ESTIMATION OF HYDRAULIC CONDUCTIVITY IN SHALLOW UNCONFINED AQUIFERS USING CONCRETE-LINED LARGE-DIAMETER HAND-DUG WELLS

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Submitted in fulfilment of the requirements in respect of the doctoral degree

Doctor of Philosophy
majoring in Geohydrology

at the
Institute for Groundwater Studies
in the
Faculty of Natural and Agricultural Sciences
at the
University of the Free State

June 2019

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DECLARATION

I, **Kehinde Olojoku Ibrahim**, declare that the thesis that I herewith submit for the doctoral degree *Doctor of Philosophy majoring in Geohydrology* at the University of the Free State, is my independent work, and that I have not previously submitted it for a qualification at another institution of higher education.

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June 2019

ACKNOWLEDGEMENTS

My profound gratitude goes to Almighty Allah for giving me the strength, ability and sound health throughout my PhD programme and for making all things possible. Glory be to his name.

My unquantifiable appreciation goes to my able and willing supervisor, Dr. Modreck Gomo, who, despite his tight schedule, read through, corrected, gave advice, suggestions and contributions to make this research work a success. I say thank you, Sir. I am also grateful to my co-supervisor, Dr. Saheed Adeyinka Oke, for his numerous contributions, both morally and financially, to make this research successful. May Allah reward you abundantly.

I am very much grateful to Prof. M.S. Dada from the Mathematics Department at the University of Ilorin in Nigeria, and Prof. Abdon Atangana from the Institute for Groundwater Studies (IGS) at the University of the Free State, for their moral assistance in the mathematical derivations of my PhD research work. God bless you.

I also use this opportunity to thank my employer, University of Ilorin, Ilorin, Nigeria, for giving me study leave for my PhD studies. I thank the Director and entire staff of IGS, University of the Free State. I also thank Mrs. Dora du Plessis, formerly from IGS, for proper editing and proof-reading of my PhD thesis.

Indeed, I am inundated with compassionate appreciation to my dearest late mother, Alhaja Raliat Ibrahim Olojoku; may Allah forgive all her sins and grant her Alijanat Fridaus. These accolades would not be completed if I forget to point out the golden tongue that does the magic work; much encouraging words from my wife, Aminat Toyin Ibrahim, for her love, care, understanding, and most especially, her prayers. I thank my dearest kid, Ashrof Akorede Alabi (Triple “A’’) Ibrahim, for his understanding and love throughout my PhD studies. I thank my father, Mallam Agboola Ibrahim, my step-mother, Alhaja Iyabo Ibrahim, and my mother and father in law, Mr. and Mrs. Ibrahim Bashir, for their unflinching love, care and prayers.

I cannot but acknowledge with gratitude the moral and financial assistance rendered by my good brothers and friends, Dr. Mumeen Adebayo Yusuf Asiribo, Engr. Dr. Abdul-Ganiyu Adeniyi (Galileo), Dr. Saheed Bello, Engr. Dr. Oladimeji Bashiru Ibrahim, Dr. Surajudeen Adesina (HOD), Dr. Abdulrasaq Haruna, Mallam Bolaji Ibrahim Bare, Mallam Olatunji Ibrahim Bare, Dr. Bashir Ojulari, Mrs Mariam Ifedolapo Oke, Mr. Babatunde Falodun, Dr.

Ismail Folorunsho, Dr. Wasiu Raji, Mr. Olanrewaju Abubakar, Mr. Kayode Oniyangi, Mr. Celphas Alepa and Mr. Ayo Komolafe.

I use this opportunity to thank every member of my family, starting from Mallam Sulaiman Ibrahim (Olori ebi), Barrister Folake Eleja, Barrister Taiwo Ibrahim, Dr. Abdulrasheed Olayinka Ibrahim, Mr. Yusuf Ibrahim, Barrister Biodun Ibrahim, Hajia Risikat Eleran, Engr. Ridwan Ibrahim, Mrs Khafilat Omowumi Ibrahim, Miss Aisha Yetunde Ibrahim, and Azeezat Ibrahim.

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ABBREVIATIONS AND ACRONYMS

EC	Electrical conductivity
GPS	Global Positioning System
IRC	International Water and Sanitation Centre
IWSC	International Water and Sanitation Centre
NARC	National Agriculture Research Council
NSDWQ	Nigerian Standard Drinking Water Quality
NWFP	North-West Frontier Province
SI	Saturation Index
TDS	Total Dissolved Solids
UNICEF	United Nations Children’s Fund
WRRI	Water Resources Research Institute
WSA	Water and Sanitation Agency

LIST OF SYMBOLS

K	hydraulic conductivity
l	litre
l/s	litre per second
m	metre
$MgHCO_3$	Magnesium bicarbonate
mg/l	milligram per litre
ρ_a	Apparent resistivity
Ωm	ohms-metre
µS/cm	microsiemens per centimetre

ABSTRACT

Large-diameter hand-dug wells are the main source of water supply for drinking, domestic and irrigation uses in many rural areas of sub-Saharan African countries and other developing countries of the world. In many rural areas of developing sub-Saharan African countries, the use of unscreened lining is the most common method of protecting large-diameter hand-dug wells against collapsing and pollution due to the simplicity and affordability of the method. This method prevents horizontal water flow to the well and water flow to the well through the well base, which makes the existing methods inapplicable for estimating hydraulic conductivity in screened hand-dug wells.

The method developed involved to derive horizontal hydraulic conductivity (K) from apparent hydraulic conductivity (Ka). To demonstrate the viability of the developed method, field recovery tests were conducted in twelve (12) unscreened concrete-lined and screened lined large-diameter hand-dug wells based on the accessibility of the wells at test site to estimate apparent hydraulic conductivity (Ka) and horizontal hydraulic conductivity (K). The geophysical study of the test site was aimed to estimate the aquifer type, depth to water table and identification of strata and vadose zone thickness. The hydrogeochemical studies involved the collection and analysis of water samples from twenty (20) large-diameter hand-dug wells at the test site during rainy and dry seasons and was aimed at monitoring the groundwater quality and groundwater type of the test site.

The results showed that the estimated apparent hydraulic conductivity Ka were lower than the horizontal hydraulic conductivity K, which indicated the effect of the unscreened concrete-lining. A relationship between Ka and K was established to make a correction factor for estimation of K from Ka by a regression analysis which showed a significant strong relationship of 0.00 between Ka and K using a bivariate Pearson correlation coefficient.

This study has formulated a method that can be used to estimate aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells. This will help to estimate the yield potential of the wells and evaluate the amount of water that can be abstracted or pumped from the wells in the rural areas of the developing world where unscreened concrete-lined large-diameter hand-dug wells are being used. Further studies are recommended to quantify the amount of energy loss in flow as a result of non-horizontal water flow into the well.

Key terms: Apparent hydraulic conductivity, Horizontal hydraulic conductivity, Large-diameter hand-dug wells, Rural-areas, Screened-lined wells, Unscreened-lined wells.

LIST OF PUBLICATIONS

Ibrahim KO & Gomo M. 2016. Evaluation of groundwater resource potential in rural part of northcentral Nigeria using vertical electrical resistivity method. *Ethiopian Journal of Environmental Studies and Management*, 9(2):1059-1070. doi:10.4314/ejesm. v9i2.11S

Ibrahim KO, Gomo M & Oke SA. 2019. Groundwater quality assessment of shallow aquifer hand dug wells in rural localities of Ilorin, Northcentral Nigeria: Implications for domestic and irrigations uses. *Journal of Groundwater for Sustainable Development*. Available online: doi: 10.1016/j.gsd.2019.100226. *www.elsevier.com/locate/gsd*

Chapter 1

INTRODUCTION

1.1 Background information

Accessibility to water supply in the rural areas has continued to be one of the most complex challenges facing developing African countries, particularly in sub-Saharan Africa. Today, this region accounts for about 40% of the water stress globally (United Nations, 2018). Groundwater serves as the most affordable means of meeting the ever-increasing demands of water resources in the rural areas for different purposes such as drinking, domestic and agricultural uses. Groundwater development has reduced poverty and promote sustainable livelihood in many rural communities, particularly in the sub-Saharan African countries (Calow et al., 2002).

One of the practically affordable means of accessing groundwater in the rural areas is mostly through a large-diameter hand-dug well which is considered as the most feasible and easiest way of accessing groundwater for domestic and irrigation uses. The definition of large-diameter hand-dug well is relative, according to the Department of Water and Forestry (2004a) defined a large-diameter hand-dug well as having a diameter greater than 0.8 metres, that allows a single community to be able to dig and remove the excavations during installation of the well. The depths of the large-diameter hand-dug wells are mostly varying, depending on the hydrogeological/ geohydrological situations and water needs of the concerned area (Gomo et al., 2019).

A large-diameter hand-dug well is excavated and constructed manually by hand with the use of simple tools such as shovels and picks that serve as the basic equipment. They normally have a diameter of greater than 0.8 m to allow a community to do proper digging and remove soils such as sands or other weathered rock materials during the construction process (South Africa, Department of Water and Forestry, 2004). The method and technicality needed for the excavation and construction depend on location, affordability and site situation which varies from one area to another.

Large-diameter hand-dug wells are suited to unconsolidated formations which make it easy to excavate by using manual methods. Large-diameter hand-dug wells can be installed in any kind of formation where manual excavation is possible. Therefore, it is possible to say that in some hydrogeological situations, large-diameter hand-dug wells can be cost-effective and cheaper to drill and give a good yield. Some good examples of these include alluvial aquifers where the water-bearing alluvial deposits are basically unconsolidated and can be excavated manually; these also goes for weathered basement aquifers which are rock materials that have undergone different stages of weathering.

Large-diameter hand-dug well construction includes the use of curb lining such as brick, rock and concrete to protect the well against collapsing. The lining is screened to allow horizontal water flow to the well and increase the well yield. For the screened hand-dug wells, standard recovery methods were developed based on Darcy's law to estimate aquifer hydraulic conductivity (Boulton & Streltsova, 1976; Herbert & Kitching, 1981; MacDonald et al., 2008; Papadopulos & Cooper, 1967; Rupp et al., 2001; Rupp et al., 2011; Rushton & De Silva, 2016; Rushton & Holt, 1981; Uribe et al., 2014; Yang & Yeh, 2004). The aquifer hydraulic conductivity is an important aquifer parameter that is used to estimate the aquifer yield and also to determine spatial water availability. This will help in determining the amount of water that can be pumped from the well over a given time and to evaluate the coverage and distribution of the water resources in order to manage and sustain the available water resources to satisfy the need of the communities.

The use of unscreened concrete-lining in protecting a large-diameter hand-dug well is a common method of lining in many rural areas of developing sub-Saharan African Countries which considered to be cheaper and the materials involved in the construction are cost effective. The use of unscreened concrete-lining prevents the horizontal water flow to the well and water flow to the well occurs through the well base, making the above-mentioned Darcy-based methods inapplicable. A review of existing methods for estimating aquifer hydraulic conductivity in hand-dug wells shows that there is no reference or mention of methods for estimating aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells; therefore, it is possible to argue that the estimation of aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells may not have been covered in the earlier work.

1.2 Aim and objectives

The aim of this research is to develop a method for estimating hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells.

The aim of the research was achieved through the following objectives:

- Reviewing of the existing methods for estimating hydraulic conductivity in large-diameter hand-dug wells.
- Development of a new method for estimating hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells.
- Testing and evaluating the proposed method using a typical rural area.
- Provide guidance on the use of the proposed method.

1.3 Thesis outline

This thesis is broadly divided into six main chapters:

Chapter 1 discusses the background information on the groundwater system, large-diameter hand-dug wells, the research aim and objectives.

Chapter 2 gives an overview on hand-dug well features, the importance and types of hand-dug wells, methods used in estimating hydraulic conductivity in screened large-diameter hand-dug wells, research gap and motivation.

Chapter 3 discusses the test site characterisation. This involves a multidimensional approach which includes geology and geohydrology characterisation of the test site.

Chapter 4 presents a development of the proposed method for estimating aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells.

Chapter 5 discusses the application of the proposed method, steps to determine aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells, and the significance of the proposed method.

Chapter 6 concludes the research and makes recommendations for the improvement of large-diameter hand-dug wells in the rural water supply.

Chapter 2

OVERVIEW ON LARGE-DIAMETER HAND-DUG WELLS

2.1 Introduction

This chapter discusses the importance of hand-dug wells as a source of rural water supply. All existing types of hand-dug wells are explained and discussed, including their features, advantages and disadvantages as part of the desktop review for this research. The methods used in estimating hydraulic conductivity (K) in screened-lined large-diameter hand-dug wells are reviewed, followed by the identification of the gap in research and a discussion of the novelty in this study.

2.2 Importance of hand-dug wells

Hand-dug wells are wells that are constructed by using simple hand tools. This also refers to a pit that is dug into the aquifer or dug into the material where permeability occurs. These wells are sunk by digging a hole as deep as necessary to reach the water. Hand-dug wells are the most common traditional methods of obtaining groundwater in the rural areas. In the rural communities where the local hydrogeological conditions are favourable, many household water needed for drinking, cooking and irrigation are supplied by hand-dug wells (Aina and Oshunrinade, 2016; Bruni and Spuhler, 2018; Gomo et al., 2019; Schram and Wampler, 2018; Mace, 1994; Pickford, 1990; WaterAid, 2008).

Hand-dug wells can provide a viable alternative to unhygienic, unprotected water and recharge sources, while avoiding the investment and maintenance costs associated with more sophisticated water supply systems. In many rural and remote areas, hand-dug wells remain the most feasible and easiest way of providing water for domestic (drinking, cooking, washing) and agricultural purposes due to their simplicity and affordability in construction.

As far back as Biblical times, hand-dug wells have been initiated through manual drilling techniques to promote irrigation at household level, and later, with technology, have been applied to development as sources of water supply for domestic uses (International Water and Sanitation Centre, 2016). In practice, especially in the rural communities of the developing world, people use hand-dug wells for various purposes which include drinking water, irrigation or water for livestock, depending on their needs (WaterAid, 2013).

Hand-dug wells are common in the developing world, especially in rural water supplies. Though some developed countries have changed to centralised water systems such as constructing boreholes, hand-dug wells are still commonly used in the rural areas of developing countries (Aina and Oshunrinade, 2016; Gibson and Singer, 1969; Gomo et al., 2019; Mace, 1994, 1999; Rushton and De Silva, 2016; Schram and Wampler, 2016).

Interest in hand-dug wells has increased and still gives much promise for arid areas. In countries such as India and Nigeria (Figure 2.1), hand-dug wells have increased the accessibility to groundwater resources (National Academy of Sciences, 2014).

Source: WaterAid (2013)

Source: Author's own (2019)

***Figure 2.1** Use of traditional hand-dug wells in India (A) and Nigeria(B)*

2.2.1 Advantages of hand-dug wells

- Equipment used for the construction of hand-dug wells is light and simple, making them suitable for use in remote areas.
- Methods used for the construction of hand-dug wells are easily understood by unskilled workers and therefore reduce the time needed for supervision.
- The methods allow for the participation of the community; it is 'their' well and therefore they are more likely to maintain it.

- Material used in the construction of hand-dug wells can be found locally and this makes it one of the cheapest methods for well construction in rural areas.
- In some hydrogeological conditions, hand-dug wells can be cost-effective to excavate and give good yields. A good example is an alluvial aquifer.

2.2.2 Disadvantages of hand-dug wells

- In a typical hard rock area, it is very difficult to penetrate deep enough and this can only be achieved by blasting, which requires hard work, is a slow process and costly.
- Since it is usually difficult for hand-dug wells to penetrate a very deep depth through the underneath hard rock in a basement terrain, there may be slight fluctuations in the water table and this can result in drought especially in the dry season.
- If no provision for protection of the water source is made, the well can easily be contaminated through surface water and human activities.

2.3 Types of hand-dug wells

2.3.1 Hand-augured tube wells

This type of hand-dug well is used in areas where other types of traditional hand-dug wells are not effective to improve water supply. This type of hand-dug well is supported with drilled well technologies using a hand auger (Harvey and Reed, 2004; Hayman, 2014). Drilling of a small diameter well by using hand-operated equipment has been practiced and proven to be successful. In an area where the water table occurs at a shallow depth in an unconsolidated aquifer, the hand-augured well can give much water at a minimum cost (Hayman, 2014; Morgan, 1999). Also, along the riverine belts and with active flood plains, hand-augered tube wells can be drill to a deep depth (Ashraf and Idris, 2000; Saeed et al., 2001, 2003a, 2003b).

This type of well is dug by hand-operated or power-driven earth augured which comprise of different components with different shapes and sizes that are used in the construction, and operated with cutting blades at the bottom that bore into the ground with a rotary motion (Figure 2.2). The most common manual augured is called a Vonder Rig which was developed by V & W Engineering in Zimbabwe.

Source: MacCarthy (2004)

Figure 2.2 Use of a Vonder Rig in Maputaland, KwaZulu-Natal

This type of rig possesses a steel tripod through which drilling rods are attached. This rig has a robust worktable that aligns the extension rods of the auger while it drills into the ground. It also possesses a winch that is attached to one of the legs of the tripod that is used to raise and lower the auger. The operation involves using four to seven healthy adult men with an experienced operator. In the process of construction, a few people are required to turn the crossbar that is attached to the auger rod, at the same time exerting downward pressure. While the supporting cable is loosened, the action will allow the downward movement of the auger to cut into the soil. The operation is continuous until the auger is occupied with soil and the process is continuous until the water table is encountered (Morgan, 1999).

The augured tube well is normally lined throughout the depth with a 125 mm diameter, class 9 u PVC pipe that has sufficient strength to withstand the bearing pressure of the surrounding soil. The well screen is normally located at the bottom three metres of the pipe. The well screen is wrapped in a geotextile material which prevents the infiltration of fine sands into the augered tube well.

2.3.1.1 Advantages of a hand- augured tube well

- It can drill through soils and weathered formations.
- It normally penetrates more deeply into the groundwater table than other hand-dug well equipment which increases the water supply.
- It is also helps to prevent seasonal shortage of water supply most especially in the dry period.

2.3.1.2 Disadvantages of a hand-augured tube well

- Difficulty of drilling in hard rock formations.
- Improved hand-augered well technologies are technically advanced, more expensive and require more materials and skilled labour than other types of hand-dug wells.

2.3.2 Hybrid dug well / Dug pit bore well

In some cases, a well is dug or upgraded through a combination of digging by hand and manual drilling (Wong and Brown, 2008), creating a so-called telescopic or hybrid well. This type of well combines the hand-dug well concept with a drilled bore well and such a well is called a dug-bored well. The hybrid well can be categorised in different ways such as a semi-centralised water supply system (Bieker and Wagner, 2010; Sapkota et al., 2015; Schramm, 2011; Schramm and Bieker, 2010; Weber et al., 2007), a distributed water supply system (Bach et al., 2013; Biggs et al., 2009; Cook et al., 2010; Makropoulos and Butler, 2010), and a semi-decentralised water system (Wang, 2015).

There are two main classes of hybrid dug well systems (Daigger and Crawford, 2007; International Water and Sanitation Centre [IWSC], 2013), namely: The first type of hybrid dug well has a drilled bore within the centre of the working dug well and in this type, both the dug well and bore contribute to the recharge. In the second type of dug bore well it has a dug pit which is about 1−2 m above the static water level, and therefore, the bore is drilled in order to have access to the aquifer, but this type has only a bore that supplies water when a pumping system is installed in the dug pit.

The hybrid well could also be called a dug pit bore well because it involves digging a pit purposely in reducing the suction lift. It has been used by farmers in many parts of India and

Pakistan since the early 1970s where they drilled one or more bores inside their dug pits to acquire a high rate of water discharge (20–24 l/s) (Nagaraj, 1994; Nagaraj et al., 1999).

The hybrid well normally has a depth ranging between 15 m and 30 m and water extraction is mostly done through a centrifugal pump (Figure 2.3).

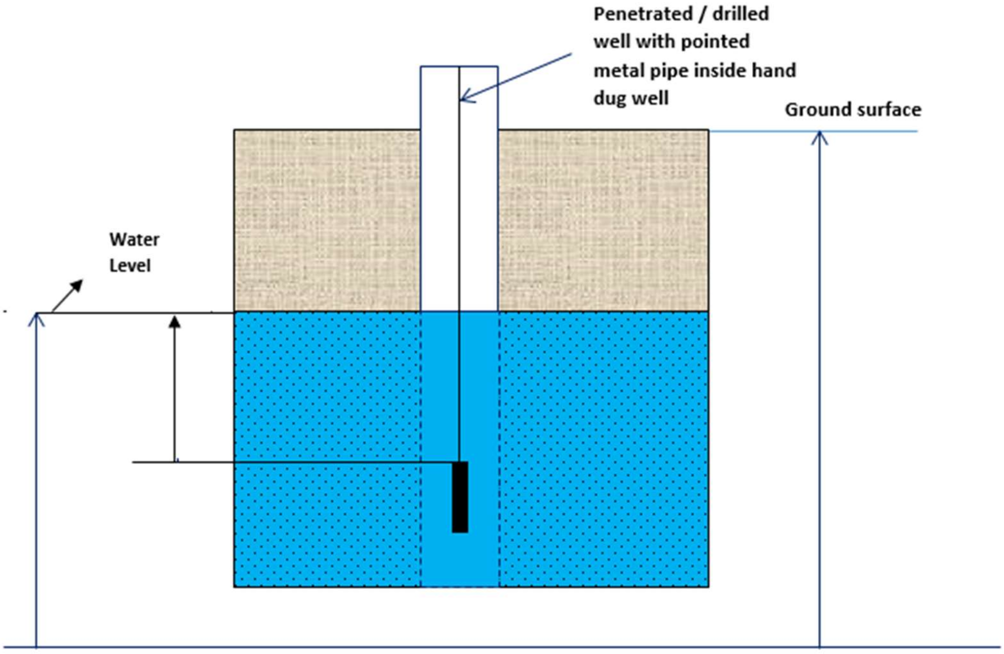


Figure 2.3 Design of a hybrid well / dug pit bore well

2.3.2.1 Advantages of a hybrid dug well

- It increases the diversity and flexibility of the water system by increasing the water availability.
- It is more flexible, as it is easier to be used for local conditions.
- It has a large savings potential in daily potable water demands through intra-urban reuse.
- It turns out to be cheaper and recognise the complexity of water economics and management.

2.3.2.1 Disadvantages of a hybrid dug well

- Since it is double wells usage (hand-dug well and drilled bore well), therefore can reduces the lifespan of the wells (Nagaraj, 1994; Nagaraj et al., 1999).

- This type of well is adopted to the lowering of bores continuously with the lowering of the water table.
- There are challenges relating to retrofitting that connect with limited land and high cost.
- Another challenge in the use of the hybrid water system is the transforming of model services provision from a centralised to hybrid water system.

2.3.3 Skimming dug well

The term 'skimming well' is a new addition to the engineering lexicon and is used for any technique having the intention to extract relatively fresh water from the upper portion of the fresh saline aquifer and in which the depth of the extraction is defined by considering the underlying saline water layer (Saeed et al., 2003a). A skimming dug well is a partially penetrating dug well in a shallow fresh groundwater layer having a pumping capacity of 28 l/s (Aslam et al., 2016). The skimming dug well usually pumps water taken from a thin fresh groundwater layer with or without minimum disturbance to the underlying saline groundwater (Ahmad, 1979; Aslam et al., 2016; Saeed et al., 2003a; Zardari et al., 2015).

This type of dug well is simple, cheap and cost-effective, and used traditionally as alternative when compared to other potential sources for the skimming of fresh groundwater, especially in fresh brackish groundwater aquifers (Zuberi and McWhorter, 1973). Skimming dug wells are also used in the managing of water-logged areas with the concept of horizontal galleries. In this type of setting, radial well points are used in the generating of high rates of water discharge. Several researchers who have investigated the performance of skimming wells, recommended the use of skimming dug wells in obtaining good quality pumped groundwater with a salinity of less than 1 000 mg/l (Aliewi et al., 2003; Asghar et al., 2002; Saravanan et al., 2014).

Improved well design and better operating strategies are necessary factors of obtaining a good quality groundwater in a skimming dug well (Saeed et al., 2003a). Skimming dug wells have been tested by WRRI–NARC at the Tropical Plants Introduction Centre, Karachi and Thana Boula Khan, to increase the yield of fresh groundwater. It has also been used as source of fresh groundwater in Pakistan, such as in the Sindh province, the brackish groundwater zone in the Southern Punjab, the southern North-West Frontier Province, and parts of the Balcochistan province where the fresh groundwater thickness is said to be less than 15 m (Aslam et al., 2016). Skimming wells are also useful in the areas with shallow groundwater and where there is ineffective subsurface drainage and a rising water table. The skimming well can be categorised into single-bore, multi-bore, scavenger, radial collector and dug well skimming wells. Among these wells, multi-bore wells are the most popular types because they are economically affordable (Saeed et al., 2003a).

2.3.4 Scavenger dug well

In order to restrict the rise of a fresh–brackish / saline interface to reach the effective pumping zone of the well, the adoption of a scavenger well system is considered as one of the possible solutions in which pumping from the production well is accompanied with brackish/salt water pumped from a scavenger well in the vicinity (Jones and Van Wonderen 1994; Vashisht and Shakya, 2016).

The concept of scavenger wells is based on the principle that the streamline pattern around a discharging well develops quickly and remains virtually unchanged once it is established. In a scavenger well system, two wells (production well and scavenger well) are installed, either in a single borehole or side-by-side boreholes. The production well screens the freshwater zone, whereas a scavenger well taps the brackish/saline water zone. The development of discharge heads due to simultaneous pumping of these wells restricts the mixing of freshwater with brackish/saline water. The discharge rates of the two wells are adjusted in such a way that the upconing caused by pumping from the production well could be countered by the down coning of the interface caused by pumping from the scavenger well (Saravanan et al., 2014; Vashisht and Shakya, 2016).

The freshwater and saline water pumping rates in scavenger wells are regulated to restrict the movement of the fresh–saline interface, and protect the quality of the fresh discharge while maximising the quantity. The proportion of fresh and saline water discharge depends on the interface depth, and the well penetration ratio with respect to the depth of the aquifer. This ratio should not be greater than the ratio of the average thickness of the freshwater lens and the saline water layer (Babushkin, 1963; Zack, 1988; Zack and Munoz-Candelario, 1984). When the two ratios are equal, the flow-divide approaches the limiting position coinciding with the interface. If the discharge ratio is smaller, then after some time, freshwater will enter the lower well, and vice versa.

2.3.5 Large-diameter hand-dug well

In the field of hydraulics, hand-dug wells are simply referred to as a large-diameter well. The large-diameter hand-dug wells are wells or holes that are made in the ground with the use of local hand-made tools (Amadi et al., 2013; Mace, 1994; Miller et al, 2017; Naik and Awasthi, 2007; Schram and Wampler, 2016; WSA, 2010). The South African Department of Water Affairs and Forestry defined a large-diameter hand-dug well as having a diameter greater than 0.8 m that allows a single community to be able to dig and remove the excavation during the construction of the well. More details on the construction, installations and maintenance of large-diameter hand-dug wells can also be found in Abbott (2001) and MacDonald and Davies (2000).

Under supervision, not especially skilled but rather physically capable workers are required in the whole construction process, while local hand-made tools such as spades, bars, picks and mattocks are used for excavation and construction. The workers that are doing the digging normally place the excavated materials in a bucket or basket which are later pulled up to the ground surface through the use of a rope and pulley which is done by other workers who dump it at distance far from the well (Figure 2.4). The depth of the well varies depending on the hydrogeological/geohydrological conditions and water needs, though a greater depth would ensure a year-round supply of water if the local hydrogeological conditions are conducive (Gomo, et al., 2019).

Source: WaterAid (2013) Source: Author's own (2019)

Figure 2.4 ***Construction of large-diameter hand-dug well***

During the excavation and construction of the well, the major goal and challenges are that there must be accuracy, both locational and dimension, that is, the centre line or axis of the excavation must be maintained as absolutely vertical as possible while maintaining the radius of the excavation as exactly as possible about the axis (WaterAid, 2013). Vertical accuracy is needed to prevent angular and offset errors, especially between the successive sections of the lining. Radial accuracy is also very important because the excavation serves as the exterior mould for the well lining.

In a situation where the radius of the excavation is too small, a thin, weak spot in the lining will occur but where the radius is too large, a thick spot of wasteful material will occur. Regardless of the method used to excavate the well to the water table, excavation below this level should never be attempted until the sides of the excavation have received the support of a permanent lining. Excavation below the water table should be carried out within precast concrete caisson rings of a smaller diameter than the rest of the well (WaterAid, 2008).

The large diameter facilitates construction and is needed to store water. The choice of diameter is very important and the diameter should be large enough to allow easy construction and create working space for workers in the construction processes. The volume of water inside the large hand-dug well below the standing water table actually acts as a reservoir which is normally considered as meeting up with the water demand during the day and would replenish itself mostly at the period when there is no abstraction from the well. Water is abstracted through the use of either a bucket with rope and windlass or by using a handpump but depends on the yield of water available and possibility to afford the maintenance of the well most especially when using handpump which is capital intensive (Laver, 2012).

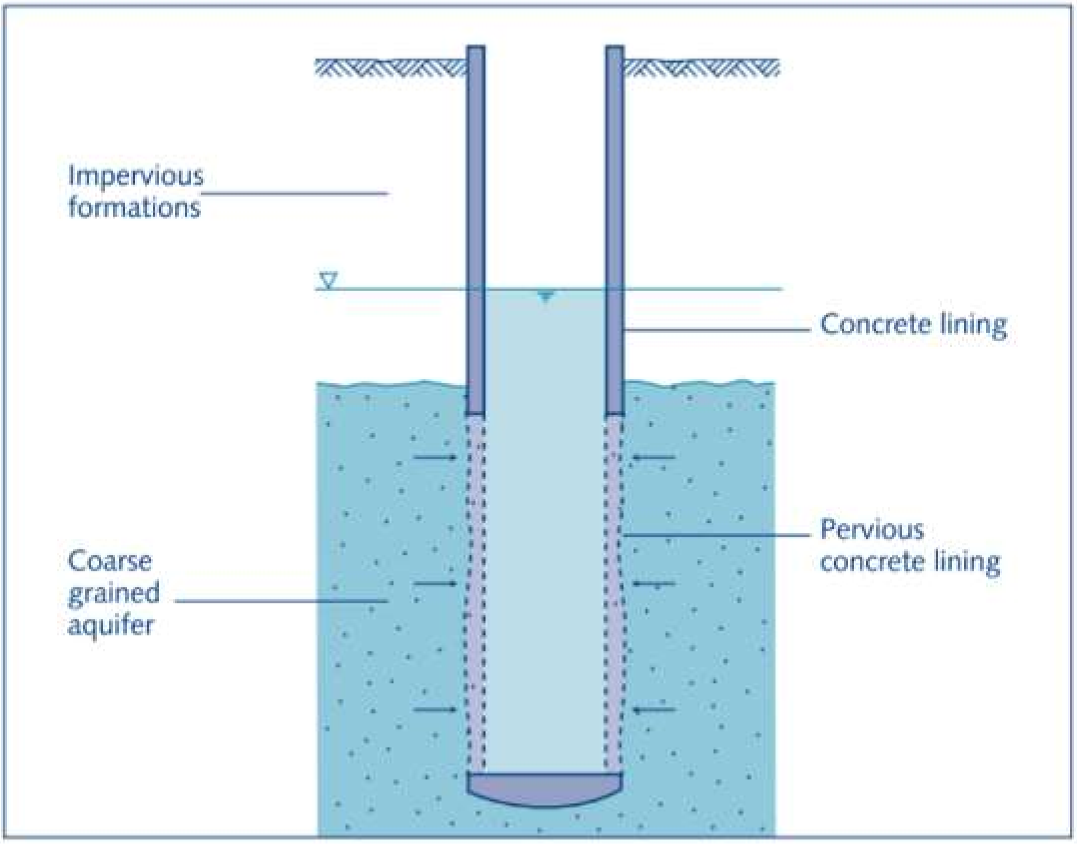
2.3.5.1 Lining and screening of a large-diameter hand-dug well

During or after excavation, a permanent lining needs to be installed unless the well is constructed in consolidated ground such as rock formations (Smet and Wijk, 2002; WSA, 2010). The lining serves several purposes. During construction, it provides protection against caving and collapse and prevents crumbling ground from filling up the dug hole. It also prevents the entry of surface water that can lead to contamination of the well (Figure 2.).

Figure 2.5 Unlined large-diameter well with contaminated water seeped in through the soil

In a convectional or modern method of lining, the section of the well penetrating the aquifer requires a lining with screen enabling the groundwater to flow into the well (Figure 2.6) and in most cases, casing is used that is often called a curb of wood staves, bricks, rocks, screened concrete or metal. The curbs are screened for entry of water and must be firmly seated at the bottom. The gravel is used to be backfilled around the curb and at the bottom of the well with the purpose to control and prevent sand entering into the well and possible caving of the well.

Some well programmers recommend the use of circular, precast concrete well rings and these rings can be produced on-site or in a local production centre. In very soft formations; the rings are sunk, starting from the surface; digging from the inside of the ring; removing the material with a bucket and adding new rings as required. In harder, semi-consolidated formations, the rings can also be inlaid after having excavated the hole completely up to the groundwater level (United Nations Children's Fund [UNICEF], 1999).



Source: Smet and Wijk (2002)

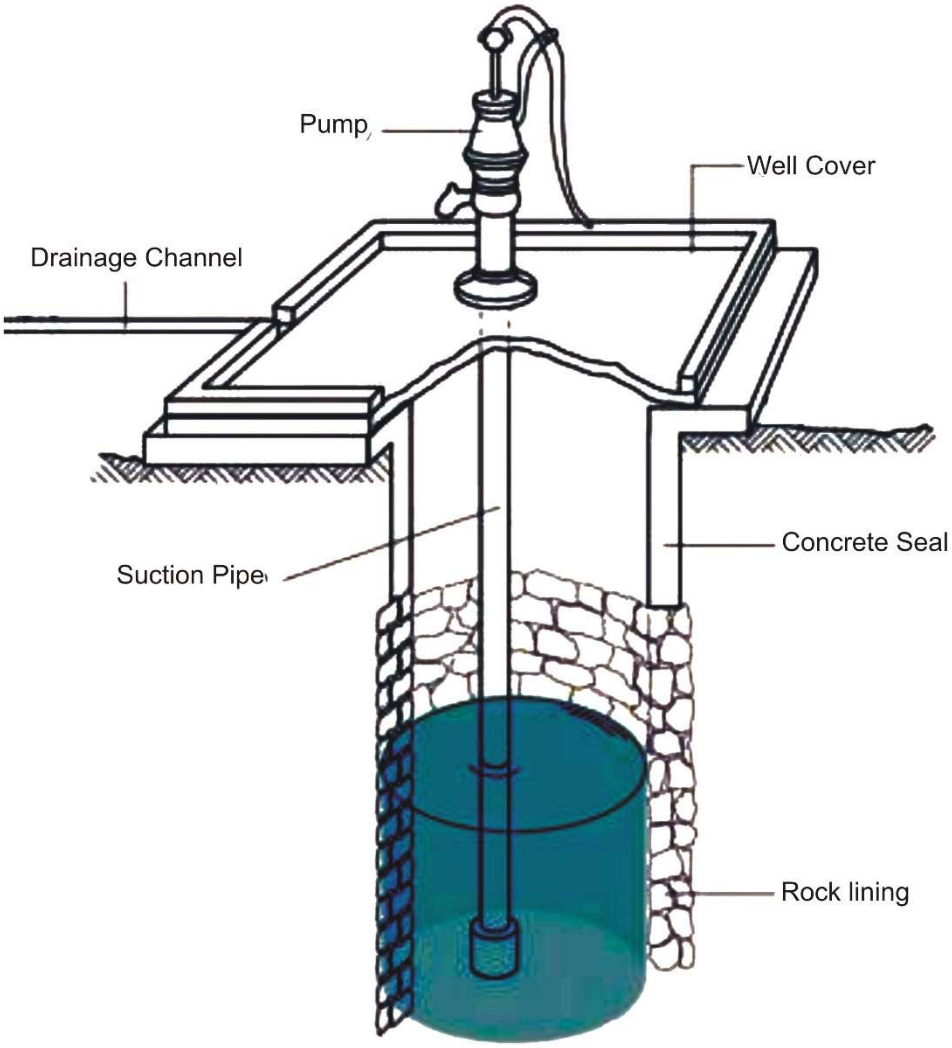
Figure 2.6 Convectional method of lining and screening of well

2.3.5.2 Components of a large-diameter hand-dug well

Large-diameter hand-dug wells usually consist of three components (Collins, 2000; WaterAid, 2013):

- **The well head**: This is the part of the well which is visible above the ground. It protects the well from contamination and generally consists of a well cover or apron, a concrete seal, a manhole (for access), a drainage channel and a pump.
- **The well shaft**: This is the section of the well between the head and the intake. It is made out of strong, durable material, which can easily be kept clean.

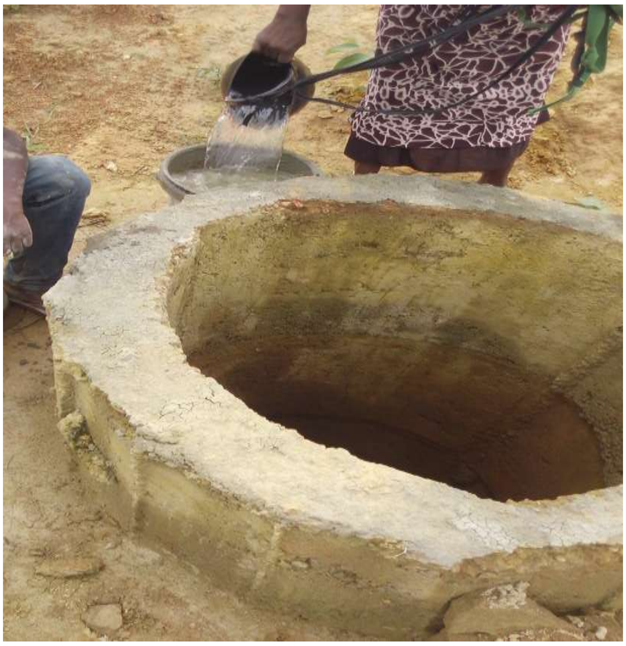
The intake: The walls of the intake are constructed in such a way as to allow water to pass from the aquifer into the well, thus creating a storage area, which can be accessed either by using a bucket or pump (Figure 2.7).



Source: Smet and Wijk (2002); see also WaterAid (2013)

Figure 2.7 Components of large-diameter hand-dug well

(a) Protected well (b) Semi-protected well



(c) Unprotected well

Source: Author's own (2019)

Figure 2.8 Different classifications of large-diameter hand-dug wells

2.3.5.3 Advantages of a large-diameter hand-dug well

- Local skills are needed for construction.
- Low cost of labour involved.
- Necessity of storing water, especially where the aquifer is of extremely low permeability.
- Repairing and maintenance is easier than other hand-dug wells.
- Long lifespan as many large-diameter hand-dug wells exist for several years.

2.3.5.4 Disadvantages of a large-diameter hand-dug well

- Construction is slow.
- Extracting large quantities of water with motorised pumps is not usually feasible.
- In a hard rock terrain, it is difficult to penetrate to a deep depth and often can only be accomplished by blasting the rock which is mostly not feasible in the rural community because of the financial cost involved.
- There is possible surface contamination in a large-diameter hand-dug well during water abstraction as some wells are not properly covered or protected.

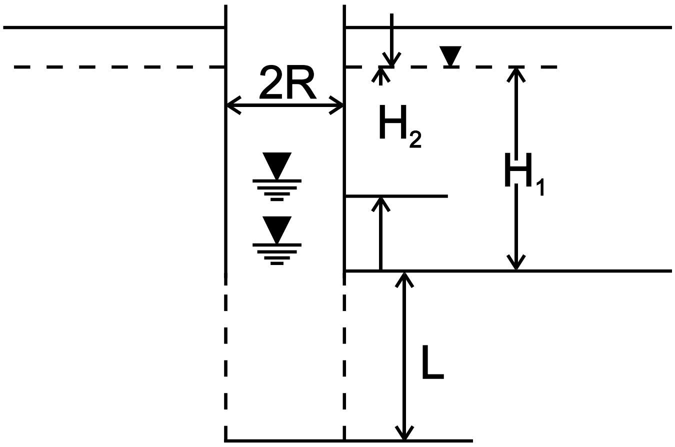
2.4 Methods of estimating hydraulic conductivity in screened large-diameter hand-dug wells

Estimation of hydraulic conductivity, especially in a borehole, is determined by conducting an aquifer field test and this involves pumping a well and observing a drawdown through one or more observatory wells while the observatory wells are sited at varying distances from the pumping well. However, hand-dug wells are typically of a larger diameter than borehole wells. It is mainly due to this difference in diameter that analysis of aquifer hydraulic characteristics becomes a challenge given the fact that the equations which are used to describe groundwater flow in small diameter wells are clearly not applicable to hand-dug wells because of their larger diameter.

There are a limited number of standard methods for analysing aquifer hydraulic characteristics in screened-lined large-diameter hand-dug wells, and these methods are continuing to evolve (Boulton and Streltsova, 1976; MacDonald et al., 2008; Papadopulos and Cooper, 1967; Rupp et al., 2001, 2011; Rushton and De Silva, 2016; Rushton and Holt, 1981; Yang and Yeh, 2004). Also, analysis of recovery data to estimate hydraulic conductivity in screened-lined large-diameter hand-dug wells have been carried out using the Hvorslev (1951) method, the Cooper et al., (1967) method, and the Bouwer and Rice (1976) method. These include the work of Akoachere and Ngwese (2016), Gupta & Singh (1987), Lai et al. (1973), McKenzie, 2008; Mishra and Chachadi (1985), Ola et al., (2016), and Patel and Mishra (1983) who have estimated hydraulic conductivity in screened-lined large-diameter hand-dug wells in a fully or partially penetrating confined aquifer. The Bouwer and Rice (1976) method have also been used in estimating hydraulic conductivity in screened-lined large-diameter hand-dug wells in fully or partially penetrating unconfined aquifers (Basak, 1982; Bjerg and Christensen, 1992; Evangelos et al., 2017; Mace, 1996, 1999; Singh and Gupta, 1986; Uribe et al., 2014).

2.4.1 Hvorslev method

Hvorslev (1951) pioneered the development of in situ tests, especially with the use of a well slug test method. This method, according to Fetter (2001), involves determining the ratio H/H(0) where H(0) or H_0 is the changes in the water level right from the pretest water level which is determined in terms of a so-called drawdown ratio (H_t). In this method, the constant groundwater level changes with the heads H_1 and H_2 (Figure 2.9), having corresponding time t_1 and t_2 with cross-sectional area A, is given as:



Source: modified after Fetter (2001)

Figure 2.9 Schematic representation of the Hvorslev method

$$t_2 - t_1 = T\left(ln\frac{H_0}{H_2} - ln\frac{H_0}{H_1}\right) \tag{2.1}$$

$$t_2 - t_1 = \frac{A}{FK}ln\frac{H_1}{H_2} \tag{2.2}$$

$$T = \frac{A}{FK} \tag{2.3}$$

Where

- K is the hydraulic conductivity
- A is the cross-sectional area of the well
- F is the shape factor based on the well design.

The Hvorslev equation for determining hydraulic conductivity is given as:

$$K = \frac{A}{F}\frac{1}{t_2 - t_1} ln \frac{H_1}{H_2} \tag{2.4}$$

Where:

- K is the hydraulic conductivity of aquifer
- A is the cross-sectional area of the well
- F is a shape factor
- H_1 and H_2 are the drawdown ratios at the times t_1 and t_2, respectively
- R_e is called the effective radius

The above analytical equation can be rewritten as:

$$\frac{\partial^2 h}{\partial h^2} + \frac{1\partial h}{r\partial r} = 0 \tag{2.5}$$

$$H(0) = H_0, h\left(R_{e,}t\right) = 0, t > 0 \tag{2.6}$$

$$h\left(R_{w,}t\right) = H(t), t > 0 \tag{2.7}$$

$$2\pi r_w K, B \frac{\partial h\left(r_{w,}t\right)}{\partial r} = \pi r_c^2 \frac{dH(t)}{dt}, t > 0 \tag{2.8}$$

$$\ln\left(\frac{H(t)}{H_0}\right) = \frac{2K_{rBt}}{r_c^2 \ln(\frac{R_e}{R_w})} \tag{2.9}$$

$$K_r = \frac{r_c^2 \ln(\frac{R_e}{r_w})}{2BT_0} (L/T) \tag{2.10}$$

Steps involved in the test and determining hydraulic conductivity using the Hvorslev method are:

1. Test starts when the water level in the well is lowered. Measure the water level periodically as the water level returns to the pretest level. Keep collecting data until 90% of the initial water level displacement is recovered.
2. From the water level measurement, determine the drawdowns and drawdown ratios.
3. Plot the head ratio (H_t) on the log scale and time (t) on the linear scale of semi-log graph paper.
4. Fit the best straight line through the set of points and choose two points on the straight line and record t_1, H_1, t_2 and H_2.
5. Calculate K using Equation 2.10 above.

2.4.1.1 Limitations of the Hvorslev method

- Specifically designed for confined aquifer systems.
- Introduced shape factor that is based on experimental work on a small diameter piezometer.

2.4.2 Cooper–Bredehoeft–Papadopulos method

The Cooper–Bredehoeft–Papadopulos method according to Cooper et al., (1967), Papadopulos and Cooper, (1967) gives a sophisticated technique for a single well test, using a slug test method for a drawdown ratio in a confined aquifer for a fully penetrating well. The equation is given as follows:

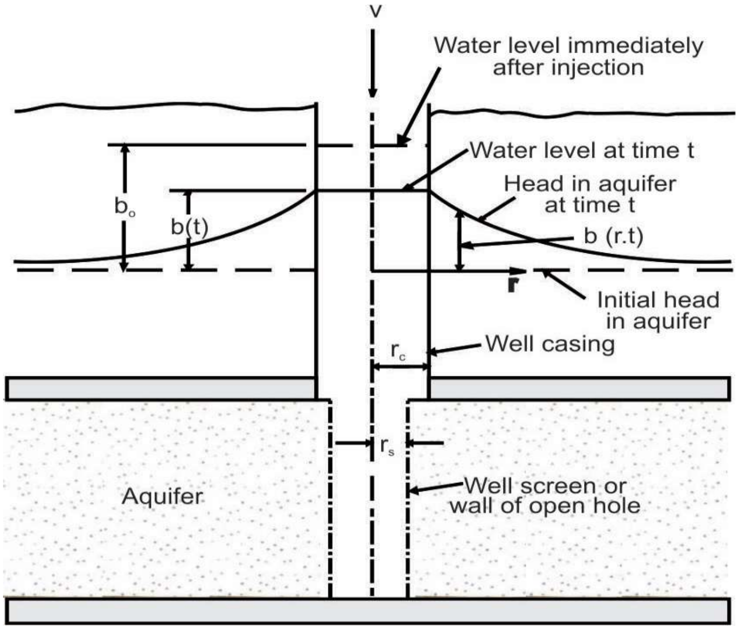
$$\frac{s}{S_o} = F(\beta,\alpha) = \frac{8\alpha}{\pi^2}\int_0^{\infty} \frac{e^{-\beta u^{2}/_{\alpha}}}{u((uJ_o(u) - 2\alpha J_I)^2 + (uY_o(u) - 2\alpha Y_I(u))^2} du \qquad 2.11$$

The head change is called s at time t while s_o is referred to as the initial head change when the water is injected or withdrawn. The parameters β and α are determined as follows:

$$\beta = \frac{T_t}{r_c^2} \qquad 2.12$$

$$\alpha = \frac{r_{s\,S}^{2}}{r_c^2} \qquad 2.13$$

Where r_c is called the radius of the well casing, T is the transmissivity, S is the storativity, and r_s is the effective radius of the well. Figure 2.10 is a schematic presentation of the Cooper–Bredehoeft–Papadopulos method.



Source: Cooper et al. (1967)

Figure 2.10 Cooper–Bredehoeft–Papadopulos method

Summary of the steps involved in the Cooper–Bredehoeft–Papadopulos method:

1. Drawdown ratio is plotted on the linear scale against time on the log scale having the same scale as the type curves.
2. Then superimpose the plot of the collected field data on the type curves and then look for the best fit with one of the type curves.
3. β is selected, which is usually 1, and find the corresponding t. Then the transmissivity is calculated as follows:

$$T = \frac{\beta r_c^2}{t} \qquad 2.14$$

4. Record α and calculate the storativity as follows:

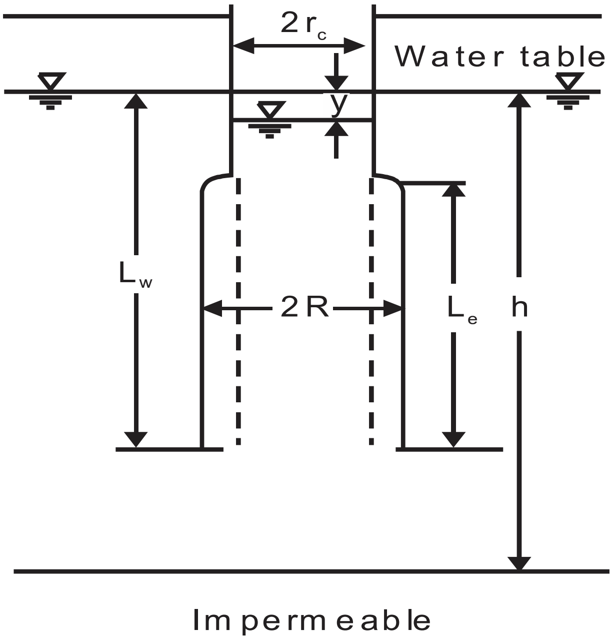
$$S = \frac{r_{c\,\alpha}^2}{r_s^2} \qquad 2.15$$

2.4.2.1 **Limitation of the Cooper–Bredehoeft–Papadopulos method**

- It is designed for a fully penetrating well in a confined aquifer condition.

2.4.3 Bouwer and Rice method

Bouwer and Rice (1976) developed a technique that has been used for determining an unconfined aquifer system for a fully or partially penetrated screened well. The Bouwer and Rice (1976) method was modified after the Thiem (1906) equation (Figure 2.11).



Source: Bouwer and Rice (1976)

Figure 2.11 Schematic description of the Bouwer and Rice method

The Bouwer and Rice method generates an equation to determine K as given below:

$$K = \frac{r_c^2 \ln\frac{R_e}{r_w}}{2L}\,\frac{\mathrm{I}}{t}\,ln\frac{y_o}{y_t}\ (L/T) \qquad 2.16$$

The above equation enables hydraulic conductivity to be calculated in an unconfined aquifer when there is a rise in the water level after a certain volume of water is removed from the well.

Where:

- K is the hydraulic conductivity of the aquifer
- L_e is the screened length
- r_c is the well radius
- r_w is the horizontal distance from the well centre to the original aquifer
- y is the drawdown and
- R_e is the radius of influence which can be calculated as follows:

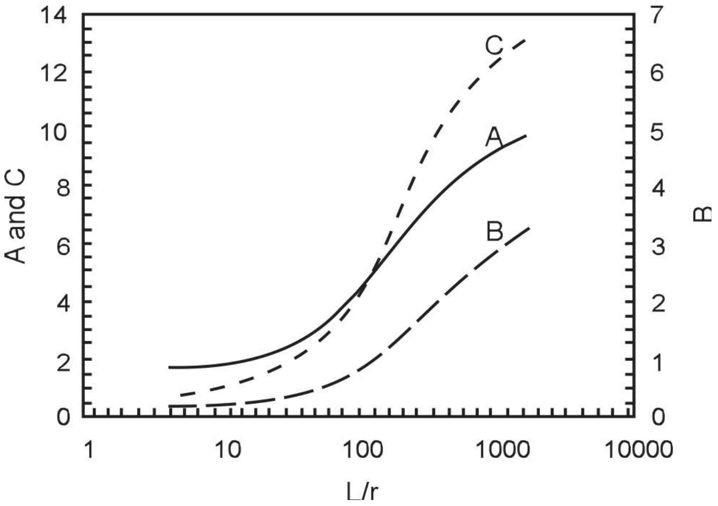
$$ln\frac{R_e}{r_w} = (\frac{1.1}{ln\frac{l_w}{r_w}} + \frac{A + Bln((H - l_w)/r_w}{\frac{l_e}{r_w}})^{-1} \qquad 2.17$$

Where:

- L_w is the length of the well in the aquifer
- A and B depend on the ratio L_e/r_w (Figure 2.12) and
- H is the thickness of the saturated material

When $L_w = H$, a simpler form of the equation is then written as follows:

$$ln\frac{R_e}{r_w} = (\frac{1.1}{ln\frac{l_w}{r_w}} + \frac{C}{\frac{l_e}{r_w}})^{-1} \qquad 2.18$$



Source: Bouwer and Rice (1976)

Figure 2.12 Dimensionless parameters A, B, and C as a function of L/r

The following are the steps involved in determining K using the Bouwer and Rice method:

1. Plot the water level changes y on a log scale versus time t on a linear scale using semi-log graph paper.
2. Approximate the straight portion of the plotted curve by a straight line and extend the line to $t = 0$.
3. Determine $\ln(R_e/r_w)$ using Equation 2.14 or Equation 2.15.
4. Record y_o and y_t for the other point on the line and calculate K using Equation 2.13.

2.4.3.1 Limitations of the Bouwer and Rice method

- Applied mostly in unconfined aquifer systems.
- Not applicable in unscreened fully or partially penetrating wells.

2.5 Research gap and motivation

In the rural communities of most sub-Saharan African countries, the use of unscreened concrete linings (Figure 2.13) in protecting large-diameter hand-dug wells against pollution, and also for protecting the walls against collapsing during and after construction, is a most common method of well lining.

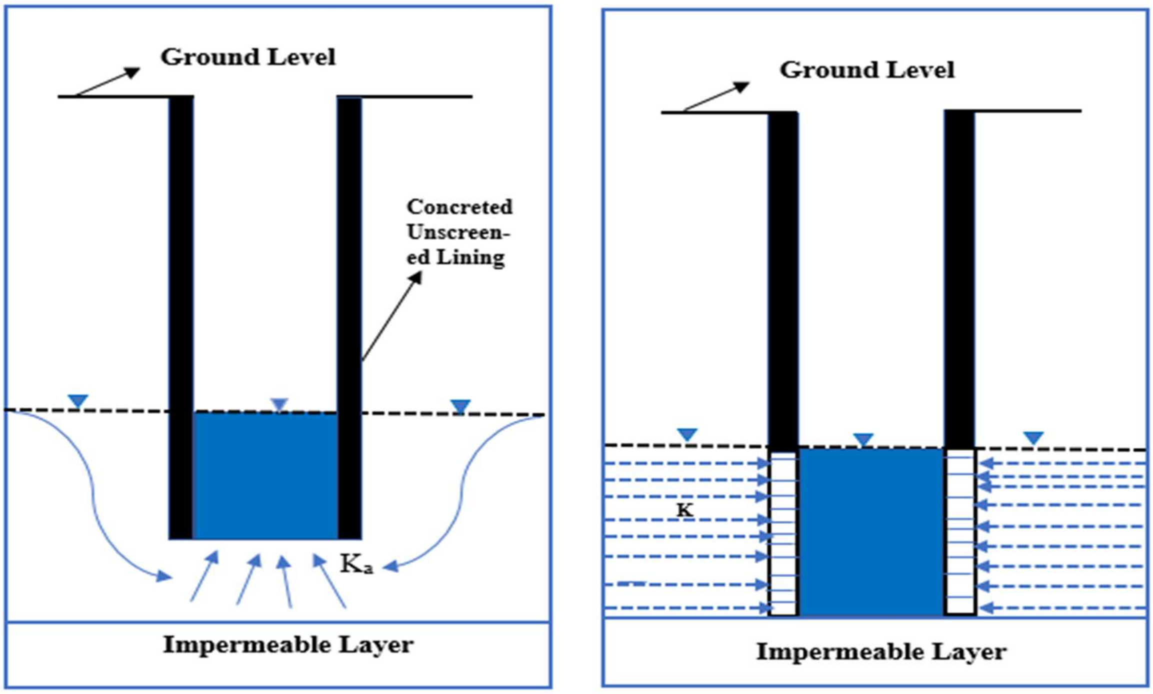
Source: Author's own (2019)

Figure 2.13 Unscreened concrete-lined large-diameter hand-dug well

This method is preferred due to the following reasons:

- Lack of technical know-how on the modern technique of lining.
- Considered to be stronger.
- Technical simplicity.
- Require use of locally available materials.
- Require low skills in the construction.
- Affordable economics.
- Community participation and the method involved is easily understood.

The main challenges in the use of unscreened concrete lining is that it does not allow the horizontal flow of water through and into the well. Water flowing to the well occurs through the uncemented well base as shown in Figure 2.14a. The Figure 2.14b shows the horizontal water flow to the well in a screened-lined well.



(a) Showing water flow to the well through well base in unscreened well (K_a is called apparent hydraulic conductivity)

(b) Showing water flow to the well in a screened well (K is called horizontal hydraulic conductivity)

Source: Author’s own (2019)

Figure 2.14 Water flow to the well in an unscreened and screened well

The use of an unscreened concrete lining results in longer recharge time. However, the review of earlier research work for estimation of K in large-diameter hand-dug wells shows that the existing methods are not applicable in the estimation of K in solid concrete-lined large-diameter hand-dug wells which results to energy loss in flow due to the use of unscreened concrete lining. Also, there is no reference or earlier research work on estimation of aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells. It is therefore possible to argue that estimating hydraulic conductivity K in unscreened concrete lined large-diameter hand-dug wells has not been covered in the previous research. This research intends to develop a method for estimating hydraulic conductivity K in unscreened concrete-lined large-diameter hand-dug wells. The techniques will involve to first establish a method for estimating the apparent hydraulic conductivity referred to as Ka. However, the estimated Ka will relatively be a low hydraulic conductivity of the aquifer formation based on the following facts:

- The flow into the well is not horizontal.
- There will be energy loss in flow due to the non-horizontal water flow into the well
- It will take longer period to recharge
- The direction of the flow moves against the force of gravity.

To account for the gaps in the above points, a true K of the aquifer formation will be determined which will take into account the horizontal flow into the well. The true K is expected to reflect true flow characteristics of the aquifer formation.

The geology and geohydrological characteristics for a large-diameter hand-dug well formation will be discussed in the next chapter using a case study of a rural area in a developing rural area of sub-Saharan African country.

Chapter 3

TEST SITE GEOHYDROLOGICAL CHARACTERISATION

3.1 Introduction

This chapter discusses the geohydrological characterisation of the study area with emphasis on rural water supplies which are mostly harnessed from large-diameter hand-dug wells. A typical rural area in the north-central part of Nigeria is used as a case study. The geological and geohydrological studies which comprise of geophysical and hydrogeochemistry studies of the area, are discussed.

3.2 Site description

The study area is a rural community situated in the Ilorin East area of north-central part of Nigeria (Figure 3.1). The area covers between latitude 8°29' and 8°36', and longitude 4°36' and 4°48', which falls within the Basement Complex of Nigeria. The area is characterised with a nucleated or clustered type of settlement pattern and forms part of the humid tropical climate with a mean annual rainfall of about 1 217 mm (Appendix A). This area is also characterised with wet and dry seasons. The wet season starts from the end of April and lasts till the end of October, while the dry period commences around November to late March with a highest average temperature of 32°C and a lowest monthly average temperature of 22°C. The mean monthly average temperature of the area is around 30°C. The highest relative humidity of the area occurs in July and the lowest is in January.

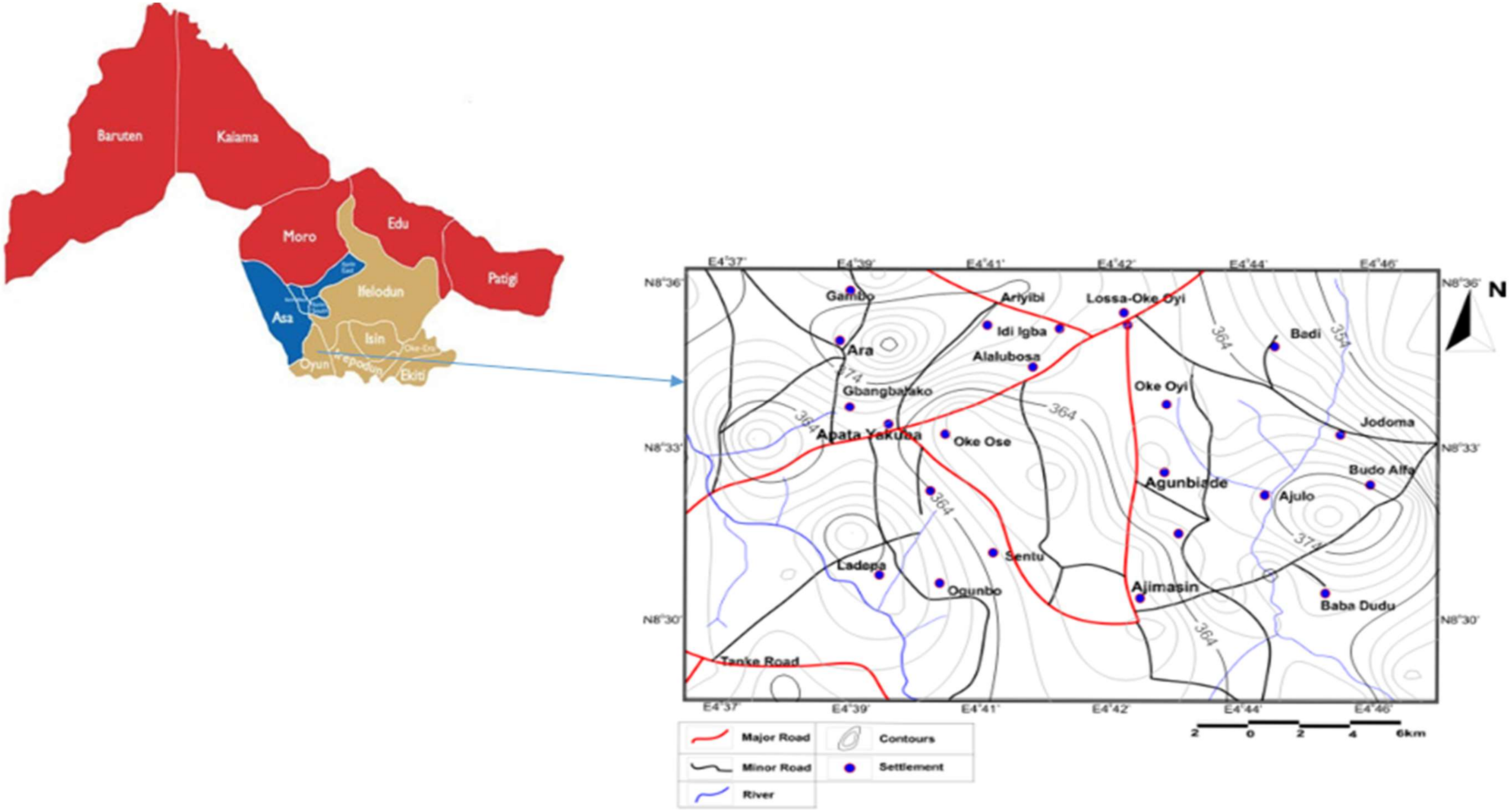


Figure 3.1 Location map of study area

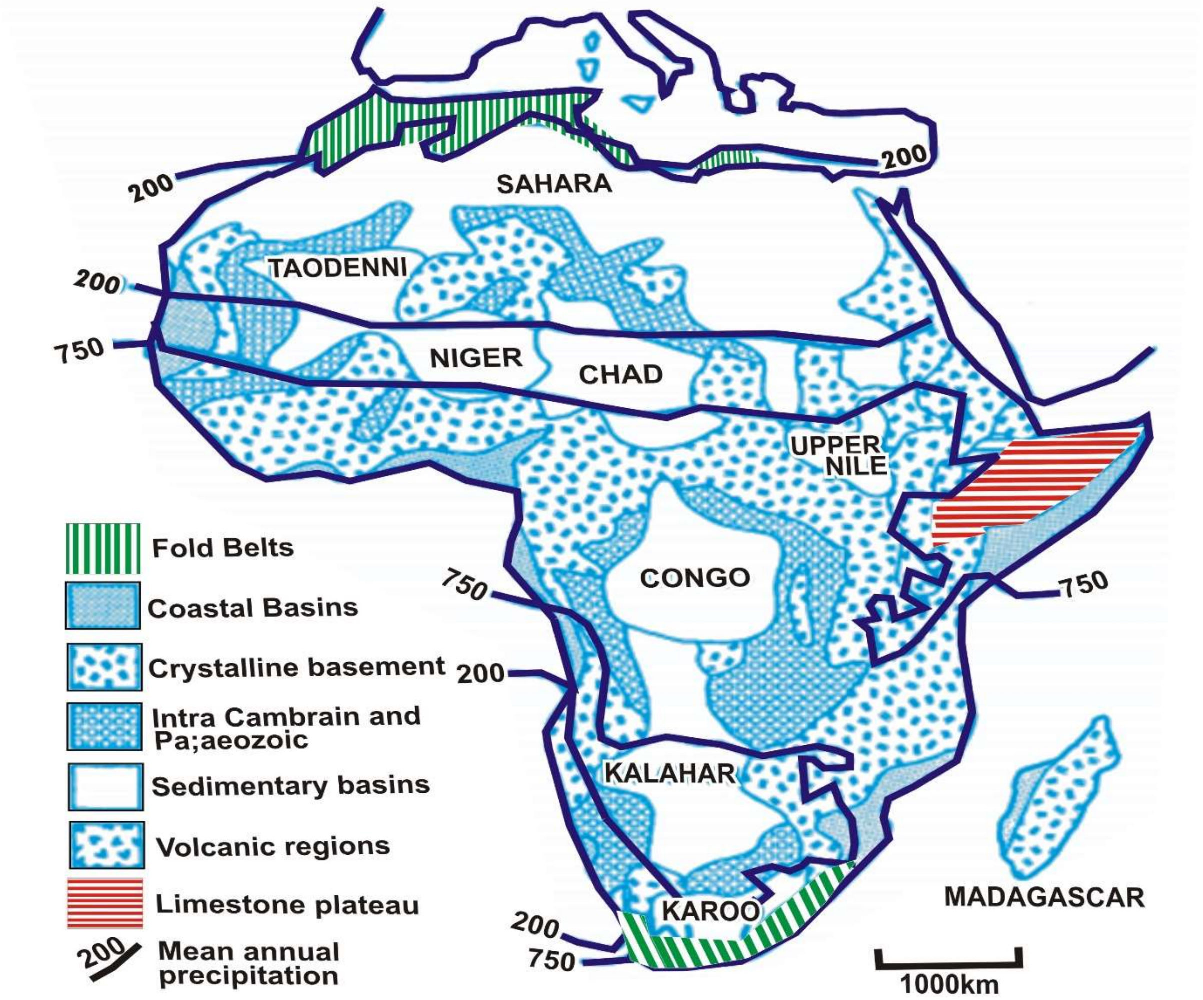
Source: Author's own (2019)

In this study area, the collection of water for drinking, cooking, washing and agricultural uses is through the abstraction of water from large-diameter hand-dug wells as shown in Figure 3.2.

Source: Author's own (2019)

Figure 3.2 People abstracting water from large-diameter hand-dug wells in the study area

The study area belongs to the Basement Complex of Nigeria. In this part of sub-Sahara Africa, the crystalline basement rock is primarily of the Precambrian age and found mostly as granitic or gneissose in type (Clark, 1985). The development of the Basement Complex aquifers occurs within the weathered overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic origin which are of the Precambrian age. The rate of weathering of the basement rocks is based on a number of factors that include: the texture and mineralogy of the parent rock (Courtois et al., 2010; Jones, 1985); the extent of fracturing within the parent rock; and the age of erosion (Taylor & Howard, 2000).



Source: After Wright (1992:2)

Figure 3.3 A modified map of Africa showing groundwater regions

3.3 Geology of study area

The search for groundwater requires a good understanding of the geological features holding the aquifer. In the study area, the development of unconfined aquifers occurs within the weathered overburden. The porosity of these weathered rocks determines their aquifer potentialities which depend on the textural and mineralogical properties of the parent rocks. Unlike the non-fractured crystalline rocks that possess low, small porosity, the porosity increases considerably in a weathered basement rock aquifers or fractured rocks and possess good aquifer characteristics.

The geological mapping of the study area was carried out on an approximate scale of 1:100 000 using appropriate and suitable field instruments. An extensive traversing was carried out through the footpaths and available roads in the areas. A topographical map on the scale of 1:100 000 was used as base map for the field exercise, and field data was determined on outcrops of the crystalline rocks such as strikes and dips.

The study area is underlain by rocks of the Basement Complex which comprise of granites of medium to coarse-grained, fine to coarse-grained porphyritic texture, and coarse-grained porphyritic texture, banded gneiss, migmatite, and metasediments which are mainly quartz-mica schist and quartzite. Structural features such as foliation, faults, joints and fractures were also found within the outcrops in the study site (Adedoyin, 2019; Annor, 1986; Adelana et al., 2008). The area is characterised by different structural features such as foliation, joints, fractures, faults and folds. Some of these structural features were observed in the varieties of outcrops exposed in the study area.

3.3.1 Granite

It is an intrusive felsic or alkaline-rich igneous rock having a high proposition of alkaline feldspar and certain amounts of feldspars (plagioclase and sodium-rich) with other minerals such as quartz, biotite and muscovite (Adedoyin et al., 2013; Annor, 1986; Oyawoye, 1964). Biotite and hornblende are mafic minerals commonly present. They are found mostly in the north-western parts of the study area (Figure 3.4a). Three varieties of the granitic rocks based on texture were identified in the area: medium to coarse-grained, coarse porphyritic type and fine to coarse-grained porphyritic types.

- **Medium to coarse-grained biotite granite**: These were observed in the north-western part of the study area. The rock is greyish to brownish in colour and is medium to coarse-grained. The rock is composed of quartz, plagioclase feldspar and biotite as the main minerals. The rock tends generally in the north-west to south-east direction striking N326° W. In some other parts of the area, the outcrop seems to trend in the north-west to south-east with strike at N312° W and dips at 80° W.

  Prominent joints were observed in this location. The strike values recorded from the joints were N300° W and N240° W.

- **Coarse porphyritic biotite granite**: This type of granite was observed as road outcrop in the southern part of the area. It was also observed in the eastern parts of the study area. The rock is light coloured and coarse in texture. The rock is mostly fractured and tends generally in the north-east to south-west direction with N320° E.
- **Fine-grained granite**: This type of granite also found in the south-eastern part of the area. The rock is light to dark in colour and fine in texture. The outcrop tends generally in the north-west to south-east direction, striking N340° W with a dip of 80° W.

Also, there are exposures of granite gneiss in some parts of the study area. It is usually of the same composition as granite. It is formed through a high-grade regional metamorphic process from pre-existing igneous rocks. It is medium to coarse-grained and consists mostly of alkaline feldspar, quartz, biotite and muscovite.

3.3.2 Migmatite

This rock is exposed at the eastern part of the area and being overlain by the superficial deposits of laterites (Figure 3.4b). A migmatite is a mixture of both metamorphic and igneous rocks. It is created when metamorphic rock such as gneiss have been partially melting in such a way that the melt crystallises to form an igneous rock which creates a mixture of the unmelted metamorphic part with the recrystallised igneous part. The mineral composition of migmatite includes quartz, potassium and sodium feldspars, and biotite. The strike is N240° E and a dip of 54° E, respectively.

3.3.3 Quartz mica schist

The quartz mica schist observed in the area is mostly weathered into greyish-brown colouration. The rock is coarse in texture and strongly foliated in the north-west to south-east direction. In some locations, the schist was found occurring alternatively with pegmatite vein. The foliation planes (strike N306° W and dip 76° E. Joint measured strike N90° E and, N75° E. The foliation planes in the schist strike in the same direction with the joints. The schist is composed of quartz, muscovite and biotite. Quartz dominates the rock, while plagioclase feldspar occurs as the least component.

3.3.4 Quartzite

Quartzite is a metamorphic rock that originates from sandstone. Quartzite consists predominantly of quartz-embedding minerals such as muscovite (mica), biotite (mica) and variable amounts of garnet. It is covering the northern to southern parts of the study area (Figure 3.4c). It trends as a dyke generally in a north-west to south-east direction in conformity with the schist. The rock also occurs as a block of boulders in some parts of the area striking N86° E and dipping 76° E. The rock is mostly milky-white or light brownish in colour.

(a) Biotite granite (b) Migmatite

(c) Quartzite (d) Pegmatite intrusion

Source: Author’s own (2019)

Figure 3.4 Rock types exposure in study area

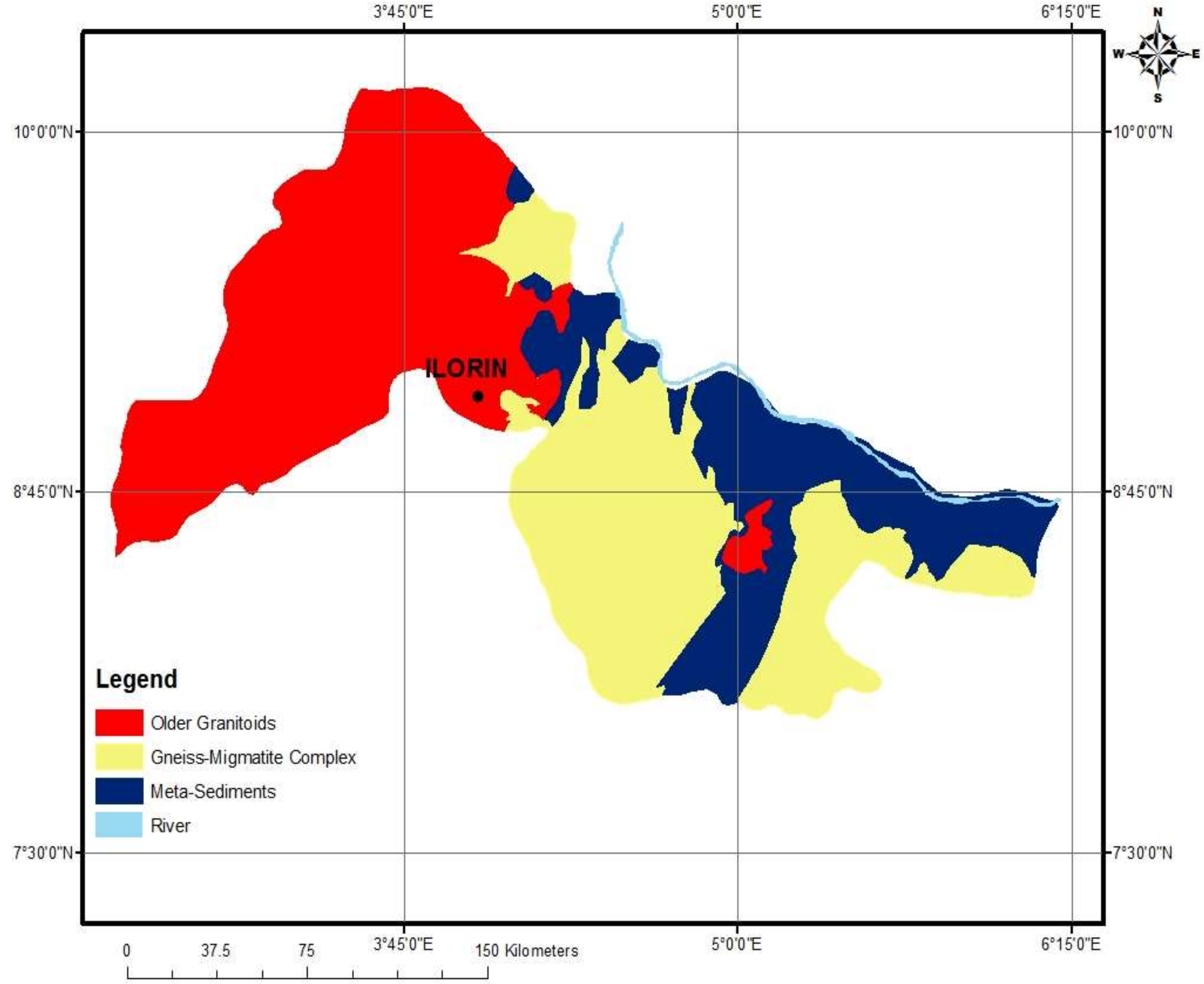


Figure 3.5 Geological map of Kwara State showing Ilorin, study area (Nigerian Geological Survey Agency, 2009)

In its simplest approach, each lithological unit was identified for an area with different rock types as the traverses were made while exact positioning was obtained each time a geological boundary is traversed and recorded with precise coordinates using a Global Positioning System (GPS).

3.4 Geophysical studies

This part of the chapter will discuss the subsurface lithological characteristics using a geophysical method and further correlation with lithological logging from pits and driller's log to get an understanding of and to elaborate information on the aquifer types and their distribution. This will also help to produce a geoelectric cross-section of the study area which will give insight into the hydrogeologic significance of the study area.

3.4.1 Field survey

A Schlumberger array was used in this research because of its wide use in geophysical exploration and because it has accurate means to acquire a large amount of data points and, furthermore, because its observations are sensitive to the lateral position and depth characteristics of the resistivity values distribution. The resistivity data was acquired through using a resistivity meter named MODEL SSR MP1. With this meter, the distance between the two current electrodes (AB/2) was increased to a maximum spread of 100 m, while the distance between the potential electrodes (MN/2) was increased to a maximum of 15.0 m. A total of twenty (20) vertical electrical soundings (VES) were carried out which spread across the test site (***Figure 3.5*** and Figure 3.6).

Apparent resistivity (ρ_a) was determined as given in the following equations:

$$p_a = n \times \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \times R_a \qquad 3.1$$

Where:

- AB is distance between the two current electrodes, while
- MN is distance between potential electrodes
- Ra is called apparent electrical resistance given by the resistivity meter.

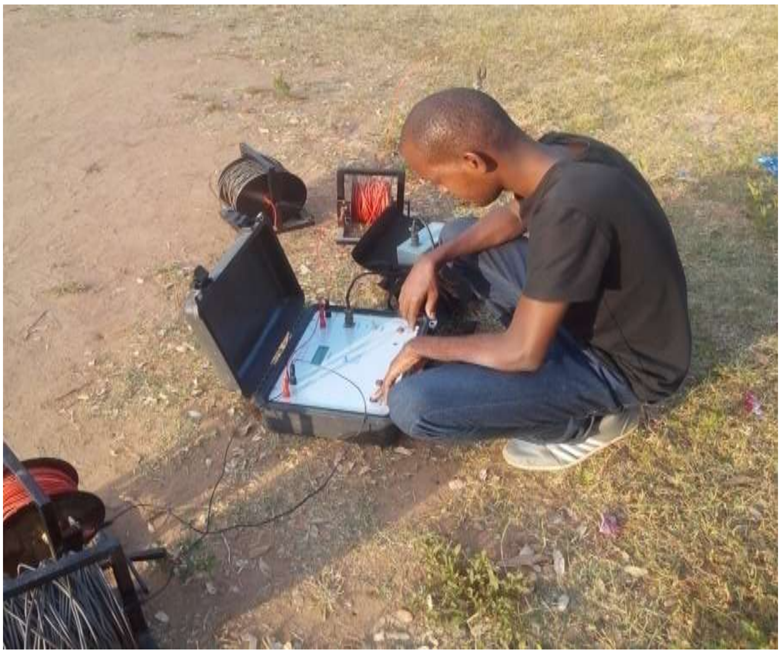
The above equation can be re-written as:

$$\rho_a = K * R_a \qquad 3.2$$

K is called geometrical factor:

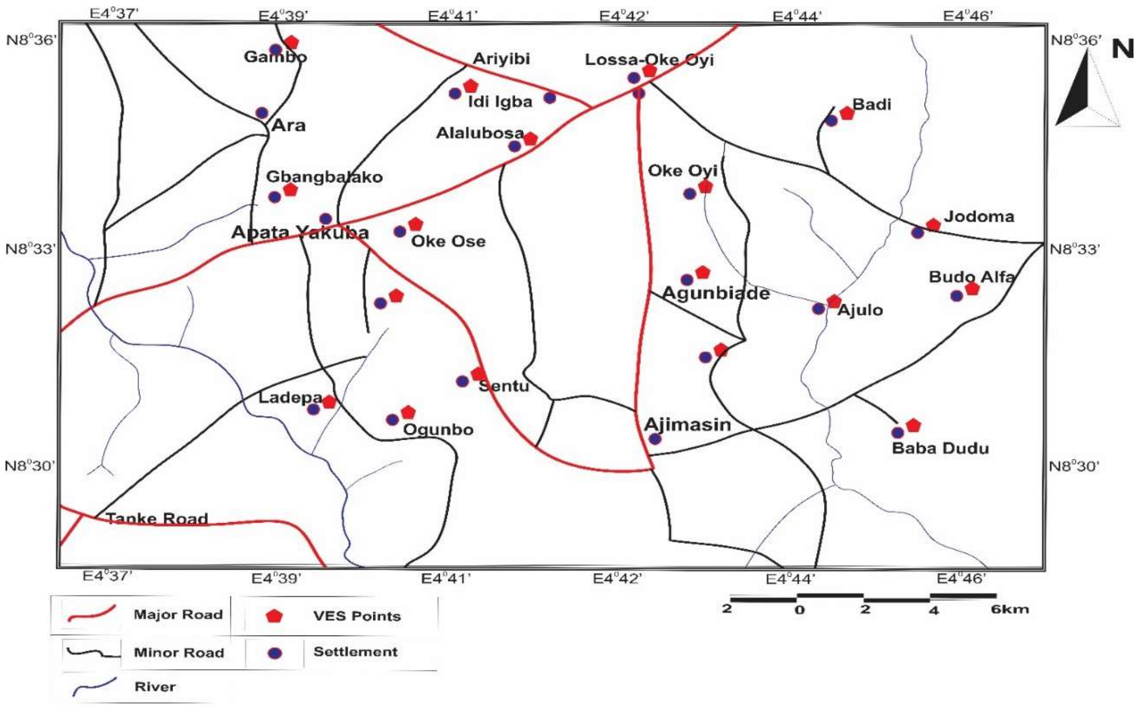
$$= n \times \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \qquad 3.3$$

The apparent resistivity (ρ_a) is plotted against the corresponding half electrode spacing (AB/2) on a bi-logarithm graph to generate the sounding curves. Sounding curves were initially interpreted by partial curve matching which gave resistivity of the layers and thicknesses which were later inverted by using IPI2 WIN software.



Source: Author's own (2019)

Figure 3.5 Collecting vertical electrical soundings data in the study area using Schlumberger array



Source: Author's own (2019)

Figure 3.6 Showing vertical electrical soundings locations in the study area

3.4.2 Results and data interpretation

The field data from VES which comprises current electrode spacing (AB/2), potential electrode spacing (AB/2), geometrical factor (K) and the apparent resistivity R (Ωm) of each VES sounding point are presented in Table 3.1 and Table 3.2. The inversion of the data into one-dimensional images was carried out. Lithology, layer depth, overall thickness of the vadose zone / overburden, together with layer thickness, were extracted from the inversion. The extracted parameters were applied in the lithological identification, vadose zone classification and hydrological implication.

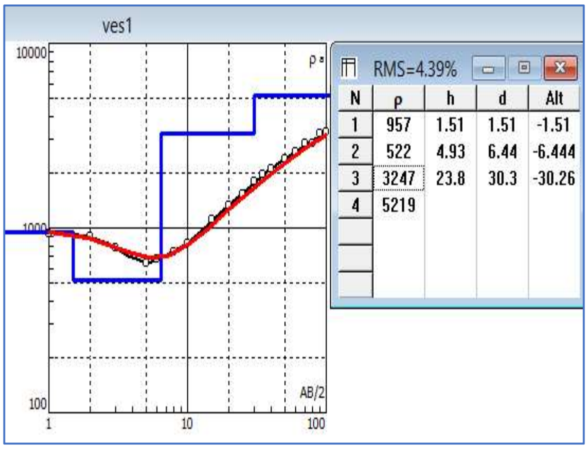
TABLE 3.1 APPARENT RESISTIVITY VALUES OBTAINED FROM THE FIELD

Current	Potential Factor	Geometrical Factor	VES 1(R)	VES 2(R)	VES 3(R)	VES 4(R)	VES 5(R)	VES 6(R)	VES 7(R)	VES 8 (R)	VES 9 (R)	VES 10(R)
AB/2 (m)	MN/2 (m)	K	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)
1.0	0.5	2.36	116	108	195	154	122	109	153	127	141	168
2.0	0.5	11.78	343	150	320	226	229	111	145	103	220	106
3.0	0.5	13.75	372	366	302	220	254	202	108	294	270	110
5.0	0.5	77.77	514	152	265	441	428	125	417	143	170	460
6.0	0.5	112.3	673	126	216	387	434	141	211	512	180	870
6.0	1.0	54.99	375	122	220	379	393	103	365	579	280	462
8.0	1.0	98.97	175	104	185	279	342	128	640	371	190	731
10.0	1.0	155.5	204	334	148	268	349	164	232	274	190	234
10.0	2.5	58.91	224	409	154	219	356	147	265	279	120	204
15.0	2.5	137.5	935	572	129	222	262	144	244	306	174	413
20.0	2.5	247.4	764	489	390	262	180	260	303	490	223	1 304
25.0	2.5	388.8	603	123	330	320	143	308	141	620	264	1 042
30.0	2.5	561.6	610	134	411	227	371	280	333	791	327	2 065
35.0	2.5	765.9	993	140	540	345	109	102	424	147	342	1 073
40.0	2.5	1 001.5	1 356	197	638	318	142	268	544	196	407	746
40.0	7.5	323.4	1 046	192	513	309	1 012	342	531	127	334	521
50.0	7.5	511.9	1 016	234	807	249	1 089	454	641	159	450	327
60.0	7.5	742.3	503	132	964	286	2 102	308	693	155	523	277
70.0	7.5	1 014.6	2 112	1 142	217	272	1 020	107	456	172	481	138
80.0	7.5	1 328.8	1 843	838	191	282	1 040	332	487	148	542	238
90.0	7.5	1 684.9	1 360	702	258	511	610	220	531	153	536	279
100.0	7.5	2 082.9	3 730	549	673	678	480	228	609	163	542	316

TABLE 3.2 APPARENT RESISTIVITY VALUES OBTAINED FROM THE FIELD

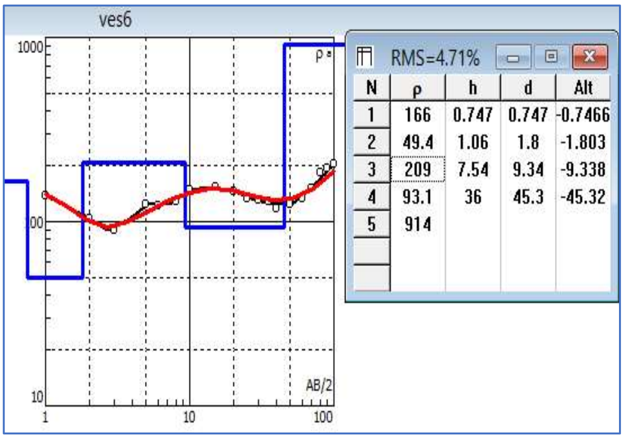
Current	Potential Factor	Geometrical factor	VES 11(R)	VES 12 (R)	VES 13(R)	VES 14(R)	VES 15(R)	VES 16(R)	VES 17(R)	VES 18(R)	VES 19(R)	VES 20(R)
AB/2 (m)	MN/2 (m)	K	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)
1.0	0.5	2.36	127	182	157	191	170	211	161	116	131	109
2.0	0.5	11.78	247	367	262	645	270	140	191	230	174	369
3.0	0.5	13.75	273	394	101	382	397	353	281	350	248	301
5.0	0.5	77.77	248	116	518	387	134	335	338	430	172	224
6.0	0.5	112.3	243	861	711	394	337	342	299	360	468	164
6.0	1.0	54.99	233	884	737	292	119	283	297	412	372	144
8.0	1.0	98.97	209	756	517	231	108	274	203	514	354	130
10.0	1.0	155.5	183	844	325	183	639	292	185	608	266	125
10.0	2.5	58.91	185	768	315	181	864	286	211	642	258	764
15.0	2.5	137.5	185	256	407	114	458	519	205	931	242	398
20.0	2.5	247.4	217	225	496	136	393	540	282	936	340	681
25.0	2.5	388.8	363	340	546	159	648	826	143	104	314	806
30.0	2.5	561.6	297	448	394	177	181	718	480	125	566	807
35.0	2.5	765.9	275	733	100	198	134	894	246	1 143	846	101
40.0	2.5	1 001.5	292	691	718	230	134	680	455	1 066	863	110
40.0	7.5	323.4	1 087	374	552	220	132	969	447	1 173	753	106
50.0	7.5	511.9	1 074	101	798	303	40	1 040	525	1 296	108	124
60.0	7.5	742.3	1 358	450	659	425	118	1 071	730	907	106	177
70.0	7.5	1 014.6	1 044	122	945	599	150	1 041	137	821	120	208
80.0	7.5	1 328.8	843	101	109	576	283	718	110	729	108	235
90.0	7.5	1 684.9	702	176	135	850	174	436	132	303	104	279
100.0	7.5	2 082.9	684	244	172	914	348	383	117	318	111	342

The calculated and estimated true resistivity from the inverse procedure gives the measured apparent resistivity. The selected representative geoelectric curves obtained in the study area are presented in Figure 3.7, while other curves are shown in Appendix B, which indicates three to five lithologic layers as shown in Table 3.3. Also, typical types of curves obtained in the study area are A, QA, KHA, KH, HA and H curves types (Figure 3.7).



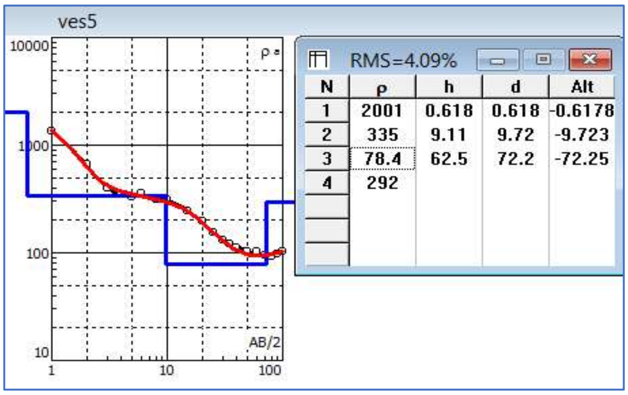
RMS=4.39%

N	ρ	h	d	Alt
1	957	1.51	1.51	-1.51
2	522	4.93	6.44	-6.444
3	3247	23.8	30.3	-30.26
4	5219			



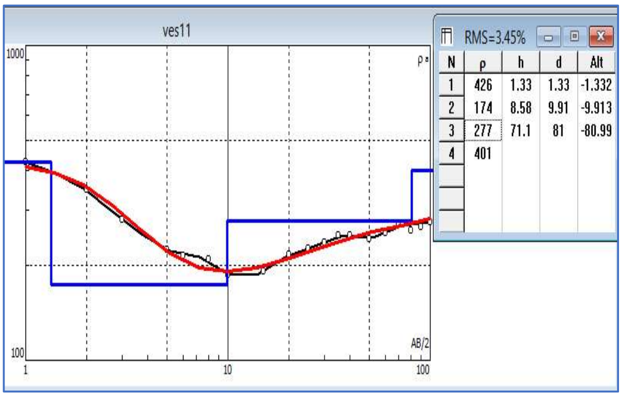
RMS=4.71%

N	ρ	h	d	Alt
1	166	0.747	0.747	-0.7466
2	49.4	1.06	1.8	-1.803
3	209	7.54	9.34	-9.338
4	93.1	36	45.3	-45.32
5	914			



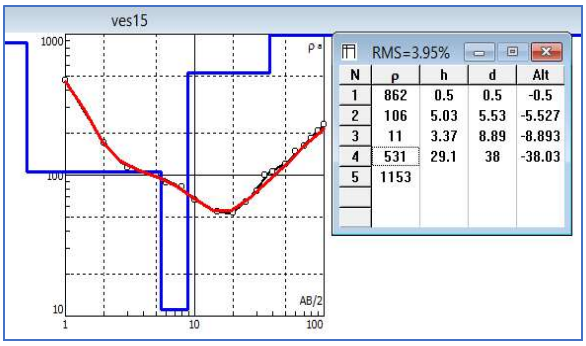
RMS=4.09%

N	ρ	h	d	Alt
1	2001	0.618	0.618	-0.6178
2	335	9.11	9.72	-9.723
3	78.4	62.5	72.2	-72.25
4	292			



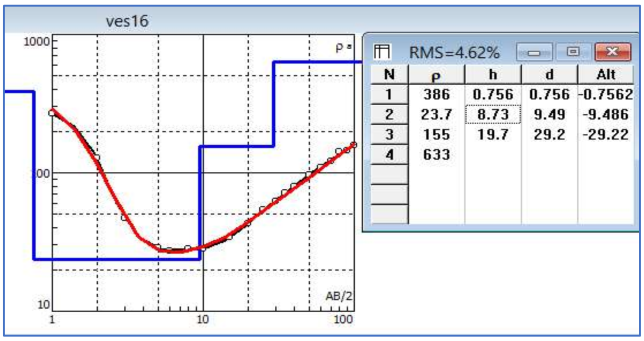
RMS=3.45%

N	ρ	h	d	Alt
1	426	1.33	1.33	-1.332
2	174	8.58	9.91	-9.913
3	277	71.1	81	-80.99
4	401			



RMS=3.95%

N	ρ	h	d	Alt
1	862	0.5	0.5	-0.5
2	106	5.03	5.53	-5.527
3	11	3.37	8.89	-8.893
4	531	29.1	38	-38.03
5	1153			



RMS=4.62%

N	ρ	h	d	Alt
1	386	0.756	0.756	-0.7562
2	23.7	8.73	9.49	-9.486
3	155	19.7	29.2	-29.22
4	633			

Figure 3.7 Geoelectric curves of the processed vertical electrical soundings data

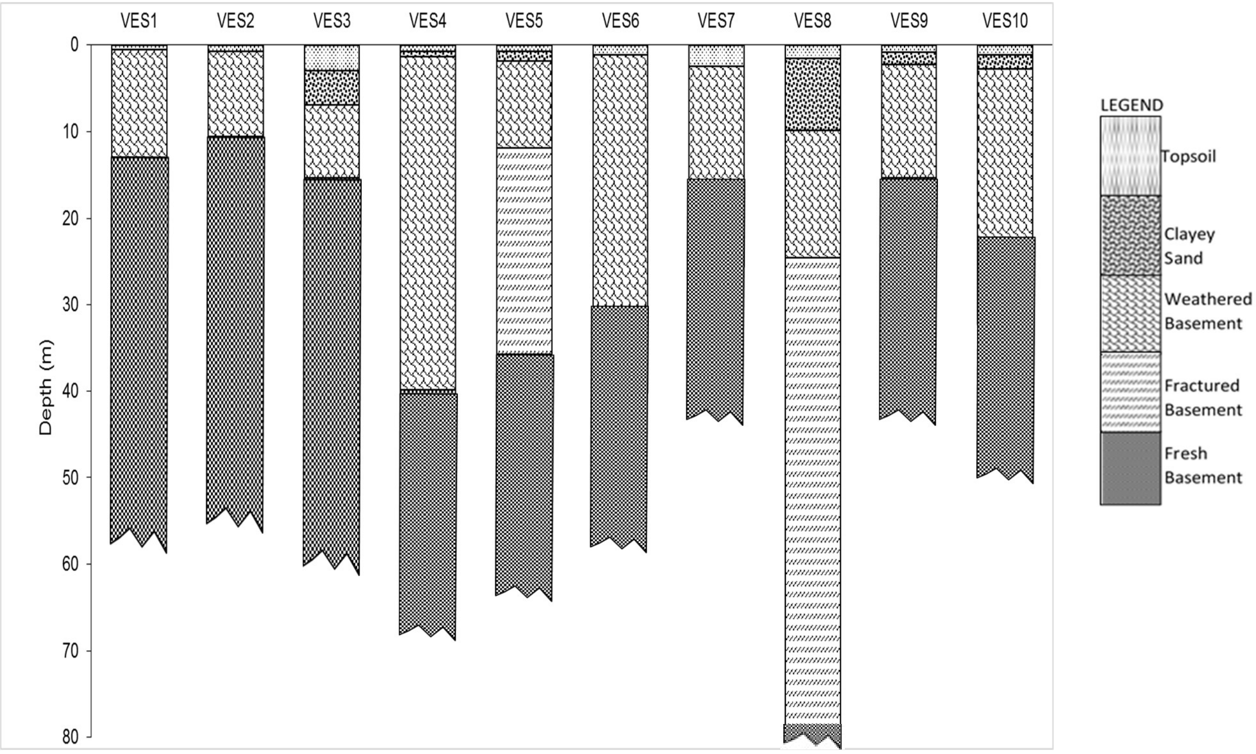
TABLE 3.3 INTERPRETED APPARENT RESISTIVITY, LITHOLOGICAL UNIT AND HYDROGEOLOGIC SIGNIFICANCE

VES	No. of layers	Resistivity (Ωm)	Thickness (m)	Depth to bedrock	Curve type	Remark	Hydrogeologic Significance
VES1	3	125	0,5	13,5	A	Topsoil	Non-aquiferous
		394	13,0			Weathered basement	Aquiferous
		9 175				Fresh basement	Non-aquiferous
VES2	3	98,2	0,711	10,4	QA	Topsoil	Non-aquiferous
		166	9,67			Weathered basement	Aquiferous
		610				Fresh basement	Non-aquiferous
VES3	4	334	2,91	15,3	KHA	Topsoil	Non-aquiferous
		189	4,02			Clayey sand	Aquiferous
		649	8,36			Weathered basement	Aquiferous
		993				Fresh basement	Non-aquiferous
VES4	4	118	0,74	39,9	KH	Topsoil	Non-aquiferous
		1 277	0,546			Clayey sand	Aquiferous
		231	38,6			Weathered basement	Aquiferous
		1 127				Fresh basement	Non-aquiferous
VES5	5	96,5	0,677	25,7	KHA	Topsoil	Non-aquiferous
		1 198	1.14			Clayey sand	Aquiferous
		595	0.108			Weathered basement	Aquiferous
		194	23.8			Fractured basement	Aquiferous
		1 384				Fresh basement	Non-aquiferous
VES6	3	118	1,08	30,2	A	Topsoil	Non-aquiferous
		243	29,1			Weathered basement	Aquiferous
		462				Fresh basement	Non-aquiferous
VES7	2	154	2,41	2,41	A	Topsoil	Non-aquiferous
		479				Fresh basement	Non-aquiferous
VES8	5	119	1,47	60,8	KH	Topsoil	Non-aquiferous
		199	8,28			Clayey sand	Aquiferous
		1 198	4,7			Weathered basement	Aquiferous
		150	54,3			Fractured basement	Aquiferous
		518				Fresh basement	Non-aquiferous
VES9	4	128	0,8	14,3	QA	Topsoil	Non-aquiferous
		1 106	0,398			Clayey sand	Aquiferous
		133	13,1			Weathered basement	Aquiferous
		1 498				Fresh basement	Aquiferous
VES10	4	118	1,1	21,3	K	Topsoil	Non-aquiferous
		213	0,632			Clayey sand	Aquiferous
		951	19,5			Weathered basement	Aquiferous
		53				Fresh basement	Non-aquiferous

VES	No. of layers	Resistivity (Ωm)	Thickness (m)	Depth to bedrock	Curve type	Remark	Hydrogeologic Significance
VES11	4	116	0,74	17,6	HA	Topsoil	Non-aquiferous
		1 435	0,363			Clayey sand	Aquiferous
		156	16,5			Weathered basement	Aquiferous
		1 435				Fresh basement	Non-aquiferous
VES12	3	148	0,665	13,3	A	Topsoil	Non-aquiferous
		437	12,6			Weathered basement	Aquiferous
		630				Fresh basement	Non-aquiferous
VES13	3	179	1,02	18,9	A	Topsoil	Non-aquiferous
		493	17,9			Weathered basement	Aquiferous
		771				Fresh basement	Non-aquiferous
VES14	4	213	0,68	20,6	HA	Topsoil	Non-aquiferous
		1 498	0,74			Clayey sand	Aquiferous
		111	19,2			Weathered basement	Aquiferous
		1 509				Fresh basement	Non-aquiferous
VES15	4	206	2,0	12,6	HA	Topsoil	Non-aquiferous
		1 394	3,95			Clayey sand	Aquiferous
		68,7	6,62			Weathered basement	Aquiferous
		97,2				Fresh basement	Non-aquiferous
VES16	4	161	1,14	42,7	H	Topsoil	Non-aquiferous
		356	5,12			Clayey sand	Aquiferous
		1 456	36,4			Weathered basement	Aquiferous
		59,9				Fresh basement	Non-aquiferous
VES17	5	108	0,61	55,3	KHK	Topsoil	Non-aquiferous
		1 346	0,28			Clayey sand	Aquiferous
		197	11,8			Weathered basement	Aquiferous
		668	42,6			Fractured basement	Aquiferous
		42,5				Fresh basement	Non-aquiferous
VES18	3	102	0,766	55,5	A	Topsoil	
		891	54,7			Clayey soil	Aquiferous
		234				Weathered basement	Aquiferous
VES19	3	144	2,24	26,5	A	Topsoil	Non-aquiferous
		367	24,3			Clayey sand	Aquiferous
		48,9				Weathered basement	Aquiferous
VES20	3	220	3,15	15,0	A	Topsoil	Non-aquiferous
		455	11,0			Clayey sand	Aquiferous

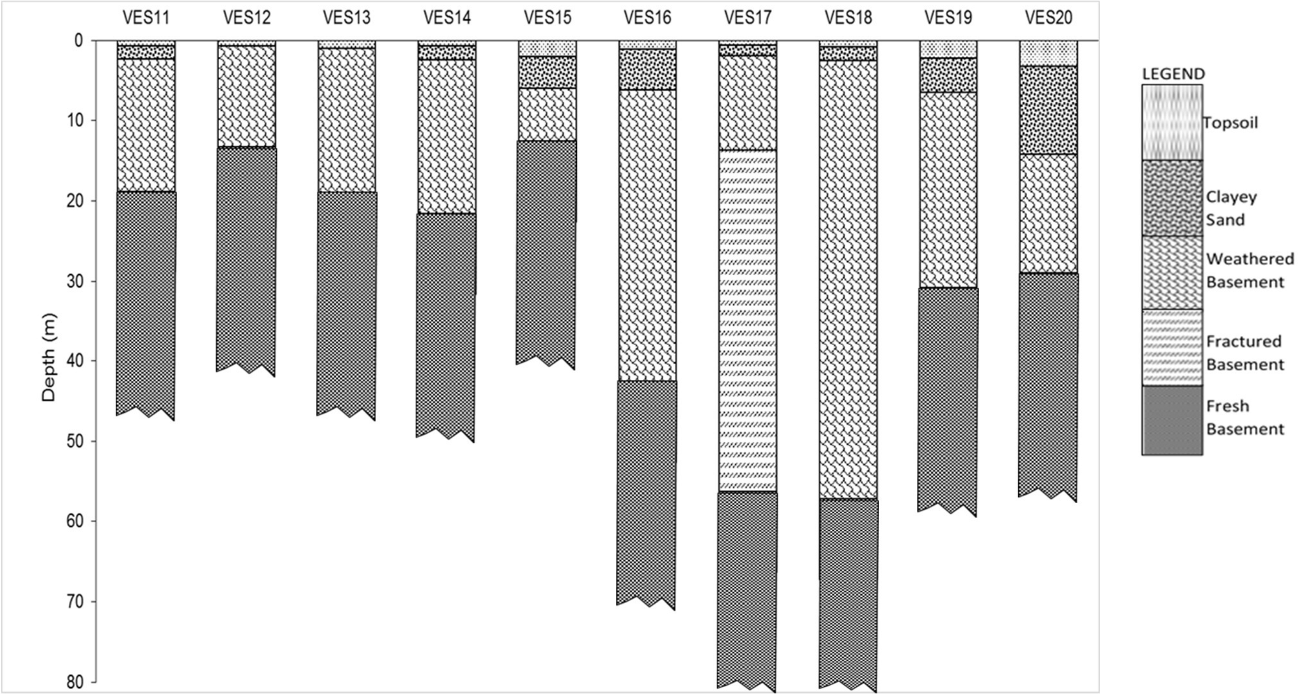
However, further lithological observations to support and interpret the geophysical features were made from the pits and drillers' log during construction of the large-diameter hand-dug wells in the study area to have a visual and proper understanding of lithological composition and also to be sure in the accuracy of the inverted model data.

A geoelectric cross-section was determined from the respective individual resistivity layer and thickness. Figure 3.9 and Figure 3.10 shows the interpreted geoelectric cross-sections of twenty (20) VES carried out in the study area while Figure 3.11 shows a 3D geological model for basement relief in the study area. The lithological units of these sections were interpreted from the VES data with good understanding of the underlying geology which was documented from the stratigraphic data and driller's geological logs. These include topsoil, clayey sand, weathered basement, fractured basement and fresh basement. However, the main good aquiferous units identified in the study area are clayey sand (with the percentage of sands greater than the clay, weathered basement aquifer zone and fractured crystalline rock aquifer. The exploitation of weathered basement aquifers in the study area is mostly harnessed through the large dimeter hand-dug wells.



Source: Author's own (2019)

Figure 3.9 Geoelectric cross-sections of the study area



Source: Author's own (2019)

Figure 3.10 Geoelectric cross-sections of the study area (Continued)

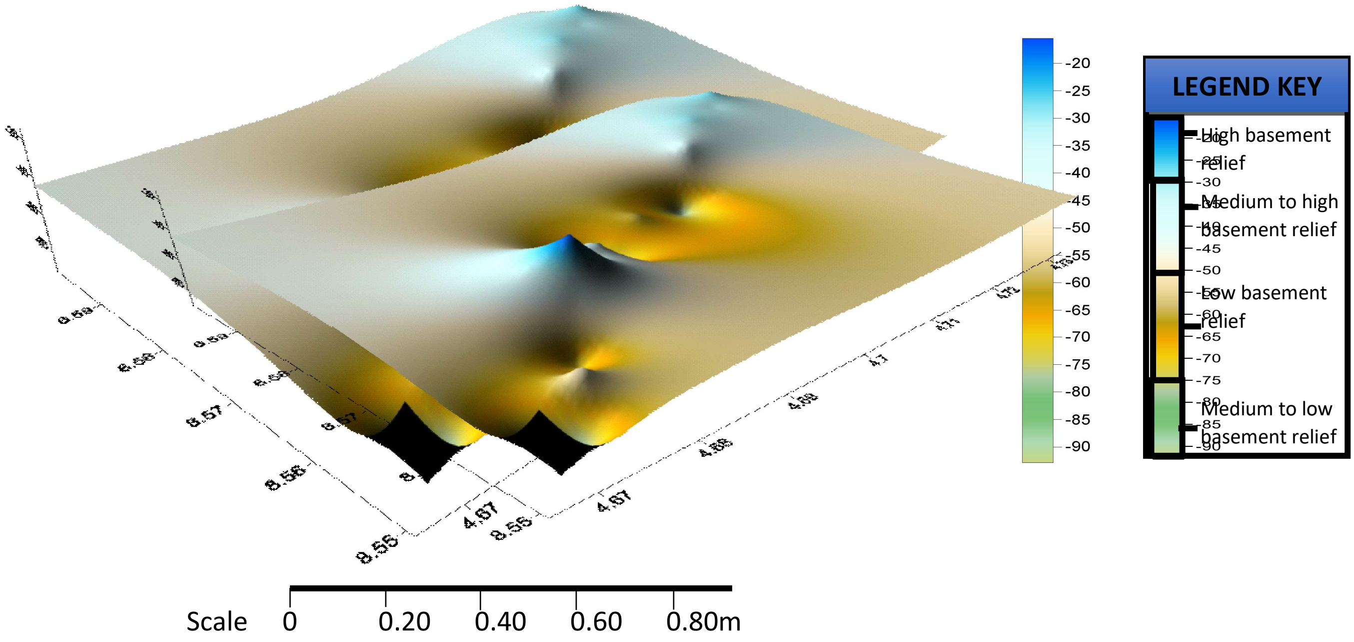


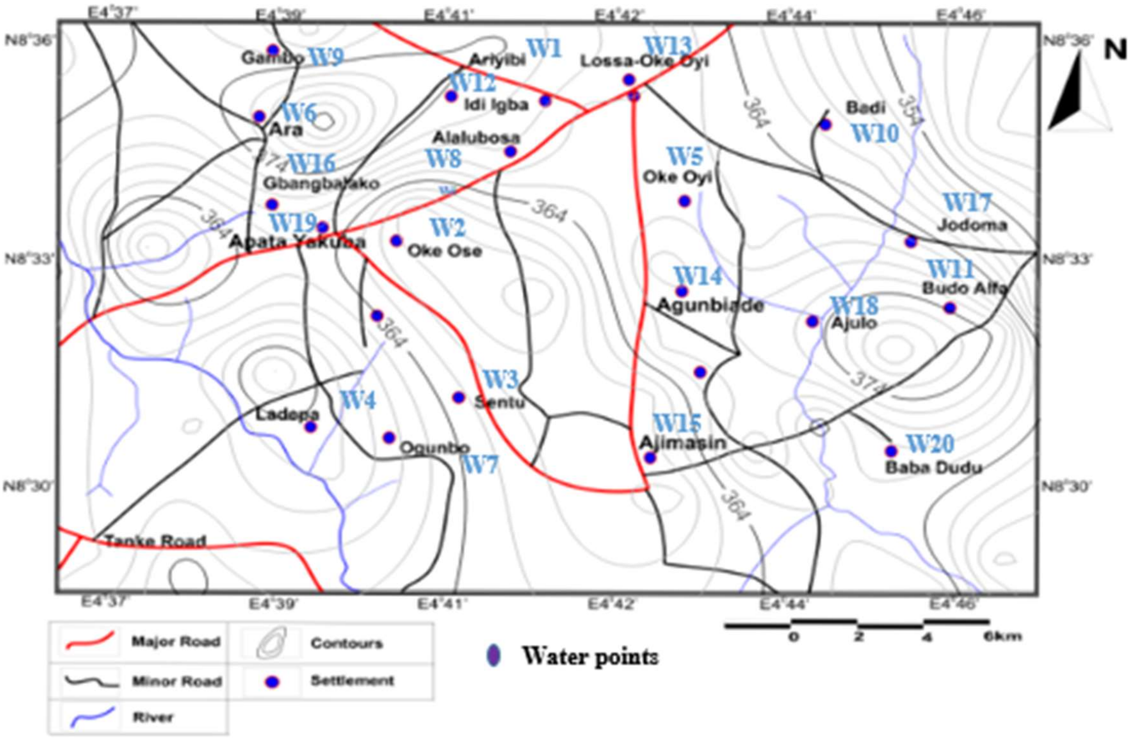
Figure 3.11 3D geological model for basement relief from VES data in study area

3.5 Hydrogeochemistry

This section discusses the hydrochemical characteristics of the groundwater aquifer systems in the study area to understand the geological processes in which the water was stored. Water as a universal solvent reacts and could easily take on the characteristics of the environment where it interacts with. This study involves the collection of groundwater samples and conduct physical and chemical analyses of the groundwater samples in the study area for their physical and chemical characteristics.

3.5.1 Field sampling

Twenty (20) water samples were randomly collected from twenty (20) large-diameter hand-dug wells in the study area. The water samples were collected round over the year in the months of March and September, representing both wet and dry seasons to allow groundwater elemental concentration monitoring. A stainless-steel bailer was used for the collection of water from below the static water level of wells and then filtered for storage into 500 ml plastic bottles that was thoroughly washed and later rinsed with the water being sampled before filling the bottles. Two samples were separately collected for each water point; one was for the determination of anions while the second one was for the determination of cations.



Source: Author's own (2019)

Figure 3.8 Water sample locations in the study area

The physical analysis of the water samples was taken directly on the field, while chemical analysis was conducted in the chemistry laboratory of University of Ilorin, Nigeria. Anions were analysed by means of convectional titration methods, while cations were determined using standard methods of Atomic Absorption Spectrophotometry.

Source: Author's own (2019)

Figure 3.9 Field measurement of physical parameters in study area

The hydrochemical processes of the groundwater can be explained through the calculation made between the ionic ratios and those changes that occur in the groundwater chemistry. Various researchers (Frohlich et al., 2008; Helstrup et al., 2007; Kim et al., 2009; Mercado, 1985; Satpathy et al., 1987; Vengosh, 2013; Westbrook et al., 2005) described different processes and factors that could aid hydrochemical characteristics of groundwater to include anthropogenic contamination, ion exchange, dissolution and dilution, water–rock interaction and interaction of seawater, especially through the precipitation and salinisation.

3.5.2 Results and interpretation

The statistical summary of the physicochemical analyses of the water samples in the study area are presented in Appendices C, D, E, F, and G. The interpretation of physical and chemical parameters for domestic use was based on the World Health Organization (WHO, 2011) standards and the Nigerian Standard for Drinking Water Quality (NSDWQ, 2007) for potable water. The pH-values for the analysed water samples ranged between 6.7 and 7.6 for the dry season with a mean of 7.1, while the pH ranged from 6.6 to 7.2 in the wet season, with a mean of 6.9. The pH for both seasons was within the acceptable permissible limits according to the WHO (2011) standard of 6.5 to 8.5; therefore, the pH of water in the area is neutral. Electrical conductivity (EC) of the water samples tested in the area ranged between 106 and 318 µS/cm and a mean of 209.2 µS/cm for the dry season, while for the wet season it ranged between 119 and 379 µS/cm and a mean of 226.6 µS/cm. The EC for the two seasons fall within the WHO (2011) permissible standards for drinking water which is 1 000 µS/cm. Total dissolve solids (TDS) in the water samples for the dry season were found to be between 96 and 176 mg/l, with a mean of 126.6, and between 107 and 176 mg/l, with a mean 132.2 mg/l for the wet season. For the two seasons, TDS is within the acceptable limit of 1 000 mg/l (WHO, 2011), therefore with TDS, water in the area is suitable for drinking.

Total hardness in the water samples for the two seasons fell within the standard limit of 500 mg/l (WHO, 2011) for the dry season, with a mean of 11.6 mg/l, and a mean of 13.1 mg/l for the wet season. The water is therefore fit for consumption. Turbidity of 5.0 Nephelometric Turbidity Units (NTU) is usually recommended (WHO, 2011) for potable water, but the water samples in the area had a mean of 2.3 in the dry season and a mean of 2.5 for the wet season and this shows that turbidity for those considered seasons falls within the recommended limits.

Calcium values in the analysed water had a mean of 2.9 mg/l for the dry season, with a mean 5.6 mg/l for the wet season. Based on the standard limit of 75 mg/l for calcium (NSDWQ, 2007; WHO, 2011), the allowable permissible limit for calcium should not exceed 75 mg/l. Water samples in the area for both seasons falls within the acceptable level of the NSDWQ and WHO standards.

Magnesium contents in the water samples for the dry season had a mean of 3.2 mg/l, and for the wet season with an average of 4.7 mg/l. When compared with the standard of 30 mg/l given by the WHO (2011), magnesium in the analysed water for the two seasons was found to be suitable for any domestic purpose. Sodium showed a mean of 4.5 mg/l for the dry season and for the wet season possessed a mean of 3.9 mg/l, while the WHO (2011) recommended limits for sodium is 200 mg/l. Therefore, all the water samples in both the seasons were found within the acceptable standard limits, making the water in the area suitable and fit for human consumption. Potassium levels in the dry season had a mean of 8.3 mg/l and a mean of 8.1 mg/l for the wet season, which were below the standard limits given by the NSDWQ (2007) and the WHO (2011). However, it was observed that in some locations, such as 13, 14, 16 and 20 in the two seasons, there were high levels in potassium concentrations. These were attributed to the soluble products of weathered minerals such as plagioclase and orthoclase feldspars of the bed rocks in the study area.

Concentrations of chloride in the water samples for the dry season had a mean of 10.2 mg/l, while for the wet season it had a mean of 6.0 mg/l, whereas the maximum permissible limits for chloride is 250 mg/l (WHO, 2011). Water samples in the two seasons were found within the standard acceptable limits. Bicarbonates had average mean values of 34.9 mg/l for the dry season and with a mean of 44.0 mg/l for the wet season. There is no specific limit provided for bicarbonates.

Sulphate concentration values in the dry season of the analysed water samples had a mean of 21.8 mg/l, and for the wet season a mean of 19.0 mg/l. The standard limit for sulphate in water is 250 mg/l (WHO, 2011). Those values for the water samples within the seasons considered, falls within the standard limits. Sulphate concentration in the water samples of the area might have occurred from indiscriminate disposal of solid and liquid wastes in the area and unlawful use of chemicals such as fertilisers by the farmers though sulphate concentration can also occur in natural water.

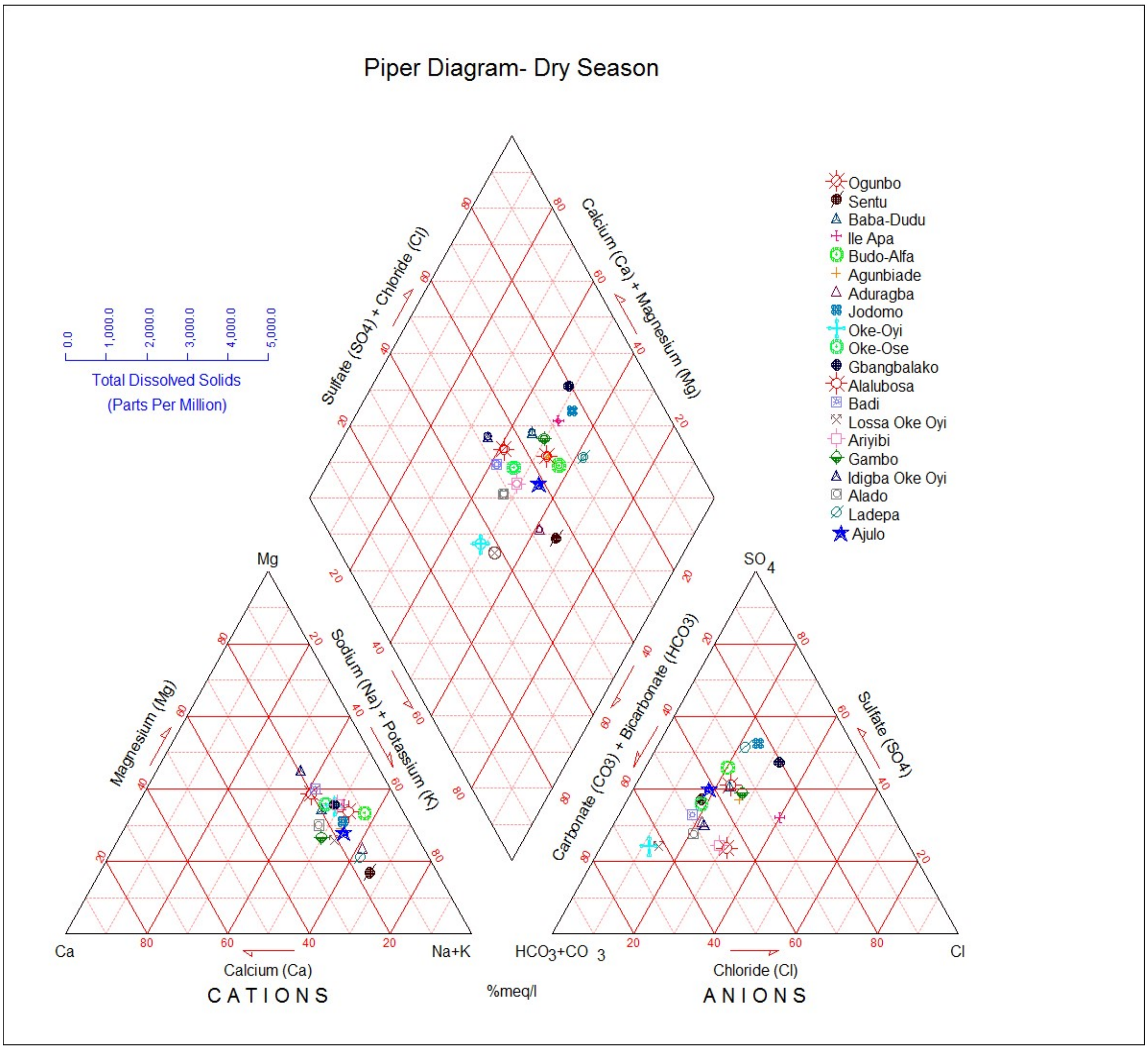
Nitrate had a mean of 2.8 mg/l for the dry season, with a mean of 2.0 mg/l for the wet season, while the acceptable standard limit for nitrate in water is 50 mg/l (WHO, 2011). All the water samples in the area for the two seasons are within the acceptable limit. The minor traces of nitrates in the water in the study area imply that there was little impact from agricultural practices in the area and small effects of sewage disposal in the area. Iron levels of the water samples in the dry season had a mean of 0.4 mg/l, while for the wet season it had an average mean of 0.08 mg/l. The standard recommended limit for iron is 3.0 mg/l (WHO, 2011). The water samples in the area for both seasons are within the acceptable limits which signifies that the water in the area is good for human health. Some traces of iron occurrence in water in the area are probably due to the weathering of iron mineral rocks in the area such as garnets, magnetite and amphibole.

3.5.3 Hydrochemical facies

The main water types in the study area were obtained through the Piper trilinear diagram (Piper, 1994). The Piper trilinear diagram illustrates the various percentage of cations (Mg^{++}, Ca^{++}, Na^{+} and K^{+}) and anions (Cl^{-}, SO_4^{2-}, CO_3^{2-}, HCO_3^{2-}) in the two triangular fields, and a combined position of all major ions in the diamond-shaped diagram that summarises the dominant cation and anion facies in terms of major ion percentages.

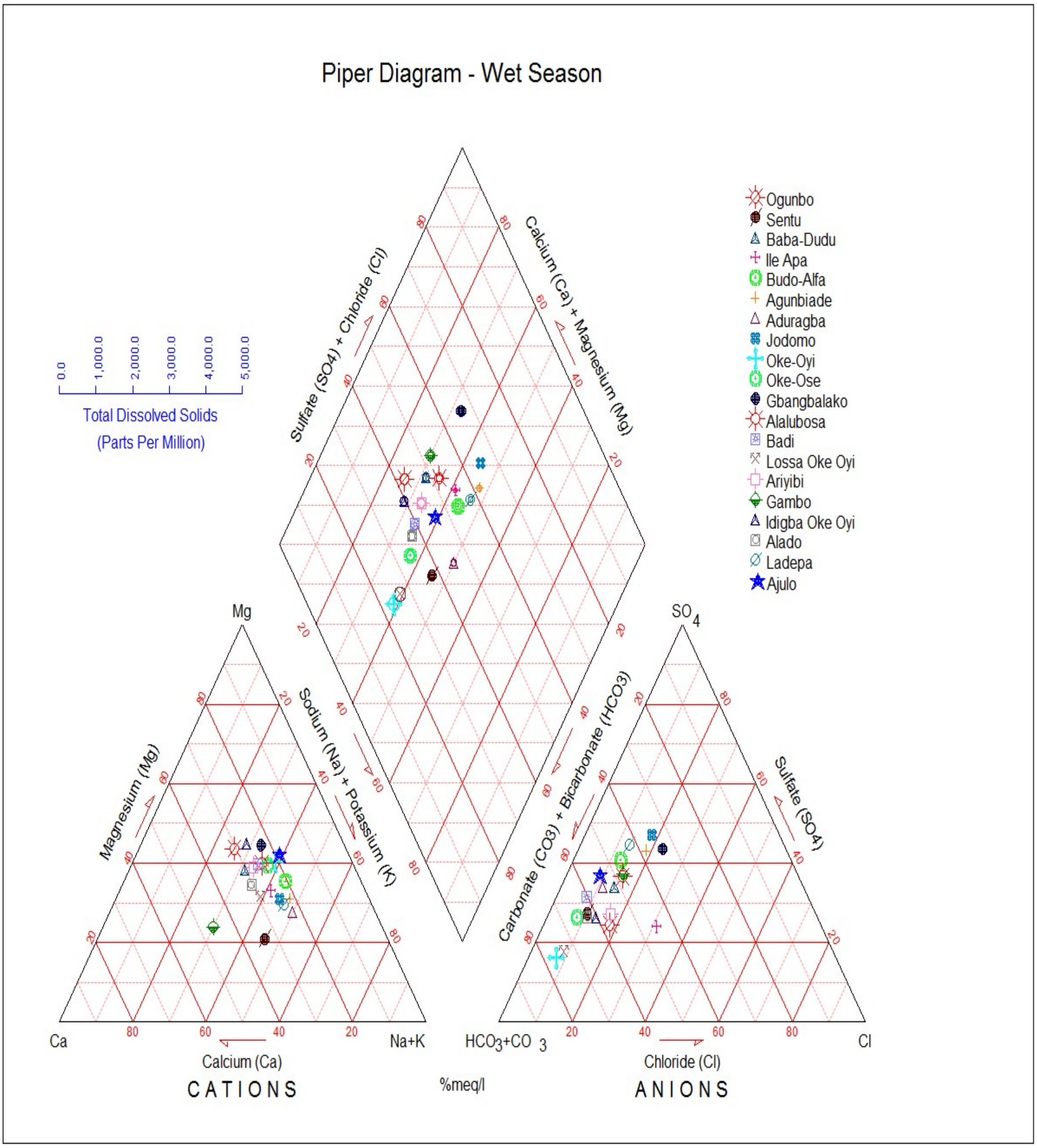
The water types are designated according to the area in which they occur on the diagram segments (Figure 3.9 and Figure 3.10). In the dry season, the cation distribution indicates that the groundwater has a sodium/potassium classification. The sodium and potassium are released into the groundwater from the soluble products of weathered minerals such as plagioclase and orthoclase feldspars of the bedrocks in the study area. Also, potassium could be released from the application of fertiliser on farm land. When fertilisers are applied to agricultural land, some portion of it might leached through the soil and to the water table. In the anion triangle, it is a mixed anion water type and a tendency towards bicarbonate water type. Bicarbonate is sourced from the atmospheric carbon dioxide dissolved by rainwater. In the wet season, there is mixed cation water type and bicarbonate anion water type.

Magnesium is probably obtained from the breakdown of some mineralogical constituents that are present in the rocks of the area. Such minerals include pyroxene, hornblende and olivine. Calcium could have been released into the groundwater by the weathering of calcic feldspar, amphibole and pyroxene. Also, the source of iron in the groundwater could be traced to the oxidation of iron minerals present and oxygenated recharge water as a result of the shallow and open nature of the groundwater system in the study area. Sulphate is released into the groundwater by the oxidation of sulphides, while chloride occurs through the meteoric (atmospheric) gases. However, the decrease in the concentration of some chemical constituents in the wet season results from dilution, and increase in the concentrations during the dry season is due to evaporation. For instance, the chemistry of precipitation varies a lot though depending on the activities that influence the chemical composition of the atmosphere. Since, water is a good solvent, as it comes in the form of rain, it tends to dissolve the chemical constituents in the atmosphere.



Source: Author's own (2019)

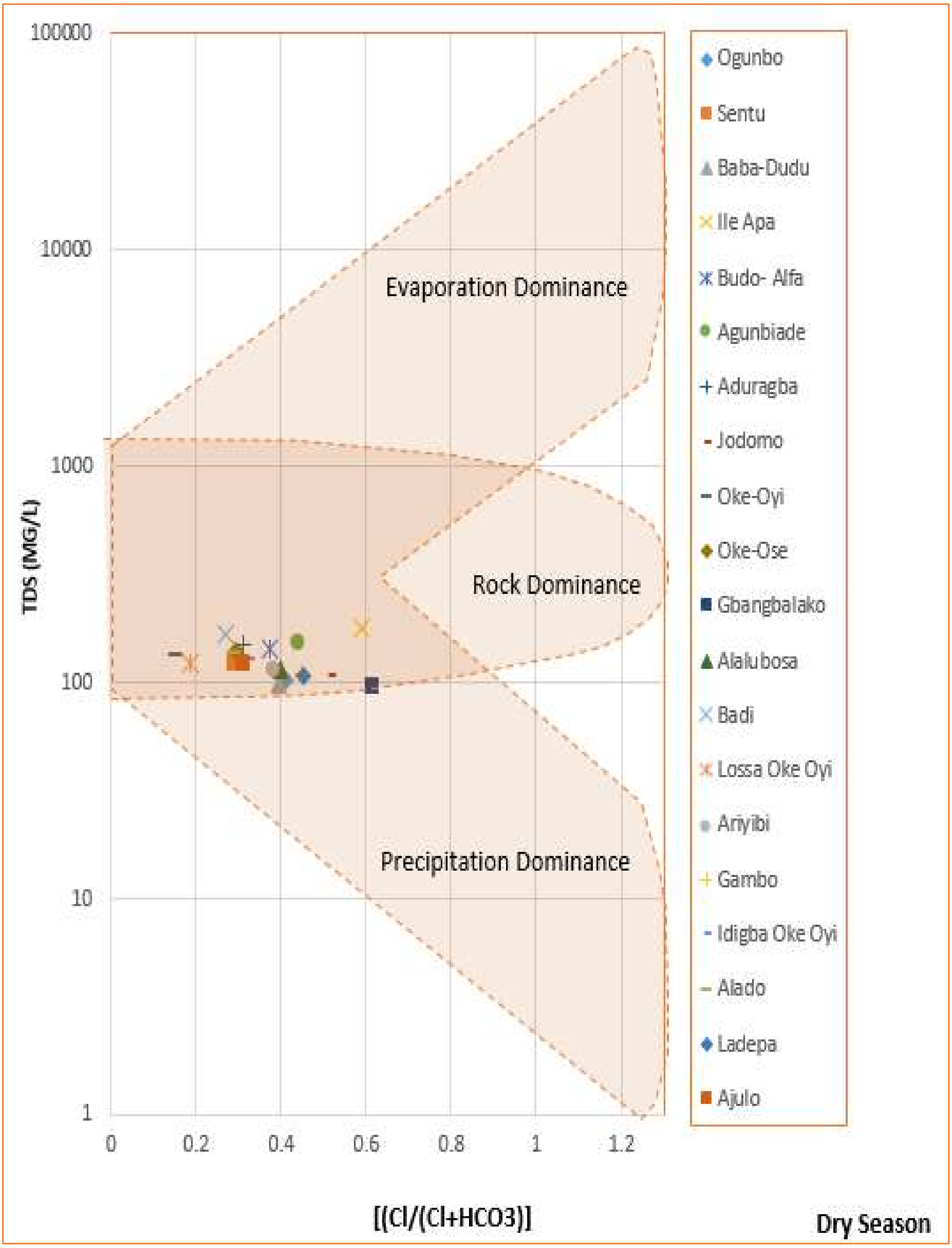
Figure 3.10 Piper trilinear diagram showing chemical characteristics of groundwater (Dry season)



Source: Author's own (2019)

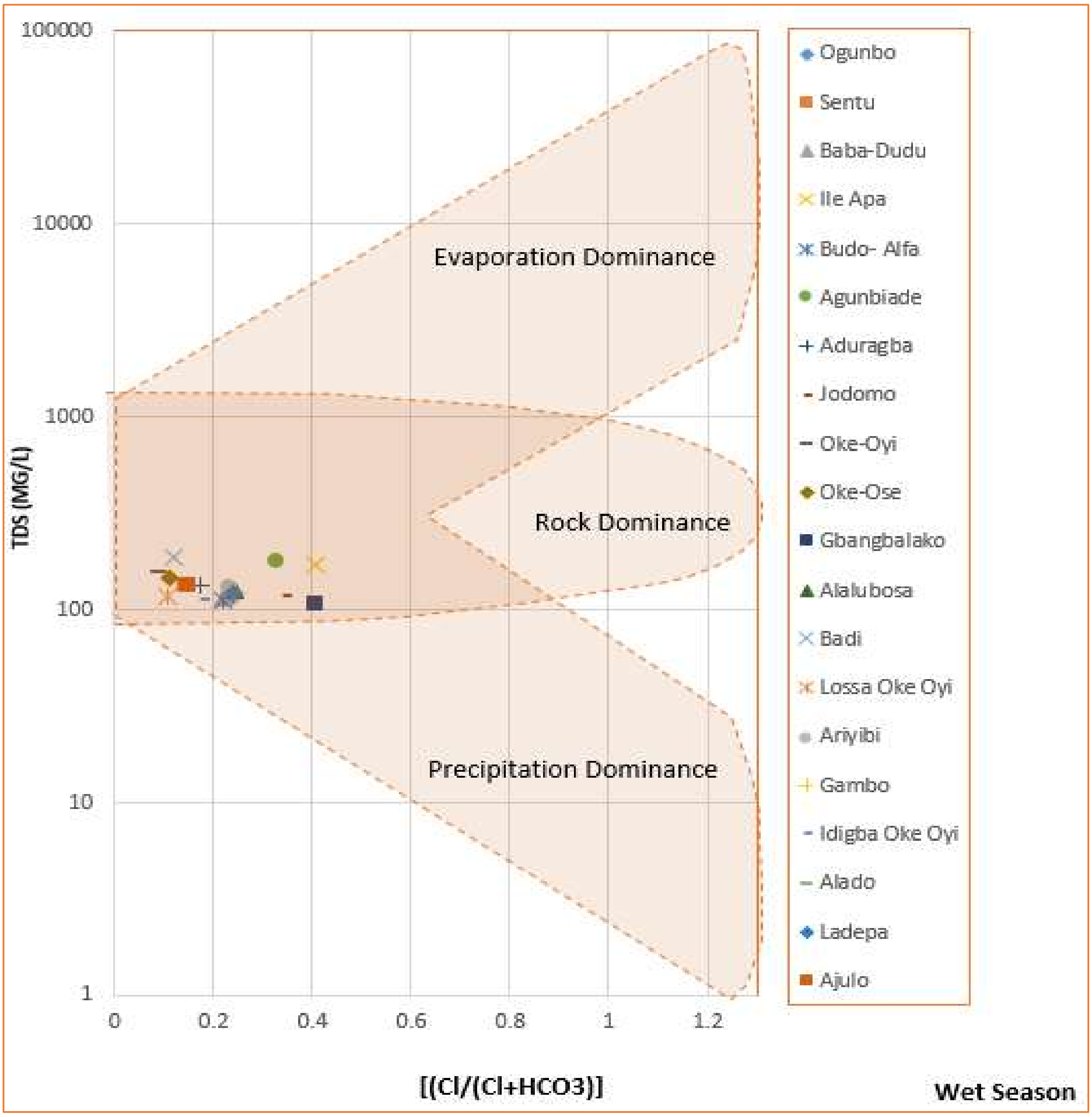
Figure 3.11 Piper trilinear diagram showing chemical characteristics of groundwater (Wet season)

Further evidence in support of water–rock interaction of groundwater in the study area is supported by the Gibbs (1970) diagram (Figure 3.12 and Figure 3.13). Most of the groundwater samples in the two seasons are plotted in the rock dominated field. This demonstrates water–rock interaction as major factor responsible for the geochemical processes controlling the groundwater chemistry in the study area.



Source: Author's own (2019)

Figure 3.12 Gibbs plots of water samples in the study area (Dry season)



Source: Author’s own (2019)

Figure 3.13 Gibbs plots of water samples in the study area (Wet season)

3.5.4 Evaluation based on saturation indices

The major elements and trace metals are transported in the chemical elements through groundwater. Both anion and cation concentrations present in groundwater form complex association, therefore aqueous complex formations are very necessary in describing aquifer characteristics because both toxicity and bioavailability of metals that usually occur in groundwater are based on the aqueous speciation or complexation of the metal (Langmuir, 1997).

Saturation Indices (SI) is useful to determine possible chemical reactions and to measure some level of chemical departures from the thermodynamic equilibrium between the aquifer and minerals present. The SI also serves as indicator for the rock types that were responsible for the major chemical constituents present in the water (Belkhiri and Mouni, 2013).

The SI of the water samples was calculated using the following equation:

$$SI = \log_{10} (IAP / K_{sp}) \tag{3.4}$$

Where:

- IAP refers to as the ion activity product and
- K_{sp} is the solubility product at a given temperature

However, the SI in a particular mineral indicates whether the groundwater is undersaturated with respect to the mineral in question when the value of SI is below 0. It is in equilibrium with the mineral when the calculated value of SI is 0, or it is regarded to be a supersaturated aqueous solution with respect to the mineral in question when the value of SI is greater than 0. Consecutively, if the groundwater is considered to be undersaturated with respect to the mineral, as has been shown with a negative SI, this means that the groundwater would theoretically dissolve that particular mineral concerned. But if the groundwater is supersaturated with respect to a particular mineral, this implies that the mineral would precipitate from the groundwater. Although there are still some uncertainties associated with the range values of SI that indicates equilibrium phases due to some anomalies from the field measures of pH-values, laboratory analysed concentrations of ions, show ionic strength and equilibrium constants that are involved during calculations of SI parameters (Langmuir, 1997).

In this study, a geochemical program called PHREEQC developed by Parkhurst and Appelo (1999), was applied in calculating SI-values for the analysed water samples in the study area during the wet and dry seasons (Appendix H and Appendix I). The results from SI calculated values showed that the water samples for the two seasons (wet and dry seasons) are greatly undersaturated with respect to anhydrite ($CaSO_4$), gypsum ($CaSO_4{:}2H_2O$), and halite (NaCl), which means that these minerals will continue to dissolve in the water.

The water is supersaturated with respect to the calcite, aragonite and dolomite which occur from the disintegration of the major mineral rocks found in the area such as mica schist and biotite granite. The oversaturation of these minerals, most especially dolomite, results from the presence of calcium and magnesium in the water. Calcium and magnesium are found in large quantities in some brine. In some cases, high amounts of calcium within the earth crust could be responsible for its presence in the groundwater. Also, almost all-natural waters, including seawater, contain either or both calcium carbonate and calcium sulphate. Calcium also forms in many silicate minerals that are present in rocks such as garnet, epidote, titanite and wollastonite. Magnesium occurrence in the water possibly results from the dissolution of mineral rocks (ferromagnesian minerals such as biotite and olivine) in the area as a high concentration of magnesium has been observed in the analysed water samples. Magnesium-rich groundwater containing a significant amount of salt is also thought to be essential for dolomite formation.

The development of the proposed method for estimating hydraulic conductivity in concrete-lined, large-diameter hand-dug wells is discussed in the next chapter.

Chapter 4

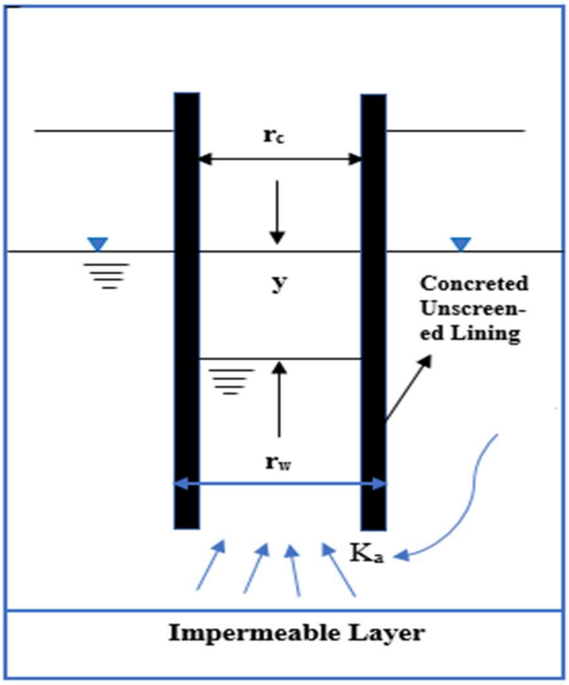
DEVELOPMENT OF THE PROPOSED METHOD

4.1 Introduction

This chapter aims at deriving a method for estimating a true hydraulic conductivity which is a true reflection of the flow characteristics of the aquifer formation in unscreened concrete-lined, large-diameter hand-dug wells. However, to obtain a true hydraulic conductivity of the aquifer formation, the apparent hydraulic conductivity (Ka) will be derived first, through which a true hydraulic conductivity (K) of the formation will be determined.

4.2 Method development

Figure 4.1 shows the flow in an unconfined aquifer for an unscreened concrete-lined, large-diameter hand-dug well, with the basic components of the proposed equation for the estimation of the Ka of aquifer formation in an unscreened concrete-lined, large-diameter hand-dug well.



Source: (Author's own (2019)

Figure 4.1 Showing flow in unscreened concrete-lined large-diameter hand-dug well in unconfined aquifer

The derivation of groundwater flow starts from Darcy's law. The Darcy's law is a simple proportional relationship between the instantaneous inflow / outflow rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance. The flow into the well (Q) at a particular value of y can be determined.

From Darcy's law, we get:

$$Q = KiA \tag{4.1}$$

In an unscreened concrete-lined large-diameter hand-dug well, the water flows to the well through the uncemented well base; therefore, the area providing water to the well is given as $A = \pi r^2$. From Figure 4.1, r_c is the inside radius of the concrete-lined well (m), r_w is the distance from the well centre to the original aquifer, y is the vertical distance between the water level in the well and equilibrium water table in the aquifer, y is (h_o–h) where h_o is the equilibrium water table in aquifer (m) and h is the water level in the well (m).

From Figure 4.1: The rate at which water will enter the base of the well is given by:

$$Q = \pi {r_c}^2 K_a \frac{\partial h}{\partial r_w} \tag{4.2}$$

Which is a functional components of the well. However, the r_w in the above equation actually represent the distance from the well centre to the original aquifer while the radial coordinate r_c as implied in the equation is the inside radius of the concrete-lined well.

By re-arranging eq. 4.2:

$$\partial h = \frac{Q}{\pi r_c K_a} \frac{\partial r_w}{r_c} \tag{4.3}$$

Integrated eq. 4.3:

$$h = \frac{Q}{\pi r_w K_a} \ln(r_c) + c \tag{4.4}$$

$$h = h_0 \; at \, r_c = R_e \quad . \tag{4.5}$$

where R_e is the effective radius over which y is dissipated (L) and c is constant

$$h_0 = \frac{Q}{\pi r_w K_a} \ln(R_e) + c \qquad 4.6$$

Eliminating the constant (*c)*:

$$h_0 - h\,(y) = \frac{Q}{\pi r_w K_a} \ln(\frac{R_e}{r_w}) \qquad 4.7$$

Where:

- h_o is the equilibrium water table in aquifer (m)
- h is the water level in the well (m)
- y is the vertical distance between the water level in the well and equilibrium water table in the aquifer (m)

From above:

$$y = \frac{Q}{\pi r_w K_a} \ln(\frac{R_e}{r_w}) \qquad 4.8$$

The flow into the well (Q) at a particular value of y for unscreened concrete-lined large-diameter hand-dug well can be calculated as:

$$Q = \pi r_w K_a \frac{y}{ln(\frac{R_e}{r_w})} \qquad 4.9$$

Where:

- Q is the flow into the well (length^3 / time)
- K_a is the apparent hydraulic conductivity of the aquifer (length / time)
- y is the vertical distance between the water level in the well and the equilibrium water table in the aquifer (L)
- R_e is the effective radius over which y is dissipated (L)
- r_w is distance from well centre to the original aquifer (L)

The terms y, R_e, and r_w are expressed in units of length. In a large-diameter hand-dug well, when the water level in the well is lowered, the recovery or rate of rise (d_y/d_t) of the water level back to the initial or pretest level is related to the inflow Q (Herbert and Kitching, 1981; Rushton and Holt,1981) given as:

$$\frac{dy}{dt} = \frac{Q}{\pi {r_c}^2} \qquad 4.10$$

Where:

- Q is the inflow of water to the well (L)
- y is the head change (L)
- t is the time (t)
- r_c is the inner radius of the well (L)

From eq. 4.9 above, where $= \pi r_w K_a \frac{y}{\ln(\frac{R_e}{r_w})}$.

By inserting equation 4.9 into equation 4.10 and integrate, a working equation will be derived to determine apparent hydraulic conductivity (K_a) for an unscreened concrete-lined large-diameter hand-dug well as follows:

Combining eq. 4.9 and eq.4.10 and integrate:

$$\frac{1}{y}\,dy = \frac{K_a r_w}{{r_c}^2 \ln(\frac{R_e}{r_w})}\,dt \qquad 4.11$$

Integrated eq. 4.11:

$$lny = \frac{K_a r_w t}{{r_c}^2 \ln(\frac{R_e}{r_w})} + constant \qquad 4.12$$

when applying eq. 4.12, between the limits y_o at t = 0 and y_t at t and solve for K_a as follows:

$$lny_0 = \frac{K_a r_w t}{{r_c}^2 \ln(\frac{R_e}{r_w})} + lny_t \qquad 4.13$$

$$lny_o - lny_t = \frac{K_a r_w t}{r_c{}^2 \ln(\frac{R_e}{r_w})} \qquad 4.14$$

$$ln\frac{y_o}{y_t} = \frac{K_a r_w t}{r_c{}^2 \ln(\frac{R_e}{r_w})} \qquad 4.15$$

$$Ka = \frac{r_c{}^2 \ln(\frac{R_e}{r_w})}{r_w}\frac{1}{t}\, ln\frac{y_o}{y_t}\ (\mathrm{L/T}) \qquad 4.16$$

Ka is the apparent hydraulic conductivity (L/T) of the formation. The Ka, r_c, r_w, and R_e in the equation are constants; $(1/t)\ln(y_o/y_t)$ will also be constant. Equation 4.16 requires plotting of the recovery curve as y on a log scale against t on a linear scale using a semi-log graph where y is the recovery drawdown and t is the time taken. Then to identify the slope where the relationship is approximately linear.

However, due to the inaccessibility to an electric resistance network analogue, and also for the fact that a resistance network could not simulate or account for unsaturated conditions which are important for traditional large-diameter hand-dug wells in unconfined aquifers where the unsaturated soil properties are considered as important factors, $\ln(\frac{R_e}{r_w})$ is therefore determined by using the empirical equation developed by Rupp et al. (2001), Rupp et al. (2011) and Uribe et al. (2014). This will improve the estimations of apparent hydraulic conductivity by accounting for the unsaturated zone and useful in the developing areas of the world where there is no access to software for numerical analysis. The equation was specifically based on the textural characteristics of the soil/rock materials surrounding the aquifer.

$$ln\left(\frac{R_e}{r_w}\right) = \frac{C_1 + C_2 ln(\Lambda({}^{d}/_{r})^2)}{1 + C_3\left(\frac{(D-d)}{D}\right)^{\frac{1}{2}}(\frac{d}{r})^{-5/8})} \qquad 4.17$$

The capillary parameter Λ in the equation is a function of water retention of the soil materials in the well (unsaturated zone) surrounding the aquifer, which is estimated from the textural properties of the soil/rock material and determined from the soil's water retention properties. Which is determined as follows:

where $\Lambda = \frac{1}{\alpha}(\theta_{ref\left(\frac{n}{1-n}\right)-1})\frac{1}{n}$ *4.18*

$$\theta_{ref} = \frac{\theta_{ref} - \theta_t}{\theta_s - \theta_t} \qquad 4.19$$

For an unconsolidated soil/rock media, C_1, C_2 and C_3 are constants. For units in metres, C_1=1.839, C_2=0.209 and C_3 = 1.614 (Rupp et al., 2001; 2011).

4.3 Derivation of horizontal hydraulic conductivity K from apparent hydraulic conductivity Ka

Hydraulic conductivity K will be determined from Ka through screened lining of large-diameter hand-dug wells to allow horizontal flow of water to the well. The Ka is estimated using the derived equation 4.16, while K is determined from the method developed for screened hand-dug wells based on Darcy's law. These will be achieved through field recovery tests in unscreened lined and screened lined large-diameter hand-dug wells.

The next chapter discusses the application of the proposed method.

Chapter 5

APPLICATION OF PROPOSED METHOD

5.1 Introduction

This chapter discusses the field application of the proposed method for estimating the hydraulic conductivity of aquifer formation from the concrete-lined, large-diameter hand-dug well. This part of the research involved conducting a field recovery test in concrete-lined, large-diameter hand-dug wells and measuring the recovery water level at time intervals which was then used to calculate recovery drawdown. The chapter further illustrates how the time–recovery drawdown data from a large-diameter hand-dug well can first be used to estimate the aquifer apparent hydraulic conductivity (Ka) and then the horizontal conductivity (K). The chapter finally discusses the steps to determine the formation of hydraulic conductivity from the recovery test in unscreened concrete-lined large-diameter hand-dug wells and the significance of derived hydraulic conductivity in large-diameter hand-dug wells.

5.2 Field testing

The location of the test site, geology and geohydrological characteristics of the study area have been discussed in Chapter 3. However, based on the well accessibility and the owner's cooperation at the study site, twelve (12) concrete-lined, large-diameter hand-dug wells which are used for domestic purposes such as cooking, washing and drinking, were selected for the study. The well radius, well depth, and static water of the wells were recorded before the commencement of the field test. This included the well depth (m), referred to as the distance from the land surface to the bottom of the well, r_c called the radius of the unscreened part of the well where the head is rising (m), and r_w is the distance from the centre of the well to the undisturbed aquifer. These wells are concrete-lined large-diameter hand-dug wells with a depth of between 8.6 m and 10.6 m and having a well radius that ranges from 0.68 m to 0.78 m. The field tests were conducted in two stages as discussed below.

5.2.1 Field Test 1

The first field test was conducted in the twelve unscreened concrete-lined large-diameter hand-dug wells to estimate the apparent hydraulic conductivity of aquifer formation. However, before the commencement of the tests, the static water levels of the tested wells were measured with the use of an electric water level probe (Figure 5.1a).

The field recovery tests were performed in the twelve unscreened concrete-lined large-diameter hand-dug wells at the study site (Figure 5.1) to estimate the apparent hydraulic conductivity of the aquifer formation. To achieve this objective, the field tests were carried out by quickly pumping the wells to draw the water level down. The pump was then turned off while the wells were monitored up to 90% of recovery. Since the aquifer was unconfined, the water levels in the wells were lowered to no more than 10% of the aquifer thickness (Herbert and Kitching, 1981; Rushton and Holt, 1981; Mace, 1999). The thickness of the aquifer is determined from the difference between the depth to the bedrock and the depth to the water table.

(a) Showing the use of an electrical water level probe

(b) Showing the preparation of the submersible pump unit for extraction of water followed by recovery monitoring

Source: Author's own (2019)

Figure 5.1 Field recovery tests performed in unscreened concrete-lined large-diameter hand-dug wells

The measured recovery water levels at specific time intervals were used to calculate the recovery drawdown in the unscreened concrete-lined large-diameter hand-dug wells as shown in Appendix J, while the recovery drawdown – time data in unscreened concrete-lined large-diameter hand-dug wells was used to estimate apparent hydraulic conductivity of the aquifer formation.

5.2.2 Field Test 2

The second field test involved screening of the twelve concrete-lined large-diameter hand-dug wells (Figure 5.2) to allow horizontal flow of water to the well in order to estimate the true hydraulic conductivity of the aquifer formation. To achieve this, field recovery tests were carried out by lowering the water level in the well and monitoring the well recovery with the same technique applied in the first field test for the unscreened concrete-lined large-diameter hand-dug wells. The measured recovery water levels at specific time intervals were used to calculate the recovery drawdown in the screened-lined large-diameter hand-dug wells as presented in Appendix K, while the recovery drawdown - time data in the screened-lined large-diameter hand-dug wells was used to estimate the true hydraulic conductivity of the aquifer formation.

Source: Author's own (2019)

Figure 5.2 Screened-lined large-diameter hand-dug wells at test site

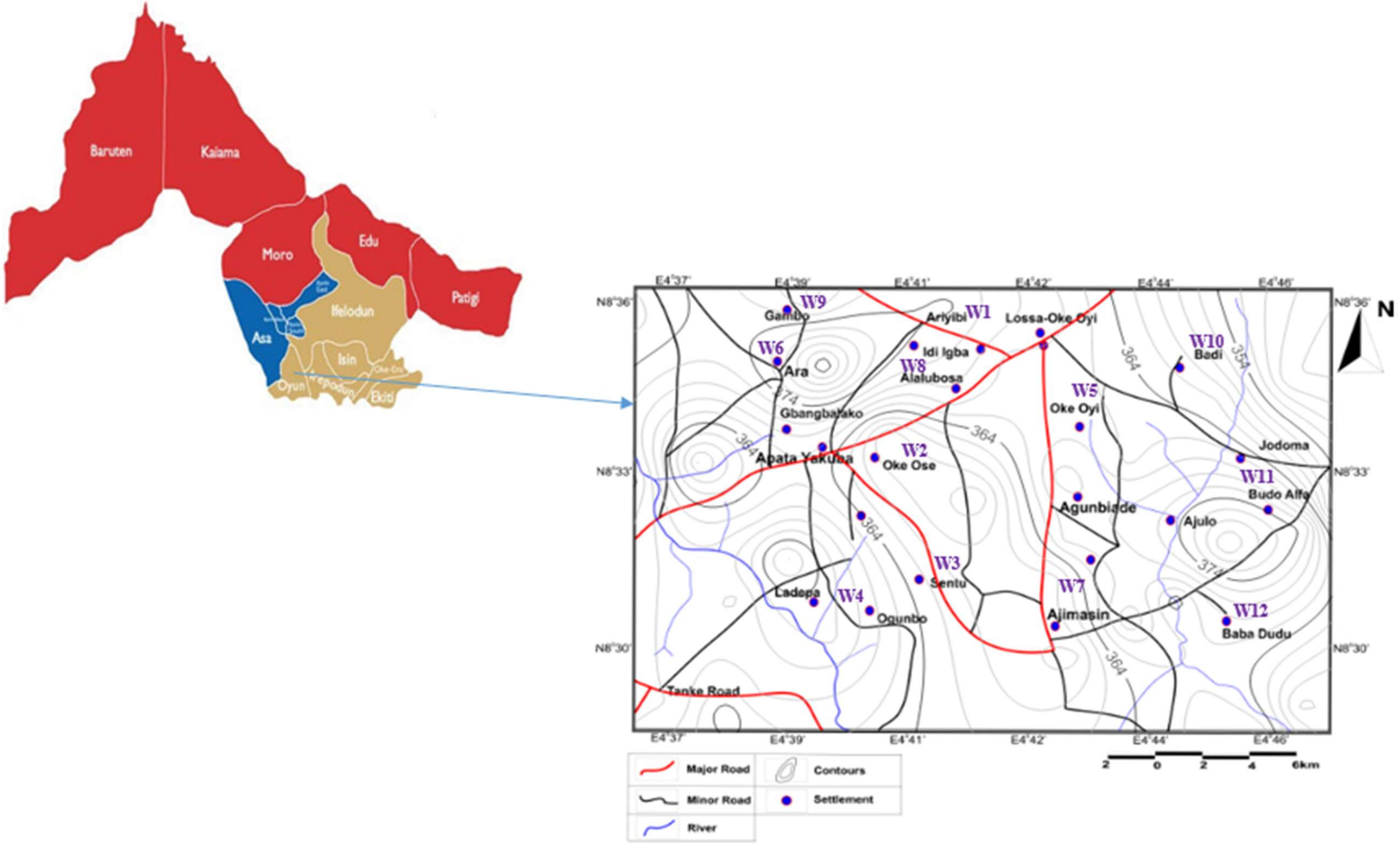
The location, depth, radius, diameter, and static water level of the unscreened concrete-lined and screened-lined large-diameter hand-dug wells for the tested wells are presented in

Table 5.1, while Figure 5.3 shows the well locations.

TABLE 5.1 LOCATION COORDINATES AND PHYSICAL DIMENSIONS OF TEST WELLS

Well no.	Well depth (m)	Well radius r_c (m)	Static water level (mbgl)*	Depth of concrete-lined well (m)	r_w (m)
W1	9.4	0.68	3.1	9.36	0.71
W2	9.8	0.75	3.4	9.73	0.77
W3	8.9	0.75	2.7	8.86	0.72
W4	9.1	0.66	2.9	9.07	0.71
W5	8.7	0.72	2.8	8.64	0.75
W6	10.6	0.75	3.7	10.53	0.77
W7	9.8	0.75	3.2	9.75	0.74
W8	10.3	0.72	3.5	10.26	0.76
W9	8.8	0.73	2.9	8.76	0.76
W10	8.6	0.78	2.8	8.51	0.81
W11	9.2	0.72	3.3	9.13	0.76
W12	10.4	0.75	3.6	10.35	0.72

*Where mbgl is defined as metres below ground level.

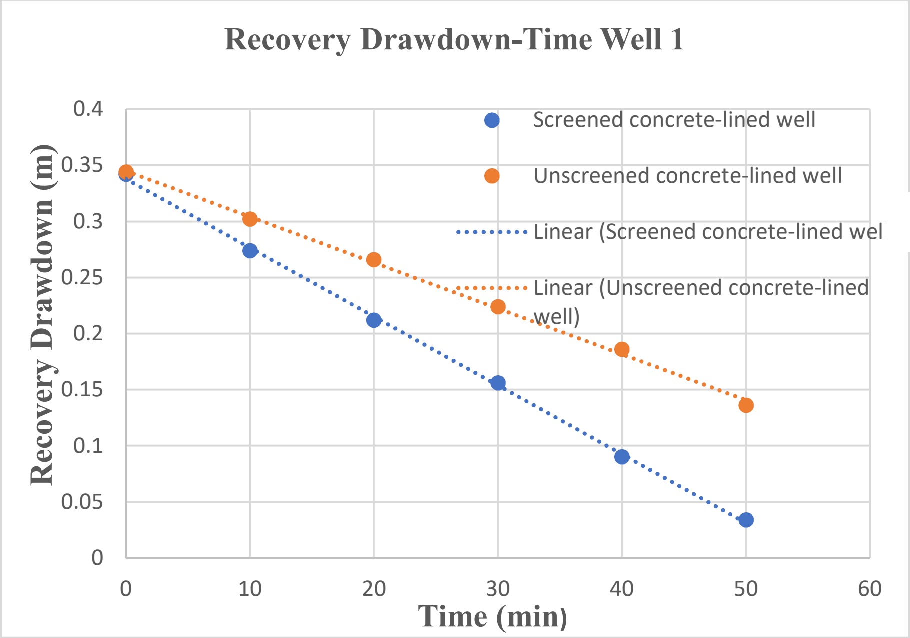


Source: Author’s own (2019)

Figure 5.3 Map of study site with well locations inserted

5.3 Analysis of recovery drawdown trends

The recovery drawdown obtained in the two methods (unscreened concrete-lined and screened large-diameter hand-dug wells) were plotted on direct linear graphs as shown in Figure 5.4 and Figure 5.5 (see also Appendix L). The well recovery is proportional to the flow rate of the well, and increases as the flow of the well increases. In a screened well (K), groundwater enters the well with a minimal amount of energy loss, and well recovery after pumping is generally rapid, and may sometimes exhibit near full recovery up to the static water level. Conversely, an unscreened well (Ka) exhibits excessive energy losses and well recovery and the time after pumping is slower.



Source: Author's own (2019)

Figure 5.4 Direct plots of recovery drawdown and time for Well 1 – unscreened and screened

Source: Author's own (2019)

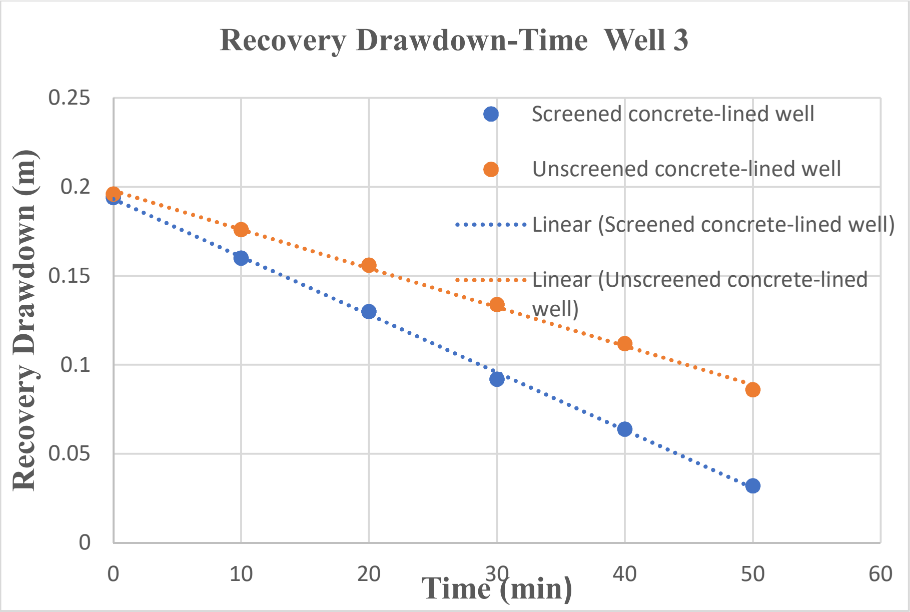


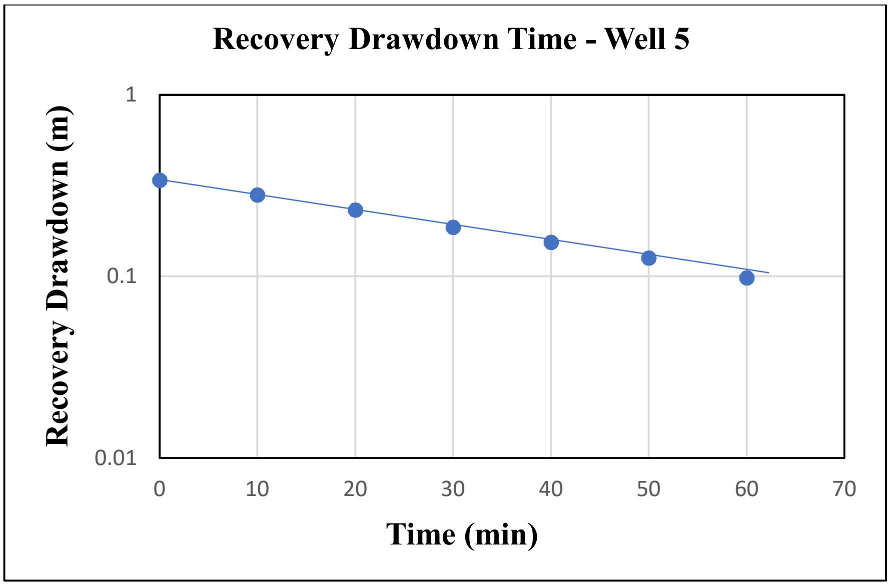
Figure 5.5 ***Direct plots of recovery drawdown and time for Well 3 – unscreened and screened***

In general, the variations in the characteristics of these wells depend on the following factors:

- The regional geology of the area.
- Soil/rock types of the aquifer.
- Construction method of the well.
- Construction materials.
- Well depth and diameter of the well.

5.4 Estimation of the apparent hydraulic conductivity

To estimate the apparent hydraulic conductivity (Ka), the calculated recovery drawdown data was plotted against recovery drawdown time. Derived from Equation 5.1, Ka, r_c, r_w and R_e are constants, and $(1/t)\ln(y_o/y_t)$ is also constant; therefore, it is required that the recovery drawdown y is plotted against time t on a semi-log graph (drawdown on the logarithmic and time on a linear scale). A best-fit straight line through the set of data points was plotted. The straight line plotted was also used to calculate the value of $(1/t)\ln(y_o/y_t)$. Figure 5.6 shows a semi-log plot of recovery drawdown against time in Well 5, while the plots for other wells are presented in Appendix M for Ka estimation.



Source: Author's own (2019)

Figure 5.6 Semi-log plot of recovery drawdown against time recorded in Well 5

The values obtained from the plotted curves, along with other well parameters, were substituted into the proposed Equation 5.1, as derived in Chapter 4, in order to estimate the apparent hydraulic conductivity (Ka) of the aquifer formation in concrete-lined large-diameter hand-dug wells.

$$Ka = \frac{r_c^2 \ln(\frac{R_e}{r_w})}{r_w} \frac{1}{t} ln \frac{y_o}{y_t} \qquad 5.1$$

Where:

- r_c is radius of the unscreened part of the well at which the head is rising (m)
- r_w is called the distance from the well centre to undisturbed aquifer (m)
- t is the time taken (min)
- the straight line plotted was used to evaluate $(1/t)\ln(y_o/y_t)$
- y_o is the water depth below water table at beginning of test
- y_t is the depth to water or drawdown, at time *t*
- R_e is the radial distance over which the difference in head is dissipated in the flow system of the aquifer

To calculate the radial distance R_e, the suggestion of Rupp et al. (2001); Rupp et al., (2011) and Uribe et al., (2014) for a large-diameter well as previously explained in Chapter 4, was used and given in Equation 5.2.

$$ln\left(\frac{R_e}{r_w}\right) = \frac{C_1 + C_2 ln(\Lambda({}^{a}/_{r})^2)}{1 + C_3\left(\frac{(d-a)}{d}\right)^{\frac{1}{2}}(\frac{a}{r})^{-5/8})} \qquad 5.2$$

Where:

- r is well radius (m)
- C_1, C_2 and C_3 are constants (m)
- a is the well base for recharge (m)
- d is distance from the water table to the well base (m)

The calculated effective radius (R_e) for the tested wells is presented in Appendix O. Table 5.2 shows the calculated data from Equation 5.1 for the twelve concrete-lined large-diameter hand-dug wells.

TABLE 5.2 WELL PARAMETERS AND ESTIMATED APPARENT HYDRAULIC CONDUCTIVITY IN METRE PER DAY FOR AQUIFER FORMATION USING THE PROPOSED METHOD

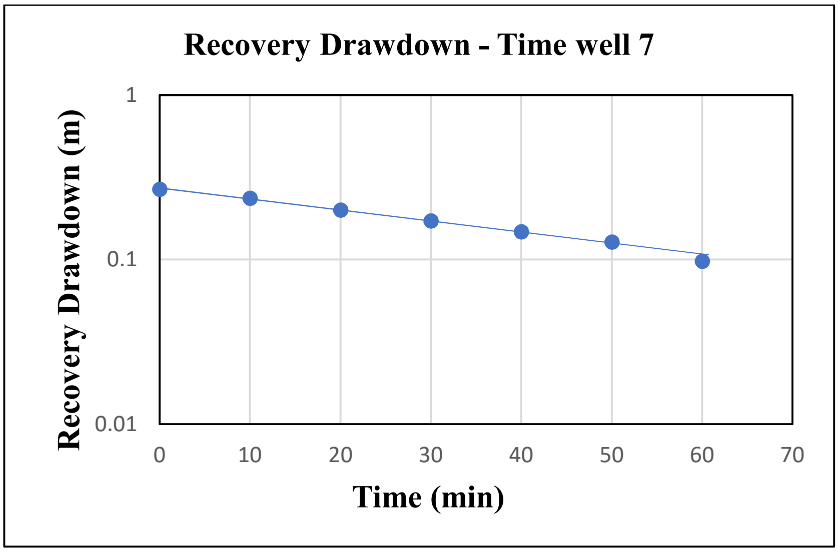
Well no.	r_c (m)	r_c^2 (m)	r_w (m)	$\ln(R_e/r_w)$	t(sec)	1/t	$\ln(y_o/y_t)$	Ka (m/s)	Ka (m/d)
W1	0.68	0.462	0.71	0.045	3 000	0.00033	0.688	6.65×10^{-6}	0.6
W2	0.75	0.563	0.77	0.082	2 400	0.00042	0.577	1.45×10^{-5}	1.3
W3	0.75	0.563	0.72	0.039	3 000	0.00033	0.693	6.97×10^{-6}	1.5
W4	0.66	0.436	0.71	0.030	3 600	0.00028	0.788	4.06×10^{-6}	0.4
W5	0.72	0.518	0.75	0.072	2 400	0.00042	0.604	1.24×10^{-5}	1.1
W6	0.75	0.563	0.77	0.082	3 600	0.00028	0.875	1.47×10^{-5}	1.3
W7	0.75	0.563	0.74	0.053	3 600	0.00028	0.793	8.50×10^{-6}	0.7
W8	0.72	0.518	0.76	0.041	3 000	0.00033	1.054	9.77×10^{-5}	0.8
W9	0.73	0.533	0.76	0.040	3 000	0.00033	0.788	7.30×10^{-6}	1.3
W10	0.78	0.608	0.81	0.105	2 400	0.00042	0.385	1.27×10^{-5}	1.1
W11	0.72	0.518	0.76	0.086	3 000	0.00033	0.750	1.45×10^{-5}	1.3
W12	0.75	0.563	0.72	0.0535	3 000	0.00033	0.718	9.91×10^{-6}	0.9

Table 5.2 shows the estimated Ka. Thus, this Ka is smaller than the true K, therefore, there is need to derive K of the aquifer formation.

5.5 Estimation of true hydraulic conductivity from apparent hydraulic conductivity

The true hydraulic conductivity (K) was determined, which take into account the horizontal flow into the well following the Darcy's law (1856). The K is expected to give a true reflection of flow characteristics of the aquifer formation. To achieve the above objective, the method of Bower and Rice (1976), developed for an unconfined aquifer of large-diameter wells, was considered following the field recovery tests conducted in twelve screened large-diameter hand-dug wells, as discussed in the field test above. The recovery field tests were equivalent to slug tests of Bouwer and Rice (1976) because the pumping period t_p to lower the water level in the well was short in comparison with the recovery period (Herbert and Kitching, 1981; Rushton and Holt, 1981; Mace, 1999). The measured recovery water levels at specific time intervals were used to calculate the recovery drawdown in the screened large-diameter hand-dug wells as shown in Appendix I.

To estimate the true hydraulic conductivity (K), the calculated recovery drawdown data was plotted against time. According to Bouwer and Rice (1976), the K, r_c, r_w, R_e, and L_e are constants, and $(1/t)\ln(y_o/y_t)$ is also constant. Therefore, on a semi-log paper, the recovery drawdown y was plotted against time t (recovery drawdown on the logarithmic and time on a linear scale). Then a best-fit straight line was made through the set of data points plotted. Figure 5.7 shows a semi-plot of recovery drawdown against time for Well 7. Plots for other wells are presented in Appendix N. The straight line plotted was used to calculate values for the $(1/t)\ln(y_o/y_t)$.



Source: Author's own (2019)

Figure 5.7 Semi-log plot of recovery drawdown against time recorded in Well 7

The values obtained from the plotted curves along with other well properties were substituted into the Bouwer and Rice (1976) Equation 5.3 to estimate the true hydraulic conductivity (K) of the aquifer formation in the screened-lined large-diameter hand-dug wells.

$$K = \frac{r_c^2 \ln \frac{R_e}{r_w}}{2L_e} \frac{1}{t} ln \frac{y_o}{y_t} \qquad 5.3$$

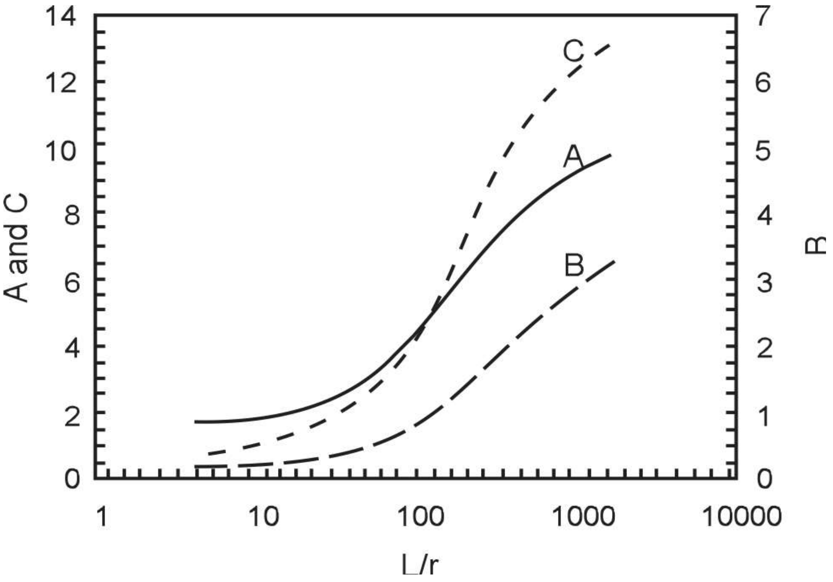
Where:

- K = true hydraulic conductivity (K) of aquifer formation (m/day)
- r_c = inner well radius (m)
- r_w = distance from the well centre to the undisturbed aquifer (m)
- L_e = length of the screen or open portion of the well (m)
- t = time taken (s)
- y_o = well water depth below water table at the beginning of test (m)
- y_t = depth to water or drawdown, at time t (m)
- R_e = is the radial distance over which the difference in head is dissipated in the flow system of the aquifer

However, Bouwer and Rice (1976) determined the values of R_e experimentally using a resistance network analogue for different values of r_w, L_w, L_e and D. However, the L_w, the length of the well in the aquifer, was equal to the distance from the water table to the bottom of the well, D, (Figure 5.2); the effective radius R_e was calculated using Equation 5.4 below according to Bouwer and Rice (1976):

$$ln \frac{R_e}{r_w} = \left(\frac{1.1}{ln \frac{l_w}{r_w}} + \frac{C}{\frac{l_e}{r_w}}\right)^{-1} \qquad 5.4$$

L_e/r_w from Equation 5.4 was obtained from the curve generated by Bouwer and Rice (1976) as shown in Figure 5.8. The calculated effective radius (R_e) for the screened large-diameter hand-dug wells is presented in Appendix P.



Source: Bouwer and Rice (1976)

Figure 5.8 A, B, and C as a function of L_e/r_w

The calculated data from the curves and estimated true hydraulic conductivity (K) of aquifer formation in the screened large-diameter hand-dug wells, using the Bouwer and Rice (1976) method is shown in Table 5.3.

TABLE 5.3 WELL PARAMETERS AND ESTIMATED TRUE HYDRAULIC CONDUCTIVITY IN METRE PER DAY OF AQUIFER FORMATION USING THE BOUWER AND RICE (1976) METHOD

Well no.	r_c^2 (m)	L_e (m)	$\ln(R_e/r_w)$	D(m)	t (sec)	1/t	$\ln(y_o/y_t)$	K (m/s)	K (m/d)
W1	0.462	6.3	1.51	6.3	3 600	0.00028	0.880	1.36E-05	1.179
W2	0.563	6.4	1.58	6.4	1 800	0.00056	0.536	2.09E-05	1.802
W3	0.563	6.2	1.58	6.2	1 800	0.00056	0.507	2.04E-05	1.759
W4	0.436	6.2	1.59	6.2	3 000	0.00033	0.742	1.37E-05	1.183
W5	0.518	5.9	1.63	5.9	2 400	0.00042	0.631	1.90E-05	1.639
W6	0.563	6.9	1.51	6.9	2 400	0.00042	0.693	1.79E-05	1.549
W7	0.563	6.6	1.54	6.6	1 800	0.00056	0.432	1.59E-05	1.373
W8	0.518	6.8	1.55	6.8	1 800	0.00056	0.489	1.62E-05	1.397
W9	0.533	5.9	1.62	5.9	2 400	0.00042	0.747	2.29E-05	1.983
W10	0.608	5.8	1.66	5.8	1 800	0.00056	0.425	2.07E-05	1.789
W11	0.518	5.9	1.60	5.9	2 400	0.00042	0.765	2.26E-05	1.950
W12	0.563	6.8	1.51	6.8	1 800	0.00056	0.495	1.73E-05	1.497

The estimated true hydraulic conductivity (K) of aquifer formation using the Bouwer and Rice (1976) method in Table 5.3 shows that the estimated true K-values are higher than the Ka-values as compared in Table 5.4. This is reasonable considering the pattern in which the water is entering the wells in the two methods as discussed earlier.

TABLE 5.4 ESTIMATED VALUES FOR APPARENT HYDRAULIC CONDUCTIVITY AND TRUE HYDRAULIC CONDUCTIVITY OF THE AQUIFER FORMATION

Well No.	K_a (m/day)	K (m/day)
W1	0.6	1.179
W2	1.3	1.802
W3	1.5	1.759
W4	0.4	1.183
W5	1.1	1.639
W6	1.3	1.549
W7	0.7	1.373
W8	0.8	1.397
W9	1.3	1.983
W10	1.1	1.789
W11	1.3	1.950
W12	0.9	1.497

Descriptive statistical correlation was determined between the estimated Ka and K-values taken at different parts of the site. Specifically, this strategy was carried out to describe the strength and direction of the relationship existing between the estimated values of Ka and K. The degree of relationship or association between the estimated Ka and K-values was measured by a correlation coefficient, denoted by r. It is sometimes referred to as the Pearson correlation coefficient and was used to measure the linear relationship or association.

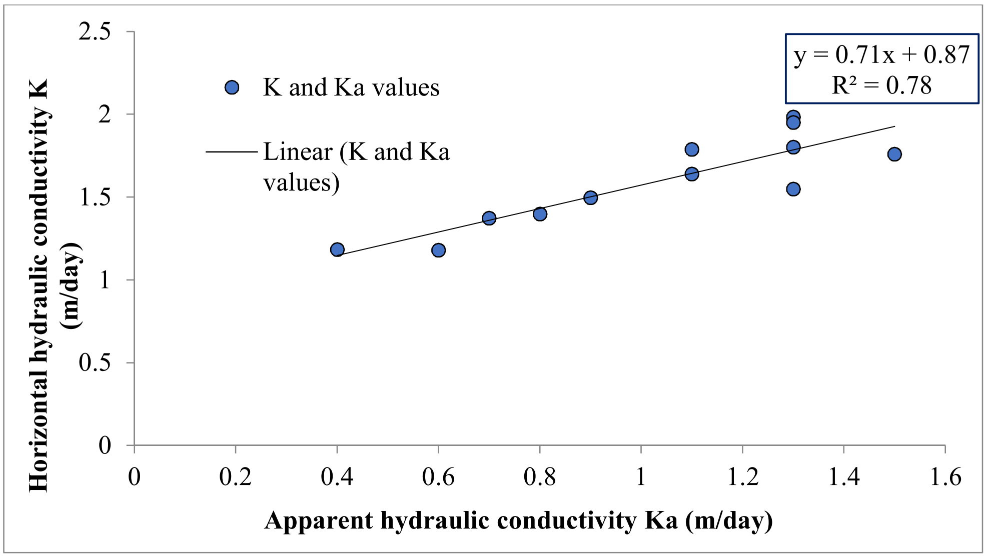
The Pearson correlation coefficient between estimated Ka and K-values was determined using SPSS software as presented in Table 5.5. The Pearson moment (r-cal.) is 0.88, with the Pearson level of significance value of 0.00, which simply indicates that there is a significant strong positive relationship between the estimated Ka and K-values.

TABLE 5.5 PEARSON CORRELATION BETWEEN THE ESTIMATED APPARENT HYDRAULIC CONDUCTIVITY AND TRUE HYDRAULIC CONDUCTIVITY VALUES

Correlations		K	Ka
K	Pearson correlation	1	0.880*
	Sig. (two-tailed)		0.000
	N	12	12
Ka	Pearson correlation	0.880*	1
	Sig. (two-tailed)	0.000	
	N	12	12

* Correlation is significant at the 0.01 level (two-tailed).

Further information on the relationship or association between the estimated the Ka and K-values was made from a regression analysis with the use of bivariate plots as shown in Figure 5.9. The regression analysis was determined by estimating the best straight line to summarise the relationship. This also helped to show how one variable or value changes on average with another.



Source: Author’s own (2019)

Figure 5.9 Bivariate plot of horizontal hydraulic conductivity K against apparent hydraulic conductivity Ka

As shown in Figure 5.9 above, there is a linear regression between the estimated Ka and K values taken from different areas, having $R^2 = 0.775$ with a linear equation as presented in Equation 5.5.

$$y = 0.71x + 0.87 \tag{5.5}$$

The linear Equation 5.5 shows the regression between two variables (Ka and K) which implies that a change by 0.71 unit in one variable results in one unit change in another. The importance of this is that once the apparent hydraulic conductivity Ka is estimated, it is therefore possible to estimate the true hydraulic conductivity K of the aquifer formation following Equation 5.6 below:

$$K = 0.71Ka + 0.87 \tag{5.6}$$

Where:

- K is the horizontal hydraulic conductivity of aquifer formation (L/T)
- Ka is the estimated apparent hydraulic conductivity of aquifer formation (L/T).

5.6 Steps to determine the formation hydraulic conductivity (K) from the recovery test in unscreened concrete-lined large-diameter hand-dug wells.

The steps in running the test and determine true hydraulic conductivity (K) in unscreened concrete-lined large-diameter hand-dug wells using the proposed recovery test method are summarised as follows:

1. Before conducting a recovery test in the well, record the initial depth to water. The test begins by pumping the well to lower the water level in the well. However, the aquifer type will determine the pumping water level required before turning the pump off. If the aquifer is unconfined, the water level is lowered no more than 10% of the aquifer thickness, but if it is confined, the water level is lowered to just above the base of the confining layer. Measure the water level periodically as the water level is returning to the pretest level. Keep collecting the data until at least 90% of the initial water level recovery is achieved.
2. From the water level measurements, calculate the recovery drawdown (y) and time taken (t).

3. Plot the calculated recovery drawdown on the log scale and time on the linear scale of semi-log graph paper.
4. Fit the best straight line through the set of data points.
5. Estimate the apparent hydraulic conductivity (Ka) using the derived equation as stated below:

$$Ka = \frac{r_c^2 \ln(\frac{R_e}{r_w})}{r_w} \frac{1}{t} ln \frac{y_o}{y_t} \qquad 5.7$$

Where:

- Ka is the apparent hydraulic conductivity (L/T)
- r_c is the inner radius of the unscreened part of the well at which the head is rising (m)
- r_w is called the distance from the well centre to the undisturbed aquifer (m)
- t is the time taken (t)
- y_o is the water depth below the water table at the beginning of test (m)
- y_t is the depth to water or drawdown, at time t
- R_e is the radial distance over which the difference in the head is dissipated in the flow system of the aquifer

6. Estimate the horizontal hydraulic conductivity (K) of the formation from apparent hydraulic conductivity (Ka) using the following empirical equation:

$$K = 0.71Ka + 0.87 \qquad 5.8$$

Where:

- K is horizontal hydraulic conductivity of the formation (L/T) and
- Ka is the estimated apparent hydraulic conductivity (L/T*)*

5.7 The significance/importance of derived hydraulic conductivity in large-diameter hand-dug wells

The derived hydraulic conductivity (K) offers the following significance to the rural water supply studies:

- Can give information on the performance and efficiency of the well yields. The estimated K-value will help to determine the amount of water that can be pumped from the well per day and this will reduce the challenges that the community face in their quest to access water supply by knowing the well yields per day. Early detection of this can give time to explore alternative sources and establish conservation measures.

- The estimated K-value will help to determining where there is a deficit in terms of water supply coverage, connections, failure and irregularity, most especially in the developing rural areas where large-diameter hand-dug wells are being mostly practiced.

- It will also be useful in the regional, national, and individual water planning to make benchmark values towards sustainability, planning and management of water supply through determining the method for well usage and the best way to recover costs.

- Technical proxies that are introduced in this derived K will offer the hydrogeologists/ geohydrologists, hydrologists, water engineers and environmentalists an opportunity to determine the magnitude of groundwater availability to a well and improve household rural water supply by giving a reliable estimate of available water to the intended beneficiaries.

Chapter 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This research thesis was primarily aimed to develop a method to estimate hydraulic conductivity in unconfined aquifers using concrete-lined large-diameter hand-dug wells. The main aim and objectives have been achieved. The conclusion from each objective are presented as follows:

- The research thesis has developed a method to the challenges encountered in the estimation of aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells.
- The application of the developed method was made in test site from recovery tests to estimate aquifer hydraulic conductivity K from apparent hydraulic conductivity Ka. The results showed that the estimated Ka values were lower than K values which indicated the effect of the unscreened concrete-lining.
- The research thesis' findings highlighted a relationship between Ka and K values and established a correction factor for the estimation of K from Ka by a regression analysis with the use of a bivariate Pearson correlation coefficient using SPSS software. The Pearson moment (r-cal.) was 0.88 with the Pearson level of significant value of 0.00, which implies a significant strong positive relationship between the estimated Ka and K values.

This research has provided important scientific information on the method for estimating aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells. The estimated aquifer hydraulic conductivity K is used to evaluate the aquifer potential and this helps to determine the amount of water that can be pumped from the well per day and to evaluate the water resources coverage and distribution in order to manage and sustain the available water resources to satisfy the need of the communities, most especially in the developing rural areas of sub-Saharan African countries and in other developing areas of the world where concrete-lined large-diameter hand-dug wells are mostly being practiced.

6.2 Recommendations

Recommendations and measures that are presented in this research are based on the recent findings and challenges faced during the course of this research. These recommendations are therefore stated as follows:

6.2.1 Recommendations to rural communities, governments and general populace

- The method and its application developed from this research study is recommended for estimation of aquifer hydraulic conductivity in unscreened concrete-lined large-diameter hand-dug wells.
- The improved type of slotted precast perforated rings as shown in Figure 6.1 below is recommended to be used in the future for lining in the construction of large-diameter hand-dug wells. This will allow horizontal seepage flow through the side walls of the well and increase the well yields, while non-perforated concrete rings can be placed in the non-productive parts of the aquifer or on top of the water table to also prevent collapse or caving of the well walls. The perforations should cover at least one-third of surface area of the concrete ring.

Figure 6.1: Recommended screened concrete lining for a large-diameter hand-dug well

- Monitoring the effects of water level withdrawal on the environment and surrounding areas is recommended. Also, securing hygienic operations around large-diameter hand-dug wells is essential. This involves the protection and cleaning of the well area (for example, fencing and covering), and disinfecting, if necessary.

- Implement, on a community basis, rural water supply systems based on identified good quality of groundwater resources harnessed through large-diameter hand-dug wells.
- Large-diameter hand-dug wells need more attention, particularly in the policy arena to promote the technical guidance in order to optimise the development, management and sustainability of these wells.

6.2.2 Recommendations for further studies

- This research recommends further studies to quantify the amount of energy loss due to flow directional changes in unscreened concrete-lined large-diameter hand-dug wells.
- Further evaluation to determine the memory vector in terms of travel time involved in the non-horizontal water flow to the well in unscreened concrete-lined large-diameter hand-dug wells.
- There is need for further research in this field such as introducing the technical guidance that will help to optimise the development, utilisation and management of large-diameter hand-dug wells.

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Appendix A

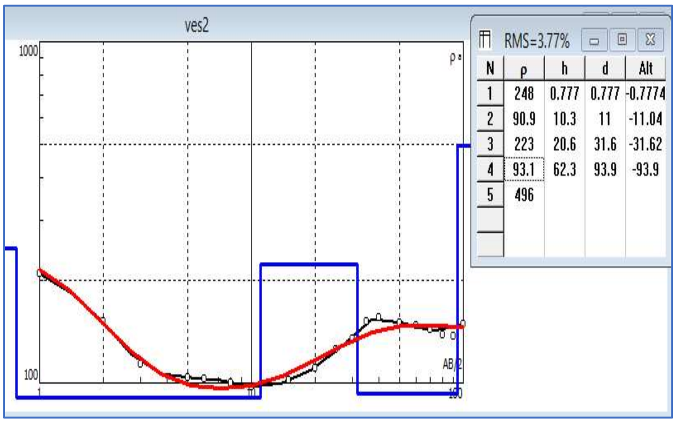
RAINFALL DATA OF STUDY AREA (2004−2018)

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
2004	0.00	2.20	2.40	22.80	68.20	262.20	93.40	163.90	268.00	9.00	0.00	0.00	892.1
2005	0.00	0.00	18.00	45.00	139.00	121.80	138.70	44.50	176.40	60.80	0.00	0.00	744.2
2006	0.00	0.00	59.40	163.20	57.20	97.80	180.80	182.70	144.50	176.70	6.50	0.00	1 068.8
2007	0.00	14.00	12.40	93.90	124.54	360.70	123.20	130.90	176.20	133.40	46.70	0.00	1 215.94
2008	18.20	33.1	4.00	67.00	260.50	159.20	211.40	145.40	243.50	98.10	31.60	0.00	1 272.0
2009	0.00	5.5	25.50	75.70	187.60	171.00	130.20	93.60	282.60	109.80	10.50	0.00	1 092.0
2010	1.20	16.1	27.50	106.60	163.70	259.60	224.10	88.20	276.20	190.00	0.00	0.00	1 353.2
2011	0.00	7.00	22.00	115.00	306.20	227.70	205.30	189.90	236.20	162.50	0.00	2.50	1 474.3
2012	0.00	0.00	9.50	123.50	35.20	184.10	394.10	329.50	343.60	88.60	3.40	5.20	1 516.7
2013	6.00	0.50	19.60	219.20	112.10	170.60	249.50	226.00	231.00	112.00	47.40	0.00	1 393.9
2014	0.00	6.50	60.90	58.20	112.20	45.10	139.10	123.70	228.30	226.40	2.00	0.00	1 002.4
2015	0.00	19.10	4.80	13.50	169.10	231.80	220.20	294.50	334.60	163.20	0.00	0.00	1 450.8
2016	26.00	0.00	0.60	173.30	205.70	162.80	202.60	168.10	200.8	84.40	0.00	7.20	1 231.5
2017	0.50	39.0	39.80	181.80	81.80	132.90	107.30	17.70	202.50	154.30	0.00	11.40	969.0
2018	6.30	34.20	71.00	321.40	163.80	154.70	82.10	94.90	391.60	259.40	0.00	0.00	1 579.4
MEAN	3.88	11.81	25.16	118.67	145.78	182.8	180.13	152.9	249.06	135.24	9.87	1.75	1 217.08

Source: Lower Niger River Basin Development Authority, Ilorin, Kwara State, Nigeria.

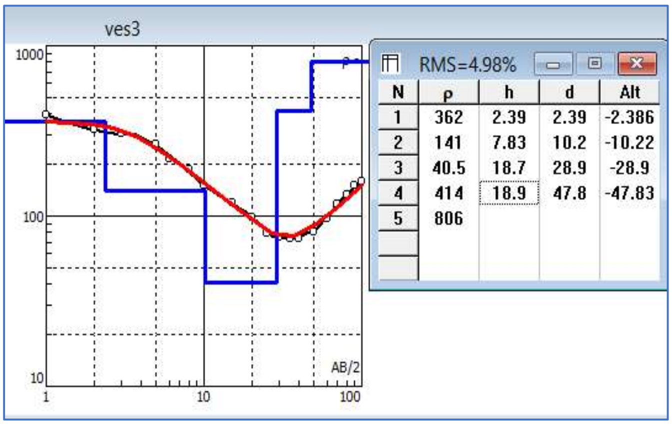
Appendix B

GEOELECTRIC CURVES OF THE PROCESSED VERTICAL ELECTRICAL SOUNDINGS (VES) DATA



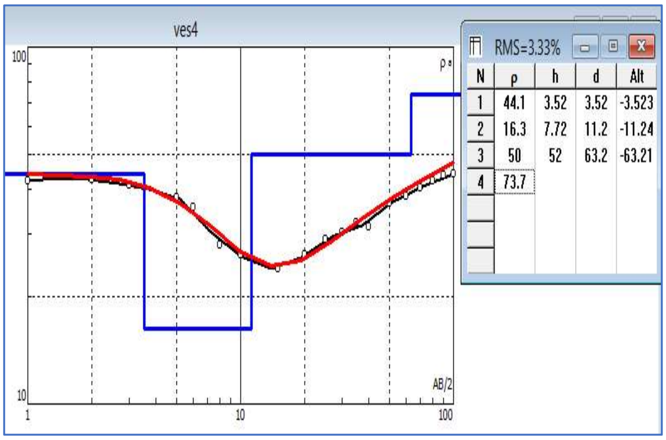
RMS=3.77%

N	ρ	h	d	Alt
1	248	0.777	0.777	-0.7774
2	90.9	10.3	11	-11.04
3	223	20.6	31.6	-31.62
4	93.1	62.3	93.9	-93.9
5	496			



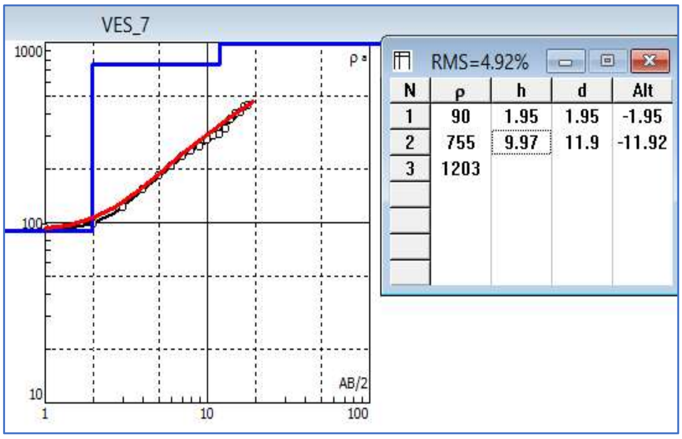
RMS=4.98%

N	ρ	h	d	Alt
1	362	2.39	2.39	-2.386
2	141	7.83	10.2	-10.22
3	40.5	18.7	28.9	-28.9
4	414	18.9	47.8	-47.83
5	806			



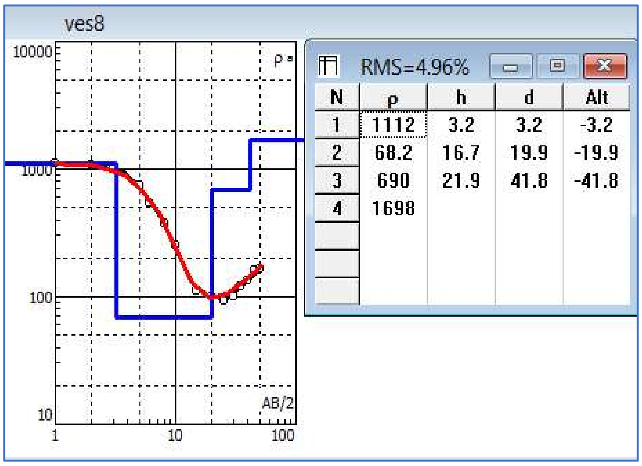
RMS=3.33%

N	ρ	h	d	Alt
1	44.1	3.52	3.52	-3.523
2	16.3	7.72	11.2	-11.24
3	50	52	63.2	-63.21
4	73.7			



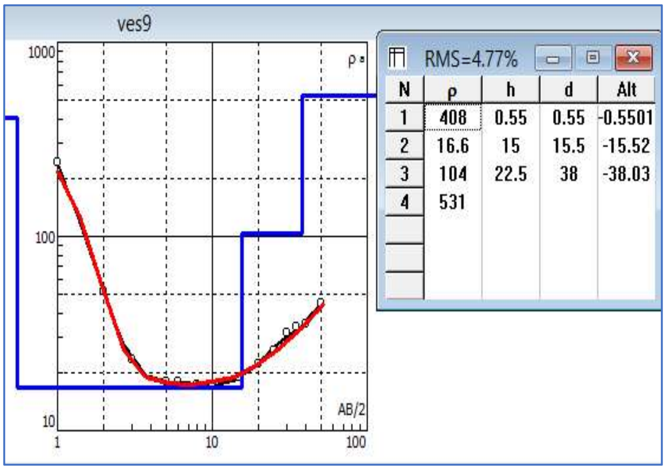
RMS=4.92%

N	ρ	h	d	Alt
1	90	1.95	1.95	-1.95
2	755	9.97	11.9	-11.92
3	1203			



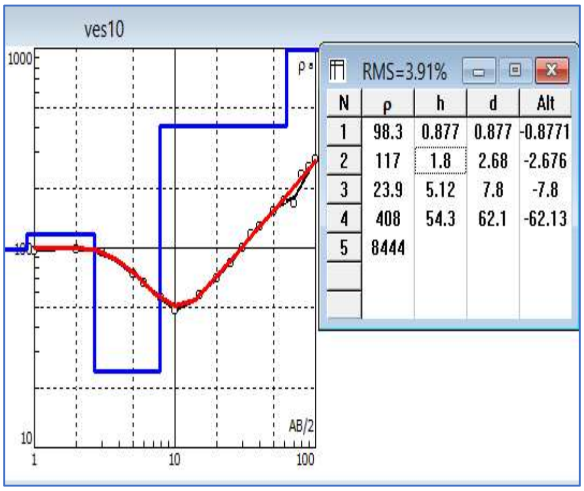
RMS=4.96%

N	ρ	h	d	Alt
1	1112	3.2	3.2	-3.2
2	68.2	16.7	19.9	-19.9
3	690	21.9	41.8	-41.8
4	1698			



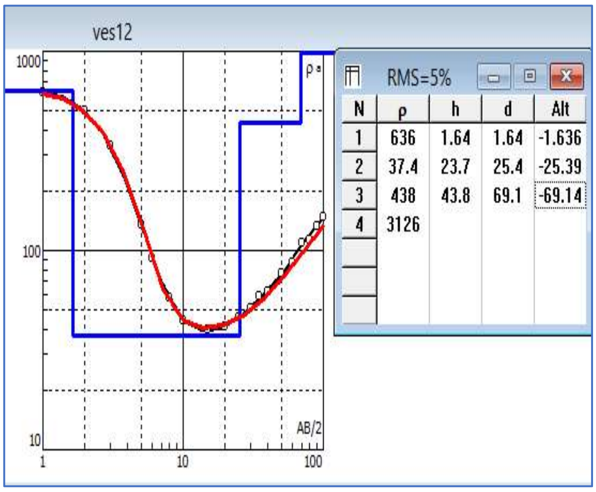
RMS=4.77%

N	ρ	h	d	Alt
1	408	0.55	0.55	-0.5501
2	16.6	15	15.5	-15.52
3	104	22.5	38	-38.03
4	531			



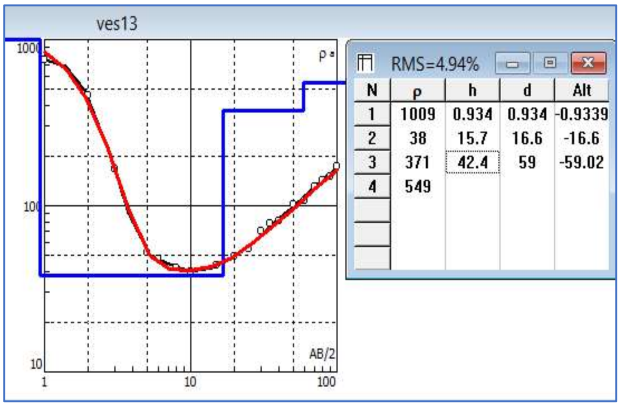
RMS=3.91%

N	ρ	h	d	Alt
1	98.3	0.877	0.877	-0.8771
2	117	1.8	2.68	-2.676
3	23.9	5.12	7.8	-7.8
4	408	54.3	62.1	-62.13
5	8444			



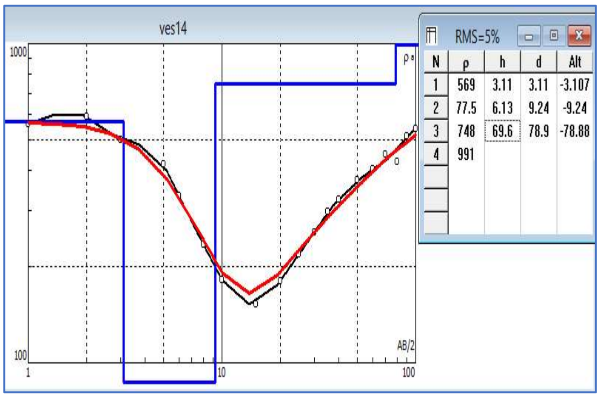
RMS=5%

N	ρ	h	d	Alt
1	636	1.64	1.64	-1.636
2	37.4	23.7	25.4	-25.39
3	438	43.8	69.1	-69.14
4	3126			



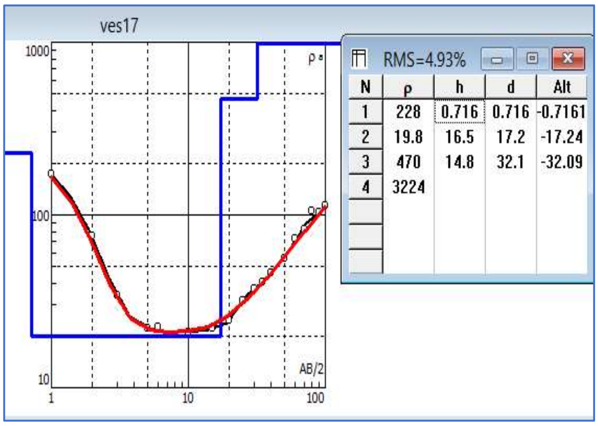
RMS=4.94%

N	ρ	h	d	Alt
1	1009	0.934	0.934	-0.9339
2	38	15.7	16.6	-16.6
3	371	42.4	59	-59.02
4	549			



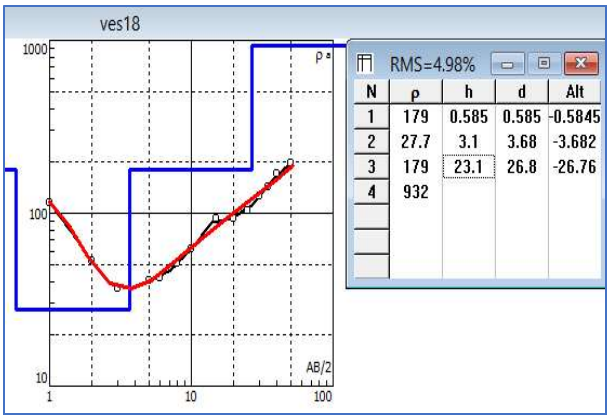
RMS=5%

N	ρ	h	d	Alt
1	569	3.11	3.11	-3.107
2	77.5	6.13	9.24	-9.24
3	748	69.6	78.9	-78.88
4	991			



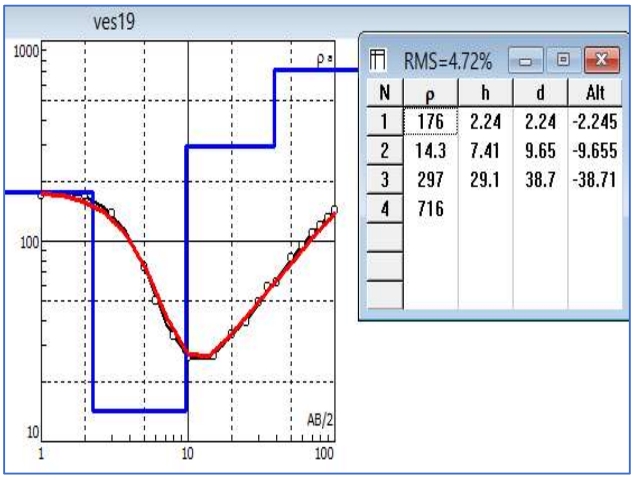
RMS=4.93%

N	ρ	h	d	Alt
1	228	0.716	0.716	-0.7161
2	19.8	16.5	17.2	-17.24
3	470	14.8	32.1	-32.09
4	3224			



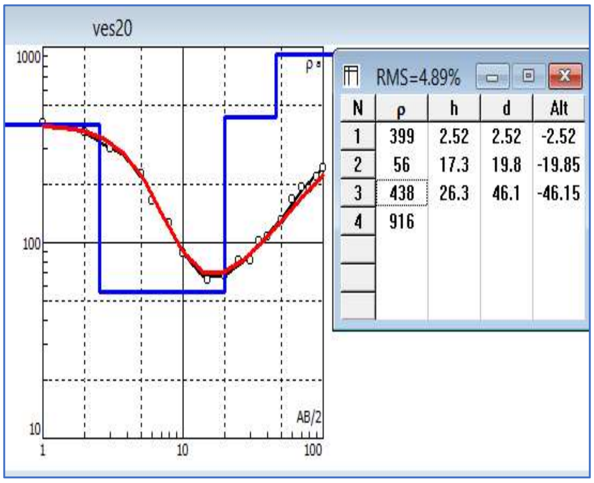
RMS=4.98%

N	ρ	h	d	Alt
1	179	0.585	0.585	-0.5845
2	27.7	3.1	3.68	-3.682
3	179	23.1	26.8	-26.76
4	932			



RMS=4.72%

N	ρ	h	d	Alt
1	176	2.24	2.24	-2.245
2	14.3	7.41	9.65	-9.655
3	297	29.1	38.7	-38.71
4	716			



RMS=4.89%

N	ρ	h	d	Alt
1	399	2.52	2.52	-2.52
2	56	17.3	19.8	-19.85
3	438	26.3	46.1	-46.15
4	916			

Appendix C
PHYSICAL PARAMETERS OF WATER SAMPLES FROM STUDY AREA (DRY SEASON)

Sample Location	Depth (m)	pH	EC (µS/cm)	Temp. (ºC)	TDS (mg/l)	TH (mg/l)	Turbidity
W7	8.7	7.0	253	24.1	102	8.1	2.1
W3	8.2	7.6	164	23.6	121	12.3	2.4
W20	8.9	7.4	318	24.2	98	11.2	2.3
W1	7.6	6.8	224	25.1	176	13.3	2.9
W11	8.1	6.8	106	28.6	142	9.2	2.1
W14	7.4	7.1	132	23.2	152	14.3	2.4
W6	9.2	6.9	124	25.3	148	12.3	2.2
W17	8.3	7.4	118	24.0	106	8.4	2.3
W5	8.7	6.7	163	27.2	132	15.2	3.0
W2	7.5	7.0	224	26.4	138	16.4	2.4
W16	10.2	7.0	298	25.1	96	9.6	2.3
W8	8.6	7.2	314	25.0	114	12.5	2.1
W10	7.6	6.7	231	25.3	168	18.6	2.2
W13	7.8	7.1	254	26.9	123	8.4	2.0
W15	9.6	7.0	217	27.1	115	9.1	2.5
W9	8.4	7.3	208	24.3	109	8.7	2.0
W12	6.8	7.2	193	25.6	128	7.2	2.0
W19	8.6	7.0	218	24.3	136	10.1	2.3
W4	8.9	6.9	151	26.0	106	8.4	2.1
W18	7.8	7.2	273	27.0	121	8.9	2.3

Appendix D
PHYSICAL PARAMETERS OF WATER SAMPLES FROM STUDY AREA (WET SEASON)

Sample Location	Depth (m)	pH	EC (µS/cm)	Temp. (ºC)	TDS (mg/l)	TH (mg/l)	Turbidity
W7	8.7	6.8	272	24.3	116	10.2	2.4
W3	8.2	7.2	182	24.1	132	16.0	2.6
W20	8.9	7.0	379	23.7	114	14.0	2.7
W1	7.6	6.7	236	26.0	169	18.4	3.1
W11	8.1	6.6	119	27.8	112	11.5	2.3
W14	7.4	7.2	154	24.7	176	15.6	2.6
W6	9.2	6.7	132	24.0	133	13.6	2.5
W17	8.3	7.2	130	24.3	118	9.0	2.4
W5	8.7	7.0	125	26.1	156	18.1	3.2
W2	7.5	6.8	239	25.2	145	17.0	2.8
W16	10.2	6.6	314	26.0	107	10.0	2.6
W8	8.6	7.0	327	26.3	124	14.1	2.1
W10	7.6	6.6	246	24.6	186	22.4	2.6
W13	7.8	6.9	273	24.4	117	9.2	2.1
W15	9.6	6.6	236	26.4	129	11.2	2.8
W9	8.4	7.1	220	25.1	121	10.9	2.2
W12	6.8	7.0	206	24.2	111	8.4	2.0
W19	8.6	6.7	232	26.2	125	10.3	2.4
W4	8.9	6.8	162	24.1	122	10.1	2.4
W18	7.8	7.0	298	25.3	132	11.4	2.5

Appendix E
CHEMICAL PARAMETERS OF THE WATER SAMPLE (mg/l) FROM THE STUDY AREA (DRY SEASON)

Sample Location	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	NO_3^{-}	Fe^{2+}
W7	5.4	6.3	8.4	7.3	13.8	34.6	14.3	2.8	0.3
W3	2.6	1.6	6.7	8.8	6.6	28.2	18.4	1.8	0.5
W20	3.4	3.6	5.4	6.2	10.4	27.6	24.6	2.9	0.6
W1	1.5	2.4	2.4	6.9	11.4	13.7	12.4	1.5	0.2
W11	1.0	2.1	3.2	6.1	9.2	26.6	28.3	2.2	0.2
W14	2.2	2.2	3.6	6.8	8.3	18.4	15.2	3.1	0.4
W6	2.0	1.9	4.9	7.4	8.4	32.1	16.4	2.9	0.3
W17	1.8	2.1	2.8	6.7	8.1	13.2	23.6	2.2	0.1
W5	2.1	2.8	3.4	6.6	8.5	80.7	24.1	2.8	0.2
W2	2.4	2.9	3.6	5.9	10.2	42.6	26.6	2.1	0.1
W16	3.3	4.5	6.1	9.3	11.4	12.5	22.7	3.3	0.3
W8	2.1	3.2	3.8	9.6	10.4	27.3	24.8	2.2	0.1
W10	3.6	4.7	3.1	10.4	9.4	44.2	23.3	3.4	0.8
W13	4.3	3.2	6.3	10.6	11.2	84.9	26.1	2.7	0.4
W15	3.4	4.8	6.9	9.6	13.4	37.5	15.4	4.1	0.1
W9	3.8	2.6	2.8	10.8	12.3	26.3	23.8	3.4	0.3
W12	3.6	5.1	3.9	6.2	11.6	42.6	21.4	3.1	0.3
W19	4.1	3.3	3.6	10.6	12.8	54.2	22.9	3.4	0.8
W4	2.1	1.6	3.3	9.4	8.2	17.4	26.4	2.6	0.5
W18	3.6	3.4	6.4	10.8	8.8	33.7	25.3	2.8	0.4

Appendix F
CHEMICAL PARAMETERS OF THE WATER SAMPLE (mg/l) FROM THE STUDY AREA (WET SEASON)

Sample Location	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	NO_3^{-}	Fe^{2+}
W7	10.8	9.4	6.5	6.9	9.8	54.0	18.1	1.6	0.2
W3	5.8	2.2	4.3	8.1	4.2	43.2	14.9	0.8	0.1
W20	7.9	6.1	5.1	7.4	6.4	39.3	20.5	1.7	0.3
W1	3.6	2.8	2.6	6.8	7.2	18.1	7.6	0.4	0.3
W11	2.2	2.3	2.1	5.6	5.2	32.4	22.4	1.3	0.1
W14	3.0	2.6	3.2	7.4	6.3	22.3	19.8	2.1	0.3
W6	3.2	2.4	4.1	6.9	4.6	38.0	18.6	1.8	0.1
W17	3.5	2.7	3.6	6.4	5.1	16.8	17.9	1.7	0.1
W5	2.8	3.3	2.3	6.3	6.2	108.2	18.2	2.3	0.3
W2	4.0	4.1	3.3	6.8	4.3	60.0	19.0	0.9	0.1
W16	6.9	8.2	5.2	10.6	7.3	18.4	18.8	2.4	0.2
W8	5.2	5.1	3.1	9.2	6.2	33.2	20.0	1.8	0.1
W10	6.8	6.3	4.4	10.1	4.3	54.6	22.4	2.6	0.3
W13	7.5	4.9	5.4	10.4	7.1	101.3	19.3	2.4	0.1
W15	8.4	7.2	6.2	9.4	8.1	46.5	17.8	2.9	0.1
W9	9.5	3.0	2.1	8.5	6.2	33.1	20.4	2.7	0.2
W12	6.9	7.1	4.3	7.2	6.5	51.7	17.8	2.6	0.1
W19	6.8	4.7	3.4	9.6	6.2	61.4	20.4	2.8	0.2
W4	3.2	2.4	2.2	8.4	4.3	23.6	19.7	2.0	0.2
W18	4.8	6.4	5.1	10.6	4.2	42.3	22.6	2.2	0.2

Appendix G
SUMMARY OF PHYSICOCHEMICAL PARAMETERS OF WATER SAMPLES FOR DRY AND WET SEASONS

Parameters	Season 1 (Dry Season)				Season 2 (Wet Season)				
	Min values	Max values	Mean value	SD	Min values	Max values	Mean value	SD	WHO (2011)
pH	6.7	7.6	7.1	0.2	6.6	7.2	6.9	0.2	6.5–8.5
EC (µS/cm)	106	318	209.2	64.8	119	379	226.6	70.9	1 200
Temp. (°C)	23.2	28.6	25.4	1.4	23.7	27.8	25.1	1.1	28
TDS (mg/l)	96	176	126.6	22.5	107	176	132.3	22.7	1 500
TH (mg/l)	7.2	18.6	11.1	3.2	8.4	22.4	13.1	3.8	500
Turbidity	2.0	3.0	2.3	0.3	2.0	3.2	2.5	0.3	5.0
Ca^{2+} (mg/l)	1.0	5.4	2.9	1.1	2.2	10.8	5.6	2.5	–
Mg^{2+}(mg/l)	1.6	6.3	3.2	1.3	2.2	9.4	4.7	2.2	20
Na^{+} (mg/l)	2.4	8.4	4.5	1.7	4.4	6.5	3.9	1.4	200
K^{+} (mg/l)	5.9	10.8	8.3	1.8	5.6	10.6	8.1	1.6	–
$C\ell^{-}$ (mg/l)	6.6	13.8	10.2	2.0	4.2	9.8	6.0	1.5	250
$HC0_3$(mg/l)	12.5	84.9	34.9	19.9	16.8	108.2	44.0	25.0	–
$S0_4^{-}$ (mg/l)	12.4	28.3	21.8	4.7	7.6	22.6	19.0	3.2	250
$N0_3$ (mg/l)	1.5	4.1	2.8	0.6	0.4	2.9	2.0	0.7	50
Fe^{2+} (mg/l)	0.1	0.8	0.4	0.2	0.1	0.3	0.2	0.08	3.0

Appendix H
SATURATION INDICES FOR WATER SAMPLES (WET SEASON)

Sample No.	SI (Anhydrite) ($CaS0_4$)	SI (Aragonite) ($CaC0_3$)	SI (Calcite) ($CaCO_3$)	SI (Dolomite) ($CaMg(CO_3)_2$	SI (Gypsum) ($CaSO_4{:}2H_2O$)	SI (Halite) (NaCl)
W7	–0.57	0.99	1.14	2.33	–0.27	–5.99
W3	–0.78	0.68	0.82	1.32	–0.47	–6.51
W20	–0.60	0.73	0.87	1.73	–0.29	–6.27
W1	–1.10	0.24	0.38	0.76	–0.79	–6.46
W11	–1.05	0.08	0.22	0.55	–0.75	–6.74
W14	–0.93	0.09	0.23	0.49	–0.63	–6.46
W6	–0.95	0.03	0.48	0.93	–0.63	–6.50
W17	–0.87	0.06	0.21	0.39	–0.57	–6.50
W5	–1.15	0.63	0.78	1.74	–0.85	–6.66
W2	–0.91	0.59	0.74	1.59	–0.61	–6.64
W16	–0.65	0.39	0.54	1.25	–0.35	–6.19
W8	–0.74	0.49	0.63	1.35	–0.44	–6.49
W10	–0.66	0.77	0.91	1.89	–0.36	–6.52
W13	–0.73	1.03	1.18	2.28	–0.43	–6.23
W15	–0.64	0.84	0.98	2.00	–0.34	–6.08
W9	–0.49	0.74	0.89	1.37	–0.19	–6.66
W12	–0.72	0.79	0.93	1.99	–0.42	–6.34
W19	–0.68	0.82	0.97	1.88	–0.38	–6.47
W4	–0.90	0.14	0.28	0.54	–0.60	–6.79
W18	–0.77	0.52	0.67	1.56	–0.47	–6.46

Appendix I

SATURATION INDICES FOR WATER SAMPLES (DRY SEASON)

Sample No.	SI (Anhydrite) ($CaS0_4$)	SI Aragonite) ($CaC0_3$)	SI (Calcite) ($CaCO_3$)	SI (Dolomite) ($CaMg(CO_3)_2$	SI (Gypsum) ($CaSO_4{:}2H_2O$)	SI (Halite) (NaCl)
W7	–0.85	0.56	0.71	1.59	–0.55	–5.71
W3	–1.02	0.13	0.27	0.43	–0.71	–6.12
W20	–0.86	0.19	0.33	0.77	–0.56	–6.04
W1	–1.30	–0.33	–0.18	–0.06	–1.00	–6.30
W11	–1.34	–0.40	–0.25	–0.10	–1.04	–6.33
W14	–1.11	–0.08	0.07	0.23	–0.80	–6.28
W6	–1.16	0.08	0.23	0 .53	–0.86	–6.15
W17	–1.09	–0.39	–0.24	–0.33	–0.79	–6.42
W5	–1.15	0.37	0.53	1.26	–0.85	–6.35
W2	–1.01	0.18	0.33	0.83	–0.71	–6.23
W16	–0.87	–0.13	0.01	0.25	–0.56	–5.93
W8	–1.06	–0.03	0.11	0.49	–0.75	–6.19
W10	–0.88	0.40	0.55	1.31	–0.58	–6.33
W13	–0.85	0.69	0.83	1.64	–0.55	–5.97
W15	–1.01	0.38	0.53	1.31	–0.70	–5.81
W9	–0.81	0.22	0.36	0.65	–0.51	–6.25
W12	–0.90	0.40	0.55	1.35	–0.60	–6.13
W19	–0.85	0.53	0.68	1.36	–0.54	–6.13
W4	–1.01	–0.23	–0.09	–0.21	–0.71	–6.35
W18	–0.84	0.28	0.43	0.92	–0.54	–6.04

Appendix J

CALCULATED RECOVERY DRAWDOWN, y (m) IN UNSCREENED CONCRETE-LINED LARGE-DIAMETER HAND-DUG WELLS

Time (min)	**y (m) Well 1**	**y (m) Well 2**	**y (m) Well 3**	**y (m) Well 4**	**y (m) Well (5)**	**y (m) Well 6**
0	0.342	0.260	0.194	0.310	0.338	0.408
10	0.274	0.212	0.160	0.264	0.280	0.348
20	0.212	0.176	0.130	0.232	0.232	0.298
30	0.156	0.136	0.092	0.188	0.186	0.246
40	0.090	0.102	0.064	0.148	0.154	0.198
50	0.034	0.064	0.032	0.112	0.126	0.152
60	–	0.026	–	0.078	0.098	0.108
70	–	–	–	–	–	0.058

Time (min)	**y (m) Well 7**	**y (m) Well 8**	**y (m) Well 9**	**y (m) Well 10**	**y (m) Well 11**	**y (m) Well 12**
0	0.266	0.302	0.380	0.284	0.264	0.348
10	0.218	0.246	0.322	0.236	0.218	0.302
20	0.178	0.196	0.266	0.184	0.176	0.256
30	0.140	0.146	0.220	0.138	0.134	0.216
40	0.098	0.098	0.176	0.092	0.090	0.170
50	0.054	0.052	0.122	0.046	0.048	0.126
60	0.022	–	0.076	–	–	0.086
70	–	–	0.028	–	–	0.046

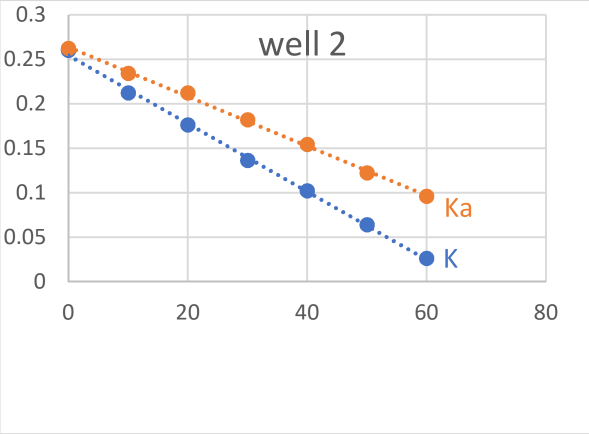
Appendix K
CALCULATED RECOVERY DRAWDOWN, y (m) IN SCREENED CONCRETE–LINED LARGE-DIAMETER HAND-DUG WELLS

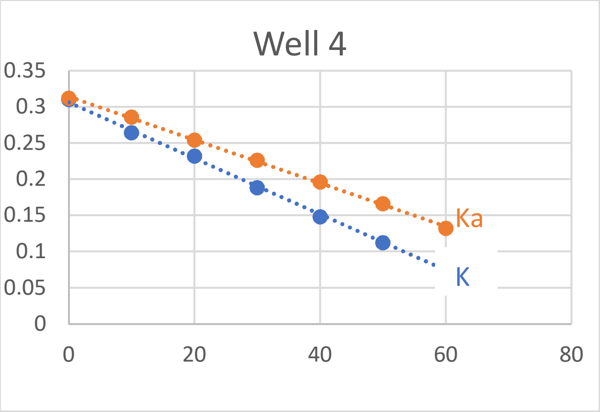
Time (min)	y (m) Well 1	y (m) Well 2	y (m) Well 3	y (m) Well 4	y (m) Well (5)	y (m) Well 6
0	0.344	0.262	0.196	0.312	0.340	0.412
10	0.302	0.234	0.176	0.286	0.306	0.374
20	0.266	0.212	0.156	0.254	0.266	0.338
30	0.224	0.182	0.134	0.226	0.224	0.298
40	0.186	0.154	0.112	0.196	0.184	0.258
50	0.136	0.122	0.086	0.166	0.156	0.218
60	–	0.096	–	0.132	0.128	0.188
70	–	–	–	–	–	0.146

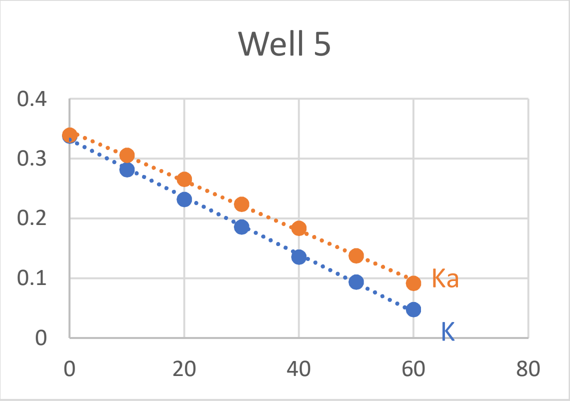
Time (min)	y (m) Well 7	y (m) Well 8	y (m) Well 9	y (m) Well 10	y (m) Well 11	y (m) Well 12
0	0.268	0.306	0.384	0.286	0.268	0.352
10	0.236	0.270	0.354	0.260	0.234	0.324
20	0.200	0.228	0.312	0.224	0.198	0.288
30	0.172	0.188	0.272	0.188	0.166	0.244
40	0.148	0.146	0.232	0.154	0.132	0.208
50	0.128	0.108	0.188	0.126	0.092	0.174
60	0.098	–	0.142	–	–	0.136
70	–	–	0.098	–	–	0.097

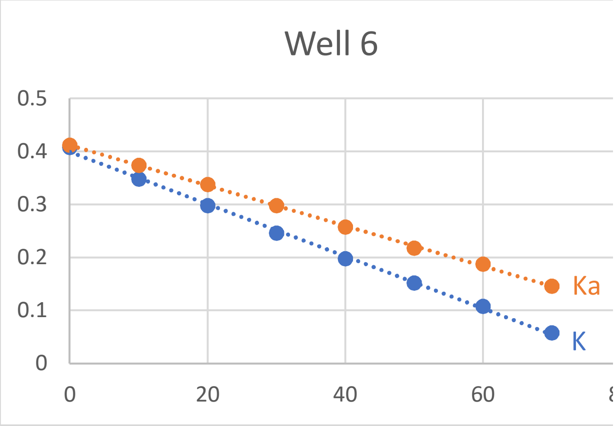
Appendix L

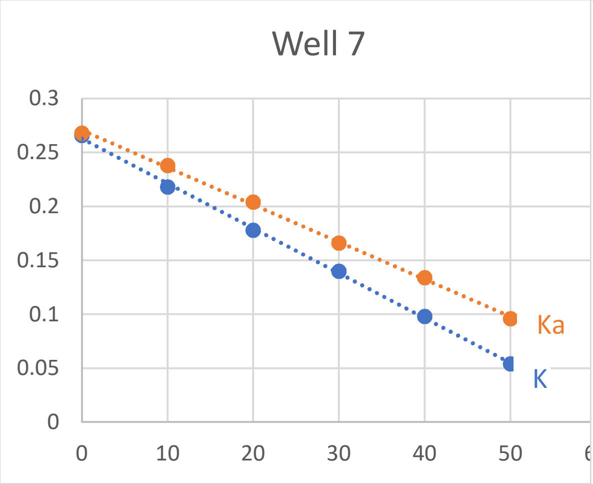
DIRECT LINEAR GRAPH OF RECOVERY DRAWDOWN AGAINST TIME FOR UNSCREENED CONCRETE-LINED AND SCREENED CONCRETE-LINED LARGE-DIAMETER HAND-DUG WELLS

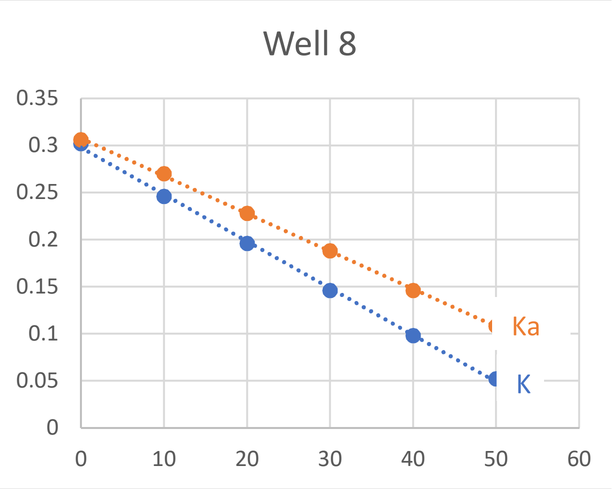


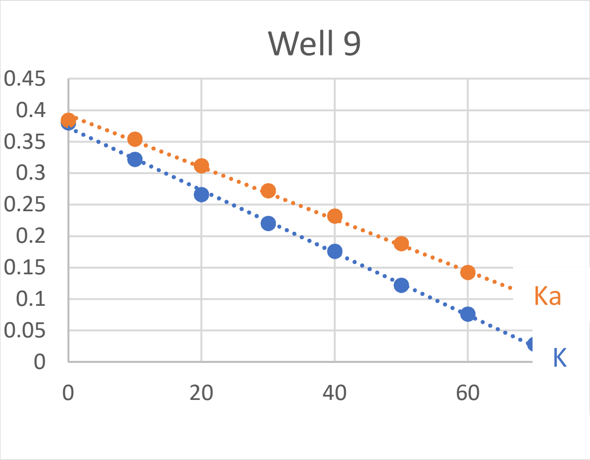


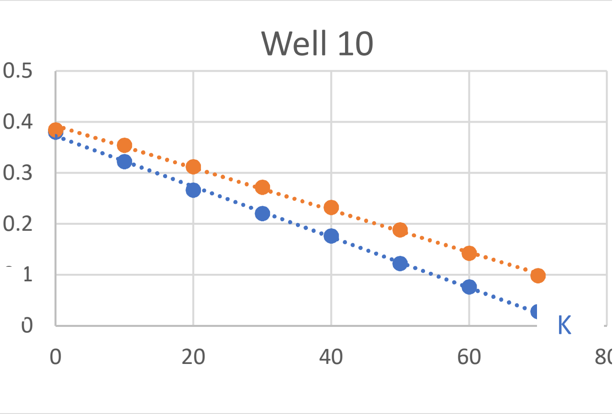


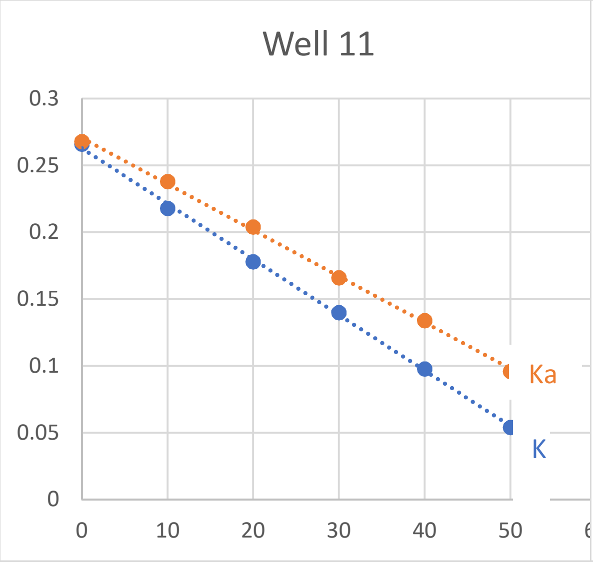


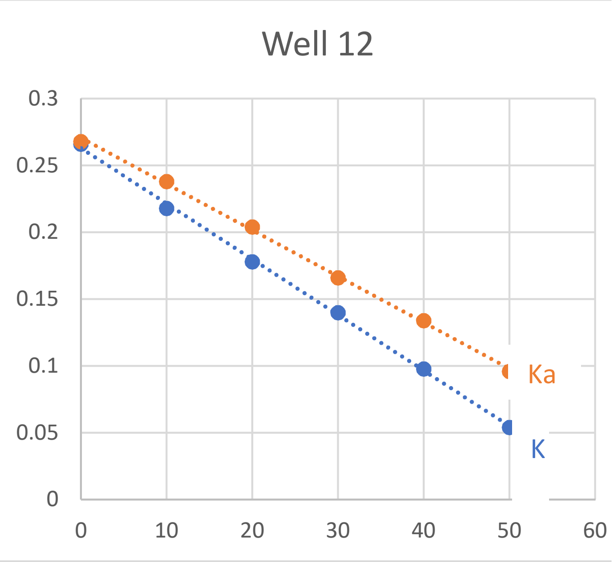

Well 7
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
6
Ka
K


Well 8
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
Ka
K


Well 9
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
Ka
K

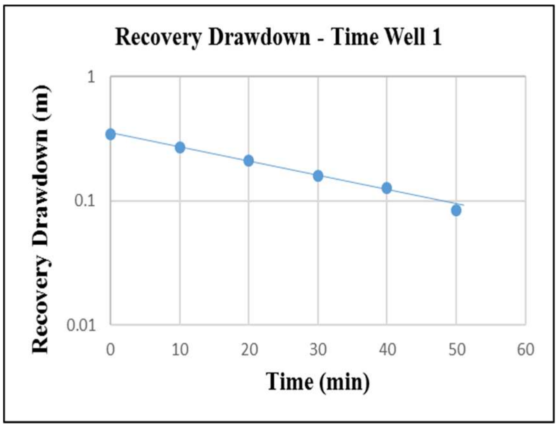

Well 10
0.5
0.4
0.3
0.2
1
0
0
20
40
60
8
K

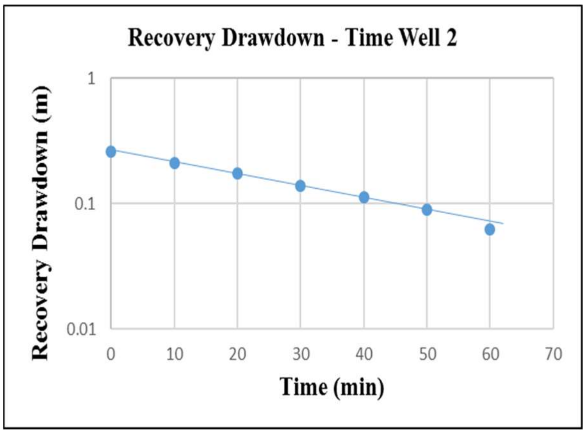

Well 11
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
6
Ka
K

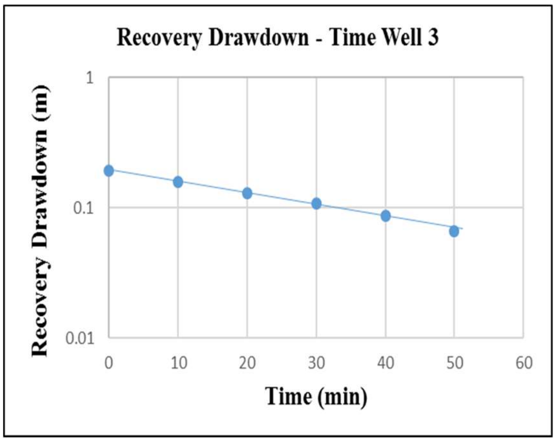

Well 12
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
Ka
K

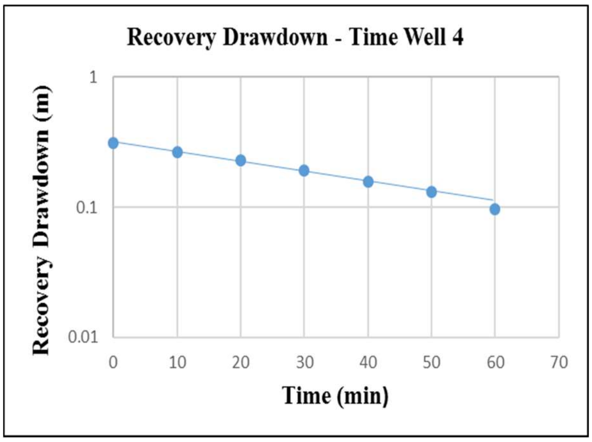
Appendix M

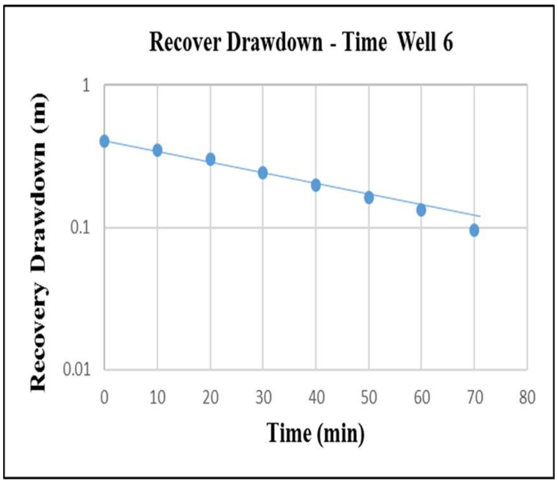
SEMI-LOG PLOTS OF RECOVERY DRAWDOWN (m) AGAINST TIME (min) FOR UNSCREENED CONCRETE-LINED LARGE-DIAMETER HAND-DUG WELLS

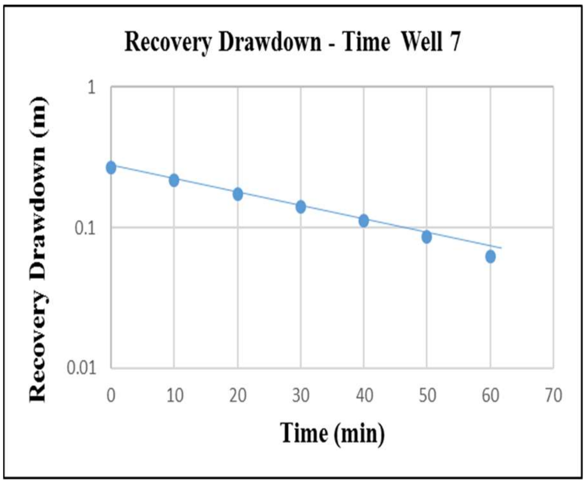


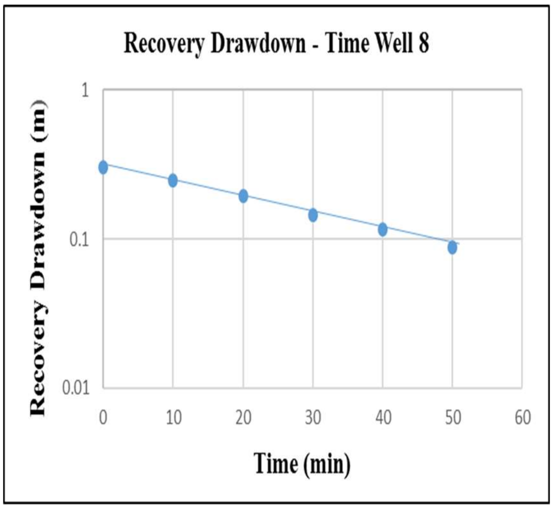


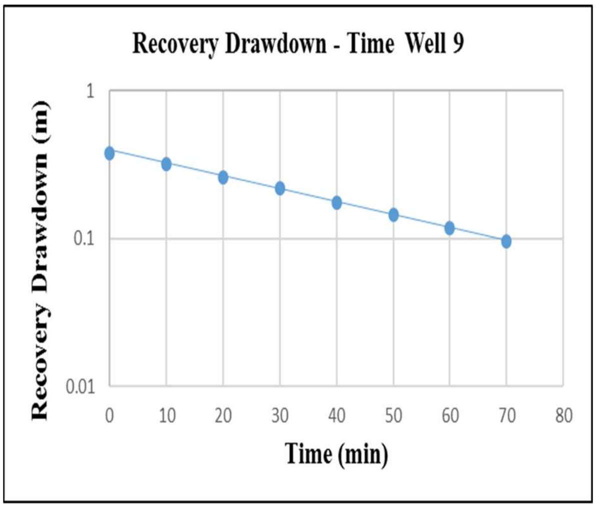


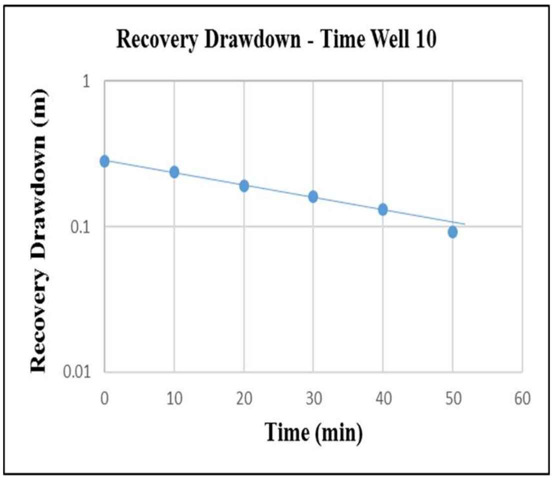


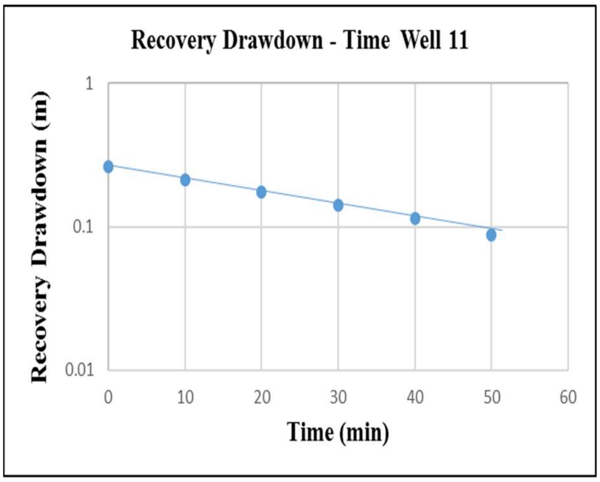


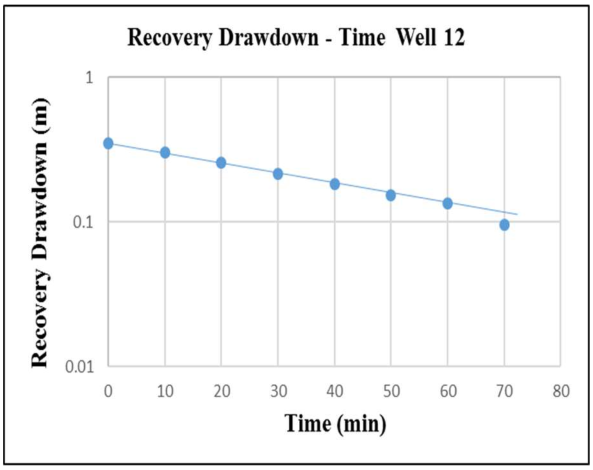



Recovery Drawdown - Time Well 8
Recovery Drawdown (m)
1
0.1
0.01
0
10
20
30
40
50
60
Time (min)


Recovery Drawdown - Time Well 9
Recovery Drawdown (m)
1
0.1
0.01
0
10
20
30
40
50
60
70
80
Time (min)

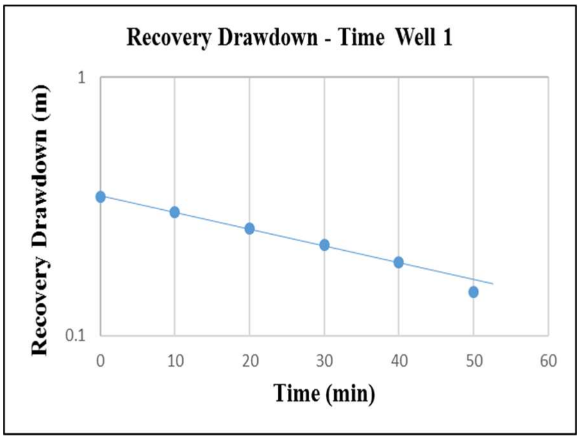

Recovery Drawdown - Time Well 10
Recovery Drawdown (m)
1
0.1
0.01
0
10
20
30
40
50
60
Time (min)

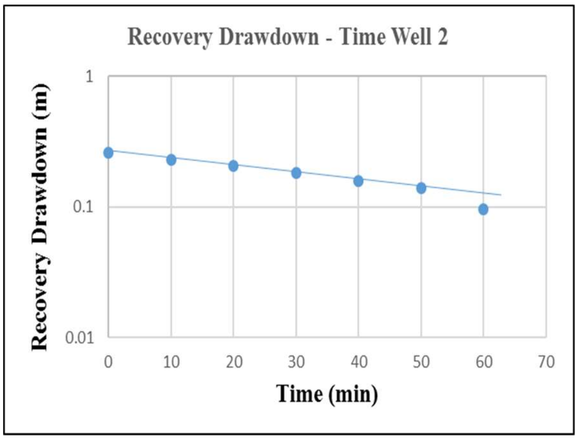

Recovery Drawdown - Time Well 11
Recovery Drawdown (m)
1
0.1
0.01
0
10
20
30
40
50
60
Time (min)

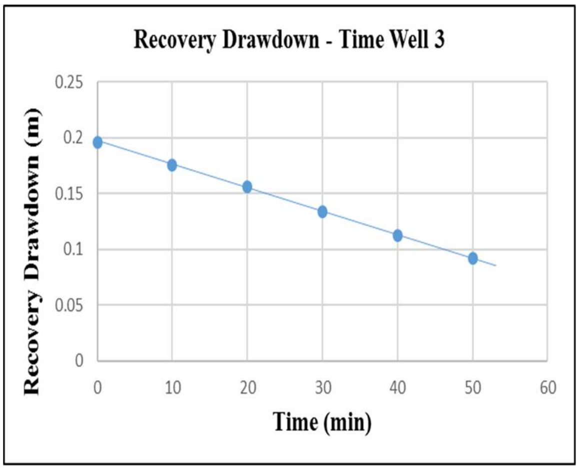

Recovery Drawdown - Time Well 12
Recovery Drawdown (m)
1
0.1
0.01
0
10
20
30
40
50
60
70
80
Time (min)

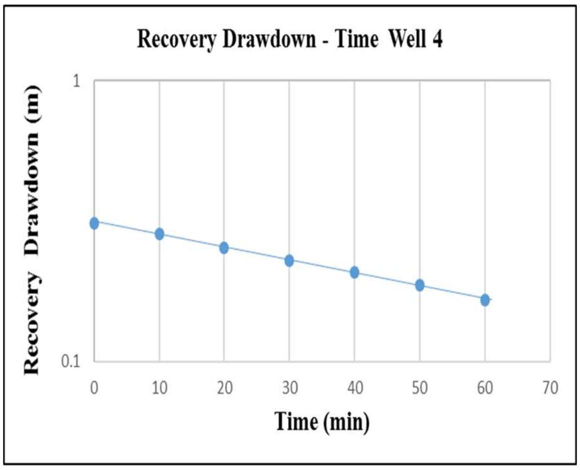
Appendix N

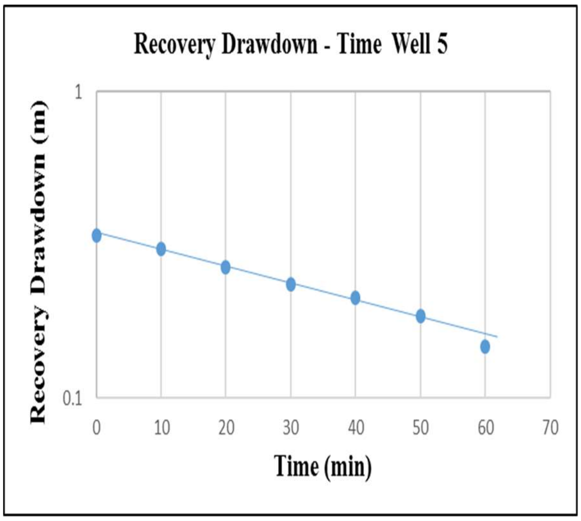
SEMI–LOG PLOTS OF RECOVERY DRAWDOWN (m) AGAINST TIME (min) FOR SCREENED CONCRETE–LINED LARGE–DIAMETER HAND–DUG WELLS

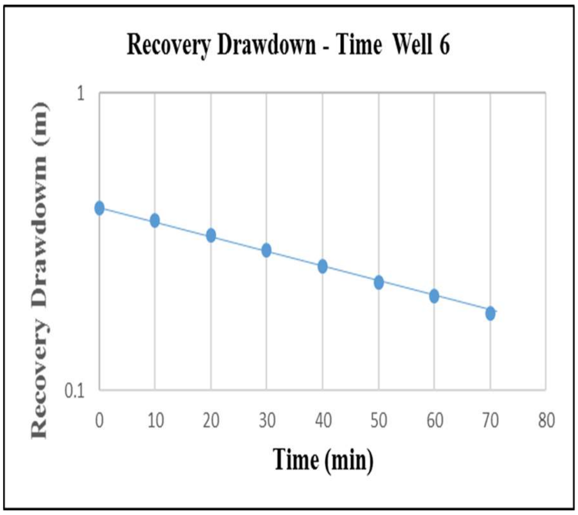


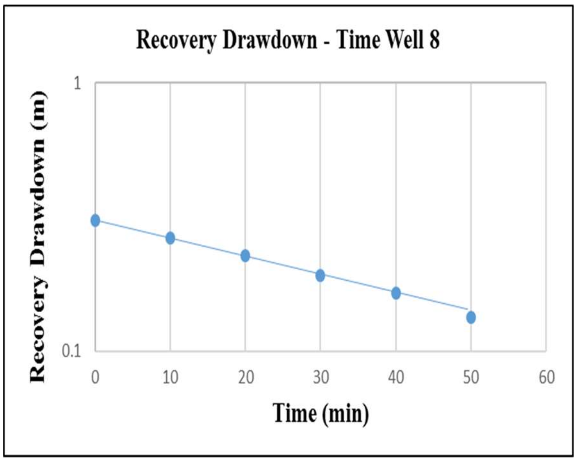


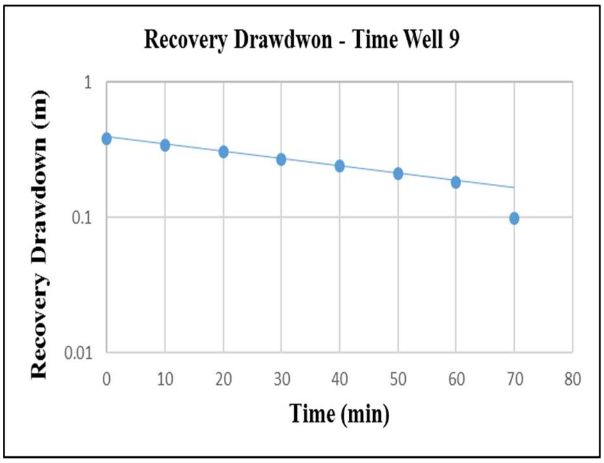


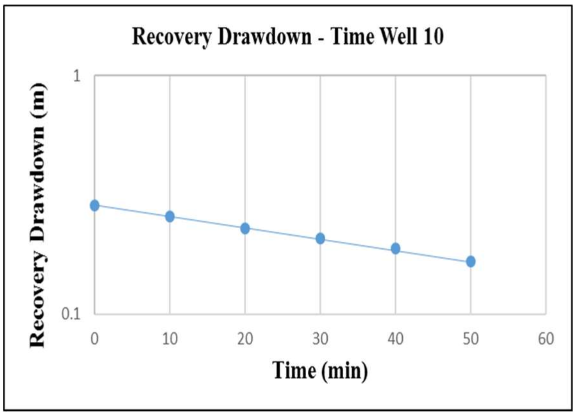


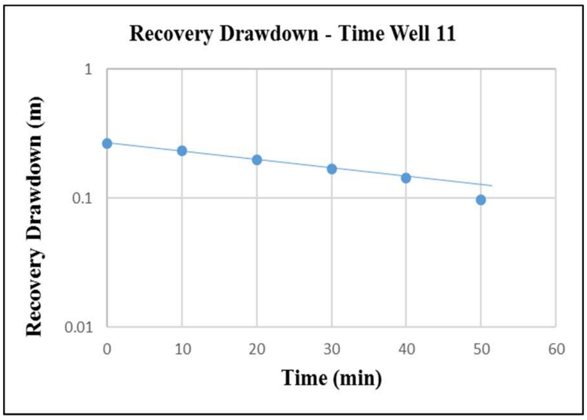

Recovery Drawdown - Time Well 5
Recovery Drawdown (m)
1
0.1
0
10
20
30
40
50
60
70
Time (min)

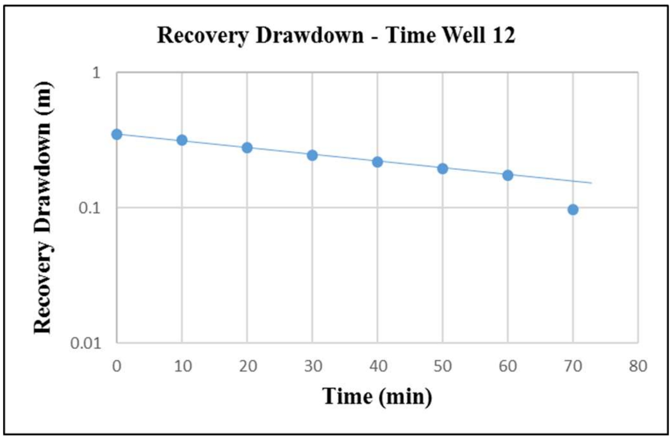

Recovery Drawdown - Time Well 6
Recovery Drawdown (m)
1
0.1
0
10
20
30
40
50
60
70
80
Time (min)


Recovery Drawdown - Time Well 8
Recovery Drawdown (m)
1
0.1
0
10
20
30
40
50
60
Time (min)


Recovery Drawdwon - Time Well 9
Recovery Drawdown (m)
1
0.1
0.01
0
10
20
30
40
50
60
70
80
Time (min)


Recovery Drawdown - Time Well 10
Recovery Drawdown (m)
1
0.1
0
10
20
30
40
50
60
Time (min)


Recovery Drawdown - Time Well 11
Recovery Drawdown (m)
1
0.1
0.01
0
10
20
30
40
50
60
Time (min)


Recovery Drawdown - Time Well 12
Recovery Drawdown (m)
1
0.1
0.01
0
10
20
30
40
50
60
70
80
Time (min)

Appendix O

CALCULATED ln(R_e/r_w) FOR UNSCREENED CONCRETE–LINED LARGE–DIAMETER HAND–DUG WELLS

Well	A	r	d	a/r	(a/r)^2	λ(a/r)^2	ln(λ(a/r)^2)	((d-a)/d)	((d-a)/d)^1/2)	(a/r)^(-(5/8))	C1+C2 (ln(λ(a/r)^2))	1+C3(((d-a)/d)^1/2)* (a/r)^(-(5/8)))	ln(Re/r_w)
1	0.04	0.68	6.3	0.058824	0.00346	0.001419	–6.558024807	0.993651	0.996820342	5.875307153	0.468372815	10.45259385	0.0448
2	0.07	0.75	6.4	0.093333	0.008711	0.003572	–5.634754048	0.989063	0.994516214	4.4027803	0.661336404	8.067119142	0.0819
3	0.04	0.75	6.2	0.053333	0.002844	0.001166	–6.753985624	0.993548	0.996768974	6.246342518	0.427417005	11.04902292	0.0387
4	0.03	0.66	6.2	0.045455	0.002066	0.000847	–7.073683026	0.995161	0.997577711	6.902623339	0.360600248	12.11384775	0.0297
5	0.06	0.72	5.9	0.083333	0.006944	0.002847	–5.861411419	0.989831	0.994902261	4.725940818	0.613965013	8.588784616	0.0715
6	0.06	0.75	6.9	0.08	0.0064	0.002624	–5.943055408	0.991304	0.995642681	4.848068619	0.59690142	8.790687674	0.0817
7	0.05	0.75	6.6	0.066667	0.004444	0.001822	–6.307698521	0.992424	0.99620492	5.433216825	0.520691009	9.735932094	0.0534
8	0.04	0.72	6.8	0.055556	0.003086	0.001265	–6.672341635	0.994118	0.997054486	6.088990769	0.444480598	10.79868367	0.0411
9	0.04	0.73	5.9	0.054795	0.003002	0.001231	–6.699928279	0.99322	0.996604404	6.141709816	0.43871499	10.87906006	0.0403
10	0.09	0.78	5.8	0.115385	0.013314	0.005459	–5.210566618	0.984483	0.992211045	3.856182313	0.749991577	7.175400747	0.1045
11	0.07	0.72	5.9	0.097222	0.009452	0.003875	–5.553110059	0.988136	0.994050096	4.291869767	0.678399998	7.885862356	0.0860
12	0.04	0.75	6.8	0.053333	0.002844	0.001166	–6.753985624	0.994118	0.997054486	6.246342518	0.427417005	11.05190133	0.0536

Appendix P

CALCULATED ln(R_e/r_w) FOR SCREENED CONCRETE-LINED LARGE-DIAMETER HAND-DUG WELLS

Well	d	r_w	B	c	d/r_w	In(d/r_w)	(1.1/ln(d/r_w)	b/r_w	c/(b/r_w)	ln Re/r_w=((1.1/ln(d/r_w))+(c/(b/r_w))^(-1)
1	6.3	0.71	6.3	1.4	8.8732394	2.1830399	0.503884505	8.8732394	0.1577778	1.511345027
2	6.1	0.77	6.1	0.8	7.9220779	2.0696535	0.531489924	7.9220779	0.1009836	1.581093835
3	5.9	0.72	5.9	0.9	8.1944444	2.1034564	0.522948795	8.1944444	0.1098305	1.580329815
4	6.1	0.71	6.1	1	8.5915493	2.1507791	0.511442579	8.5915493	0.1163934	1.59277258
5	5.6	0.75	5.6	0.5	7.4666667	2.0104487	0.547141549	7.4666667	0.0669643	1.628383811
6	6.4	0.77	6.4	1.2	8.3116883	2.1176628	0.519440594	8.3116883	0.144375	1.506442464
7	6.2	0.74	6.2	1.1	8.3783784	2.1256544	0.517487701	8.3783784	0.1312903	1.541359239
8	6.4	0.76	6.4	1.1	8.4210526	2.1307348	0.516253821	8.4210526	0.130625	1.545884589
9	5.4	0.76	5.4	0.4	7.1052632	1.9608358	0.56098527	7.1052632	0.0562963	1.620006258
10	5.5	0.81	5.5	0.2	6.7901235	1.9154691	0.574271851	6.7901235	0.0294545	1.656379455
11	5.5	0.76	5.5	0.5	7.2368421	1.9791849	0.555784343	7.2368421	0.0690909	1.600319419
12	6.2	0.72	6.2	1.3	8.6111111	2.1530534	0.51090234	8.6111111	0.1509677	1.510870527