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Article

Application of Aquifer Delineation and Hydrogeophysical Techniques in Estimating Groundwater Recharge to Enhance Water Allocation in Groundwater-Dependent Areas, Northern Cape, South Africa

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Abstract: The aquifer delineation using a hydrogeophysical survey was carried out in De Aar, a small town in the eastern part of the Karoo supergroup, Northern Cape, South Africa. In this region, the current approach for estimating recharge, water allocation plans, and water monitoring does not consider the existence of different types of aquifers. Instead, it assumes there is one aquifer system and therefore the area might have one value of recharge. This study aimed to delineate aquifers into unconfined and confined aquifers for estimating recharge and demonstrate the use of geophysics techniques in delineating aquifer systems. Six VES stations and seven profile lines were measured using a Wenner array configuration and ground magnetotelluric method, respectively. VES data was processed using IPI2win software while electric potential difference curve was interpreted together with lithological data. Four significant layers of low (0.9-8.1 Ωm), moderate (22.4-125 Ωm), and high 68-177 Ωm) resistivity values were delineated suggestive of the different lithological formations. The subsurface profile mapping using ground magnetotelluric methods did not suggest groundwater accumulations below 50 m, instead supported shallow groundwater potentials boreholes. These results have provided a double layer aquifer system thereby suggesting that recharge estimation need to be carried out in two different aquifer systems to enhance water allocation plans, and water monitoring in groundwater-dependent areas similar to prevailing conditions in the current study area.

Keywords: apparent resistivity; electric potential difference; magneto-telluric; unconfined; confined

1. Introduction

Aquifer delineation is a fundamental aspect of the quantification of local and regional groundwater recharge. It is mostly critical in arid environments where surface water resources are often scarce, and groundwater is from sole source aquifers as a potable water supply. Woodford., [1] describes a sole-source aquifer system as an aquifer that is used to supply 50% or more domestic water for a given area, and for which no alternative source is available should the aquifer be depleted. Knowledge of groundwater recharge is equally important; however, it requires a good understanding of shallow and deeper aquifers both vertical and horizontal heterogeneity of the aquifer system [2]. A poor understanding of the aquifer systems and rates of aquifer recharge can

lead to poor groundwater allocation plans and management practices by groundwater practitioners. The current approach for estimating recharge, water allocation plans, and groundwater management practices does not take into consideration that different types of aquifers exist in one area. Instead, it uses quaternary catchment delineation which assumes there is one aquifer system and therefore the area might have one value of recharge. Estimating the rates of aquifer recharge in the karoo regions requires a deep understanding of the different types of aquifers that exist and their hydraulic properties to provide more knowledge of the geological patterns. Thus, the objective of conducting this study was to delineate the various aquifer units into unconfined and confined aquifers to get an understanding of the possible mechanism of aquifer recharge within the De Aar catchment wellfield, Northern Cape Province, South Africa. The wellfield forms part of the eastern Karoo system with aquifers being dominated by sandstone, mudstone, limestone, shale, and dolerite sill formations. This region is predominately underlined by fractured rock aquifers of low storage capacity which receive limited and highly variable recharge [3]. Their groundwater exploitation potential during prolonged droughts is largely controlled by the temporal variability of recharge[3]. This study argues that unless different aquifer types and boreholes tapping into each aquifer type are delineated, the determination of reliable estimates for groundwater recharge rates to enhance groundwater allocation plans and management practices will remain erroneous.

A review desktop study was conducted to select De Aar as a study area by utilizing existing information that included groundwater level data, borehole depth, depth of water strikes, borehole casing, blow yields, groundwater quality, abstraction volumes, GRA II recharge values, groundwater allocations, and previous consultancy reports were reviewed to identify the gap and capture relevant information that can be used in the current study. The gap analysis review identified that the study area has been historically subjected to intensive prolonged drought resulting in declining groundwater levels, and some boreholes drying due to low recharge [4]. Previous groundwater development and exploitation studies were dominated by the community water supply and agricultural activities to characterize the shallow aquifer systems in the study area. To date, the shallow aquifers are well understood due to detailed research and groundwater exploration studies conducted within the study area by various research organizations [5]. Nevertheless, the development of groundwater resources in the Karoo region has been faced with multiple challenges due to the complexity of the aquifer systems [6]. This is despite the fact that shallow groundwater is typically encountered in weathered layers near the surface [3]. At greater depths, groundwater within the system is often associated with fractured layers within the crystalline basement system. The influence of dolerite intrusions on the occurrence of groundwater makes these structures the primary targets for the positioning of successful borehole drilling. However, even though the shallow aquifers (<300 m depth) are well-researched and well-understood, deep groundwater aquifers, including their connectivity with shallow aquifers, are poorly understood [3]. The mineralogical composition of sandstone, mudstone, limestone, shale, and dolerite is detectable through geophysical techniques.

Several geophysical techniques have been developed and used for delineating the subsurface aquifers, which control the extension and thickness of the aquifers [7,8]. This includes techniques such as geoelectrical and electromagnetic methods. Electrical methods are generally classified according to the energy source involved which is either natural or artificial[9]. Those under natural source methods include self-potential (SP), telluric current, and magnetotelluric while those under artificial source methods include resistivity, electromagnetic (EM), and induced polarization (IP) methods[9]. The current research used both methods, which are the use of the ground magnetotelluric method using the PQWT-TC300 system and the electrical resistivity sounding method using an instrument called the Geotrone G41 model. Geophysical studies in groundwater exploration involve two stages: i) deep aquifer delineation and ii) shallow aquifer delineation. In deeper aquifer delineations, the survey depths are beyond the weathered zone of 100 m thickness in hard rock formation whereas in shallow aquifer delineations, the survey depth is 20 to 30 m thickness [10]. The electrical resistivity method is deemed the most used technique in aquifer delineation of groundwater systems due to its simplicity in physical principle and efficient data acquisition but has its limitations [11]. The greatest limitation of this method is that it does not consider lateral changes

in the subsurface resistivity which can result in errors in the interpreted resistivity and thicknesses of the layers [12]. Besides its limitations, the electrical resistivity method can provide detailed information about subsurface layer variations [13]. The method has the potential to identify subsurface structures, aquicludes, and aquitards, which normally are more conductive than the surrounding layers and are sensitive to geological properties, like clay content [14].

Hydrogeophysical survey methods are often found useful particularly in groundwater exploration for community water supply projects [7,15,16]. In the eastern Karoo, South Africa, Vegter., [17] used electrical resistivity and refraction seismic methods combined with exploration drilling to map the thickness and depth of the alluvium deposits. Their investigation reported that three aquifer types can be distinguished i.e., (a), basalt of alluvial deposit, which is usually coarse-grained, weathered, and fractured Beaufort and Ecca strata, and (b), dolerite with optimal fracturing in the vicinity of the intrusive contacts and combination of (a) and (b). He further explains that Karoo strata and dolerite owe their water-bearing properties to fracturing which is generally limited to the top between 20-30 m below ground surface. The probability of striking water is highest between depth 5 to 15 m and individual water striking yields are mostly 1.0 l/s. Water strike yields and permeability decrease with depth meanwhile groundwater level depth in the valleys is very shallow mostly less than 5 m. The study concluded that electromagnetic systems may prove effective for profiling alluvial aquifers, the reason being overlapping resistivities of alluvial deposits and bedrock. Moreover, numerous studies applying electrical resistance geophysical methods in groundwater evaluation have been widely reported for different aquifer systems. For example, Bairu et al., [18] applied vertical electrical sounding and horizontal profiling methods to provide important subsurface geophysical information useful in evaluating the subsurface geological formations, geological structures, and cavities in Northern Ethiopia. Their study concluded that further core drilling investigations are required. Sunmonu et al., [19] carried out a similar study involving twelve vertical electrical soundings (VES) to delineate the subsurface to understand the aquifer pattern in the Ogbagba area, Nigeria. Their study revealed that the insufficiency of groundwater exploitation in the study area was due to the geologic formation of the aquifers and the depth to which groundwater has been abstracted. They concluded that, if these mistakes are corrected, their area of study can start to enjoy groundwater exploitation adequately. In Dakhla Oasis, Egypt, Mohamaden., et al., [15] used geoelectric techniques to detect groundwater aquifer and subsurface stratigraphy and structures. Three geoelectric units were identified composed mainly of sand and gravel with relatively high resistivity values (7.61–346 Ωm) and the thicknesses (0.252–9.19 m). In Malaysia, Riwayat et al., [20] reported that several problems exist regarding the application of conventional techniques as they only provide information at the actual drilling point. They reported that errors and negative readings encountered during data acquisition were usually due to dried conditions reducing electrode contact geology. Besides limitations and uncertainties associated with the method, their study also showed that the application of the electrical resistivity method can successfully help researchers in mapping several aquifers of interest and solving problems, especially during a preliminary stage in groundwater exploration. In India, Niaz et al., [21] used seventy-seven Schlumberger array vertical electric sounding (VES) methods in delineating aquifer properties along with vulnerability mapping in Gujrat district and surrounding areas of Punjab province, Pakistan whereas AL-Juboury et al., [22] delineated the effect of saline groundwater on the resistivity of the middle part of Dammam formation southwest of Samawah city, Southern Iraq, Asia. Two-dimension (2-D) measurement survey points were performed by using the Wenner-Schlumberger array configuration. Their results found that the thickness and depth of the groundwater aquifers vary between the survey points according to the degree of the fractures and level depth relative to the water level in the study area. They concluded that the effect of the saline groundwater that rises caused a significant reduction in resistivity of the groundwater-bearing zone along the fault plane. The results of these studies have been used to refine the aim and objective and inform the selection of appropriate methods suitable for the current study.

Another geophysical survey method used in this current study includes the ground magnetotelluric techniques, which use electrical potential difference (mV) as the main parameter for

groundwater exploration [23,24]. This method has recently been favoured and has gained attraction in the groundwater exploration field in Africa. Gomo [24] suggests the need to extensively understand the ground magnetotelluric geophysical application in groundwater exploration. The magnetotelluric method is a passive surface geophysical technique that uses the earth's natural electromagnetic fields to investigate the electric resistivity structure of the subsurface from depths of tens of meters to tens of kilometres [24]. It is particularly useful in delineating deep structures due to its deep penetration, which is not achievable with other conventional geophysics equipment methods [25]. Fewer studies have recently used this technology, exclusively as a complementary method in combination with any of the traditional commonly used methods such as electrical resistivity (ER) as suggested in Gomo., [24]. This method, measures and records the natural variations of the earth's magnetic and electric fields at each ground magnetotelluric station for specified fixed depths with a 2D tomography model being produced from a system inbuilt inverse model [25].

Some additional studies that have reported the successful application of the ground magnetotelluric method in groundwater studies include, Hassan et al., [26] who applied this method in estimating groundwater recharge rates and identified groundwater recharge zones in the Kakia and Esamburbur sub-catchment Narok. The geophysical survey results showed that the south-central and southeast zones of the sub-catchment are potentially good groundwater recharge zones and therefore suitable for managed aquifer recharge structures to augment the groundwater resources. In Nigeria, Oyegoke et al., [23] assessed the effectiveness of the geophysical assessment of boreholes drilled in basement complex terrain at Afe Babalola University, using the method. Their results revealed that two boreholes were accurately sited on vertical fractures and weathered formations meanwhile other two boreholes were wrongly sited at the locations of poor groundwater-yielding zones. In South Africa, Gomo., [24] has successfully conducted a hydrogeophysical investigation study to provide an overview of the theoretical background on the use of the electric potential difference in Audio magnetotelluric geophysics for groundwater exploration and shares recent field results from the application of the technology in typical karoo and hard rock formations. His study revealed that the electric potential difference measured with the magnetotelluric equipment correlated well with lithology and groundwater occurrence at two observation sites. The water strikes occurred in sandstone formation of various degrees of disintegration and were associated with contrasts of low electric potential differences in the range of 0.005–0.019 mV. These findings suggest therefore that the changes in electric potential difference can be used to delineate potential aquifers and vertical variation of geology. Furthermore, Khan et al., [27] applied ground magnetotelluric methods in an integrated geophysical approach for groundwater investigation in the North-western part of Pakistan and managed to successfully locate aquifers with relative depths and electric resistivity (ER) survey for investigating the groundwater salinity. Their study further revealed that the electric potential difference as the main variable was found very useful and efficient providing data about groundwater potential zone, and water quality relative to depths. Thus, the method was applied as a complimentary method as it has proved to be an effective tool for aquifer characterization and delineation as required in the current study.

2. Study Area Description

2.1. Local Setting

The study was conducted in De Aar, a small town under jurisdiction of the Umthanjeni Local Municipality, located within the eastern part of the Karoo supergroup, Northern Cape Province, South Africa (Figure 1d). The study falls within the lower orange water management area (WMA) and is situated in the quaternary catchment drainage region D62C and D62D. For this current study, the study area was further divided into three parts, namely the lower, middle, and upper catchments (Figure 1b). The lower catchment site has an altitude ranging between 1183 and 1233 m, meanwhile, the middle, and upper catchment sites have the maximum altitude in excess of 1261 and 1404 m, respectively. The study area covers an average size of 2226 km². The population census figure for the period 2022 estimated that 46 587 persons live in De Aar. In terms of climate, the study locality falls within a semi-arid climate region with an average annual rainfall of 4.7 mm and most of the rainfall

occurring in summer starting from November/December and ending in March/April according to the South African Weather Service (SAWS). Geomorphologically, the prominent features that describe the study area are scattered rings of dolerite hills stretching up to 12 km in diameter for over 50-60 km² built by horizontally disposed dolerite sheets [17,28]. The area is designated as lowland with mountainous hills between river valleys. The Elandsfontein spruit which rises along the south-easterly of Hanover and Brak River in the easterly of Caroluspoort coupled with a few minor tributaries drains the entire study area (Figures 1b). The confluence of the two rivers system is situated about 10km north-west of De Aar town. Both rivers flow for a very short period often during and after heavy rainfall. The intermediate valley areas are often dissected by numerous dolerite hill slopes [28]. The catchment vegetation includes various species which bear the characteristics of shrubs of hills and grass. The riverbed is below the groundwater table, resulting in standing pools of water along Elandsfontein spruit and Brak River systems [29].

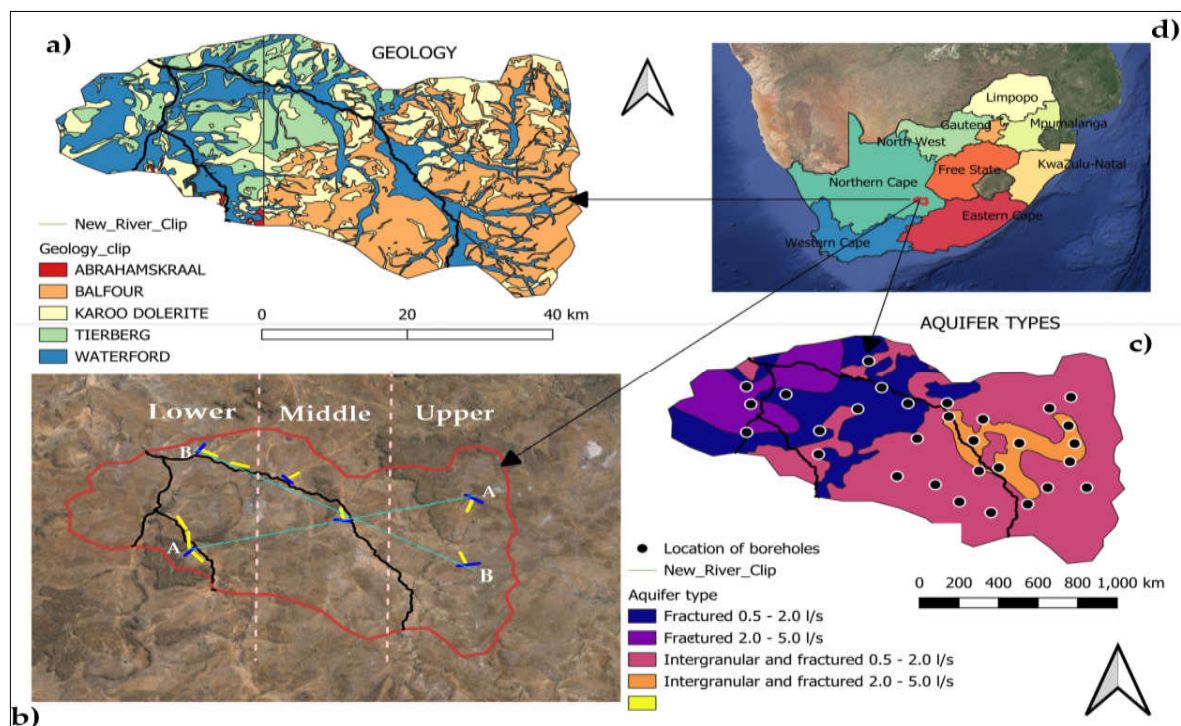


Figure 1. a, b, c, and d: Study area map showing the sedimentary and igneous outcrop of the basement rocks, aquifer types, and topographical landscape with Brak river and Elandsfontein spruit draining the study.

2.2. Hydrogeological Setting

The study area is mainly characterized by the Karoo sedimentary fractured rock units that lie horizontally with a dip angle of fewer degrees with local deviations which are mainly caused by the prominent dolerite intrusions [29]. The stratigraphy of the study area has been investigated by Vegter [29]. Geologically, the area consists of Ecca and Beaufort group sediments which are represented by Tierberg and Middleton formation. The oldest group belongs to the Ecca group composed of dark grey shale and siltstone formation which occupies the lower catchment (northwestern site) and a portion of the middle catchment (northeastern site). The succession of shale is interrupted on several horizons by layers and lenses of siltstone and fine-grained sandstone. The Beaufort Group sediments are of the late Permian age composed of mudstone, siltstone, and sandstone formation. Where sediments have been fractured by intrusive dolerite formations, the rocks become important groundwater-bearing zones [17]. The dolerites usually intrude in the form of dyke, sheets, and sills and varying thicknesses. Ring-shaped structures of dolerite are common and overlap up to 30 m wide with many outcrops' curves. They vary in width from 1 to > 10 m and in length from 1 to 7 km. Their

forms and orientation are variable and change to virtually horizontal sheet bodies. The kimberlites are deposited in the upper catchment southeast of the study area in the form of pipes or dykes [17,28]. Their visibility can be recognized as the line of denser vegetation. The alluvial deposits are confined to the river valley and are extremely heterogeneous both laterally and vertically. The maximum thickness of the alluvium is in the order of 10-15m. The surface limestone deposits, which resulted from a buildup of salts in the layers after evaporation in areas with shallow groundwater tables are widespread albeit thin. The groundwater quality can be classified as class II water type with the electrical conductivity (EC) varying between 150-250 mS/m with total dissolved solids (TDS) exceeding 1000 mg/l[30]. The dolerite is not highly groundwater productive; however, the groundwater is often struck in the sedimentary section of both the upper and lower contact zones in the dolerite sections[29]. Water strike in sedimentary layers directly overlying dolerite is considerably higher than in the underlying dolerite sections.

3. Material and Methods

3.1. Electrical Resistivity-Sounding Data Acquisition

The field geophysical survey was conducted using the Geotrone electrical resistivity (ER) meter model G41 to measure the subsurface resistivity in the vertical electrical resistivity sounding using the Wenner array configuration [31]. During the investigation, the assumption was that geological sections are mainly horizontally layered (consisting of different geological layers) or pseudo-layered structures due to the influence of groundwater level and weathering [32]. This configuration was adopted due to its strongest signal strength, and greater sensitivity to vertical resistivity variation or structures lying horizontally concerning the rocks [31,33].

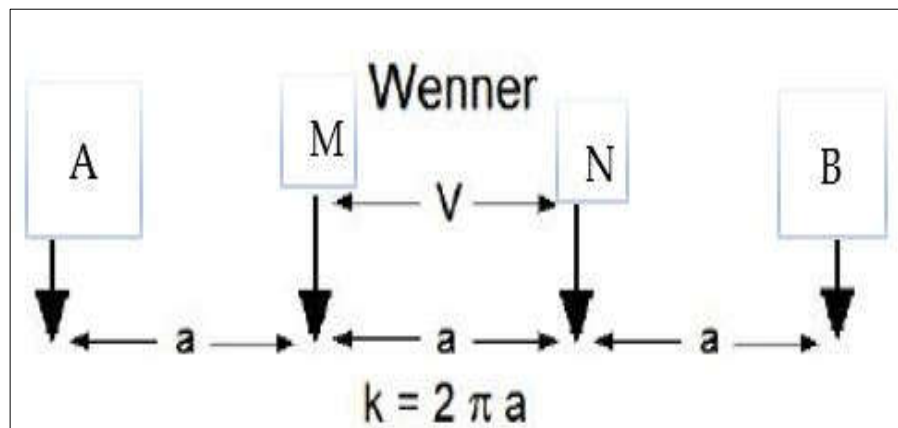


Figure 2. Wenner array configuration with its geometric factors. The current(I) is injected into the ground through the A and B electrodes while the voltage difference is measured between the M and N electrodes.

The theoretical framework for the approach is based on the fact that for each measurement, an electric current is passed between electrodes A and B, and the potential difference between electrodes M and N is recorded [32,33]. The resulting variation in electrical voltages depends on the amount of current passed between electrodes A and B and is transformed into apparent resistivity ρ_a , which is defined as the resistivity of the isotropic, homogeneous half-space that would produce the equivalent voltage [12]. The progressive increase in the distance between the current electrodes causes the current lines to penetrate to a greater depth depending on the vertical distribution of conductivity [12]. The potential electrode depth was therefore determined by $AB/3$ of the Wenner array. The equipment used in this study had an inbuilt algorithm to process the data into apparent resistivity.

The apparent resistivity is given by the following formula:

$$\rho_a = K \cdot \frac{V_{MN}}{I_{AB}} \quad (1)$$

where $\phi_{MN} = \phi_M - \phi_N$ is the difference in potential between electrodes M and N, I_{AB} is the current passed between electrodes A and B, and G is the electrode-array-dependent geometric factor. For the Wenner array configuration, the geometric factor is given by

$$K = 2\pi a. \quad (2)$$



Figure 3. a, b, and c: Field setup of the electrical resistivity survey during the field investigations.

The vertical electrical sounding (VES) data was collected in an intensive field investigation done on the three sub-catchments in November 2023 (Figure 1b). Seven VES stations were established across the study area to delineate different types of aquifers into unit of unconfined and confined aquifer layers along the survey lines [34]. Two VES stations were established in the lower catchment (Renostepoort and Blaaukrantz farms), two stations in the middle catchment (Paarde Valley, and Caroluspoort farms), and two stations in the upper catchment (Zewefontein farms). The field-derived resistivity data was initially sorted on a Microsoft Excel spreadsheet as the principal input for the IP2WIN software. The interpretation of the VES data was done by partial curve matching, for which a plot is matched with standard master curves to obtain the best fit of layer parameters thereby resistivities, thicknesses, and depth for each layer are derived from which a resistivity and depth model is derived [35]. The resistivity values provided 1D dimensional spatial curve graphs depicting various layers of the subsurface geometry [36]. The resistivity and thickness values were further interpolated to infer regional pseudo-cross-sections A-A (Figure 9). The regional pseudo-cross-sections obtained from the subsurface resistivity were later further interpreted by describing each resistivity layer and compared to the corresponding borehole logs cross-sections.

3.2. Ground Magnetotelluric Method

The ground magnetotelluric method was used in this study as a complimentary passive method for delineating different types of aquifer layers (confined and unconfined aquifer systems). This method was chosen because it uses basic principles of natural electromagnetic field observation to study the subsurface structures, with no artificial electric field source and a high anti-interference ability [37]. The instrument works by measuring the electric field component of the earth's electromagnetic field in different frequencies which subsequently demarcate the structures of high groundwater potential [27]. The PQWT-TC300 series equipment was used for these procedures (Figure 4).



Figure 4. The image of the PQWT-TC 300 series automatic mapping groundwater detector (AMWD).



Figure 5. a and b: Field procedures of the ground magneto-telluric surveys during the investigations.

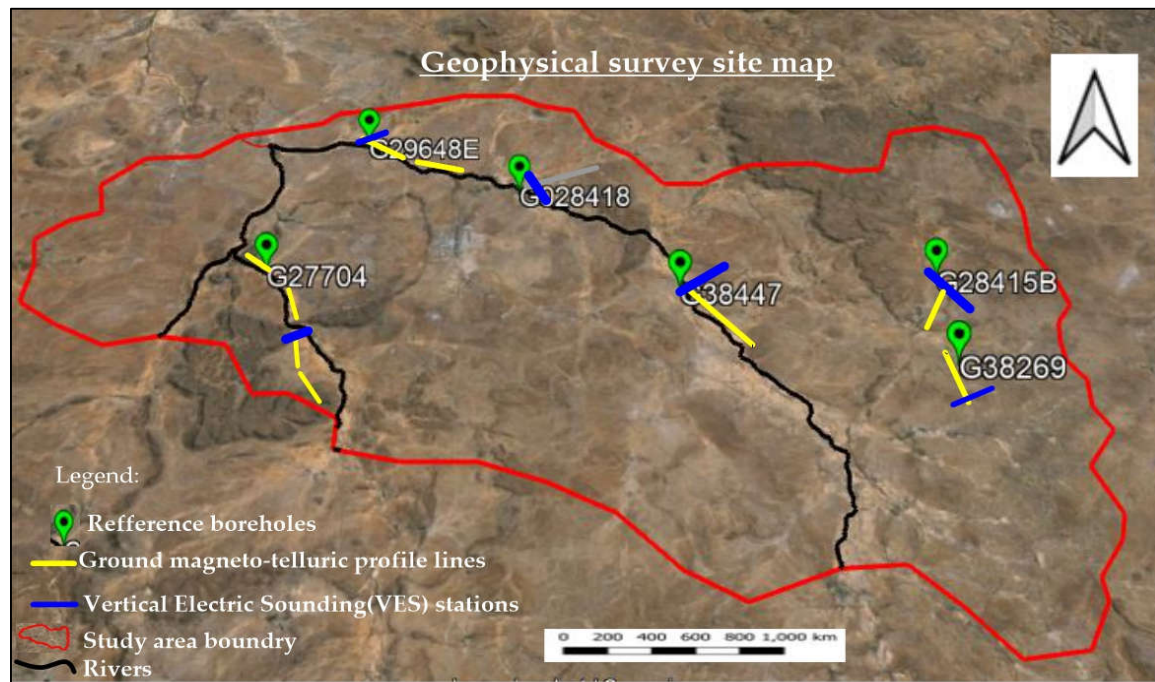


Figure 6. Geophysical survey sites showing the vertical electric sounding stations and ground magneto-telluric profile lines.

The survey was done using two non-polarizable electrodes with a spacing of 10 m apart. In the beginning, electrodes 1 and 2 were placed on the ground at points 10 m apart along the transverse line. Raw data consisting of electric potential differences for a specific frequency was downloaded in Excel format. The data was sorted using Microsoft Excel to understand the electric potential difference (mV) corresponding to the depth of penetration. To enhance visualization of the subsurface geometry; electric potential difference (EPD) data was plotted against depth to generate an EPD curve using Microsoft Excel [24]. The interpretation was done by comparing the 2D images and the electric potential difference curves with lithology data obtained from reference boreholes following the co-relation between the electrical potential difference values and subsurface geological conditions [24].

3.3. Lithological Cross-Section of the Existing Boreholes

Figure 7a-f show the geological cross-sections of the study area. The borehole lithostratigraphic cross-sections were obtained from the drill log data from the Department of Water and Sanitation (DWS) National Groundwater Archives (NGA) database system. Firstly, a line of two points (e.g., A-A) was drawn to mark the topographic elevation along the survey line. Secondly, the elevations line was transformed into a cross-section, showing the topography of the ground surface using Suffer software program [38]. Information from the borehole logs were inferred to construct the subsurface sections. Twelve (12) boreholes drilled along the Elandsfontein spruit, and Brak river representing the lower catchment site, thirteen (13) boreholes drilled along the Brak river representing the middle catchment, and ten (10) boreholes drilled in headwaters representing the upper catchment site were used to create the geological cross-sections. The information from the borehole logs (cross-sections) in this study were interpreted in comparison with hydrogeophysical survey data to interpret how data relate to one another. The main challenge encountered during this process was to transform data from scattered boreholes into a profile line.

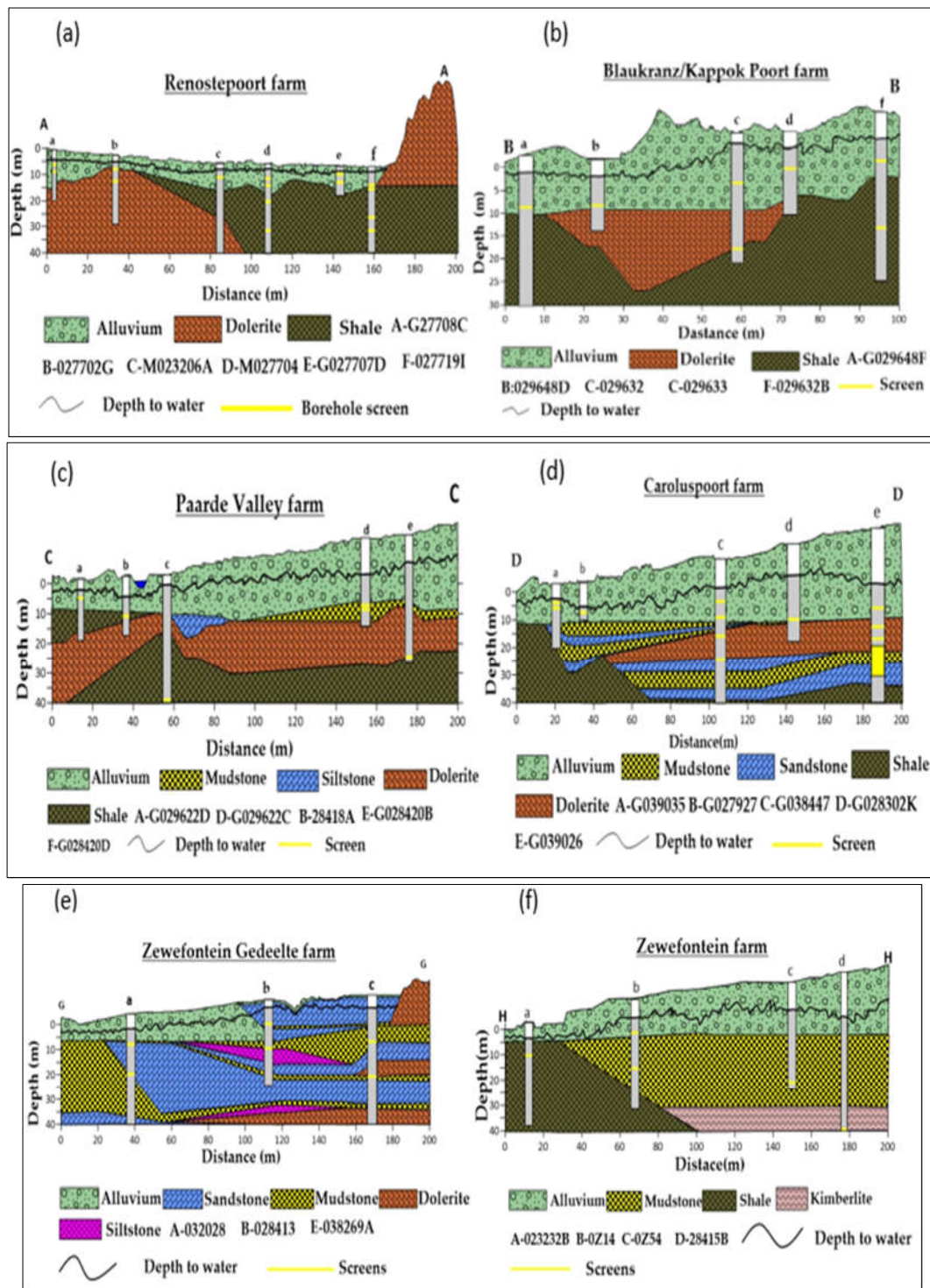


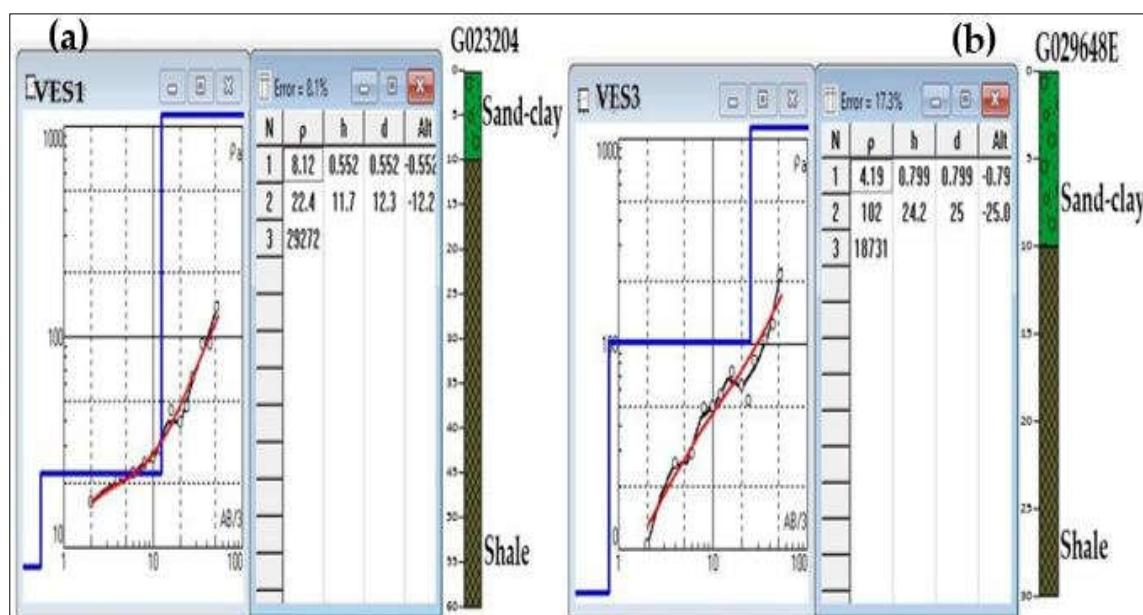
Figure 7. a and b: Show the geological cross-section of the lower catchment areas. c and d: Show the geological cross-section of the middle catchment areas. e and f: Show the geological cross-section of the upper catchment areas.

4. Results and Discussion

4.1. Electrical Resistivity Results and Lithostratigraphic Cross-Section

The interpretation of the vertical electrical sounding (VES) curves involved analysis of the apparent resistivity and grouping of the curves to establish a regional pseudo-cross-section of the area (Figure 9). The VES results coupled with lithological data from boreholes were integrated with the interpretation to complement and boost the confidence level of the VES results. Figure 8a–f show

the VES curves plotted along with lithological logs. The VES results were processed, interpreted, and analyzed using the IPI 2win software. As stated earlier, the Wenner array configuration method was selected for the survey due to its strongest signal strength in noisy areas and greater sensitivity to vertical resistivity variation and structures lying horizontally. The apparent resistivity values were plotted against electrode spacing $AB/3$. The error margin of data collected was 8.1%-VES1; 6.39% - VES2; 17.3%-VES3; 3.5%-VES4; 3.2%-VES5 and 2.9%-VES6 (Figures 8a–f). The apparent resistivity values were interpreted in terms of layer thickness and correlation with lithostratigraphic logs that were constructed from the drill records obtained from the NGA database system. The interpretation of the VES results suggests a good correlation between the stratigraphic layers and the borehole logs, where the number of layers on resistivity data was coincident in agreement with those of profile boreholes (Figure 8a–c). The results revealed a multiple and varying layer medium with three to four significant layers as inferred from the different apparent resistivity values. The first layer was inferred to be topsoil (black color) material of low resistivity values (0.9-8.1 Ωm) in the lower and middle catchment areas, with relatively higher resistivity values (196-213 Ωm) in the upper catchment despite having the same thickness and depth. This variation in electrical resistivity values is attributed to the varying degrees of soil moisture and clay content within the medium with areas of low resistivity having relatively higher soil moisture in the top layer. The high resistivity values in the upper layer were also attributed to the unweathered rocky-gravel top layer that was observed in this section and attributed to the presence of intrusive rocks. The second layer is composed of weathered sand-clay (dark blue-light blue color) materials of low to moderate resistivity values (22.4-15 Ωm), thickness values (1.3-24.2 Ωm), and depth values (2.4-25 m) in the lower and middle catchments. The third layer in the middle catchment is composed of shale, intercalating wet sandstone, and mudstone (up to 3.0 Ωm) meanwhile, the upper catchment is composed of dolerite, kimberlite, and dry interchanging sandstone and mudstone which are correlating with high resistivity values (68.8-177 Ωm). Woodford., [39]described the occurrence of sandstone, mudstone, and shale in high-lying terrain as alternating with sand shale. The low-resistivity material did not extend beyond the middle catchment area, which gave rise to the high-resistivity material's exposure to the near surface in the upper catchment. The third layer in the lower catchment and the fourth layer in the middle and upper catchment were detected at maximum penetration depth with high resistivity values up to 29272 Ωm , suggesting the start of a dry bedrock formation.



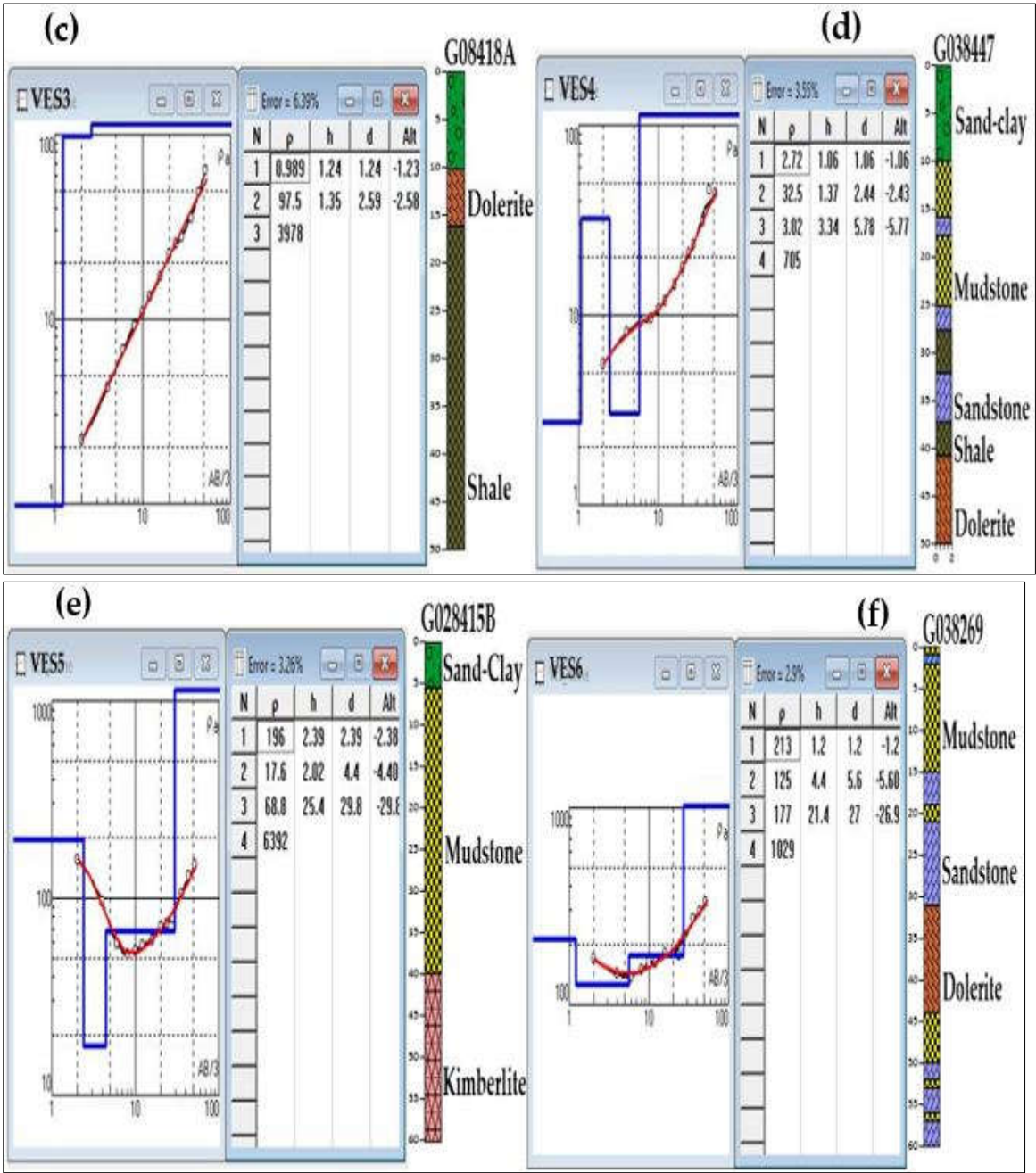


Figure 8. a and b: VES sounding curve generated in Renostepoort and Blaukranz farm in the lower catchment area. **c and d:** VES sounding curve generated in Paarde Valley and Caroluspoot farm in the middle catchment area. **e and f:** VES sounding curve generated in Zewe Fountein and Gedeelte fountain farm in the upper catchment area.

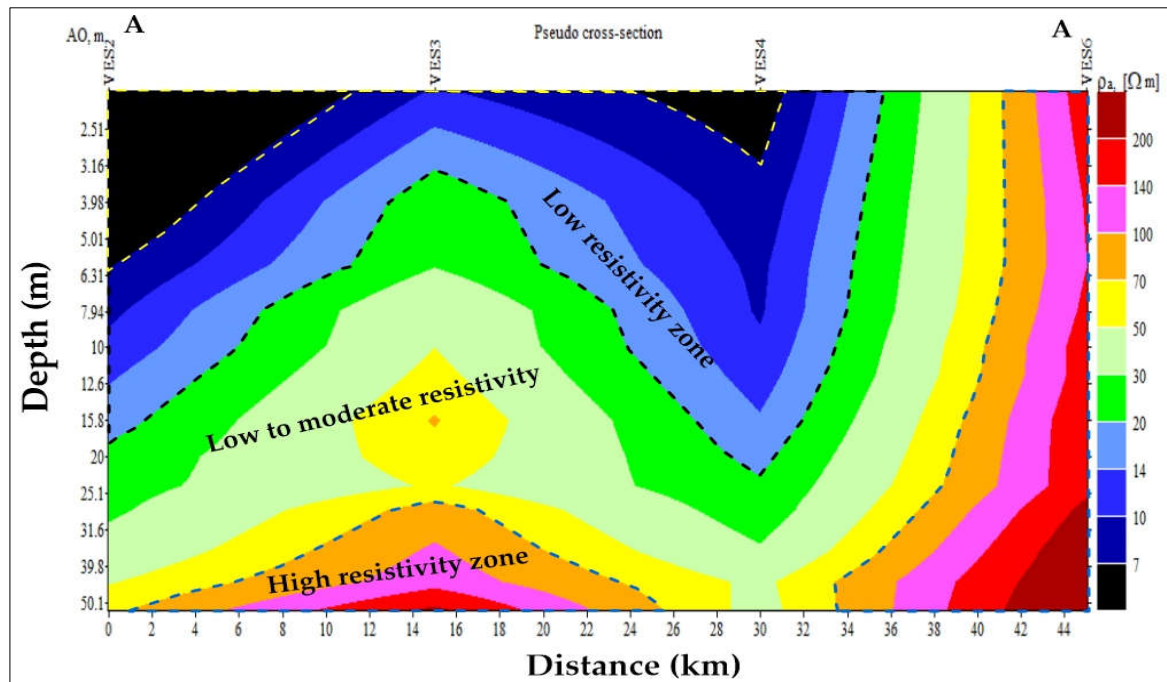


Figure 9. Regional pseudo-cross-section integrating four VES stations i.e., VES2-Lower catchment, VES3-Middle catchment, VES4-Middle catchment, and VES6-Upper catchment.

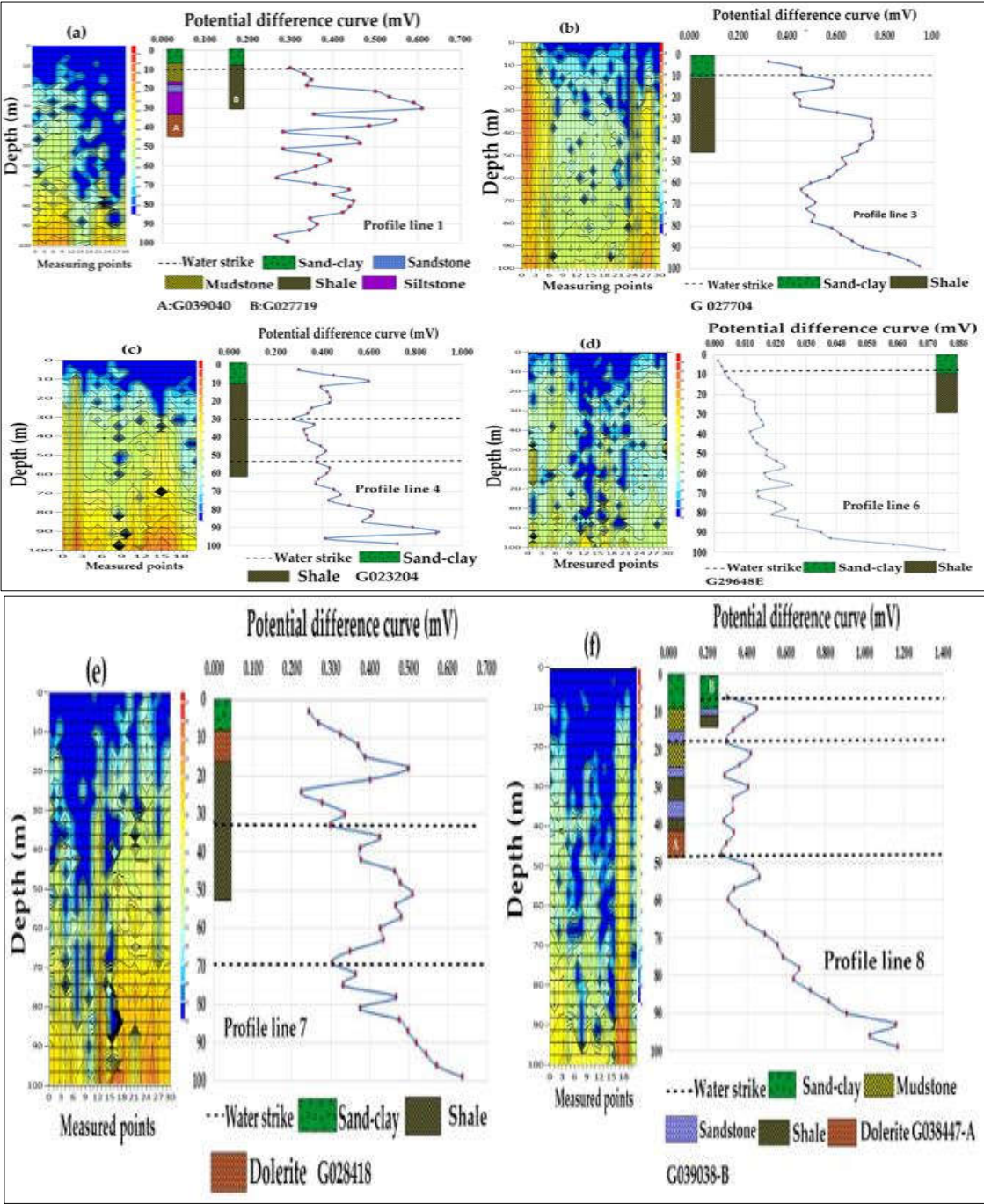
The pseudo-cross-sections developed show that the medium consists of at least four layers in the upper catchment and three to four layers in the lower and middle catchment area (Figure 9). The regional distribution of the low resistivity in the lower and middle catchment areas extended for about 36 km. The regional spread, thickness, and depth of the higher resistivity structures (pseudo-cross-section) were not estimated as they represented the last unit beyond investigation depth which composed of other solid and dry formations like dolerite, kimberlite, and sandstone. Kimberlite dykes are found in the upper catchment with high resistivity east and southeast of De Aar on VES6 (Figure 8e,f). The second and third layers in this study were interpreted as unconfined and confined basement bedrock aquifers respectively based on their resistivity values and corresponding geology from borehole logs. According to Vegter and Woodford., [17,28] groundwater is more often struck in the sedimentary formations of both the upper and lower contacts zones than in the dolerite sections and the yields in the sedimentary strata directly overlaying dolerite tend to be considerably higher than in the underlying dolerite. Below 20 m depth, there exists the third layer which is interpreted as a semi-confined or confined basement aquifer of low to moderate resistivity values. Below 50 m depth, there exists the fourth layer which was interpreted as dry bedrock basement aquifers of high resistivity values.

According to Vegter., [28] these basement aquifers are often fractured and confined with decreasing permeability and yields with depth. The unconfined aquifer lies at a depth ranging from 6.3 m to between 15 and 20 m and the confined aquifers lie at a depth of 20 m. Vegter., [28] reported that alluvial aquifers in De Aar appear to be semi-confined (leaky), or semi-confined or unconfined with delayed yield. The result of this study is also comparable to similar studies reported by Nazifi and Lambon [40] in the central region of Ghana and Mohamaden et al., [15] in Egypt. Sunmonu et al., [19] found that 75% of the aquifers in Ogbagba, Nigeria was confined aquifers while the remaining 25% were unconfined aquifers. The clayey sand layer had 75%, sandy clay constituted 16.7% and fractured bedrock shared the remaining 8.3%. In this study, most boreholes are drilled into both unconfined and confined aquifers with few boreholes drilled into high resistive zone. The water strike in these boreholes is variable with the majority of strikes limited to unconfined aquifers. The average depth to water level lies approximately 3.0 to 5 m with shallow depth seen in boreholes close to the river valley. The shallow water levels follow the superficial nature of the aquifers [17]. The

shallowness of the groundwater levels is exaggerated by the fact that the production boreholes, as well as monitoring boreholes, are drilled in the river valley anticipating river-aquifers interaction.

4.2. Ground Magnetotelluric (GMT) Survey Results

The results obtained from using the passive magnetotelluric method were used as a localized complementary method [23] (Figures 10a–h). The subsurface profile maps and the electrical potential difference curves generated coupled with lithological logs from boreholes were used as references during the geophysical survey. The lithological logs were retrieved from the Department of Water and Sanitation (DWS) National Groundwater Archives (NGA) database system. The correlation between electric potential different curves with the lithological logs from boreholes was interpreted together coupled with profile maps to boost the confidence level of the results. Eleven profile stations were established across the study area, but only those with reliable and valid data sets were presented. Six profile stations were established in the lower catchment (profile lines 1- 6), three stations were established in the middle catchment (profile lines 7-9), and two stations were established in the upper catchment (profile lines 10-11). The profile lines 1-6 were established at the lower catchment underlined by shallow weathered sand-clay at the top followed by shale, and dolerite formation. Their length varied between 200 m and 320 m with 20 to 32 points measured at 3m to 5m, with penetration depth intervals up to 100 m maximum depth of investigation (Table 1). Profile lines 7 to 9 were generated at the middle catchment area comprising shale, dolerite interchanging sandstone, and mudstone formation. Their profile length varied between 200 m and 250 m with 20 to 25 points measured at 4m to 5m penetration depth intervals up to 100 m maximum depth of investigation (Table 1). The upper catchment profile lines 10-11 were established at the upper catchment area underlined by dolerite, kimberlite, and interchanging dry sandstone, and mudstone rock formations. Each profile length was 250 m with 25 points each measured at 4m to 6m penetration depth interval up to 150 m maximum depth of investigation (Table 1). Data was processed through an in-built algorithm to generate 2D tomography profile maps. The raw data was processed using Microsoft Excel to generate an electric potential difference curve, which was interpreted together with lithology data from reference boreholes. According to Gomo., [24] elevated electric potential difference values suggest a relatively hard resistive formation as is expected with fresh dolerite and dry sandstone. The dark blue and light blue colors of the profile map represent the weathered zone of low electric potential difference (mV). The results of the profile map show areas with viable weathered zones at variable depths ranging from the top going down to 80m. According to Oyegoke et al., [23] a deep weathered zone indicates viable vertical fracturing cutting across horizontal measuring points. The blue and light blue colors were interpreted as groundwater potential recharge zones, meanwhile, light green and yellow colors were interpreted as middle electric potential difference values of sedimentary rock like shale, and mudstone. The red colors were interpreted as igneous rock of high electric potential difference values represented by dolerite and kimberlite formations. According to Garamoon et al., [41] in Kakia and Esamburbur sub-catchment Narok, Kenya, blue, light blue, and light-yellow colors indicated the presence of low potential difference value materials like water, soft mud, and some metal minerals. The yellow color represented the presence of a middle potential difference value material like rocks. While the red color indicated the presence of high potential difference value materials like high-density hard rock formation.



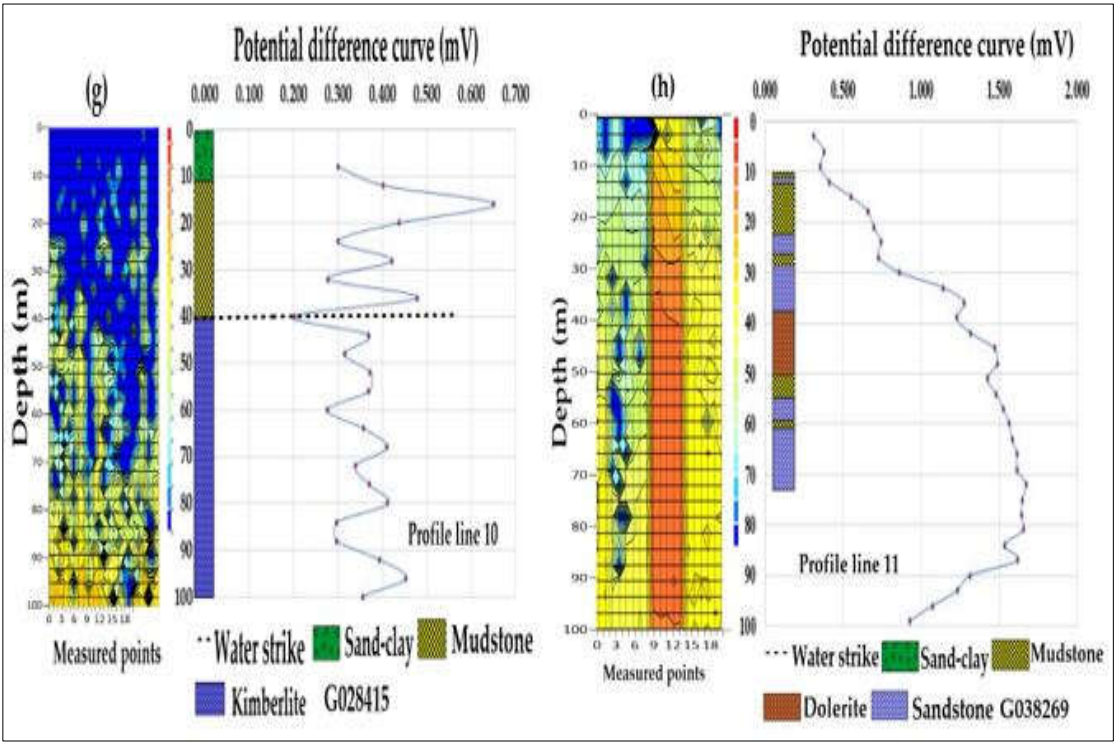


Figure 10. (a, b, c, and d): Subsurface profile maps and the electrical potential difference curves generated coupled with lithological profile boreholes along the lower catchment area. (e and f): Subsurface profile maps and the electrical potential difference curves generated coupled with lithological profile boreholes along the middle catchment. (g, and h): Subsurface profile maps and the electrical potential difference curves generated coupled with lithological profile boreholes along the upper catchment.

Table 1. Summary of the borehole’s information used as references during geophysical survey.

Study sites	BH no	Y	X	Line length(m)	Interval (m)	Depth(m)	WL (m)	Elev.	Water Strike (m)	Lithology	Casing (m)
Lower	G039040	-30.666	23.8654	1	240	4	45	3.23 1220	4,7-11	Silt-Clay, Mudstone	12
	G27719I	-30.6679	23.8757	2	240	4	48	3.13 1227	4,9,12,24,42	Sand, Shale, Dolerite	6.5
	G27704	-30.6729	23.8778	3	320	3	45	5.14 1216	8, 10, 14, 30	Sand-clay, Shale	14.6
	G23204	-30.7045	23.9006	4	200	5	62	1233	10,18	Shale	10
	G29646C	-30.5556	23.95382	5	200	5	36	1183	6.5	Clay	
	G29648E	-30.5506	23.9388	6	300	3	28	4.83 1190	8	Sand	10
Middle	G028418	30.5991	24.0596	7	250	6	24	3.86 1231	33	Shale	
	G38447	-30.6886	24.1781	8	200	5	42	4.77 1261	5, 8, 17, 24	Sand-clay, Mudstone	
	G39038	-30.6609	24.1614	9	200	5	13	4.23 1256	4, 7- 9	Sand-clay, Shale	
Upper	G28415B	-30.6776	24.3648	10	250	6	103	7.03 1404	40	Kimberlite	
	G38269	-30.7478	24.3667	11	250	6	60	9.89 1389	25, 29, 31	Sandstone	5.5

The results of the passive GMT methods in this study complimented well with the vertical electric sounding cross-sections as both methods indicated that the area consists of two zones of low and high resistivity. This was evident during field investigation supported by shallow groundwater level depth ranging between 3-9 m. For example, potential groundwater bearing zones were identified in profile line 1 at point 27 down to 70 m depth, profile line 2 at point 15 down to 30m depth as well as profile line 3 at point 14 down to 85 m depth in the lower catchment. In the middle catchment, the potential targets for drilling boreholes were identified on profile line 7 at points 7 to 9 going down to 50 m depth and profile line 8 from points 6 to 9 and 15 going down to 70 m depth. Lastly, in the upper catchment, the drilling target zone was identified on profile line 10 at points 1 to 25 going down to 70 m except for profile map 11 where no potential drilling target was identified. The upper unconfined aquifer layers in this study did not exist in some of the locations like on profile

11 in the upper catchment, giving rise to confined aquifer layers closer to the surface (Figure 9). The subsurface profile mapping using ground magnetotelluric methods did not suggest groundwater accumulations below 50 m, instead supported shallow groundwater potentials boreholes. The study results are also comparable to Amos-Uhegbu et al., [42] and hence the study managed to apply hydrogeophysical methods to delineate aquifer layers, thereby enhancing the understanding of the subsurface structures. The lithological logs from the reference boreholes in the current study coincide well with the profile map and potential difference curve results as both methods display a heterogenous nature of the subsurface conditions.

5. Conclusions

This study has demonstrated the importance of using hydrogeophysics techniques to delineate aquifers into units of confined and unconfined aquifers especially in groundwater-dependent areas to enhance groundwater allocation plans and management practices. The VES results coupled with lithological data from boreholes were integrated into the interpretation to validate the results. Three-to-four-layers medium was inferred from the results depending on the section of the catchment. The upper unconfined aquifer layers in this study did not exist in some parts of the study areas (e.g., in the upper catchment along VES 6 and profile line 11), giving rise to confined aquifer layers closer to the surface. The regional distribution of the low resistivity structures spatially extended for approximately 36 km occupies the lower and middle catchment areas. High groundwater potential has dominated the lower and middle catchment more than the upper catchment thereby suggesting mapped out site's probable for a groundwater recharge scheme. The regional spread of the high electrical resistivity structures was not estimated as they represented last unit of investigation. The results managed to infer the start of the geological dry bedrock that is inclusive of sandstone, siltstone, dolerite, and kimberlite. These basement aquifers were fractured as confined aquifers. Boreholes investigated in this study were drilled in either unconfined aquifer of clay intercalated with a sand layer and confined aquifer compose of shale, sandstone, mudstone siltstone, dolerite, and kimberlite formation. The results from the passive ground magnetotelluric methods have complimented well with the vertical electric sounding results, thereby having successfully delineated aquifer subsurface structures. The lithological logs from the reference boreholes and other geological materials coincide well with the geophysical profile results that are suggestive of different lithological formations. This study has demonstrated that hydrogeophysical techniques to delineate aquifer units with an analysis of lithological data provide meaningful insights into the interpretation of resistivity, profile map, and electric potential difference values. These results have provided a clear foundation basis for estimating recharge in two different aquifer systems to enhance water allocation plans and groundwater management practices.

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