

Master Thesis in Geosciences

Hydrogeological Investigations of Deep Coastal Aquifers, Tanzania

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FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Faculty of Mathematics and Natural Sciences

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Cover Photo: Kimbiji area in Dar es Salaam, near drilling site, Indian Ocean in the background.

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However, I alone am responsible for any shortcomings or omissions; I wish to state that except for the quotations and references made, I take responsibility for whatever is written in this thesis.

Apolkarpi Peter James

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ABSTRACT

Borehole geophysical logging is viable method of determining the water quality and hydrogeological parameters of aquifers. A recent study was conducted to delineate the distribution of formation water salinity profile down to 600 meters below land surface of the Kimbiji coastal aquifer located 40 km south of the commercial capital, Dar es Salaam coastal plain in Tanzania. A hydrogeologic seismic cross section was also constructed. The borehole geophysical methods included short and long normal resistivity, natural gamma, spontaneous potential, temperature and caliper.

The logs show high permeability and the presence of formation fresh water as indicated by the separation of short/long normal resistivity readings down to 600m. The potential aquifers were determined based on the natural gamma values less than 23 counts per second to map the sandy intervals. The temperature log shows increasing values with depth from the surface up to 450 meters. This indicates that there is no vertical flow of the water in the borehole along this depth interval and it reflects the normal geothermal gradient. From 460 to 520 and 560 to 612 meters below land surface the log shows a constant or nearby constant temperature with depth which indicates the natural movement of water along the borehole axis (zones of vertical borehole-fluid movement). A clearly curved temperature signature was observed between 540 to 440 meters and this was interpreted as an effect of groundwater flow. A caliper log was used to identify fractures and possible water-producing openings and correct other geophysical logs for changes in borehole diameter. Major fractures and most interesting, occurred at 505 to 515 and 560 to 612 meters below land surface which coincides directly with the change in temperature gradient. These are interpreted as the most important water producing zones as indicated by both temperature log and caliper log.

The classification method used in this thesis defines freshwater as having a total dissolved solids concentration of less than 1100 mg/l; waters with a total dissolved solids concentration greater than 1100 mg/l are considered to be saltwater (or saline). For the aquifer formation the pronounced peak values of salinity occur at depth 330.5 to 331 meters below the land surface with pronounced peak value of 1590 mg/l at 330.7 meter.

The lowest value of salinity along the profile is 526 mg/l. The salinity values show decrease trend with depth with more freshwater from 480 down to 612 meters. The average salinity for the whole potential aquifer was 850 mg/l. The calculated salinity profile in the Kimbiji aquifer is interpreted to be residual in which most parts of the aquifer have been completely flushed out by meteoric water.

The depth to the top of Eocene seismic reflector which is the base of Kimbiji aquifer is tectonically controlled as indicated by the seismic cross section.

The virtually untapped Kimbiji coastal aquifer system is considered to be an important supplemental source of water for public use in the highly populated coastal area of Dar es Salaam in Tanzania.

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Appendix B: Seismic reflection profile for traversing line 2 (TPDC archive).

CHAPTER ONE

1.0 Introduction

Water is an indispensable resource for human life. The global demand for fresh water doubles every 20 years (Foster, 1999). The high demand for freshwater, suggests clearly that, surface water can no longer meet the projected total demand. This growing demand is putting enormous pressure on water resources. Since many of the surface water sources have been degraded or depleted, due to exposure to pollution, increase in population, deforestation in the catchment areas, changes in climate and over-exploitation, much pressure is being exerted on the groundwater sources. Groundwater is well suited for this purpose because of its wide distribution, dependability, comparatively more accessible; it can provide cheap convenient individual supplies, it is generally less capital intensive to develop, the quality usually meets the requirements for human consumption, available all year round and the technologies for its abstraction are amenable to community level operation and maintenance.

Groundwater can be defined as subsurface water that occurs in voids, fractures and permeable geological formations. It accounts for about 97% (excluding permanently frozen water) of the Earth's useable freshwater resource (Canter, *et al.*, 1987, Leopold, 1974). It plays an important role in maintaining soil moisture, stream flow and wetlands. Over half of the world's population depends on groundwater for drinking water supplies. In the United Kingdom about 30% of the public water supplies are derived from groundwater, in the United states of America about 50%, Denmark 99% (Tebbutt, 1992), and in Germany 70% (Trauth and Xanthopoulos,1997). In Tanzania, 30% of the population is directly depending on groundwater (Materu, 1996).

Groundwater, however, particularly in the coastal areas is vulnerable to saltwater intrusion. Coastal aquifer investigations require thorough knowledge about the processes of sedimentation, transgression and regression of the sea and tectonic processes to predict the possible aquifers and the incursion of the sea water. The presence of saline in the groundwater widely results in significant deterioration of the quality. This deterioration

has contributed to a larger extent to escalating water supply cost, some aquifers abandoned and an increase in water resource scarcity, usually the water from these intruded aquifers is unsuitable for drinking purposes.

The contribution of the geophysical methods applied to the coastal aquifer is a vital tool for the calculation and determination of the formation water salinity, thorough investigations enable the delineation of the salinity content within the aquifer. These layers or strata within the aquifer with high salinity content can be avoided during well design through casing.

1.1 Scope and objective of the study

Water resources in Tanzania are under increasing pressure and the information about groundwater resources is increasingly important. The water resources for Dar es Salaam are insufficient due to shortage of rain and an increasing population. The water to more than three million people is today mainly provided by surface water from nearby streams. The idea is to investigate the ground water potential in the Coastal Neogene Province that has been recorded in several deep wells drilled for petroleum exploration. Geophysical data provides a unique tool for determining potential aquifers and their water quality.

The main purpose of this study is to construct a depth profile of formation water salinity and the hydrogeologic seismic cross section, so that the potential aquifers can be documented and defined in a regional context.

1.2 Geographic location and population

Tanzania is located in Eastern Africa between longitude 29° and 41° east. Latitude 1° and 12° South and is among the three countries within the East African region, others being Kenya and Uganda. It harbours the African continent's land peak of Kilimanjaro mountain, and the famous Serengeti National park including the Ngorongoro Crater. The country has a population exceeding 35 million and a geographical area of about 945,000 km², of which 6.5% is water bodies. There are over 120 tribal languages, united by a

common tongue, “Swahili”. Economically, agriculture (mostly peasantry type) is the backbone, others being mining and industrial sectors. Though Tanzania is generally considered to be a well-watered country having good rainfall, many rivers and lakes and huge groundwater deposits, the water supply coverage is only 54.2% and 42% for urban and rural areas, respectively (Ishengoma, 1998; Mato *et al.*, 1998). This fact is supported by Section 12 (b) of the National Environmental Policy (1997); which states: “Despite considerable national effort, over half the people in towns and in the countryside do not have access to good quality water for washing, cooking, drinking and bathing”.

The city of Dar es Salaam which is the study area is located on the Indian Ocean coast of Tanzania, at around latitude 6°50' south and longitude 39°15' east and has an area of about 135 km² and a population exceeding 3.8 million.



Figure 1.1: Map of Tanzania



Figure 1.2: Location of Kimbiji study area in Dar Es Salaam, Tanzania.

1.3 Climate, Physiographic and drainage

Tanzania has a tropical type of climate. In the highlands, temperatures range between 10°C and 20°C during cold and hot seasons respectively. The rest of the country has temperatures never falling lower than 20°C. The hottest period spreads between November and February (25°C – 33°C) while the coldest period occurs between May and August (15°C – 20°C).

Two rainfall regimes exist over Tanzania. One is unimodal (December - April) and the other is bimodal (October -December and March - May). The former is experienced in southern, south-west, central and western parts of the country, and the later is found to the north and northern coast.

In the bimodal regime the March - May rains are referred to as the long rains or Masika, whereas the October - December rains are generally known as short rains or Vuli.

Tanzania is the biggest of the East Africa countries (i.e. Kenya, Uganda and Tanzania). It has a spectacular landscape of mainly three physiographic regions namely the Islands and the coastal plains to the east; the inland saucer-shaped plateau; and the highlands. The Great Rift Valley that runs from north east of Africa through central Tanzania is another landmark that adds to the scenic view of the country. The rift valley runs to south of Tanzania splitting at Lake Nyasa; one branch runs down beyond Lake Nyasa to Mozambique; and another branch to north-west alongside Burundi, Rwanda, Tanzania and western part of Uganda. The valley is dotted with unique lakes which include Lakes Rukwa, Tanganyika, Nyasa, Kitangiri, Eyasi and Manyara. The uplands include the famous Kipengere, Udzungwa, Matogoro, Livingstone, and the Fipa plateau forming the southern highlands. The Usambara, Pare, Meru, Kilimanjaro, the Ngorongoro Crater and the Oldonyo Lengai, all form the northern highlands.

Tanzania is divided into five major drainage systems and these are: the Indian Ocean drainage system, the internal drainage of Lake Eyasi, Natron and Bubu Depression complex, the internal drainage of Lake Rukwa, Atlantic Ocean drainage system and Mediterranean Sea Drainage system.

1.3.1 Description of the study area

The area of research for this study is located at Kimbiji in the coastal plains of Tanzania, which is approximately 40 kilometers south of the commercial capital, Dar Es Salaam, between latitudes 6°58' and 6°92'N and longitudes 39°22' and 39°34'E. Temperature

ranges between 17°C and 33°C and average humidity of 67%-96%. High temperatures are common throughout the dry season from December to March and comparatively lower temperatures prevail through April to October. The area is characterized by rainfall of between 1000 and 1400 mm per annum, the wet season is usually between March and May. The average evaporation rate is 2100mm per annum.

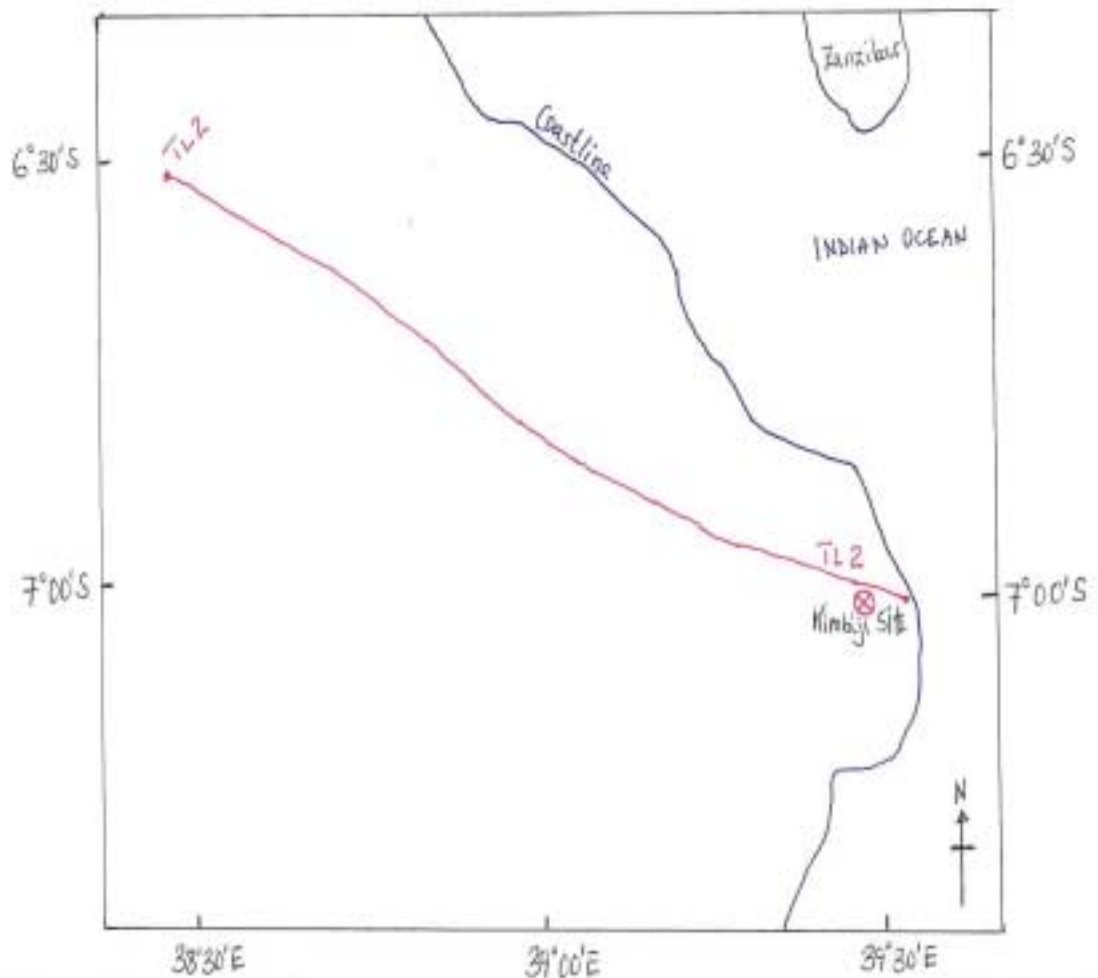


Figure 1.3: Location map of Kimbiji Site and Seismic Traversing Line 2 (TL 2). The total length of Traversing Line 2 is 64 kilometer.

1.4 Groundwater Resource in Tanzania

The occurrence of groundwater is largely influenced by geological conditions. Hydrogeologically about 75% of Tanzania (Kongola *et al.*, 1999) is underlain by crystalline basement complex rocks of variable composition and ages, but predominantly Precambrian, which form the basement aquifers (for example the Pangani and Makutopora basins). Other aquifer types include Karroo (found in Tanga), coastal sedimentary formation of limestone and sandstone (e.g. Dar Es Salaam), and the alluvial sedimentary sequence, which mostly include clay, silt, sand and gravel, and volcanic materials (e.g. Kahe -Pangani basin). The groundwater potential of every type of aquifer differs much from place to place or basin wise. The recharge is mostly by direct rainwater infiltration. Preferential recharge is from high intensity rainfall and through fractures.

Quantification of the groundwater resources of the country has not yet been possible because of lack of requisite data. However, some efforts have been done in assessing groundwater resources in Rufiji and Pangani River Basins, where systematic and basin-wise attempts to evaluate the groundwater resources potential have started. (Kongola *et al.*, 1999). Groundwater development has concentrated mainly on shallow wells for domestic purposes over a wide part of the country (mainly rural areas). They are also commonly used in the periurban fringes where there is no distribution network and places with unreliable supply. Groundwater is the main source of water supply in municipalities like Dodoma, Arusha, Shinyanga, Moshi and Singida. Many other urban areas exploit groundwater to augment supply from surface water sources. The boreholes are mainly found in urban settings, some are over 100 m deep. There are over 5000 recorded deep boreholes drilled both as exploratory and production wells throughout the country.

Most of the use of groundwater is for domestic purpose, irrigation, industrial and livestock. For example, at present 88% of groundwater extracted from the Pangani river basin is used for irrigation, 4% for industrial use and 8% for domestic use. In many urban areas groundwater and surface water are used conjunctively e.g. the City of Dar es Salaam. Throughout the country shallow wells are used for domestic water supply, i.e. hand-dug wells and improved wells. Groundwater is currently being used for irrigation

purposes in sugarcane, paddy, horticulture, vegetable and flower farming (e.g. Tanzania Planting Company, TPC-Moshi, and sugar cane plantation and Kilombero sugar estates). Groundwater utilization for industrial use is more concentrated in urban areas, especially Dar es Salaam where about 80% of the industries are located. Due to inadequate water supplies many industries have opted for constructing private wells to augment surface water supply. Industries in Dar es Salaam, like Tanzania Breweries Ltd. (TBL), Tanzania Cigarette Company (TCC), Friendship Textile (Urafiki), Ubungo Farm Implements (UFI), Kibuku, Mpishi, and Tanzania Portland Cement factory (TPC - Wazo Hill) etc, have private wells (Mato *et al.*, 1998, Drilling and Dam Construction Agency, 2001). The list is rapidly increasing and similar trends are observed in Arusha municipality.

Generally, the natural groundwater quality in Tanzania is considered potentially good, acceptable for most use. The main problems are salinity, high fluoride concentration, hardness and corrosion. The high concentration of chloride (salinity) in groundwater is the main problem especially in the coastal and central regions of the country (like Singida, Shinyanga, Lindi and Mtwara), where there is a high evaporation rate and poor drainage. In Lindi and Mtwara regions, high carbon dioxide in groundwater has been reported (Kongola *et al.*, 1999), which causes groundwater to be corrosive. High fluoride concentrations are common problems in the areas surrounding the Rift valley system (e.g. Kilimanjaro, Arusha, Singida and parts of Shinyanga regions) Materu, 1996; Mato *et al.*, 2000). High iron content in groundwater has been observed in Mtwara and Kagera regions (Kongola *et al.*, 1999). Nitrate levels of more than 100 mg/l have been reported in the Makutupora basin, Dodoma and Singida town (Nkotagu, 1996; Kongola *et al.*, 1999). Figure 1.3, shows the general groundwater quality in Tanzania.

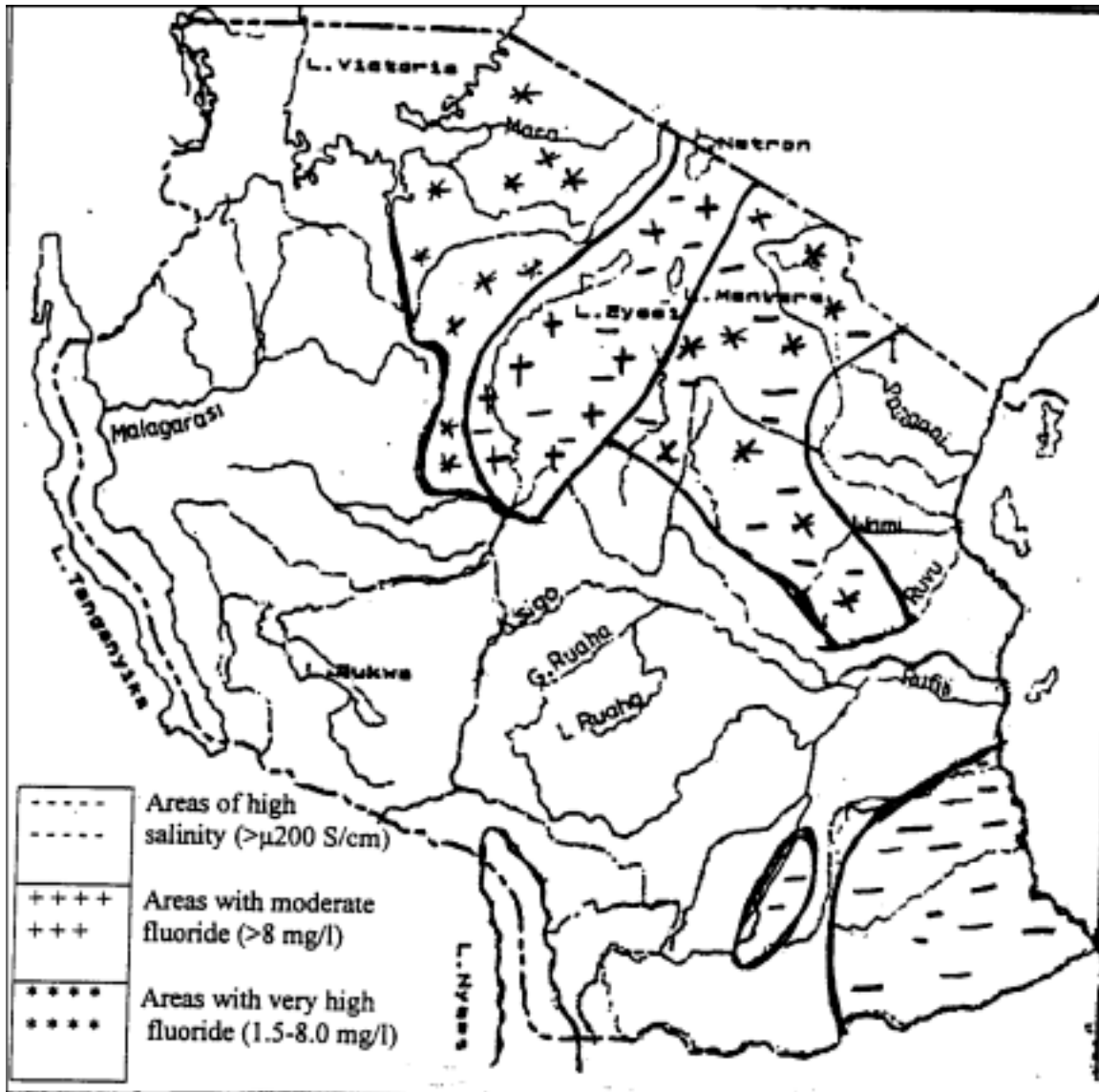


Figure 1.4: General groundwater quality in Tanzania (Cited in Rweyemamu, 1999)

1.5 Regional geological setting

1.5.1 Regional tectonics

Tanzania is located in an area affected by major tectonic events commencing in the Permo-Triassic with the breakup of Gondwana and continuing to present-day. The development of the post-Gondwana East Africa Continental Margin is separated into two major phases, rift and drift. The Tanzanian coastal area is unique within East Africa in showing an almost complete stratigraphic sequence from the Karroo to recent times,

permitting the development of models for the continental margin in terms of sedimentation, local warping and dating of fault movements.

A combination of four major tectonic events has contributed to the evolution of Coastal Tanzania; a failed NNE rift, a successful NNW rift, an EW graben and the right lateral drift of Madagascar.

The Selous Basin occupies the failed rift in the southern area of the Coastal Basin. To the north, the rift is occupied by the Ruvu Basin, to the north-west of the Dar es Salaam Platform. The successful rift margin is occupied by the present-day Ruvuma and Mandawa basins, which are situated east of Selous and separated by the Masasi Spur basement high. North of these basins the east west trending Rufiji Trough cuts across both successful and failed rifts.

Offshore Tertiary Basins parallel the coast is associated with large, down-to-the-basin faults, which demarcate the present coastline. A series of broad troughs and anticlines parallel the coast offshore. The islands of Pemba, Zanzibar, Latham, and Mafia appear to be basement-cored uplifts.

1.5.2 Rift phase (Permian, Triassic and early Jurassic)

During the rift stage, the Gondwana continent was split into many parts, which remained in contact with each other. These splits gave rise to basins in which predominantly continental sediments were deposited at relatively high sedimentation rates. During later episodes of extension, sea-floor spreading (drifting) and the development of a passive margin generally followed rifting of continental crust. A few rifts, however, failed and did not progress to the drifting stage.

1.5.3 Drift phase

Beginning in the Middle Jurassic, East and West Gondwana separated and East Gondwana broke up into a number of continental plates (India, Antarctica, and

Australia). The continental margins of the fragmented continents underwent gradual thermal subsidence, and became repositories for marine sediments as seaward-thickening wedges, which overstep the underlying rift basins.

During the late Cretaceous, India began to separate from Madagascar, and this was accompanied by a major episode of igneous activity throughout the Late Cretaceous and Early Tertiary. The rifting between Africa and Arabia commenced in the Oligocene and created ocean crust in the Miocene. The East Africa Rift System propagated in a southerly direction from the Gulf of Aden and has been active since the Miocene.

1.6 Regional stratigraphy

The break up of Gondwana initiated the formation of basement controlled coastal and early interior basins.

The early depositional history of the coastal basins was initiated in the Late Paleozoic, (Carboniferous?) or Permo-Triassic and continued through the rift phase until the end of the Early Jurassic (Karoo of some authors). The rift phase or synrift stratigraphic units from the top of basement to the end of Early Jurassic are best represented in the Selous, Ruvu, Mandawa, and Ruvuma basins of eastern Tanzania and in the rock basin in the southwest.

In the Selous Basin, the Carboniferous to Permo-Triassic interval consists of about 10 km of fluvial, deltaic, continental and lacustrine deposits of the Dwyka and Stigo Series, overlain by the Triassic Tanga Beds. This sequence is in part equivalent to the Lower Sakamena source rocks of Madagascar.

In the Mandawa Basin, the Tanga Beds are overlain by clastics and evaporites of the Nondwa Formation (Early Jurassic). Significant thicknesses of salt are associated with these sediments and have been identified throughout the basin. Pre Middle Jurassic sections are also preserved in Rufiji trough and Dar es Salaam platform.

From Middle Jurassic onwards, the coastal basins were established as the continental shelf of a passive margin and subjected to various deltaic and marine depositional environments. Several transgressive and regressive phases resulted in 4,000 m of Mesozoic and another 4,500 m of Tertiary sediments being deposited. These sediments consist of marine marls, shales, sandstones and limestones.

In the interior basins deformation commenced in the carboniferous with an estimated 4000 m of Karoo deposits. Further thicknesses of up to 2000 m of continental sandstones and shales were deposited during the late Jurassic and early Cretaceous eras.

The post-rift phase started in the Middle Jurassic with a regional unconformity, and initiated a marine transgression, accumulating thick shales of the Makarawe Formation and limestones of the Kidugalo and Mtumbei Formations. The regional unconformity separated the Karoo continental deposits from the marine Jurassic sediments. North of the Kisarawe-1 well, the Jurassic has not been reached by drilling. The seismic control suggests that the Jurassic is buried very deep offshore, beneath the thick Cretaceous-Tertiary cover.

The Middle to Late Jurassic transgression was followed by regression in the Early Cretaceous, resulting in predominantly clastic sediments in the south, including the Neocomian Songo Songo reservoir sandstone of the Kipatimu Formation and limestones and conglomerates in the north.

A regional Middle Cretaceous unconformity and the deposition of thick platform carbonates culminated the regression and initiated another major marine transgression in the Late Cretaceous. This resulted in the deposition of the shelf sands and slope shales of the Ruaruke Formation. At this time there was also some tectonic activity resulting in the development of several fault systems separating the shallow marine environment in the west from the deep marine environment in the east.

Paleocene deposition was associated with the last phase of transgression continuing from Late Cretaceous times and with contemporaneous subsidence in the coastal and offshore areas. Several uplifts occurred in the Late Tertiary, represented by unconformities at the base of the Eocene and Miocene, followed by Middle Eocene to Recent regressive sediments of continental, deltaic and marine facies.

1.7 Geology

The topographic variations in Tanzania are strongly controlled by geology. The central plateau is composed of ancient (Precambrian rocks) crystalline basement rocks. These are predominantly faulted and fractured metamorphic rocks with some granite.

The northern and southern highland regions are parts of the major East African Rift system which extends northwards through Kenya and Ethiopia, and which has developed over the last 30 million years through extreme crustal tension, rift faulting and volcanic activity. The Gregory Rift extends with a north-north-west trend through northern Tanzania and the Western Rift extends north-west to south-east along the south-western margin of Tanzania. The geology of the Rift zones comprises volcanic and intrusive rocks, largely of basaltic composition, but with some rare sodic alkaline rocks and igneous carbonates (e.g. Oldoinyo Lengai volcano). Some of the volcanic centres are active (producing new lava and ash formations periodically) and associated with hot springs.

Much of the south-eastern part of the country is composed of sedimentary rocks of various ages (Palaeozoic to Recent), including the Karroo Sandstone which extends from the coast at the Kenyan border south-westwards to Lake Nyasa. The sediments are mixed formations, including sandstones, mudstones and limestones. The Karroo Sandstone includes some coal seams.

The coastal plain consists of largely unconsolidated sediments (beach sands, dunes and salt marsh) together with some limestone deposits (Nkotagu, 1989).

1.7.1 Regional Geology of coastal Tanzania

Geologically coastal Tanzania is made up of Precambrian (Ubendian-Usagaran, 700-840 my) (Maboko, 2001) basement rocks and overlying sedimentary formations; Karoo (Carboniferous-Triassic), Jurassic, Cretaceous, Tertiary and Quaternary. The Precambrian granulites, granites, amphibolites and marbles are separated from the sedimentary successions by a prominent NE-SW striking fault zone-the famous Tanga fault. This fault zone has been active with varying intensity through geological time and has partly controlled the sedimentation in the area. The Tanga fault-zone displays an accumulated throw of several thousand meters. The main activity took place in Karoo time, but it was also active through the Mesozoic and Tertiary e.g. Late Jurassic and in the early Miocene time. This fault and sub-parallel comparable coastal lineaments, e.g. in the Kimbiji and Ras Machuisi area, are cut perpendicular by smaller fault systems.

The Karoo (Late Carboniferous to Triassic) succession consists of fluvial, alluvial to lacustrine sediments which were deposited in fault controlled basins, along the Tanga fault. The syn-sedimentary faulting resulted in deposition of locally more than 3000 m thick successions of conglomerates, sandstones and finer (silt and clay) grained siliciclastic units. Presently these beds are cropping out in the western part of the basin, towards Uluguru Mountains (Mvuha, Mgeta area). These beds are forming the sedimentary base in the down to the west half grabens, dipping about 10 degrees. The Karoo successions are consequently present in the larger parts of the ruvu basin and it has been identified in the seismic lines of the regions.

The Jurassic and Cretaceous beds in the area have a general 7 to 10 degrees dip towards east. After the youngest Karoo (Triassic) and the deposition of evaporites topping off the Karoo, the Jurassic sea transgressed from the north-east. Simultaneously the rifting activity slowed down, compared to the high syn-sedimentary activity characterizing the Karoo half graben systems. The Tanga fault activity took place in the region, as did the Pugu Hills to the east. The confined half graben sedimentation was eventually succeeded by a wide coastal plain leading to shallow shelf conditions. The Ngerengere Formation succeeds the Karoo. It is early Jurassic to late Triassic age (Arkel, 1956., Kent et al.,

1971). The Ngerengere beds are up to 760 m in thickness (Kent et al., 1971) and consist of coarse grained, continental siliciclastic sediments (Kent et al., 1971; Mbede and Dualeh, 1971). Increasing marine influence during early Jurassic transgression, ended with fully marine conditions established in Middle Jurassic. The transgressing Jurassic sea flooded the area across the Tanga fault and even farther west.

The high relief regions around the uplifted western part of the Tanga fault functioned as source areas for the succeeding coarse grained clastics (Ngerengere and overlying Jurassic formations), but the uplifted basement also was the sole of growth for carbonate build-ups such as reefs and oolite bars. Formations typically found in areas with reduced clastic sedimentation (e.g. Kidugallo, Lugoba, Msata). The stratigraphical relations of the Lugoba formation and the Kidugallo Oolites are discussed (Weier, 1981; Kapilima, 1984; Mbede and Dualeh, 1997). They could very well represent the same depositional event. These carbonate units are cropping out in a narrow belt along the Tanga lineament. Similar oolites have, however, also been described from Tanga, where 340 m of Jurassic carbonates are found (Arkell, 1956). The thickness of these carbonate units seems to vary, but a possible overall thickness of 300m is indicated. Transgressive Jurassic developments shifted across coastal Tanzania. The lower Cretaceous has been described as an overall regressive unit, while transgressive developments dominate in the upper Cretaceous. Sand and silts, commonly with rather high carbonate contents, were deposited in the area and are today making up to more than 2300m thick shallow marine successions.

The Tertiary successions, with probably a thin Paleogene (Kent et al., 1971, in figure 1.4, 1000 m as found locally) and definitely a thick Neogene (in particular Miocene) following on top of the Cretaceous (Kajato and Weier, 1983). Succeeding a regressive Oligocene development, transgressive Miocene sedimentation developed with simultaneous intense and renewed tectonic activity along the Tanga fault zone and its coastal derivatives. This tectonic activity can be related to rifting and establishment of the present East African Rift system to the west, in concert with the opening of the Gulf of

Aden and red sea to the north (Schlich, 1974; Mbede, 1991). The Miocene transgression was followed by a regressive phase, which ended in the present coastline configuration.

The tectonic activity during Miocene can be linked to the large scale East African rifting events, splitting up and southwards movements of Madagascar. This happened in Jurassic/Cretaceous transition (Mbede, 1991), and is a response to the opening of the Indian Ocean. This evidently resulted in an eastwards tilting of the present coastal areas. From this time the coastal zone generally developed as passive margin.

1.7.2 Structures

The coastal area of Dar es Salaam region has tentatively been divided into three main blocks namely Wazo, Dar es Salaam and Kimbiji.

Generally the blocks lie within an area traversed by a series of lineaments and faults. The lineaments are classified into regional, intermediate and local faults. Furthermore, the strike directions of the lineaments tend to form two recognizable sets NNE and NNW.

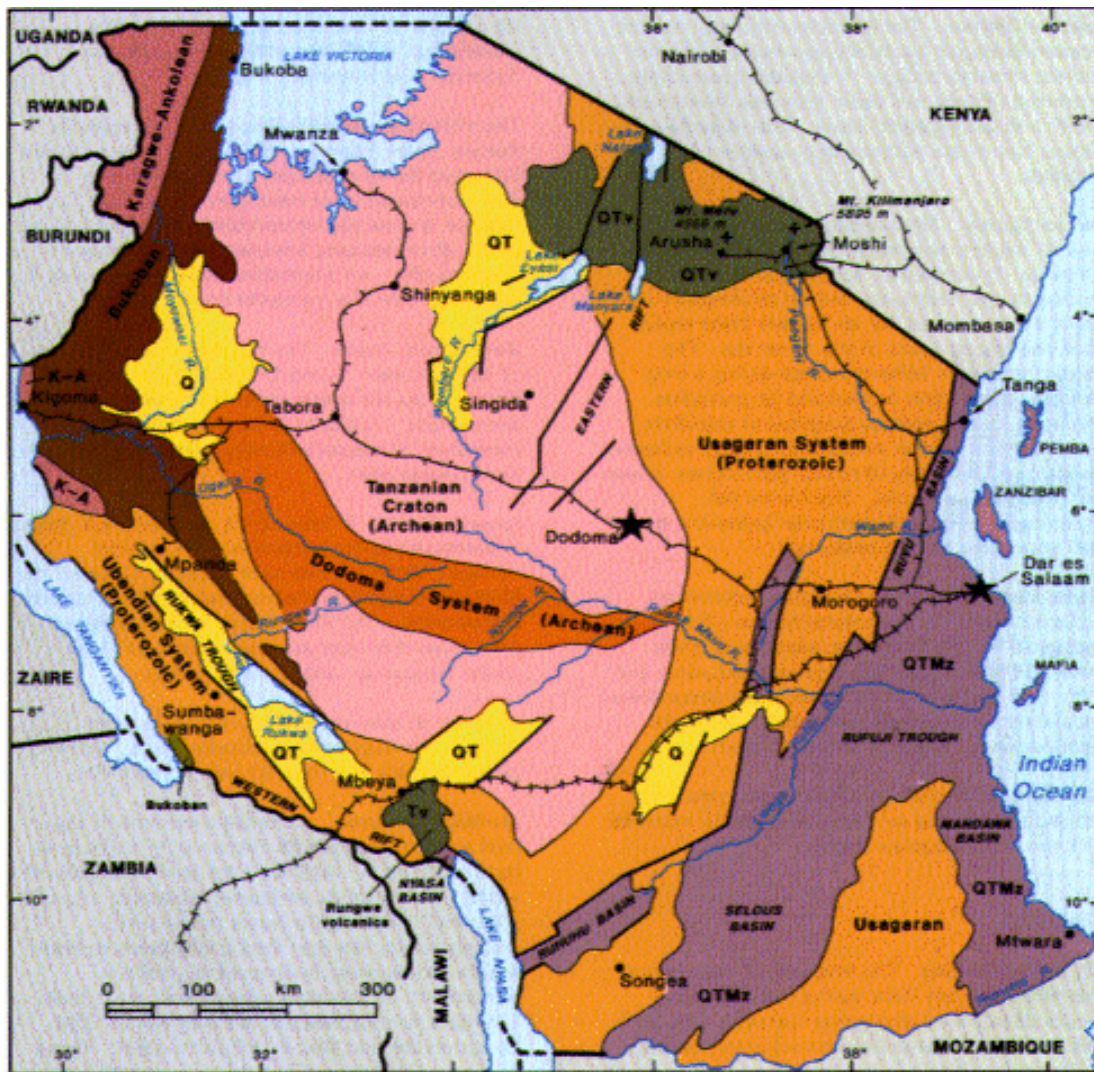
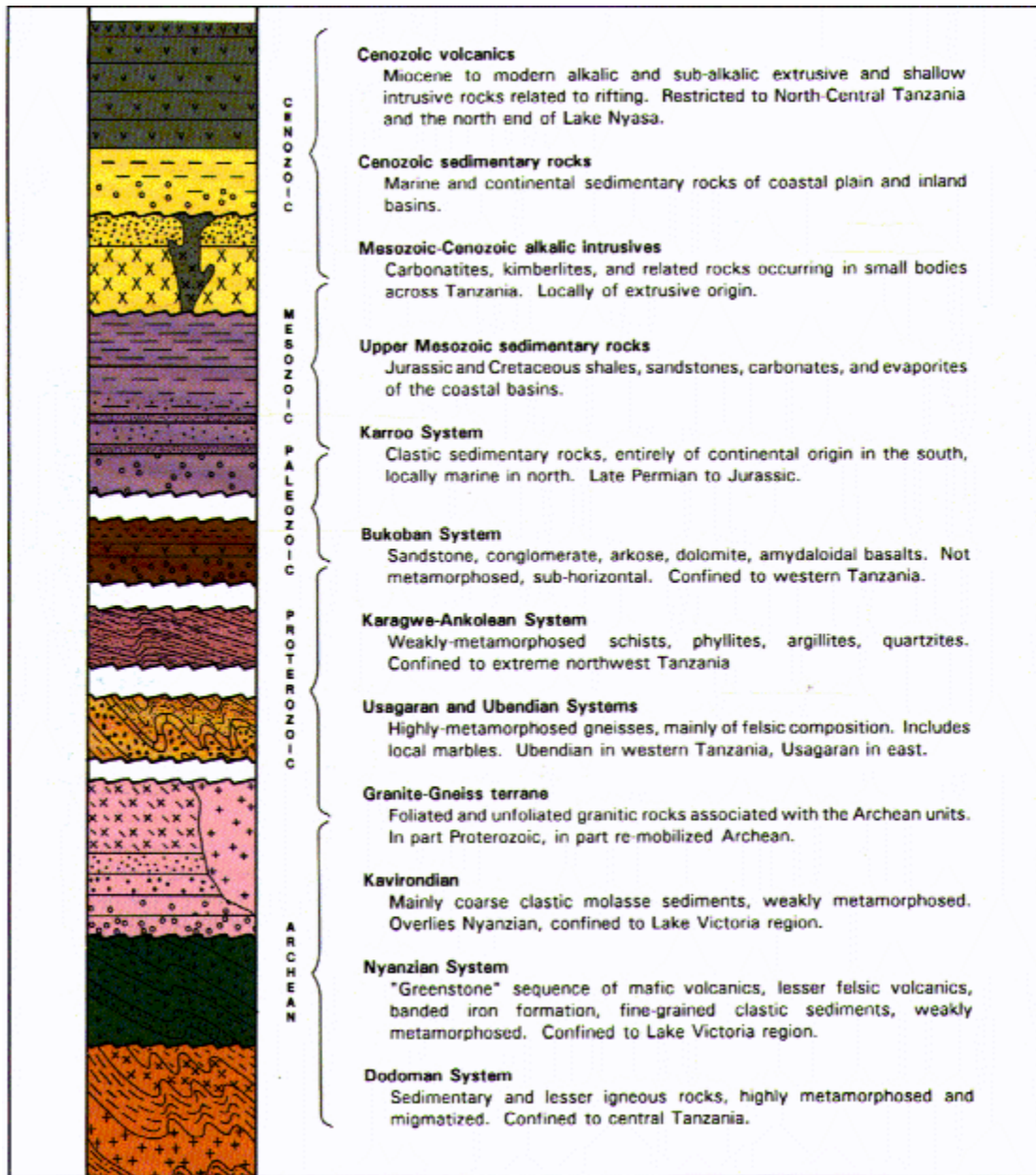


Figure 1.5: Geological Map of Tanzania



1.7.3 Depositional conditions at the studied site

The sediment characteristics and stratigraphical developments of the Miocene sands in the Kimbiji area indicate that fluvial controlled sedimentation of mineralogically mature sediments, in a mouth bar setting was possible; a fluvial system of a low relief coastal plain meeting the ocean. The sedimentation was controlled by a large fluvial sediment supply and extensive faulting parallel to the coast along eastwards dipping, listric faults

in combination with a basinwards tilting of the hinterland. This tectonic setting, intensive erosion and extensive fluvial sediment supply of highly reworked sediments, could originate from a paleo-Rufiji to the south. This may explain the deposition of large volumes of Miocene clean sands as well as the development of large prograding deltas across the Dar es Salaam embayment and the Zanzibar channel. Mbede and Dualeh (1997) indicate an E-W Rufiji depression could already have been formed in Oligocene-Lower Miocene. During such large rates of clastic sedimentation the lack of marine fossils is possible. Kent et al, (1971) presented microfossil datings of the Neogene. The onshore Miocene beds are overlain by regressive fluvial to estuarine Plio-Pleistocene sands in the existing depressions such as Ruvu valley and Rufiji depression.

Mpanda (1997) indicated that large amounts of coarse sediments were deposited south of Kimbiji in Miocene. Mpanda (1997) refer to these as continental clastics. Large amounts of this material may have been reworked when entering the marine regime.

CHAPTER TWO

2.0 Methodology

This chapter describes both the methods and methodology employed in this thesis. In terms of methods, this chapter describes what the primary data sources are, how data were collected, and how they were organized. In terms of methodology, this chapter explains the theoretical approach to the data. This chapter provides a contribution towards the essential goal of this thesis, to describe how the formation water salinity can be determined and documentation of the potential aquifers based on the geophysical data.

2.1 Field methods

In the field the resistivity of the mud filtrate was determined for every 6 meters drilling interval. Mud filtrate was obtained by taking freshly circulated drilling mud after every 6 meters and pressed with 10kbar pressure to obtain mud filtrate and its resistivity was measured and recorded.

The viscosity of the drilling mud was measured for every 30 minutes by using the one liter container, marsh funnel and stop watch. The procedure was as follows: The funnel was held in upright position with index finger over the outlet, the drilling mud was poured through the screen in the top of the funnel until the drilling mud reached the marked line just beneath the screen, the finger was removed from the outlet and the number of seconds it took to fill the accompanying container up to the marked line equivalent to one liter was determined and recorded. This was important as the proper viscosity enables the drilling fluid to effectively bring up drill cuttings and to build a good wall cake. The wall cake helps support the borehole and keep it from collapsing when drilling in unconsolidated material.

2.2 Geophysical methods

2.2.1 Seismic Reflection

Seismic reflection profiling involves the measurement of the two-way travel time of seismic waves transmitted from surface and reflected back to the surface at the interfaces between contrasting geological layers. Reflection of the transmitted energy will only occur when there is a contrast in the acoustic impedance (product of the seismic velocity and density) between these layers. The strength of the contrast in the acoustic impedance of the two layers determines the amplitude of the reflected signal. The reflected signal is detected on surface using an array of high frequency geophones. The seismic energy is provided by a 'shot' on surface. For shallow applications this will normally comprise a hammer and plate, weight drop or explosive charge. In most reflection surveys shots are deployed at a number of different positions in relation to the geophone array in order to obtain reflections from the same point on the interface at different geophones in the array. Each common point of reflection is termed a common mid-point (CMP) and the number of times each one is sampled determines the 'fold coverage' for the survey. Traces relating to the same CMP are stacked together to increase the signal-to-noise ratio of the survey before being combined with other CMP's stacked traces to produce a reflection profile. In order to stack related CMP traces a stacking velocity is applied to each trace. This accounts for the difference in two-way travel time between the normal incidence reflection (vertical travel path below the shot) and those at increasing offsets from the shot (known as the normal moveout or NMO). The stacking velocity will vary down the trace to take account of the increase in velocity with depth for each reflection event. The time it takes for a reflection from a particular boundary to arrive at the geophone is called the travel time. If the seismic wave velocity in the rock is known, then the travel time may be used to estimate the depth to the reflector. For a simple vertically traveling wave, the travel time, t from the surface to the reflector and back is given by the formula:

$$t = 2d/V$$

where d is the depth to the reflector and V is the wave velocity in the rock.

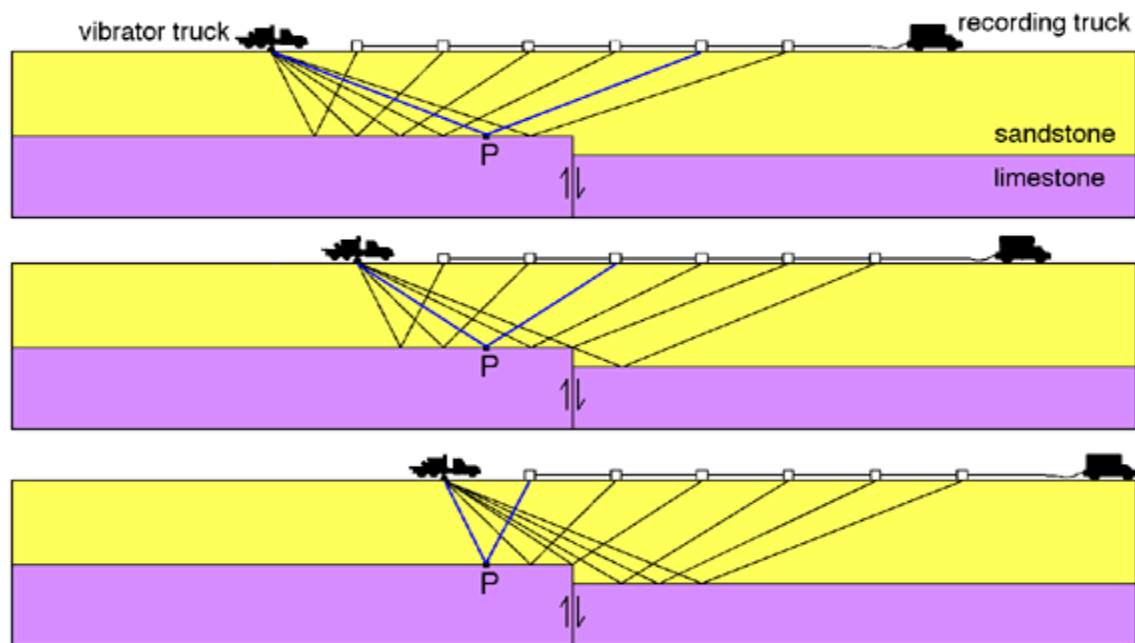


Figure 2.1: Depicts the reflected rays after hitting the surface with different acoustic impedance, source and receivers (geophones). Illustrate the seismic reflection phenomenon (Ikelle, 2005).

Seismic reflection profiles and seismic traversing lines map were collected from Tanzania Petroleum Development Corporation (TPDC) archives to analyze the information about the underlying sediments of the Kimbiji area and to locate the position of the Kimbiji groundwater well based on the information from the seismic profiles. In this study the details were used to construct a geologic cross section for traversing line two (TL-2) which runs along Kimbiji site, intentionally to show the depth to the top of Eocene formation which is the base (aquicludes) of this aquifer system.

The seismic traversing line map was digitized; for each shot point the two way travel time along the traversing area from the surface to the top of Eocene reflector were read and documented. The underlying top Eocene shale and limestone sequence forms the base of the aquifer. The contact between this shale and the overlying sand is a very good seismic reflector that can be traced over a large area. It has been interpreted on the old seismic lines acquired for the petroleum exploration in the region around Dar Es Salaam. The elevation above sea level from the seismic reflection profiles were read and documented for each shot point along the traversing area.

The realm of seismic data typically has been horizontal distance and vertical time. The distance from the surface to the top Eocene reflector was calculated based on the provided seismic velocities between layers with a contrast in the acoustic impedance and the travel time between these layers. There were two pronounced layers; the first layer displayed the two way travel time and its respective velocity from the surface to the contact between underlying water table surface. This interpreted as the unsaturated zone. The second layer displayed the two way travel time and its respective velocity from the water table surface to the top of Eocene reflector which forms the base of that aquifer.

The calculations of the distance from the surface to the top of Eocene reflector for each shot point along the traversing line two (TL-2) based on the provided seismic velocities were determined by using the following formula:

For first layer:

Velocity = Distance traveled / Elapsed time

For the reflected ray the travel time, $t_1 = 2h_1/v_1$

The distance from the surface to the reflector is given by; $h_1 = t_1v_1/2$

Whereby:

t_1 is the travel time from the surface to reflector

h_1 is the thickness of the first layer

v_1 is the velocity of the first layer

For the second layer:

For the reflected ray the travel time, $t_2 = 2h_2/v_2$

The distance from the surface to the reflector is given by; $h_2 = t_2v_2/2$

Whereby:

t_2 is the travel time from the water table surface to the top of Eocene reflector

h_2 is the thickness of the second layer

v_2 is the velocity of the second layer

The distance from the surface to the top of the Eocene reflector for each short point along the seismic profile is determined by summing the distances for the individual layers;

$$H = t_1v_1/2 + t_2v_2/2$$

Whereby:

H is the distance from the surface to the top of Eocene reflector.

2.2.2 Borehole geophysical logging

The borehole geophysical logging plays a vital role by providing information on the characteristics of the rocks and fluid penetrated by boreholes. This information is useful for litho-structural interpretation of the aquifer systems as well as for evaluation of hydrogeologic characteristics and the water quality distributions in the aquifer system.

The multi parameter analog or digital geophysical logging of water wells is a post drilling approach to optimize the design and development of the wells. The prime objectives of the geophysical logging are; to identify distinct boundaries between different hydrogeological units, to determine water quality, to decide the proper setting of the screen depths against productive aquifers and casing against the collapsible formations and also sealing against bad quality of formation water. The other objectives include defining and delineating the aquifer geometry and its framework in space and time.

Geophysical logging provides measurements of various physical properties of different formations and their fluid contents penetrated by the borehole during the drilling. The measuring sensors, commonly known as probes are lowered into the borehole to measure continuous changes in physical properties vertically and a continuous record so obtained is known as a geophysical log. The process is defined as geophysical logging. It can be run in all boreholes including those cased with metal or plastic casing and filled with water brine, mud, drilling foam or air. The greatest return of information is derived from open (uncased) boreholes filled with formation water or mud. In plain cased boreholes investigation of the geological formation is limited to the nuclear logs and with plastic casing induction logs may be used. The logging equipment consists essentially of four units i.e. down hole instrument probe; cable winch; power and processing modules and data recording units.

The probes contain appropriate sensors to enable specific properties to be measured, which provide output in the form of electric signals. These signals are transmitted to the surface recording system through the cable and winch and which may either be in analog or of digital form. The cable has double outer layer of high tensile steel or polyurethane, which serves the dual purpose of supporting the probe and conveying electrical power as well as signals to and from the probe. The winch serves to raise or lower the probe into the borehole and to measure its precise depth position. This is achieved by passing the cable round a measuring sheave of known diameter linked to an accurate depth measuring system. The surface instrumentation typically consists of two sections, one provides power and the other processes the electric signals from the probes for recording purposes. Data recorder units enable encoding the signals from the probe or surface modules and drive the plotter to produce field logs.

Geophysical logging in this study was used to characterize the potential aquifer and determination of the formation water quality based on the salinity content surround Kimbiji Well. Geophysical methods used at the site included borehole caliper, natural gamma, short normal resistivity, long normal resistivity, spontaneous potential and temperature. The application of borehole geophysical logging methods to ground-water investigations is presented in Keys (1990).

2.2.2.1 Caliper logging

A caliper log is simply a record of the changes in hole diameter with depth. The probe has three mechanical arms which are opened at the bottom of the well, where they expand to the diameter of the borehole. As the tool is drawn up the well, the arms expand and contract as the hole diameter changes. The probe detects the extent to which the arms are opened and sends the measurement to the surface, providing an accurate log of borehole diameter. Changes of borehole diameter are related to well construction, such as casing or drilling-bit size, and to fracturing or caving along the borehole wall.

Principles and instrumentation

Many different types of caliper probes have been described in detail by Hilchie (1968). The most common type of probe used for logging water wells has three arms, each approximately the diameter of a pencil, that are spaced 120° apart and mechanically coupled together. Arms of different lengths can be attached to this type of probe to optimize sensitivity for the borehole-diameter range expected. Mechanical caliper probes have been used to measure a maximum borehole diameter of 42 in. A typical water-well caliper probe has arms that are connected together to move a linear potentiometer so changes in resistance, transmitted to the land surface as voltage changes, are proportional to average borehole diameter. In some probes, the voltage changes are converted to a varying pulse rate to eliminate the effect of changes in resistance of the cable. Three-arm averaging and single-arm caliper probes will operate on single conductor cable; however, probes having multiple independent arms may require more conductors.

Single-arm caliper probes commonly are used to provide a record of borehole diameter while another type of log is being made. The single arm also may be used to decentralize another probe, such as a side collimated gamma-gamma probe. Some single-arm decentralizing caliper probes use a pad or wide arm that does not allow borehole roughness to be resolved. A single-arm caliper probe has an advantage in that the arm generally follows the high side of a deviated hole. A three-arm averaging caliper probe does not function properly in highly deviated boreholes, because the weight of the tool forces one arm to close, which closes the other two arms.

2.2.2.2 Natural gamma logging

Natural gamma logs record the amount of natural gamma radiation emitted by the rocks surrounding the borehole. The most significant naturally occurring sources of gamma radiation are potassium-40, uranium and thorium. These are concentrated in minerals such as feldspar, mica and glauconite, which in turn are prevalent in clay and shale. The clay minerals have very high absorption and ion exchange capacities. They are therefore, able to absorb the heavy radioelements released during the decomposition of other minerals. Due to such process there always is an unusually large or high concentration of

radioelements in shale and clays as compared to sand. These natural radioactivities of sands and clay/shale could be measured through natural radioactive logging to distinguish and delineate these formations.

Basic concepts

Gamma logs, also called gamma ray logs or natural-gamma logs, are the most widely used nuclear logs in groundwater applications. The most common use is for identification of lithology and stratigraphic correlation, and for this reason, gamma detectors are often included in multi-parameter logging tools. Gamma logs provide a record of total gamma radiation detected in a borehole and are useful over a very wide range of borehole conditions. The petroleum industry has adopted the American Petroleum Institute (API) gamma ray unit as the standard for scales on gamma logs. The API gamma-ray unit is defined as 1/200 of the difference in deflection of a gamma log between an interval of very low activity in the calibration pit and the interval that contains the same relative concentrations of radioisotopes as average shale, but approximately twice the total activity. The API values of field standards can be determined when that pit is used so that reference values are available when logging. In groundwater sometimes the counts per second has been adopted as the gamma ray unit. The volume of material investigated by a gamma probe is related to the energy of the radiation measured, the density of the material through which that radiation must pass, and the design of the probe. Under most conditions, 90% of the gamma radiation detected probably originates from material within 150 to 300 mm of the borehole wall.

Background information

Because of frequent variations from the typical response of gamma logs to lithology, some background information on each new area is needed to reduce the possibility of errors in interpretation. Gamma logs are used for correlation of rock units; however, this approach can lead to significant errors without an understanding of their response within the area being studied. For example, gradual lateral change in grain size or increase in arkosic materials in sandstone may change the response of gamma logs. In igneous rocks, gamma intensity is greater in the silicic rocks, such as granite, than in basic rocks,

such as andesite. Orthoclase and biotite are two minerals that contain radioisotopes in igneous rocks; they can contribute to the radioactivity of sedimentary rocks if chemical decomposition has not been too great. Gamma logs are used widely in the petroleum industry to establish the clay or shale content of reservoir rocks. This application also is valid in groundwater studies where laboratory data support such a relation.

2.2.2.3 Normal resistivity logging

In this log the electrical resistivity of the formation around the borehole is measured. In a borehole drilled with mud, the mud cake is formed against the side of the borehole wall. The resistance of this mud cake is different from that of the rock-formation. Behind the mud cake, flushed-zone is formed where the mud filtrate replaces the natural formation water. At some distance from the borehole wall the rock formation is uncontaminated and has the true resistivity of the formation, which could be obtained by proper interpretation of geophysical logs. The extent of the mud-flushed zone depends upon the drilling technique, rock type and ground water conditions etc.

The case of multi-electrode probes enables resistance measurements to be made of known or assured volumes of earth and hence the measurements are calibrated in terms of resistivity. Common electrode arrangements are the 16 inch for short normal resistivity and 64 inch for long normal resistivity. The short normal resistivity is designed to measure the resistivity of the invaded zone of the formation close to the borehole while the long normal resistivity is used to obtain the resistivity of both the invaded zone and undisturbed formation where native formation water is found beyond the invaded zone. The radius of investigation is approximately equal to the electrode spacing.

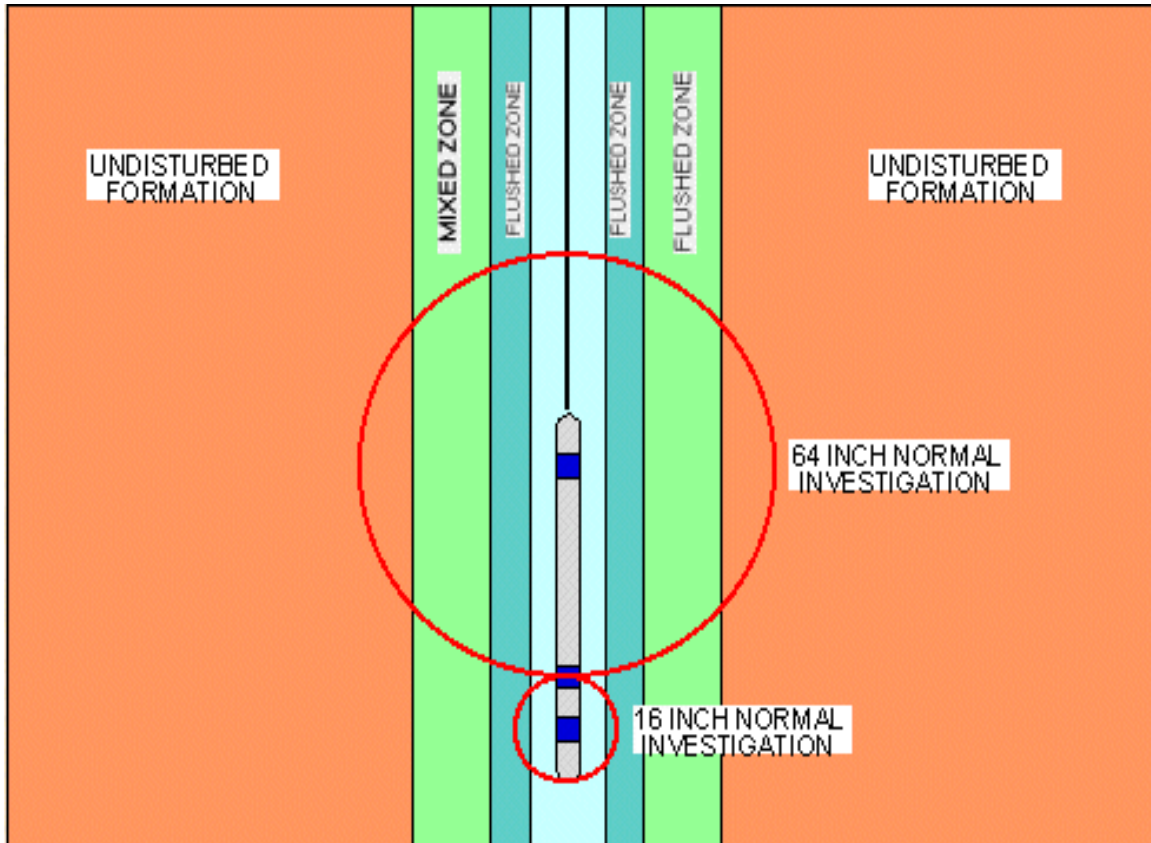


Figure 2.2: Depicts the short normal resistivity and long normal resistivity investigation zones. Long normal (64 inch) investigates both the flushed zone, mixed zone and undisturbed zone whereas short normal (16 inch) investigates the flushed zone only.

Basic concept

Among the various multi-electrode resistivity-logging techniques, normal resistivity is probably the most widely used in groundwater hydrology, even though the long normal log has become rather obsolete in the oil industry. Normal-resistivity logs can be interpreted quantitatively when they are properly calibrated in terms of Ωm . Log measurements are converted to apparent resistivity, which may need to be corrected for mud resistivity, bed thickness, borehole diameter, mudcake and invasion to arrive at true resistivity.

Definition

By definition, resistivity is a function of the dimensions of the material being measured; therefore, it is an intrinsic property of that material. Resistivity is defined by the formula:

$$R = rS/L$$

Whereby:

R is the resistivity in ohmmeter

r is the resistance in ohm

S is the cross section area in square meter

L is the length in meter

The principles of measuring resistivity are illustrated in figure 2.4. If 1 amp of current from a 10-V battery is passed through a 1-m³ block of material, and the drop in potential is 10 V, the resistivity of that material is 10 Wm. The current is passed between electrodes A and B, and the voltage drop is measured between potential electrodes M and N, which, in the example, are located 0.1 m apart, so that 1 V is measured rather than 10 V. The current is maintained constant, so that the higher the resistivity between M and N, the greater the voltage drop will be. A commutated DC current is used to avoid polarization of the electrodes that would be caused by the use of direct current.

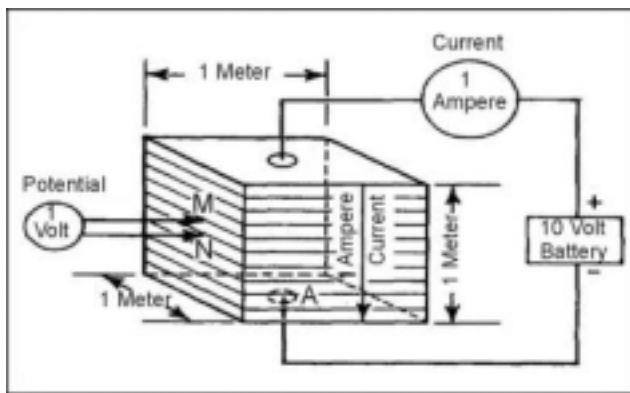


Figure 2.3: Principles of measuring resistivity in Ohm-meter. Example is 10 Ohm-meter.

Data of acquisition

AM spacing. For normal-resistivity logging, electrodes A and M are located in the well relatively close together, and electrodes B and N are distant from AM and from each other, as shown in figure 2.3. Electrode configuration may vary in equipment produced by different manufacturers. The electrode spacing, from which the normal curves derive

their name, is the distance between A and M, and the depth reference is at the midpoint of this distance. The most common AM spacings are 40 and 162 cm (16 and 64 in); however, some loggers have other spacings available, such as 10, 20, 40 and 81 cm (4, 8, 16, and 32 in). The distance to the B electrode, which is usually on the cable, is approximately 15 m; it is separated from the AM pair by an insulated section of cable.

The N electrode usually is located at the surface, but in some equipment, the locations of the B and N electrodes may be reversed. Constant current is maintained between an electrode at the bottom of the sonde and a remote-current electrode. The voltage for the long normal (162 cm (64 in)) and the short normal (40 cm (16 in)) is measured between a potential electrode for each, located on the sonde, and a remote potential electrode. The SP electrode is located between the short normal electrodes. The relative difference between the volumes of material investigated by the two normal systems also is illustrated in figure 2.2. The volume of investigation of the normal resistivity devices is considered to be a sphere, with a radius approximately twice the AM spacing. This volume changes as a function of the resistivity, so that its size and shape are changed as the well is being logged.

Although the depth of invasion is a factor, short normal (40 cm (16 in or less)) devices are considered to investigate only the invaded zone, and long normal (162 cm (64 in)) devices are considered to investigate both the invaded zone and the zone where native formation water is found.

2.2.2.4 Spontaneous potential logging

Spontaneous potential logs record the naturally occurring electrical potential difference along the borehole and can be used to identify changes in lithology, bed thickness, streaming potential due to water movement, and salinity of formation water under some geologic conditions (Keys, 1990). Reading against shale/clays formations are relatively constant and are referred as 'shale baseline'. Opposite permeable formations the SP curve typically shows deflections to the left (negative SP) or to the right (Positive SP) of shale-base line depending upon the relative salinity of the drilling mud and formation water.

Basic concept

Spontaneous potential (SP) is one of the oldest logging techniques. It employs very simple equipment to produce a log whose interpretation may be quite complex, particularly in freshwater aquifers. This complexity has led to misuse and misinterpretation of spontaneous potential (SP) logs for groundwater applications. The spontaneous potential log (incorrectly called self potential) is a record of potentials or voltages that develop at the contacts between shale or clay beds and a sand aquifer, where they are penetrated by a drill hole. The natural flow of current and the SP curve or log that would be produced under the salinity conditions given are in figure 2.4

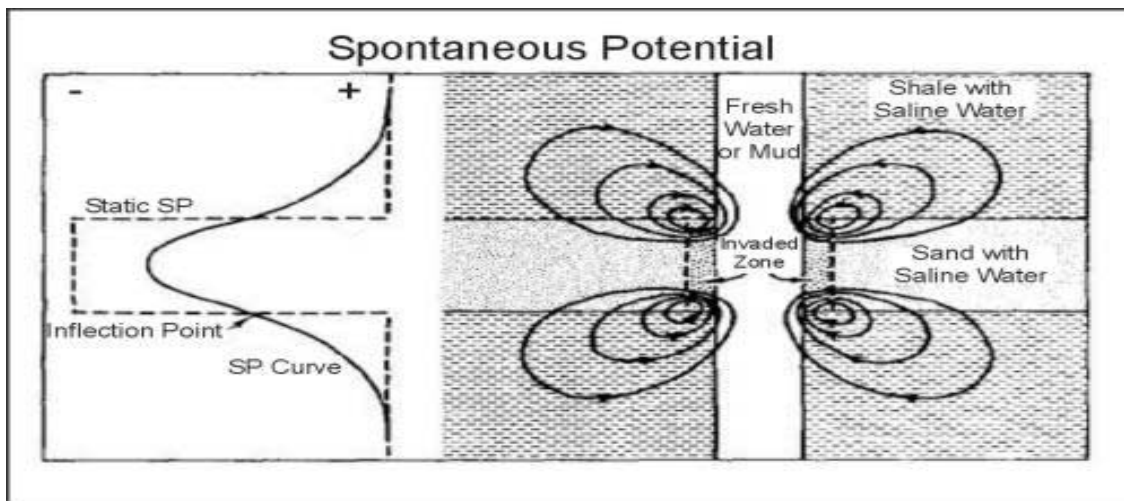


Figure 2.4: Flow of current at typical bed contacts and the resulting spontaneous potential curve and static values. Show the responds of spontaneous potential in shale and sand layers with saline pore water.

Data acquisition

The SP measuring equipment consists of a lead or stainless steel electrode in the well connected through a millivolt meter or comparably sensitive recorder channel to a second electrode that is grounded at the surface. Spontaneous potential is a function of the chemical activities of fluids in the borehole and adjacent rocks, the temperature, and the type and amount of clay present; it is not directly related to porosity and permeability.

The chief sources of spontaneous potential in a drill hole are electrochemical, electrokinetic, or streaming potentials and redox effects. When the fluid column is fresher than the formation water, current flow and the SP log are as illustrated in Figure 2.4; if the fluid column is more saline than water in the aquifer, current flow and the log will be reversed. Streaming potentials are caused by the movement of an electrolyte through permeable media. In water wells, streaming potential may be significant at depth intervals where water is moving in or out of the hole. These permeable intervals frequently are indicated by rapid oscillations on an otherwise smooth curve. Spontaneous potential logs are recorded in millivolts per inch of chart paper or full scale on the recorder. Any type of accurate millivolt source may be connected across the SP electrodes to provide calibration or standardization at the well. The volume of investigation of an SP sonde is highly variable, because it depends on the resistivity and cross-sectional area of beds intersected by the borehole. Spontaneous potential logs are more affected by stray electrical currents and equipment problems than most other logs.

These extraneous effects produce both noise and anomalous deflections on the logs. An increase in borehole diameter or depth of invasion decreases the magnitude of the SP recorded. Obviously, changes in depth of invasion with time will cause changes in periodic SP logs. Because the SP is largely a function of the relation between the salinity of the borehole fluid and the formation water, any changes in either will cause the log to change.

2.2.2.5 Temperature logging

Temperature logs record the water temperature in the borehole. Temperature logs are useful for delineating water-bearing zones and identifying vertical flow in the borehole between zones of differing hydraulic head penetrated by wells. Borehole flow between zones is indicated by temperature gradients that are less than the regional geothermal gradient.

Principles and instrumentation

Most temperature probes used in ground-water studies use a glass-bead thermistor mounted in a tube that is open at both ends to protect it from damage and to channel water flow past the sensor. The thermistor may be enclosed in a protective cover, but the cover should be made of materials of substantial thermal conductivity and minimal specific heat to permit fast response time. Response time is fastest, about 1 s, when the glass-bead thermistor is exposed to the fluid, but without the cover breakage is more likely. The thermistor is thermally insulated from the body of the logging probe.

A small electrical current is conducted through the glass-bead thermistor to measure changes in resistance that occurs as a function of temperature. The changes in resistance of the thermistor are converted to a varying pulse rate to eliminate the effect of changes in resistance of the logging cable. Electronic components in the probe that might change output because of thermal drift are placed in a constant temperature oven that maintains a temperature higher than the ambient temperature. For high-temperature logging in geothermal wells, platinum resistor sensors may be used; they have an accurate, stable, and linear response but a much longer response time. In a simple version of a geothermal-well probe, the probe contains no electronics; therefore, changes in electrical leakage in the logging cable can introduce an error.

Two general types of temperature logs are commonly made. One type, called simply a temperature log, is a record of temperature versus depth. The other type, the differential-temperature log, is a record of the rate of change in temperature versus depth. A differential-temperature log is more sensitive to changes in temperature gradient. Most differential temperature logs do not use a scale; if a scale is used, it is in degrees per foot. A differential-temperature log can be considered the first derivative of a temperature log; it can be obtained by two different types of logging probes or by computer calculation from a temperature log.

One type of differential-temperature probe measures the difference in temperature between two sensors that are placed one to several feet apart along the vertical axis of the

probe (Basham and Macune, 1952). The other type of differential-temperature probe uses one sensor and an electronic memory so that the temperature at one time can be compared with the temperature at a selected previous time (Johns, 1966). When the latter type of probe is used, logging speed must be maintained accurately. With either type of probe, the recorder can be set at a reference gradient, which will plot as a straight line. Departures from the reference gradient will be recorded as deflections on the log. The same result can be derived from computer analysis of a digitized temperature log; such analysis has the advantage that the spacing or delay can be varied in the computer to provide maximum sensitivity.

2.2.3 Delineation of the potential aquifer

Natural gamma logs were used to delineate the potential aquifer in collaboration with other logs. The unit for gamma value is counts per second. In this study gamma values less than 23 counts per second were filtered to map the sandy intervals and considered as potential aquifer by using mathematical logic. All values greater than 23 counts per second were considered as shales, clays or marls.

2.2.4 Water quality

After delineation of the potential aquifer the next step was determination of the formation water quality based on salinity values within the potential aquifer. Archie formula (Archie, 1942) was used to derive the equation for formation water resistivity based on short normal resistivity, long normal resistivity and resistivity of the mud filtrate.

Mud filtrate was obtained by taking freshly circulated drilling mud after every 2 meters and pressed with 6 bar pressure to obtain mud filtrate and its resistivity was measured and recorded.

From Archie formula; the formation factor is expressed as: $F = a/\Theta^m$

Whereby: **a** is an empirically derived constant referred to tortuosity of the formation

Θ is the porosity

m is the cementation factor

The typical values applied are:

For carbonates: $a = 1$, $m = 2$, consolidated sands: $a = 0.81$, $m = 2$ and unconsolidated sands $a = 0.62$, $m = 2.15$

Formation water resistivity, R_w

Formation water resistivity was determined from the electrical logs mainly short normal resistivity, long normal resistivity and the measured resistivity of the mud filtrate. The equations were derived as follows:

Long resistivity, $R_o = F \cdot R_w$ (i)

Short/normal resistivity, $R_{xo} = F \cdot R_{mf}$ (ii)

On combining equation (i) and (ii)

Formation water resistivity; $R_w = (R_o/R_{xo}) \cdot R_{mf}$

Whereby; R_o is the true resistivity of the formation

R_{xo} is the resistivity of the flushed zone

R_w is the formation water resistivity

R_{mf} is the resistivity of the mud filtrate

Conductivity in microSiemens per centimeter (microS/cm) = $10000/R_w$

Salinity in milligrams per liter (mg/l) = $0.7 \cdot \text{Conductivity (microS/cm)}$

CHAPTER THREE

3.0 Field work

3.1 Groundwater drilling

The field work was conducted in Dar Es Salaam, Tanzania at Kimbiji site from October to November in 2006 in which the Kimbiji Production Well was drilled. The total depth of the well was 613 meters.

3.2 Drilling techniques

There are two commonly types used for groundwater drilling namely cable tool driller and mud rotary driller.

Cable tool rigs are sometimes called pounders, percussion, spudder or walking beam rigs. They operated by repeatedly lifting and dropping a heavy string of drilling tools into the borehole. The drill bit breaks or crushes consolidated rock into small formations, the bit primarily loosens material.

Rotary drilling technique was used at the site. It uses a sharp, rotating drill bit to dig down through the earth's crust. Much like a common hand held drill, the spinning of the drill bit allows for penetration of even the hardest rock.

The basic rotary drilling system consists of four groups of components. The prime movers, hoisting equipment, rotating equipment and circulating equipment all combine to make rotary drilling possible.

Prime movers in a rotary drilling rig are those pieces of equipments that provide the power the entire rig. The energy from these prime movers is used to power the rotary equipment, hoisting equipment and the circulating equipment.

Hoisting equipment on a rotary rig consists of the tools used to raise and lower whatever other equipment may into or come out of the well, such as drill pipes, drill bit and drill collars. The most visible part of the hoisting equipment is the derrick, the tall tower-like structure that extends vertically from the well hole.

Rotating equipment consists of the components that actually serve to rotate drill bit, which in turn digs the hole deeper and deeper into the ground. Rotating equipment consists of a number of different parts, all of which contribute to transferring power from the prime mover to the drill bit itself. The prime mover supplies power to the rotary, which is the device that turns the drill pipe, which in turn is attached to the drill bit.

Below the drill pipe are drill collars which, which are heavier, and stronger than normal drill pipe. The drill collar helps to add weight to the drill string, right above the bit, to ensure there is enough downward pressure to allow the bit to drill through hard rock. This helps control drilling (e.g. making a straight hole) and prevents the pipe from kinking and breaking. The number and nature of drill collars on any particular rotary rig can be altered depending on the down hole conditions experienced while drilling.

A rotary drill bit is located at the bottom end of the drill string, and is responsible for actually making contact with the subsurface layers, and drilling through them. The drill bit is responsible for breaking up and dislodging rock, sediment, any anything else that may be encountered while drilling. There are dozens of drill bit types, each designed for different subsurface conditions. Different rock layers experienced during drilling may require the use of different drill bits to achieve maximum drilling efficiency. There are two types of drill bits most commonly used in the water well drilling industry. These are blade or drag bit and tricone or roller cone bits as they are often known.

Drag bits have short blades, each forged to a cutting edge and faced with tungsten carbide tips. Short nozzles direct jets of drilling fluid down the faces of the blades to clean and cool them (Driscoll, 1986). A blade bit is a drag bit in which the blades can be replaced. Drag bits have a shearing action and cut rapidly in sands, clays and some soft rock

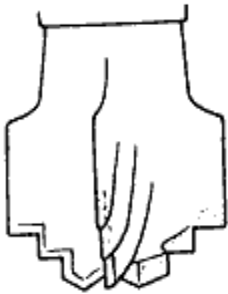
formations. Most drilling is done using the Drag bit (especially in clay and sands). However, it does not work well in coarse gravel or hard-rock formations. Whenever possible, drag bits should be used to drill pilot holes because they produce cuttings which are easiest to log.

Roller bits have three or more cones ("rollers" or "cutters") made with hardened steel teeth or tungsten carbide inserts of varied shape, length and spacing. They are designed so that each tooth applies pressure at a different point on the bottom of the hole as the cones rotate. The teeth of adjacent cones intermesh so that self-cleaning occurs. The cutting surfaces of all roller bits are flushed by jets of drilling fluid directed from the inside (centre) of the bit. Roller bits exert a crushing and chipping action, making it possible to cut hard rock formations. Long tooth roller cone bits are used for soft formations with short toothed bits used for hard formations.

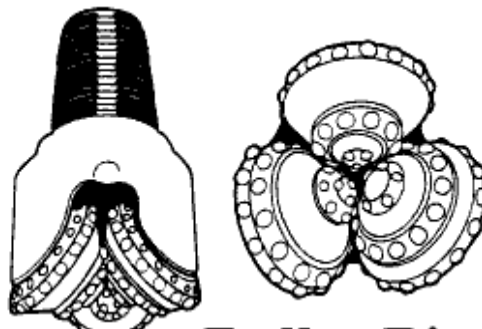
Circulating system is the final component of the rotary drilling. There are number of main objectives of this system, including cooling and lubricating the drill bit, removing debris and cuttings, and coating the walls of the well with a mud type-cake. The mud system circulates drilling mud in the hole. Drilling mud was stored in steel mud pits beside the rig. Pumps, called mud hogs, force the drilling mud through a hollow rubber tube. The drilling mud then flows down through the hollow rotating drill string and jets out through holes in the drilling bit on the bottom of the well. The drilling mud picks rock chips (cuttings) from the bottom of the well. It flows up the well in the space between the rotating drill string and well walls (annulus). At the top of the well, the mud flows through the blowout preventers and on to a series of screens called the shale shaker and cyclones. The shale shaker is designed to separate the cuttings from the drilling mud. Other devices are also used to clean the drilling mud before it flows back into the mud pits. The components of the circulating system include drilling fluid pumps, compressors and related plumbing fixtures.



Figure 3.1: Depicts the drilling rig to the right, drill pipes, mud pump and settling pit in the left at Kimbiji site



Drag bit



Roller bit



Figure 3.2: Roller bit applied at Kimbiji site. The diameter of the bit is 311 mm.



Figure 3.3: Worn drag bit as it was pulled out from the well at Kimbiji site

3.2.1 Drilling mud

Drilling mud was created by thoroughly mixing water with clay to a desired consistency. Drilling mud is usually a clay and water mixture. A common drilling mud is made of bentonite clay and is called gel. A heavier drilling mud can be made by adding barite (BaSO_4). Various chemicals are also used in different situations. The drilling mud liquid is usually water (freshwater based or salt-water-based) but is sometimes oil-based. After the fluid was mixed, sufficient time was allowed to elapse to ensure complete hydration of the clay prior to it being circulated into the hole. If this was not done, the clays may swell in the hole or in the aquifer itself.

Drilling fluids must be mixed thick (viscous) enough to bring soil cuttings up from the bottom of the hole to the surface, yet not so viscous as to prevent their settling out in the mud pits. It is, therefore, very important to understand the properties of drilling mud and their proper use: The ability of a fluid to lift cuttings increases rapidly as viscosity (the degree to which a fluid resists flow under an applied force) and up-hole velocity are increased. After cuttings are brought to the surface, however, it is essential that they drop out as the fluid flows through the settling pit. The desired results were obtained by properly designing the mud pits, controlling the viscosity and weight of the drilling fluid and adjusting the pump speed.

During the drilling process, solids accumulate in the drilling fluid - especially when drilling silt, clay or weakly consolidated shale (Driscoli, 1986). The thickness of the drilling fluid often needs to be adjusted during drilling by adding more water and/or removing some of the accumulated cuttings from the settling pit.

Fluid which is too thick will be difficult to pump and will cause unnecessary wear of the mud pump since cuttings will not have settled out of the mud before the mud is pumped back down the borehole. It will also make it difficult to remove the mud from the borehole walls and adjacent aquifer during well development. The rate of penetration is also potentially reduced.

If the mud is too thin, cuttings will not be brought to the surface and the drill bit and drill pipe may get stuck in the borehole by settling cuttings. In addition, thin mud can result in excessive migration of mud into the formation, thus decreasing the potential yield of the well.

At the bottom of the well, there are two fluid pressures. Pressure on fluids in the rock tries to cause the fluids to flow into the well. Pressure exerted by the weight of the drilling mud tries to force the drilling mud into the surrounding rocks. If the pressure on the fluid in the subsurface rock is greater than the pressure of the drilling mud, the water, gas, or oil will flow out of the rock into the well. This often causes the sides of the well to

cave or stuff in, trapping the equipment. In extreme cases, it causes a blowout. In order to control subsurface fluid pressure, the weight of the drilling mud is adjusted to exert a greater pressure on the bottom of the well. This is called overbalance, and the drilling mud is then forced into the surrounding rocks. The rocks act as a filter and the solid mud particles cake to the sides of the well as the fluids enter the rock. This filter or mud cake is very hard. Once the filter cake has formed, the sides of the well are stabilized and subsurface fluid cannot enter the well.



Figure 3.4: Depicts mud pit, shaker, and cyclones at Kimbiji site. The shaker used to separate sand, silt and other cutting materials from the mud coming direct from the borehole for further circulation.



Figure 3.5: Depicts the mixing tank and mud pumps at Kimbiji site. The pumps used to pump the mud from the mixing tank to the cyclones before pumped again to the borehole.



Figure 3.6: Mud pumps at Kimbiji site. These mud pumps (right) used to pump the mud from settling pit (left) to the borehole.

3.2.2 Drilling mud viscosity

Viscosity is a measurement of a fluid's resistance to flow; the greater the resistance, the higher the viscosity. The viscosity of drilling mud is influenced by the gelatin-related density and the solids content. The viscosity can be controlled by adding drilling mud and adjusting the pH. The viscosity should be adjusted depending upon the type of material being drilled, the drilling rate and the hole size.

The viscosity of the drilling fluid is also a function of the rate of flow for the pump and the size of the borehole. The bigger the borehole, the lower the upper velocity of the fluid. At lower velocities, the viscosity is higher because electric charge on the clay particles will hold in a tighter bond. This is why the clay in the drilling fluid tends to gel when the fluid is at rest. Different types of clay have a wide range of hydration potential. The more the clay hydrates, the more it expands and has more lifting ability. Sealing clays like bentonite and montmorillonite are preferred because of their ability to swell.

When properly hydrated in water, these clays can swell to approximately 10 times their original volume. Bentonite and montmorillonite hydrate only in fresh water.

Viscosity can be measured with a Marsh Funnel. The procedure is as follows: Hold funnel in upright position with index finger over the outlet, pour the drilling fluid through the screen in the top of the funnel until the drilling fluid reached the marked line just beneath the screen, remove the finger from the outlet and measure the number of seconds it takes to fill the accompanying container up to the marked line which is equivalent to one liter.

Material being drilled	Marsh funnel viscosity
Natural swelling clay	32 to 37
Normal conditions (including non-swelling clay and fine sand)	40 to 45
Medium sand	45 to 55
Course sand	55 to 65
Gravel	65 to 75
Course gravel	75 to 85

Table 3.1: This table can be used to decide whether the drill mud is thick enough for the effective drilling.



Figure 3.7: Marsh funnel used at the site to determine the mud viscosity



Figure 3.8: Marsh funnel showing the pouring mesh side. The mesh side used to filter the mud so that the outlet can not be blocked.

The pH of the drilling fluid can affect performance of the drilling mud. Drilling mud will have maximum hydration where the pH is between 8.0 and 9.0

Drilling fluid must have enough time to hydrate. Proper viscosity enables the drilling fluid to effectively bring up drill cuttings and to build a good wall cake. The wall cake helps support the borehole and keep it from collapsing when drilling in unconsolidated material.

3.2.3 Control of the Borehole

Loosing fluid to the formation typically causes borehole problems. The higher the fluid loss, the greater the potential for weakening the formation to the point of collapse or thickening the wall cake. At the site there was a 20m³ tank filled with thick mud ready to be added in the borehole in case of loss of mud circulation.

CHAPTER FOUR

4.0 Results

4.1 Borehole geophysical logs

Borehole geophysical logs were collected in Kimbiji well (PW-1). The reference measuring point for all logs is land surface. Depth of well are given in meter below land surface. Continuous profiles of the geophysical properties were acquired from the bottom of the borehole to the surface. Geophysical logs are presented in Figures 4.1, 4.2, 4.3, 4.4 and 4.5 for short normal resistivity and long resistivity, gamma, spontaneous potential, temperature and caliper respectively. Table 4.6 shows the geophysical logs values for every 0.1 meter interval down to 612.9 meters.

Caliper log shows the total depth of the borehole is 613 meters and it is cased to 30 meter below land surface (fig 4.5). The caliper log shows pronounced deviations of the well diameter at 582-599, 557-581, 520-530, 501-517, 376-380, 339-348, 279-286, 229-243, 193-195, 86-108, 47-71, 41-42 and the decrease in well diameter at 260.9-258.9 meters below land surface.

Gamma log shows pronounced low gamma readings at 590-566, 484-481, 467-446, 401-398, 388-384, 380-376, 348-337, 320-289, 285-280, 277-253, 248-229, 223-194, 153-149, 146-89, 87-70, 61-55 and 52-47 meters below land surface.

Long normal resistivity and short normal resistivity logs show pronounced elevated readings at 340-344, 280-282, 231-248, and 179-181 meters below land surface. At depths 381-613 meters below land surface both long normal resistivity and short normal resistivity show pronounced lower values almost below 10 ohm meter.

Temperature log shows the increase of temperature with depth from the surface down to 460 meters. From 460 to 520 and 560 to 612 meters below land surface the log shows a constant or nearby constant temperature with depth. Temperature gradient or geothermal gradient is $0.02^{\circ}\text{C}/\text{m}$ or $20^{\circ}\text{C}/\text{km}$.

Spontaneous potential log shows the values increase with depth from 1300 mV at 30 meters to 1410 mV at the bottom of the well. There were no pronounced deflections along the profile as it was expected. The spontaneous potential log was almost smooth.

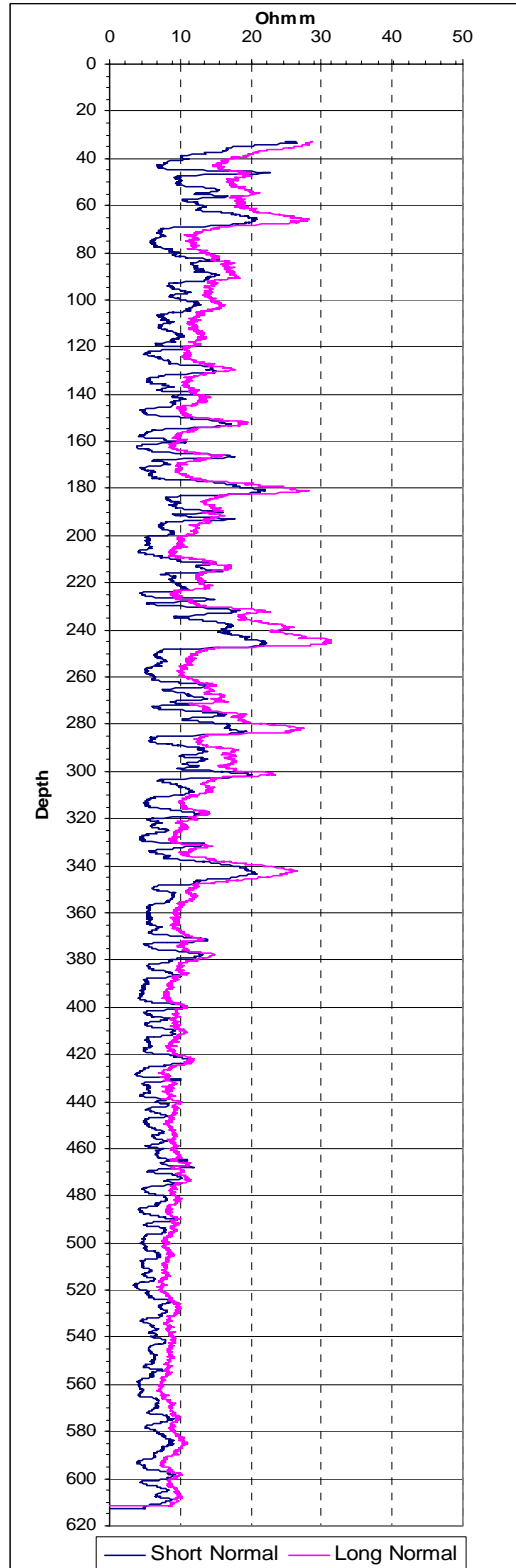


Figure 4.1: Plot of normal resistivity log versus depth. Depict the electrical resistivity of the formation around the borehole. The long normal resistivity (red) indicates the resistivity values for both flushed zone (invaded zone) and undisturbed zone whereas the short normal resistivity (blue) indicates the resistivity values for flushed zone (invaded zone) only.

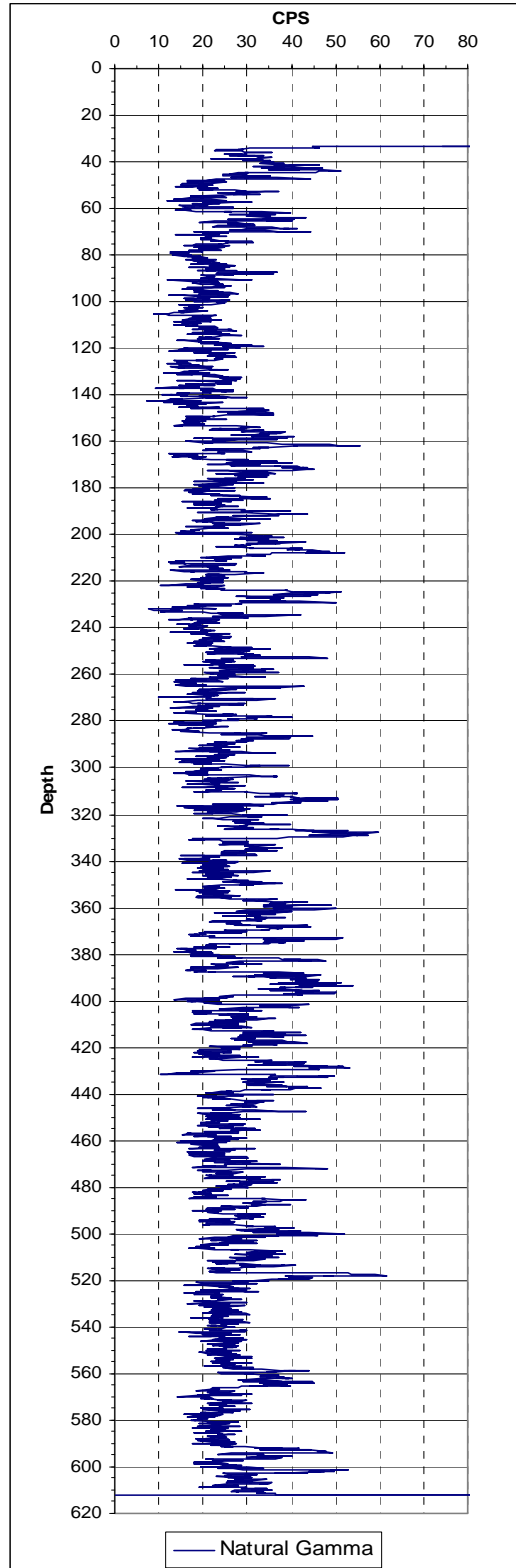


Figure 4.2: Plot of gamma log versus depth. Depict the amount of natural gamma radiation emitted by the rocks surrounding the borehole. This log distinguishes and delineates sands and clay/shale formations for aquifer mapping.

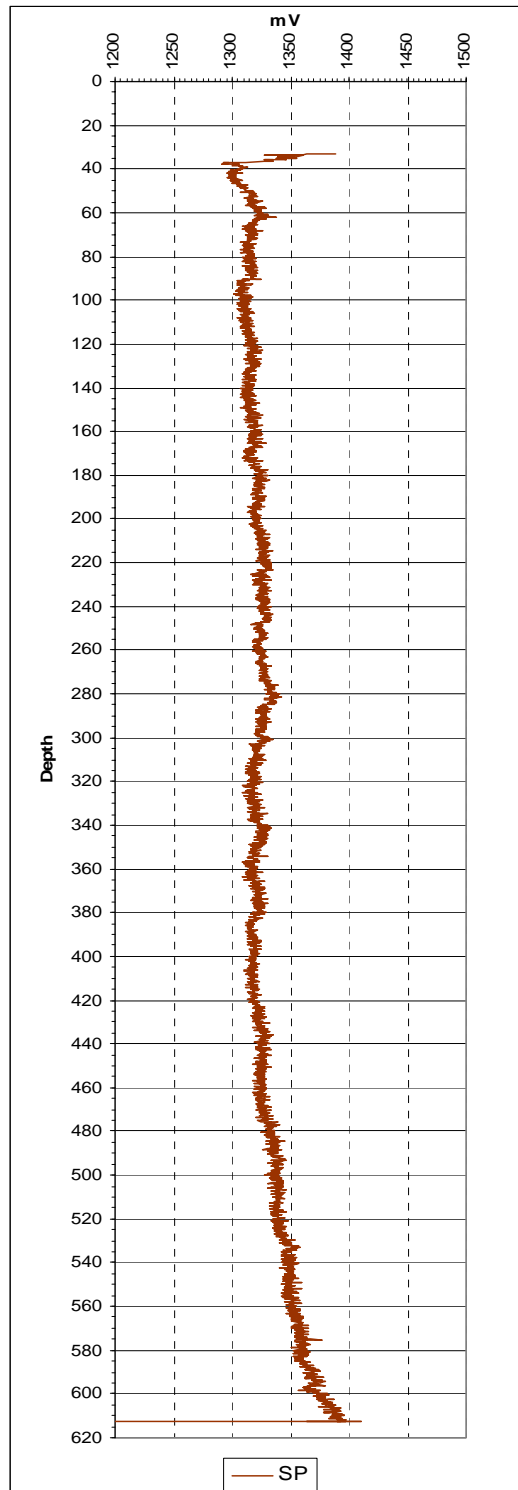


Figure 4.3: Plot of spontaneous potential log versus depth. Spontaneous potential shows the potentials or voltages that develop at the contacts between shale or clay beds and a sand aquifer.

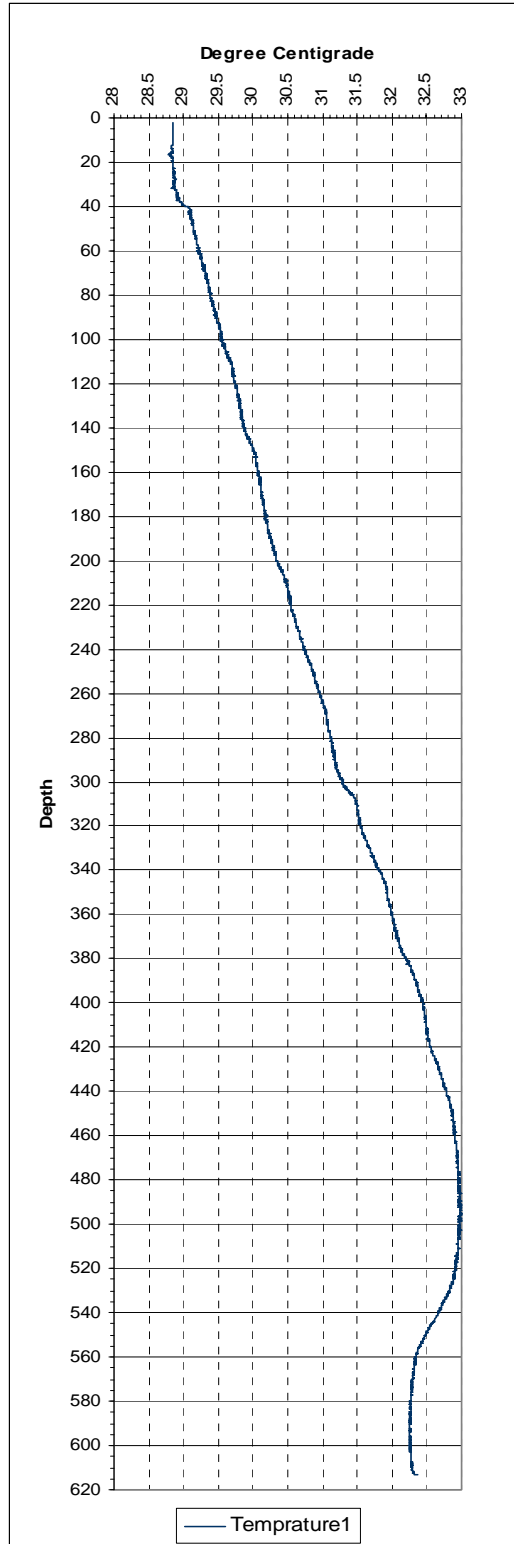


Figure 4.4: Plot of temperature log versus depth. Depict the water temperature in the borehole, useful for delineating water bearing zones and identifying vertical flow in the borehole. Borehole flow between zones is indicated by temperature gradients that are less than the regional geothermal gradient.

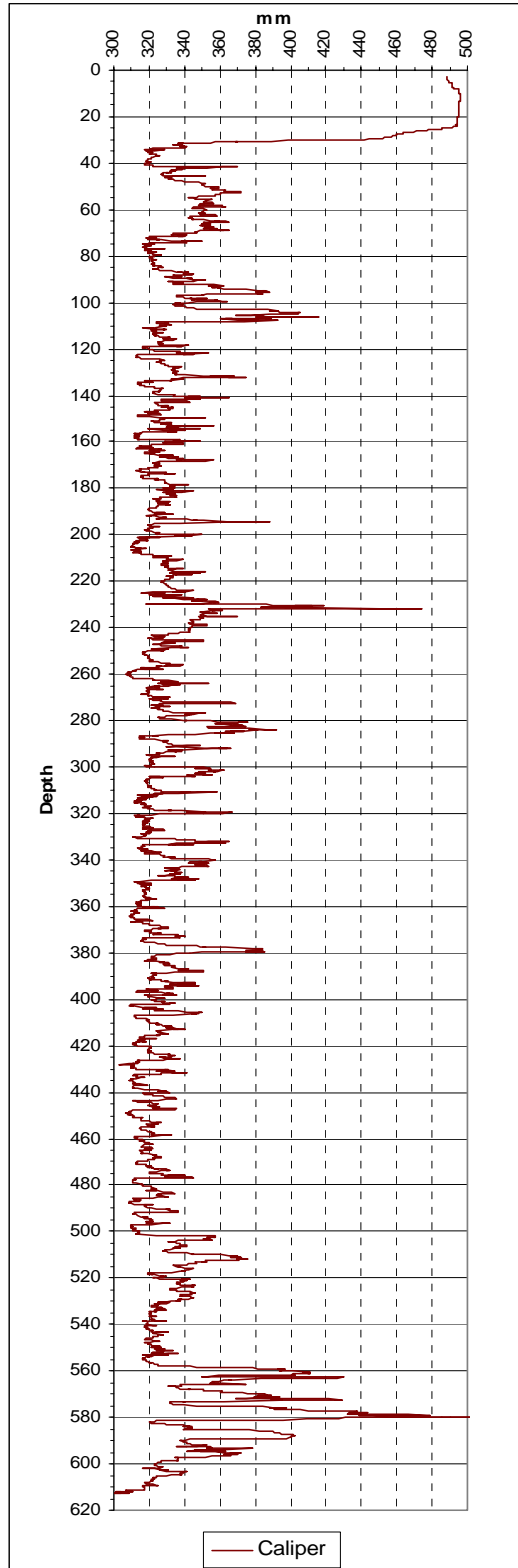


Figure 4.5: Plot of caliper log versus depth. Depict the changes in borehole diameter with depth. Changes of borehole diameter are related to well construction, such as casing or drilling bit size and to fracturing or caving along the borehole wall.

4.2 Water quality

4.2.1 Formation water salinity

Formation water resistivity was calculated from the resistivity of mud filtrate, short normal resistivity and long normal resistivity based on Archie formula (Archie, 1942). Formation water resistivity values were converted to conductivity in the units of micro Siemens per centimeter. Formation water salinity for every 10 centimeter down to 612.9 meters was calculated from the conductivity.

4.2.2 Salinity profile

Salinity profile was determined for the only aquifer formation (figure 4.6) and then filtered to get the required profile for the potential aquifer with formation water salinity less than 1100 milligram per liter (figure 4.7). For the aquifer formation the pronounced peak values of salinity occur at depth 330.5 to 331 meters below the land surface with pronounced peak value of 1590 milligram per liter at 330.7 meter. The lowest value of salinity along the profile is 526 milligram per liter. The salinity values show decrease trend with depth with more freshwater from 480 down to 612.9 meters. The average salinity for the whole potential aquifer was 850 milligram per liter.

4.3 Seismic hydrogeological cross section

The length of traversing line 2 is 64 kilometers. The depth to the top of Eocene seismic reflector (figure 4.8 & 4.9) indicates the maximum depth to that reflector is 1173 meters below land surface with an average elevation of 85m; the depth to the water table at that point is 34 meters below land surface. The minimum depth to the top of Eocene seismic reflector is found at 525 meters below land surface with an elevation of 152 meters and the water table at 24 meters below land surface. The average depth to the top of seismic reflector is 850 m.

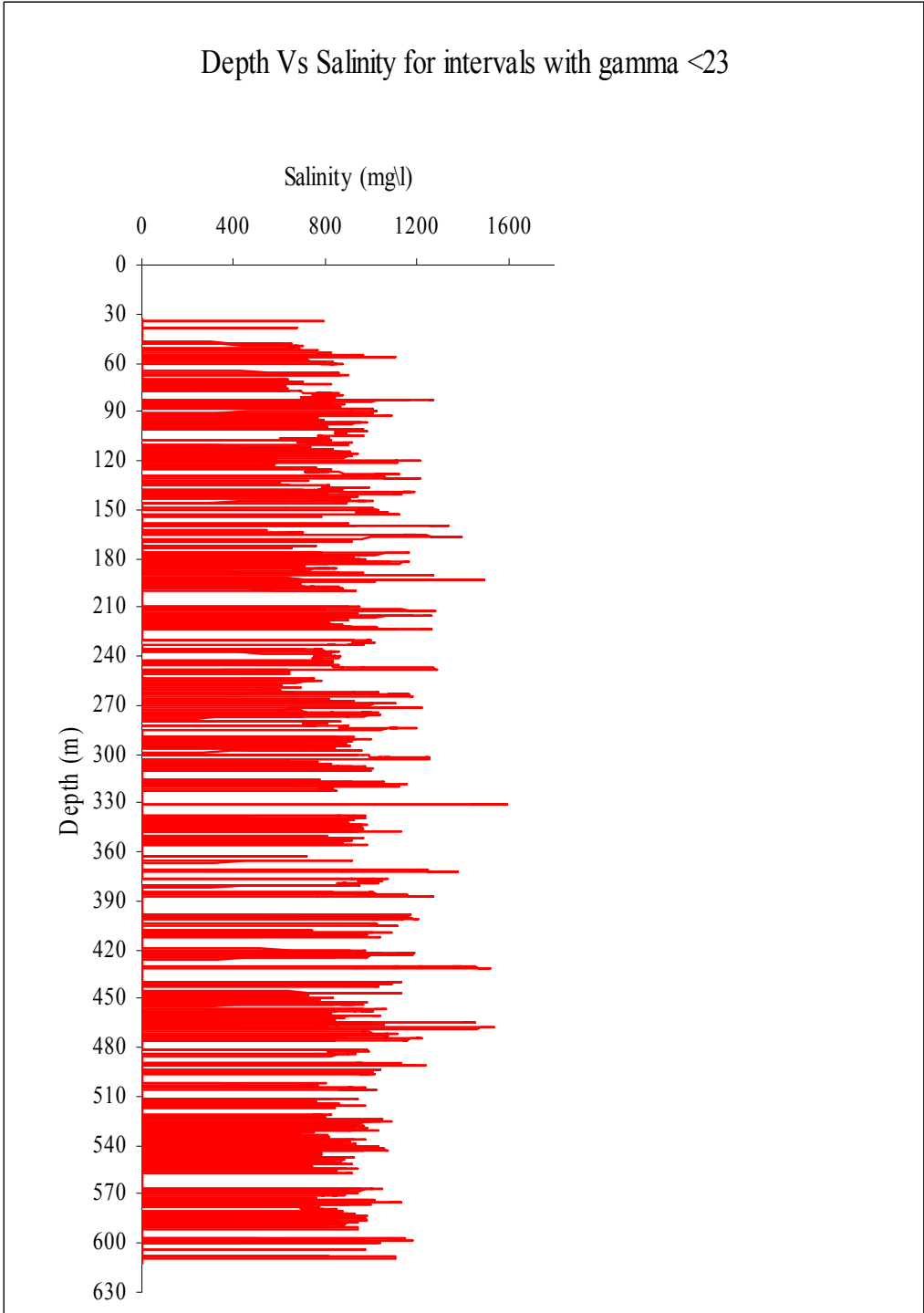


Figure 4.6: Plot of salinity versus depth. Depict salinity profile along the selected aquifer formation for intervals with gamma less than 23 counts per second (sandy formations).

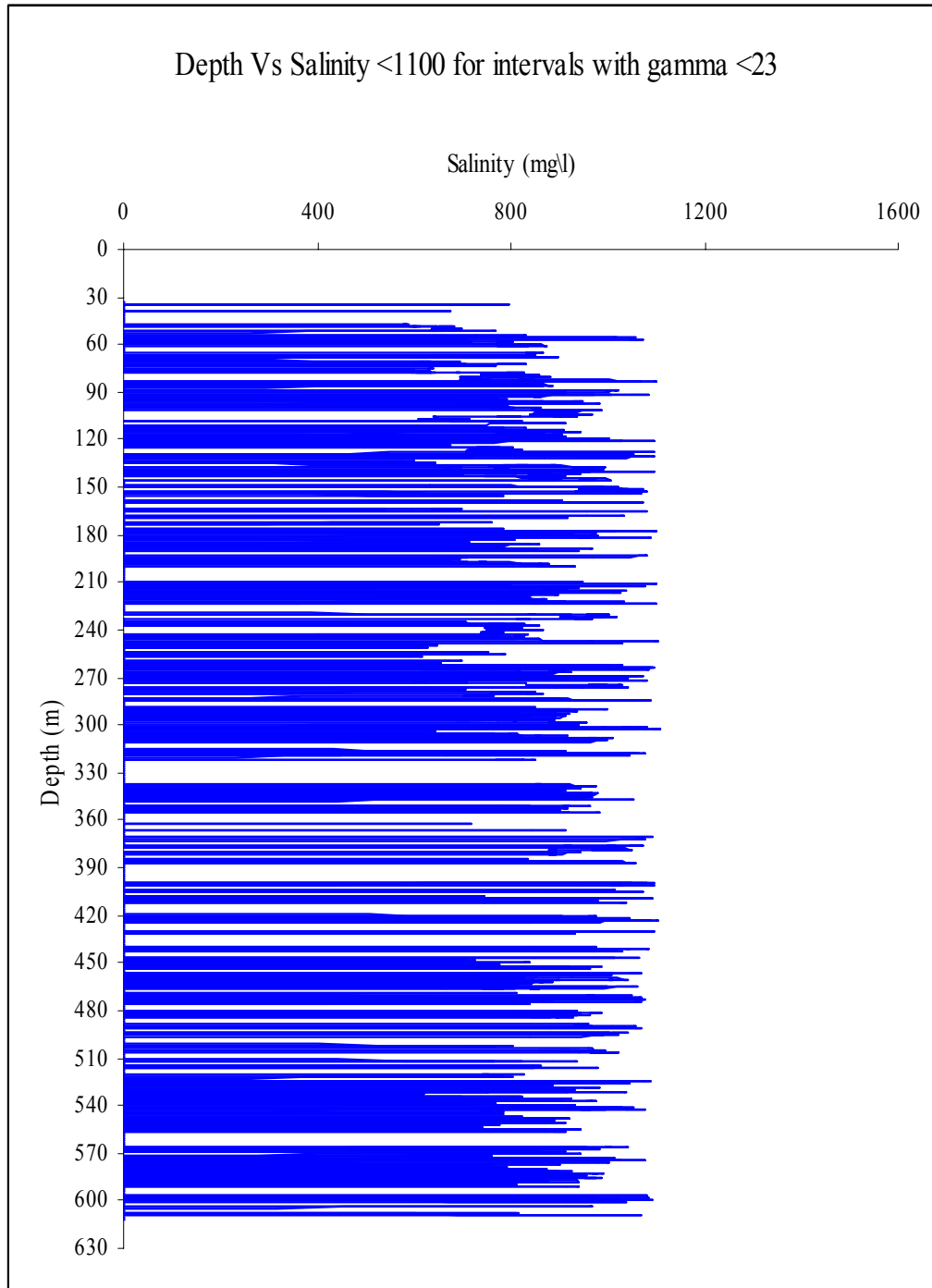


Figure 4.7: Plot of Salinity versus depth. Depict salinity profile along the potential aquifer with salinity less than 1100 mg/l for intervals with gamma less than 23 counts per second (sandy formations).

From (m)	To (m)	Total length (m)	Type
73.00	0.00	73.00	casing
146.00	73.00	73.00	screen
175.00	146.00	29.00	casing
180.00	175.00	5.00	screen
183.00	180.00	3.00	casing
189.00	183.00	6.00	screen
198.00	189.00	9.00	casing
201.00	198.00	3.00	screen
212.00	201.00	11.00	casing
218.00	212.00	6.00	screen
241.00	218.00	23.00	casing
309.00	241.00	68.00	screen
337.00	309.00	28.00	casing
349.00	337.00	12.00	screen
418.00	349.00	69.00	casing
424.00	418.00	6.00	screen
448.00	424.00	24.00	casing
476.00	448.00	28.00	screen
522.00	476.00	46.00	casing
555.00	522.00	33.00	screen
566.00	555.00	11.00	casing
580.00	566.00	14.00	screen
600.00	580.00	20.00	casing

Table 4.2: Depict the well design based on the water quality from the salinity profile along the potential aquifer with salinity less than 1100 mg/l for intervals with gamma less than 23 counts per second (sandy formations). The total screen length down to 600 meters in various intervals is 254 meters whereas casing length is 346 meters.

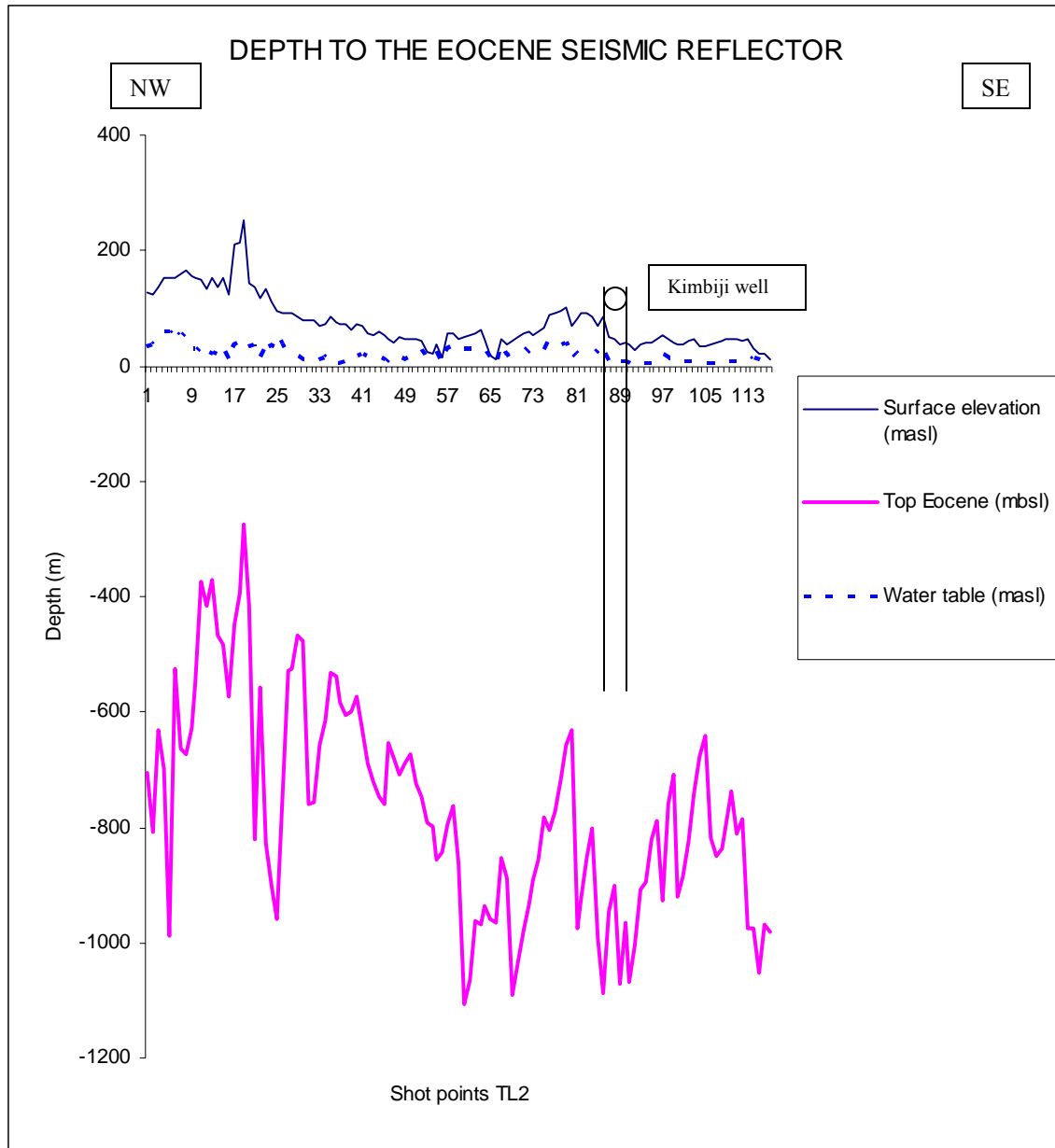


Figure 4.8: Seismic hydrogeologic section for traversing line 2, depicting topography, water table and top of Eocene seismic reflector (base of the aquifer). The length of the profile is 64km. (masl means: meters above sea level; and mbsl; meters below sea level)

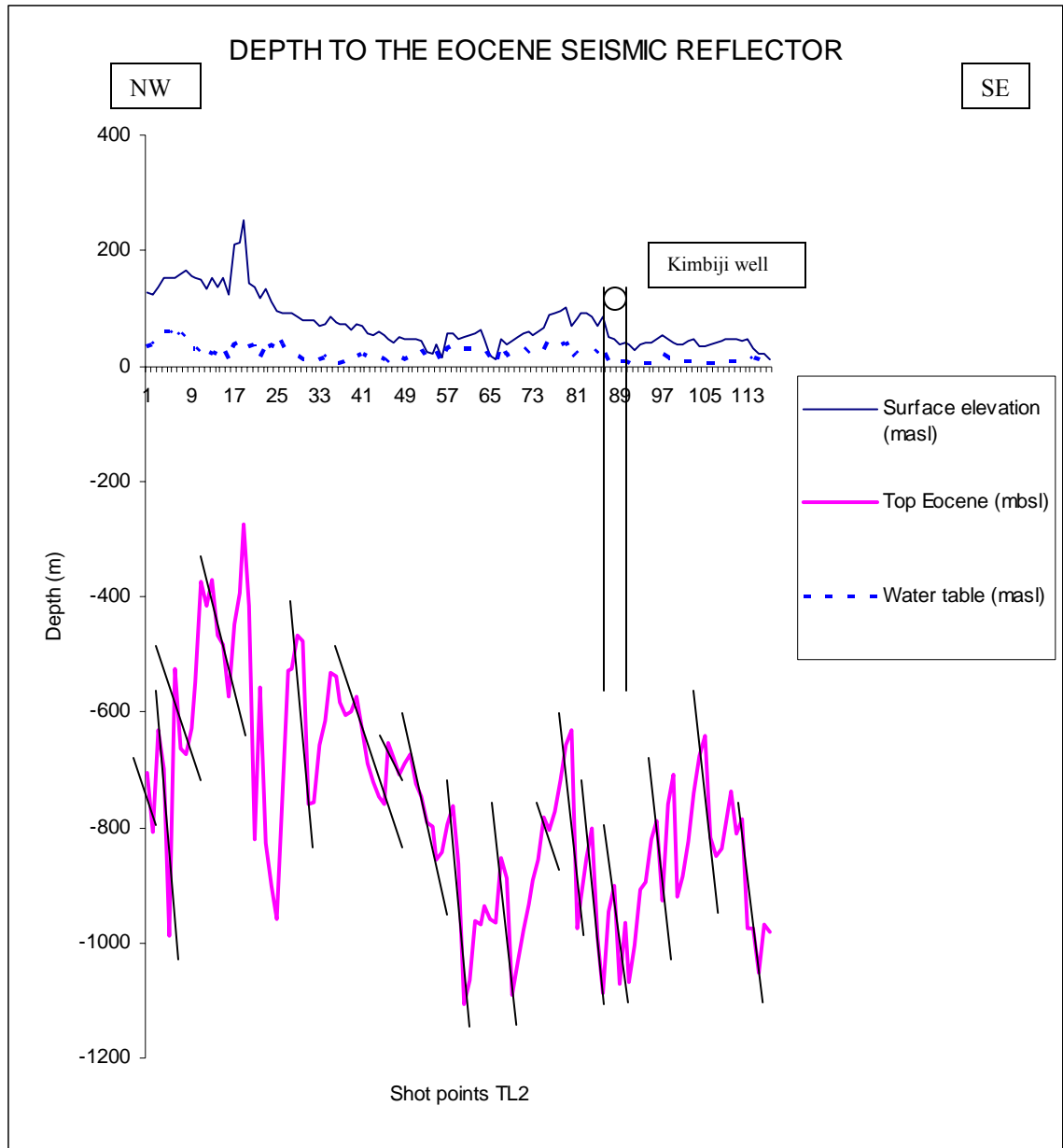


Figure 4.9: Seismic hydrogeologic section for traversing line 2, depicting topography, water table, top of Eocene seismic reflector (base of the aquifer) and overview of the tectonics (faults). The length of the profile is 64km.

CHAPTER FIVE

5.0 Discussion and Conclusion

5.1 Discussion

5.1.1 Normal resistivity log

Electrical methods have been widely applied in coastal and island environments because of their ability to detect increases in the pore water conductivity (Stewart, 1999). The electrical resistivity of an aquifer is controlled primarily by the amount of pore space of the aquifer (that is, the aquifer porosity), degree of sorting (grain size) and by the salinity of the water in the pore space (water chemistry or water quality); increases in either the porosity or the concentration of the dissolved ions result in increases in the conductivity of the groundwater. When variations in clay content, chemistry and porosity are small, changes in electrical resistivity is primarily a function of changes in the clay size fractions. The resistivity decreases when the porosity increases and when the formation water salinity increases or when grain size decreases.

Because seawater has high concentration of dissolved ions, its presence in a coastal aquifer can be inferred from measurements of the spatial distribution of electrical resistivity.

The most important application of normal resistivity logs in groundwater hydrology is for determining water quality. Normal-resistivity logs measure apparent resistivity; if true resistivity is to be calculated from these logs, a number of factors must be considered (Lynch, 1962). Although not all these factors are significant under all conditions, corrections must be applied for each under some conditions. The factors include resistivity of the invaded zone (R_i), diameter of the invaded zone (D_i), mud resistivity (R_m), borehole diameter (d), bed thickness (h), resistivity of adjacent beds, and AM spacing. Temperature corrections must be applied to any measurement of resistivity. Apparent resistivity from logs may be equal to, greater than, or less than true resistivity, depending on the specific factors.

Turcan (1966) used a practical field method to estimate ground-water quality in Louisiana from resistivity logs. The method is based on establishing field formation factors for aquifers within a limited area, using electric logs and water analyses. After a consistent field formation factor is established, the long normal log or any other resistivity log that provides a reasonably correct R_t can be used to calculate R_w from the relation $F = R_o/R_w$.

The relation between resistivity as determined from normal resistivity logs and concentration of dissolved solids in ground water is valid only if the porosity and clay content are relatively uniform and R_o from the logs approximates R_t . Only in sediments having uniformly distributed intergranular pore spaces is bulk resistivity proportional to R_w . This relation applies to some limestone and dolomite, but the method does not apply to rocks having randomly distributed solution openings or fractures. Because the flow of electrical current is related to tortuosity, two rocks having the same average porosity will have different resistivities if one has uniformly distributed intergranular porosity and the other has randomly distributed vugs.

Additional factors that may cause errors in determining water quality from resistivity logs because of their effect on the measured or apparent formation factor are shape, packing, uniformity, and mean size of the particles, pore water resistivity, matrix resistivity, ion exchange and surface conduction (Biella and others, 1983).

The normal-resistivity log (figure 4.1) was used to calculate the quality of the water in the aquifer at the Kimbiji well site in Dar Es Salaam, Tanzania. The resistivity log show significant and consistent separation between short and long resistivity values, indicating high permeabilities and the presence of fresh formation water down to 600 m. The short normal resistivity values are less than long normal resistivity values along all the profile; this also indicates that the formation water is fresher than the drilling mud in the borehole.

Long normal and short normal resistivity log shows the abrupt decrease from 480 meters below land surface down to 612.9 meters in which the values of both fall below 11 ohm meter. The diminishing resistivity through a sand interval can be caused by changes in grain size, poorer water quality (water chemistry) and amount of pore space of the aquifer (that is, the aquifer porosity) or a combination of both. Since the calculation of salinity indicates freshwater in that depth intervals these changes of the normal resistivity may be attributed by the degree of sorting (changes in grain size) and the amount of pore space of the aquifer (aquifer porosity) or a combination of both.

5.1.2 Natural gamma log

Radioactivity is the emission of rays caused by the spontaneous change of one element into another. Although several types of rays are emitted, only gamma rays have enough penetration to be of practical importance in logging the natural radioactivity of rocks.

The natural gamma or gamma log measures the intensity of natural-gamma radiation emitted from rocks penetrated by the borehole. The most common emitters of gamma radiation are uranium-238, thorium-232, their daughter elements, and potassium-40. These radioactive elements are concentrated in clays by adsorption, precipitation, and ion exchange. Fine grained sediments, such as in shale or siltstone, usually emit more gamma radiation than sandstone, limestone, or dolomite. Although there is no fixed rule regarding the amount of radioactivity a given rock may have, shales, clays and marls are generally several times more radioactive than clean sands, sandstones, limestone and dolomites. The radioactivity of clean sands, i.e., sands free of shaly materials (shale, clay and marl) is generally very low. Sands that contain some shaly material have a somewhat higher radioactivity, and the increase is proportional to the amount of shale, clay and marl contained. Therefore, shaly sands and sandy shales generally have a radioactivity that is between that of clean sands and that of shale.

The gamma ray curve is therefore a "formation log" and permits distinguishing clay, marl and shale beds from sands, gravels, sandstones and limestones. Shaly and clayey sands or gravels are generally mediocre aquifers. They can usually be identified by their

intermediate radioactivity and comparison between electric and gamma ray logs of the same well.

In many areas, desirable aquifers are separated from unwanted ones by very thin impervious beds that are impossible to locate on the driller's log and difficult to pick up on the electric log. It is often possible to locate such thin beds on the gamma ray logs.

Note that the gamma ray log is affected neither by the type of formation water nor by the salinity of the drilling mud.

Gamma log shows pronounced low gamma readings at 590-566, 484-481, 467-446, 401-398, 388-384, 380-376, 348-337, 320-289, 285-280, 277-253, 248-229, 223-194, 153-149, 146-89, 87-70, 61-55 and 52-47 meters below land surface. These readings with less than 23 counts per second were interpreted as clean sands or limestone and referred as a potential aquifer for this study area. The huge aquifer lies between 146-89 meters.

5.1.3 Temperature log

Temperature logging records the temperature of the water in the borehole (Williams and Conger, 1990). In boreholes with no vertical borehole flow, the temperature of the borehole water generally increases with depth as a function of the geothermal gradient in the surrounding rocks. Temperature gradients less than the geothermal may indicate intervals with vertical borehole flow. The depth intervals where natural movement of the water occurs along the borehole axis are indicated on the temperature logs by a constant or nearby constant temperature (Conaway, 1987, Prenskey, 1992).

There are various factors that influence temperature behavior in the well. These include the natural temperature of the formations penetrated by the well, heat conductivity between the well and surrounding formation, diffusivity of mechanicals such as packers, heat convection attending fluid flow, and thermal changes of fluids under dynamic conditions.

The generation and dissipation of the earth's heat is ad infinitum. The heat flux from the core travels to the surface through the various lithologies. This geothermal profile will vary from area to area and the slope of the geothermal temperature versus the depth (referred to as geothermal gradient) will vary from formation to formation. The geothermal gradient depends on the thermal conductivity of the lithology. The higher the thermal conductivity the more easily the heat is transported through the rock. Though varying at different locations the gradient will typically be 0.47 and 0.6°C per 30 m of depth. This gradient is key and becomes the reference when interpreting temperature logs. While the fluids trapped within the earth remain static, the geothermal gradient will be normal for that area. Once the fluid moves it will transport some of the temperature from its depth of origin. When the fluid moves it will change the temperature around the borehole where it travels. The new amount of temperature change per depth then becomes a dynamic temperature gradient. The rate or slope of this temperature change will be steeper near its origin and gradually move parallel to the normal geothermal slope. Actual temperature at a given depth will then be different from the normal geothermal temperature.

If the fluid movement ceases then the temperature in the well will start to move back to the original geothermal temperature for that area and depth. This "decay" in temperature back to normal will be determined by the time of the fluid movement, the volume of fluid and the conductivity between the well and the formation. The "temperature decay" is extremely useful in qualifying fluid movement and in some cases the movement can be quantified.

During the drilling process, drill mud is circulated in the drill string and the annulus to carry cuttings out of the borehole. At the same time, heat is advected along the borehole and diffused laterally into the formation. The host rock is either heated or cooled. This transient thermal perturbation produces a characteristic curved temperature signature in the temperature log. Heat advection by fluid flow introduces curvature in a temperature log as well as diffusion of transient variations of ground surface temperature. (Bredenhoef and Papadopulos 1965, Clauser 1988), for instance, interprets the curvature of a

temperature log as an effect of groundwater flow. For non equilibrated temperature logs this yields inaccurate flow estimation. Often, the maximum temperature in a borehole would be underestimated.

Normally in a well where no flow has occurred for sufficient time to permit thermal equilibrium to be established a temperature log reflect the geothermal gradient in the rocks. If vertical flow occurs in a well at a high rate, the temperature log through that interval will show little change. Vertical flow, up or down, is very common in wells that are completed through several aquifers or fractures that have different hydraulic head, although the flow rate is seldom high enough to produce an isothermal log.

The temperature log from Kimbiji site (figure 4.4) shows increasing values with depth from the surface up to 450 meters this indicates that there is no vertical flow of the water in the borehole along this depth interval and it reflects the normal geothermal gradient. From 460 to 520 and 560 to 612 meters below land surface the log shows a constant or nearby constant temperature with depth which indicates the natural movement of water along the borehole axis (zones of vertical borehole-fluid movement). These are the water (producing) bearing zones. This natural movement of water at the depth of 460 to 520 and 560 to 612 meters coincides with the major fractures as indicated by caliper log in which the borehole diameter increases from 311 millimeter up to 530 millimeter at the depth of 580 meters. A clearly curved temperature signature was observed between 540 to 440 meters and this was interpreted as an effect of groundwater flow.

These movements of water have contributed much in modifying the quality of groundwater as shown in the salinity profile (figure 4.6).

5.1.4 Caliper log

The average borehole diameter was recorded by caliper logs, which may be related to fractures, lithology, or drilling methods. A caliper log was used to identify fractures and possible water-producing openings and correct other geophysical logs for changes in borehole diameter. The term fracture used in this study in association with the caliper log

interpretation identify a change in borehole diameter that may not necessarily indicate a bedding plane separation, lithologic contact, or fluid producing or fluid receiving zone but may simply indicate an enlargement of the borehole.

The average diameter of the borehole was 12.25 inch or 311.15 millimeter. Major fractures and most interesting, occurred at 505 to 515 and 560 to 612 meters below land surface which coincides directly with the change in temperature gradient. These are interpreted as the most important water producing zones as indicated by both temperature log and caliper log. Also there were some minor changes of the borehole diameter along the profile probably related to lithology or drilling methods.

5.1.5 Salinity profile

The Kimbiji aquifer system is considered to be a valuable supplemental source for public-water supply in Dar es Salaam. The primary purpose of the study reported here was to describe the distribution of salinity with depth in this aquifer system.

Most chemical concentration in this report are given in milligrams per liter, which is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water.

Coastal ecosystems are sensitive to the salinity and nutrient concentrations of coastal waters. Ground water can be a significant source of freshwater to some coastal waters, and its role in delivering excess nutrients to coastal ecosystems is of increasing concern because of widespread nutrient contamination of shallow ground water (U.S Geological Survey, 1999)

Saturated geologic materials that yield usable quantities of water to a well or spring are called aquifers. An aquifer can consist of a single geologic formation, a group of formations, or part of a formation (Lohman et al, 1972). The capacity of geologic material to transit water is characterized by the material's hydraulic conductivity, which is commonly referred to as the permeability of the material. Confining units (or confining

layers) are geologic units that are less permeable than aquifers. Because of their lower permeability, confining units restrict the movement of ground water into or out of adjoining aquifers. Aquifers and confining units are mapped on the basis of the degree of contrast in hydraulic conductivity among geologic units (Sun and Johnson, 1994). Generally, there is a close correlation between the type of geologic formation and its water yielding properties. For example, unconsolidated sands and gravels, sandstones, and limestones commonly are major sources of ground water supplies (aquifers), whereas beds of silt and clay function primarily as confining units (Heath, 1984).

Ground water in Dar es Salaam coastal zone occurs in confined, semi confined and unconfined aquifers as indicated by natural gamma and normal resistivity logs figure 4.1 and 4.2 respectively. Where water completely fills the pore spaces of an aquifer that is overlain by a confining unit, the aquifer is referred to as confined (or artesian). In contrast, where water only partially fills the pore spaces of an aquifer, the upper surface of the saturated zone (which is called the water table) is free to rise or decline, and the aquifer is referred to as unconfined or phreatic (or as a water table aquifer).

The general pattern of fresh ground water flow in coastal aquifers is from inland recharge areas where groundwater levels (hydraulic heads) typically are highest to coastal discharge areas where groundwater levels are lowest. Hydraulic head (often simply referred to as 'head') is a measure of the total energy available to move groundwater through an aquifer, and groundwater flows from location of higher head (that is, higher energy) to locations of lower head (lower energy).

Groundwater recharge in the studied area is mostly by effective rainfall and rivers. This water may reach the aquifer rapidly, through macro-pores or fissures, or more slowly by infiltrating through soils and permeable rocks overlying the aquifer. A change in the amount of effective rainfall will alter recharge, but so will a change in the duration of the recharge season. Various types of aquifer will be recharged differently. An unconfined aquifer is recharged directly by local rainfall, rivers, and lakes, and the rate of recharge will be influenced by the permeability of overlying rocks and soils. A confined aquifer,

on the other hand, is characterized by an overlying bed that is impermeable, and local rainfall does not influence the aquifer. It is normally recharged from lakes, rivers, and rainfall that may occur at distances ranging from a few kilometers to thousands of kilometers. Recharge rates also vary from a few days to decades. The hinterland of Dar es Salaam mainly Pugu, Mkuranga, Ruvu and Kisarawe plays an important role in replenishing the Kimbiji coastal aquifer. The dipping angle for the bedding planes is minimal resulting in a several kilometers of infiltration of rainwater and river water from the hinterland to the coastal aquifer. The infiltration is about 50-70% of the total annual precipitation, approximately 550-770 mm/yr. Also Kimbiji area is almost flat therefore most of the precipitation is infiltrated and conveyed to groundwater due to highly permeable formation and absence of surface runoff.

Fresh groundwater comes in contact with saline groundwater at the seaward margins of coastal aquifers. The seaward limit of freshwater in a particular aquifer is controlled by the amount of freshwater flowing through the aquifer, the thickness and hydraulic properties of the aquifer and adjacent confining units, and the relative densities of saltwater and freshwater, among other variables. Because of its lower density, freshwater tends to remain above the saline (saltwater) zones of the aquifer, although in multilayered aquifer systems, seaward flowing freshwater can discharge upward through confining units into overlying saltwater. As used in this thesis, saltwater is defined as water having total dissolved solids concentration greater than 1100 milligram per liter (mg/l). Seawater has total dissolved solids concentration of about 35000 milligrams per liter, of which dissolved chloride is the largest component (about 19000 milligrams per liter).

All water contains dissolved chemical materials called 'salts'. When the concentration of these dissolved materials becomes great, the water is referred to as 'saltwater' or as 'salty', 'brackish', or 'saline'.

The classification method used in this thesis defines freshwater as having a total dissolved solids concentration of less than 1100 milligrams per liter; waters with a total dissolved solids concentration greater than 1100 mg/l are considered to be saltwater (or

saline). This somewhat arbitrary upper limit of freshwater is based on the suitability of the water for human consumption. Although waters with total dissolved solids concentrations of greater than 1100mg/l have been used for domestic supply in some areas of Dar es Salaam where water of lower dissolved solids concentration is not available, water containing more than 2000 to 3000 mg/l total dissolved solids is generally too salty to drink (Freeze and Cherry, 1979). Brackish water can be defined as those having a total dissolved solids concentration of 1100 to 35000 mg/l. The upper concentration limit for brackish water is set at the approximate concentration of seawater (35000 mg/l). Water with a dissolved solids concentration exceeding that of seawater is called brine. Although there are different types of brines in terms of chemical composition, the largest number represents concentrated seawater containing mostly sodium chloride (Krieger et al, 1957).

Two additional characteristics of water that are important in groundwater systems are density and viscosity, both of which are dependent on the type and amount of solutes dissolved in the water. As noted by Reilly (1993), density is important because it is part of fluid movement through a groundwater system (pressure head); moreover, the density and viscosity of the water affect the hydraulic transmitting properties (permeability and hydraulic conductivity) of the groundwater system, which influence the rate of fluid movement.

Although seawater in the ocean and estuaries that laterally bound the eastern seaboard of Tanzania is by far the primary source of saline water to coastal groundwater systems, a number of other sources can affect coastal groundwater quality (Krieger et al, 1957; Feth et al, 1965; Custodio, 1997; Ritcher et al, 1993; Jones et al, 1999). These sources include: precipitation, sea spray accumulation, entrapped fossil seawater in unflushed parts of an aquifer and dissolution of evaporitic deposits.

Submarine groundwater discharge is a widespread phenomenon throughout the world (Johannes, 1980). The outflow in coastal areas is driven by the elevation of the land based groundwater system that causes a positive hydraulic head. Seepage from

unconfined aquifers may occur at various locations, ranging from above the water line at low tide to as far as 14 km from the shore (Johannes, 1980), and at depths of more than 30 m (Simmons, 1992). The majority of the outflow, however, occurs close to the shore (Johannes, 1980). The flux of groundwater into coastal waters can be substantial. By using the distribution of radium (^{226}Ra) as a tracer of freshwater input to nearshore waters of the South Atlantic Bight, Moore (1996) estimated that groundwater flow was of the order of 40% of the river flow to the bight.

In case of Kimbiji site submarine groundwater discharge probably may be another factor which contributed to the presence of freshwater down to 600 meters below land surface. The aquifer replenished with freshwater through submarine groundwater discharge to the Indian Ocean.

The salinity profile shows some areas with anomalies higher salinity greater than 1100 mg/l. The anomalies salinities in these areas could have resulted from the preferential encroachment of sea water into zones of higher permeability during Pleistocene high stands of sea level. These anomalies then persisted because of incomplete flushing by meteoric water probably due to fine grained, low permeability and porous nature of some layers within the aquifer.

There are two theories which explain the origin of saline water in the coastal aquifer system; these are conventional cell theory and residual salinity theory. The conventional cell theory proposed by Kohout (1965), calls for the upward movement of saline water from the lower zone of the aquifer system and mixing of this water with seaward-flowing freshwater in the upper part of the aquifer system. The residual salinity theory explains that the original saline pore water of deposition or later invaded seawater has not been completely flushed out by meteoric water.

The origin of salinity in Kimbiji aquifer can be explained by the residual salinity theory. The residual salinity explains that the original saline pore water of deposition or later invaded seawater has not been completely flushed out by meteoric water.

Original or replenished non saline pore water from the time of deposition may well be preserved, even under the sea, due to a number of reasoning including; protective clay barriers (aquicludes), low fresh water density (Ghyben Herzberg conditions) and high relative artesian pressure caused by recharge through heterogeneous beds from the mainland.



Figure 5.1: Depicts the submarine groundwater discharge in the Indian Ocean. This photo was taken in 2003 in Zanzibar, Tanzania. It indicates that submarine groundwater discharge is common phenomenon along the Indian Ocean. (The photo taken by Dr Ian Bryceson, UMB (Norway))

5.1.6 Hydrogeologic seismic cross section

The contact between Eocene shale and the overlying Miocene sand is a very good seismic reflector that can be traced over a large area. It has been interpreted on the old seismic lines acquired for the petroleum exploration in the region around Dar es Salaam. The constructed hydrogeologic seismic cross section indicates clearly the depth from the surface to that reflector. The top Eocene shale sequence forms the base (aquiclude) of the Kimbiji aquifer. The thickness overlying that Eocene formation is tectonically controlled. The seismic section indicates various depths which can be drilled to tap that vital deep Miocene aquifer formation. The water table shown in the seismic section, however, represents the water table of the upper unconfined aquifer layer.

5.2 Conclusion

For delineation of fresh water bearing sands sandwiched within clays of a coastal region, electrical and natural gamma logs are highly useful. The short and long normal resistivity together with natural gamma logs referred to a representative well of such a region, identify the permeable and impermeable horizons as well as formation water salinity at the qualitative analysis stage. Combination of natural gamma and electrical logs has allowed detection of fresh water aquifer at Kimbiji coastal plain, Dar es Salaam, which could not be otherwise detected. The calculated salinity profile in the Kimbiji aquifer is interpreted to be residual in which most parts of the aquifer have been completely flushed out by meteoric water. There are no signs of seawater intrusion in the formation water hence the aquifer can be utilized as a supplement for surface water in Dar es Salaam.

The virtually untapped Kimbiji coastal aquifer system is considered to be an important supplemental source of water for public use in the highly populated coastal area of Dar es Salaam in Tanzania. More research should be done to delineate the extent of the aquifer, aquifer parameters, age determination, residence time and combining both geophysical methods and geochemical methods for the determination of the formation water salinity to be more precisely.

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