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Posted Date: 24 July 2024

doi: 10.20944/preprints202407.1867.v1

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Article

Application of Hydrogeophysical Techniques in Delineating Aquifers for Estimating Groundwater Recharge Potentials to Enhance Water Allocation in Groundwater-Dependent Systems, Northern Cape, South Africa

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Abstract: Application of aquifer delineation using hydro-geophysical techniques was conducted in De Aar, eastern part of the Karoo region, Northern, South Africa. This study is aimed at demonstrating the use of hydrogeophysical techniques in delineating aquifer systems into unconfined and confined in order to estimate areas and zones likely to control groundwater recharge. An integrated hydrogeophysical approach using vertical electrical resistivity sounding (VES) and ground telluric methods were applied to delineate subsurface structures. Six VES surveys and seven profile surveys were measured using a Wenner array configuration and ground telluric method respectively. VES data was processed using IPI2win software and used to produce a 2D inference of the subsurface electrical resistivity model. The telluric passive surveys were processed through an automated in-built algorithm to generate 2D profile maps while the electric potential difference curve was interpreted with the lithological cross section constructed 2D conceptual model. The VES results showed four significant layers of low (0.9-8.1 Ωm), moderate (22.4-125 Ωm), and high 68-177 Ωm) electrical resistivity values which is suggestive of the different lithological formations. Additionally, the subsurface model from ground telluric methods, supported shallow groundwater potentials boreholes with inference of less groundwater accumulations below 50 m. These hydrogeophysics results were correlated to the drill chip lithological results and both suggested a double-layer aquifer system, which may therefore suggest that recharge estimation needs to be carried out in two different aquifers. The study therefore successfully demonstrated the use of geophysics techniques in delineating aquifer systems, thereby enhancing the identification of potential recharge areas.

Keywords: Apparent Electrical resistivity; Electric Potential Difference; telluric; Unconfined; Confined

1. Introduction

Aquifer delineation is crucial for measuring local and regional groundwater recharge, particularly in arid regions with limited surface water. Such environments include cases where groundwater is from sole-source aquifers and serving as the primary potable water supply, (defined by Woodford., [1] as systems supplying over 50% of domestic water with no alternative source if depleted). In such areas, understanding groundwater recharge locality controls is essential for managing the hydrologic cycle, developing effective water allocation plans, and implementing accurate water monitoring practices, [2]. A lack of understanding about aquifer systems and their recharge rates can lead to inadequate groundwater allocation plans and ineffective water monitoring practices. The current approach for estimating recharge and planning water allocation do not account for the presence of multiple aquifer types within one area, relying instead on broad quaternary catchment delineation assumptions, which may lead to inaccurate uniform recharge values. This is despite the fact that various methods, including geological, hydrogeological, geophysical, and remote sensing techniques, can be applied to delineate aquifers and assess groundwater recharge potential zones[3]. Hydrogeological experiments and geophysical surveys are valuable for understanding groundwater recharge processes and spatial-temporal variations, but they often focus on single factors or rely on indirect, site-specific experiments [3].

Various geophysical techniques, including geoelectrical and electromagnetic methods, are used to delineate subsurface aquifers by assessing their extent and thickness [4,5]. The study employs both ground telluric and electrical resistivity sounding methods [6] Geophysical studies in groundwater exploration typically involve deep and shallow aquifer delineation stages [7]. The electrical resistivity method, widely utilized due to its simplicity and efficient data acquisition, is particularly effective in delineating groundwater systems [8]. However, it has limitations, such as not accounting for lateral changes in subsurface electrical resistivity, which can lead to errors in layer interpretation [9]. Despite these limitations, the method offers detailed insights into subsurface layer variations, identifying structures like aquicludes and aquitards sensitive to geological properties such as clay content. [10,11]. Hydrogeophysical survey methods are also widely applied in groundwater exploration for community water supply projects [4,12,13]. In the eastern Karoo region of South Africa, Vegter. [14], utilized electrical resistivity and refraction seismic methods alongside drilling to map alluvium deposit thickness and depths, distinguishing three aquifer types: coarse-grained basalt, weathered and fractured Beaufort and Ecca strata, and dolerite near intrusive contacts. Globally, electrical geophysical methods have been used extensively in groundwater studies. In Northern Ethiopia, Bairu et al. [15], employed vertical electrical sounding and horizontal profiling to assess geological formations and structures. Sunmonu et al. [16], conducted a similar study in Nigeria using vertical electrical soundings to map aquifer patterns. In Egypt, Mohamaden., et al. [12], utilized geoelectric techniques for aquifer and subsurface stratigraphy detection while in Malaysia, Riwayat et al. [17], highlighted challenges with conventional techniques providing limited point-specific data. In Pakistan, India, Niaz et al. [18], applied Schlumberger array vertical electric soundings for aquifer delineation and vulnerability mapping, respectively, and AL-Juboury et al. [19], studied saline groundwater effects on electrical resistivity in Dammam formation, Iraq, Asia.

This study is aimed at demonstrating the use of hydrogeophysical techniques in delineating aquifer systems into unconfined and confined in order to estimate areas and zones likely to control groundwater recharge. It argues that unless different aquifer types and drill log borehole lithologies into each aquifer type are delineated, accurate estimates of groundwater recharge rates cannot be achieved, which is crucial for improving groundwater allocation plans and water monitoring practices. The De Aar municipal wellfield, situate in the eastern part of the Karoo supergroup, Northern, South Africa is used as a specific case study. Estimating recharge potential in the Karoo supergroup, with its diverse sediment groups and physical properties, requires a detailed understanding of aquifer types and geological patterns [14]. Most boreholes in this region have reported low safe yields (<1 L/s), yet significant volumes of groundwater are extracted daily for community water supply. The Karoo fractured rock aquifers with low storage capacity receive

limited and highly variable rainfall recharge [20]. Their groundwater exploitation potential during prolonged droughts is largely controlled by the temporal variability of recharge [20].

2. Study area description

2.1. Local setting

The study was conducted in De Aar, Local Municipality, Northern Cape Province, South Africa and is part of the eastern Karoo supergroup (Figure 1d). In terms of hydrological basins, the study is within the lower Orange Water Management Area (WMA) and encompasses the quaternary catchment drainage regions D62C and D62D. The area was further subdivided into three parts: the lower (altitude from 1183 to 1233 m), middle (altitude from 1233 to 1261m), and upper catchments (altitude from 1261 to above 1404m), (Figure 1b). The study area covers approximately 2226 km² with a semi-arid climate characterized by an average annual rainfall of 27 mm calculated from monthly totals. The majority of this rainfall typically falls during the summer months, starting from November/December and ending March/April. Geomorphologically, the study area is characterized by scattered rings of dolerite hills, reaching diameters of up to 12 km and covering an area of 50-60 km² and are formed by horizontally layered dolerite sheets [21]. The region is classified as lowland interspersed with mountainous hills nestled between river valleys [22]. The Elandsfontein spruit, originating southeast of Hanover and Brak River near Caroluspoort, along with several minor tributaries, drains the entire study area (Figure 1b). The confluence of these two ephemeral river systems lies approximately 10 km northwest of De Aar town. These rivers typically flow briefly, and mainly during and after heavy rainfall. The intermediate valley areas are frequently intersected by numerous slopes of dolerite hills [14]. The riverbeds lie below the groundwater table, leading to the formation of standing pools of water along the Elandsfontein Spruit and Brak River systems [14].

2.2. Geology and Hydrogeological setting

The study area is primarily defined by Karoo sedimentary rock formations, which are horizontally layered with a slight dipping, occasionally altered by notable dolerite intrusions. Vegter [14] has conducted investigations into the stratigraphy of the study area and ascertained that the area is composed of Ecca and Beaufort Group sediments, specifically the Tierberg and Middleton formations. The Ecca Group, the older of the two, consists of dark grey shale and siltstone formations found predominantly in the lower catchment (north-western site of the study area) and extending into parts of the middle catchment (north-eastern site) [22]. Layers and lenses of siltstone and fine-grained sandstone intermittently interrupt the shale succession at various horizons [4]. The Beaufort Group, dating to the late Permian period, comprises mudstone, siltstone, and sandstone formations. In areas where these sediments have been fractured by intrusive dolerite formations, the rocks serve as significant groundwater-bearing targets [14,23]. Dolerites typically intrude as dykes, sheets, and sills of various thicknesses. Ring-shaped dolerite structures are frequent, overlapping up to 30 meters wide with curved outcrops. These formations range in width from 1 meter to over 10 meters and in length from 1 to 7 kilometers [23]. Their shapes and orientations vary, transitioning into nearly horizontal sheet bodies. Kimberlites, deposited in the upper catchment southeast of the study area, occur as pipes or dykes [23]. Alluvial deposits are primarily found within river valleys and exhibit significant lateral and vertical heterogeneity [22]. The maximum thickness of these deposits' ranges from 10 to 15 meters. Surface limestone deposits, formed from salt buildup in layers after evaporation in areas with shallow groundwater tables, are widespread but generally thin less than 5 m. Groundwater quality is classified as class II, with electrical conductivity (EC) ranging from 150 to 250 mS/m and total dissolved solids (TDS) exceeding 1000 mg/l [1,24]. Although dolerite intrusive formation itself is not highly groundwater productive, high yielding groundwater strikes are often encountered in the sedimentary section of both the upper and lower contact zones with the dolerite zones [14]. The water strike in sedimentary layers above dolerite is significantly greater than in the underlying dolerite sections.

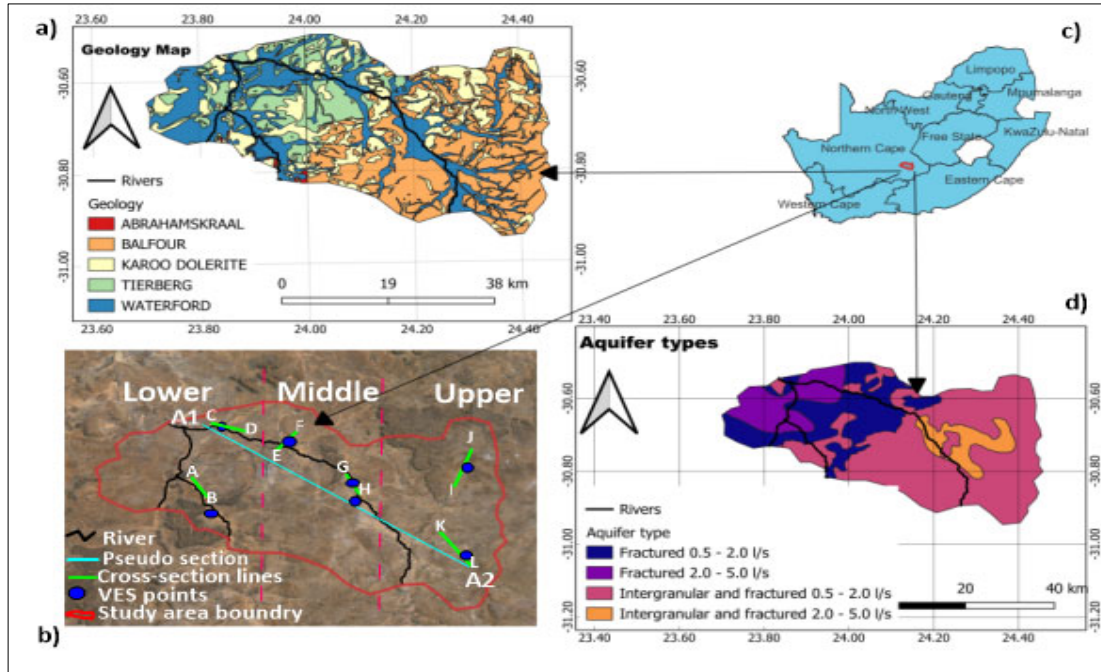


Figure 1. The study area map depicts the sedimentary and igneous outcrops of the basement rocks, various aquifer types, and the topographical landscape, including the drainage by Brak River and Elandsfontein Spruit.

3. Material and methods

3.1. Electrical resistivity Sounding data acquisition

The Vertical Electrical Sounding (VES) surveys were conducted using the Geotron electrical resistivity (ER) meter model G41 to measure the subsurface apparent electrical resistivity in the Wenner array configuration [25,26] (Figure 2). The Wenner array configuration was chosen for its robust signal strength in noisy environments and enhanced sensitivity to vertical electrical resistivity variations and horizontal structures. The investigation proceeded under the assumption that geological sections are predominantly horizontally layered, comprising various geological strata or pseudo-layered structures influenced by groundwater levels and weathering [27].

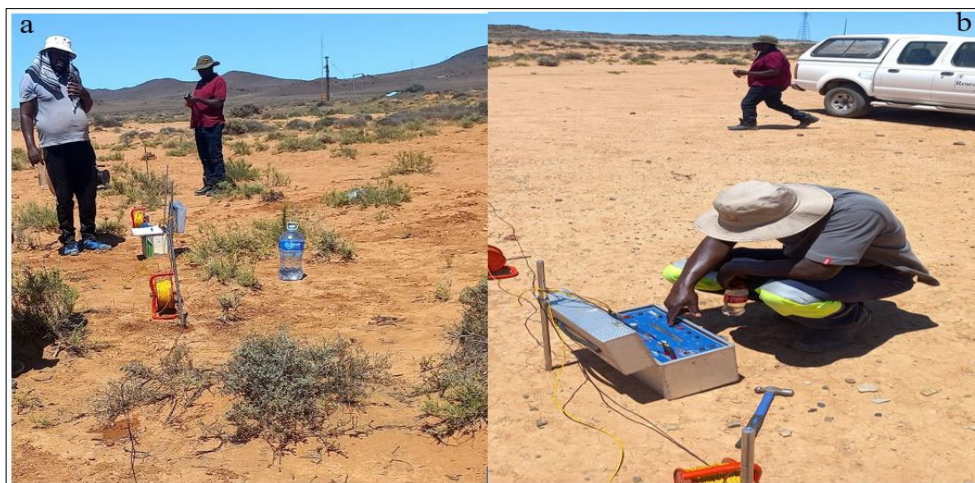


Figure 2. Field setup of the electrical electrical resistivity survey during the field investigations.

Seven VES stations were strategically placed throughout the study area to map various aquifer types, distinguishing between unconfined and confined aquifer layers along the survey lines [28]. At least two VES stations were established in each of the catchment subsections, (Figure 3) electrical resistivity Interpretation of the VES data involved partial curve matching using IP2WIN software [29,30], where plots were compared with standard master curves to determine optimal layer parameters such as resistivity's, thicknesses, and depths. This process facilitated the development of an electrical resistivity-depth model for each area [31]. The electrical resistivity values were used to create 1D spatial curve graphs illustrating the layers of subsurface geometry [32]. The electrical resistivity and thickness values were interpolated to create two-dimensional (2D) regional pseudo-cross-sections A1-A2 (Figure 7). These pseudo-cross-sections, derived from subsurface electrical resistivity data, were subsequently interpreted to describe each electrical resistivity layer and correlated with corresponding borehole log cross-sections.

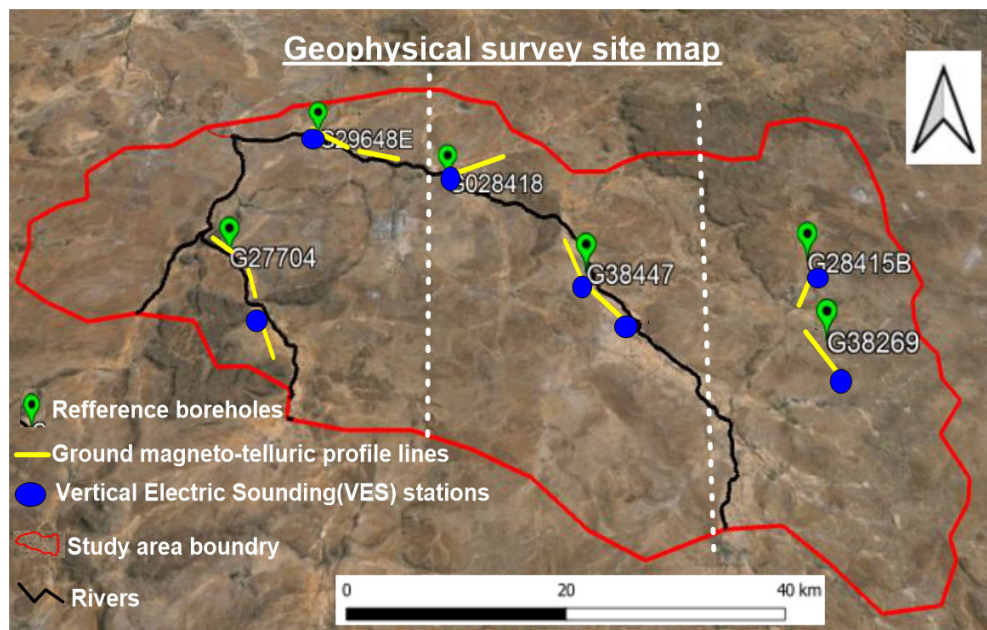


Figure 3. Study area map showing the geophysical field sites displaying the locations of vertical electric sounding stations and ground telluric profile lines.

3.2. Ground magnetotelluric method

In this study, the ground telluric method was employed as a complementary passive technique to delineate various aquifer layers (including confined and unconfined systems). This method was selected due to its reliance on natural electromagnetic field observations, avoiding artificial electric field sources, and demonstrating high resistance to interference [33]. The ground telluric geophysical survey technique utilizes electrical potential difference (mV) to explore groundwater resources [34], [35]. It has gained popularity in Africa for its ability to investigate subsurface electric electrical resistivity structures using the Earth's natural electromagnetic field [12,15,36]. Gomo [35] emphasizes the importance of understanding this method for groundwater exploration, noting its capability to delineate deep structures with greater penetration compared to conventional methods. As such the method is increasingly employed alongside traditional techniques like electrical resistivity, providing 2D images through inverse modeling to interpret subsurface conditions [35,37]. Several studies highlight the effective application of the ground telluric method in groundwater exploration. For instance, Hassan et al., [38] employed this technique to estimate groundwater recharge rates and identify recharge zones in the Kakia and Esamburbur sub-catchment of Narok, Kenya. Their results indicated potential recharge zones in the south-central and southeast areas suitable for managed aquifer recharge structures. In Nigeria, Oyegoke et al., [34] assessed borehole effectiveness in

basement complex terrain at Afe Babalola University, and precisely inferred vertical fractures and weathered formations, contrasting with less productive sites. In South Africa, Gomo., [35] conducted a hydrogeophysical study on Karoo and hard rock formations, correlating electric potential difference measurements with lithology and groundwater presence at observation sites. In the North-western part of Pakistan, Khan et al., [39] utilized ground telluric methods to locate aquifers and assess groundwater salinity, demonstrating its effectiveness in aquifer characterization and delineation alongside traditional methods. The instrument operates by measuring the electric field component of the Earth's electromagnetic field across various frequencies, which in turn delineates structures with high groundwater potential [39]. The PQWT-TC300 series equipment was utilized for these procedures (Figure 4).



Figure 4. Field procedures for conducting ground telluric surveys during the investigations.

3.3. Lithological cross-section of the existing boreholes

The geological cross-sections of the study area were constructed from data obtained from borehole drill chip logs sourced from the Department of Water and Sanitation (DWS) National Groundwater Archives (NGA URL: <https://www.dws.gov.za/NGANet/Security/WebLoginForm.aspx>). The data obtained from total of 12 boreholes were drilled along the Elandsfontein Spruit and Brak River, representing the lower catchment area, while 13 boreholes were drilled along the Brak River, representing the middle catchment. Additionally, 10 boreholes were drilled in the headwaters, representing the upper catchment site. Initially, a line connecting two points (e.g., A-B) was drawn to mark the topographic elevation along the survey line. Subsequently, this elevation line was converted into a cross-section using specialized software [40], illustrating the surface topography. Borehole log information was then utilized to construct 2D hydrogeological cross sections (Figure 7). The interpretation of drill log cross-sections was integrated with hydrogeophysical results to establish the applicability of these techniques in delineating aquifer layering so as to infer zones of groundwater recharge potential.

4. Results and Discussion

4.1. Electrical resistivity results and lithostratigraphic cross-section

The interpretation of the vertical electrical sounding (VES) curves involved analyzing the apparent electrical resistivity and grouping them to create a regional pseudo-cross-section of the area (Figure 9). The data from VES surveys were processed, interpreted, and analyzed using the IPI 2win software. Apparent electrical resistivity values were plotted against electrode spacing AB/3, with data error margins of 8.1% (VES1), 6.39% (VES2), 17.3% (VES3), 3.5% (VES4), 3.2% (VES5), and 2.9% (VES6) (Figures 8a-f). These values were interpreted in terms of layer thickness and correlated with lithostratigraphic cross-sections presented in Figure 7. The interpretation of VES results indicated a strong correlation between stratigraphic layers and borehole logs, with consistent layering observed across profiles (Figure 8a-c). The findings presented in Figure 8 and Figure 9 suggest a subsurface medium consisting of multiple layers, typically three to four significant layers identified based on varying apparent electrical resistivity values. The top layer, characterized by low electrical resistivity (0.9-8.1 Ωm) in the lower and middle catchments and higher electrical resistivity (196-213 Ωm) in the upper catchment, was attributed to differences in soil moisture and clay content. The higher electrical resistivity values in the upper catchment are linked to unweathered rocky gravel layers and intrusive rocks. The second layer consists of weathered sand-clay materials (dark blue and light blue) with electrical resistivity values ranging from 22.4 to 15 Ωm , thickness from 1.3 to 24.2 meters, and depths from 2.4 to 25 meters in the lower and middle catchments. The third layer in the middle catchment comprises shale, intercalated with wet sandstone and mudstone (up to 3.0 Ωm), while the upper catchment features dolerite, kimberlite, and alternating dry sandstone and mudstone, characterized by higher electrical resistivity values (68.8-177 Ωm). Woodford., [23] described the occurrence of alternating sandstone, mudstone, and shale in elevated terrain that is suggested by the pseudo cross sections. The low electrical resistivity material was confined to the middle catchment area, contrasting with the high-electrical resistivity material exposed near the surface in the upper catchment. The third layer in the lower catchment and the fourth layer in the middle and upper catchment were identified at maximum penetration depth, indicating the beginning of a dry and consolidated bedrock.

The pseudo-cross-section (A1-A2) suggests a subsurface that consists of at least four layers in the upper catchment and three to four layers in the lower and middle catchment areas (Figure 9). In the lower and middle catchment areas, the regional extent of low electrical resistivity covers approximately 36 km. The regional distribution, thickness, and depth of higher electrical resistivity structures depicted in the pseudo-cross-section could not be inferred as they are deeper layers beyond the investigation depth but are presumed to be composed of solid and dry formations (dolerite, kimberlite, and sandstone). Kimberlite dykes with high electrical resistivity values are in the upper catchment, east and southeast of De Aar on VES6 (Figure 8e). The second and third layers in this study were interpreted as unconfined and confined basement bedrock aquifers, respectively, based on their electrical resistivity values and corresponding geology from borehole logs. According to Vegter [22] and Woodford., [23] groundwater is frequently encountered in the sedimentary formations at both the upper and lower contact zones compared to the dolerite sections. Additionally, Vegter [4,22] reported that the groundwater yields in the sedimentary layers directly above dolerite are significantly higher than those in the underlying dolerite. At depths below 20 meters, the third layer is identified as a semi-confined or confined basement aquifer with low to moderate electrical resistivity values. Below 50 meters' depth, the fourth layer is interpreted as dry bedrock basement aquifers with high electrical resistivity values.

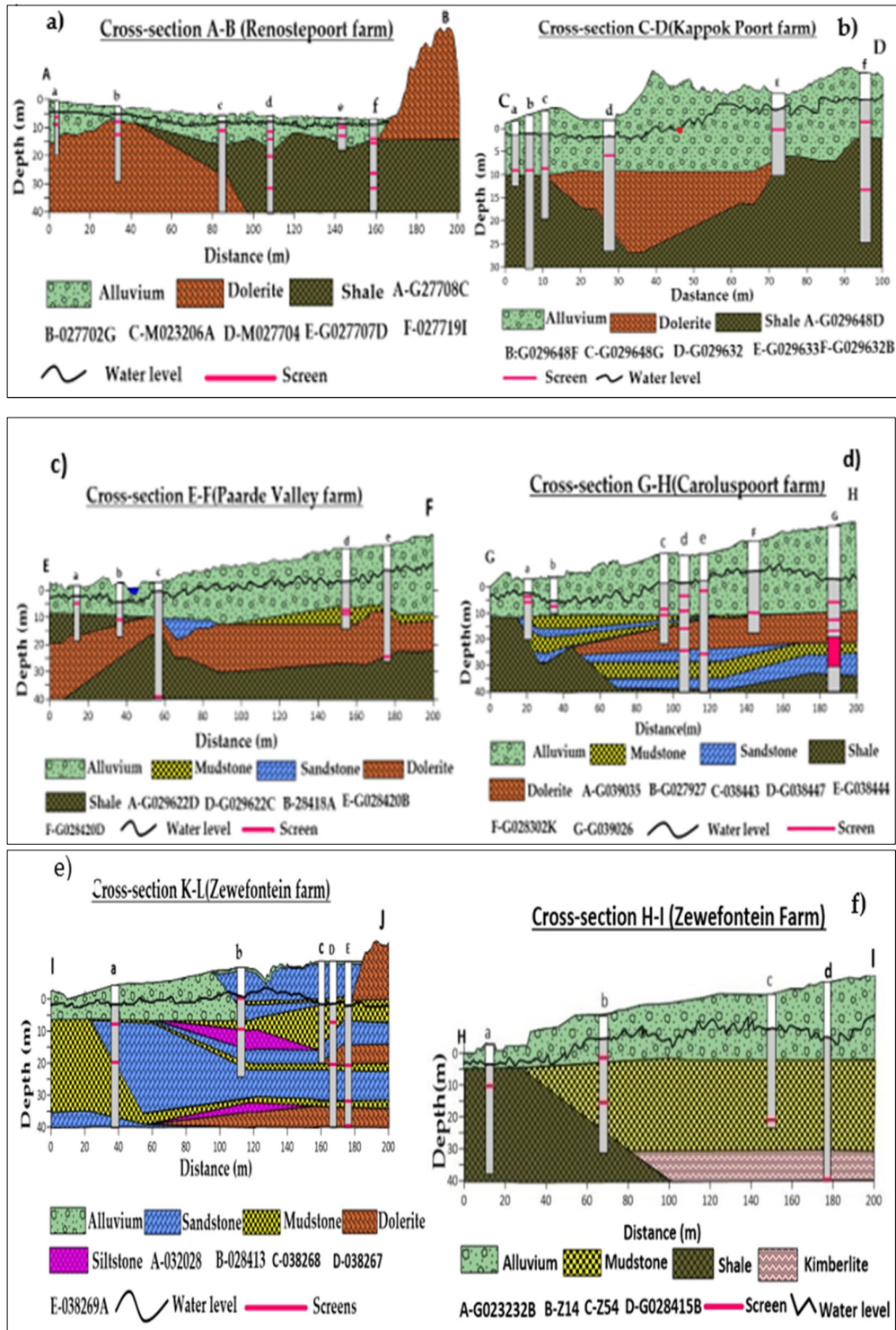
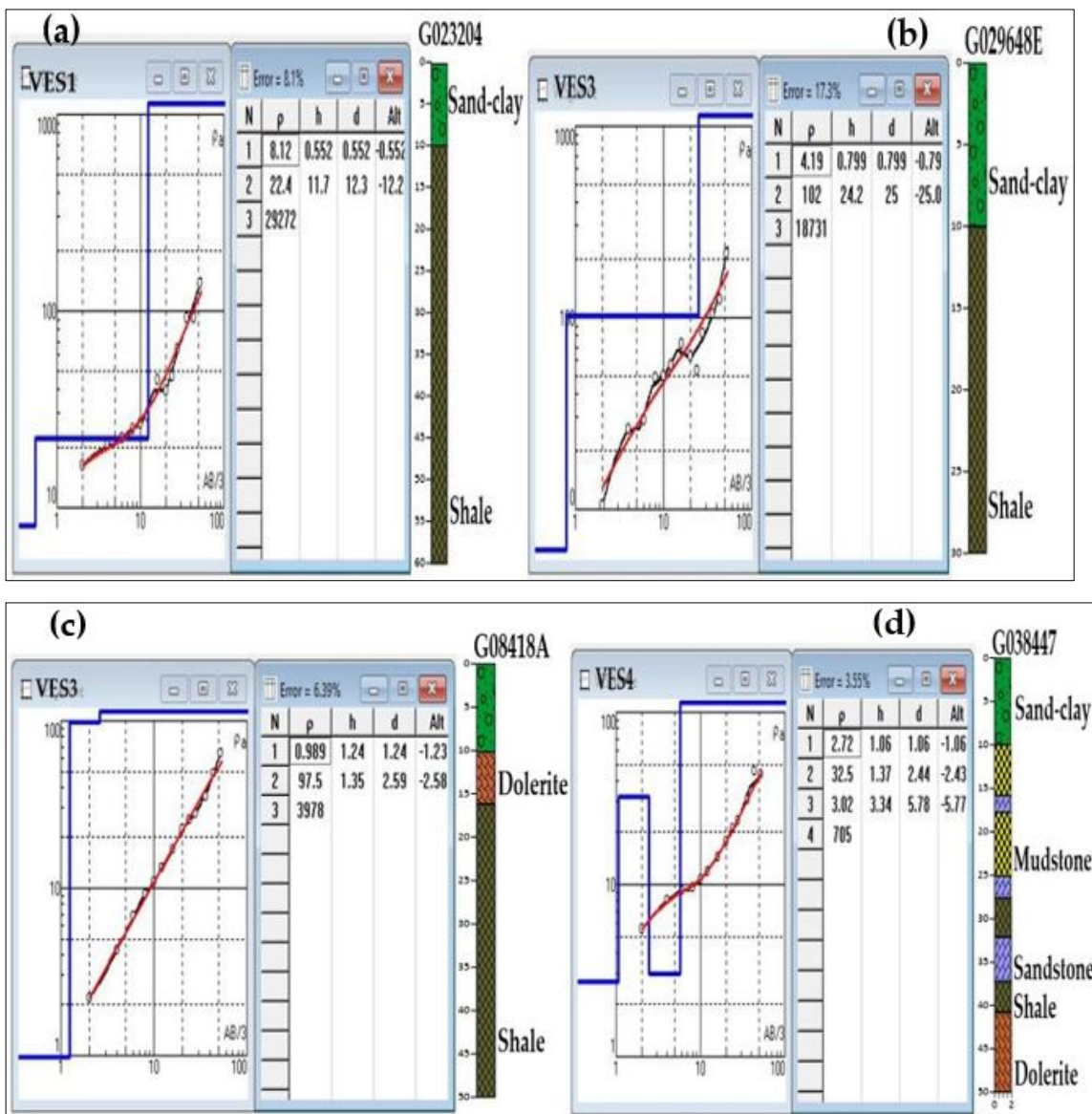


Figure 7. a and b: The geological cross-section of the lower catchment areas. c and d: The geological cross-section of the middle catchment area. e and f: The geological cross-section of the upper catchment areas.



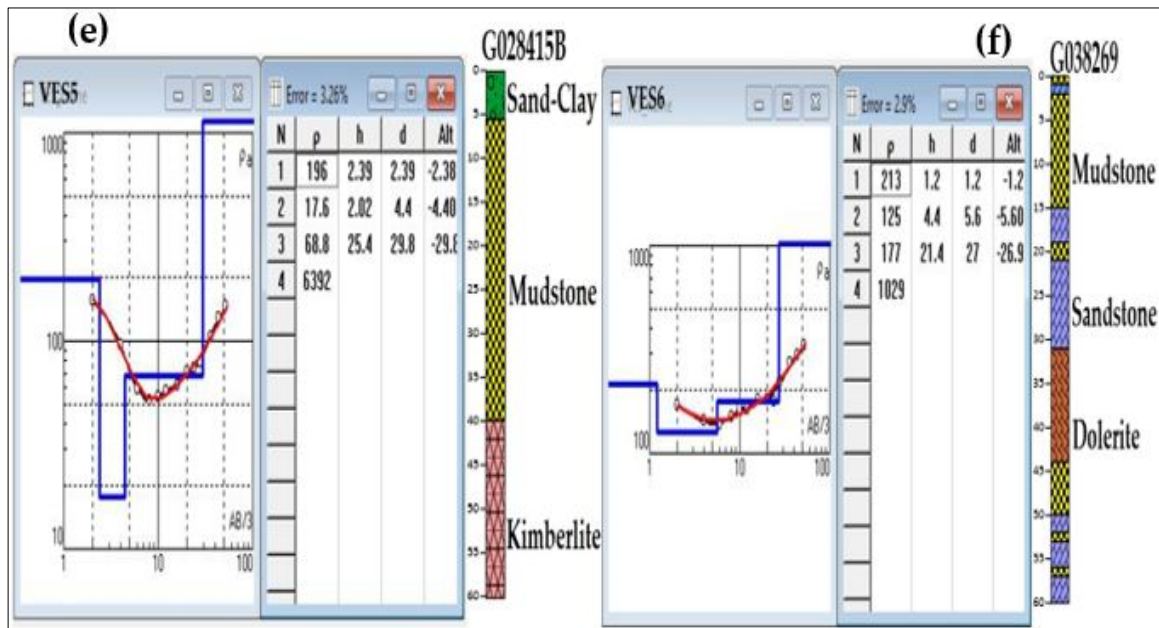


Figure 8. a and b: VES sounding curve generated in Renostepoort and Blaukranz farm (Lower catchment area). **c and d:** VES sounding curve generated in Paarde Valley and Caroluspoot farm middle catchment area. **e and f:** VES sounding curve generated in Zewe Fountein farm (Upper catchment area).

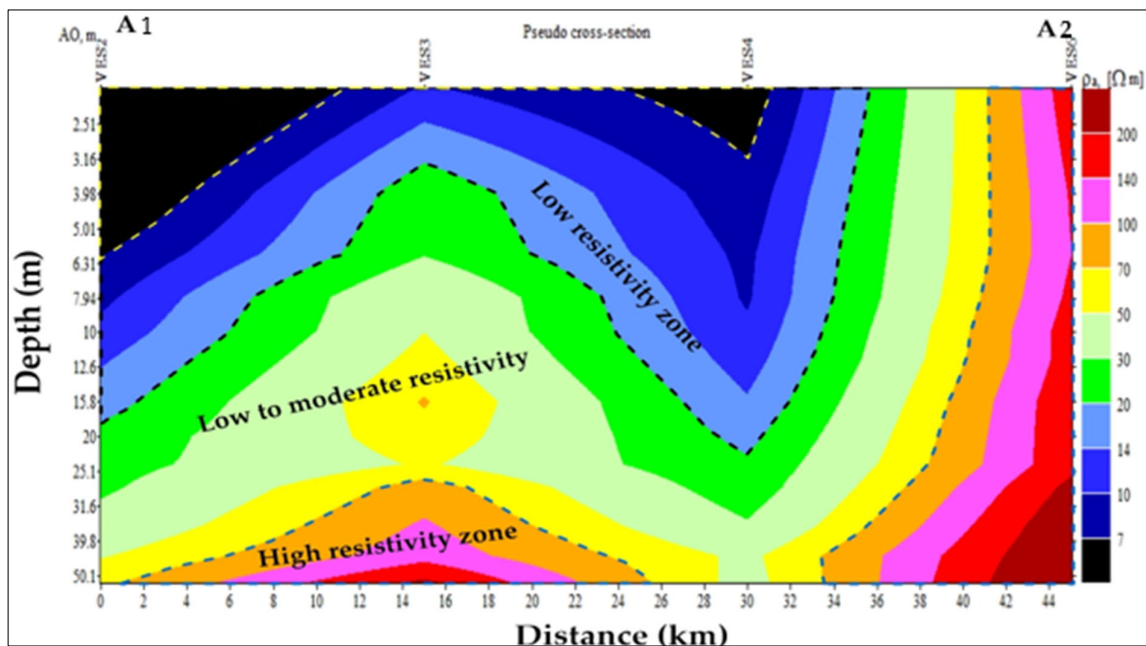


Figure 9. Regional pseudo-cross-section integrating four VES stations i.e., VES2-Lower catchment, VES3-Middle catchment, VES4-Middle catchment, and VES6-Upper catchment.

According to Vegter [22], these basement aquifers are typically fractured and confined, exhibiting decreasing permeability and yields as depth increases. The unconfined aquifer is found at depths ranging from 6.3 meters to between 15 and 20 meters, while the confined aquifers are situated at a depth beyond 20 m. Vegter., [22] suggests that alluvial aquifers in De Aar are observed to be semi-confined (leaky), semi-confined, or unconfined with delayed yield. The findings of this study

align with similar research conducted by Nazifi and Lambon [41] in the central region of Ghana and Mohamaden et al., in Egypt [30].

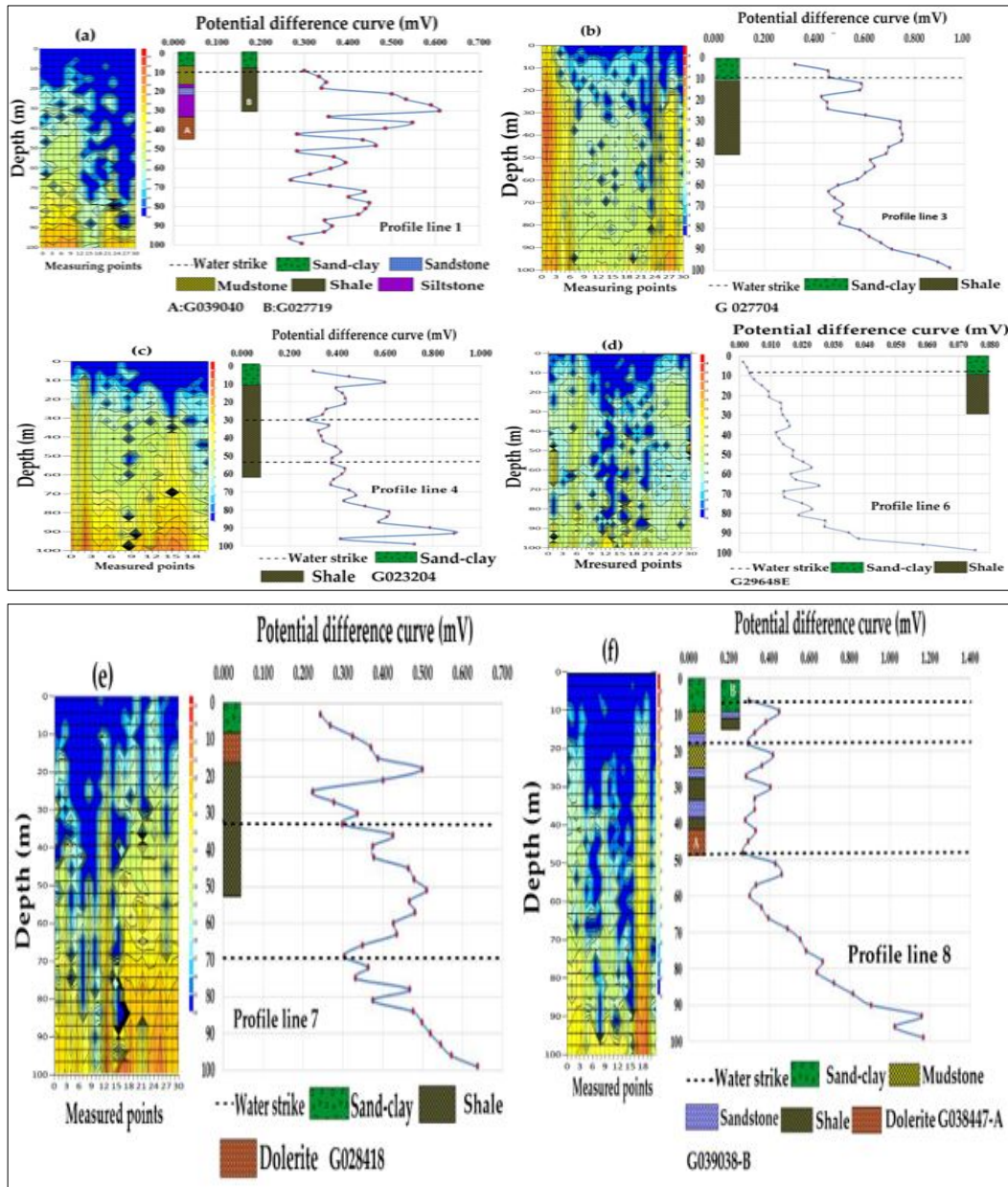
Their study found that the area was underlain by three to four layers with depth to aquifer varying between 0.48 to 7.42 m. The average aquifer thickness was about 14.78 m [42]. Mohamaden study found three geologic layers of which the first layer was sand and gravel with high resistivity (7.61–346 Ω m) and thin thicknesses (0.252–9.19 m) [30]. The second layer was composed of shale with very low resistivity (0.3–8.68 Ω m) and depths ranging from 4.18 to 56.4 m, while the third layer promised of sandstone with moderate resistivity (68.5–1585 Ω m). Sunmonu et al., [16] reported that 75% of aquifers in Ogbagba, Nigeria was confined, with the remaining 25% being unconfined. They noted that the clayey sand layer constituted 75%, sandy clay accounted for 16.7%, and fractured bedrock made up the remaining 8.3%. In the current study, most boreholes penetrated both unconfined and confined aquifers, with a few drilled into high resistive zones. Water strikes in these boreholes varied, with the majority found in unconfined aquifers. The average depth to water level ranged approximately from 3.0 to 5 meters, with shallower depths observed in boreholes near the river valley. These shallow water levels are attributed to the superficial nature of the aquifers [22]. Furthermore, the groundwater levels near the river valley are influenced by the river- aquifer interaction, and production and monitoring boreholes are strategically located in anticipation of this an increased recharge potential due to the interaction.

The passive telluric method was used as a complementary hydrogeophysical method [34] (Figure 10a-h). Subsurface profile maps and electrical potential difference curves were generated and correlated with the constructed lithological logs for the study area. Eleven profile stations were established across the study areawith six stations situated in the lower catchment (profiles 1-6), three in the middle catchment (profiles 7-9), and two in the upper catchment (profiles 10-11). In the lower catchment (profiles 1-6), the profile results are correlated with lithostructural logs from from shallow weathered sand-clay at the top to shale and dolerite formations, with the geophysical profile line lengths varying from 200 to 320 meters (Table 1). The middle catchment profiles (7-9) consisted of shale, alternating with dolerite, sandstone, and mudstone, with lengths ranging from 200 to 250 meters (Table 1). Profiles 10-11 in the upper catchment were characterized by dolerite, kimberlite, and alternating dry sandstone and mudstone formations, with a uniform length of 250 meters (Table 1). As mentioned earlier, data processing involved using an in-built algorithm to generate 2D tomography profile maps and electric potential difference curves, which were interpreted alongside lithological data from reference boreholes. Elevated electric potential difference values, as highlighted by Gomo (24), indicate electrically resistive formations such as fresh dolerite and dry sandstone. The profile maps depicted weathered zones in dark blue and light blue colors, extending from the surface down to 80 meters, indicative of viable vertical fracturing, according to Oyegoke et al., [34]. The blue and light blue colors were interpreted as groundwater potential recharge zones and layers, meanwhile, light green and yellow colors were interpreted as middle electric potential difference values of sedimentary rock like shale, and mudstone. Blue and light blue colors on the map denoted groundwater recharge potential zones, while light green and yellow indicated moderate electric potential differences typical of sedimentary rocks like shale and mudstone. Red colors corresponded to high electric potential difference values, indicating igneous rocks such as dolerite and kimberlite, as explained by Garamoon et al., [43] in Kakia and Esamburbur sub-catchment Narok, Kenya.

Table 1. Summary of borehole information used as references during the 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 | G0390 40 | -30.666 | 23.8654 | 1 | 240 | 4 | 45 | 3.23 | 1220 | 4,7-11 | Silt- Clay, Mudstone Sand, Shale, Dolerite | 12 |
| | G2771 9I | - 30.6679 | 23.8757 | 2 | 240 | 4 | 48 | 3.13 | 1227 | 4,9,12,24,42 | Sand- clay, Shale | 6.5 |
| | G2770 4 | - 30.6729 | 23.8778 | 3 | 320 | 3 | 45 | 5.14 | 1216 | 8, 10, 14, 30 | Shale | 14.6 |
| | G2320 4 | - 30.7045 | 23.9006 | 4 | 200 | 5 | 62 | | 1233 | 10,18 | Shale | 10 |
| | G2964 6C | - 30.5556 | 23.95382 | 5 | 200 | 5 | 36 | | 1183 | 6.5 | Clay | |
| | G2964 8E | - 30.5506 | 23.9388 | 6 | 300 | 3 | 28 | 4.83 | 1190 | 8 | Sand | 10 |
| Middle | G0284 18 | 30.5991 | 24.0596 | 7 | 250 | 6 | 24 | 3.86 | 1231 | 33 | Shale | |
| | G3844 7 | - 30.6886 | 24.1781 | 8 | 200 | 5 | 42 | 4.77 | 1261 | 5, 8, 17, 24 | Sand- clay, Mudstone Sand- clay, Shale | |
| | G3903 8 | - 30.6609 | 24.1614 | 9 | 200 | 5 | 13 | 4.23 | 1256 | 4, 7- 9 | Shale | |
| Upper | G2841 5B | - 30.6776 | 24.3648 | 10 | 250 | 6 | 103 | 7.03 | 1404 | 40 | Kimberlite | |
| | G3826 9 | - 30.7478 | 24.3667 | 11 | 250 | 6 | 60 | 9.89 | 1389 | 25, 29, 31 | Sandstone | 5.5 |

The survey utilized two non-polarizable electrodes spaced 10 meters apart. Raw data, consisting of electric potential differences at a specific frequency were plotted against depth to create an EPD curve using Microsoft Excel as reported in [35]. The overall interpretation involved comparing 2D processed profiles and electric potential difference curves with lithology data obtained from reference boreholes, establishing correlations between electric potential difference values and subsurface geological conditions [35].



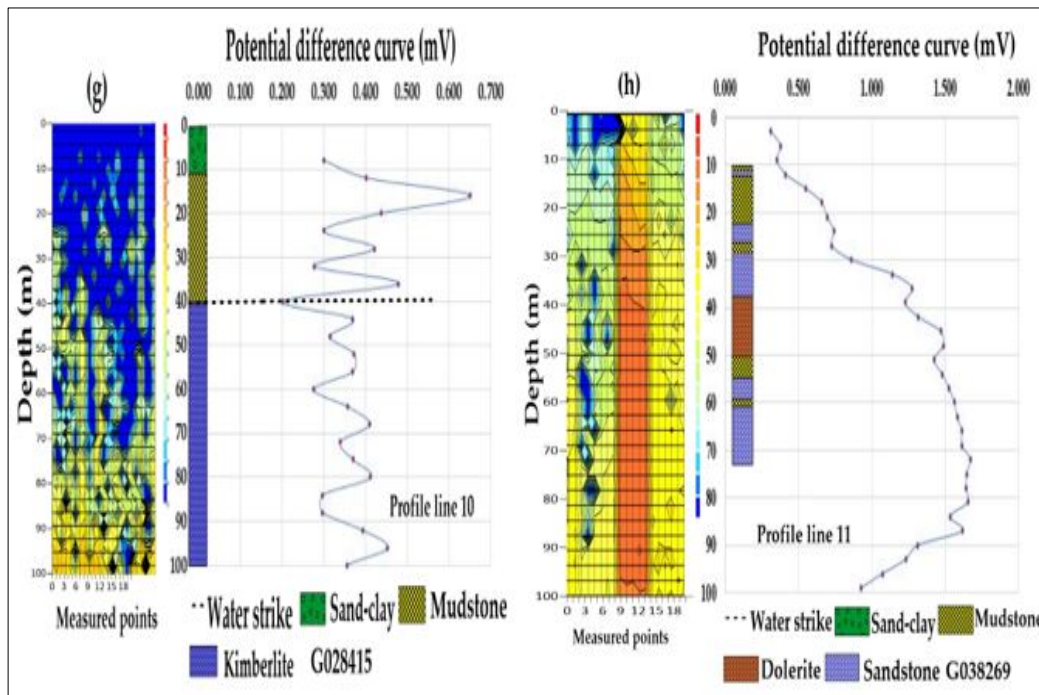


Figure 10. a, b, c, and d): Subsurface profile maps and the electrical potential difference curves generated coupled with lithological profile boreholes along the lower catchment area. **e and f):** Subsurface profile maps and the electrical potential difference curves generated coupled with lithological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

The results from the passive Ground Telluric methods in this study complemented the findings from vertical electric-sounding cross-sections, revealing two distinct zones of low and high electrical resistivity across the area. During field investigations, shallow groundwater levels were observed, ranging from 3 - 9 m in depth. For instance, potential groundwater recharge potential areas were identified in profile line 1, ranging from point 27 - 70 m depth, in profile line 2 from point 15 - 30 m depth, and in profile line 3 from point 14 - 85 m depth in the lower catchment. In some locations, like profile 11 in the upper catchment, the upper unconfined aquifer layers were absent, leading to confined aquifer layers closer to the surface (Figure 9). The subsurface profile mapping using ground telluric methods did not indicate groundwater accumulations below 50 meters, reinforcing the presence of shallow groundwater potentials for borehole placements. The study's findings are consistent with those of Amos-Uhegbu et al., [44] demonstrating the successful application of hydrogeophysical methods in delineating aquifer layers and enhancing understanding of subsurface structures. The lithological logs from reference boreholes in this study form the basis for calibration of hydrogeophysical results and confirms the heterogeneous nature of subsurface layering within the study area.

5. Conclusions

This study underscores the significance of employing hydrogeophysical techniques to delineate aquifers into confined and unconfined units, particularly in groundwater-dependent regions, to enhance groundwater allocation strategies and management practices. Integration of VES results with lithological data from boreholes validated the findings, revealing a three-to-four-layer medium across different sections of the catchment. In some areas, such as the upper catchment along VES 6 and profile line 11, upper unconfined aquifer layers were absent, indicating confined aquifers closer to the surface. Low electrical resistivity structures were spatially distributed over approximately 36

km in the lower and middle catchment areas, suggesting significant groundwater potential conducive for groundwater recharge initiatives. The extent of high electrical resistivity structures, marking the final investigation unit, was not fully estimated. The study identified the onset of geological dry bedrock comprising sandstone, siltstone, dolerite, and kimberlite formations, fractured into confined aquifers. Boreholes examined in the study intersected either unconfined aquifers of clay intercalated with sand layers or confined aquifers composed of shale, sandstone, mudstone, siltstone, dolerite, and kimberlite. The results from passive ground telluric methods complemented those from vertical electric sounding, effectively delineating subsurface aquifer structures. Consistency between lithological logs from reference boreholes and geophysical profile results confirmed the distinct lithological formations. This study demonstrates that hydrogeophysical techniques, combined with lithological data analysis, yield valuable insights into interpreting electrical resistivity, profile maps, and electric potential difference values. The findings from this study therefore establish a foundation for estimating recharge in diverse aquifer systems, thereby enhancing water allocation strategies and groundwater management practices.

Author Contributions: Conceptualization, T.K. and H.P.; methodology, L.B.; software, I.M., L.B.; validation, I.M., T.K. and H.P.; formal analysis, L.B.; investigation, L.B., T.K., H.P., and I.M.; resources, H.P., T.K., I.M.; data curation, L.B., T.K., H.P., and I.M.; writing—original draft preparation, L.B.; writing—review and editing, L.B., T.K., H.P., and I.M.; visualization, L.B.; supervision, T.K., and H.P.; project administration, L.B.; funding acquisition, L.B., and T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Department of Water and Sanitation, South Africa. The fieldwork was co-funded by the University of the Western Cape (UWC) and the Council for Scientific and Industrial Research (CSIR).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable

Acknowledgments: This paper forms part of the corresponding author's Ph.D. studies currently underway. The author wishes to thank the following institutions: the National Department of Water and Sanitation, the University of the Western Cape, the Council for Scientific and Industrial Research, and the University of Namibia for their unwavering contributions. The authors acknowledge the contributions of the following individuals for their technical support and resources during field investigations; Madlala T., Makhetha J., Fenini P., and Xaza A. To the reviewers, the author is grateful for their valuable time and comments on this manuscript.

Conflicts of Interest: Not applicable

Declaration: The grammar and spelling were checked and corrected using both Grammarly.

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