ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Mohamed Jama HUSSEIN

THE USE OF ELECTRICAL RESISTIVITY METHOD FOR GROUNDWATER EXPLORATION IN SOOL AND GEBILEY REGIONS IN SOMALILAND

DEPARTMENT OF GEOLOGICAL ENGINEERING

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We certify that the thesis titled above was reviewed and approved for the award of the degree of the Master of Science by the board of jury on 31/01/2020.

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ABSTRACT

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In this thesis study, hydrogeological and geophysical studies were conducted to determine the groundwater potential of Somaliland. The aim of the study is to identify suitable aquifer areas for groundwater drilling in selected cities and villages. In this thesis study, groundwater research was conducted in three different regions of Somaliland. Geophysical studies were carried out in Sool Region, Togdheer Region, and Awdal Region. In this thesis study, the Vertical Electrical Sounding method was used in groundwater research. Resistivity measurements were carried out using the Schlumberger electrode opening at 19 VES measurement points in four different regions. AB / 2 expansion has been taken at a maximum of 700 meters in the study area. Using the apparent resistivity values obtained from the study area in the Surfer program were prepared apparent resistivity floor maps of underground for AB / 2 100 m, 150 m, 200 m, and 400 meters. With these maps, lateral and vertical changes in the apparent resistivity values in the study area have been clearly identified. IPI2Win computer program was used to evaluate the VES data obtained from the study area. As a result of the evaluation, it was determined that the real resistivity values of underground layers ranged from a minimum of 0.24 ohms to a maximum of 5574 ohms. It was determined that the thickness of the underground layers varied from a minimum of 0.14 m to a maximum of 342 m. Geoelectric maps of the underground were created using the resistivity values and thickness values obtained. By correlating these geoelectric maps with the geology of the region, areas with suitable groundwater potential in the study area were determined. Areas with groundwater potential are designated as VES 2 in the Godalo region, VES 2 in the Gambadho region, VES 1 in the Qoryale region, and VES 4 in the Magalo'ad region. The maximum drilling depth in the study area was determined as 350 meters. A sufficient amount of groundwater was obtained by drilling afterward at the proposed measurement points. The drinking water requirement of the region was provided.

Key words: Geophysics, Groundwater investigation, Vertical Electrical Sounding, Somaliland

ÖZ

YÜKSEK LİSANS TEZİ

SOMALILAND'TA SOOL VE GEBİLEY BÖLGELERDE YERALTI SUYU ARAMA İÇİN ELEKTRİK ÖZDİRENÇ YÖNTEMİ KULLANIMI.

Mohamed Jama HUSSEIN

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Bu tez çalışmasında Somaliland'ın yeraltı suyu potansiyelini belirlemek için hidrojeolojik ve jeofizik çalışmalar yapılmıştır. Çalışmanın amacı, seçilen şehirlerde ve köylerde yeraltısuyu sondajı için uygun akifer alanlarını tanımlamaktır. Bu tez çalışmasında, Somaliland'in üç farklı bölgesinde yeraltısuyu araştırması yapılmıştır. Jeofizik çalışmalar Sool Bölgesi, Togdheer Bölgesi ve Awdal Bölgesinde gerçekleştirilmiştir. Bu tez çalışmasında yeraltısuyu araştırmasında 'Düşey Elektrik Sondaj (DES)' yöntemi kullanılmıştır. Dört farklı bölgede toplam 19 DES ölçüm noktasında Schlumberger elektrod açılımını kullanarak ölçümler gerçekleştirilmiştir. Çalışma alanında AB/2 açılımı maksimum 700 metre alınmıştır. Surfer programında çalışma alanından elde edilen görünür özdirenç değerleri kullanılarak AB / 2 100 m, 150 m, 200 m ve 400 metre için yeraltının görünür özdirenç kat haritaları hazırlanmıştır. Bu haritalar ile çalışma sahasında görünür özdirenç değerlerindeki yanal ve düşey değişimler net olarak tespit edilmiştir. Çalışma sahasından elde edilen DES verilerini değerlendirmek için IPI2Win bilgisayar programı kullanılmıştır. Değerlendirme sonucunda yeraltındaki tabakaların gerçek özdirenç değerleri minimum 0.24 ohm-m ile maksimum 5574 ohm-m arasında değiştiği tespit edilmiştir. Yeraltındaki tabakaların kalınlıklarının ise minimum 0.14 m ile maksimum 342 m arasında değiştiği belirlenmiştir. Elde edilen özdirenç değerleri ve kalınlık değerleri kullanılarak yeraltının jeoelektik haritaları oluşturulmuştur. Bu jeoelektrik haritaların bölge jeolojisiyle korele edilmesiyle çalışma sahasında uygun su potansiyelirinin olduğu alanlar belirlenmiştir. Su potansiyelinin olduğu alanlar Godalo bölgesinde DES 2, Gambadho bölgesinde DES 2, Qoryale bölgesinde DES 1 ve Magalo'ad bölgesinde DES 4 ölçüm noktaları olarak belirlenmiştir. Çalışma sahasındaki maksimum sondaj derinliğ 350 metre olarak tespit edilmişitir. Önerilen ölçüm noktalarında daha sonra sondaj yapılarak yeterli miktarda yeraltısuyu elde edilmiştir. Bölgenin içme-suyu ihtiyacı sağlanmıştır.

Anahtar kelimeler: Jeofizik, Yeraltısuyu araştırması, Düşey Elektrik Sondaj, Somaliland

EXTENDED ABSTRACT

Somaliland has been identified as one of the most drought-prone regions in the Horn of Africa. In the country, the rain falls in the form of a downpour and for a short time. The regions with low precipitation in the country have less rainfall density according to areas where the average annual rainfall is relatively higher. Due to the high temperature prevailing in the region, the annual average potential plant water consumption varies between 1800 mm with 2500 mm.

The need for groundwater supply in many parts of Somaliland is known to be extremely severe and this is due to the very low effective annual precipitation as mentioned above. Several deep drilling projects have been carried out in Somaliland, but due to the lack of hydrogeological information, the success rate of groundwater development or the drilling of successful wells has been very low. At the same time, it has been discovered that the groundwater is not in the areas where the Taleex Gypsum Formation is located and that it is salty in areas where other evaporitic geological units are located.

The general purpose of this thesis covers the determination of aquifer areas containing freshwater in areas defined as a high priority.

In this thesis, hydrogeological and geophysical studies were conducted to determine the groundwater potential of Somaliland. The aim of the study is to identify suitable aquifer areas for groundwater drilling in selected cities and villages. In this way, increasing the accessibility of people living in those areas to have healthy drinking water and eliminating the water shortage reaching the serious size in the region.

In this thesis study, groundwater research was conducted in three different regions of Somaliland. Geophysical studies were carried out in Sool Region, Togdheer Region, and Awdal Region. Geophysical studies were carried out to determine the groundwater potential in the city of Godalo in the Sool region, the city of Gambadho and Qoryale in the Togdheer Region and the city of Magalo'ad

in the Awdal Region. These mentioned regions are determined as the places that need the most groundwater.

There are two separate litho-stratigraphic units Auradu Limestone formation and Taleex Gypsum Formation in the Godaalo region. It is very important to detect the Auradu limestone unit by geophysical research. Because this unit is very important in terms of groundwater potential.

In this thesis study, the Vertical Electrical Sounding method was used in groundwater research. Resistivity measurements were carried out using the Schlumberger electrode opening at 19 DES measurement points in four different regions.

The electrode array used in the study area was chosen according to the suitability of the topography of the regions. The orientation of the profiles has been regularly maintained in the north-south direction. The device used in Vertical Electrical Sounding measurements is ABEM SAS 1000 Terrameter. In addition, measurements were made in the study area using electrodes, four cable reels, and an external 12 volt DC Battery.

The reason why the Schlumberger electrode array is preferred in the application of the Vertical Electric Drilling (VES) method in the study. The area is that this electrode array is advantageous compared to the other electrode array.

AB/2 expansion has been taken at a maximum of 700 meters in the study area. Using the apparent resistivity values obtained from the study area in the Surfer program were prepared apparent resistivity floor maps of underground for AB / 2 100, 150, 200 and 400 meters. With these maps, lateral and vertical changes in the apparent resistivity values in the study area have been clearly identified. All map data obtained regarding the underground were evaluated together with the geological features of the region.

IPI2Win computer program was used to evaluate the VES data obtained from the study area. Because of the evaluation, it was determined that the real resistivity values of underground layers ranged from a minimum of 0.24 ohms to a maximum of 5574 ohms. It was determined that the thickness of the underground layers varied from a minimum of 0.14 m to a maximum of 342 m. Geoelectric maps of the underground were created using the resistivity values and thickness values obtained.

By correlating these geoelectric maps with the geology of the region, areas with suitable groundwater potential in the study area were determined. Areas with groundwater potential are designated as VES 2 in the Godalo region, VES 2 in the Gambadho region, VES 1 in the Qoryale region, and VES 4 in the Magalo'ad region.

The maximum drilling depth in the study area was determined as 350 meters. A sufficient amount of groundwater was obtained by drilling afterward at the proposed measurement points. The drinking water requirement of the region was provided.

According to the resistivity data obtained from the study area, it was determined that the possible groundwater presence in some regions may be salty, especially in the regions where the evaporite geological units are located. For this reason, attention should be paid to drilling in the recommended drilling depths.

As a result of Vertical Electric Drilling measurements in Godalo, Gambadho, Qoryale and Magaload regions in the study area, relatively good water-bearing layers were found in the Auradu limestone unit and alluvium units.

In this thesis study; As a result of geophysical and geological studies, the aquifer areas with freshwater at different depths were determined in different areas within the study area, and soundings were made and the aquifers containing sufficient, healthy and potable groundwater needed by the people of the region were identified.

GENİŞLETİLMİŞ ÖZET

Somaliland, Afrika Boynuzu'ndaki en kuraklığa eğilimli bölgelerden biri olarak tanımlanmıştır. Ülkede yağan yağmur sağanak şeklinde ve kısa süreliğine düşmektedir. Ülkede düşük yağışlı bölgeler, ortalama yıllık yağış miktarının nispeten daha yüksek olduğu bölgelere göre daha az yağış yoğunluğuna sahiptir. Bölgede hakim olan yüksek sıcaklık nedeniyle, yıllık ortalama potansiyel bitki suyu tüketimi 1800 mm ile 2500 mm arasında değişmektedir.

Somaliland'ın birçok bölgesinde yeraltısuyunun temini durumuna olan ihtiyacın son derece şiddetli olduğu bilinmektedir ve bunun nedenide yukarıda belirtildiği gibi çok düşük etkili yıllık yağış miktarıdır. Somaliland'da birkaç derin sondaj projesi gerçekleştirilmiştir, ancak hidrojeolojik bilgi eksikliği nedeniyle, yeraltı suyu gelişiminin başarı oranı veya başarılı kuyuların sondajı çok düşük olmuştur. Aynı zamanda yeraltı suyunun Taleex Alçı Formasyonunun bulunduğu alanlarda olmadığı ve diğer evaporitik jeolojik birimlerin bulunduğu alanlarda tuzlu olduğu keşfedilmiştir.

Bu tezin genel amacı, yüksek öncelikli olarak tanımlanan alanlarda tatlı su içeren akifer alanlarının belirlenmesini kapsamaktadır.

Bu tez çalışmasında Somaliland'ın yeraltı suyu potansiyelini belirlemek için hidrojeolojik ve jeofizik çalışmalar yapılmıştır. Çalışmanın amacı, seçilen şehirlerde ve köylerde yeraltısuyu sondajı için uygun akifer alanlarının tanımlamaktır. Böylelikle o bölgelerde yaşayan insanların sağlıklı içme suyuna sahip olma erişilebilirliğini arttırmak ve bölgedeki ciddi boyuta ulaşan su kıtlığını gidermektir.

Bu tez çalışmasında, Somaliland'in üç farklı bölgesinde yeraltısuyu araştırması yapılmıştır. Jeofizik çalışmalar Sool Bölgesi, Togdheer Bölgesi ve Awdal Bölgesinde gerçekleştirilmiştir. Jeofizik çalışmalar Sool Bölgesi'ndeki Godalo şehri, Togdheer Bölgesi'nde bulunan Gambadho ve Qoryale şehri ve Awdal Bölgesi'nde bulunan Magalo'ad şehrinde yeraltısuyu potansiyelini belirlemek için yapılmıştır. Bu belirtilen bölgeler yeraltısuyuna gereksinimi en yüksek olan yerler olarak tespit edilmiştir.

Godaalo bölgesinde iki ayrı lito-stratigrafik birim olan Auradu Kireçtaşı formasyonu ve Taleex Alçı Formasyonu bulunmaktadır. Auradu kireçtaşı birimini jeofizik araştırmalarla tespit etmek çok önemlidir. Çünkü bu birim yeraltısuyu potansiyeli bakımından oldukça önemlidir.

Bu tez çalışmasında yeraltısuyu araştırmasında 'Düşey Elektrik Sondaj (DES)' yöntemi kullanılmıştır. Dört farklı bölgede toplam 19 DES ölçüm noktasında Schlumberger elektrod açılımını kullanarak ölçümler gerçekleştirilmiştir.

Çalışma alanında kullanılan elektrot aralığı, bölgelerin topografyasının uygunluğuna göre seçilmiştir. Profillerin yönü, kuzey-güney yönünde düzenli olarak korunmuştur. Dikey Elektrikli Sondaj ölçümlerinde kullanılan cihaz ABEM SAS 1000 Terrameter'dir. Ayrıca, ölçüm alanında elektrotlar, dört kablo makarası ve harici 12 voltluk DC Batarya kullanılarak ölçümler yapılmıştır.

Çalışma alanında Düşey Elektrik Sondaj (DES) yönteminin uygulanmasında Schlumberger elektrot dizisinin tercih edilmesinin nedeni, bu elektrot dizisinin diğer elektrot dizisine kıyasla daha avantajlı olmasıdır.

Çalışma alanında AB/2 açılımı maksimum 700 metrede alınmıştır. Surfer programında çalışma alanından elde edilen görünür özdirenç değerleri kullanılarak AB/2 100 m, 150 m, 200 m ve 400 metre için yeraltının görünür özdirenç kat haritaları hazırlanmıştır. Bu haritalar ile çalışma sahasındaki görünür özdirenç değerlerindeki yanal ve düşey değişimler net olarak tespit edilmiştir. Yeraltı ile ilgili elde edilen tüm harita verileri bölgenin jeolojik özellikleri ile birlikte değerlendirilmiştir.

Çalışma sahasından elde edilen DES verilerini değerlendirmek için IPI2Win bilgisayar programı kullanılmıştır. Değerlendirme sonucunda yeraltındaki tabakaların gerçek özdirenç değerleri minimum 0.24 ohm-m ile maksimum 5574 ohm-m arasında değiştiği tespit edilmiştir. Yeraltındaki tabakaların kalınlıklarının ise minimum 0.14 m ile maksimum 342 m arasında değiştiği belirlenmiştir. Elde edilen özdirenç değerleri ve kalınlık değerleri kullanılarak yeraltının jeoelektik haritaları oluşturulmuştur.

Bu jeoelektrik haritaların bölge jeolojisiyle korele edilmesiyle çalışma sahasında uygun su potansiyelirinin olduğu alanlar belirlenmiştir. Su potansiyelinin olduğu alanlar Godalo bölgesinde DES 2, Gambadho bölgesinde DES 2, Qoryale bölgesinde DES 1 ve Magalo'ad bölgesinde DES 4 ölçüm noktaları olarak belirlenmiştir.

Çalışma sahasındaki maksimum sondaj derinliğ 350 metre olarak tespit edilmişitir. Önerilen ölçüm noktalarında daha sonra sondaj yapılarak yeterli miktarda yeraltısuyu elde edilmiştir. Bölgenin içme-suyu ihtiyacı sağlanmıştır.

Çalışma sahasından elde edilen rezistivite verilerine göre bazı bölgelerde olası yeraltı suyu varlığının, özellikle de evaporit jeolojik birimlerinin bulunduğu bölgelerde tuzlu olabileceği belirlenmiştir. Bu nedenle önerilen sondaj derinliklerinde sondajın yapılmasına özen gösterilmelidir.

Çalışma alanı içerisinde olan Godalo, Gambadho, Qoryale ve Magaload bölgelerinde Düşey Elektrik Sondaj ölçümleri sonucunda Auradu kireçtaşı biriminde ve alüvyonlu birimlerde nispeten iyi su taşıyan tabakalar bulunmuştur.

Bu tez çalışmasında; Jeofizik ve jeolojik çalışmalar sonucunda, çalışma alanı içindeki farklı alanlarda farklı derinliklerde tatlı su içeren akifer alanları belirlenmiş, sondajlar yapılmış ve bölge halkının ihtiyaç duyduğu yeterli, sağlıklı ve içilebilir yeraltı suyu içeren akiferler tespit edilmiştir.

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Most importantly, I wish to express my gratitude to all members of my family (my mother, and sister) who supported me and encouraged me to continue my work. Finally, I dedicate this thesis to my beloved mother.

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1. INTRODUCTION

1.1. General Introductions

Groundwater is a natural resource of great significance. Over 2 billion people worldwide rely on their daily supply on groundwater. Like a large number of industries, a significant proportion of the world's farming and irrigation relies on groundwater. Either groundwater or surface water is used for water supply depends largely on the position of aquifers relative to the demand level. A major urban population with high water demand would only be able to take advantage groundwater if the aquifer, usually a sedimentary rock, had favorable storage and distribution properties, whereas in a sparsely settled rural district, weak aquifers, such as weathered basement rock, have more minimal yet necessary water supplies (Niemann, 2007).

The volume of water remains largely constant on, beneath, and above the surface of the earth. Although a small amount of water vapor can escape into space, through chemical reactions during volcanic emanations, additional new water is constantly produced as juvenile water. Table 1.1 displays measurements of the amounts on, above and below the earth's surface of various types of ice. Freshwater accounts for only 2.5% of all earth's water, but not all of this water is usable for human use. Water in polar ice caps, other ice and snow types, soil moisture, marshes, biological systems and the atmosphere are not readily available. As a result, only the 10,530,000 km^3 of groundwater, 91,000 km^3 of freshwater in lakes, and the 2,120 km^3 of water in rivers are considered attainable for use and comprise a total of 10,623,120 km^3 consequently, groundwater.

Table 1.1. Estimates of Relative Volumes of Water of Various Kinds on Earth (Niemann,2007).

Water source	Water volume, in cubic miles	Water volume, in cubic kilometers	Percent of freshwater	Percent of total water
Oceans, Seas, & Bays	321,000,000	1,338,000,000	--	96.54
Ice caps, Glaciers, & Permanent Snow	5,773,000	24,064,000	68.7	1.74
Groundwater	5,614,000	23,400,000	--	1.69
Fresh	2,526,000	10,530,000	30.1	0.76
Saline	3,088,000	12,870,000	--	0.93
Soil Moisture	3,959	16,500	0.05	0.001
Ground Ice & Permafrost	71,970	300,000	0.86	0.022
Lakes	42,320	176,400	--	0.013
Fresh	21,830	91,000	0.26	0.007
Saline	20,490	85,400	--	0.006
Atmosphere	3,095	12,900	0.04	0.001
Swamp Water	2,752	11,470	0.03	0.0008
Rivers	509	2,120	0.006	0.0002
Biological Water	321,000,000	1,338,000,000	0.003	0.0001

In many parts of Somaliland, groundwater investigation is going on. Several geophysical explorations are being done in the quest of locating this all-important resource

SHAAC (2015), applied methods of electrical resistance in groundwater exploration at 18 places located in Somaliland. In the second phase of the survey, nine sites were investigated and a study aimed at identifying strong yielding wells to be fitted with hand pumps to provide the communities with drinking water.

Results showed that large aquifers were limited to rough, fractured sandstone formation and no water was contained in the wetland or fresh rock aquifers.

Electrical resistivity methods may have been used more commonly in groundwater studies than any other geophysical method. Resistivity is a barometer of the ability to withstand electrical current flow through materials; it is the opposite of electrical conductivity and is an inherent property of the material. For electrical resistivity techniques, a likely low frequency (< 1 Hz) current is injected into the ground between two current electrodes, while one or more pairs of potential electrodes are used to measure electrical potential differences. At the low frequencies measured, the loss of energy is regulated by ion and electronic conduction. The ion conduction is the product of the electrolyte. At the low frequencies measured, energy loss is driven by ion and electronic conduction. Ionic conduction results from the electrolyte filling of the interconnected pore space as well as the ground conduction by the creation of an electrical double layer with a grain-fluid structure. Electronic conductivity resulting from the formation of continuous conductive channels of metallic minerals is typically not necessary for most environmental applications. The existing distribution can be visualized using equipotential lines, with current flow lines running parallel to these surfaces. The fraction of the current total flow that enters a specific depth is the function of the current electrode spacing and positioning, the distribution of the electrical resistance of subsoil materials, and the topography (Hubbard, 2011).

1.2. Statement of the Problem

The drinking water situation in Somaliland is poor particularly in rural areas where women and children travelling long kilometers to obtain water for household and livestock use. Generally, surface water supplies are inaccessible due to their reliance on seasonal climatic changes, which either leave the conventional surface water-storage tanks partly or empty. The majority of Somalis do not have access to an increased water source and improved sanitation facilities.

Furthermore, it is known to be extremely serious in several areas of Somaliland and this is due to its very low efficient annual rainfall. Thus, the expansion of groundwater can be the primary source of water supply in the nation as a whole. Several profound drilling projects have been conducted in Somaliland, but owing to an absence of previous hydrogeological understanding, the rate of success of the expansion of groundwater or the drilling of productive wells has been quite small. Likewise, the quality of groundwater was discovered to be saline, particularly in the fields covered by the Taleex Gypsum Formation and other evaporated geological units. The overall objective of this thesis is to improve the availability of water and sanitation in areas identified as high priority and those having acute shortages of freshwater supply.

1.3. Justification of the Study

A lot of time, money and other resources were wasted in drilling and hand-dug of unproductive boreholes or wells. This waste of resources could have been reduced or totally avoided by the use of electrical resistivity studies. Interpretation of geophysical studies with detailed geological information could help in selecting borehole drilling or hand-dug sites.

1.4. Purposes and Objects of the Study Area

The objective of the study is to define appropriate sites for borehole drilling in chosen cities and villages and to enhance the accessibility of water and sanitation in these fields, recognized as a top priority and with severe water shortages.

1.5. Scope of the Study

This thesis focuses on the location of possible groundwater zones where two sites are situated in the Sool Region, one in the Togdheer Region and one in the Awdal Region. Sites located in the Sool Region are Godalo (Godalo District) and Gambadho, Qoryale, which is located in the Togdheer Region, and Magalo'ad, which is located in the Awdal Region. These sites have been identified as areas of acute drinking water shortage. Apart from Gambadho, which is located along the main asphalt road, connecting Burco to Garoowe towns, which can be accessed all year round, other sites the accessibility is relatively good of during dry seasons, along the existing tracks with four-wheel drive vehicles. However, during the wet seasons, due to the muddy nature of the roads, the accessibility is very difficult.

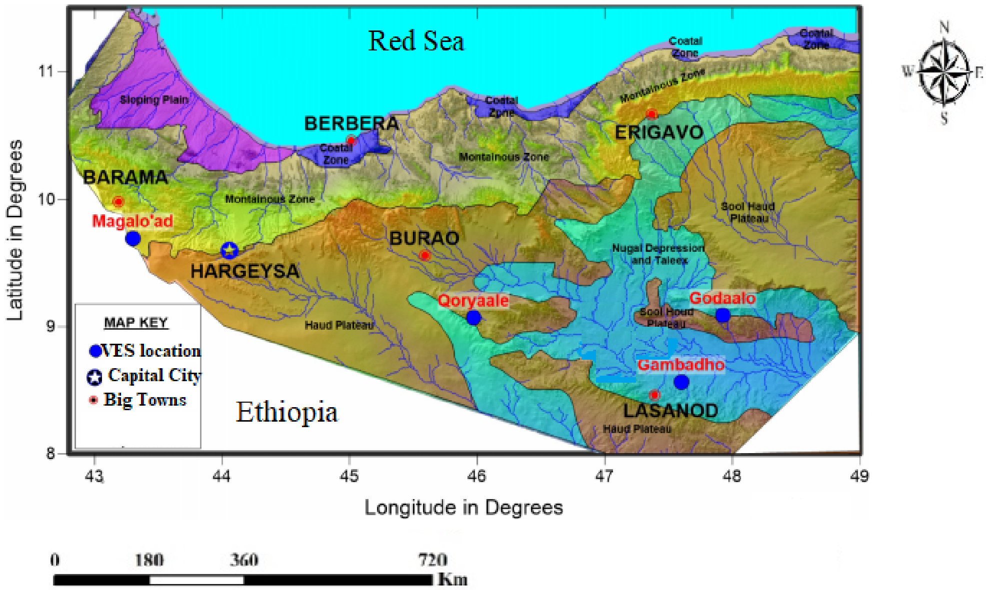


Figure 1.1. Map Of The Study Area

2. LITERATURE REVIEW

2.1. Groundwater

Groundwater is water that exists in interstitial spaces and cracks in rocks and sediments below the Earth's surface. This originates as rain or snow and then moves through the soil and rock into the groundwater system, where it eventually returns to the surface of streams, lakes or oceans. Groundwater is about 1% of the water on Earth (most water is in oceans), but groundwater is up to 35 times the amount of water in lakes and streams. Groundwater occurs anywhere just below the surface of the Earth but is generally limited to a depth of less than 750 meters. The quantity of groundwater is equal to a 55 m thick layer spread over the entire surface of the Earth. Technical note: Groundwater researchers usually limit the use of the word "groundwater" to groundwater that can flow freely into a well, tunnel, spring, etc. This definition excludes subterranean water in an unsaturated zone. The unsaturated zone is the region between both the ground of the soil and the top of the groundwater scheme. The unsaturated zone consists of earth materials and open spaces that encompass some moisture but, for the most part, this zone is not saturated with water. Groundwater is discovered below the unsaturated zone where all of the open spaces between sedimentary materials or in broken rocks are submerged in water and the water has a pressure higher than the atmospheric pressure (Freeze and Cherry, 1979).

2.1.1. The History of Groundwater

The extraction of groundwater resources has long preceded the development of geology, let alone hydrogeology. At the end of the seventeenth century, it was commonly thought that water coming from springs could not be collected from precipitation because it was thought that the quantity was inadequate and that the Earth was too impervious to allow rainwater to penetrate far below the surface. A good understanding of the hydrological cycle was achieved by the end of the seventeenth century.

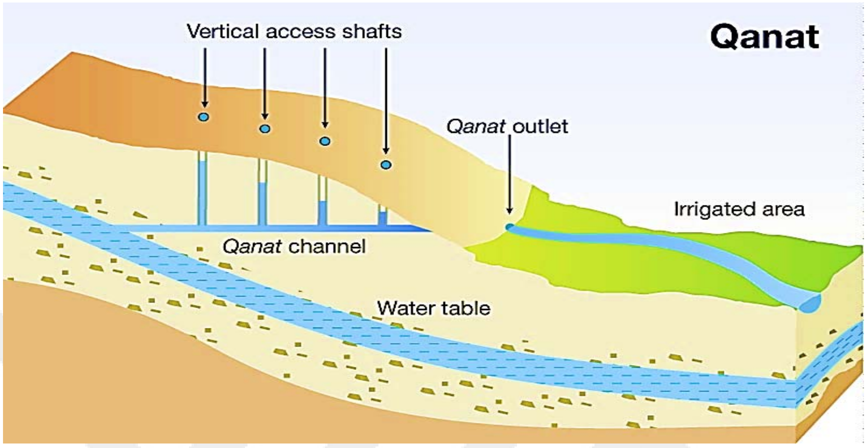


Figure 2.1. Longitudinal section of a qanat. (education.mei.edu, 2014)

The Englishman William Smith (1769–1839), the father of English geology and the author of the map of England (1815), was one of the early applications of the theories of geology to solve hydrological problems. Throughout his work as a canal and colliery surveyor in the south of England, Smith studied the various soils and the existence of the rocks from which, they were extracted and used his knowledge of the rock sequence to locate groundwater resources to feed the canal peaks and to supply individual buildings and towns .

The industrial revolution has resulted in an overwhelming demand for water resources to supply new towns and cities, with Sheffield, Manchester, Newcastle, and areas of London relying on the groundwater. Increased demand for water has given impetus to research into the financial aspects of geology. It was at that time that Lucas coined the term ' hydrogeology' and developed the first real hydrogeological map (Niemann, 2007).

Figure 2. 2. Irrigation canal supplied with water by a qanat or falaj in Oman (Niemann, 2007)

2.1.2. Groundwater and the Hydrologic Cycle

Water evaporates and flows into the atmosphere and becomes part of the sky. It drops like snow down to earth. Then it will evaporate again. It happens repeatedly in a never-ending cycle. This hydrological cycle never ends. Water keeps moving and changing from a solid to a liquid to a gas, repeatedly (Chandra et al., 2008).

Precipitation produces runoff that flows across the surface of the ground and helps fill lakes and rivers. It also percolates and travels downward to replenish aquifers under the ground through gaps in the soil and rock. With an overview ratio, some areas get more rain than others do. Normally these areas are close to oceans or large water bodies, which cause more water to evaporate and form clouds. Many areas are getting fewer. Such regions are often far from seawater and near to mountains. The water vapor condenses to form ice and freezes as clouds move up and over mountains. Snow is falling in the mountains.

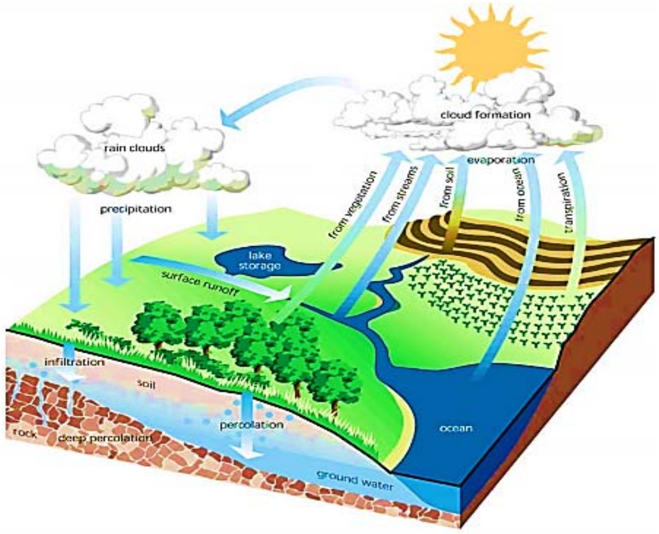


Figure 2. 3. A schematic representation of the hydrological cycle (Freeze and Cherry, 1979)

Referring to Table 2.1, if we exclude from consideration the 94% of Earth's water that lies at high salinity levels in rivers and seas, then groundwater accounts for about two-thirds of the world's freshwater wealth.

Table 2. 1.Estimated Water Balance of the World (Freeze and Cherry, 1979)

Parameter	Surface area $(km^{2)}*10^6$	Volume $(km^{2)}*10^6$	Volume (%)	Equivalent depth (m)*	Resident time
Oceans and seas	361	1370	94	2500	~ 4,000 years
Lakes and reservoirs	1.55	0.13	< 0.01	0.25	~ 10 years
Swamps	< 0.1	< 0.01	< 0.01	0.007	1-10 years
River channels	< 0.1	< 0.01	< 0.01	0.003	~ 2 weeks
Soil moisture	130	0.07	< 0.01	0.13	2 weeks – 1 year
Groundwater	130	60	4	120	~ 2 weeks – 10,000
Icecaps and glaciers	17.8	30	2	60	years
Atmospheric water	504	0.01	< 0.01	0.025	10-1000 years
Biospheric water	< 0.1	< 0.01	< 0.01	0.001	~ 10 days

2.1.3. Occurrence of Groundwater

Groundwater sub-surface deposition can be divided into areas of aeration and saturation. The aeration area involves interstices that are partly covered by water and partly by wind. In the saturation field, under hydrostatic pressure, all interstices are full of water. Instead of most of the earth's landmasses, a single aeration zone occupies a single area of saturation and goes up to the earth's surface. As indicated in Figure 2.4.

In the aeration zone (unsaturated area) vadose water occurs. This total area can be further divided into the soil water area, the intermediate vadose area (subsoil zone) and the capillary region (Figure 2.4). The saturated area reaches from the base of the soil to the impermeable rock surrounding it. The water table or the phreatic layer establishes the upper surface of the saturation zone in the absence of impermeable strata (Freeze and Cherry, 1979).

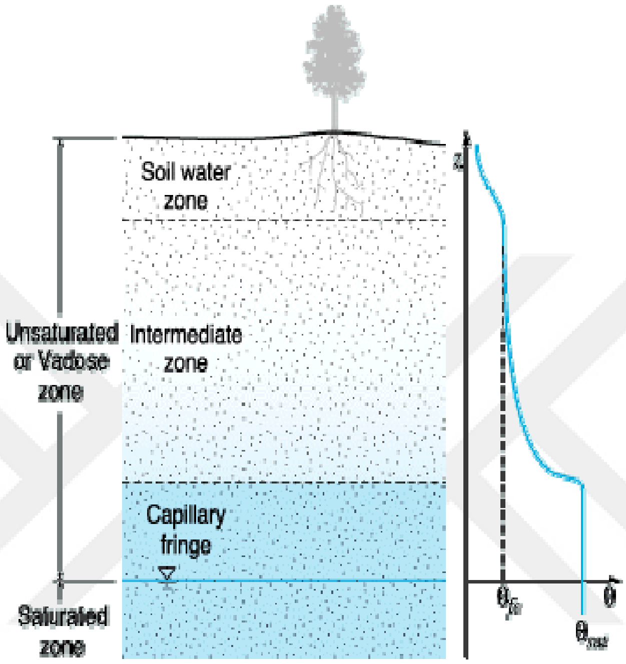


Figure 2.4. A schematic cross-section showing the typical distribution of subsurface water in simple of the unsaturated zone and the saturated zone below the water table (ldeo.columbia.edu, 2010)

2.1.4. Water Table and Aquifers

2.1.4.1. Water Table

The water table is the water level layer in an unconfined aquifer where atmospheric pressure is present. It is the level at which water in an unconfined aquifer is to remain in a well drilled (Soupios et al., 2007). When the outflow from the aquifer is recharged, the water table goes up and down. In addition, the water table is in constant motion to change its surface to maintain a balance between the refill and the outflow. The water table usually follows the topographical characteristics and is elevated below ridges and low below valleys. However, the topographic ridge and the water Table ridge may not coincide and flow from one aquifer to the other aquifer, called watershed leakage, may occur. Wherever the water table intersects the ground surface, a perched water table or a spring is created when a relatively small impermeable stratum divides a small water source from the main groundwater body. Wells drilled under the perched water table, delivering very small amounts of water up to the low impermeable stratum and soon going dry (Song et al., 2012).

2.1.4.2. Aquifer

Aquifer is a natural area under the surface (geological formation) containing sufficiently large quantities of water to be economically significant. "This definition is very relative and subjective, because a thin sandstone bed can economically produce water for a household to a well at a rate of 5.5 m^3/d, but would not be enough to supply a well with water-needed irrigation. However, it could be regarded by a strict definition as an aquifer.

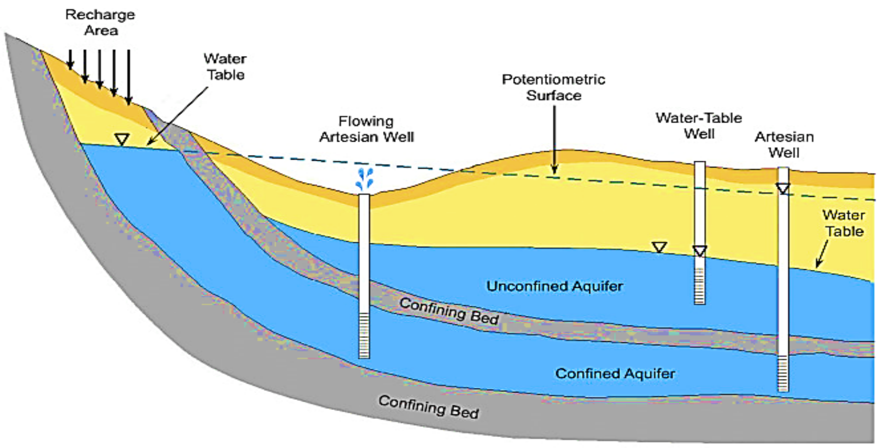


Figure 2.5. Illustration of observation wells in unconfined and confined aquifers. The potentiometric surface and water table (Andriyani et all., 2016)

Artesian or confined aquifers are popular in glaciated regions of the world where a body of sand and gravel may have been covered with clay-rich till or lacustrine sediments. It may also occur in porous bedrock such as the famous Dakota aquifer of Cretaceous Age, which rises from west to east on the crystalline rocks of the Black (Meixner, 2008).

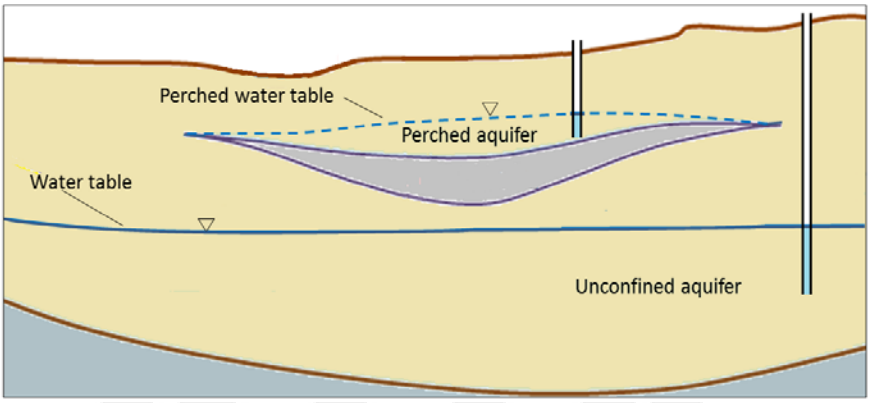


Figure 2.6. Shows the Cross-Section of a Perched Aquifer (Steven Earle, 2015)

These are deposits of sand or gravel or other material covering portions of impermeable surfaces such as clay. Throughout periods of high recharge levels, these aquifers will grow saturated and actually contain enough water for temporary use. During dry weather and after pumping, the perched aquifers often become dry. Most people make the mistake of finishing a well in a perched aquifer, assuming that they save money by digging for water more deeply, but end up running out of water when the perched aquifer is drained (Meixner, 2008).

2.1.5. Aquifer Properties

The aquifer characteristics are the physical features of the rock that affect the deposition, preservation, and removal of the groundwater. In some books, such aquifer features are called hydraulic properties. Porosity, permeability coefficient, recharge and discharge, basic yield and particular retention are the aquifer characteristics to be explored in this study (La Vigna., 2013).

2.1.5.1. Porosity

Porosity (n) is the proportion of rock or soil that is void of material, the greater the space of the pore or the greater the quantity of rock and soil, the greater the porosity and the greater the ability to hold liquid. It is mathematically defined by the equation:

$$n=\frac{Vv}{V}\times 100\% \quad (2.1)$$

Where

n is the porosity (percentage)

Vv is the volume of void space in a unit volume of earth materials (L^3, cm^3 or m^3)

V is the unit volume of earth material, including both voids and solids (L^3, cm^3 or m^3).

Porosity in sediments or sedimentary rocks depends on grain size, grain form, degree of sorting, and level of cementing. In rocks, the porosity depends on the size, arrangement, and pattern of cracks and fractures.

Table 2.2. Range of Values of Porosity (Freeze and Cherry, 1979)

Formation	n (%)
Unconsolidated deposits	
Gravel	25 - 40
Sand	25 - 50
Silt	35 - 50
Clay	40 - 70
Rocks	
Fractured basalt	5 - 50
Karst limestone	5 - 50
Sandstone	5 - 30
Limestone, dolomite	0 - 20
Shale	0 – 10
Fractured crystalline rock	0 - 10
Dense crystalline rock	0 – 5

2.1.5.2. Coefficient of Permeability

Permeability is the convenience with which a soil mass or a rock can flow with water. The permeability coefficient (K) is equivalent to the release (m^3/s) of soil mass under the hydraulic gradient unit per unit region (m^2). Since the discharge per unit area is equal to the velocity, the permeability coefficient has the velocity dimension [L / T]. Usually expressed in terms of cm / s, m / s, m / day, etc. The permeability coefficient is also referred to as hydraulic conductivity.

$$k = \frac{Cd^2{}_m}{\mu} \rho g \qquad (2.2)$$

Where

C = the shape factor which depends upon the shape, particle size and packing of the porous media,

d_m = the mean particle size (d50) (L, m)

ρ = the mass density (M/L^3, Kg/m^3)

g = the acceleration due to gravity (L/T^2, m/s^2)

μ = the viscosity (M/T.L, Kg/s.m)

Highly porous rock with little or no porous interconnection is possible, and therefore high porosity does not necessarily imply high permeability, but bad porosity usually outcomes in low permeability. Typical measurements of hydraulic conductivity geological products are given in Table 2.3.

Table 2. 3. Hydraulic Conductivity for Unconsolidated and Hard Rocks (Freeze and Cherry, 1979)

Medium	**K (m/day)**
Unconsolidated deposits	$10^{-8} – 10^{-2}$
Clay	1 - 5
Fine sand	5 - 20
Medium sand	20 - 10^{2}
Coarse sand	10^{2}
Gravel	- 10^{3}
Sand and gravel mixes	5 - 10^{2}
Clay, sand, gravel mixes (e.g. till)	10^{-3}
Hard Rocks	
Chalk (very variable according to fissures if not soft)	30.0
Sandstone	3.1
Limestone	0.94
Dolomite	0.001
Granite, weathered	1.4
Schist	0.2

2.1.5.3. Recharge and Discharge

As seen in below Figure 2.7, groundwater is a part of the complex hydrological cycle and somehow water can join and exit the subsurface. Recharge is considered the sub-surface liquid. Recharge to the ground usually results from infiltration of surface water down into the ground (from wind, seasonal rivers, snow melting, urinating livestock, etc.). The amount of pore space filled with water (or the degree of saturation) rises to 100% (i.e. total saturation) as water flows through the soil, sand, and rock. Just as water enters the saturated zone, it eventually has to exit it. Water streams from the saturated area are known as discharge (Uliana, 2012).

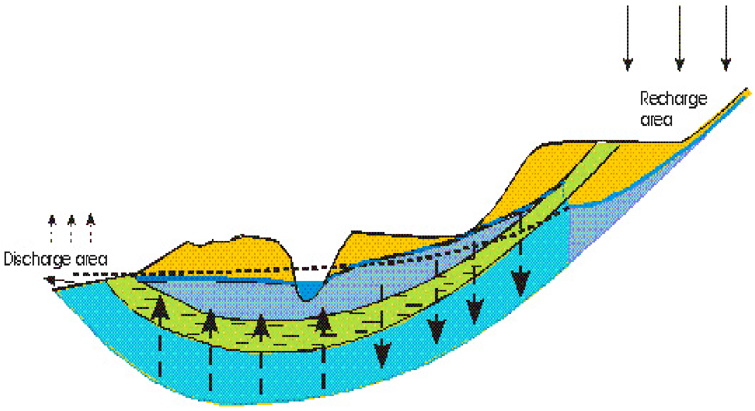


Figure 2.7. Recharge and Discharge (Laboratory of ecohydrology ECHO VICAIRE - Module 3)

2.1.5.4. Specific Yield and Specific Retention

When we saturate a rock and enable it to drain by gravity, a certain proportion of the water will be retained in the pore spaces by surface tension and tight pore throats. The fraction that drains is the general yield (S_y) and the fraction that is retained is called the unique retention (S_r) (Uliana, 2012). More definitions that are stringent are:

$$S_y = \frac{Volume_{drained}}{Volume_{total}} \quad (2.3)$$

$$S_r = \frac{Volume_{retained}}{Volume_{total}} \quad (2.4)$$

Note that $S_y + S_r$ = total porosity.

2.2. Geophysical Techniques for Groundwater Investigation

In groundwater studies, many geophysical techniques have been implemented with some displaying more success than others display. Geophysics has been used in the past either as an instrument for mapping groundwater resources or as an instrument for discriminating groundwater characteristics. For groundwater resources, mapping the geophysics is not the groundwater but the geological condition in which the water exists. Potential field techniques, gravity and magnetic, were used to map regional aquifers and characteristics of large-scale basins. Seismic methods have been used to delineate bedrock aquifers, broken rock formations. It has been shown that electrical, electromagnetic techniques are particularly relevant to groundwater research as many of the hydro-geologically important geological characteristics such as porosity and rock permeability can be associated with electrical conductivity signatures.

Methods for general practice have been developed for groundwater research geophysical techniques but as MacDonald et al. (2001) point out, situations with complex geology and hydrogeology do not lend themselves to the generic approach and require specific targeting of methods for particular problems. Many geophysical techniques have been used to identify groundwater, but once again, indirect mapping and monitoring of polluted and clean groundwater has been shown with the most effective electrical and electromagnetic methods. The use of geophysics for groundwater studies was partly encouraged by a desire to reduce the risk of drilling dry holes as well as a desire to offset the costs of low groundwater development. The geophysicist also provides useful guidelines for the hydrogeological analysis of potential groundwater sources and the assessment of current groundwater contamination today. A brief discussion on the development of geophysical surveys for groundwater application is given prior to a review of individual geophysical methods (Gassman, 1951).

2.2.1. Electrical and Electromagnetic Method

Electrical and electromagnetic methods have been commonly used in groundwater geophysical investigations due to the frequently occurring relation between electrical properties, geological formations and their liquid content. Many electrical methods generate an electrical current in the ground by interacting directly with the ground. Then the resulting electrical potential is used to measure the surface conductivity difference and inverse resistivity (Badrinarayanan, G. T., 2018). Different materials and their fluids may be capable of conducting an electrical current. Sequences with a high content of clay show higher conductivity as do saturated sequences and particularly sequences in which saline fluids (or sometimes other contamination) occur. The traditional electrical survey field procedure focuses on injecting an electrical current directly into the ground (direct current electrical resistivity test) and measuring the response (electrical potential drop) to the current over a given distance. Ground Penetration Radar is a method for electrical calculation of the displacement present in the ground (Reynolds, 2011).

Asry et al. (2012), In the Indonesia, ground-penetrating radar is commonly used for hydrogeological analysis in groundwater management. Falling water levels and declining water quality have a serious impact on agriculture, protection of biodiversity and availability of drinking water. provided examples of the types of hydrogeological applications currently in use in the Netherlands with four main radar targets: (a) tectonic and sedimentary structures; (b) water tables in sandy deposits in push moraines, river terraces and sand dunes; (c) water tables perched separately from local water tables; and (d) burial spatial size and consistency (Van Overmeeren , 1994)

2.2.2. Gravity Method

Gravity methods are not used in hydrogeology as much as electrical methods, but can still play a significant role (Carmichael and Henry, 1977). Their more common use is to identify low-density rocks that are considered to be ideal aquifers in buried rock valleys, such as alluvium (Lennox and Carlson, 1967) Instead of interpreting Bouguer phenomena, the impact of rising groundwater levels can be tracked using a gravimeter. For instance, a rise in groundwater level of 30 m may result in a change in g of 170 μGal in a rock with a porosity of 33 percent and particular retention of 20 percent. Therefore, it is possible to use a gravimeter at a given location to track very small changes in g. The only changes of gravity should be the amount of water in the rock interstices after adjustments of instrument drift and Earth tides (Awad et al., 2009). Therefore, for a known form aquifer, a measured gravity shift can be converted into an approximation of the actual yield of the aquifer in accordance with a limited number of water level measurements at a small number of wells (Reynolds, 2011). Likewise, repeated gravity measurements were used to estimate the drawdown rate, the degree of saturation of the steam zone and the recharge volume of the geothermal field of Wairakei, North Island, New Zealand (Hunt, 1977).

2.2.3. 2D Multi-electrode Electrical Resistivity Imaging (ERI)

This technique, called Electrical Resistivity Imaging (ERT), finds applications in the fields of environment groundwater, civil engineering and archaeology. The images acquired (apparent resistivity pseudo sections) are analyzed by inversion code which provides interpreted resistivity and depth values for the anomalies found along the profile (Bernard and Vermeersch, 2006). Unlike traditional techniques, the method of profiling, where the only difference in resistivity with lateral sub-surface extensions is recognized as sub-surface, where only variability and discontinuity of depth resistivity are known as profile anomalies (Aziman et all., 2018). ERI studies both vertical and lateral resistivity distribution under the entire profile at the same time. This specific procedure of resistivity helps to distinguish water-bearing areas around two survey points. The two dimensional (2D) data produced utilizing multi-electrodes results in high-density pseudo-sections with dense sampling of apparent resistivity measurements at shallow depth ranging from surface to a depth of 300 m in a short time (Dewashish, 2012).

The ERI process is commonly used in groundwater, ecological and geotechnical studies (kumari et al., 2012).

In groundwater discovery, electrical resistivity methods were used (Sharma and Baranwal, 2005). The conventional sounding and profiling resistivity approach offers a 1-D subsurface template that is not sufficient for mapping areas of complex subsurface geology. Therefore, the key drawbacks of these approaches are the simplistic sounding representation assumption of horizontally stratified earth system that does not suit the local geological model, and failure of the profiling approach to measure resistivity changes with depth (Griffiths and Barke, 1993).

Electrical resistivity tomography (ERT) offers a more practical sub-surface 2-D resistivity model where changes in resistivity in both the vertical and horizontal direction along the survey line are regularly mapped even in the presence of geological and topographical complexities (Loke, 2000). The 2D ERT approach was a useful technique for studying shallow electrical subsurface structures in different environments (Yang et al., 2002)

The use of ERT in Africa is becoming widespread, according to their study for using ERT emphasized that in an undulating terrain in Alabata, Ibadan, and southwest Nigeria with elevations ranging from 265 to 278 m above mean sea level (MSL). With a long wet season and relatively constant temperatures throughout the year, the study area has a tropical wet and dry climate. Data on field resistivity was collected across six traverses in this analysis. Traverses 1, 2 and 6 were oriented along N-S azimuth while traverses 3, 4 and 5 were guided along E-W with traverses ranging from 140 m to 200 m. Wenner set with a spacing of 5 m of the electrode and a maximum of five rates for each traverse was achieved (Jayeoba and Oladunjoye, 2015).

The study conducted in Ethiopia on the site of the newly established Wolkite University Campus to determine the competence of the near-surface formations as foundational materials. For this reason, integrated geophysical surveys involving 2D Tomography of Electrical Resistivity (ERT), Vertical

Electrical Sounding (VES) and magnetic surveys were used. The findings of the ERT and VES show the presence of medium to low resistivity topsoil, an even lower second layer of resistivity of clay and/or high moisture content underpinned by weathered and fresh bedrocks, and a variety of vertical or near-vertical discontinuities and poor site areas. The magnetic anomaly maps mapped the weak zones resulting from the subsurface structures and the Euler depth map and 2D magnetic simulation, showing the depth of the magnetic sources associated with the rock. (Haile and Atsbaha, 2014).

Methods of resistivity are very sensitive to earth resistivity variations and are therefore useful to distinguish lithological units and variations within lithological units (Abdulkadir and Eritro, 2017). These characteristics and adjustments are typically very important in relation to the occurrence of groundwater. Sounding and profiling of traditional DC resistivity has effectively capitalized on this dimension of the survey of resistivity, but is low in spatial coverage. The multielectrode resistivity approach has overcome this weakness in the survey of resistivity by using microcomputer control (Owen et al., 2006).

2.3. Some Groundwater Geophysical Exploration in Somaliland

The use of geophysical techniques is not much popular in Somaliland but there has been some improvement in the current years. The important roles in the use of geophysical methods for groundwater investigations are being realized in the current decade and it is the duties of the geophysicists educate and encourage the groundwater drilling and production companies, government agencies, and other people involved in groundwater investigation on the need of the usage of geophysical methods in groundwater prospecting.

According to SHAAC (2015), electrical resistivity profiling and sounding were used in 18 sites of Somaliland to delineate regions of fractured zones, faults and the thickness of layers that might give clues to the presence of groundwater. The VES measurements were taken at different sites around the town, three VES measurements and one resistivity and IP profile were conducted. All the VES Measurements were executed using the Schlumberger measuring array with the current electrode spacing expanded to 1400 m at each VES point (AB/2 = 700 m), the resistivity and IP profile was conducted using Werner configuration. The VES data has been interpreted both qualitatively and subsequently by means of recognized modelling software (Interpex ID sounding Inversion, Resist and IPI-Win) 1-D programs to provide quantitative 1-D depth-resistivity model interpretation of the probed locations of measurement and analysis of equivalent solutions.

2.4. Stratigraphy of Somaliland

Somaliland's geology and several documents collected in the 1950s by the Former Somaliland Protectorate's Geological Survey. The 1986 Report on Faillace and Faillace Hydrogeology and Water Quality was based on the works described above. The University of Florence (1973) also has several geological maps. The categorizations that occur in the study of various geological Formations should follow the reports described above. The region's geological successions (in order of succession) can be broadly divided into:

a) Polio-Pleistocene to Recent deposits: Consist of alluvial, colluvial, sand-dunes and Coral limestone.
b) Tertiary: Consists of Limestone, evaporitic rocks and thick extensive series of sedimentary rocks.
c) Cretaceous: Sandstone and Limestone.
d) Jurassic: Limestone, shale, and sandstone.
e) Precambrian: Basement rocks.

The region's geological history can be traced back to the Precambrian Period, reflecting the basement system's metamorphic and igneous rocks. Specific phases of decline and transgression and localized volcanism preceded the urban metamorphism. During the Precambrian era, vast sediments accumulated and at the end of the era, a period of regional folding and metamorphism has occurred. The initial sediments were exposed to high temperature and pressure as a result of this large-scale tectonic activity, which caused partial melting and subsequent recrystallization and growth of new minerals. Various types of gneisses, schists, and granites are formed depending on the parent material and the prevailing temperature and pressure. The complex of the Precambrian Basement stretches along the escarpments of the Plateau.

During the Lower Eocene, when the Auradu Silestone was deposited, the barren land occupied by the Nubian Sandstone was submerged by a deep-sea incursion. The ocean slowly receded during the Middle Eocene and an evaporative climate existed, with the Taleex Formation deposited anhydrite, gypsum, and marls. During the Upper Eocene, further marine ingression culminated in the Karkar Formation of shales covered by calcarenites, coastal cherty calcareous with marl intercalations (*FAO-SWALIM*, 2012).

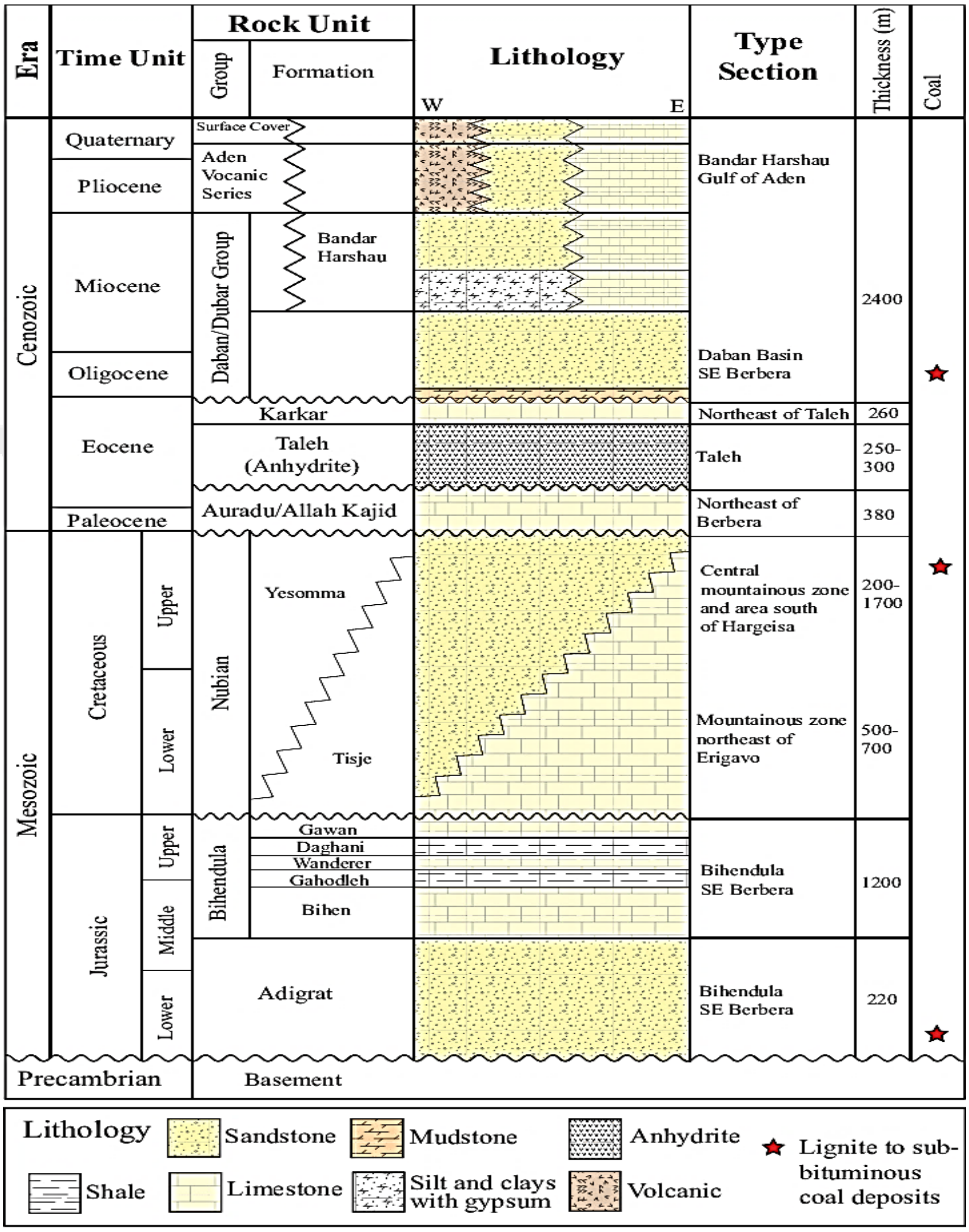


Figure 2. 8. General stratigraphic column of Somaliland showing stratigraphic occurrences of lignite and coal deposits (Ali, 2009).

2.4.1. Basement Complex

Complex Basement outcrops in Somaliland primarily in its northwestern portion (Awdal, Hargeisa), in Berbera and Sheekh (also known as Sheik or Shiikh) and along a narrow belt of the Ceerigabo-Ahl Madow escarpment. It typically consists of intruded schists, orthogenesis, quartzites, and paragneiss in granite, diorite, and gabbro.

The prevalent form of rock is orthogenesis. Most acid type dykes usually cross the gneissic rocks. We also found a suite of younger, low-grade metamorphic rocks above Pre-Cambrian crystalline rock, consisting primarily of folded sandstone, conglomerate shales, quartzite, and crystalline calcareous intercalations. (*FAO-SWALIM*, 2014)

Figure 2. 9. Ortogneiss rocks of the Basement complex near Beeyo Doofar (FAO-SWALIM, 2014).

2.4.1.1. Jurassic rocks

The detailed description of Jurassic Fm. In the analysis Faillace and Faillace (1986), you will find it. A dense series of continental deposits (basal sandstone) followed by marine beds constitute the Jurassic. The basal sandstone in its upper section includes thinly bedded calcareous, which marks the transition from continental to marine environments. The thickness varies from place to place and is primarily due to lateral facial change; Gowan (220 m) measured the thickest series. The basal sandstone form was Liassic. A sequence of 1,000 m thick Jurassic marine sediments outcrops in Bixinduule between Sheik and Berbera.

2.4.1.2. Nubian Sandstone

The Nubian Sandstone is a typical continental and/or lagoon formation that is deposited in a moist and warm climate. The Nubian sandstone uncomfortably overlooks the plateau escarpment and Jurassic rocks on the Basement Complex, and the Auradu claystone is regularly underlined from Hargeisa to the north and the east. The formation occurs sporadically of conglomerate beds of fine to coarse-grained white to red-brown quartz sandstone. The sandstone is smooth and cool, often cross-bedded. Siltstones, shales and calcareous sandstones are present in some locations as well as hard sandstone forming rocky barriers across togga beds.

In the southern part of the districts of Hargeisa and Gebiley, the sandstone outcrops. There have been numerous investigations in sandstone areas along the Ethiopian border, particularly near Wajaale, Geed-Balaadh, Alleybadey, Salaxlay, and Baligubadle, The sandstone's thickness rises southward and southeastward. The thickness at Jifo Urey near Gebiley (Hargeysa-Borama road) is just a few meters thick. The thickness in the Wajaale region is about 100 m, while the thickness in the southeast towards Baligubadle can reach 500 m.

Figure 2. 10. Yesomma sandstones near Borama (FAO-SWALIM, 2012).

2.4.1.3. Auradu Series

The Auradu series is made up of gray to white, rough and massive calcareous, sometimes unbedded. The calcareous Auradu outcrops in a broad, discontinuous and fault-dissected belt bordering the edge of the plateau cliff where the Nubian Sandstone overlaps. This stretches from the Hargeisa region to Burco, Ceerigabo, and Qandala, with various outcrops covering large areas between Berbera and Ceerigabo. The thickest sequence, 380 m, was measured near Ceerigabo. In the Nugaal Valley, where the formation of Taleex gypsum is based on calcareous, Auradu calcareous is also widely exposed.

The top part of the Auradu Formation consists of massive calcareous alternating with thinly bedded calcareous layers, sometimes chalky or gypsy, with calcareous shales.

2.4.1.4. Taleex Formation

This formation is named after the city of Taleex in the Sool region and it is the study area, where it stands out for a 250-meter portion. A typical evaporative formation is formed in a shallow sea under arid climate and deposition. It is made up of a series of massive and thick anhydrite beds with calcareous and gypsum intercalations. In this series, bricks, sand and gravel deposits deposited by rivers within shallow lagoon habitats are also present locally.

In some cases, lateral shifts for facies from gypsum and anhydrite to calcareous are known. Changes occur regularly from anhydrite through gypsum calcareous to thick calcareous and can be easily tracked for a relatively short distance. In the Nugaal Valley, where it covers a large part of the Sool and Nugaal areas, a larger succession of anhydrite series occurs.

2.4.1.5. Karkar Formation

The Karkar Formation is made up of fossil, bedded calcareous, marly calcareous and white marls. Limestone is often karstified with a well-developed cavern network. Including white to yellow to red, the hue varies. In some areas, thin layers of gypsum and sometimes-thin shale also occur. The series on the Taleex Formation is usually conformable and its thickness ranges from 200 to 400 m. Karkar's interaction with the Taleex Formation underlying is often marked by 2-3 meters of lateritic sand and weathered rocks.

The Karkar Formation is infiltrated by the well in the Sool Plateau at Rako Raaxo for 230 m. The well is situated at the foot of a 30 m high Karkar calcareous hill making Rako Raaxo 260 m of maximum thickness (Faillace and Faillace, 1986).

Figure 2. 11. Recording data on spring issued from Karkar Fm. (FAO-SWALIM, 2012)

2.4.1.6. Oligocene to Miocene

In the northern region of the Daban Basin, located north of Sheekh, the Lower Daban Series replaces the Karkar Formation. The latter takes place in combination with the Taleex Formation and consists of sediments deposited in coastal and lagoonal environments. The sediments contain varying intercalations of sandstone, shales, calcareous sandy clay, and anhydrite. The average thickness of the Lower Daban Series is 465 m.

2.4.1.7. Pleistocene to Recent Alluvium

Dense deposits of Pleistocene to Recent sediments were found in the plateau areas between the foothills and the coastal coasts. The sediments differ with a mixed texture from coarse gravel to dense clays. The late Tertiary and early Quaternary was filled with some closed basins by fresh alluvial sediments (terrace). Geed Deeble, the largest of these basins, is situated north of Hargeisa, where several streams converge. The water wells of Hargeisa Utility have penetrated the alluvial deposits of this basin for a thickness of 170 m but may exceed 200 the deposits consist of red sandy clay products with sand lenses and coarse gravel. Alluvial soil from the piedmont to near the coastal strip was also deposited in the sloping plain.

Figure 2. 12. Shallow well dug on the terrace alongside the main togga stream (FAO-SWALIM, 2014).

In several places along the coast as well as in the hinterland, sand dunes consisting of reddish to yellow to grey sand are found. In the area east of Berbera, coastal sand dunes are especially developed. Inland, sand dunes are well formed along the plateaus of Sool and Hawd along depressions and narrow valleys. In different localities along the Gulf of Aden as well as along the Indian Ocean, elevated beaches are observed.

Red soil abounds over large areas of the Hawd and Sool plateaus filling depressions and ancient valleys and preventing direct analysis of the underlying rocks. Red soil consists mainly after Faillace and Faillace (1986) of slightly clayey fine quartz sand. According to Macfadyen, in some areas "the deposit is recorded as an ancient reddish soil, primarily derived from Nubian sandstone denudation." Red soil and other soft materials of alluvial origin, consisting of isolated lenses of coarse sand, gravel and conglomerate, have an average thickness of 20-30 m; their thickness can reach up to 70-80 m, as found in water wells drilled in Burco Plateau. (*FAO-SWALIM*, 2014).

Figure 2. 13. Anhydrite of Taalex Fm. covered by recent red soils (FAO-SWALIM, 2014).

2.5. General Hydrogeology

Somaliland's surface waters are part of three major river basins:

1. Gulf of Aden basin
2. Dharoor basin
3. Nugaal basin

The resulting geomorphology closely follows the ground drainage. Much of the region drains toward the Indian Ocean in a southeasterly direction; the extreme north drains its runoff into the Aden Gulf.

The drainage network in the northern mountains is small to very dense, influenced by regional topography, precipitation, and geology. The study area has no perennial rivers. The rivers and drainages only after periods of heavy precipitation have surface water. Nevertheless, there are many small streams called toggas (wadis) from the plateaus and mountains in the north that have annual flows in some stretches and in other stretches have a complex groundwater relationship (subsurface flow) where groundwater is paid. Most of these small streams can carry high floods and debris after heavy rainfall. In Togga Hargeysa, for instance, on several occasions, several river learning and control systems can be destroyed. The runoff period lasts from a few hours to a couple of days. Several shallow wells also enter the underground stream of toggas, which is an important source of water for humans and livestock in the area. Togga Waheen, T. Durdur, T. Biji, and T.Silil constitute 3,000 km^2, 3,850 km^2, 3,560 km^2, 1,930 km^2 (Faillace & Faillace, 1986) in the western part of the study area in the Awdal and Woqooyi Galbeed areas.

In the Central part of the study area, the major toggas are the T. T. Hodmo, Jangarra, and the T. Belgeabili, 3,700, 3,800 and 4,800 km^2, respectively, with catchments. We all flow to the Gulf of Aden as well. The remaining region, with the exception of the coastal belt, forms a broad plain gently sloping south where it meets the valleys of Bokh and Nugal (*FAO-SWALIM*, 2014).

2.6. Geology of the Study Area

Two distinct litho-stratigraphic units have been found in the Godalo region, the Auradu Limestone formation outcropping hills south of the city, and the Taleex Gypsum Formation outcropping in the city and north of the city. There seemed to have been several fault lines. In order to avoid the expected saline water in the Taleex Gypsum Formation, the areas underlying the Auradu limestone formation were concentrated for the geophysical investigation.

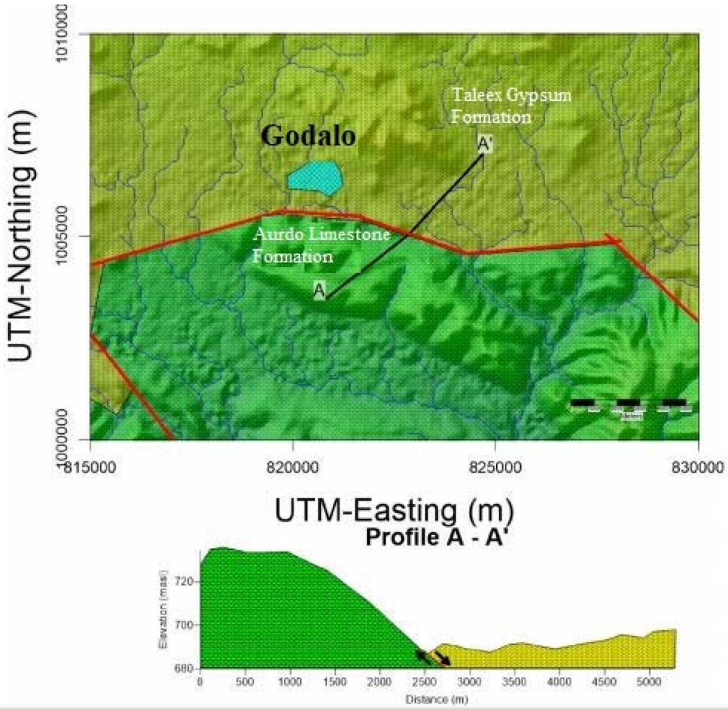


Figure 2. 14 Geology map of Godaalo area

The geology of Gambdho area a consists of Reasonably thick alluvial sediments underpinned by the Taleex Gypsum Formation. The northern part of the Gambadho area is predominated by alluvial sediments made up of gypsum sand and gravel originating from the Karkar limestoneformation which was eroded from the upstream areas which were found to outcrop the Karkar formation.

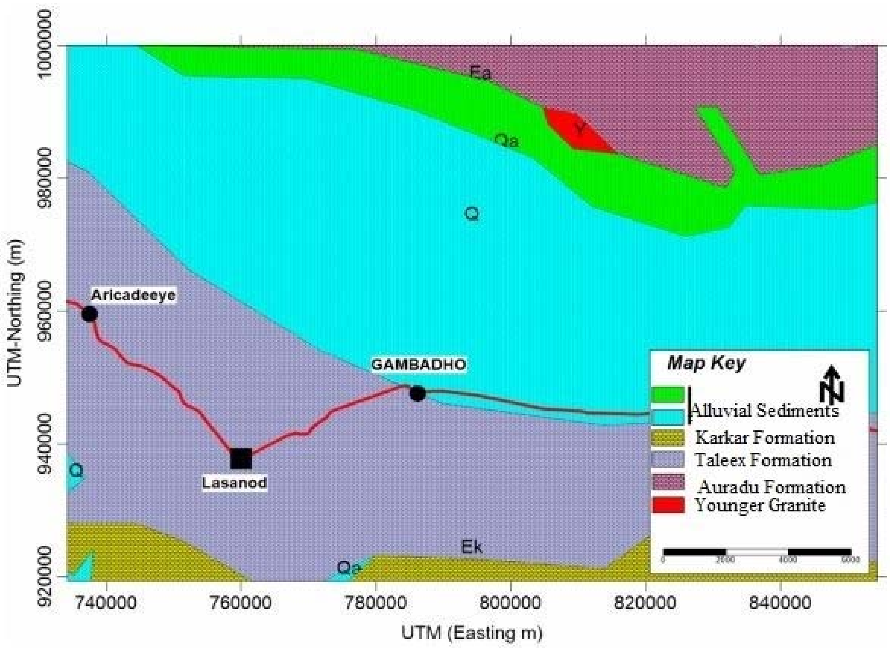


Figure 2. 15 Geology map of Gambadho area

The region of Qoryale belongs to the Haud Plateau, the surface geology as mapped during the field survey. The region is underpinned by the deposition of the Auradu limestone. Slightly thick alluvial sediments have been found in the flood plain area.

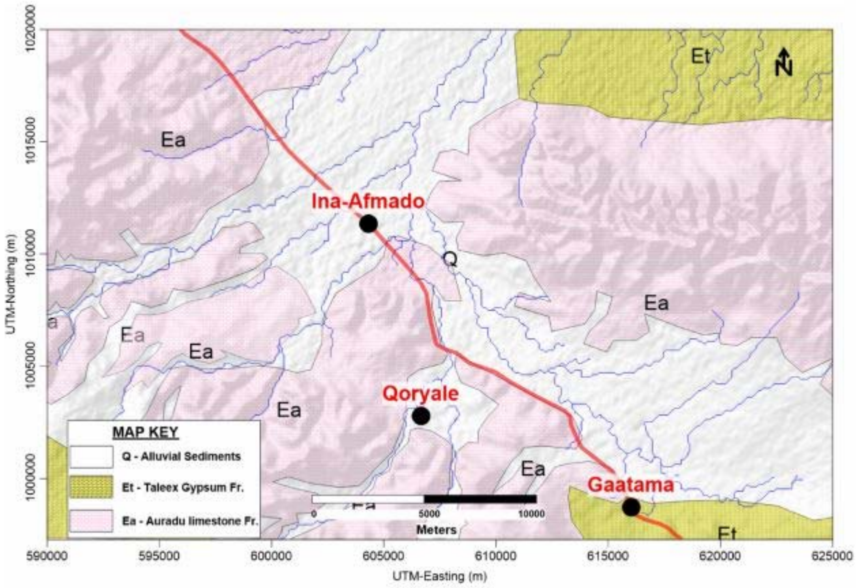


Figure 2. 16 Geology map of Qoryale area

Based on the existing geological map as well as the field survey results, three geological geological formation outcrops in and around Magalo'ad region as are as follows: 1.Complex basement 2.Limestone 3.Jurassic. New and alluvial sediment Basement complex is situated on the northern side of Magalo'ad. Basement complex is precambrian in age and is formed by heavily fragmented metamorphic pelitic and semi-pelitic rocks.

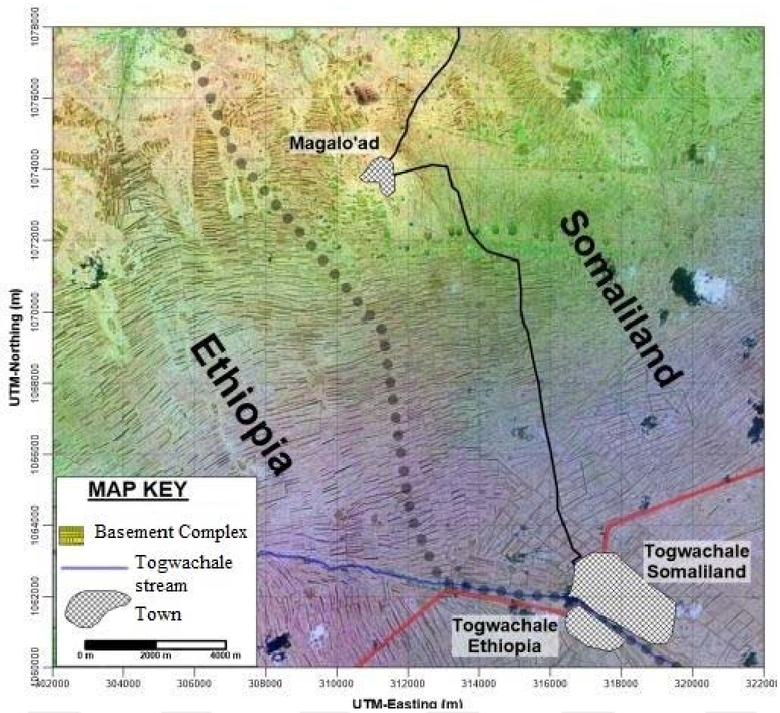


Figure 2. 17 Geology map of Magalo’ad area

Basement rocks in Magalo'ad can be considered an impervious surface and the creation of groundwater is impossible. Most of the boreholes drilled in the area surrounding Magalo'ad, most of the boreholes were abandoned because they were dry and hit the basement rocks at a shallow depth. Such boreholes successfully drilled, such as those wells drilled in the town of Togwachale, they are abandoned due to low yields or are dry when they reach fresh basement rocks at shallow depths. Basement rocks in the Magalo'ad region can not therefore be considered an aquifer.

The Jurassic limestone is heavily fragmented and karstified, but from a hydrogeological point of view, due to its well-developed fractures and later karstification processes, this group is known to be the strongest aquifer. Nevertheless, in Magalo'ad, the Jurassic limestone is irrelevant because, due to erosion, the unit has been eroded and isolated remains could be found in the region.

Pleistocene to Recent sediments are found to be covered in the area and can be found in the valleys and along the river beds. The sediments are of mixed texture and consist of alluvial clay, silt and limestone gravel.

2.7. Climate, Rainfall and Temperature Study Area

In particular, Somaliland's climate can be categorized as arid and semi-arid climate, with an average annual rainfall in mountain regions near Hargeysa and Erigavo ranging from 500–600 mm / year and decreasing to less than 100 mm / year as inland in the flatter zone of the Sool Region and in the coastal areas parallel to the Gulf of Aden. The distribution of precipitation is a bi-modal style pattern and in localized storms, the rain tends to fall. Somaliland's climate is determined by the annual monsoon systems and changes in the monsoon winds are responsible for seasonal changes. Intertropical convergence zone simultaneous motion (Faillace and Faillace1986) controls wind direction. Throughout rainy seasons, moist sea air is swept inland by westward winds, while during dry seasons; dry northeastern and southeastern monsoons are swept into Somalia, bringing dry continental air masses. Locally known as the GU ' (April to June) and the Deyr (October to November), there are two rainy seasons. Two dry seasons locally known as Jilaal (December to March) and Haggaa (July to September) contrast the rainy seasons. The Berbera region receives an average annual rainfall of 57 mm with at least 1.8 mm and a total rainfall of 96.3 mm per year. In the coastal strips between Berbera and Zeylac, it receives similar or even less than the 57 mm/year. In Tog-Wajaale area, it receives an average annual rainfall of between 500 to 600 mm/year, while areas south of Hargeysa, the average annual rainfall are 400 – 300 mm/year.

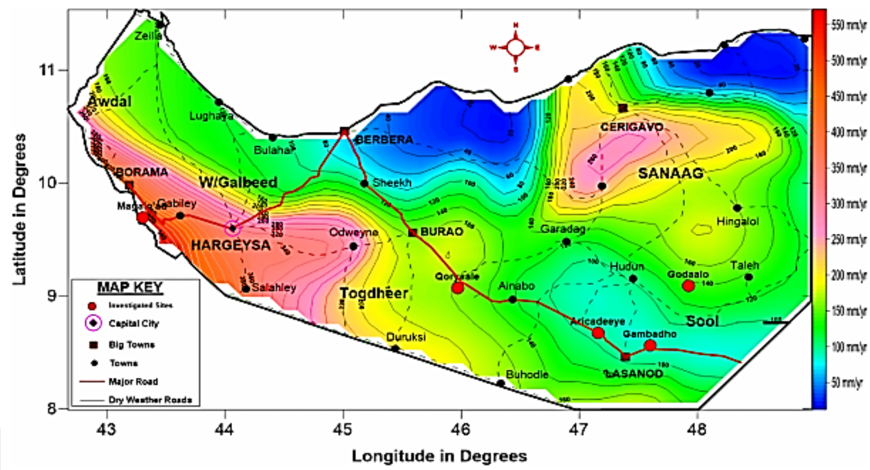


Figure 2. 18. Annual rainfall map of Somaliland (SHAAC 2014)

In the study sites, in the Magalo'ad area close to Tog Wajaale, the peak precipitation is expected and its average annual rainfall is projected to be 500 mm/year. The estimated annual rainfall in the Togdheer area of Qoryale is 160 mm/yr. Godalo is situated in the high mountains of Sool, receiving around 140 mm / yr. While Gambadho located in the depression of Nugaal, receive less than 100 mm/yr.

There are two rainy seasons, known locally as the Gu ' (April to June) and the Deyr (October to November), as can be seen below figure 2.13 Two dry seasons locally known as Jilaal (December to March) and Haggaa (July to September) replace the rainy seasons.

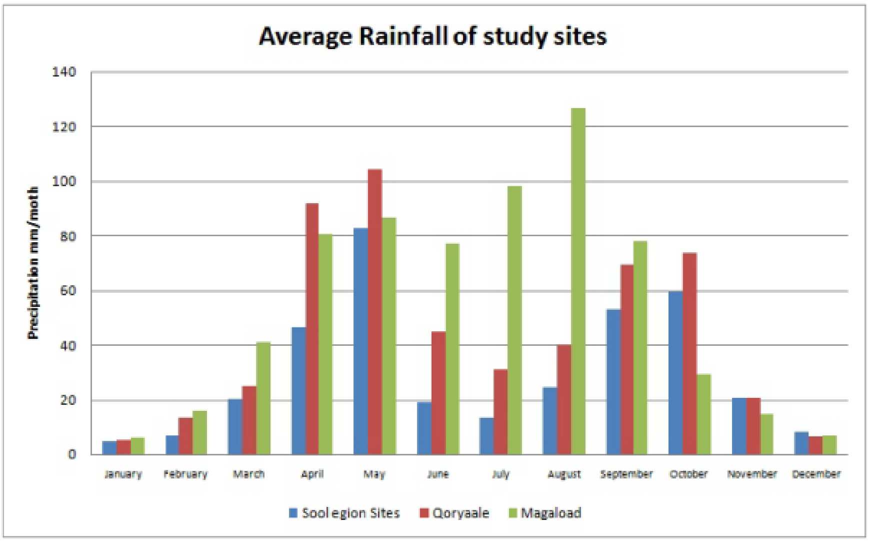


Figure 2. 19. Average rainfall of study area (SHAAC 2014)

Somaliland has been described as one of the Horn of Africa's most drought-prone areas. Torrentially and for a short time, rainfalls. The low precipitation regions in the country have a lower rainfall rate than those areas where the mean annual rainfall is relatively higher. With very high evapotranspiration, the region is very arid, so the return from precipitation to groundwater is very small. The average annual capacity for evapotranspiration varies from 1800 to 2500 mm due to the high temperature in the area. The region is characterized by strong wind circulation, which causes moisture loss in both plants and soils. The mean annual speed of the wind is 2.9 km/sec in relatively high altitude areas, whereas in the low altitude areas attain 5.8 km/sec. Mean monthly temperature ranges from 15 – 25^{0}C in the mountain regions to 25 – 35^{0}C in inland areas. The coastal areas, the temperature sometimes exceeds 35^{0}C. Similarly, high monthly temperature is recorded in Nugaal Depression.

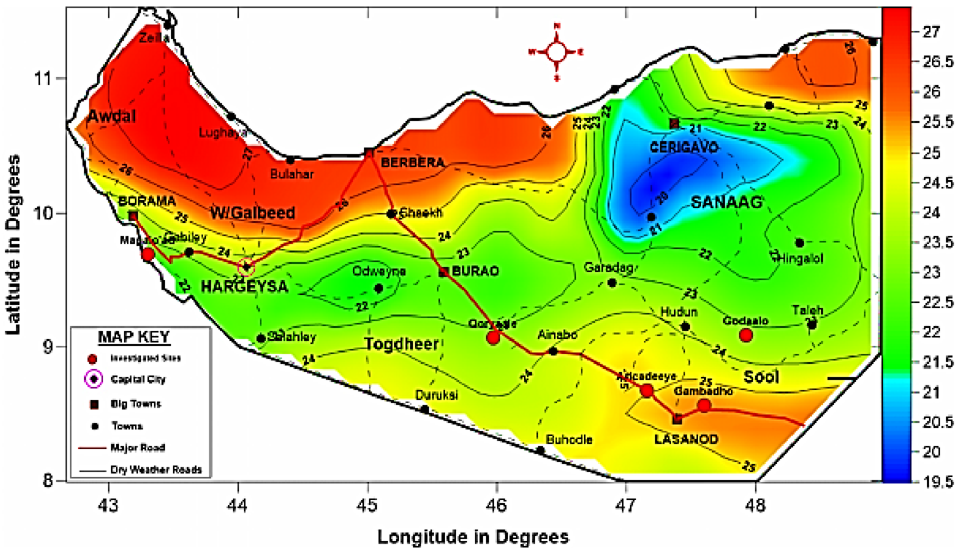


Figure 2. 20. Temperature distribution map in Degree Celsius (March) (SHAAC, 2014).

3. THEORETICAL BACKGROUND

3.1. Introduction to Resistivity Surveying

The aim of electrical surveys is to determine the distribution of subsurface resistivity by measuring on the surface of the ground. From these measurements, it is possible to estimate the true resistivity of the subsurface. The ground resistivity is related to specific geological parameters such as the rock's mineral and fluid content, porosity and water saturation degree. Hydro-geological, mining and geotechnical studies have used electrical resistivity surveys for many decades. It was used for environmental studies more recently. Resistivity method are usually performed by injecting current through two current electrodes into the ground (C1 and C2 in Figure 1) and measuring the resulting difference in voltage at two potential electrodes (P1 and P2). The apparent resistivity (ρa) value is determined from the current (I) and voltage (V) values.

$$\rho a = k \; V / I \qquad (3.1)$$

Where, k is the geometric factor, which depends on the arrangement of the four electrodes. Resistivity meters normally give a resistance value,

$$R = V/I, \qquad (3.2)$$

So in practice, the apparent resistivity value is calculated by

$$\rho a = k \; R \qquad (3.3)$$

The measured resistivity value is not the true subsurface resistivity, but an "apparent" value that is the resistivity of a homogeneous ground, which provides the same resistance value for the same configuration of the electrode. A complex relationship is the relationship between the "apparent" resistivity and the "actual" resistivity. In order to determine the true subsurface resistivity, the determined apparent resistivity values must be reversed using a computer program (M. H. Loke, 2000).

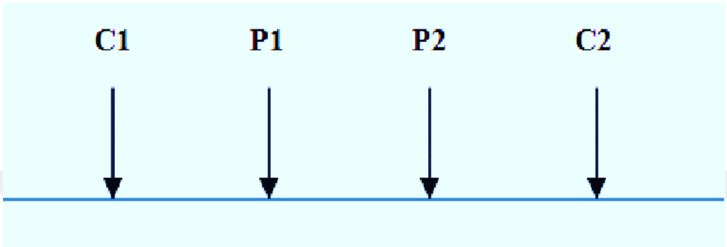


Figure 3.1. Geometry of a conventional array with four electrodes to measure the subsurface resistivity

Electrical resistivity surveys are usually very useful and convenient when searching for groundwater and in the exploration of mineral. It can also provide information about the subsurface formations when potential measurements are taken at the surface. Electrical Resistivity Tomography (ERT) Electrical Resistivity Imaging (ERI) which is a non-invasive method, is extremely useful for understanding the sub-surface formations and for depth estimations of natural resources. (Naganjaneyulu et al., 2015).

The electrical resistivity method as a tool for geophysical exploration, is based on the fact that the underlying rock materials can impose resistance to the flow of current and as such ohm's law could be applied to them if the earth is homogenous, the resistivity measured is called true resistivity otherwise, the term apparent resistivity is used and this is a weighted average of the resistivities of the various formation.

The usual practice in resistivity survey measurements is to introduce current into the ground by means of two current electrodes and potential drop is measured through a second pair of potential electrodes. The flow of current within the earth is affected by subsurface formation and hence the distribution of electric potential.

Conduction of electricity in the ground occurs through the interstitial water present in the rock and which contains some dissolved salts invariably. Low resistivity usually indicates the presence of water (clay) in the formation, this is therefore as important as water salinity in establishing the true resistivity of a medium (Collins et all., 2013).

Due to the work of the Schlumberger brothers, the resistivity principle emerged in the 1920s. For about the next 60 years, traditional-sounding surveys (Koefoed, 1979) are commonly used for qualitative analysis. The center point of the electrode array remains fixed in this process, but the distance between the electrodes is increased to provide more data on the deeper parts of the subsurface (Loke, 2000).

Conrad Schlumberger who conducted the first experiments in the field of Normandy developed the technique of resistivity survey. explain the historical and theoretical background of resistivity method starting with the equation that related diffusivity and ionic mobility of ions in liquid, then to the work of Archie which was titled ‘The electrical resistivity log as an aid to determining some reservoir characteristics. This work of Archie plays a great role in the development of the theory of the resistivity method. There have been several contributions from several physicists and geoscientists particularly geophysicists to the development and improvement of the theories, instrumentations and the interpretation of the resistivity method as a geophysical technique (Nazifi, 2015).

According to Breusse in (Zohdy , 1990), Real progress in the application of electrical methods to groundwater exploration started during the Second World War. French, Russian and German geophysicists were primarily responsible for the theory and in practice of direct current electrical exploration methods.

The resistivity of a geological structure can vary significantly, depending on the porosity, water content and the concentration of salts in groundwater. This enables both a quantification of the water content and an estimation of the groundwater quality (i.e., salt content). However, the resistivity for different materials, is not unique. Resistivity of water may vary from 0.2 to over 100 Ω m depending on its ionic concentration and the amount of dissolved solids (Palacky ,1987).

Resistivity of natural water and sediments without clay vary from 1 to 120 Ω m (Zohdy and Martin, 1993). Because of these confusing effects, the lithology and groundwater quality effects cannot be differentiated by the geoelectric resistivity survey alone. For an effective use of VES survey, correlation with the chemistry of groundwater obtained by sample data is required (Sikandar et all., 2010).

3.2. Resistivity Method

The resistivity method is an electrical method used in the survey of horizontal and vertical discontinuities in the electrical properties of the ground, and also in the detection of three dimensional bodies of anomalous electrical conductivity. It is widely used in the search for suitable groundwater sources and in the monitoring of groundwater contamination forms. (Kearey et al, 2002)

It is used in construction surveys to identify underwater cavities, faults and fissures, permafrost, mineshafts etc. and in archaeology to chart the real extent of the remains of ancient buildings' buried foundations, among many other applications (Reynolds, 1997).

Resistivity methods have been used in two types of application mainly:

a) To survey areas for the location of subsurface materials with abnormally high or low resistivity compared to the surroundings.
b) To estimate the depth of subsurface boundaries, that separate layers of different resistivity and to estimate these resistivity values.

Most researchers have proposed the regular use of resistivity methods in fields such as geothermal, mining, irrigation, environmental engineering and archaeological applications.

3.3. Basic Principles of Resistivities

Resistance (R) is directly proportional to its length (L) and indirectly proportional to the cross-sectional area (A) that can be expressed as:

$$R = \rho * L/A \qquad (\Omega) \qquad (3.4)$$

Where ρ is known as the specific resistivity, characteristic of the material and independent of its shape or size with Ohm’s Law

$$R = \delta V/I \qquad (\Omega) \qquad (3.5)$$

Where δV is the potential difference across the resistor and (I) is the electric current through the resistor, the specific resistivity may be determined by:

$$\rho = (A/L) * (\delta V/I) \qquad (\Omega m) \qquad (3.6)$$

Lithology, porosity, and the degree of saturation of pore space and salinity of pore water determine the electrical properties of rocks in the upper part of the crust of the earth. Such factors also contribute to a material's resistivity, which is the electrical conductivity reciprocal. The resistivity of earth materials can be measured by measuring the distribution of electrical potential generated by the surface of the earth by an electrical current flowing through the earth. Vertical electrical soundings are point measurements at certain positions that provide data on the layering of vertical resistivity. Profiles of resistivity, on the other hand, are carried out to obtain information on lateral changes in apparent resistivity along a cross-section (Walton, 2010).

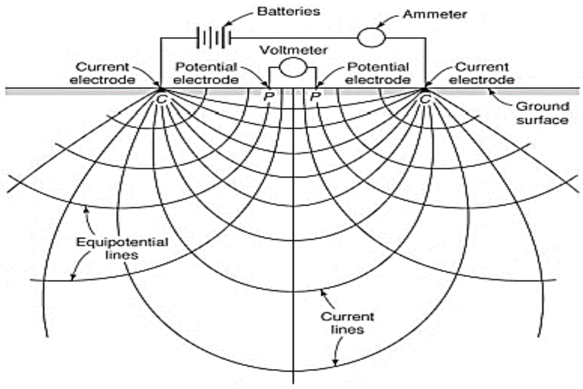


Figure 3. 2. Schematic diagrams illustrating the basic concept of electrical resistivity measurement (Walton, 2010).

3.4. Electrical Resistivity Method Procedures

Imagine an electrical uniform cube L side-length through which a current (I) passes. The material inside the cube prevents the current conduction of electricity through it, seeing a possible drop (V) between opposite faces. The resulting resistance (R) is proportional to the length (L) of the resistive material and inversely proportional to the cross-section area (A). The real resistivity is the proportionality constant (referred by symbol

$R \propto L/A$

$$R = \rho \frac{L}{A} \tag{3.7}$$

Whereρ, the constant of proportionality is known as the electrical resistivity or electrical specific resistance.

According to Ohm's Law, the resistance is given by:

$$R = \frac{\Delta V}{I} \quad (3.8)$$

Where ΔV is the potential difference across a resistor, and I is the electrical current through a resistor.

Substituting equation (2.1) in equation (2.2), we get:

$$\rho = \frac{\Delta V}{I}\frac{A}{L} \quad (3.9)$$

3.5. Resistivity Sounding Techniques

Using two metal electrodes (current electrodes), an electrical current (I) is applied to the ground during the sounding of resistivity, also known as Vertical Electrical Sounding (VES). Sub-surface variations in electrical conductivity determine the current flow pattern in the soil and hence the distribution of electrical potential.

A measure of this is received between a second pair of metal electrodes (Potential electrodes) placed near the center of the array in terms of voltage drop (δV) The ratio (δV/I) provides a direct measurement of the ground resistance from which the apparent resistivity (ρ_a) of the surface is measured and the electrode spacing (Zarroca et al., 2011).

The measurement configuration consists of a resistivity meter (usually placed in the middle of the array), connected to two current electrodes (AB) and two potential electrodes (MN) to the left. Many electrical configurations are used for resistivity survey; however, the most commonly used is Schlumberger's Vertical Electrical Sounding range for Schlumberger array measurement with an increasing set of Current Electrodes that enables the current flow to reach slowly higher depths. The apparent resistivity as a function of the electrode separation AB provides information on the vertical variation in resistivity. The depth of penetration, therefore, varies depending on the range of the electrodes. The point at which a change in earth layering is observed depends on the contrast of resistivity but is usually around a quarter of the existing AB spacing electrode. (John Milson, 2003).

3.6. Resistivities of Rocks and Minerals

All materials, including soil and rock, have an intrinsic property that governs the relationship between the current density and the gradient of the electrical potential. Variations in earth materials ' resistivity, whether vertically or laterally, result in variations in the relationship between the current being applied and the potential distribution as measured on the surface, which reveal something about the subsurface materials ' structure, intensity, and physical properties. The various electrical geophysical techniques identify materials through whatever correlation occurs in their electrical properties. Materials that differ geologically, as described in a lithological log from a drill hole, may or may not vary electrically, and may or may not be differentiated by an electrical resistivity survey. Properties that influence the resistivity of a soil or rock include porosity, water content, composition (mineral tile and metal content), and salinity of pore water and grain size distribution.

(1) In an electrically conductive object that lends itself to definition as a one-dimensional body, such as an ordinary wire, Ohm's law describes the relationship between the current and potential distribution.

$$V = IR \tag{3.10}$$

Where

V = difference of potential between two points on the wire

I = current through the wire

R = resistance measured between the same two points as the difference of potential

The resistance (R) of a length of wire is given by

$$R = \rho \frac{L}{A} \quad (3.11)$$

Where

ρ = resistivity of the medium composing the wire

L = length

A = area of the conducting cross-section

(2) In most earth materials, the conduction of electrical current occurs almost entirely in the water surrounding the pore spaces or joint openings, as most soil and rock forming minerals are practically non-conductive. Clays and a few other minerals, including magnetite, specular hematite, iron, pyrite and other metallic sulfides, can be found in enough concentrations to contribute significantly to soil or rock conductivity.

(3) Water is practically non-conductive in a pure state, but with the addition of chemical salts in solution, it becomes a conductive electrolyte, and the conductivity is proportional to the salinity. The effect of rising temperature is to increase the conductivity of electrolytes. Resistivity increases if pore water freezes, possibly by a factor of 104 or 105, depending on the salinity. Nevertheless, for soil or rock this effect is diminished by the fact that not all pore water is simultaneously freezing and that some unfrozen fluid usually occurs even at temperatures well below zero. The deposition of dissolved salts and the adsorption of moisture on grain surfaces to reduce the freezing temperature. Nonetheless, electrical resistivity tests carried out on frozen ground are likely to encounter difficulties due to the high resistivity of the frozen surface layer and poor contact resistance of the electrodes (Zhang et al., 1989).

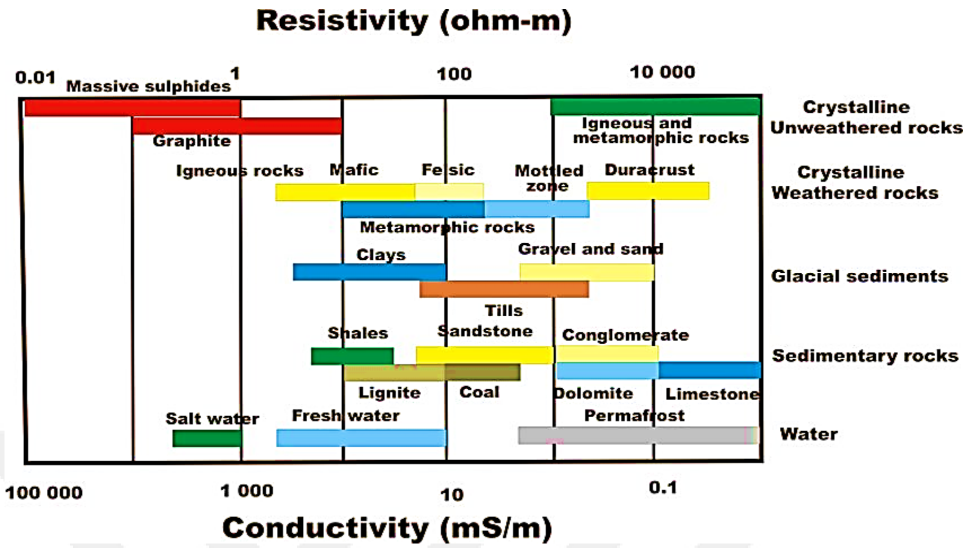


Figure 3. 3. Typical resistivity (conductivity) ranges for rocks and unconsolidated materials (Hunter et all., 2016).

3.7. Current Flow in the Ground

Suppose an electrical circuit is installed as the resistor with the moon. In two different locations, two metal stakes acting as electrodes are driven into the ground. Another act as a source and one serves as a drain and is attached to battery terminals. Current is forced to pass through pathways from the source to the sink (Figure 3.3). The direction of current flow in each electrode is considered separately and then the combined effect is considered later to determine the pattern of three-dimensional current flows in the earth.

Ohm's law refers to the current, potential difference, and resistance, $-\delta V = \delta R I$, Substituting $\delta R = \rho \delta L / \delta A$

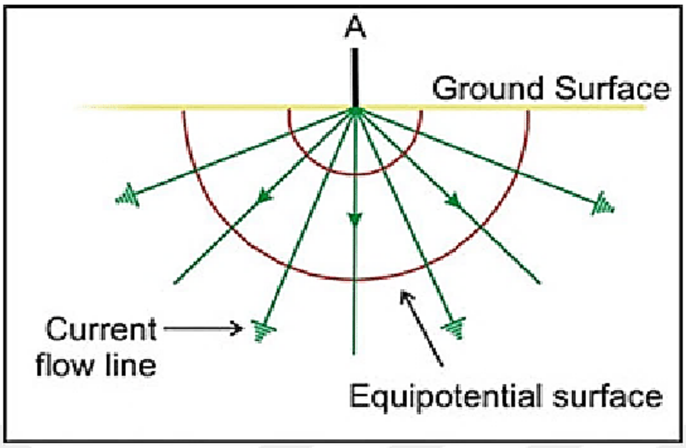


Figure 3. 4. Simplified current flow lines and equipotential surfaces arising from a single current source (Hites, 2006).

$$\frac{\delta V}{\delta L} = -\frac{\rho I}{\delta A} = -\rho i \tag{3.12}$$

$\delta V/\delta L$ Represents the potential gradient through the component in voltm^{-1} and I the current density in Am^{-2}. In general, the current density in any direction within the material is given by a negative partial derivative of the potential in that direction divided by the resistance. Imagine a single current electrode on the surface of a material of uniform resistance r. The circuit is completed by a current sink at a large distance from the electrode. Current flows radially away from the electrode in such a way that the current distribution is uniform over the hemispheric shells based on the original a distance r from the electrode, the shell has a surface area of , so the current density i is given by:

$$i = \frac{1}{2\pi r^2} \tag{3.13}$$

From equation (3.12), the potential gradient associated with this current density is

$$\frac{\delta V}{\delta L} = -\frac{\rho I}{\delta A} = -\rho i \tag{3.14}$$

The potential V_r at distance r is then obtained by integration

$$V_r = \int \partial V = -\int \frac{\rho I \partial r}{2\pi r^2} = \frac{\rho I}{2\pi r} \quad (3.15)$$

The constant of integration is zero since $V_r = 0$ when $r = \infty$

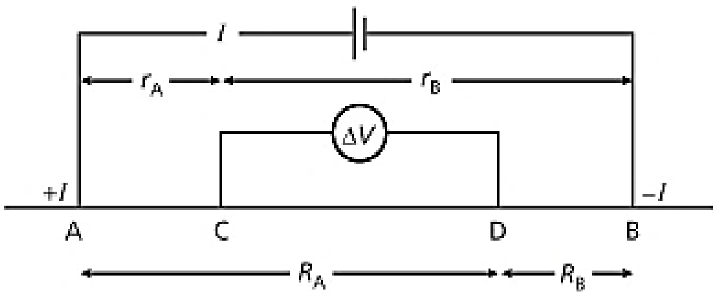


Figure 3. 5. The generalized form of the electrode configuration used in resistivity measurements (Busby 2003)

Equation (3.15) helps to measure the potential at any point on or below a homogeneous half-space surface. Fig's hemispheric plates. 3.3 Label constant voltage surfaces and are known as equipotential surfaces. Then consider the case where the current sink is a finite distance from the source (Fig. 3.5). The potential V_C for an internal electrode C is the sum of potential V_A and V_B inputs from the current source at A and the sink at B.

$$V_C = V_A + V_B \quad (3.16)$$

From equation (3.15)

$$V_C = \frac{\rho I}{2\pi}\left(\frac{1}{r_A} - \frac{1}{r_B}\right) \quad (3.17)$$

Similarly

$$V_D = \left(\frac{1}{R_A} - \frac{1}{R_B}\right) \quad (3.18)$$

Absolute potentials are difficult to monitor so the potential difference ▲V between electrodes C and D are measured

$$\Delta V = V_C - V_D = \frac{\rho I}{2\pi}\left(\frac{1}{r_A} - \frac{1}{r_B}\right) - \left(\frac{1}{R_A} - \frac{1}{R_B}\right) \quad (3.19)$$

Thus

$$\rho = \frac{2\pi r^2}{1\left(\frac{1}{r_A} - \frac{1}{r_B}\right) - \left(\frac{1}{R_A} - \frac{1}{R_B}\right)} \quad (3.20)$$

In fact, the ground is not uniform as assumed in the resistivity equation derivation and due to the sub-surface inhomogeneity; the resistivity varies with the relative position of the electrodes. Any measured value is then referred to as the apparent resistivity πa and will depend on the inhomogeneity shape (Herman, R., 2001).

$$\rho_a = 2\pi \frac{\Delta V}{I} \frac{1}{k} \quad (3.21)$$

Where K is the geometrical factor and is expressed as;

$$K = \left(\frac{1}{r_A} - \frac{1}{r_B}\right) - \left(\frac{1}{R_A} - \frac{1}{R_B}\right) \quad (3.22)$$

3.8. Field Procedure of Resistivity Method

Resistivity surveys are performed to address the needs of two distinctly different types of perception problems: (1) variation in resistivity with depth, suggesting more or less horizontal stratification of earth materials; and (2) variations in lateral resistivity that may include soil lenses, isolated ore bodies, faults, or cavities. For the first type of problem, measurements of apparent resistivity at a single location (or around a single center point) with systematically varying electrode spacing are performed. Sometimes this technique is called vertical or vertical electrical sounding (VES). Lateral variation surveys can be carried out at spot or grid locations or cross lines a technique often called horizontal profiling, on a definite basis (Vouillamoz et al., 2007).

In general, vertical electrical sounding (VES) is used in the study of horizontal or near-horizontal interfaces, also known as' electrical drilling' or' expanding probe.' The current and potential electrodes are held at the same relative spacing and the entire range is gradually expanded around a fixed central point. Consequently, readings are taken as the current hits lower depths gradually. For geotechnical surveys, the method is widely used to determine overburden thickness and also to classify horizontal areas of porous strata for hydrogeology.

Constant separation traversing (CST), also known as electrical profiling, is used to assess differences in lateral resistivity. The current and potential electrodes are held at a defined distance and pushed slowly along a profile. This technique is used in mineral prospecting to locate faults or shear zones and in localized bodies to detect anomalous conductivity. It is also used in geotechnical surveys to determine variations in bedrock thickness and the incidence of steep discontinuities. Results of a series of CST traverses with fixed electrode spacing can be used in the development of resistivity contour maps (Loke, 2000).

3.9. Electrode Arrays

From the device development it could be deduced that it is better suited to solve conductive characteristics than high resistivity characteristics. The method of resistivity was originally designed after all to prospect the rock. Nonetheless, the high resistivity anomalies could be detected if an electrode array is carefully selected and the field structure is thick enough. So far, we have not noticed any unique electrode arrangement. Nonetheless, essentially four electrodes are required, their location significantly influences the results and may be the factor deciding whether the survey is successful or not.

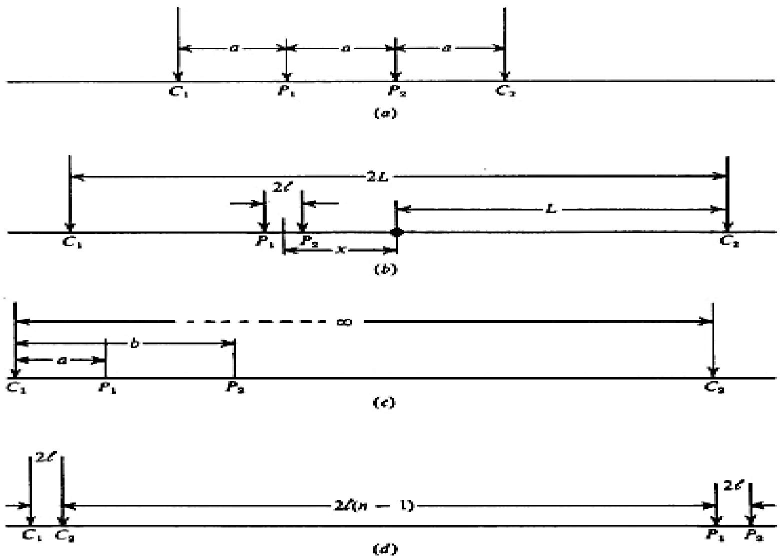


Figure 3.6. Commonly used electrode arrays (Telford et al. 1990). (a) Wenner (potential) array. All the distances between the electrodes are equal. (b) Schlumberger (gradient) array. The distance between the potential electrodes is much smaller than the distance between the potential and current electrodes. The most common configuration is to put the measuring dipole in the center of the array. (c) Pole-dipole array. One of the current electrodes is much further from measuring dipole than the second one. (d) Dipole-dipole array. The measuring dipole is remote from the current electrodes.

Most common electrode arrays are shown in Fig. 3.6 They can be divided into three basic groups: potential arrays, gradient and dipole arrays. Potential arrays calculate the potential between two relatively distant electrodes, read voltage values are large (due to the long distance between potential electrodes) and this type of arrays is, therefore, suitable for surveys where there are issues with electrode grounding or high noise rates. The arrays of gradients measure the possible difference between two near-up electrodes. If this spacing is small enough (theoretically zero distance), we can conclude we are measuring the gradient (the first potential derivative). Therefore, the measured resistivity changes at the borders of anomalous bodies will be sharper.

Wenner array. Compared to the distance between the potential and current electrodes, there is a relatively large gap between the potential electrodes in this potential range. Therefore, the possible readings would be reasonably large and the array would be ideal for areas with poor grounding conditions and areas likely to be high noise. Use the formula below to measure this type of array's apparent resistivity

$$\rho_a = 2\pi a \frac{\Delta V}{I} \tag{3.22}$$

Schlumberger array. This set is very flexible. Since it is a gradient array, the anomalies measured are smaller and positioned better than the Wenner array. This setup is often used in the sounding process.

$$\rho_a = \frac{\pi l^2}{2l} \frac{\Delta V}{I} \tag{3.23}$$

Pole-dipole array. This is a set of gradients of three electrodes. One of the existing electrodes is positioned in a large distance from the array (in infinity) and does not switch with it. The appropriate distance between the remaining current electrode and the measuring (potential) dipole is at least five times the distance. In this situation, the influence of the distant electrode is negligible and the near electrodes electrical field is closer to that of a point source rather than a dipole field. The design often used is a mix of two forward and backward pole-dipole arrays. The potential dipole is normal for both and the forward dipole on one side of the potential dipole has a current electrode, while the opposite dipole on the other side. The present "infinity" electrode is again specific to both. Two measurements are taken on each stage–forward and reverse, using both the current electrodes (an average of these two readings shows the value to be read if the Schlumberger range is used). The main advantage is the classification,

$$\rho_a = 2\pi an(n+1)\frac{\Delta V}{I} \tag{3.24}$$

Dipole-dipole array. this is the most resistant set of those listed, but also the most susceptible to noise. The calculated resistivity values clearly delineate sub-surface structures, but the picture created is complicated with side lobes, etc. (Fig. 3.6), making things complicated when observing complex geology. With this configuration, the depth measurement could be about one-fourth the length of the dipole centers. Nonetheless, a fifth or six times the distance between the electrodes in the dipole is the maximum recommended spacing between the dipole. If the range is greater, too small voltages are read and a measurement error increases rapidly. If a greater penetration depth is needed, there is a need for greater separation of electrodes in the dipole (Reynolds, J. M., 2011).

$$\rho_a = \pi an(n+1)(n+2)\frac{\Delta V}{I} \tag{3.25}$$

3.10. Use of Resistivity Method for Hydrogeological Investigation

Resistivity surveys are usually limited to relatively small-scale investigations due to the work involved in planting the electrodes before each measurement, for this reason, methods of resistivity are not widely used in the exploration of recognition. With the growing existence of non-contact conductivity measuring devices, however, it is likely (Zananiri et al., 2006). Probably the most commonly used use of resistivity surveys is in hydrogeological investigations, as important information on geological structure, lithologies and subsurface water resources can be given without the high cost of a detailed exploration program. The results will decide the minimum position (Busby, 2003).

3.11. Limitation of Resistivity Method

The internal resistance of the potential measuring circuit must be much lower than the ground resistance between the potential electrodes in order for the electrical resistivity method to operate using a collinear array. If not, the future circuit provides an alternative low-resistance route for current flow and the measured resistance is meaningless (Reynolds, 2011). Most commercial resistivity equipment has an input resistance of at least 1 MΩm, which is adequate in most cases. In the case of low-temperature glacier ice, which itself has a resistivity of up to 120 MΩm, substantially higher input resistance is required (preferably of the order of 10^{14} Ω).

The survey of resistivity is an effective method for delineating shallow layered sequences or vertical discontinuities involving resistivity changes. Nevertheless, it is suffering from a range of limitations:

1. There are vague definitions. Consequently, in order to distinguish between valid alternative interpretations of resistivity data, independent geophysical and geological controls are required.
2. Interpretation is limited to basic configurations of the structure. It may be impossible to interpret any variations from these basic circumstances.
3. Topography and the effects of variations in near-surface resistivity can mask the effects of more profound variations.
4. The method's depth of penetration is limited by the total electrical power that can be injected into the ground and by the physical complexity of setting long cable lengths. For most surveys, the realistic depth limit is about 1 km. (Busby, 2003).

4. INSTRUMENTATION AND METHODOLOGY

4.1. Methodology

This thesis consisted of a hydro-geological and geophysical survey conducted and evaluated the groundwater potential of four sites located in three regions of Somaliland. Namely, Godalo, Gambadho, Qoryale and Magalo'ad. In each site and in various geological formations and topography, a total of minimum three to maximum six Vertical Electrical Soundings (VES) are performed to locate geological irregularities and voids that are supposed to trigger groundwater. GPS was used to capture topographical data and locations of suitable locations, water points, geological contacts and other relevant data. Assessment was carried out to locate the nearest quarry for building materials such as gravel, sand and rocks for future construction of the water scheme.

In the region, hydrological and water quality data was obtained from the study sites. The study areas' geology, geomorphology, topography and hydrology were reasonably studied in the field in order to understand the occurrence of local and regional groundwater. In addition, water sources have been evaluated and inventoried, namely wells dug and existing boreholes available in the study areas. Similarly, specific and general problems were collected during the field related to the existing water supply. This chapter will also clarify field techniques, data acquisition and data processing of resistivity methods.

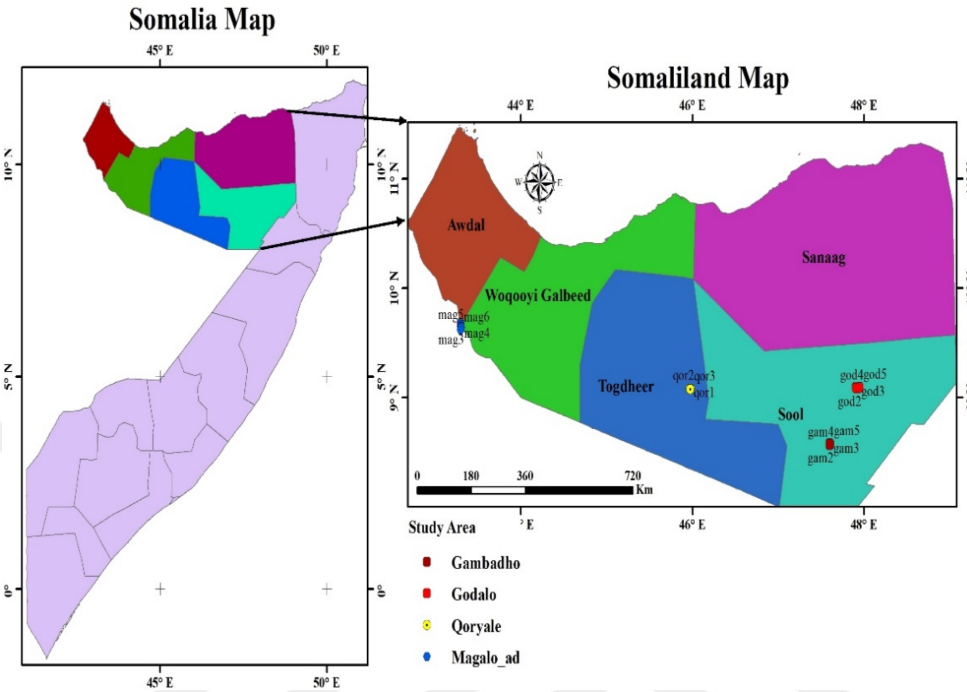


Figure 4. 1. Map of the Study Area

4.2. Instrumentation of the Resistivity method

Vertical Electrical Sounding, resistivity methods was used in this research work. The feasibility of water supply source, identification and design activities was made through the application of standard geological and geophysical techniques. The equipment was used for the resistivity surveying is the ABEM Terrameter SAS 1000C. This system was developed and marketed by ABEM. ABEM is a part of the Guideline Geo Group, global leader in geophysics and geo-technology. Below is an image of the ABEM SAS 1000C.

Figure 4.2. Measuring resistivity method at the field

4.2.1. Description of ABEM Terrameter SAS 1000C

ABEM Terrameter SAS 1000 is a highly skilled resistivity / IP device suitable for a wide variety of applications. This minimizes unnecessary field time by concurrently calculating both resistivity and IP and can be extended with a number of accessories. ABEM Terrameter SAS 1000 was designed for demanding field work under harsh conditions and has been well tested in all parts of the world through years of field work. The cast aluminum case is durable, robust, but lightweight and easy to carry. It includes a powerful built-in constant current transmitter running on either a battery pack clip or an external source of power.

Galvanically isolated, the input channel is merged with a high-resolution receiver that offers an amazing dynamic range. An intuitive user interface makes the ABEM Terrameter SAS 1000 easy to use and calculated data is imported and managed using the SAS Utility Program, which also handles protocols and transfers data to the most common software formats for interpretation. The Terrameter SAS 1000 is capable of performing VES, 2D and 3D scanning as well as borehole logging surveys

4.2.2. ABEM Terrameter SAS 1000C handling and operation

The Terrameter must be handled carefully, as with all geophysical equipment, to prevent damage. The Terrameter's operation is not complex, but easy. The Terrameter is located halfway between the potential electrode (M and N) by taking a resistivity measurement on a surface. Then the P1 and P2 terminals are connected to the M and N terminals. The sounding cable array ABEM is used with different conductors at the end of the electrode.

Current electrodes (A and B), respectively, are attached to CI and C2 terminals. Such cables run parallel to the Terrameter and are symmetrically arranged with respect to the potential electrodes. After the setup is complete, the power is turned on. The mode is now set to Resistivity and the Measure Knob is activated to allow measurement of resistivity. Once measurement of resistivity is taken and another reading is registered or the array is moved to another position to continue the measurement of resistivity until the end of the survey.

4.2.3. Operating Theory of ABEM Terrameter SAS 1000C

The SAS 1000 Terrameter operates in three modes: mode of resistivity, induced mode of polarization and mode of measurement of voltage. Only the resistivity mode theory will be discussed due to the context of this work. It includes a battery powered, deep-penetrating resistivity meter with an output sufficient to isolate the current electrode from 2000 meters under good surveying conditions in the resistivity-surveying mode. Discrimination and programming differentiate between DC voltages, self-potentials, noise, and incoming signals. The detector tests the response voltage signals at discrete intervals when eddy currents, polarization induced, and cable transients have declined to low levels (Abem, 2010).

4.3. Methodology

4.4. Introduction

Generally, before the geophysical surveys in the study area were performed, desk studies, analysis of available aerial photos and terrain assessment studies were conducted to make geophysical studies easier and more efficient. Geophysical surveys and the analysis of results from geophysical surveys will be addressed in this paragraph.

4.5. Field data Collection

The electrical sounding survey were conducted by using ABEM SAS1000 Terrameter, four cable reels and external 12 volt DC Battery. For Vertical Electrical Sounding (VES), since Schlumberger array configuration has a practical advantages compared to other configurations, Schlumberger array configurations was used for this survey. For Resistivity single depth profiles with an approximate length of between 500 to 1000 m were carried out at each site. Point measurements were taken at intervals of 100 m.

4.5.1. Digital Topographic and Geological Maps

- Digital topographic maps were collected and analyzed, covering the whole of Somaliland, and used to prepare base maps. The TOPOMAPS are 1:2500, 000-scale SPOT satellite image and Landsat image has been obtained and analyzed covering large areas of Somaliland including the sites investigated.
- A 30 m resolution Digital Elevation Model (DEM) covering the whole of Somaliland was obtained and used for modeling topography and regional

physiographical and drainage systems. Geological Map of Somaliland at digital format prepared by SWALIM Somalia was re-digitized and prepared the modified geology of each investigated sites.

4.5.2. Borehole Logs

Available oil wells and water borehole logs have been collected. Digitized and converted the hard copies of collected borehole logs into digital formats. Digital formats were used from the borehole data to construct a borehole database in which lithological details, water hit, static water level, dynamic water level, well design and other aquifer properties were used to develop the database.

4.6. Vertical Electrical Sound (VES)

The field procedure used Vertical Electrical Sounding (VES) using schlumberger array that carried out at nineteen (19) VES stations. The orientation of the profiles was maintained a regular direction of north-south. The electrode spacing to be used was selected from the areas suitable for the topography of the regions. The apparent resistivity values obtained from the field was evaluated with IPI2 Win software and 2-dimensional geo-electric map of the underground was be obtained. In addition, AB / 2 = 50,100,150, 200 and 400 m underground apparent resistivity maps was obtained using surfer software, all the map data obtained were evaluated together with the geological characteristics of the region and appropriate aquifer areas was determined. The Schlumberger array consists of four (4) collinear electrodes. The outer two electrodes are current source electrode and the inner two electrodes are potential (receiver) electrodes.

Two geophysical software were used to analyze and interpret field data: IPI2 Win (Geophysical Program) and Surfer 13 (Golden Software product). The data was copied and pasted to the VES notepad window (similar to the excel window) and automatically generated logarithmic data curves. The curves created were studied and they were derived from the starting models. Using the inversion button, the data is inverted starting with the user models. Thus increasing the error thus the feasible minimum value, the estimated and the measured resistivity values are adjusted. The inverted data was stored in the format of Bitmap Image, defined as the sounding curve, and the other output is a pseudo portion of the sounding curve, consisting of apparent resistivity and depth. To remove unwanted images and add additional data to the outputs, the sounding curves and the fake segment are modified using Microsoft Pain.

5. RESULTS AND DISCUSSIONS

5.1. Introduction

In this study as in any other groundwater exploration, it is not the groundwater itself that is the target of the geophysical investigations, but rather it is the geological situations in which the groundwater exist.

Freshwater resistivity values range from 10 to 100 Ωm and usually aquifer resistivity can range from 50 to 2000 Ωm depending on the aquifer's geology. As seen from the work of (Anechana, 2013), mostly when examining groundwater; in a hard rock (resistant) environment, the target will be a low resistivity anomaly, while in a clay or salt (conductive) environment, a high conductive anomaly will most likely correlate to a freshwater aquifer. Within sedimentary layers, by its thickness, the material of aquifer resistivity can be considered indicative of the aquifer's value.

5.2. Interpretations and Discussions of VES Models

5.2.1. Modeled Electrical Resistivity Curves

The black circles in the interpretation of VES curves represent the measured data, red line represents the calculated data and the blue line represents the interpreted resistivity sections, N is the number of layers, ρ is the apparent resistivity, h is the thickness and d is the depth to interface of each layer.

5.2.2. Godalo Town

Godalo is a newly created capital of Godalo district of Sool Region and is situated on the Sool Haud Plataea. The town can be accessed by using a 100 km dry weather road from Higlo, which is situated on the main asphalt road from Lasanod to Garoowe towns. This dry weather road can be accessed only during dry seasons with four-wheel Drive vehicles. The geographical coordinates of Godalo town can be approximated as 47.92379^0 East longitude and 9.08910^0 North

Latitude with an average elevation of 690 m. In this district, The VES measurements were taken at different sites around the town, five VES measurements were conducted.

There is no drilled borehole in the area that could be caused as a calibration for VES interpretation therefore, only geophysical and relevant general geological information has relied upon the interpretation of the collected field data. All the VES measurements were executed using the Schlumberger measuring array with the current electrode spacing expanded to 1400 m at each VES point (AB/2 = 700 m).

Table 5. 1. Godalo VES Locations

Longitude	**Latitude**	**VES ID**
47.59669	8.57150	VES 1
47.59913	8.56749	VES 2
47.59631	8.57914	VES 3
47.59619	8.56531	VES 4
47.60247	8.57477	VES 5

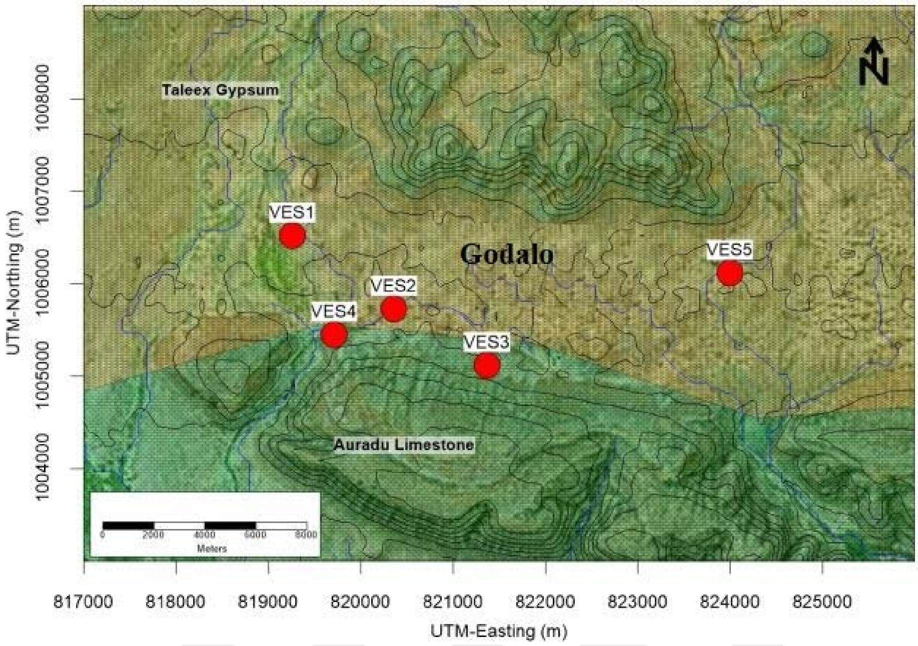


Figure 2. 21 Godaalo VES Location Map

5.2.2.1. Existing Water Supply Sources

Currently, people obtain drinking water from large diameter sinkholes located in the town and due to high pollution and surface water contamination and the current water source is determined to be not fit for human consumption. The sanitary condition of the unprotected sinkhole is very poor, therefore, the community has reported a high mortality rate especially from children and elders. According to the local health professions, waterborne and water wash related deceases are common in this area.

Figure 5. 1. Sink hole (unprotected) of Godalo area (SHAAC, 2010)

It is rather difficult to estimate the exact water demand for the town due to unreliable population figure and the movement pattern of people due to their semi-nomadic nature

5.2.2.2. Godalo VES-1 Interpretations

Godalo VES-1 Interpretations VES1 was conducted at about 2.5 km west of the town. The area was mapped to be underlain by the Taleex Gypsum Formation.

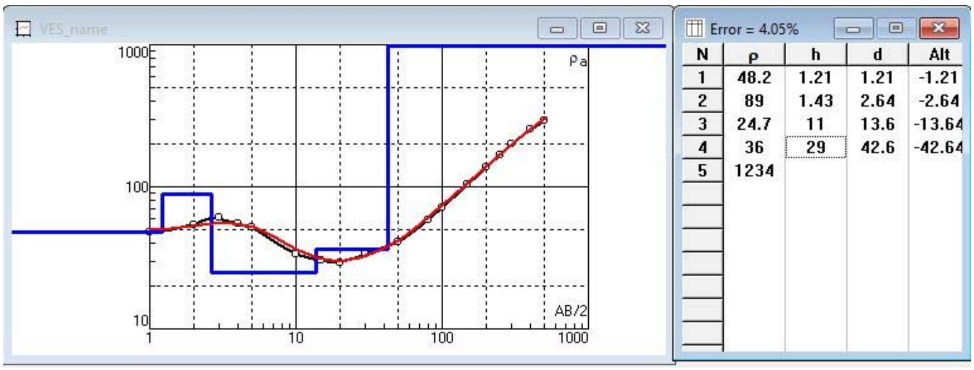


Figure 5. 2. Modeled Electrical Resistivity Curve of Godalo VES 1

Table 5. 2. Hydrogeological Interpretation of Godalo VES 1

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	48.2	1.21	1.21	Sandy with minor clay to soil	No
2	89	1.43	1.53	Sand	No
3	24.4	11	12.4	Highly weathered gypsum	No
4	36	29	41.5	Wet and weathered gypsum	No
5	1234	∞	>41.5	Fresh anhydrite	No

Godalo VES 1 has identified five geo-electrical layers and maximum penetration of 41.5 m depth was reached. According to the interpretation, the upper two geo-electric layers are alluvial sediment underlain by highly weathered gypsum and below the depth of 41.5 m depth very hard rock was encountered, which is most likely massive anhydrite unit. Due to the shallow nature of the aquifer zone, which is 29 m in Taleex gypsum formation and bounded by massive anhydrite unit, this site is not recommended from drilling.

5.2.2.3. Godalo VES-2 Interpretations

Godalo VES 2 is selected at inferred fault zone between Taleex Gypsum Formation and Auradu Limestone and is situated at about 1000 m west-southwest of the town.

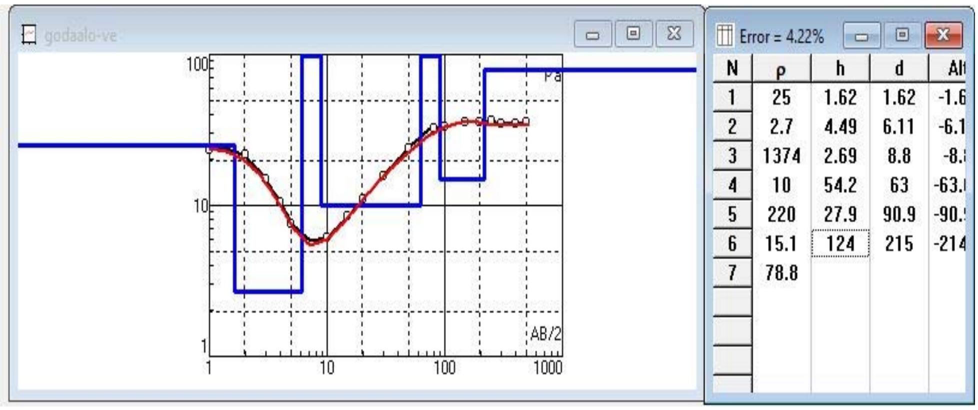


Figure 5. 3. Modeled Electrical Resistivity Curve of Godalo VES 2

Table 5. 3. Hydrogeological Interpretation of Godalo VES 2

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	25	1.62	1.62	Sandy top soil	No
2	2.7	4.49	6.11	Clay	No
3	1374	2.69	8.8	Hard limestone	No
4	10	54.2	63	Shale 5	
5	220	27.9	90.9	Less weathered limestone	No
6	15.1	124	215	Highly weathered limestone with shale	Yes
7	78.8	∞	215	Weathered Limestone	Yes

At these VES sites, seven geo-electrical layers were identified and maximum penetration of 215 m depth was reached. According to the interpretation, the upper two geo-electric layers are interpreted as alluvial sediment underlain by limestone of different degrees of weathering extending beyond 215 m depth. The water-bearing unit is found within the highly weathered and fractured limestone and extends beyond 215 m depth.

Based on the resistivity value of 15.1 and 78.8 Ωm, the limestone is highly weathered and the aquifer zone extends beyond the attained depth, hence, at the this VES site, deep borehole with a maximum recommended drilling depth of 230 to 250 m depth can be drilled at the location of VES2.

5.2.2.4. Godalo VES-3 Interpretations

VES 3 is again selected areas outcropping the Auradu Limestone Formation and is located at about 900 m east of Godalo town.

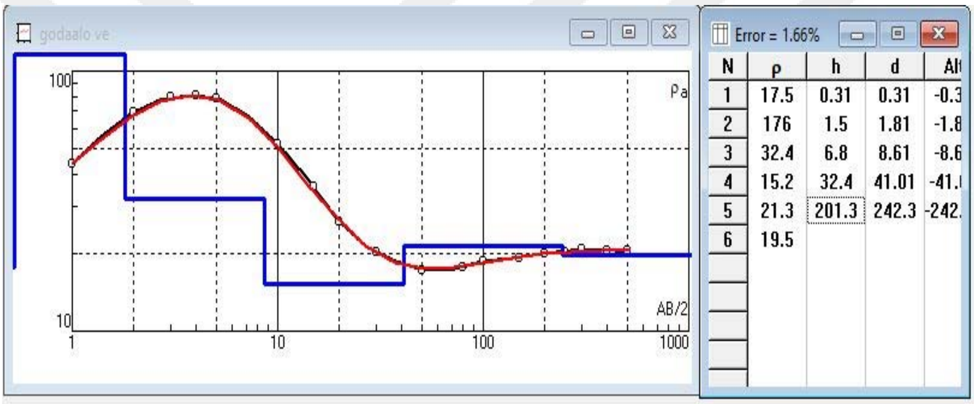


Figure 5. 4. Modeled Electrical Resistivity Curve of Godalo VES 3

Table 5. 4. Hydrogeological Interpretation of Godalo VES 3

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	17.5	0.31	0.31	Top soil	No
2	176	1.5	1.81	Less fractured limestone	No
3	32.4	6.8	8.61	Weathered limestone	No
4	15.2	32.8	41.01	Highly weathered limestone with shale	No
5	21.3	201.3	242.3	Highly weathered limestone	Yes
6	19.5	∞	242.3	Highly weathered limestone	Yes

According to the interpretation, the area is underlain by thin topsoil underlain by limestone of different degrees of weathering. The water-bearing strata were identified within the highly weathering limestone and extends beyond 242.3 m depth. The resistivity value 21.3 Ωm of the water-bearing strata indicates that the degree of weathering is very high and the groundwater quality is determined to be fresh. At this site, a borehole can be drilled with maximum expected drilling depth is 250 m depth.

5.2.2.5. Godalo VES-4 Interpretations

Godalo VES 4 was conducted about 1.8 km east southwest of the town

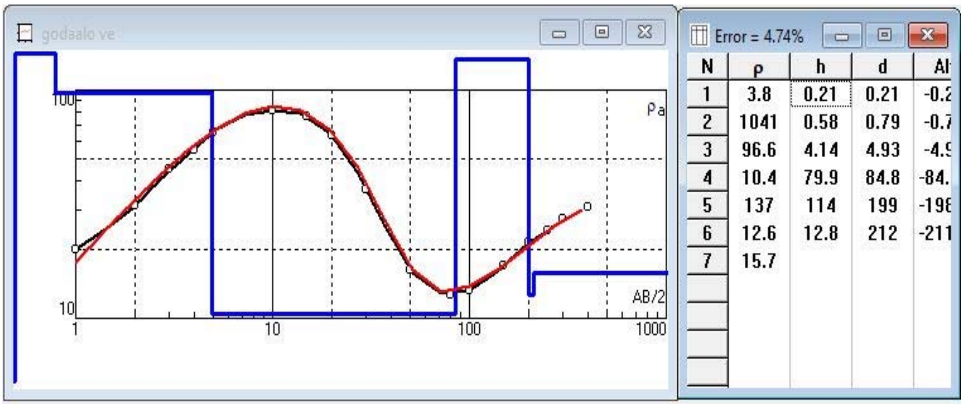


Figure 5. 5. Modeled Electrical Resistivity Curve of Godalo VES 4

Table 5. 5. Hydrogeological Interpretation of Godalo VES 4

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	3.8	0.21	0.21	Clay Top soil	No
2	1041	0.58	0.63	Hard limestone	No
3	96.6	4.14	4.77	Less weathered limestone	No
4	10.4	79.9	84.7	Shale	No
5	137	114	199	Less weathered limestone	No
6	12.6	12.8	212	Highly weathered limestone	Yes
7	15.7	∞	> 212	Highly weathered limestone	Yes

These VES sites, seven geo-electrical layers were identified and maximum penetration of 212 m depth was reached. Similar to those VES sites conducted in areas underlain by the Auradu limestone Formation, the aquifer zone is determined to be within the highly weathered limestone and extends beyond 212 m depth. However, based on the relatively low resistivity value of the water-bearing strata of 12.8 Ωm indicates that water quality is clay. Although, this site can be drilled, due to less quality of the expected groundwater, this site is not recommended for drilling.

5.2.2.6. Godalo VES-5 Interpretations

Godalo VES5 was conducted in areas underlain by the Taleex Gypsum Formation and similar to VES1.

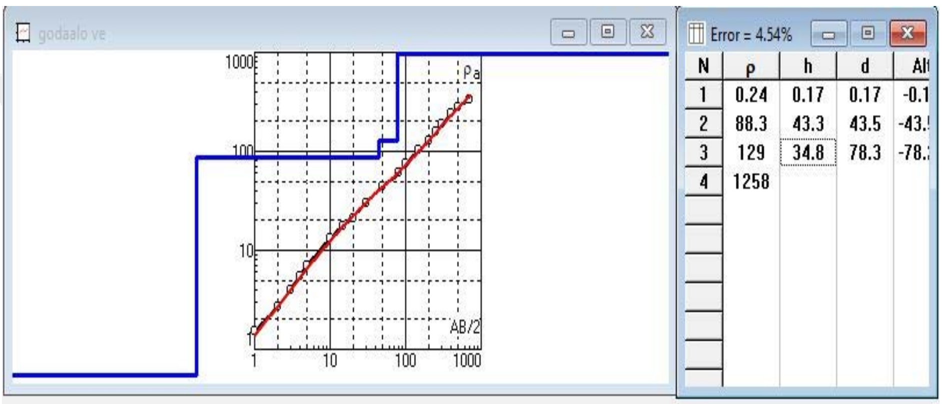


Figure 5. 6. Modeled Electrical Resistivity Curve of Godalo VES 5

Table 5. 6. Hydrogeological Interpretation of Godalo VES 5

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	0.24	0.17	0.17	Gypsiferous top soil	No
2	88.3	43.3	43.5	Fractured gypsum	no
3	129	34.8	78.3	Less weathered Gypsum	No
4	1258	∞	> 70.3	Fresh anhydrite	No

The shallow aquifer was identified, and however, at shallow depth massive anhydrite was encountered. Due to the shallow nature of the aquifer zone in Taleex gypsum formation, which is bounded by massive anhydrite unit, this site, is not recommended from drilling.

5.2.2.7. VES Evaluation and Discussions

Based on the resistivity interpretations of VES sites conducted around Godalo area, two geological units with contrast resistivity values were encountered. VES1 and VES 5 were conducted in areas underlain by the Taleex Gypsum formation, while VES2, VES3, and VES4 were conducted areas underlain by Auradu limestone formation. The raw resistivity data for different depths were gridded and contoured in order to understand the spatial variation to clearly definite the two distinct geological units. The depth of AB/2 of 200 m and 400 were created and relationship was compared.

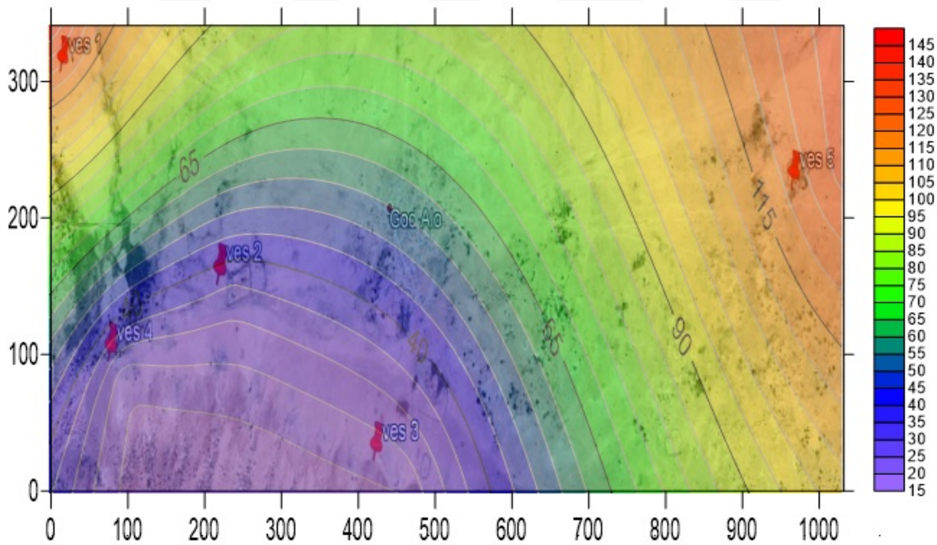


Figure 5. 7. Map showing Apparent Resistivity at 200 m AB/2

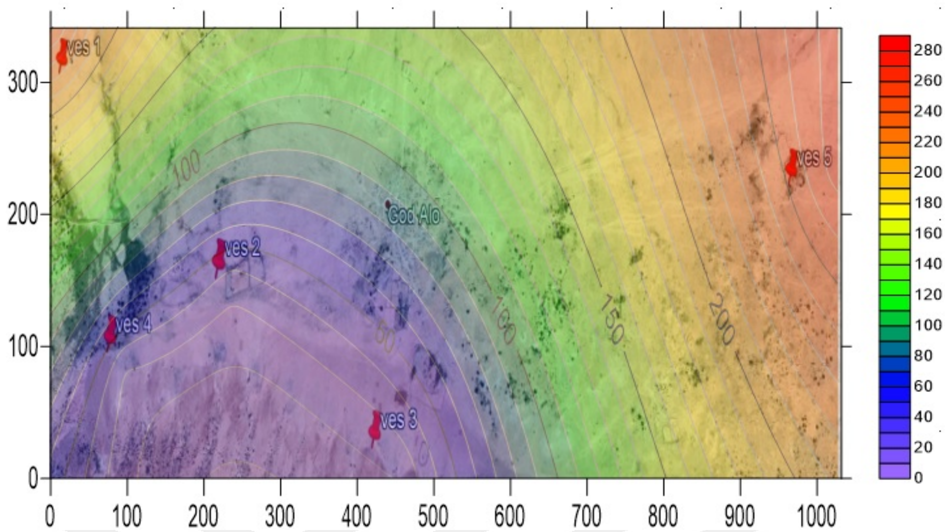


Figure 5. 8. Map showing Apparent Resistivity at 400 m AB/2

Based on the above depicted spatial variations of the apparent resistivity maps at 200 AB/2 and 400 AB/2, clearly correlate both maps, and areas underlain by the Taleex gypsum formation have shown of having very high resistivity value compared with areas underlain by the Auradu limestone. Areas underlain by the Taleex Gypsum formation is predominated by massive anhydrite, while, areas underlain by the Auradu limestone is predominated by highly weathered and fractured limestone which has relatively low resistivity value below 80 Ωm.

In this case, the best suitable to be selected for drilling shall be based on identifying areas of having relatively low resistivity values and in this case, the locations of VES2, VES3, and VES4 satisfy the selection criteria.

Similarly, to understand the vertical variation of resistivity values of the Godalo area, resistivity cross-section was created. As can be observed from the resistivity cross-section, VES1 and VES5 were conducted in the Taleex Gypsum formation area and its resistivity increases with depth, which indicates the presence of compact anhydrite. As you go towards VES2, VES3, and VES4, which are located areas, underlain by the Auradu limestone formation, the resistivity value stabilizes at 30 Ωm, which indicates the presence of highly weathered and fractured limestone. For this reason, either the location of VES2 and VES3 can be selected for the drilling.

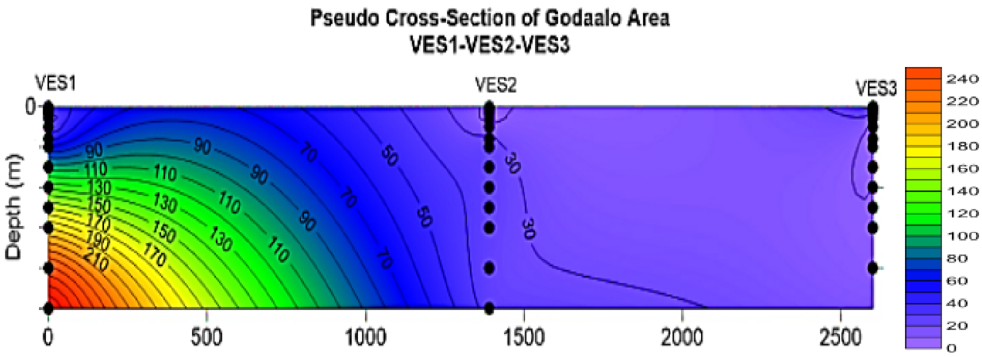


Figure 5. 9. Resistivity Pseudo Cross-Section of Godalo area

5.2.3. Gambadho Village

Gambadho is a relatively small village located on the main road from Lasanod to Garoowe towns and is situated at about 30 km east of Lasanod town. Since Gambadho is located on the main asphalt road, it can be accessed all year round. The geographical coordinates of Gambadho village can be approximated as 47.59984^0 East longitude and 8.564233^0 North Latitude with an average elevation of 576 m.

5.2.3.1. Existing Water Supply Sources

Previously, one shallow well was drilled by the Chinese road construction company is the seventies of the last century. No information about this shallow well was obtained during the field survey other than that the borehole was abandoned due to falling pipes and the pump. This indicates that the well was not properly maintained. Currently, the community obtains its water supply source from individually owned Berkads (ponds). The sanitary condition of the Berkads is very poor. In addition, during prolonged dry seasons, most of the Berkads dry up and the community is forced water trucking.

Table 5. 7.Gambadho VES Locations

Longitude	Latitude	VES ID
47.59669	8.57150	VES 1
47.59913	8.56749	VES 2
47.59631	8.57914	VES 3
47.59619	8.56531	VES 4
47.60247	8.57477	VES 5

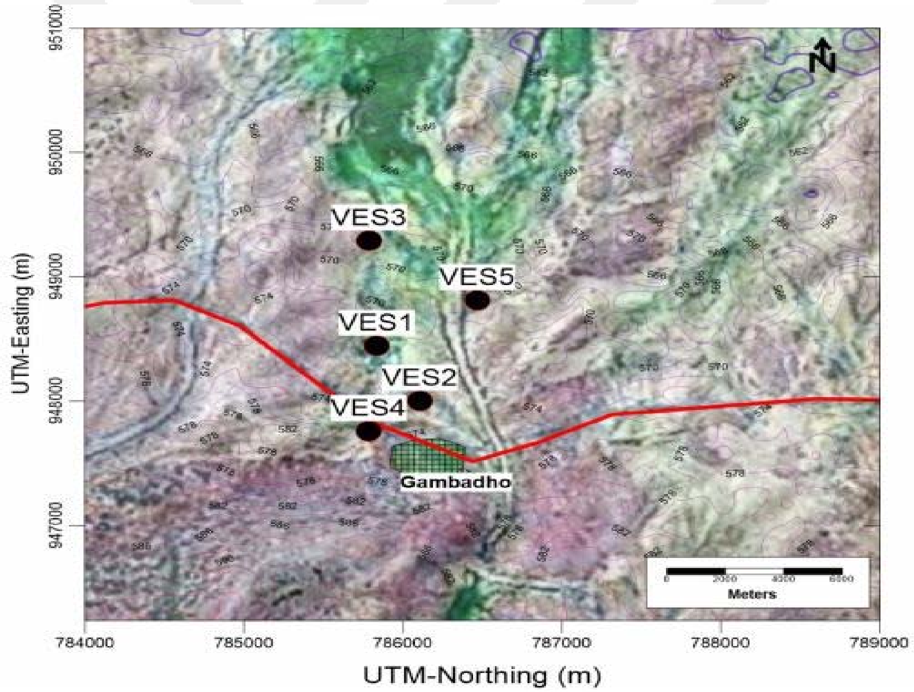


Figure 2. 22 Gambadho VES Location Map

5.2.3.2. Gambadho VES-1 Interpretations

VES1 was conducted adjacent to the abandoned borehole is Gambadho area and was taken as calibration VES.

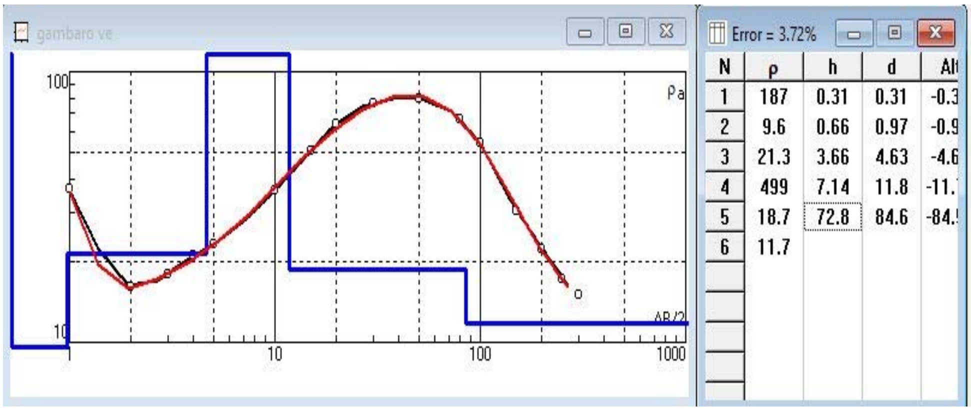


Figure 5. 10. Modeled Electrical Resistivity Curve of Gambadho VES 1

Table 5. 8. Hydrogeological Interpretation of Gambadho VES 1

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	187	0.31	0.31	Gravel Top soil	No
2	9.6	0.66	0.97	Clay with sand	No
3	21.3	3.66	4.63	Sandy clay	No
4	499	7.14	11.8	Gravel	No
5	18.7	72.8	84.6	Wet sand with minor clay	Yes
6	11.7	∞	> 84.6	Highly weathered gypsum	No

This VES site was conducted adjacent to the abandoned borehole drilled by the Chinese road company almost forty years ago. There is no information about this borehole other than that the well was drilled to a depth of 80 m.

According to the interpretation of VES1, six geoelectric layers were identified and penetration of 84.6 m depth was reached. The upper five layers were interpreted as alluvial sediments composed of sandy clay, sand, and gravel underlain by highly weathered gypsum.

The good water-bearing unit, which is 72.8 m thick containing freshwater, was identified, however, as you go depth, the water quality is found to deteriorate.

It seems that the Chinese company who drilled the well had known this information; hence, the well was drilled at 80 m depth in order to avoid the saltwater.

5.2.3.3. Gambadho VES-2 Interpretations

VES2 was conducted at 550 m southeast of the abandoned borehole, in a good-flooded area.

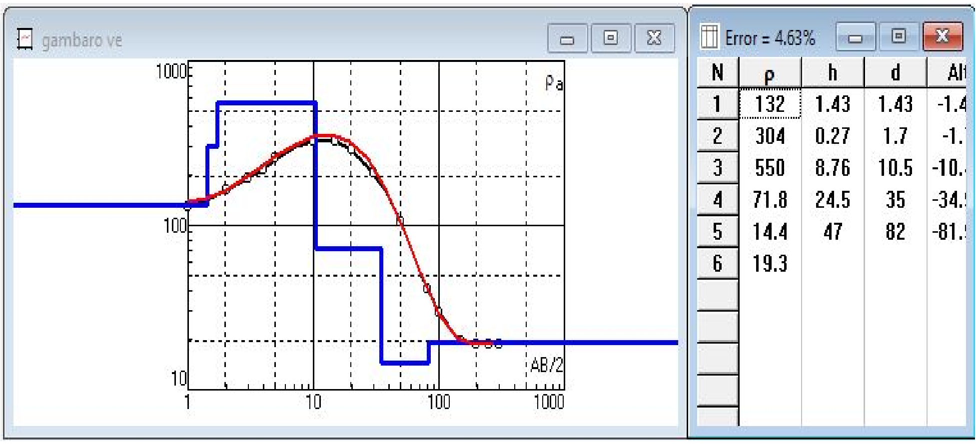


Figure 5. 11. Modeled Electrical Resistivity Curve of Gambadho VES 2

Table 5. 9. Hydrogeological Interpretation of GambadhoVES 2

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	132	1.43	1.43	Dry top soil	No
2	304	0.27	1.7	Gravel with sand	No
3	550	8.76	10.5	Gravel	No
4	71.8	24.5	35	Sand	No
5	14.4	47	82	Sandy clay	Yes
6	19.3	∞	> 82	Weathered gypsum	No

Similar to VES1, the area is found to be underlain by alluvial sediments of different particle sizes up to the depth of 82 m depth, underlain by weathered gypsum. The shallow groundwater quality is found to be similar to those of VES1. Hence, at this site, shallow well can be drilled with a maximum drilling depth of 80 m depth.

5.2.3.4. GambadhoVES-3 Interpretations

VES3 was conducted at about 850 m north of the abandoned borehole.

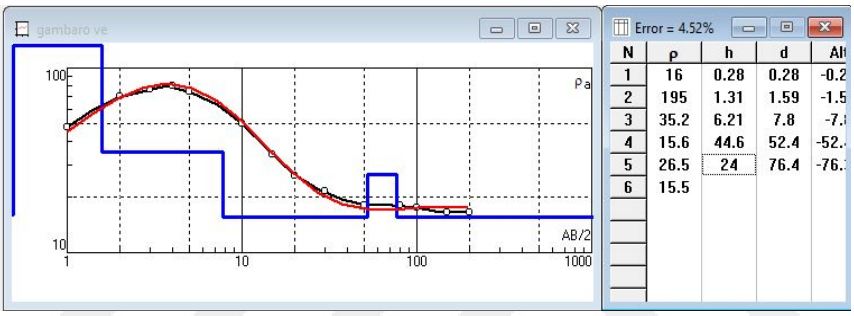


Figure 5. 12. Modeled Electrical Resistivity Curve of Gambadho VES 3

Table 5. 10. Hydrogeological Interpretation of Gambadho VES 3

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	16	0.28	0.28	Sandy clay top soil	No
2	195	1.31	1.59	Gravel	No
3	35.2	6.21	7.8	Sand	No
4	15.6	44.6	52.4	Sandy clay	Yes
5	26.5	24	76.4	Wet sand	Yes
6	15.5	∞	> 76.4	Weathered gypsum	No

According to the interpretation, the area is underlain by reasonably thick alluvial sediments of different particle sizes underlain by weathered gypsum of Taleex gypsum formation. Similar to the previously discussed VES sites, reasonably good groundwater quality is found within the alluvial sediments. For this reason, any borehole drilled in this site should be drilled within the alluvial sediments and the drilling should not penetrate the underlying Taleex Gypsum unit.

5.2.3.5. Gambadho VES-4 Interpretations

Gambadho VES 4 was conducted south of the road at about 200 m west of the village

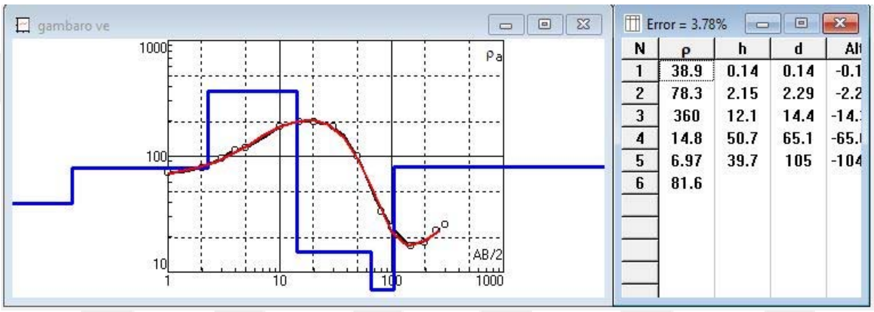


Figure 5. 13. Modeled Electrical Resistivity Curve of Gambadho VES 4

Table 5. 11. Hydrogeological Interpretation of Gambadho VES 4

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	38.9	0.14	0.14	Sandy clay top soil	No
2	78.3	2.15	2.29	Sand	No
3	360	12.1	14.4	Gravel	No
4	14.8	50.7	65.1	Sandy clay	Yes
5	6.97	39.7	105	Highly weathered gypsum	No
6	81.6	∞	> 105	Fractured gypsum	No

These VES sites, six geo-electrical layers were identified and maximum penetration of 105 m depth was reached. 50.7 m thick good water-bearing unit is found within the lower part of the alluvial sediments extending up to 65.1 m depth, however, below this depth, highly weathered gypsum is found. Based on the relatively low resistivity value of the water-bearing strata in the gypsum which of 6.97 Ωm indicates that water quality is salty. Hence, any borehole drilled in this site should not reach beyond 65 m depth.

5.2.3.6. Gambadho VES-5 Interpretations

VES5 was conducted at the eastern bank of Gambadho stream and is situated at about 2 km from the village.

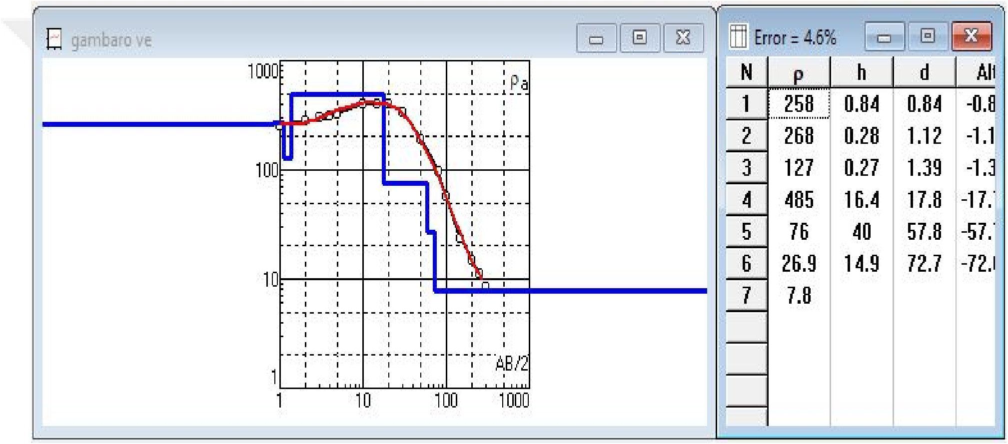


Figure 5. 14. Modeled Electrical Resistivity Curve of Gambadho VES 5

Table 5. 12. Hydrogeological Interpretation of Gambadho VES 5

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	258	0.84	0.84	Gravelly top soil	No
2	268	0.28	1.12	Gravel	No
3	127	0.27	1.39	Gravel with sand	No
4	485	16.4	17.8	Gravel	No
5	76	40	57.8	Sand	Yes
6	26.9	14.9	72.7	Wet sand	Yes
7	7.8	∞	> 72.7	Highly weathered gypsum	No

40 m thick good water-bearing unit is found within the lower part of the alluvial sediments extending up to 57.8 m depth, however, below this depth, highly weathered gypsum is found. At this site, shallow aquifer zone is found to extend up to 72.7 m depth and was found to underlain by highly weathered gypsum.

5.2.3.7. VES Evaluation and Discussions of Gambadho Village

According to the interpretation of five VES, data conducted in the Gambadho area, reasonable thick alluvial sediments of different grain sizes cover the valley and underlain by highly weathered gypsum. The alluvial sediments were found to host shallow aquifer with a reasonable quality of groundwater. The thickness of alluvial sediments was found to vary from place to place, hence, mapping the thickness of alluvial sediments in the Gambadho area will facilitate the identification of the best suitable site to be drilled. The raw resistivity data for different depths were gridded and contoured, in order to understand the spatial variation of alluvial sediments in order to select the best suitable site to be drilled.

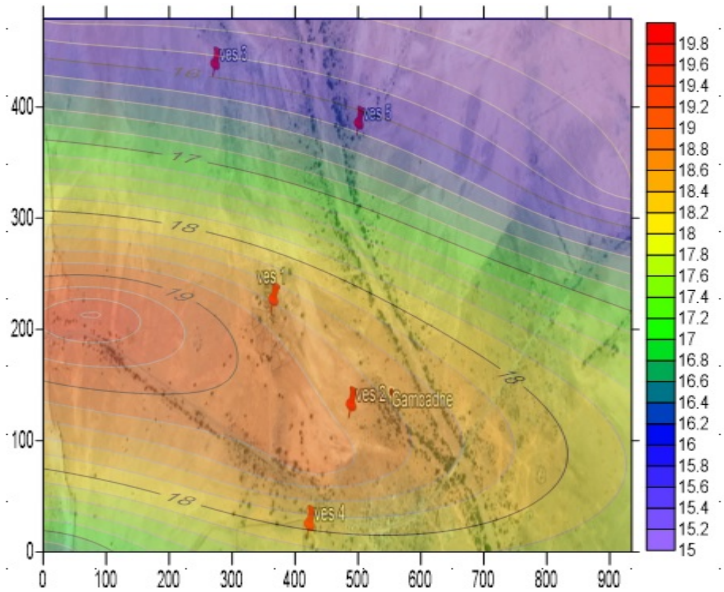


Figure 5. 15. Map showing Apparent Resistivity of Gambadho at 200 m AB/2

For the depth of AB/2 200 was created. one aquiferous zone was identified in the Gambadho area which is the upper alluvial aquifer. The good aquiferous zone targeted for this water investigation is the shallow alluvial aquifer which characterized by relatively resistivity value above 17 Ωm, compared with the low resistivity value of the Taleex gypsum formation.

As you can see on the above resistivity map at 200 AB/2 in Figure 5.15, a high resistivity zone was found to be an area located between VES1 (abandoned borehole) and the location of VES 2, while the resistivity decreases northward which is at downstream. Hence, any borehole drilled in this area shall be selected either the location of VES1 or VES 2. Since VES 1 is the location of the abandoned boreholes, the location of VES 2 is selected for the drilling. Vertical variation of resistivity values of the Gambadho area in the Figure below shows that the resistivity decreases with depth, indicating that the groundwater quality deteriorates with depth. Hence, any borehole drilled in the area shall tap water only the upper shallow alluvial aquifer.

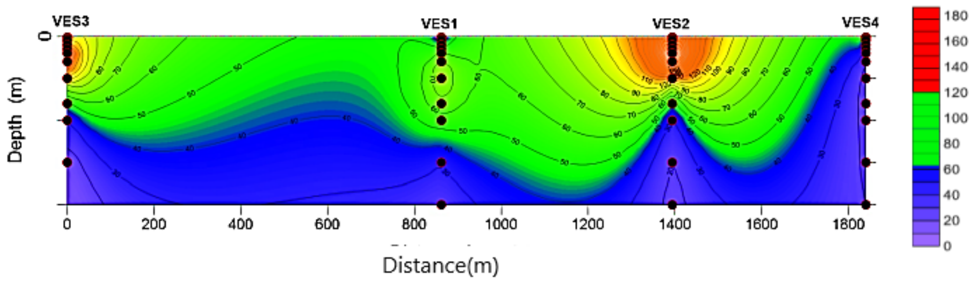


Figure 5. 16. Resistivity Pseudo Cross-Section of Gambadho area

5.2.4. Qoryale Town

Qoryale is a new capital of Qoryale district located at about 60 km south of Burco town and is situated at about 3 km off the main asphalt road. There are about 10 villages under the jurisdiction of the Qoryale district. The residents of the town were estimated at about 1000 families, and there are about 2000 pastoralists living around the town.

Although the town is situated at about 3 km off the main asphalt road, the accessibility is good and can be accessed all year round. The geographical coordinates of Qoryale town can be approximated as 45.97020^0c East longitude and 9.06823^0c North Latitude with an average elevation of 920 m.

5.2.4.1. Existing Water Supply Sources

Deep borehole was drilled in the town and was abandoned due to unprofessional drilling and lack of technical expertise during drilling and subsequent rehabilitation. Originally, the drilling company was contracted to drill 200 m deep borehole without knowing the groundwater condition of the area. The well was drilled, cased and gravel packed, without borehole drilling supervision, and as a result, the well ended up to be dry.

Then, the community and the NGO who funded the drilling of the well decided to extend drilling up to 315 m depth instead of drilling new borehole. Inside 8-inch casing was drilled using small drilling bit and drilling reached at 315 m depth, and the bottom part of the well was left uncased. As a result of the uncased part of the well, the borehole was quickly sanded up; hence, the well was abandoned. Currently, the town receives its water supply from unprotected hand-dug wells excavated in the dry streambed located east of the town along the Qoryale stream. During dry seasons, most of the dug wells dry up and people are forced to fetch water from distant sources.

Figure 5. 17. Qoryale town abandoned borehole with Water scheme construction (SHAAC. 2014).

Table 5. 13. Qoryale VES Locations

Longitude	Latitude	VES ID
45.96606	9.07680	VES 1
45.97796	9.07957	VES 2
45.96606	9.07451	VES 3

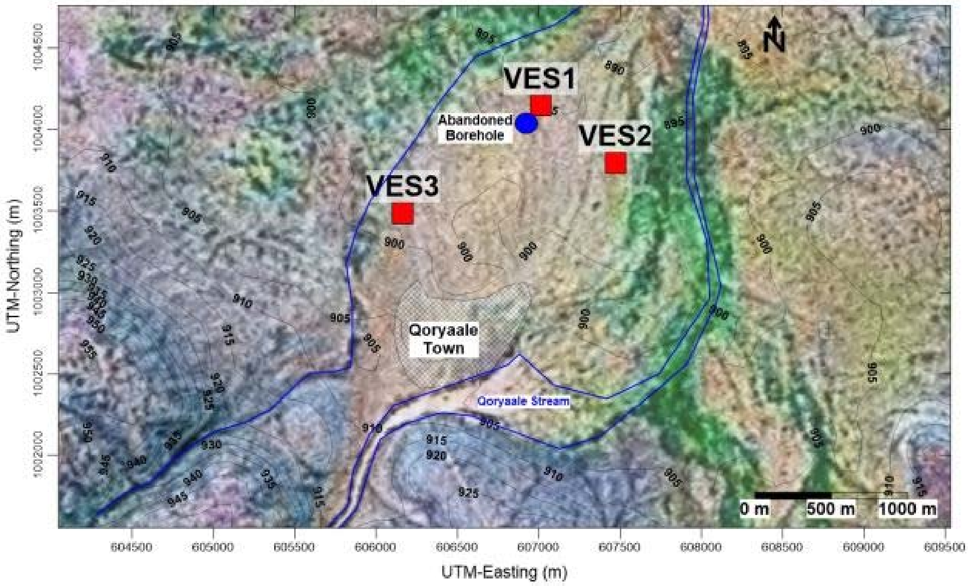
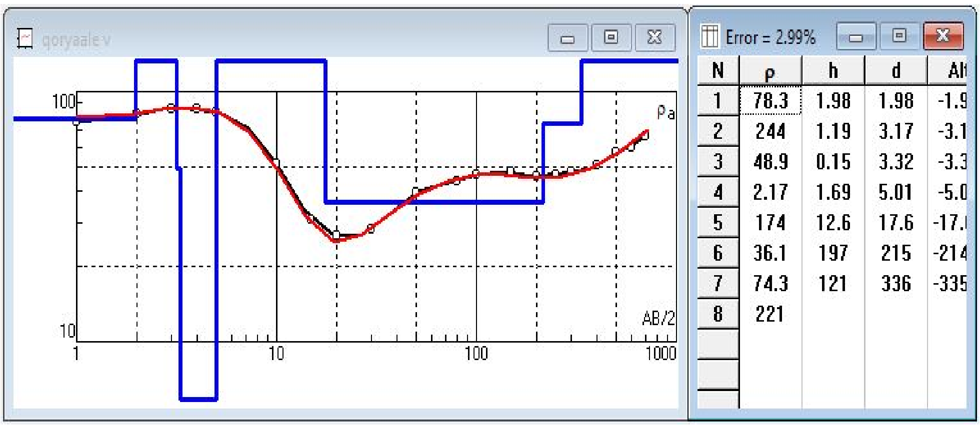


Figure 2. 23 Qoryaale areas VES Location Map

5.2.4.2. Qoryale VES-1 Interpretations

VES1 was conducted adjacent to the abandoned borehole, and the data was taken as calibration VES.



N	ρ	h	d	Alt
1	78.3	1.98	1.98	-1.9
2	244	1.19	3.17	-3.1
3	48.9	0.15	3.32	-3.3
4	2.17	1.69	5.01	-5.0
5	174	12.6	17.6	-17.
6	36.1	197	215	-214
7	74.3	121	336	-335
8	221			

Figure 5. 18. Modeled Electrical Resistivity Curve of Qoryale VES 1

Table 5. 14. Hydrogeological Interpretation of Qoryale VES 1

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	78.3	1.98	1.98	Sandy top soil	No
2	244	1.19	3.17	Gravel	No
3	48.9	0.15	3.32	Sand	No
4	2.17	1.69	5.01	Pure heavy clay	No
5	174	12.6	17.6	Gravel	No
6	36.1	197	215	Highly weathered limestone with minor shale	No
7	74.3	121	336	Weathered limestone containing fresh water	Yes
8	221	∞	[illegible]	Less fractured limestone	Yes

According to VES1 interpretation, eight geo-electrical layers were identified and maximum penetration of 336 m depth was reached. The upper five layers extending up to the depth of 17.6 m depth were interpreted as alluvial sediments composed of pure heavy clay, sand, and gravel.

The alluvial sediments were found to be underlain by three geo-electrical layers extending beyond 336 m depth and were interpreted as limestone of different degrees of weathering and fracturing. The water-bearing strata were found to be within the weathered limestone and extend beyond the underlying less fractured Limestone. Based on the apparent resistivity value of the aquifer zone of 74.3 Ωm, the groundwater quality is found to be fresh. If drilled at this site, the well should be drilled to a maximum depth of 350 m deep.

5.2.4.3. Qoryale VES-2 Interpretations

A team from Somaliland Water Ministry previously investigated this site and the community insisted to be reinvestigated.

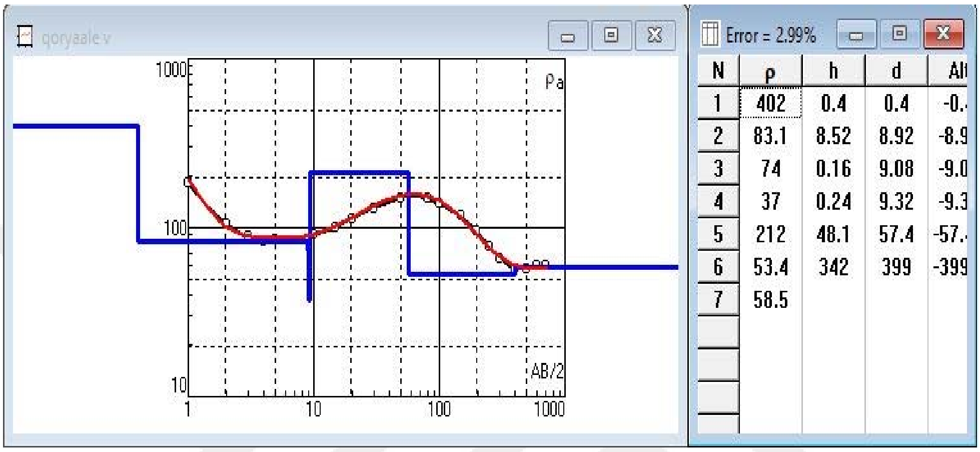


Figure 5. 19. Modeled Electrical Resistivity Curve of Qoryale VES 2

Table 5. 15. Hydrogeological Interpretation of Qoryale VES 2

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	402	0.4	0.4	Dry top soil	No
2	83.1	8.52	8.92	Gravel with sand	No
3	74	0.16	9.08	Sand	No
4	37	0.24	9.32	Sandy clay	No
5	212	48.1	57.4	Less fractured limestone	No
6	53.4	342	399	Weathered limestone	Yes
7	58.5	∞	> 399	Weathered limestone	Yes

Similar to VES1, at this site, the topsoil is underlain by alluvial sediments of different grain sizes and extends up to 9.32 m depth and underlain by a geo-electric layer that was interpreted as less fractured limestone having a resistivity value of 212 Ωm and extends up to 57.4 m depth. Thick 399 m geo-electric layer of having a resistivity value of 53.4 Ωm were identified and interpreted as weathered limestone.

The aquifer zone was interpreted to contain within the weathered limestone and extends within the underlying geo-electric layer. Similar to VES1, if drilled the location of VES2, the maximum recommended drilling depth is 350 m depth.

5.2.4.4. Qoryale VES-3 Interpretations

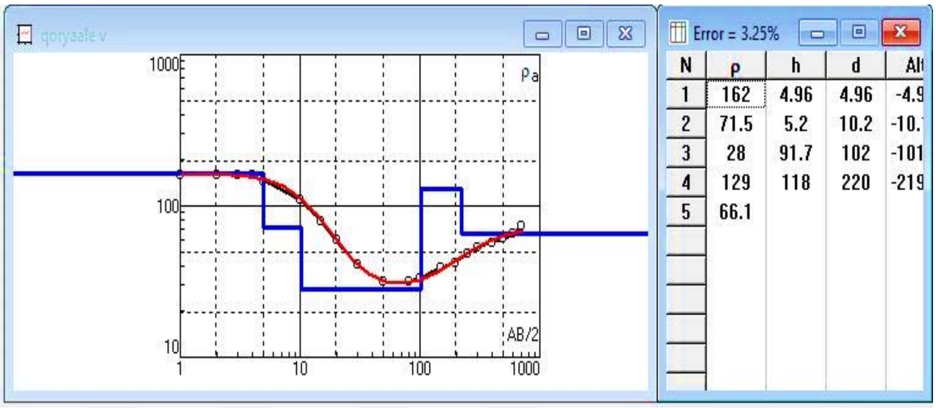


Figure 5. 20. Modeled Electrical Resistivity Curve of Qoryale VES 3

Table 5. 16. Hydrogeological Interpretation of Qoryale VES 3

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	162	4.96	4.96	Dry topsoil	No
2	71.5	5.2	10.2	Sand	No
3	28	91.7	102	Highly weathered limestone with shale	No
4	129	118	220	Less weathered limestone	No
5	66.1	∞	> 220	Weathered limestone	Yes

Similar to VES1 and VES2, the VES3 area was found that alluvial sediments underlain by limestone underlie the topsoil. The water-bearing unit was found within the weathered limestone starting at 220 m depth and extends beyond this depth. Similar to previous VES sites, this site can be drilled with maximum expected drilling depth of 350 m depth.

5.2.4.5. VES evaluation and Discussions of Qoryale Town

All three VES sites water-bearing unit was identified, however, since the aquifer is within the Auradu limestone, its aquifer is the fractured type of aquifer. The intensity of fracturing and the degrees of weathering will determine the expected yield of any borehole drilled in the fractured aquifer. For this reason, the selection of the best suitable site to be selected for drilled will be based on identifying that have the highest degree of weathering and fracturing. The raw resistivity data for different depths were gridded and contoured in order to understand the spatial variation of alluvial sediments in order to select the best suitable site to be drilled. For the depth of AB/2 of 200 was created.

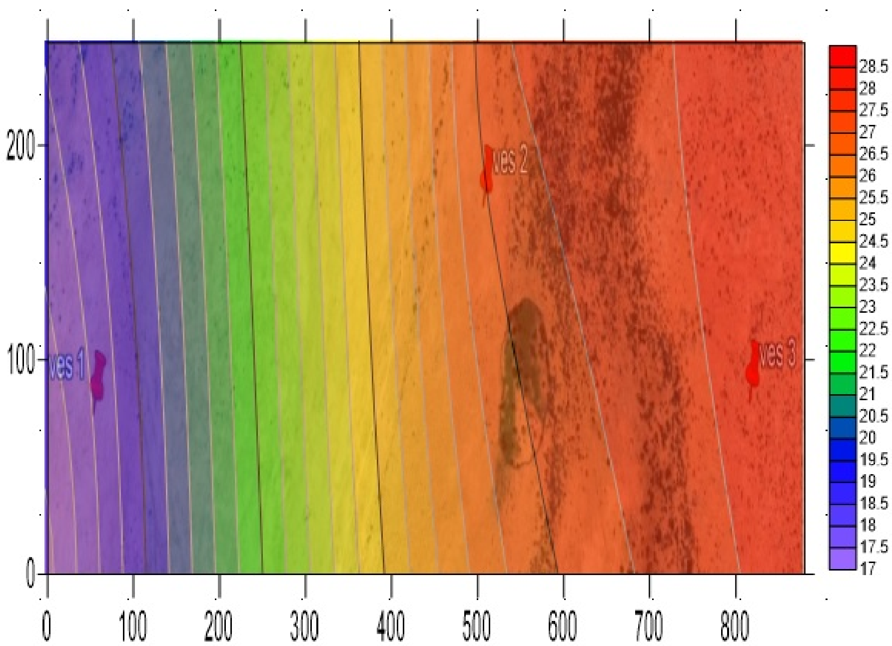


Figure 5.21. Map showing Apparent Resistivity of Gambadho at 200 m AB/2

Hence, resistivity cross-section connecting VES1-VES2-VES3 was prepared so as to determine the site that will have the highest degree of weathering. and in this case, the site that has the lowest apparent resistivity of the expected aquifer zone shall be selected. So, the best suitable to be selected for drilling shall be based on identifying areas of having relatively low resistivity values and in this case, the locations of VES1 satisfy the selection criteria.

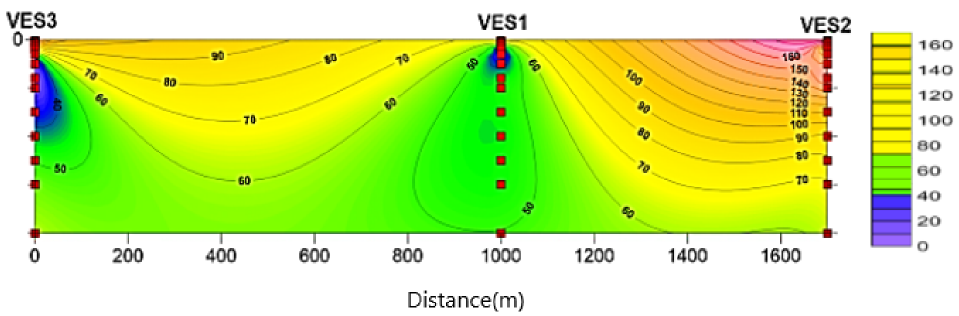


Figure 5.22. Resistivity Pseudo-cross-section of Qoryale area

As it can be observed from above-depicted resistivity Pseudo Cross-Section and gridded contour map, VES 2 and VES 1, the expected aquifer zone will have an average resistivity value of 50 to 60 Ωm, while the location of VES2, high resistivity value of between 70 to 80 Ωm is expected to have the water-bearing unit. Hence, the VES 2 location is the least weathered and fractured compared to VES1 and VES3. Therefore, either the location of VES1 or VES3 can be selected for drilling.

Since the VES1 site has previously been drilled and water systems such as an elevated reservoir, generator house, and guardhouse have been built, it will be wise for the consultant to consider all these structures and incorporate them into the planned water supply for the town of Qoryale. For these reasons and the geophysical findings, the location of VES1 is recommended for drilling and maximum recommendation.

5.2.5. Magalo'ad District

Magalo'ad is a relatively small town with a large agro-pastoral community and recently been nominated by the Somaliland Government as the Capital city of Magalo'ad District of Awdal. Magalo'ad district has its boundary with Boorama district to the north, Gebiley district to the east and Somali Region of Ethiopia to the south and west.

Magalo'ad town can be accessed from the commercial city of Togwachale town that can be accessed through an asphalt road from Kalabeydh village to Togwachale town. Then, a dry weather road from Togwachale to Magalo'ad could be accessed. This dry weather road can be used only during dry seasons. The geographical coordinates of Qoryale town can be approximated as 43.30112^0 East longitude and 9.69355^0 North Latitude with an average elevation of 1750 m.

5.2.5.1. Existing Water Supply Sources of Magalo'ad District

Former Somali Government has drilled a borehole around Magalo'ad area but was abandoned due to being dry and reaching the Basement rocks at shallow depth. Three water ponds that supply water to the community, however, during dry seasons, most of the ponds dry up and people relay water from distance borehole located on the other side of the international boundary in Ethiopia and water trucking.

Table 5.17. Magalo'ad VES Locations

Longitude	Latitude	VES ID
43.29811	9.68261	VES 1
43.29675	9.67076	VES 2
43.29841	9.64911	VES 3
43.30094	9.64288	VES 4
43.30771	9.63956	VES 5
43.29696	9.61823	VES 6

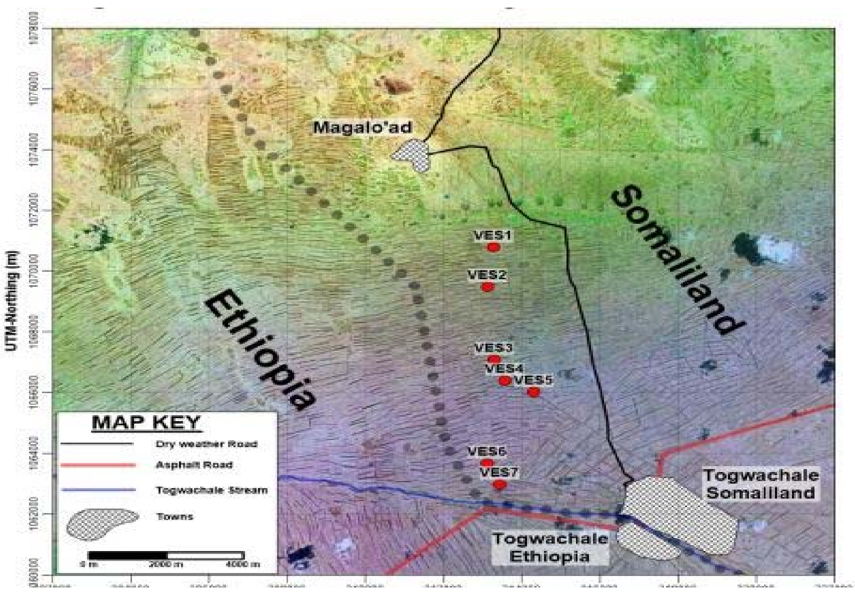


Figure 2. 24 Magalo'ad area VES Location Map

5.2.5.2. Magalo'ad VES-1 Interpretations

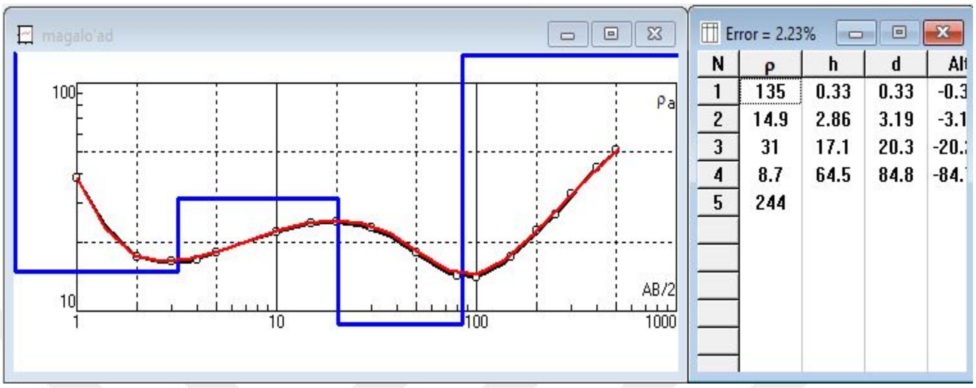


Figure 5.23. Modeled Electrical Resistivity Curve of Magalo'ad VES 1

Table 5.18. Hydrogeological Interpretation of Magalo'ad VES 1

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	135	0.33	0.33	Dry top soil	No
2	14.9	2.86	3.19	Sandy clay	No
3	31	17.1	20.3	Sand	No
4	8.7	64.5	84.8	Sandy clay	Yes
5	244	∞	> 84.8	Basement	Yes

According to VES1 interpretation, Apart from the topsoil, the area is underlain by alluvial sediments consisting of sand and sandy clay up the depth 84.8 m depth. The alluvial sediments were found to be underlain by the Basement rocks. The water-bearing unit at this site was found with the sandy clay unit. Although the borehole was abandoned, it seems the reason could be ether technical drilling difficulties as the predominant lithology is loose alluvial sediments or could be low yield.

5.2.5.3. Magalo'ad VES-2 Interpretations

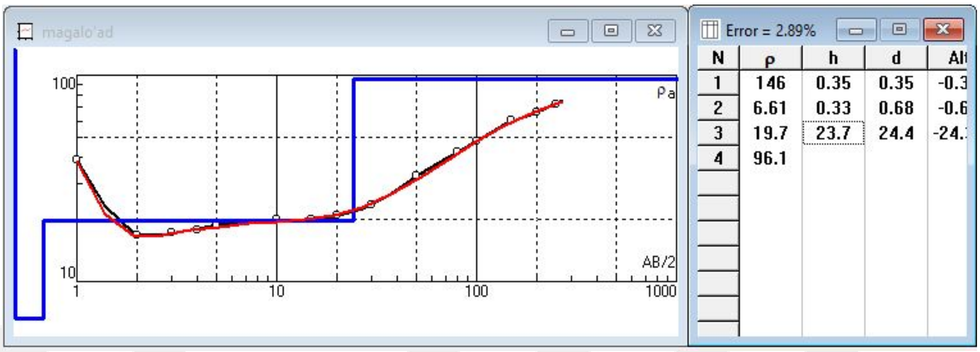


Figure 5.24. Modeled Electrical Resistivity Curve of Magalo'ad VES 2

Table 5.19. Hydrogeological Interpretation of Magalo'ad VES 2

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	146	0.35	0.35	Dry top soil	No
2	6.61	0.33	0.68	Clay	No
3	19.7	23.7	24.4	Sandy clay	No
4	96.1	∞	> 24.4	Weathered Basement	No

At this VES sites, thin alluvial sediments were found to be underlain by the Basement rocks. Due to the shallow nature of the basement rocks, water-bearing strata were not Identified. Hence, a borehole cannot be drilled at this site.

5.2.5.4. Magalo'ad VES-3 Interpretations

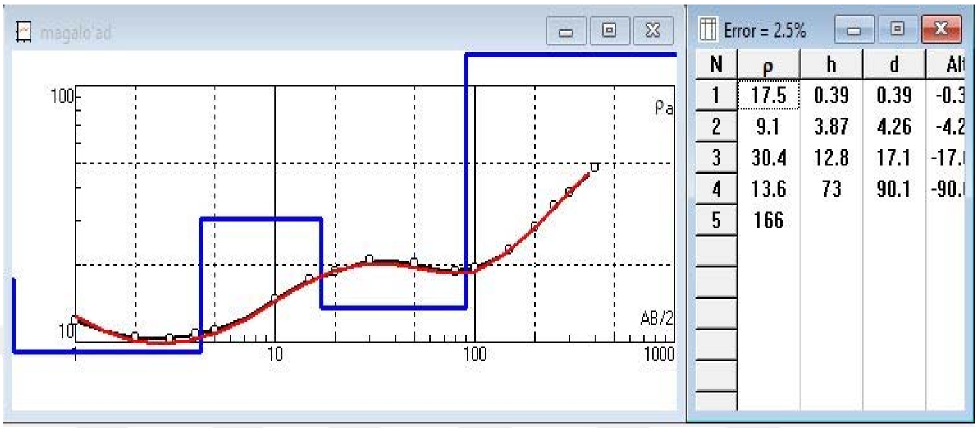


Figure 5.25. Modeled Electrical Resistivity Curve of Magalo'ad VES 3

Table 5.20. Hydrogeological Interpretation of Magalo'ad VES 3

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	17.5	0.39	0.39	Sandy clay top soil	No
2	9.1	3.87	4.26	Clay	No
3	30.4	12.8	17.1	Sand	No
4	13.6	73	90.1	Sandy clay	Yes
5	166	∞	> 90.1	Basement	No

Similar to VES1 and VES2, the VES3 area was found that the topsoil is underlain by alluvial sediments underlain by Basement rocks. The water-bearing unit was found within the sandy clay unit and extends up the basement rocks at 90.1 m depth. This site can be drilled, the well will be shallow less than 100 m depth.

5.2.5.5. Magalo'ad VES-4 Interpretations

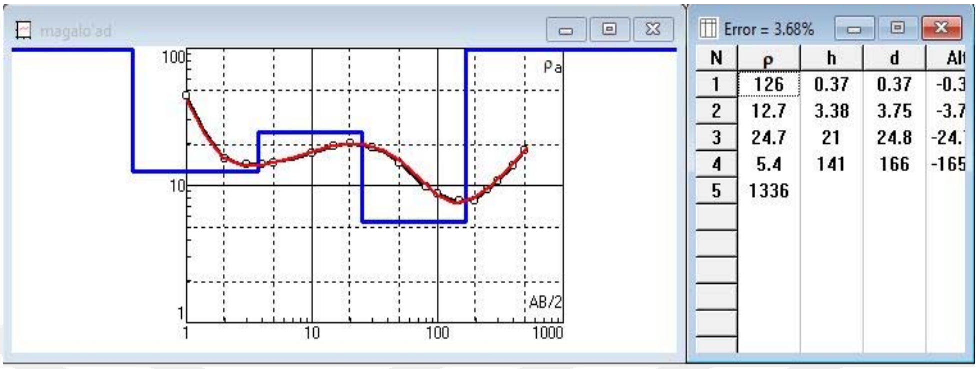


Figure 5.26. Modeled Electrical Resistivity Curve of Magalo'ad VES 4

Table 5.21. Hydrogeological Interpretation of Magalo'ad VES 4

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	126	0.37	0.37	Dry top soil	No
2	12.7	3.38	3.75	Sandy clay	No
3	24.7	21	24.8	Sand	No
4	5.4	141	166	Wet sandy clay	Yes
5	1336	∞	> 166	Basement	No

Similar to VES1, VES2, and VES3, the location of VES4 was found that the topsoil is underlain by thick alluvial sediments, which extends up to 166.02 m depth and underlain by Basement rocks. The water-bearing unit was found within the sandy clay unit and extends up the basement rocks. At this site, a reasonably deep aquifer of about 170 m depth could be drilled.

5.2.5.6. Magalo'ad VES-5 Interpretations

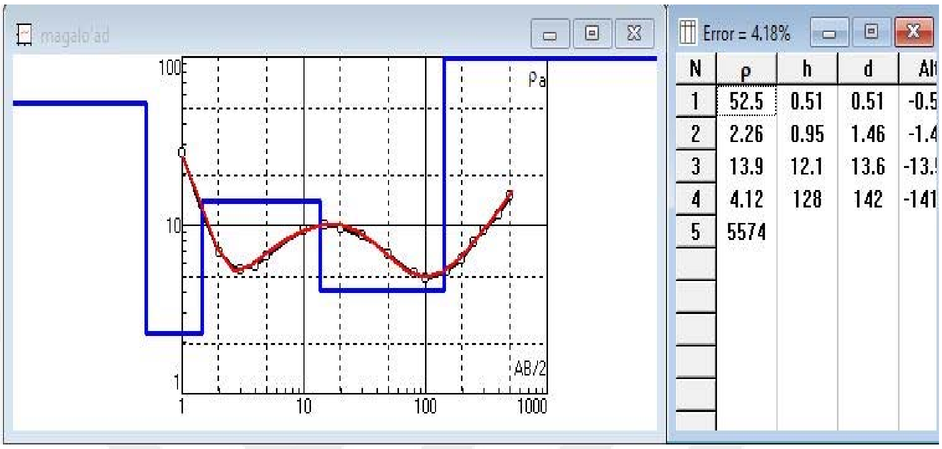


Figure 5.27. Modeled Electrical Resistivity Curve of Magalo'ad VES 5

Table 5.22. Hydrogeological Interpretation of Magalo'ad VES 5

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	52.5	0.51	0.51	Sandy top soil	No
2	2.26	0.95	1.46	Clay	No
3	13.9	12.1	13.6	Sandy clay	No
4	4.12	128	142	Wet sandy clay	Yes
5	5574	∞	> 142	Basement	No

Similar to VES 4, the location of VES 5 was found that the topsoil is underlain by thick alluvial sediments, which extends up to 142 m depth and underlain by Basement rocks. The water-bearing unit was found within the sandy clay unit and extends up the basement rocks. At this site, a reasonably deep aquifer of about 150 m depth could be drilled.

5.2.5.7. Magalo'ad VES-6 Interpretations

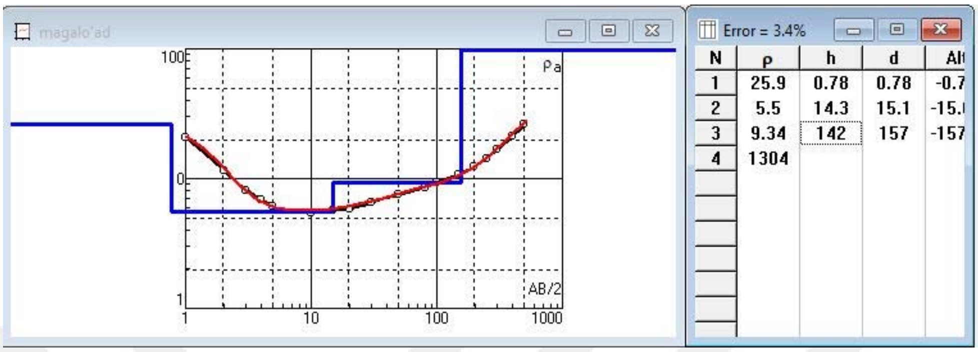


Figure 5.28. Modeled Electrical Resistivity Curve of Magalo'ad VES 6

Table 5.23. Hydrogeological Interpretation of Magalo'ad VES 6

Layer	Resistivity(Ωm)	Thickness(m)	Depth(m)	Interpretation	Aquiferous
1	25.9	0.78	0.78	Sandy top soil	No
2	5.5	14.3	15.1	Sandy clay	No
3	9.34	142	157	Sandy clay	No
4	1304	∞	> 157	Basement	Yes

VES 6 is situated at about 2 km east of a borehole drilled by the Ethiopian Government on the other side of the boundary. The borehole was told to be drilled up to the basement rocks at 180 m depth. At this VES site, similar to previous VES sites, thick alluvial sediments extending up to 157 m depth were identified underlain by the basement rocks. The water-bearing unit is found within the sandy clay unit. If drilled at this site, the recommended drilling depth is 160 m depth.

5.2.5.8. VES evaluation and site selection

Several boreholes drilled in and around Magalo'ad area was abandoned due to low yield or due to being dry because of the Basement rocks reached at shallow depth, due to lack of highly weathered and well-developed fractures in the basement can be considered as an impervious layer and groundwater development is unlikely. Hence, identifying, thick alluvial sediments overlain on the basement could store groundwater and there will be a possibility of exploiting groundwater in the alluvial deposit. Hence, the best suitable site to be selected for drilled will be based on identifying areas of having the maximum thick alluvial sediments. resistivity cross-section connecting all the VES sites along the North-South profile was prepared.

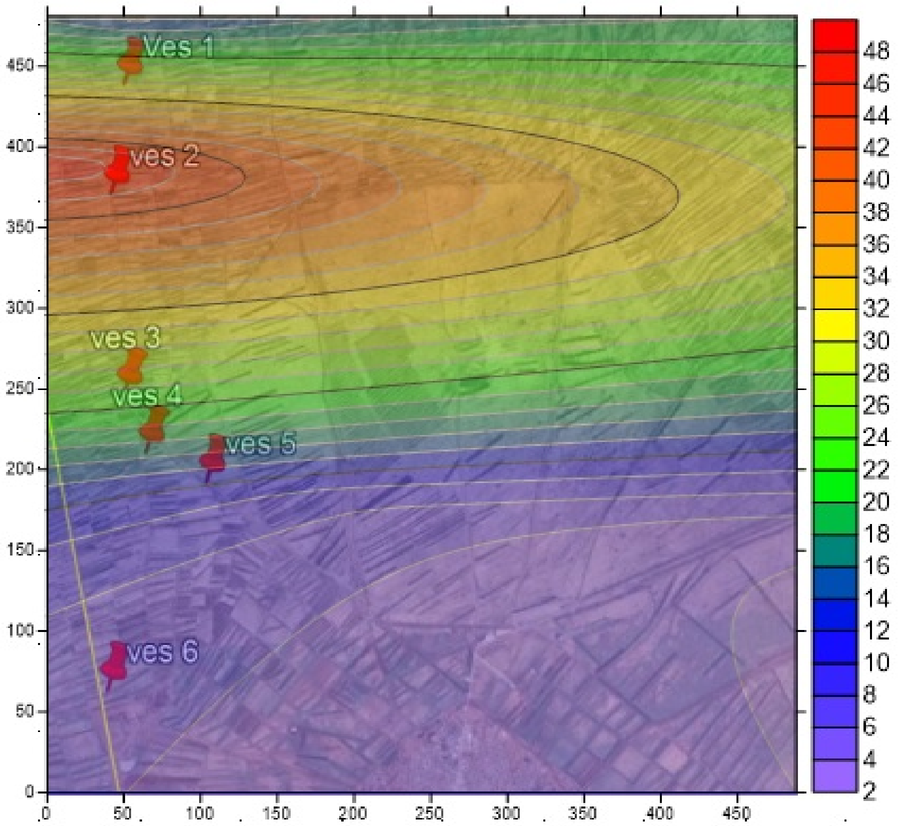


Figure 5.29. Map showing Apparent Resistivity at 100 m AB/2

The raw resistivity data for different depths were gridded and contoured in order to understand the spatial variation of alluvial sediments in order to select the best suitable site to be drilled. For the depth of AB/2 of 100 m was created. As can be observed from above and contoured, The northern VES sites namely VES1, VES2 and VES3, high resistivity values predominate, while the southern VES sites low resistivity value area predominated. At VES 4 area, sharp vertical contact of low and high resistivity values is clearly marked, and this could be the presence of a fault in which, the northern part is uplifted while the southern part there down drops.

6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

During the study every effort was made to examine every potential water source for each studied site and based on the findings, the appropriate water source for each village/town is selected. A lot of effort has been dedicated to groundwater sources because groundwater is more reliable and sustainable than surface water. The major aim of this water investigation was to identify the best location of a borehole drilling and because of this detailed water investigation.

According to the findings from the surfer Software, in Godalo two geological units with contrast resistivity values were encountered. VES1 and VES 5 were conducted in areas underlain by the Taleex Gypsum formation, while VES2, VES3, and VES4 were conducted areas underlain by Auradu limestone formation.

The raw resistivity data for different depths were gridded and contoured in order to understand the spatial variation to clearly definite the two distinct geological units. For the depth of AB/2 of 200 m and AB/2 400 m were created and the relationship was compared. Both maps were clearly correlated, and areas underlain by the Taleex gypsum formation have shown of having very high resistivity value compared with areas underlain by the Auradu limestone. Areas underlain by the Taleex Gypsum formation is predominated by massive anhydrite, while, areas underlain by the Auradu limestone is predominated by highly weathered and fractured limestone which has relatively resistivity value below of 80 Ωm.

In Gambadho the raw resistivity data for different depths were gridded and contoured, in order to understand the spatial variation of alluvial sediments in order to select the best suitable site to be drilled. For the depth of (AB/2), 200 m was created. one aquiferous zone was identified in the Gambadho area which is the upper alluvial aquifer. The good aquiferous zone targeted for this water investigation is the shallow alluvial aquifer which characterized by resistivity value above 17 Ωm, compared with the low resistivity value of the Taleex gypsum formation which is under alluvial aquifer in this gypsum formation, we cannot find water due to it is geological formation.

In Qoryale, the raw resistivity data for different depths were gridded and contoured in order to understand the spatial variation of alluvial sediments in order to select the best suitable site to be drilled. For the depth of AB/2 of 200 was created. Hence, the resistivity cross-section connecting VES1-VES2-VES3 was prepared to determine the site that will have the highest degree of weathering. In this case, the site that has the lowest apparent resistivity of the expected aquifer zone shall be selected. So, the best suitable to be selected for drilling shall be based on identifying areas of having relatively low resistivity values and in this case, the locations of VES1 satisfy the selection criteria

In the raw resistivity, data for different depths were gridded and contoured in order to understand the spatial variation of alluvial sediments in order to select the best suitable site to be drilled. For the depth of AB/2 of 100 m was created. The northern VES sites namely VES1, VES2 and VES3, high resistivity values predominate, while the southern VES sites low resistivity value area predominated. At VES 4 area, sharp vertical contact of low and high resistivity values is clearly marked, and this could be the presence of a fault in which, the northern part is uplifted while the southern part there down drops.

6.2. Recommendations

6.2.1. Godalo Recommendations

Two distinct geological units were mapped in Godalo area. In the town and the northern part of the area was found that Taleex Gypsum is underlain while the southern part is predominated by the Auradu limestone formation.

- Both areas were investigated and areas underlain by the Taleex Gypsum formation are found to be predominated by massive anhydrite, while, areas underlain by the Auradu limestone are predominated by highly weathered and fractured limestone which has relatively resistivity value below 80 Ωm. Relatively good water-bearing strata were found within the Auradu limestone formation.
- Both, the location of VES2 and VES3 can be drilled, however, considering the relatively high resistivity value of VES2 compare with the resistivity value of VES3, it seems that the water quality is slightly better in VES2 than VES3.
- Therefore, the location of VES2 is recommended for drilling and the maximum recommended drilling depth is 230 to 250 m depth.

6.2.2. Gambadho Recommendations

The subsurface geology of the Gambadho area was found to be composed of reasonably thick alluvial sediments underlain by highly weathered gypsum of Taleex gypsum Formation.

- Based on the resistivity survey result, a shallow water-bearing unit containing freshwater was identified within the alluvial sediments characterized by a relatively high resistivity value of above 17 Ωm and extends to an average depth of 80 m depth.
- Below the depth of 80 m depth, another, deep aquifer characterized by relatively low resistivity values of below 10 Ωm which indicates salt was identified within the Taleex Gypsum Formation that emphasis us we cannot find water.

- Any borehole drilled in the Gambadho area shall be shallow in order to tap groundwater from the alluvial sediments, and the well shall not be deep more than 80 m depth.
- The location of VES2 which is close to the village is recommended, and the maximum recommended drilling depth is 80 m depth.
- In order to avoid accidentally penetrating the Taleex gypsum formation and tapping the salt, a competent site Geologist should follow the drilling activities.

6.2.3. Qoryale Recommendations

Qoryale area, the subsurface geology is found to thin alluvial sediments underlain by limestone of Auradu limestone formation.

- The aquifer zone was determined to be deep, starting below 250 m depth.
- The degree of weathering of the expected water-bearing unit was found to decrease toward the location of VES2.
- Based on the resistivity interpretations, the locations of either VES3 and VES1 can be drilled, however, considering the water scheme already in place at the location of VES1, the consultant has selected the location of VES1, with a maximum expected drilling depth of 350 m deep.

6.2.4. Magalo'ad Recommendations

The major aim of this water investigation was to identify the best location of a borehole drilling and as a result of this detailed water investigation, the following conclusions and recommendations are made:

- The predominant lithological units that outcrops in Magalo'ad and its surrounding areas are Alluvial sediments underlain by the Basement Rocks.
- Due to faulting and formation of Grabens, the basement rocks at the northern side of the study area were found to be uplifted, hence, the basement rocks either outcrops or could be shallow. Therefore, close to the town, the basement rocks were found to be shallow, and any borehole drilled will be either dry of low yield.
- However, as you go toward the south, due to the down drop of the Basement, and sedimentation of thick alluvial sediments, the basement rocks could be deep and the location of VES 4 could be reached at 170 m depth.
- The water-bearing strata were found within the Alluvial sediment (Sandy clay)
- The aquifer zone is determined to be huge and extends beyond up to 170 m depth.
- Therefore, the location of VES 4 is found to be an appropriate site to be drilled and the maximum expected drilling depth is 170 m depth.

The following table is synopses of the recommended sources and locations of the recommended drilling sites.

Table 5.24. Details of the recommended sources

No	Investigated Sites	Recommended VES Site	Geographic Coordinates in Degrees		Recommended Depth (m)
			Longitude	Latitude	
1	Godalo	VES 2	47.91411^{0}	9.086727^{0}	230-250
2	Gambadho	VES 2	47.59913^{0}	8.56749^{0}	80
3	Qoryale	VES 1	45.96606^{0}	9.07680^{0}	350
4	Magalo'ad	VES 4	43.30094^{0}	9.64288^{0}	170

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