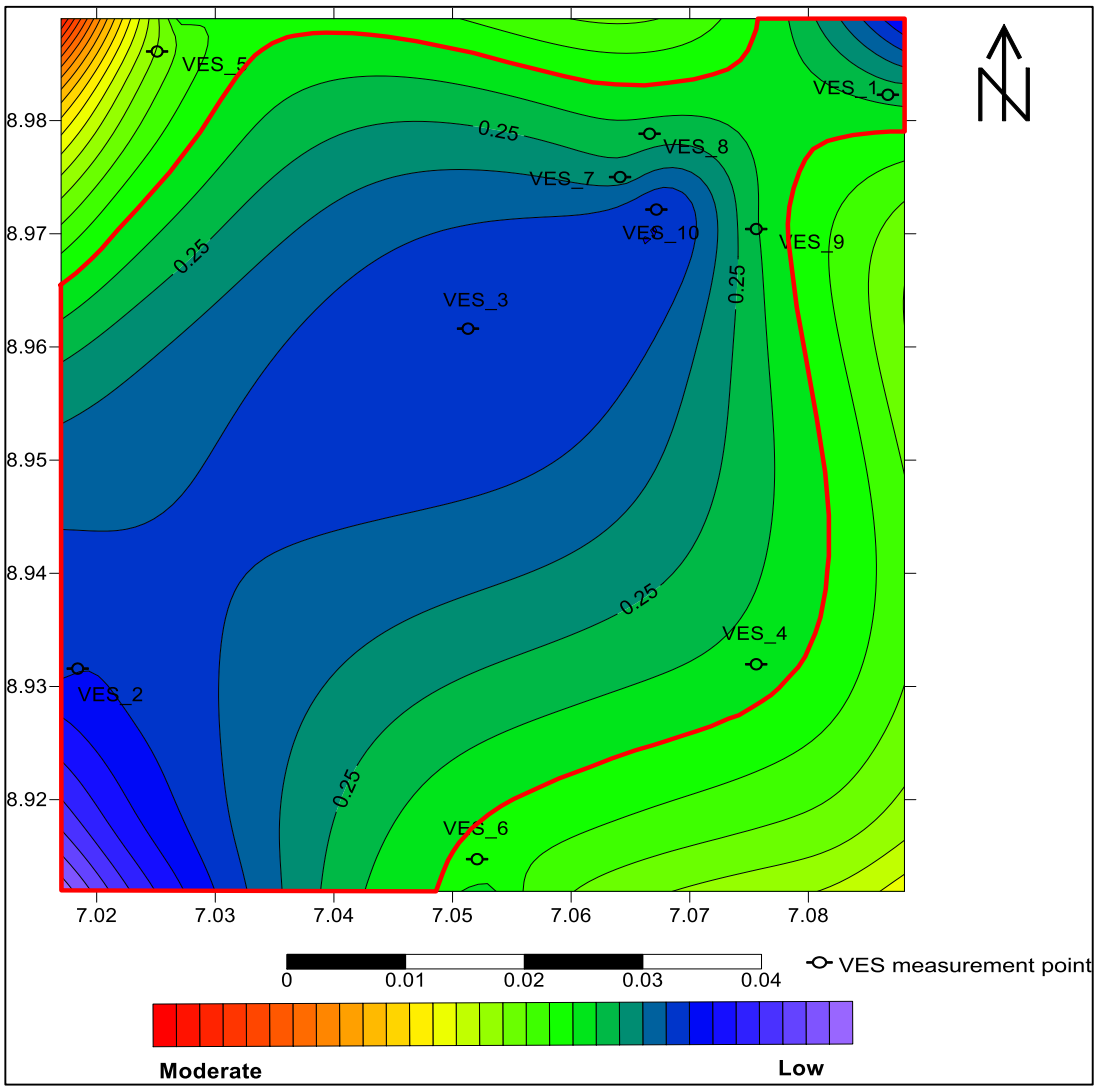

Figure 4.11: Aquifer protective capacity map for the study area

The longitudinal conductance value is highly correlated with the clay content and transmissivity value (Nugraha *et al.*, 2022; Oteri, 1981). The transmissivity of the aquifer decreases as the value of the longitudinal conductance increases (Figure 4.12). In hydrogeologic study, the weathered basement rock rich in clay constitutes a good aquifer protective capacity (Okogbue & Omonona, 2013).

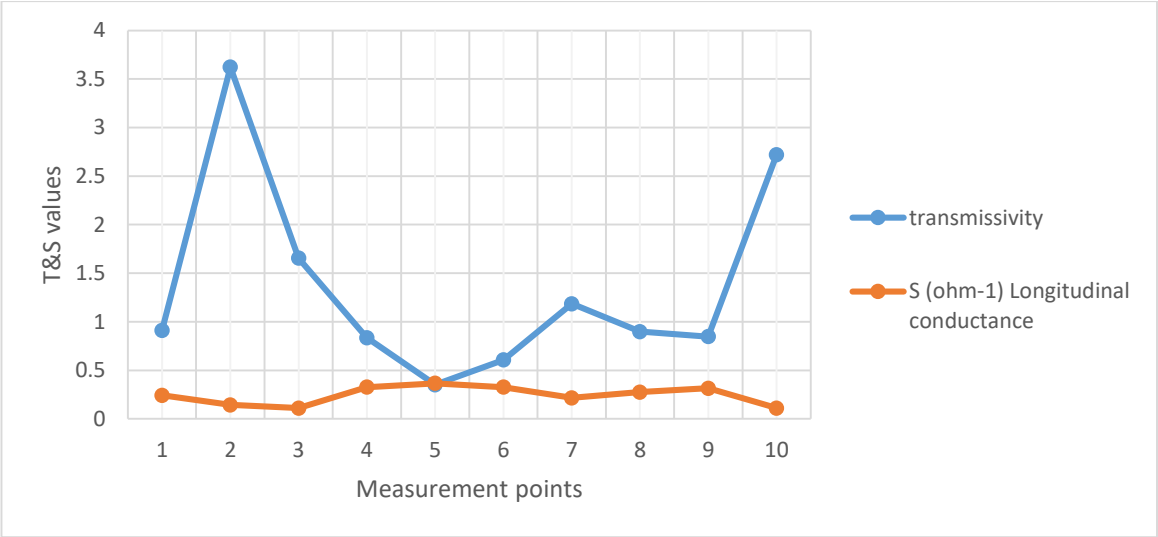

Figure 4.12: Comparing the Longitudinal conductance (S) and Transmissivity (T) Correlation

Infiltration occurs easily in terrains classified as having weak protective capacity than those of moderate protective capacity, consequently the transport of contaminants is barely restricted there. This implies that area characterized as of weak aquifer protection capacity is vulnerable to pollution of groundwater resources of which various anthropogenic sources are present in the study area.

CHAPTER FIVE

5.0 CONCLUSION, RECOMMENDATION AND CONTRIBUTION TO THE KNOWLEDGE

5.1 Conclusion

The study area is underlain by granite-gneiss comprising of feldspar, quartz and biotite and whose alignment is characterized by gneissic foliation of alternating felsic and biotite. The structural pattern in the area has NE-SW principal direction followed by SE-NW direction. The results of the geoelectrical survey show that the area is characterised by subsurface sequences of 4 to 5 layers all of which depic (laterite, reddish brown, sandy clay and clayey sands), underlain by weathered/fractured layer and fresh bedrock.

The groundwater potentials and the protective capacity of the Gwagwalada were established through hydrogeological and geophysical investigations: The groundwater flows in a NE-SW direction, coincides with the principal joint direction, a confirmation that the groundwater flow direction in the study area is structurally controlled. Pumping test results show that the transmissivity values ranged from 0.35 m^2/day to 3.63 m^2/day with an average value of 1.36 m^2/day. Base on the Krasny's transmissivity standards classification, the aquifers in the study area are categorized into two, namaly very low and low. The standard deviation of transmissivity index values reveal an extremely heterogeneous hydrogeological environment in the study area. Ranged from 0.045 to 0.18 m/day, the hydraulic conductivity values characterized a semi-pervious relative permeability in the entire study area. The combination of transmissivity, and hydraulic conductivity characterize the groundwater potential zones in the study area into low and moderate. The longitudinal conductance (S) values classified the study area into two aquifer protective capacity zones, namely weak and

moderate. The weak aquifer protective capacity is defined by the low values of S, ranging from between 0.110 and 0.143 Ω^{-1}; the values of longitudinal conductance having defined the moderate aquifer protective capacity are ranged between 0.216 and 0.366 Ω^{-1}. The results obtained from this research provide a baseline for estimating the amount of groundwater available for exploitation in the study area.

5.2 Recommendation

It is recommended that a qualitative analysis of this water be carried out, which will enable both quantitative and qualitative information to be known as required in water demand analysis for a proper planning and management of water resources.

5.3 Contribution to the knowledge

The contribution to the knowledge that emerged from this research is the establishment of groundwater potential and aquifer protective capacity maps (Figures 4.10 and 4.11) of parts of Gwagwalada where the research was conducted. The groundwater potential map was drawn up based on hydraulic properties, namely transmissivity and hydraulic conductivity. The research was able to characterize the groundwater aquifer potential and the aquifer protective capacity in the study area into low and moderate categories.

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APPENDIX A (PICTURES CAPTURED DURING DATA COLLECTION)

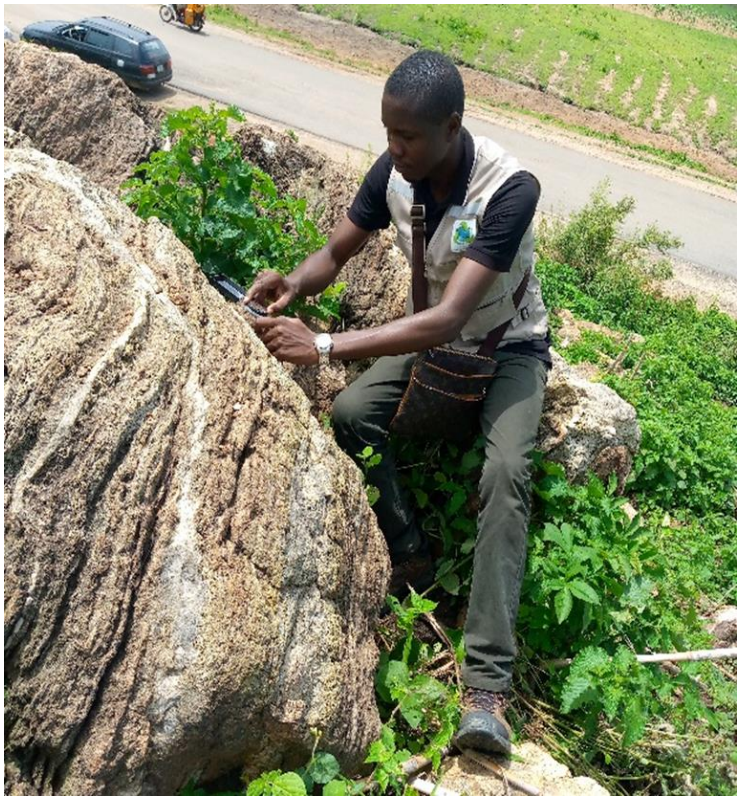


Plate I: Joint trends measurement within the study area



Plate II: Static water level measured (N08° 59' 28.4", E 07°04' 58.2")



Plate III: VES measurements



Plate IV: Pumping Test exercise on-going at one of the boreholes sites at Gwagwalada area

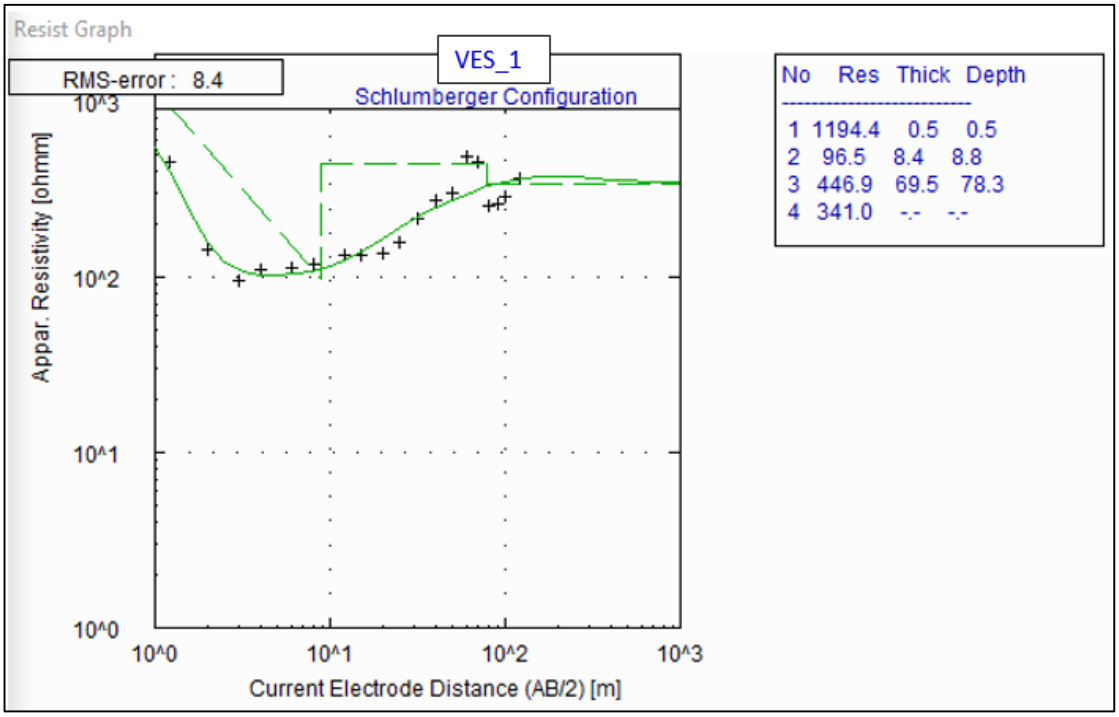


Plate V Pictures with the geological team during data collection

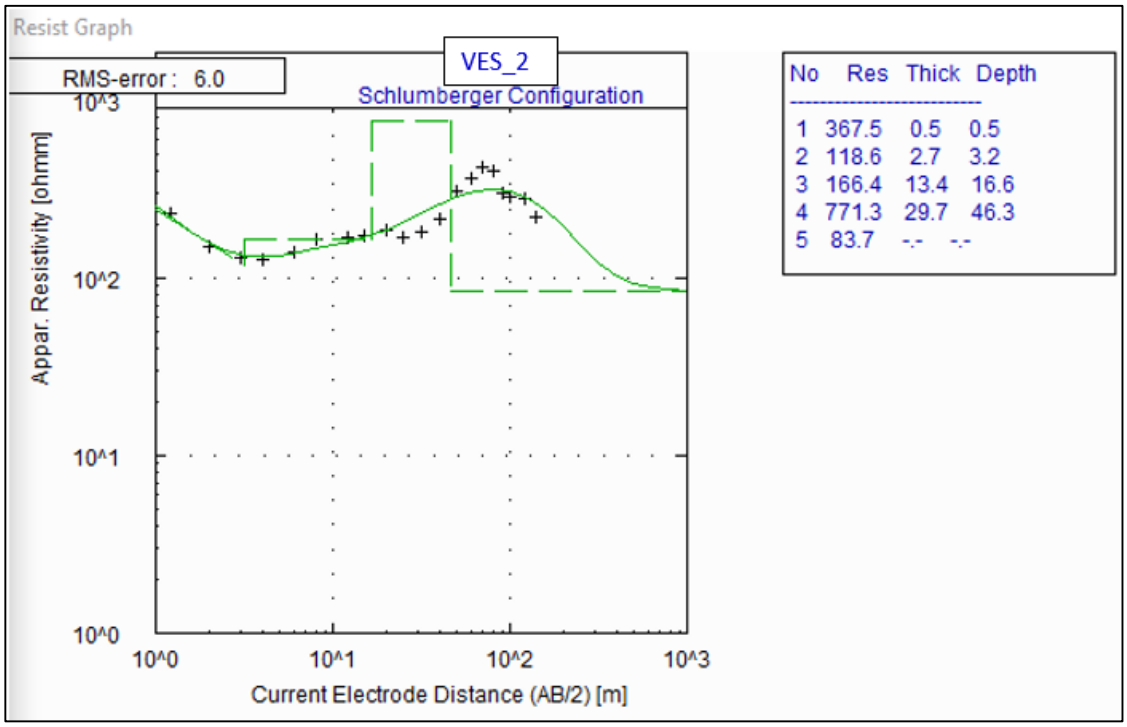


Plate VI: Pictures with the security agents during data collection

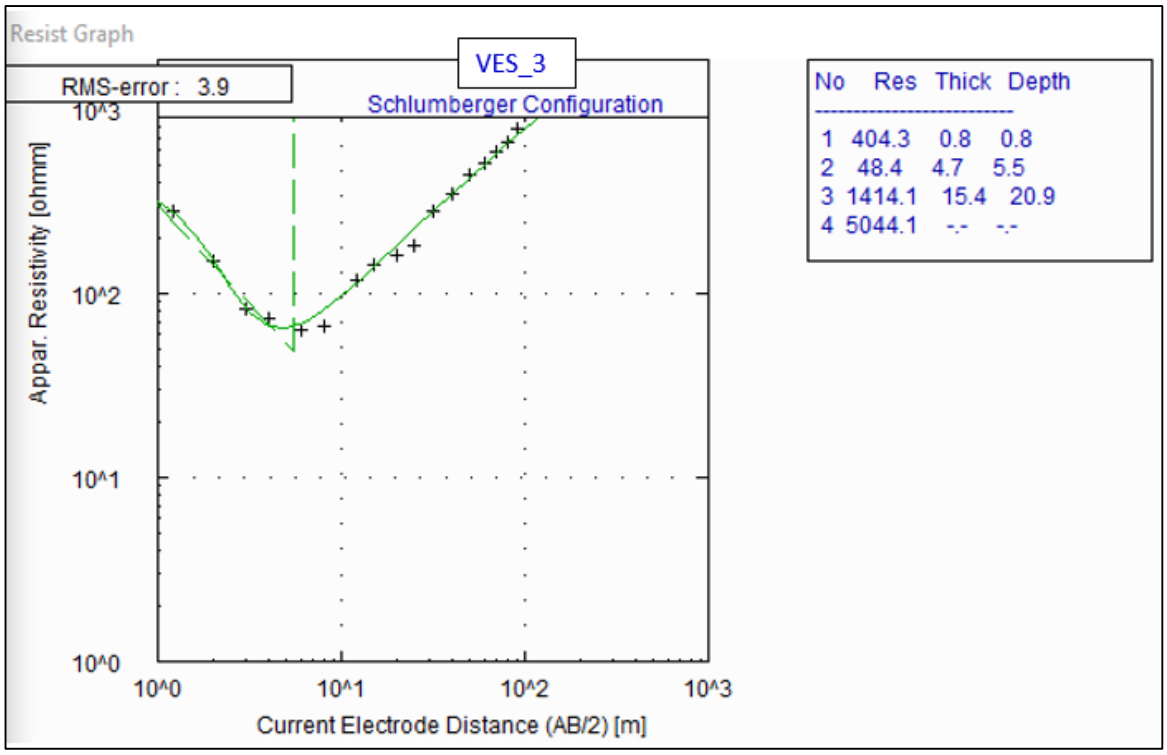
APPENDIX B (COMPUTER MODELLED CURVES FROM VES DATA)



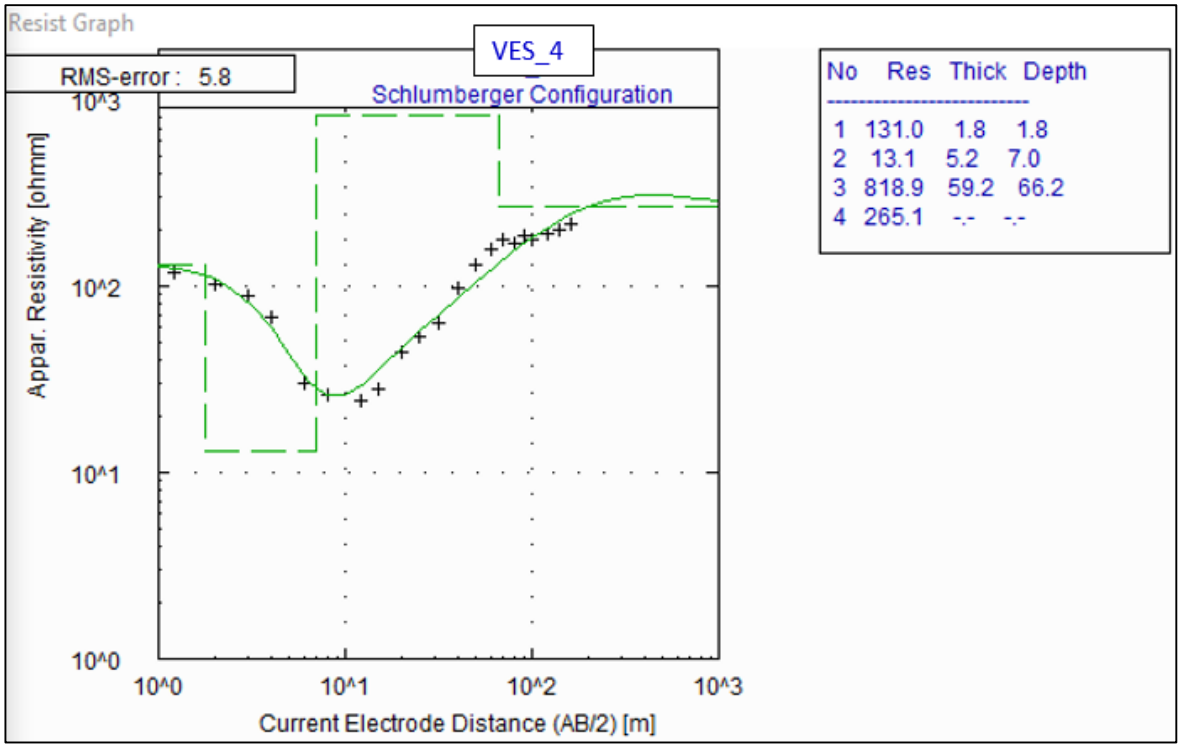
Computer modelled curve for VES 1



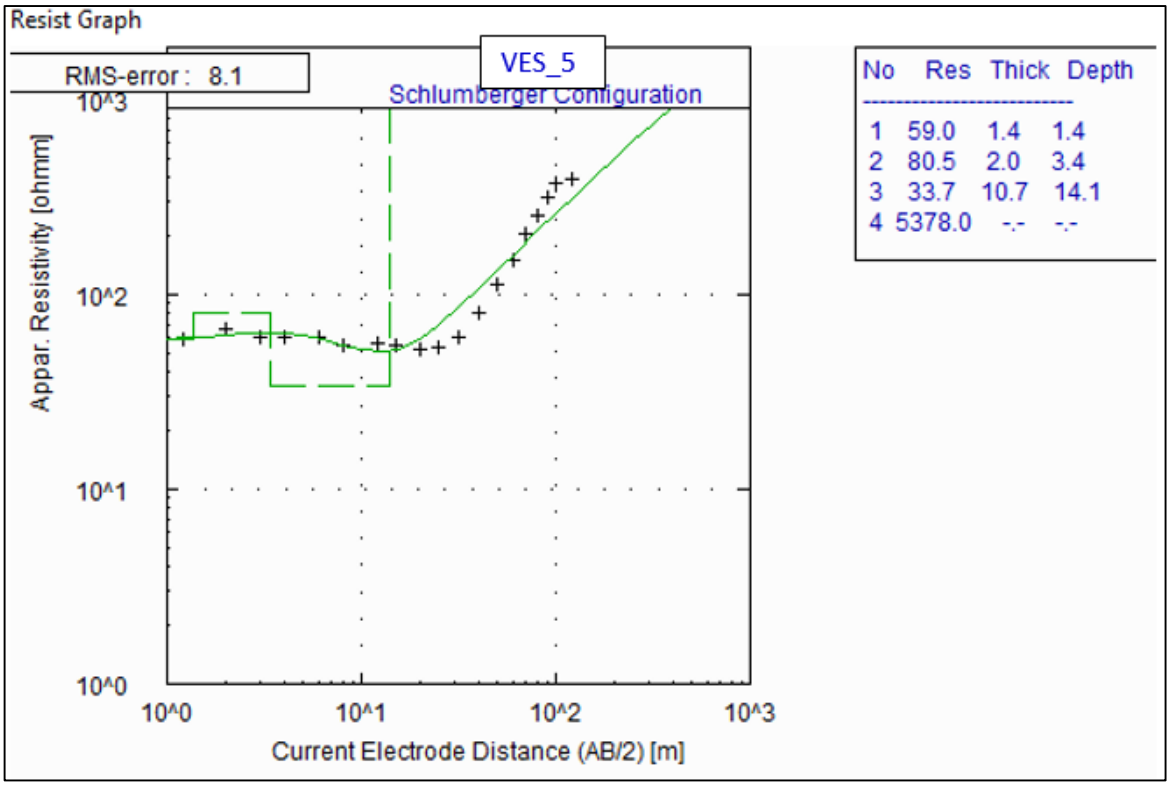
Computer modelled curve for VES 2



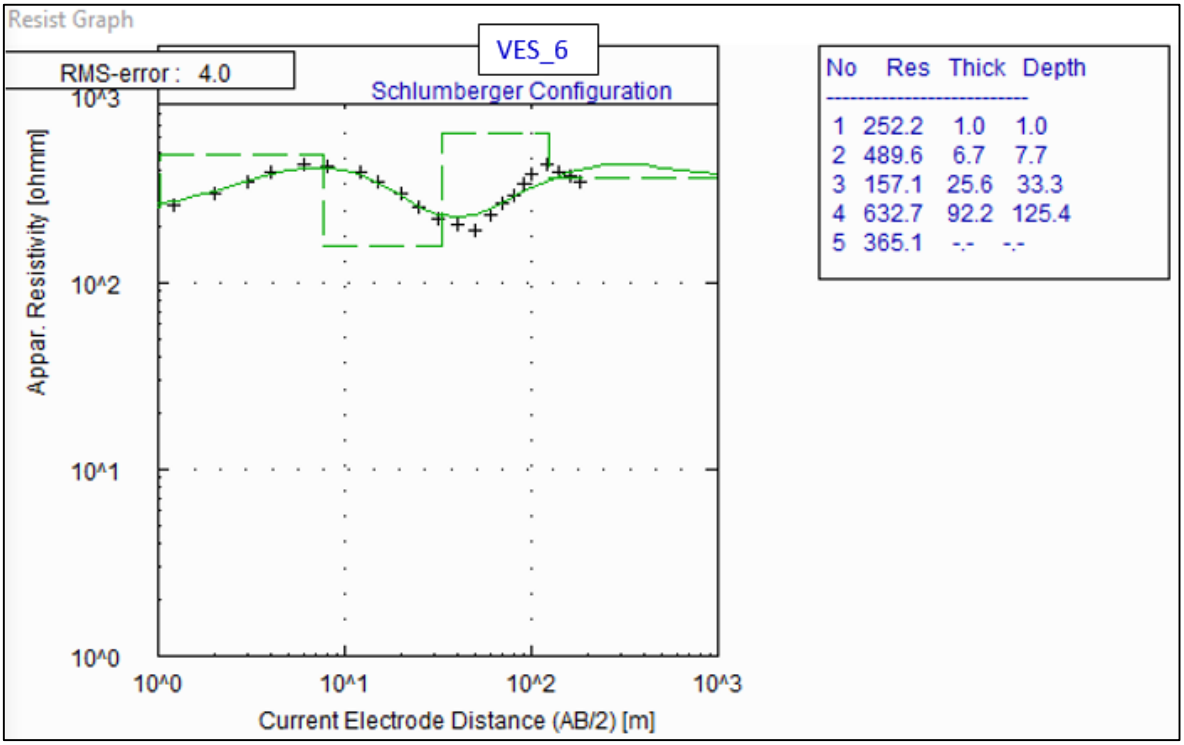
Computer modelled curve for VES 3



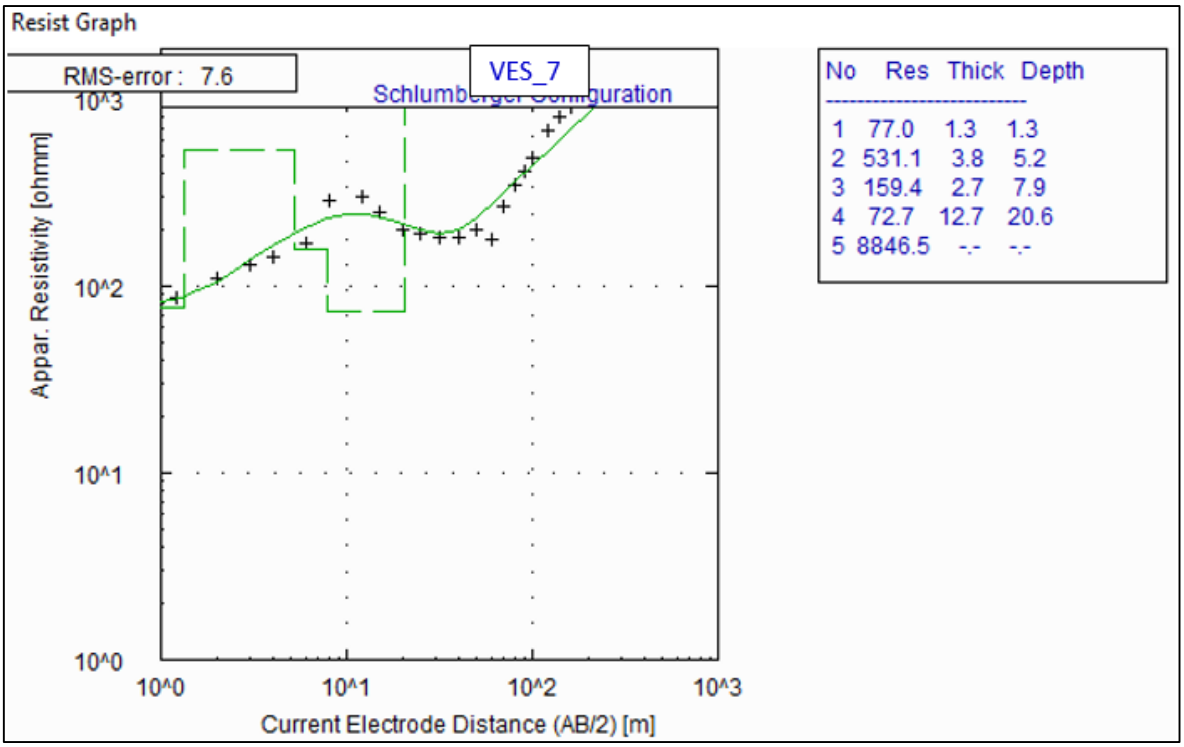
Computer modelled curve for VES 4



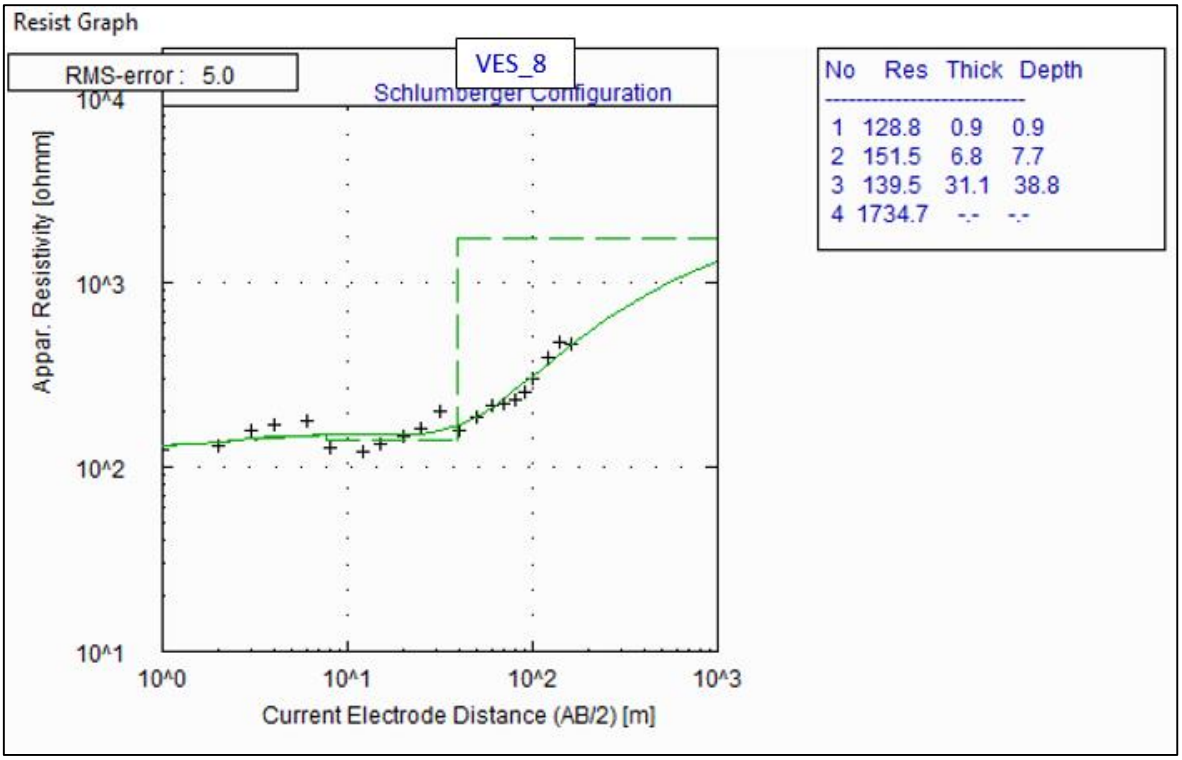
Computer modelled curve for VES 5



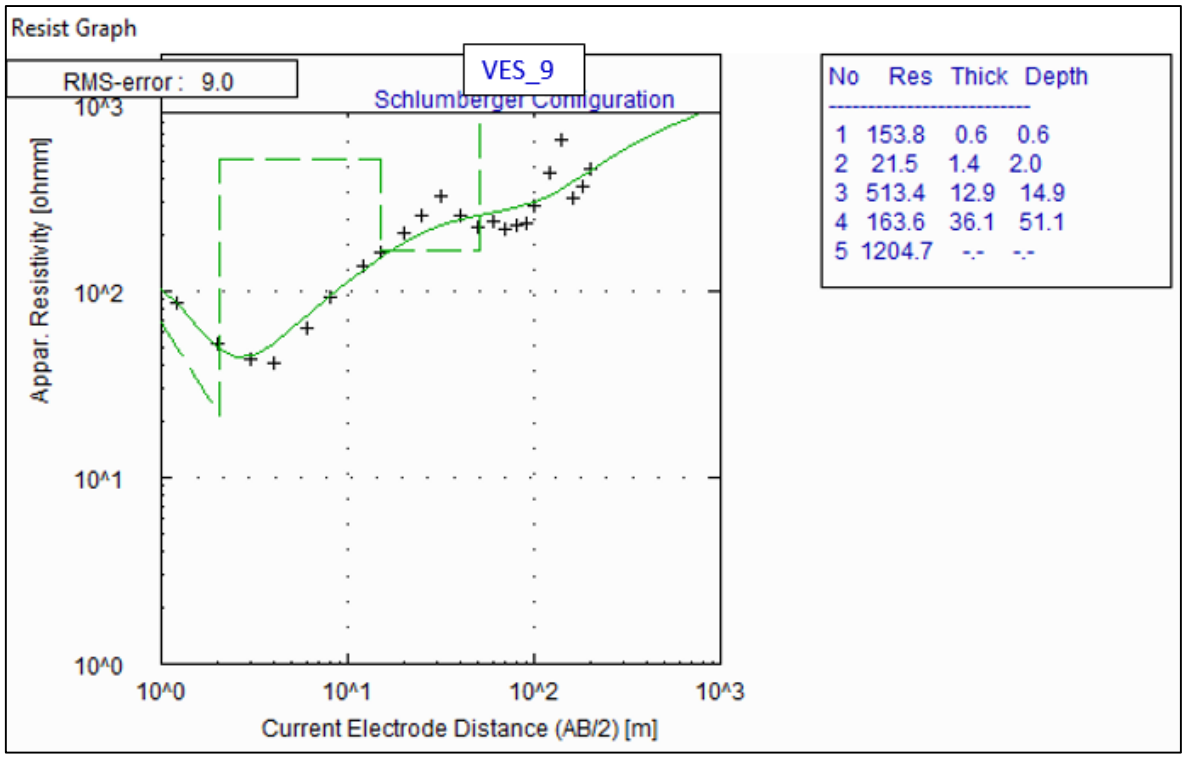
Computer modelled curve for VES 6



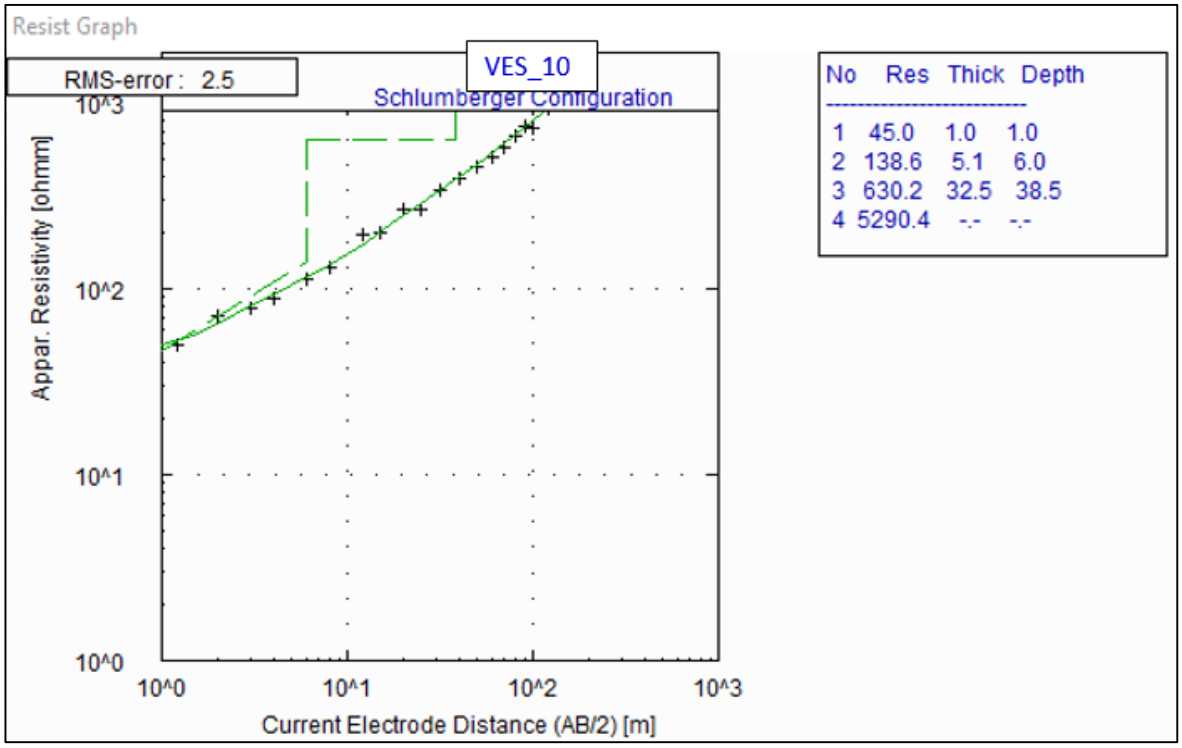
Computer modelled curve for VES 7



Computer modelled curve for VES 8

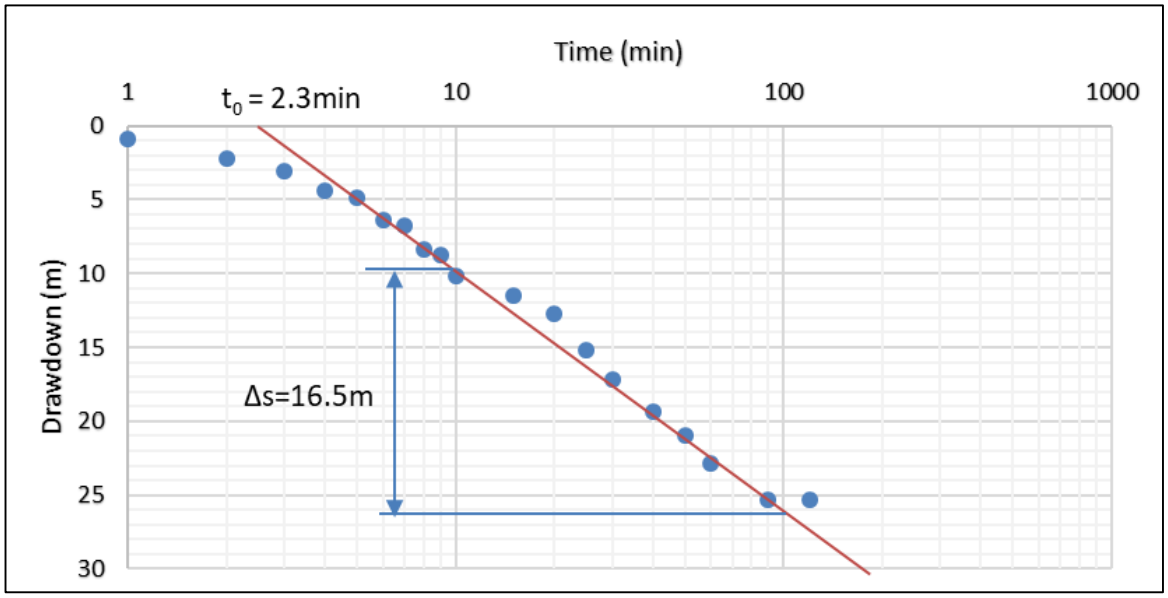


Computer modelled curve for VES 9

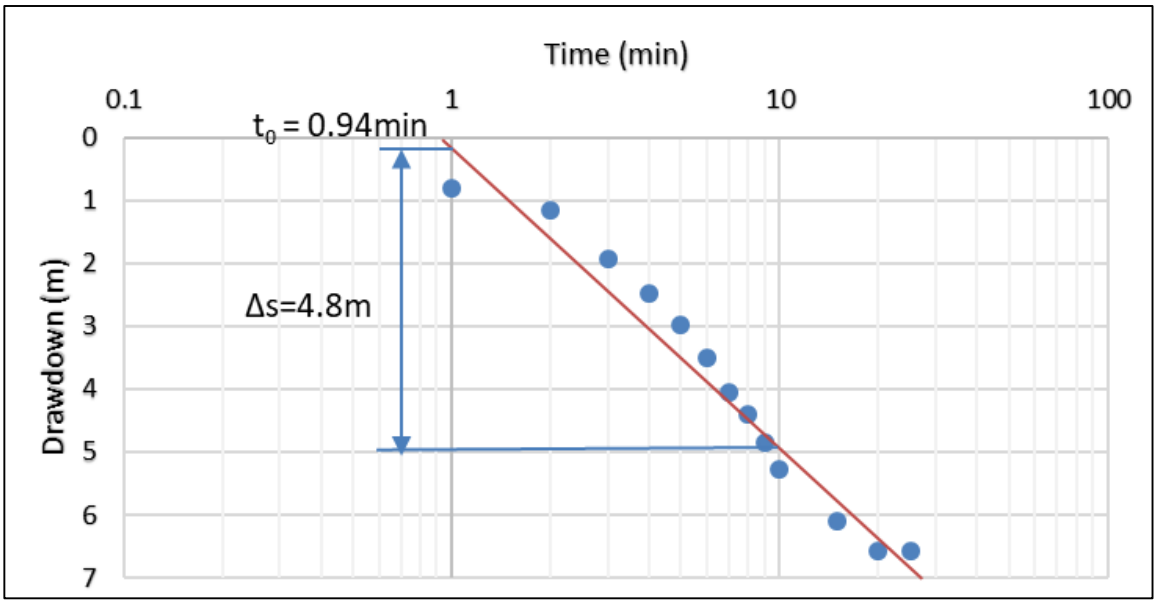


Computer modelled curve for VES 10

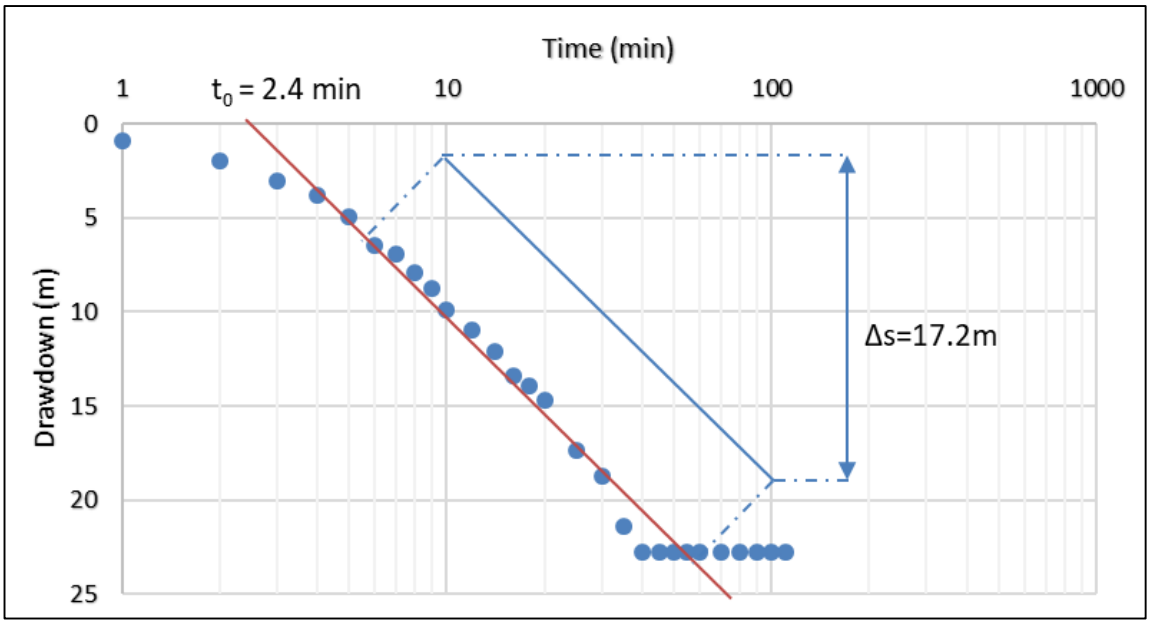
APPENDIX C (GRAPHS OF TIME VERSUS DRAWDOWN)



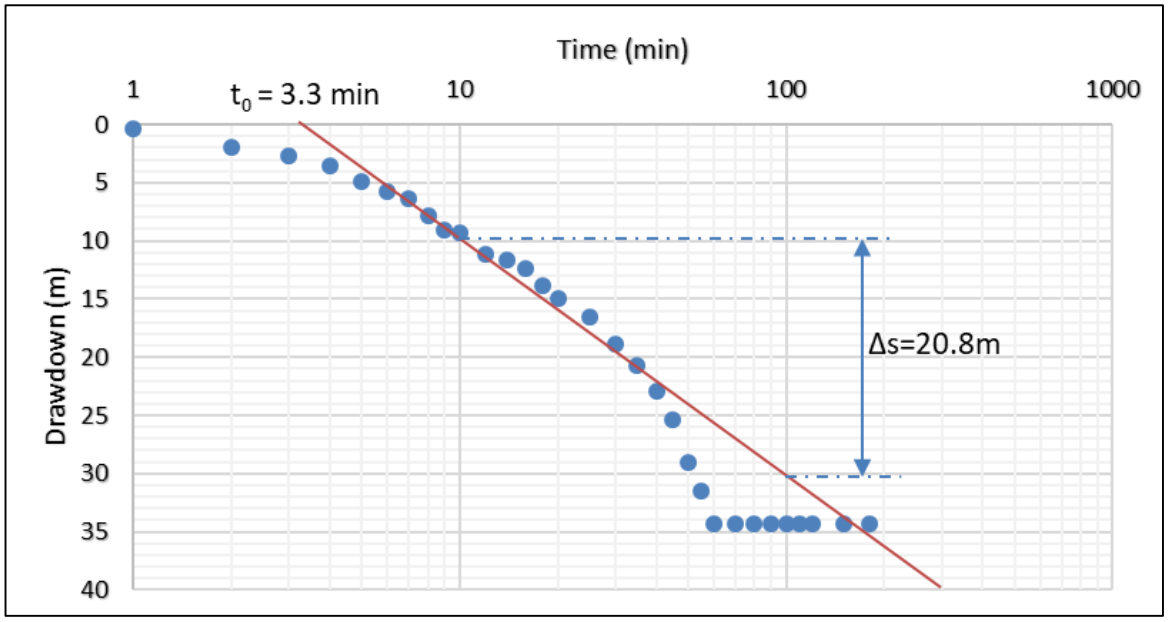
Semilogarithmic plot of time-drawdown for borehole 1



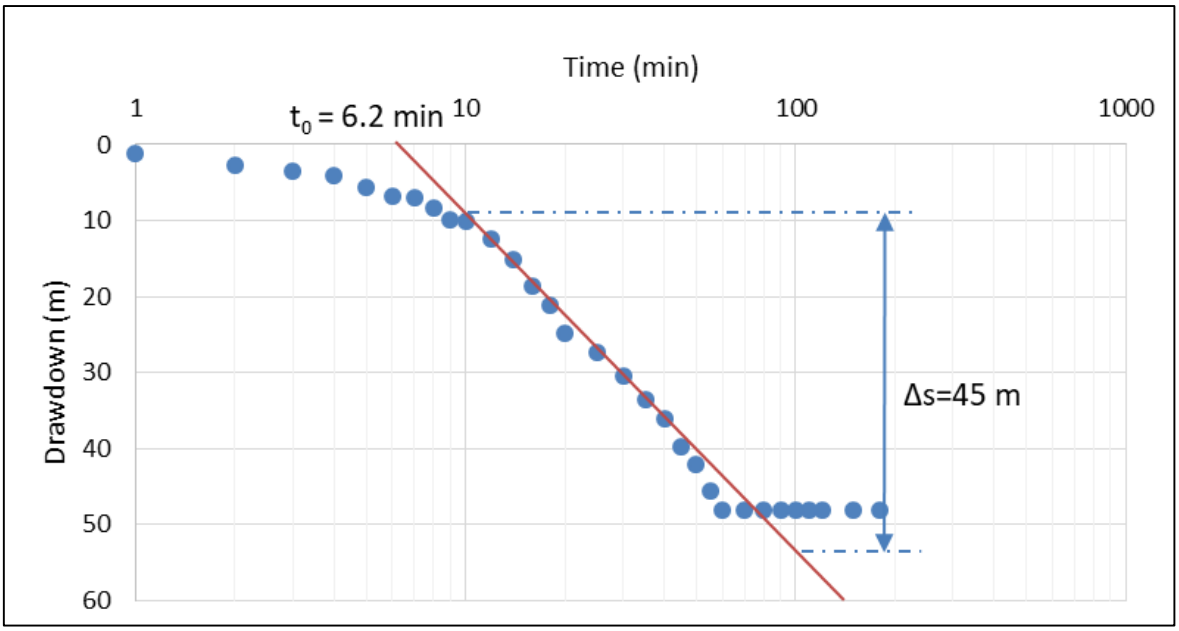
Semilogarithmic plot of time-drawdown for borehole 2



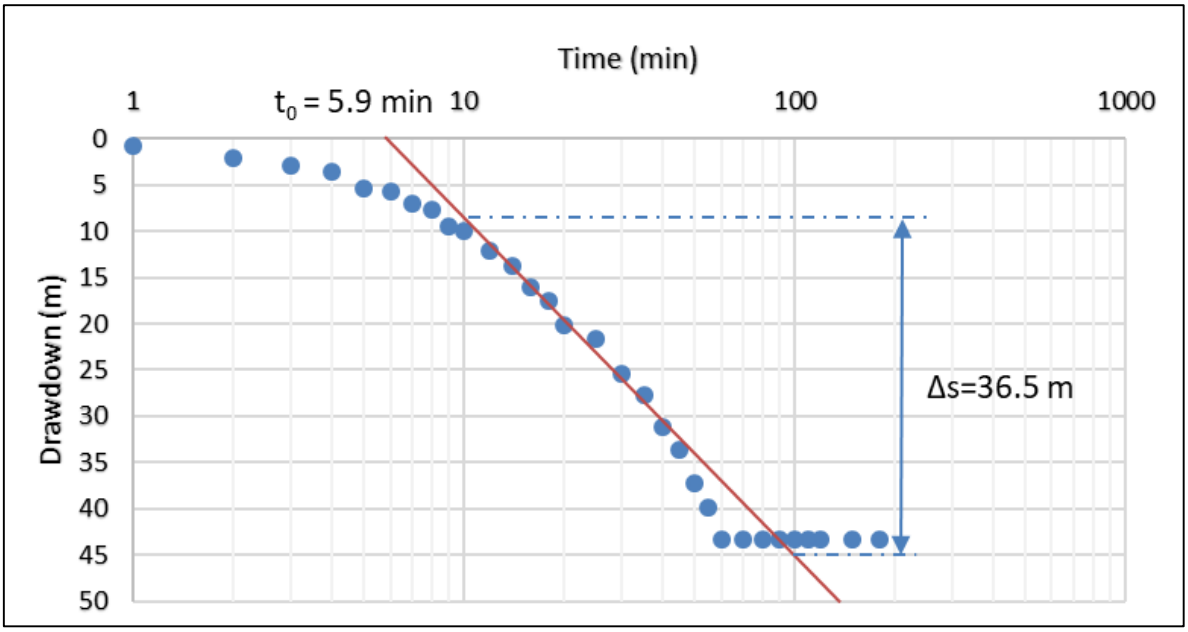
Semilogarithmic plot of time-drawdown for borehole 3



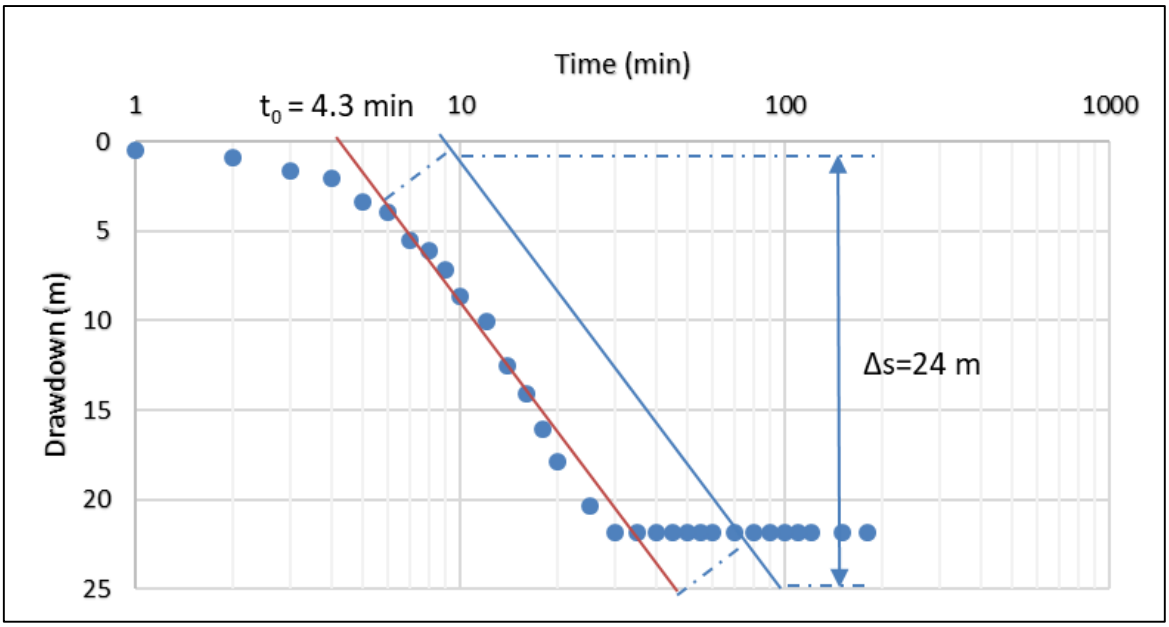
Semilogarithmic plot of time-drawdown for borehole 4



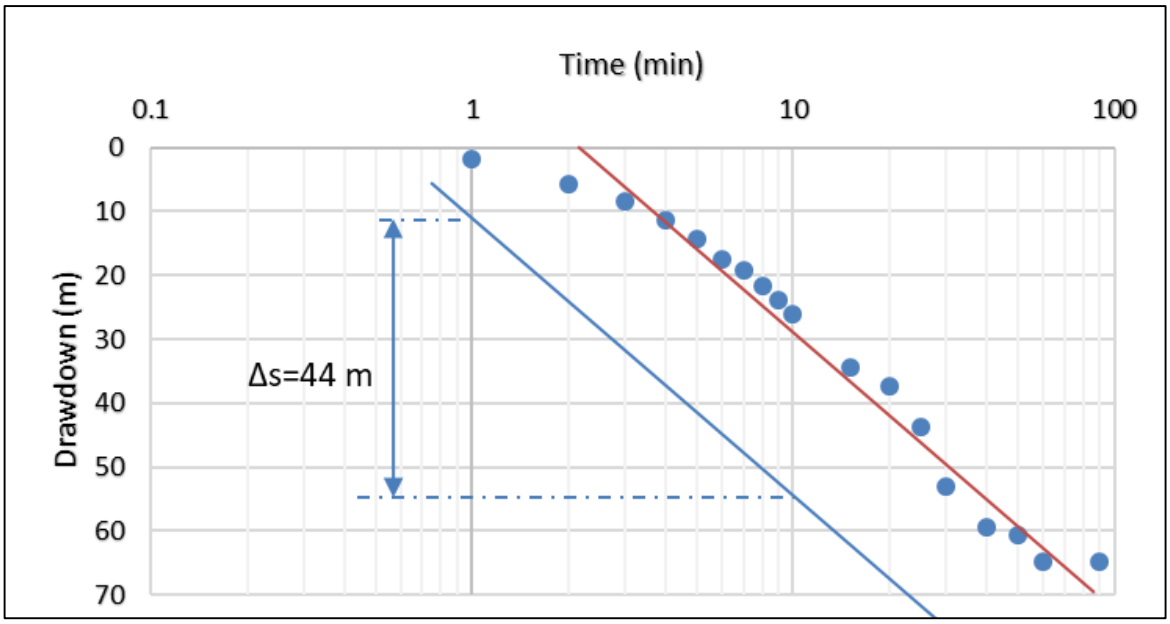
Semilogarithmic plot of time-drawdown for borehole 5



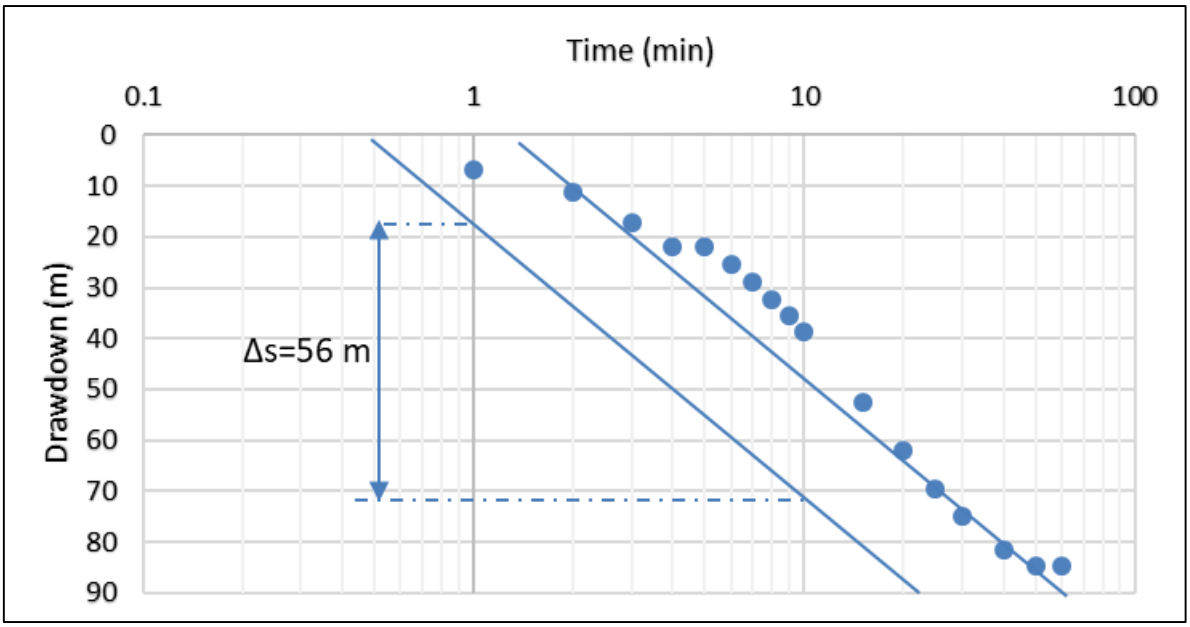
Semilogarithmic plot of time-drawdown for borehole 6



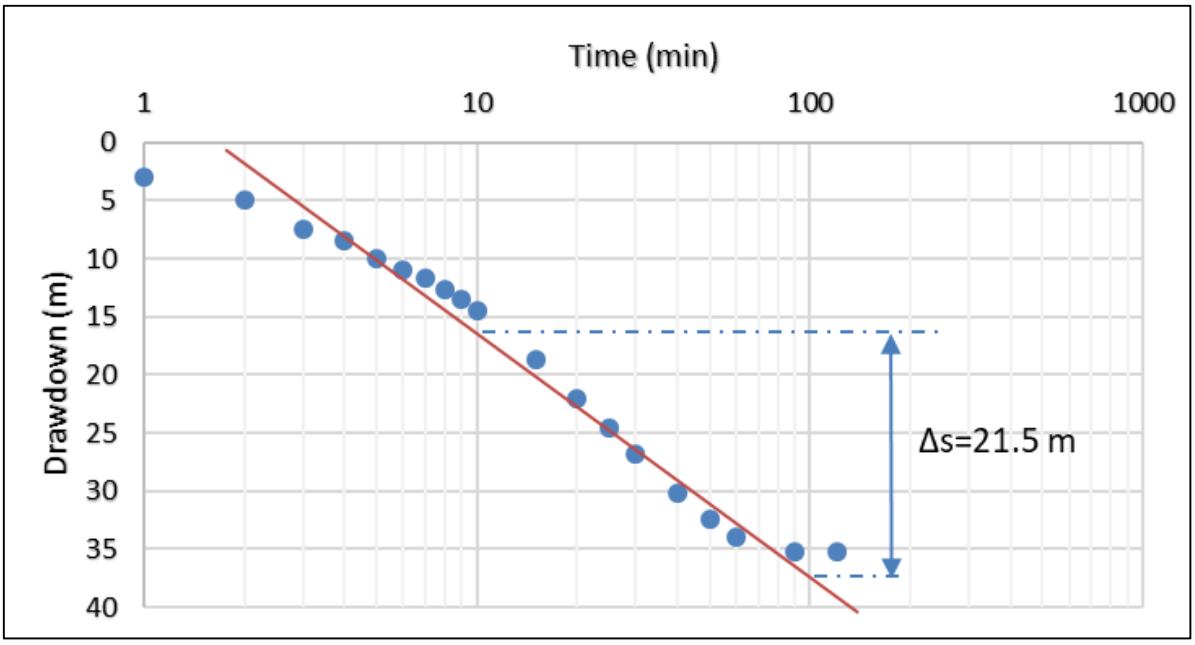
Semilogarithmic plot of time-drawdown for borehole 7



Semilogarithmic plot of time-drawdown for borehole 8



Semilogarithmic plot of time-drawdown for borehole 9



Semilogarithmic plot of time-drawdown for borehole 10

APPENDIX D (PUMPING TEST DATA)

Pumping test data for borehole 1

Location .....Dukpa..... Borehole n⁰ : .....1..... Date.....24/06/2022

Coordinates.....7,0875 E .....8.985...N Altitude .....

Depth:.....155 m..... SWL:.....19.4 m.....

Pump setting:.....152 m..... Yield:.....0.95 l/s.....

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recover water level (m)	Residual drawdown (m)
0	19.4	0	0	44.75	25.35
1	20.28	0.88	1	43.12	23.72
2	21.63	2.23	2	42.91	23.51
3	22.49	3.09	3	41.14	21.74
4	23.78	4.38	4	40.67	21.27
5	24.29	4.89	5	39.15	19.75
6	25.81	6.41	6	38.72	19.32
7	26.16	6.76	7	37.46	18.06
8	27.74	8.34	8	36.11	16.71
9	28.15	8.75	9	35.84	16.44
10	29.58	10.18	10	34.27	14.87
15	30.89	11.49	15		
20	32.47	12.77	20		
25	34.57	15.17	25		
30	36.54	17.14	30		
35			35		
40	38.8	19.4	40		
45			45		
50	40.37	20.97	50		
55			55		
60	42.29	22.89	60		
70			70		
80			80		
90	44.75	25.35	90		
100			100		
120	44.75	25.35	120		
150	44.75	25.33	150		
180	44.75	25.33	180		
210			210		
240			240		
300			300		

Pumping test data for borehole 2

Location ..... Kaida ..... Borehole n°: ..... 2 ..... Date 25/06/2022

Coordinates ..... 7.015 ..... E ..... 8.9342 ..... N Altitude .....

Depth: ..... 130 m .....

Pump setting: ..... 120 m .....

SWL: ..... 9.3 m .....

Yield: ..... 1.1 l/s .....

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recover water level (m)	Residual drawdown (m)
0	19.4	0	0	44.75	25.35
1	20.28	0.88	1	43.12	23.72
2	21.63	2.23	2	42.91	23.57
3	22.49	3.09	3	41.14	21.74
4	23.78	4.38	4	40.67	21.27
5	24.29	4.89	5	39.15	19.75
6	25.81	6.41	6	38.72	19.32
7	26.16	6.76	7	37.46	18.06
8	27.74	8.34	8	36.11	16.71
9	28.15	8.75	9	35.89	16.44
10	29.58	10.18	10	34.27	14.87
15	30.89	11.49	15		
20	32.17	12.77	20		
25	34.57	15.17	25		
30	36.54	17.14	30		
35			35		
40	38.8	19.4	40		
45			45		
50	46.37	20.97	50		
55			55		
60	42.29	22.89	60		
70			70		
80			80		
90	44.75	25.35	90		
100			100		
120	44.75	25.35	120		
150	44.75	25.35	150		
180	44.75	25.35	180		
210			210		
240			240		
300			300		

Pumping test data for borehole 3

Location.....Parsa..... Borehole n°: .....3..... Date..26/06/2022

Coordinates.....7.0428.E .....8.9658.N Altitude.....

Depth:.....124.....m..... SWL:.....11.4...m.....

Pump setting:.....120...m..... Yield:.....1.8 l/s.....

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recovery water level (m)	Residual drawdown (m)
0	11.4	0	0	34.21	22.81
1	12.32	0.92	1	33.71	22.39
2	13.36	1.96	2	32.14	20.74
3	14.41	3.01	3	31.68	20.28
4	15.21	3.81	4	30.1	18.7
5	16.35	4.95	5	29.45	18.05
6	17.86	6.46	6	28.83	17.43
7	18.31	6.91	7	27.16	15.76
8	19.32	7.92	8	26.42	15.02
9	20.14	8.74	9	25.7	14.3
10	21.28	9.88	10	24.33	12.93
15			15		
20	26.11	14.71	20		
25	28.73	17.33	25		
30	30.14	18.74	30		
35	32.83	21.43	35		
40	34.21	22.81	40		
45	34.21	22.81	45		
50	34.21	22.81	50		
55	34.21	22.81	55		
60	34.21	22.81	60		
70	34.21	22.81	70		
80	34.21	22.81	80		
90	34.21	22.81	90		
100		22.81	100		
120		22.81	120		
150		22.81	150		
180		22.81	180		
210			210		
240			240		
300			300		

Pumping test data for borehole 4

Location..Gwapwalada Borehole n°: ....4..... Date..27/06/2022

Coordinates.....7.0765..E .....8..92.96.N Altitude.....

Depth:.....172 m..... SWL:.....7.8 m.....

Pump setting:.....160 m..... Yield:.....1.1 l/s.....

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recovery water level (m)	Residual drawdown (m)
0	7·8	0	0	42·12	34·32
1	8·21	0·41	1	41	33·2
2	9·76	9·96	2	39·81	32·01
3	10·49	2·69	3	37·12	29·32
4	11·35	3·55	4	36·73	28·93
5	12·67	4·87	5	35·26	27·46
6	13·56	5·76	6	34·69	26·89
7	14·11	6·31	7	33·17	25·37
8	15·66	7·86	8	32·83	25·06
9	16·81	9·01	9	31·11	23·31
10	17·15	9·35	10	30·49	22·69
15			15		
20	22·81	15·01	20		
25	24·35	16·55	25		
30	26·67	18·87	30		
35	28·55	20·75	35		
40	30·71	22·91	40		
45	33·19	25·39	45		
50	36·84	29·04	50		
55	39·26	31·46	55		
60	42·12	34·32	60		
70	"	34·32	70		
80	"	34·32	80		
90	"	34·32	90		
100	"	34·32	100		
120	"	34·32	120		
150	"	34·32	150		
180	"	34·32	180		
210			210		
240			240		
300			300		

Pumping test data for borehole 5

Location.....Paika..... Borehole n°: .....5..... Date...28/06/2022

Coordinates.....7.0251.E .....8.9892..N Altitude.....

Depth:.....138...m..... SWL:.....3.1.m.....

Pump setting:.....120..m..... Yield:.....1..0..l/s.....

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recovery water level (m)	Residual drawdown (m)
0	3.1	0	0	51.25	48.15
1	4.26	1.16	1	50.83	47.73
2	5.79	2.69	2	49.11	46.01
3	6.68	3.48	3	48.69	45.59
4	7.11	4.01	4	47.25	44.15
5	8.79	5.69	5	46.79	43.69
6	9.86	6.76	6	45.14	42.04
7	10.13	7.03	7	44.68	41.58
8	11.45	8.35	8	43.12	40.02
9	12.94	9.84	9	42.59	39.49
10	13.16	10.06	10	41.13	38.03
15			15		
20	27.96	24.86	20		
25	30.44	27.34	25		
30	33.57	30.47	30		
35	36.6	33.5	35		
40	39.11	36.1	40		
45	42.85	39.75	45		
50	45.15	42.05	50		
55	48.73	45.63	55		
60	51.25	48.15	60		
70	"	48.15	70		
80	"	48.15	80		
90	"	48.15	90		
100	"	48.15	100		
120	"	48.15	120		
150	"	48.15	150		
180	"	48.15	180		
210			210		
240			240		
300			300		

Pumping test data for borehole 6

Location.....Checheyi..... Borehole n°: .....6..... Date..29/06/2022

Coordinates.....7.0472.E .....8.9680 N Altitude.....

Depth:.....1.93...m..... SWL:.....5.5..m....

Pump setting:.....185..m..... Yield:.....1.4 l/sec....

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recovery water level (m)	Residual drawdown (m)
0	5.5	0	0	48.82	43.32
1	6.28	0.78	1	47.23	41.73
2	7.62	2.12	2	46.59	41.09
3	8.37	2.87	3	45.81	40.31
4	9.1	3.6	4	44.23	38.78
5	10.85	5.35	5	43.68	38.18
6	11.24	5.74	6	42.11	36.61
7	12.6	7.1	7	41.9	36.4
8	13.17	7.67	8	40.22	34.72
9	14.93	9.43	9	39.57	34.07
10	15.42	9.92	10	38.86	33.36
15			15		
20	25.73	20.23	20		
25	27.14	21.64	25		
30	30.9	25.4	30		
35	33.19	27.69	35		
40	36.65	31.15	40		
45	39.14	33.64	45		
50	42.74	37.24	50		
55	45.39	39.89	55		
60	48.82	43.32	60		
70		43.32	70		
80		43.32	80		
90		43.32	90		
100		43.32	100		
120		43.32	120		
150		43.32	150		
180		43.32	180		
210			210		
240			240		
300			300		

Pumping test data for borehole 7

Location: NNPC Gas Plant Borehole n°: 7 Date: 30/06/2022

Coordinates: 7.0630 E 8.9761 N Altitude:

Depth: 138 m

Pump setting: 130 m

SWL: 5.3 m

Yield: 1.8 l/sec

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recovery water level (m)	Residual drawdown (m)
0	5.3	0	0	27.11	21.81
1	5.81	0.51	1	26.73	21.43
2	6.21	0.91	2	25.14	19.84
3	6.93	1.63	3	24.83	19.53
4	7.31	2.01	4	23.12	17.82
5	8.62	3.32	5	22.59	17.29
6	9.53	3.93	6	21.9	16.6
7	10.84	5.54	7	20.32	15.02
8	11.35	6.05	8	19.68	14.38
9	12.46	7.16	9		
10	13.93	8.63	10		
15			15		
20	23.17	17.87	20		
25	25.69	20.39	25		
30	27.11	21.81	30		
35	27.11	21.81	35		
40	27.11	21.81	40		
45	27.11	21.81	45		
50	27.11	21.81	50		
55	27.11	21.81	55		
60	27.11	21.81	60		
70			70		
80			80		
90			90		
100			100		
120			120		
150			150		
180			180		
210			210		
240			240		
300			300		

Pumping test data for borehole 8

Location. NNPC Gas Plant Borehole n°: 8 Date. 30/06/2020

Coordinates. 7.0680.E 8.9782.N Altitude.

Depth: 200 m SWL: 2.3 m

Pump setting: 180 m Yield: 25 l/s

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recovery water level (m)	Residual drawdown (m)
0	2.3	0	0	67	64.7
1	4.2	1.9	1	65.1	62.8
2	8.1	5.8	2	64.22	61.92
3	10.8	8.5	3	63	60.7
4	13.6	11.3	4	61.42	59.12
5	16.68	14.38	5	60.3	58
6	19.9	17.6	6	59.51	57.21
7	21.6	19.3	7	58.9	56.6
8	23.9	21.6	8	56.33	54.03
9	26.29	23.99	9	55.1	52.8
10	28.3	26	10	54.11	51.81
15	26.3	34.3	15	50.8	48.5
20	39.7	37.4	20	44.42	42.12
25	46.1	43.8	25	38.9	36.6
30	55.28	52.98	30	32.2	29.5
35			35		
40	61.8	59.5	40	25.25	22.95
45			45		
50	63	60.7	50	15.55	13.25
55			55		
60	67	64.7	60	8.56	6.25
70			70		
80			80		
90	67	64.7	90	5.6	3.3
100			100		
120			120	3.55	1.25
150			150	2.3	0
180			180	2.3	0
210			210		
240			240		
300			300		

Pumping test data for borehole 9

Location NNPC Gas Plant Borehole n°: 9 Date 21/07/2022

Coordinates 7.072.0 E 8.97.33 N Altitude

Depth: 150.8 m SWL: 1.2 m

Pump setting: 139 m Yield: 3 l/sec

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recover water level (m)	Residual drawdown (m)
0	1.2	0.00	0	85.80	84.60
1	8.10	6.90	1	84.20	83.00
2	12.33	11.13	2	83.42	82.22
3	18.30	17.10	3	79.80	78.60
4	21.90	21.90	4	77.90	76.70
5	23.25	22.05	5	75.51	74.31
6	26.72	25.52	6	73.20	72.00
7	30.13	28.83	7	72.33	71.13
8	33.53	32.33	8	70.80	69.60
9	36.75	35.55	9	68.28	67.08
10	39.79	38.59	10	65.46	64.26
15	53.64	52.44	15	61.51	60.31
20	63.32	62.12	20	45.55	44.35
25	70.73	69.53	25	41.25	40.05
30	76.21	75.01	30	37.56	36.36
35	82.65	81.45	35		
40	82.65	81.45	40	32.22	31.02
45	85.		45		
50	85.80	84.60	50	25.55	24.35
55			55		
60	85.80	84.60	60	21.22	20.02
70			70		
80			80		
90			90		
100			100		
120			120		
150			150		
180			180		
210			210		
240			240		
300			300		

Pumping test data for borehole 10

Location NNPC Gas Plant Borehole n°: 10 Date 21.07.2022

Coordinates 7.066 E 8.97.17 N Altitude

Depth: 149 m SWL: 2.8 m

Pump setting: 125 m Yield: 3.7 l/s

Pumping Phase			Recovery Phase		
Time since pumping stated (min)	Pumping water level (m)	Drawdown (m)	Time since pumping stopped (min)	Recover water level (m)	Residual drawdown (m)
0	2.8	0	0	38.64	35.24
1	5.75	2.95	1	35.24	32.44
2	7.75	4.95	2	33.5	30.7
3	10.3	7.5	3	32.03	29.23
4	11.3	8.5	4	30.68	27.88
5	12.75	9.95	5	29.3	26.5
6	13.75	10.95	6	28.03	25.23
7	14.41	11.61	7	26.84	24.04
8	15.43	12.63	8	25.15	22.35
9	16.33	13.53	9	24.39	21.59
10	17.2	14.4	10	23.5	20.7
15	21.5	18.7	15	19.4	16.6
20	24.78	21.98	20	16.69	13.89
25	27.42	24.62	25	11.25	8.45
30	29.63	26.83	30	7.69	4.89
35			35		
40	33.	30.2	40	4.54	1.74
45			45		
50	35.15	32.35	50	3.11	0.31
55			55		
60	36.79	33.99	60		
70			70		
80			80		
90	38.04	35.24	90	2.8	
100			100		
120	38.04	35.24	120	2.8	
150			150		
180			180		
210			210		
240			240		
300			300		

APPENDIX E (VERTICAL ELECTRICAL SOUNDING DATA)

Schlumberger Data Sheet for VES 1

Location.....Dukpa..... VES n°: ....1..... Date..04/07/2022..

Coordinates.....7.0881..E .....8.9838.....N Altitude.....

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	449	
2.0	0.5	143	
3.0	0.5	96	
4.0	0.5	111	
6.0	0.5	112	
8.0	0.5	119	
12	0.5	133	
15	0.5	134	
20	0.5	136	
25	0.5	156	
32	5.0	215	
40	5.0	275	
50	5.0	298	
60	5.0	488	
70	10	452	
80	10	257	
90	10	259	
100	10	290	
120	10	266	
140	10		
160	20		
180	20		
200	20		

Schlumberger Data Sheet for VES 2

Location.....Kaida..... VES n°: .....2..... Date..04/07/2022

Coordinates.....7.017....E .....8.932.1..N Altitude.....

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	234	
2.0	0.5	149	
3.0	0.5	131	
4.0	0.5	128	
6.0	0.5	140	
8.0	0.5	167	
12	0.5	168	
15	0.5	175	
20	0.5	187	
25	0.5	171	
32	5.0	183	
40	5.0	213	
50	5.0	312	
60	5.0	364	
70	10	418	
80	10	402	
90	10	300	
100	10	290	
120	10	280	
140	10	221	
160	20		
180	20		
200	20		

Schlumberger Data Sheet for VES 3

Location..... Passa..... VES n°: ...3..... Date...05/07/2022

Coordinates.....7.0517..E .....8.9618...N Altitude.....

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	279	
2.0	0.5	149	
3.0	0.5	83	
4.0	0.5	74	
6.0	0.5	64	
8.0	0.5	67	
12	0.5	117	
15	0.5	145	
20	0.5	160	
25	0.5	183	
32	5.0	283	
40	5.0	344	
50	5.0	438	
60	5.0	513	
70	10	597	
80	10	663	
90	10	788	
100	10	920	
120	10	1000	
140	10	1138	
160	20		
180	20		
200	20		

Schlumberger Data Sheet for VES 4

Location... Gwagwalada VES n°: 4 Date... 05/07/2022

Coordinates... 7.0758.E ... 8.9322 ...N Altitude.....

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	118	
2.0	0.5	103	
3.0	0.5	88	
4.0	0.5	68	
6.0	0.5	30	
8.0	0.5	26	
12	0.5	24	
15	0.5	28	
20	0.5	44	
25	0.5	54	
32	5.0	63	
40	5.0	97	
50	5.0	130	
60	5.0	158	
70	10	176	
80	10	169	
90	10	188	
100	10	176	
120	10	190	
140	10	200	
160	10	213	
180	10		
200	10		

Schlumberger Data Sheet for VES 5

Location.....Paiko..... VES n°: .....5..... Date..06/07/2022

Coordinates.....7.0268..E .....8.9829...N Altitude.....

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	59	
2.0	0.5	67	
3.0	0.5	61	
4.0	0.5	60	
6.0	0.5	60	
8.0	0.5	55	
12	0.5	56	
15	0.5	54	
20	0.5	52	
25	0.5	53	
32	5.0	61	
40	5.0	86	
50	5.0	114	
60	5.0	149	
70	10	203	
80	10	257	
90	10	315	
100	10	370	
120	10	390	
140	10		
160	10		
180	10		
200	10		

Schlumberger Data Sheet for VES 6

Location... Chechuyi ..... VES n°: ..... 6 ..... Date... 06.07.2022

Coordinates..... 7.0528 E ..... 8.9789 N Altitude.....

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	261	
2.0	0.5	300	
3.0	0.5	345	
4.0	0.5	390	
6.0	0.5	432	
8.0	0.5	422	
12	0.5	391	
15	0.5	350	
20	0.5	298	
25	0.5	256	
32	5.0	220	
40	5.0	205	
50	5.0	190	
60	5.0	233	
70	10	270	
80	10	293	
90	10	341	
100	10	383	
120	10	437	
140	10	391	
160	10	370	
180	10		
200	10		

Schlumberger Data Sheet for VES 7

Location..NNPC...Gas Plant VES n°: ....7..... Date...07/07/2022

Coordinates.....7.0645.E .....8.9751....N Altitude.....

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	87	
2.0	0.5	109	
3.0	0.5	130	
4.0	0.5	145	
6.0	0.5	170	
8.0	0.5	287	
12	0.5	300	
15	0.5	250	
20	0.5	200	
25	0.5	190	
32	5.0	180	
40	5.0	184	
50	5.0	199	
60	5.0	178	
70	10	267	
80	10	345	
90	10	407	
100	10	490	
120	10	674	
140	10	810	
160	10	900	
180	10		
200	10		

Schlumberger Data Sheet for VES 8

Location NNPC Gas Plant VES n°: 8 Date 07/07/2022

Coordinates 7.0673 E 8.9789 N Altitude

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	124	
2.0	0.5	129	
3.0	0.5	158	
4.0	0.5	169	
6.0	0.5	179	
8.0	0.5	128	
12	0.5	121	
15	0.5	133	
20	0.5	148	
25	0.5	162	
32	5.0	199	
40	5.0	156	
50	5.0	186	
60	5.0	217	
70	10	219	
80	10	233	
90	10	256	
100	10	302	
120	10	390	
140	10	480	
160	10	460	
180	10		
200	10		

Schlumberger Data Sheet for VES 9

Location NNPC Gas Plant VES n°: 9 Date 08/07/2022

Coordinates 7.0762 E 8.9710 N Altitude

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	86	
2.0	0.5	52	
3.0	0.5	43	
4.0	0.5	41	
6.0	0.5	63	
8.0	0.5	94	
12	0.5	135	
15	0.5	161	
20	0.5	203	
25	0.5	254	
32	5.0	323	
40	5.0	253	
50	5.0	219	
60	5.0	235	
70	10	215	
80	10	225	
90	10	229	
100	10	287	
120	10		
140	10		
160	20		
180	20		
200	20		

Schlumberger Data Sheet for VES 10

Location NNPC Gas Plant VES n°: 10 Date 08/07/2022

Coordinates 7.0677 E 8.9723 N Altitude

AB/2 m	Mn/2 m	Ohm-m	Remark
1.0	0.5	50	
2.0	0.5	72	
3.0	0.5	78	
4.0	0.5	88	
6.0	0.5	114	
8.0	0.5	130	
12	0.5	195	
15	0.5	200	
20	0.5	265	
25	0.5	270	
32	5.0	339	
40	5.0	392	
50	5.0	452	
60	5.0	515	
70	10	572	
80	10	663	
90	10	743	
100	10	731	
120	10	923	
140	10		
160	10		
180	10		
200	10		