Journal of Geography and Geology; Vol. 5, No. 3; 2013
ISSN 1916-9779 E-ISSN 1916-9787
Published by Canadian Center of Science and Education

Modelling the Subsurface Geology and Groundwater Occurrence of the Matsheumhlope Low Yielding Aquifer in Bulawayo Urban, Zimbabwe

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Received: July 9, 2013 Accepted: August 12, 2013 Online Published: August 19, 2013

doi:10.5539/jgg.v5n3p158 URL: http://dx.doi.org/10.5539/jgg.v5n3p158

Abstract

This study is focused on determining the nature, extend and spatial variation of the subsurface and groundwater in the Matsheumhlope low yielding aquifer so as to improve the understanding of groundwater occurrence within Bulawayo Metropolitan area. The abstraction and utilisation of groundwater from crystalline basement complexes have often been hampered by the high rate of borehole failure. For instance, borehole failure in the Matsheumhlope wellfield that characterises the greater part of Bulawayo City, Zimbabwe, is often ascribed to many factors which are yet to be investigated locally and regionally. The electrical resistivity method was used to establish the depth, thickness and sequence of geological units in the low yielding aquifer. Satellite data were used to delineate the lineaments and assess the topographic features of the area. Geological samples obtained from boreholes were correlated with the geophysical pseudo sections to give a better view of the subsurface and groundwater occurrence in the area. Geographic Information Systems (GIS) was used to model the geophysical characteristics of the subsurface giving the potential groundwater occurrence in the area. The study confirmed that the Matsheumhlope aquifer is a heterogeneous unconfined aquifer with a shallow depth to the basement rock in highlands of the study area. The results also showed high spatial variation of subsurface formations and groundwater potential over short distances, thereby indicating the complex nature of mapping basement aquifers. Borehole failure in the area was attributed to the occurrence of shallow depth of the bedrock underlying some parts of the aquifer. Therefore the results of the study recommended that the structural and geodynamic analysis of the fractures of the whole Matsheumhlope aquifer should be done using both structural mapping and geophysical methods.

Keywords: Groundwater; borehole drilling; vertical electrical sounding; low yielding aquifer; crystalline basement complex

1. Introduction

Hydrogeological conditions, such as spatial and temporal variability of basement aquifers cause problems in many urban areas that rely on groundwater. In addition to basic data problems, the distribution of water within Africa is not uniform and the continent has the greatest spatial, and temporal, supply variability of any region in the world (Walling, 1996). This makes it difficult to give broad overviews on groundwater management difficult. Considering the general scarcity and variability of hydrogeophysical data in most arid and semiarid zones of Southern Africa, this is to be expected. This is particularly realised in areas which are under extreme environmental conditions of drought and erratic rainfall patterns like Zimbabwe. The overpopulation and industrial activities in its major cities is straining the already existing surface water resources. An example is the Bulawayo Metropolitan which is located in the semi-arid region of western Zimbabwe that experiences perennial water shortages for domestic and industrial use.

Several studies on groundwater potential in the Bulawayo Metropolitan were carried out resulting in the identification and evaluation of the Matsheumhlope aquifer (e.g. Martinelli & Hubert, 1985; Weaver et al., 1992;

Mangore, 2002; Mangore & Rusinga, 2004; Rusinga & Taigbenu, 2004; Muchingami et al., 2012; Chuma et al., 2013). However, the Matsheumphlope wellfield is a marginally good aquifer which cannot support large drawdowns that could make it more vulnerable to contamination from urban sewer and landfill activities. Rusinga and Taigbenu (2004) reported that the Matsheumhlope wellfield is demarcated into three aquifers according to the abstraction rate per day (Figure 1), namely: *the high yielding aquifer* (yield of more than 120 m^3 per day), *medium yielding aquifer* (20-120 m^3 per day) and the *low yielding aquifer* (less than 20 m^3 per day). Borehole failure has been widely reported in the low yielding aquifer but is not documented. Harvey, (2004) defined borehole failure as a situation in which a borehole that has been deemed 'successful' at the time of drilling subsequently fails to deliver a sufficient yield of safe water throughout the year. This may occur due to depletion of groundwater levels in weathered aquifers and insufficient recharge of fractured aquifers resulting in dry boreholes. Borehole failure in crystalline basement aquifer has been one of the major constraints in the development of groundwater in Sub-Sahara (Foster, 1984; Wright, 1992; Lovell, 2009). The geological features of the Bulawayo aquifer system bear semblance to those of basement formations that have earlier been studied and investigated (Wright, 1992; Charlton & Foster, 1995). Monitoring and research need to be done to achieve a better understanding of subsurface geology and groundwater systems.

Incorporation of a densely sampled geophysical data with conventional hydrogeological data increases the amount of data available for the characterization of the aquifer and has the potential to significantly improve the estimates of hydraulic parameters and their spatial correlation of structures over those obtained from borehole data alone (Hubbard & Rubin, 1998; Olayinka & Barker, 1990; Soupios et al., 2007). Geophysical techniques such as electrical resistivity have been used extensively in the search for suitable groundwater and to locate subsurface cavities, faults and fissures (Pozdnyakova et al., 2001; Al-Tarazi et al., 2006). Surface geophysical resistivity surveys may indicate the depth and extent of concealed weathered pockets, which may ensure against risk of failure. On the hand, hydrogeological surveys such logs of rock and soil encountered during drilling can provide the most direct and accurate means for the delineation of high-conductivity and low-conductivity strata. The character, thickness, and succession of the underlying geological formations provide important data on existing aquifers, aquitard, aquicludes and interaction between surface water and the subsurface (U.S. Army Corps of Engineers, 1999). Lineaments extracted from the remotely sensed data and other ancillary data also give important information on subsurface features that may control the movement and/or storage of groundwater.

Therefore the specific objectives of this study were to establish the depth, thickness and sequence of geological units in the low yielding aquifer; to correlate the vertical electrical sounding (VES) curves with geological setting of the area and relate them to the aquifer potential. The intention is to identify the major factors responsible for borehole failures and declining yield in the wellfield so as to recommend appropriate solution as well as to identify area(s) of high groundwater potential in the low yield aquifers based on available groundwater information and geophysical data.

2. Geographical and Geological Setting

Bulawayo Metropolitan lies in the complex basement aquifer of the semi-arid western region of Zimbabwe (Figure 1). The study area lies within the Matsheumhlope Wellfield which is the main underground water resource aquifer in Bulawayo City. It covers the following suburbs: Montrose, Ilanda, Hillside East, Hillside West, Hillside, Hillcrest, Malindela, Morningside, Greenhill and Barham Green. It lies between latitude 20°10'15"S to 20°12'44"S and longitude 28°33'7"E to 28°37'14"E covering an area of approximately 10 km^2 (Figure 2). The study area straddles the broad watershed and the immediate margins of the central axis of the Southern Africa's river basins. Meteorological Service Department (2009) reported that the area receives an average seasonal rainfall of 560mm which is very low compared to most of the northern part of Zimbabwe.

The area is underlain by the Balawayan Formation that comprises the Upper Greenstone Belt and the surrounding granitic terrain, both of Achaean age, which is cut by Protezoic plugs and dykes of grabbo and dolerites (Garson & Mutsvangwa, 1995; Rusinga & Taigbenu, 2004) as shown in Figure 2. Its topography is closely controlled by the geology and to some extent by the horizontal tectonic processes. The topography is characterised by abrupt slopes resulted in napes of metabasalt rocks being transported over older greenstone. Minor, but fairly persistent, thin-branded iron-formation horizons in parts of northern Ilanda and eastern Greenhill are interflow exhalites formed during interruptions in volcanic activity. The hilly areas have excellent exposures of both volcanic types, and also of associated sills and minor intrusions of very resistant metadolerite and metagrabbo (Garson & Mutsvangwa, 1995). Accordingly, the area is covered by a generation of secondary vegetation that is closely related to the underlying rock type and environmental changes that occurred.

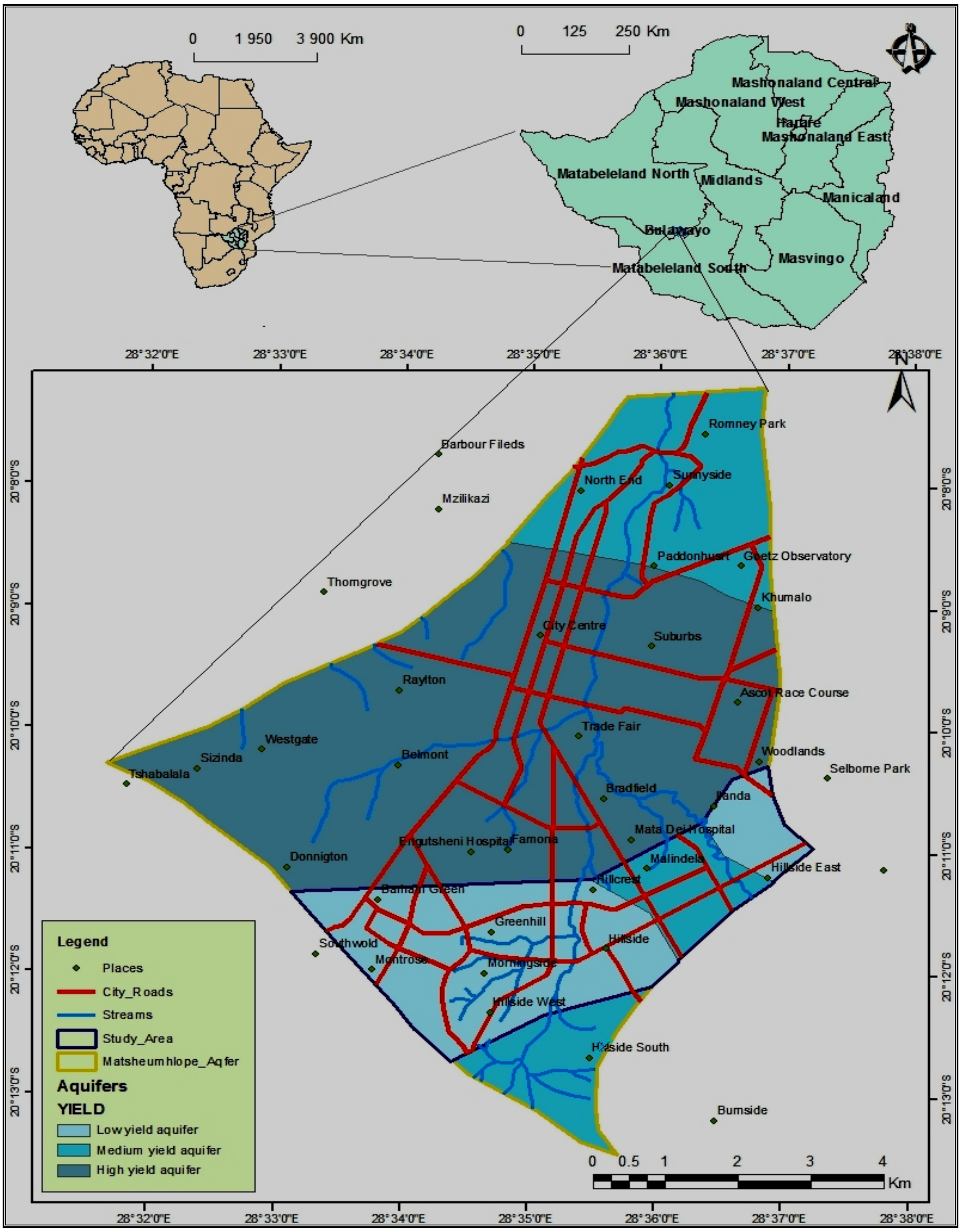

Figure 1. The Matsheumhlope Wellfield – modified using ArcGIS 9.3 software from Rusinga and Taigbenu (2004). The study area is shown on the map as the "*Low Yielding Aquifers*". The area lies over the southern half of the Bulawayo Metropolitan area

3. Materials and Methods

The study to model the nature, extend and spatial variation of the subsurface and groundwater in the Matsheumhlope low yielding aquifer within Bulawayo City was carried out in three phases, which are: terrain and field investigation, borehole logging and geophysical survey. The results obtained were weighted and overlaid in an ArcGIS environment to give a detailed analysis of the possible occurrence of both the subsurface and groundwater at the same time giving an elucidation on the probable factors that causes borehole failure in the study area.

3.1 Terrain Investigation

Detailed field explorations were conducted to gather hydrologic and geologic information verifying previously collected information and to identify areas of high recharge potential and favourable areas for drilling boreholes. During the desk study and geological mapping exercise, all surface features that could influence the occurrence of groundwater were logged down and their locations were noted for further investigation. The surface features noted during the survey included: (i) topographic low lands such as confluence of rivers or streams, stream valleys and vlei, (ii) geological contacts indicated by changes in soil type and remnant vegetation, (iii) exposed sheared quartz veins that indicate weathered and fractured zones, (iv) hilly areas and rock outcrops such as boulders, sheet rock.

The Digital Elevation Model (DEM) data acquired from the ASTER satellite was combined with the Global Positioning System (GPS) data to observe the variations in terrain since it affects the movement of groundwater. The lineaments were identified by visual interpretation of both LANDSAT ETM+ and DEM processed images. ArcGIS 9.3 Software was used to delineate the surface features which were associated with the occurrence of groundwater. Lineaments, as expected, are strongly correlative with structures that have obvious surface expression. When a lineament is perceived, a tonal representation of reflectance contrast that is related to variations in vegetation, soils, and topography is observed.

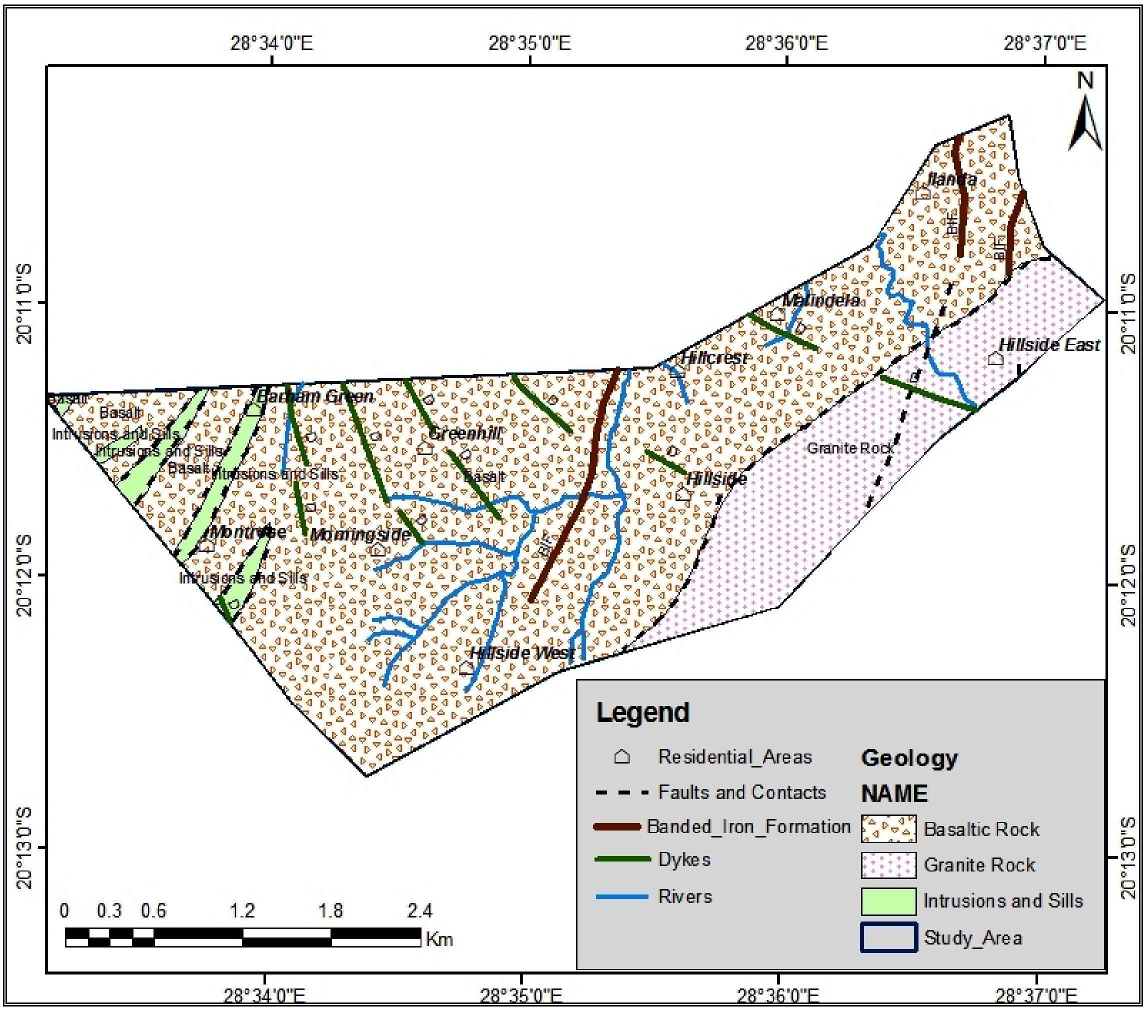

Figure 2. Geology of the study area showing a trend of basaltic rock in contact with granitic rock and intrusions

3.2 Borehole Logging

Samples of soil and rocks were collected from three boreholes drilled in the study area. All the boreholes were drilled using the air-rotary drilling method. This is a well-established method that has been used for centuries in exploration of groundwater, geological structures and aquifer characteristics. Although the method is expensive, it provides in-depth information on the subsurface that may augment the geophysical investigations. Logs were recorded directly in the field without transcribing from a field book or other documents. This technique lessens the chance for errors when copying the results manually and allows the completed document to be field-reviewed closer to time of drilling (Price, 1996). The samples were collected from the fragments of rocks that were brought to the surface through air-rotary drilling as shown in Figure 3. Samples were collected on the surface at every 6 m depth, which is the length of the drill pipe by the use of a bucket and settling pit. All cuttings were passed through the diverter and exit at one point. This resulted in much better cutting recovery and prevented contamination of samples by material sloughing back into the annulus. The borehole logging information obtained from Greenhill site was evaluated and interpreted with the aid of LogPlot 7 software.

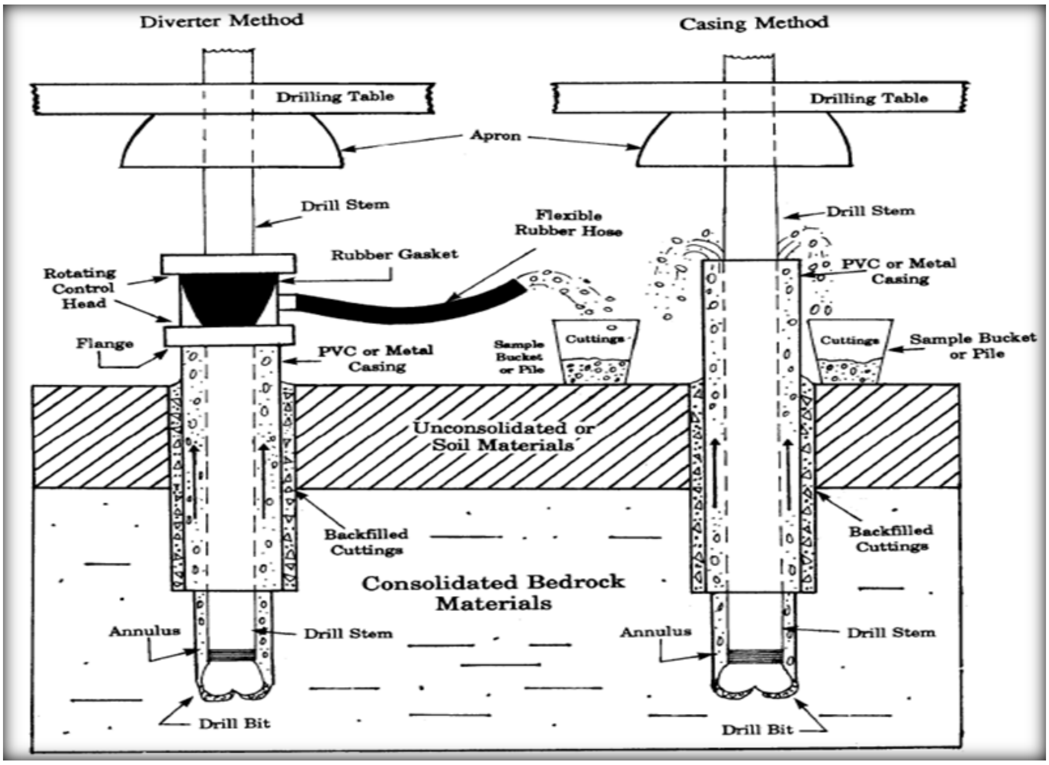

Figure 3. Schematic diagrams of diverter and casing for collection of rotary cuttings (Price, 1996)

3.3 Geophysical Survey

The electrical resistivity method was carried out in the area in order to obtain the depth to the bedrock, bedrock topography, locate areas with high groundwater potential and correlate borehole drilling samples with geophysical properties. The Schlumberger electrode configuration was adopted for the acquisition of vertical electrical sounding (VES) data in the field using the *MiniSting Earth Resistivity Meter*. The *Garmin etrex Vista Cx GPS* was used to mark the positions, elevations and to trace the previously marked points (Waypoints). A total of 36 VES profiles were performed in the period between February 2011 and April 2011. Most of the VES surveys were done in areas where borehole failures were reported. Figure 4 illustrates the sequential spreading of the current electrodes and the voltage electrodes with respect to the reference point. The distinctive colours of the voltage electrodes are corresponding to the chronological spreading of the current electrodes where values of apparent resistivities were recorded. The resistivities of the different layers were recorded directly from the resistivity meter which is capable of sending current into the earth subsurface through a pair of conducting electrodes, automatically computing and displaying the apparent resistivity of the subsurface structure under investigation. The effective depth of penetration obtained using the Schlumberger arrays is generally 20% to

40% of the outer electrode spacing (AB), depending on the earth resistivity structure (Edwards, 1977; NGA, 2000).

3.4 Interpretation of Resistivity Sounding

The interpretation of VES data using IPI2Win software is presented in three sections: VES curve, pseudo section and resistivity section. The resistivity values and the sampling interval on the curve were used automatically to create the first approximation of the corresponding multilayer model. Thereafter, the layer thicknesses and resistivity values of the model were modified through a number of iterations until the best-fit between the calculated curve and the apparent resistivity curves was reached. According to Geoscan-M (2001), the IPI2Win software has the capability to solve both the forward and inverse problems for Schlumberger arrays for the cross-sections with resistivity contrasts. Linear filtering was used in the forward problem. The algorithm provides a fast and accurate direct solution for a wide range of models, covering all geological scenarios. The inverse problem is solved using a variant of the Newton algorithm of the least number of layers or regularized fitting minimizing algorithm using Tikhonov's approach to solve incorrect problems (Geoscan-M, 2001).

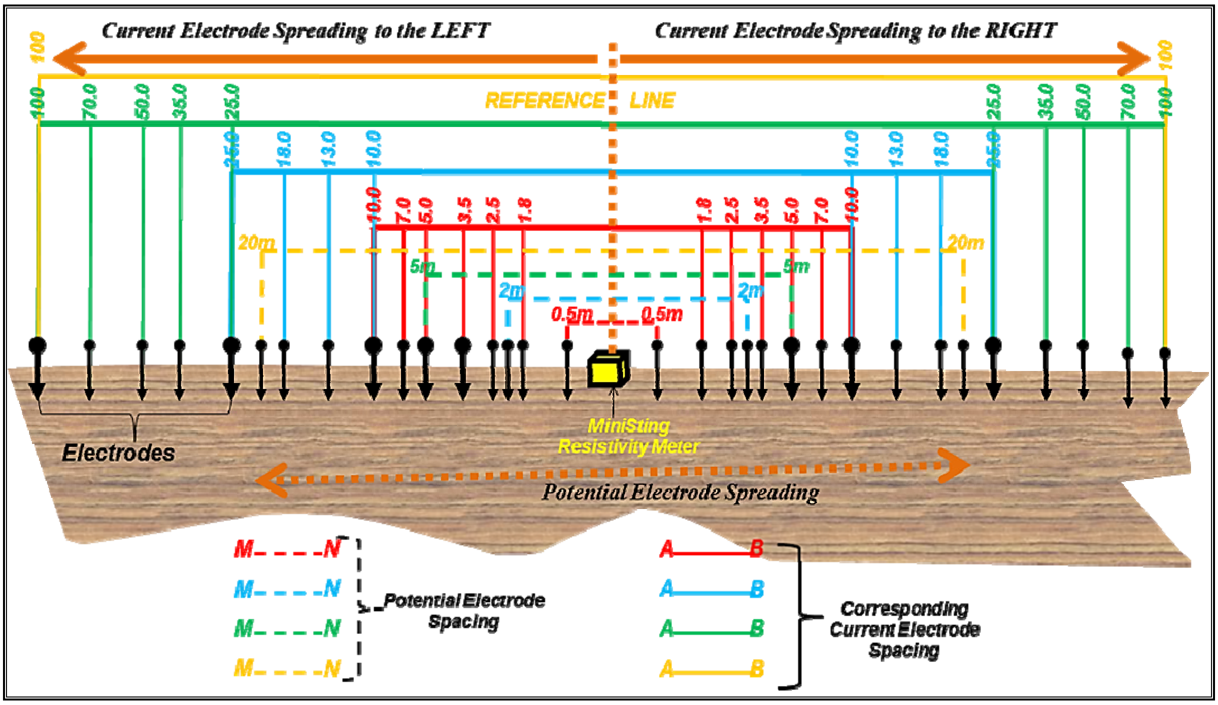

Figure 4. VES Survey – the Schlumberger configuration. The sequential electrode spreading is represented by the colours of both current (AB) and potential electrodes (MN)

3.5 Modelling of the Subsurface and Groundwater Occurrence

GIS was used to give a spatial variation of subsurface topography as well as creating a model of the groundwater occurrence in the study area. Groundwater occurrence model was based on the geophysical characteristics of the subsurface which was then integrated into the ArcGIS software. The typical relationship between (Bernardi et al., 1988; Gopalan, 2011) overburden thickness and the resistivity of the geological layers in crystalline basement rocks was used to determine the potential boreholes success rates. Table 1 gives the archetypal comparison of the aquifer yield, the resistivity of the overburden material and groundwater potential in greenstone rock which underlain the study area. Normally, resistivity of geologic formations which are highly weathered lies between 50-250 Ωm. Table 2 shows the relationship between overburden thickness and boreholes success rates in crystalline rocks of Zimbabwe (Jones, 1985; Martinelli & Hubert, 1985; Wright, 1992; Chilton & Foster, 1995). The weighted percentages of the apparent resistivities of the 36 VES stations were overlaid with the weighted depths of the bedrock and the potential yield resulting in a better understanding of the groundwater occurrence.

Table 1. Comparison of aquifer potential and resistivity of layered regolith (Wright, 1992; Gopalan, 2011)

Resistivity (Ωm)	**Yield(ℓ/s)**	**Groundwater Potential**
< 100	3-4	Very Good
100-150	2-3	Good
150-200	1-2	Fair
200-300	<1	Poor
> 300	Zero	Nil/Massive rock

Table 2. The relationship between overburden thickness and boreholes success rates in crystalline rocks of Zimbabwe (Jones, 1985; Martinelli & Hubert, 1985; Chilton & Foster, 1995)

Thickness of overburden (m)	**Success rate (%)**
<10	0
10-20	25
20-25	45
>25	70

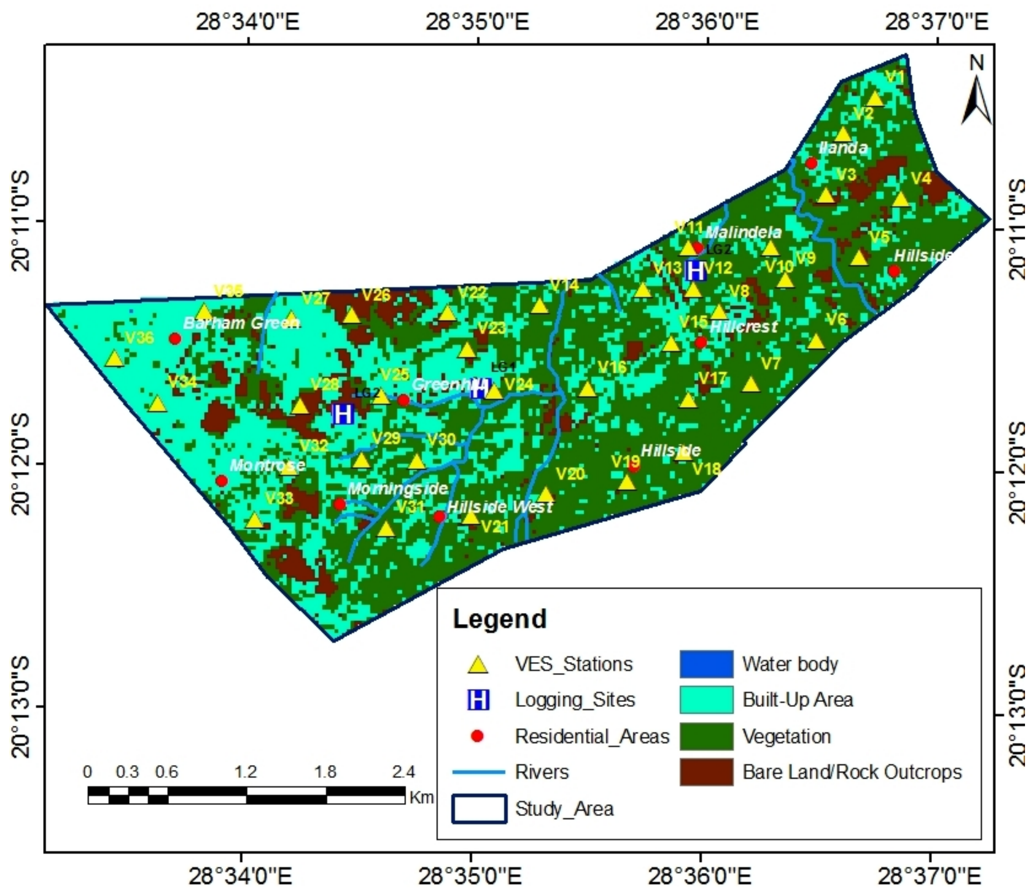

Figure 5. The study area showing the land use/land cover, boreholes, logging sites and distribution of VES sites. The area covers at least ten suburbs of Bulawayo City

4. Results and Discussion

4.1 Elevation and Lineament Analysis

The thematic map produced from the classification of the LANDSAT EMT image of 2010 shows that most of the land is built up, Figure 5. The southern part of the study area shows considerable vegetation cover that mainly consists of exotic trees/shrubs. The natural vegetation that still exists in the area is mainly branchystegia and thorn-brush. Land use and land cover normally influence the rate of recharge of the aquifer. Hard surfaces such roads, roof tops and pavements reduce the rate of infiltration. The effect of land use / cover is also manifested either by reducing runoff and facilitating, or by trapping water on their leaf. Water droplets trapped in this way go down to recharge groundwater.

The DEM data and the GPS ground truthing data produced a terrain representation of the study area (Figure 6). Highest altitudes were found around Montrose and Hillside West with an average value of 1434 m above sea level on the other hand the lowest altitudes were observed (1358 m) in Malindela, along the *Matsheumhlope River*. The sudden changes in elevation was observed and this is associated with conjugate of lineaments which are an indicator of extensive weathering and intrusions that in the exist area (Figure 6). According to O'Leary et al. (1976) lineaments are mappable linear surface features, which differ distinctly from the patterns of adjacent features and presumably reflect subsurface phenomena. Since lineaments are weak zones, they can serve as conduits for movement or accumulation of groundwater in the subsurface. Most of the lineaments are found in Malindela and Hillcrest where there is a contact of metabasalt rock, granitic rock and the high-magnesia metabasalt. Small trends are also found in the hilly part of Barham Green, where there are fringes of dykes. The main direction of the lineaments is north-easterly the study area which agree with what was discovered in Chuma et al. (2013). The ENE-WSW to NE-SW lineaments are largely due normal faults with possibly of a small amount of transcurrent movement.

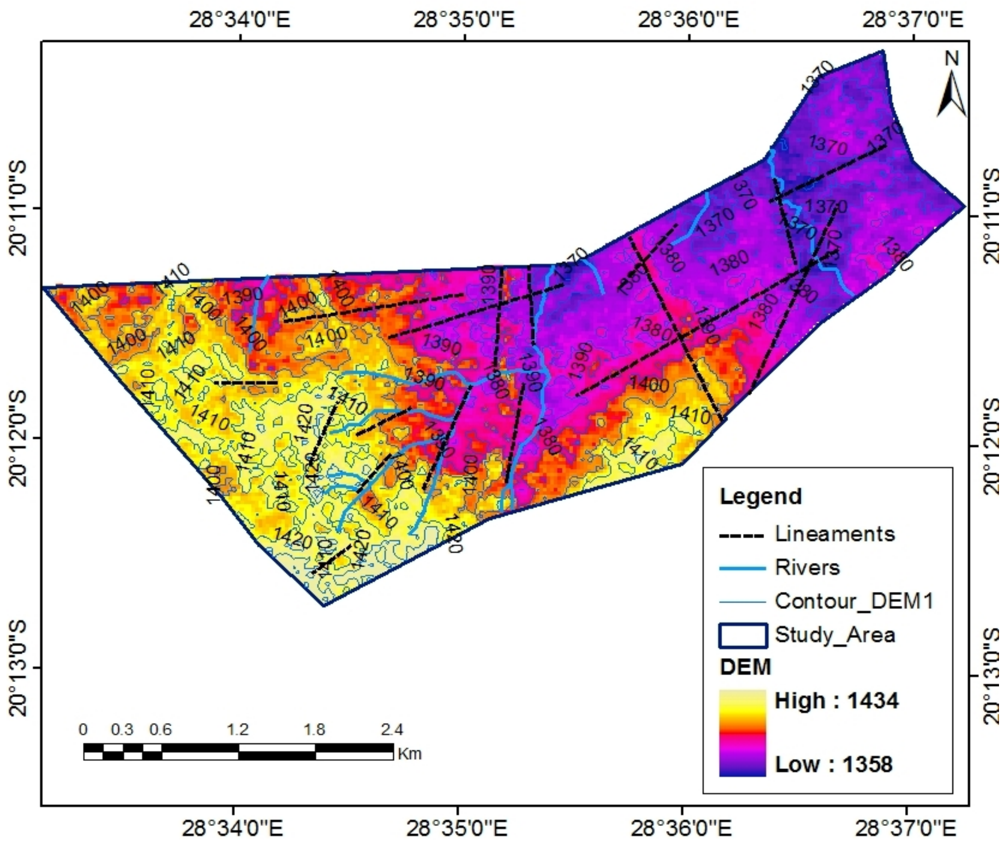

Figure 6. The DEM representation of terrain and extracted lineaments

The DEM and GPS-elevation data was further modelled into three dimensional surface maps which helped to identify the geomorphology of the study area irrespective of the construction that has taken place (Figure 7). Most of the geomorphological and relief features can be traced from the surface maps which influence the movement of surface and groundwater movement. The high level of terrain variability that was observed can be attributed to the volcanic activities that took place in the area (Amm, 1965). The area is hilly with an extensive plateau to the south and small plateaus to the north and east. Studies have shown that topography of the land surface determines the general direction of groundwater flow, and also influences groundwater recharge and discharge (Boonstra & de Ridder, 1990). Areas such as Morningside, Greenhill, Barham Green, Ilanda, Montrose and Hillside East are located on highlands and are characterised by a downward flow of water. Therefore, these areas are the recharge zones of the entire aquifer. Discharging in the aquifer occurs into the lower dispositional areas of Malindela and Hillcrest.

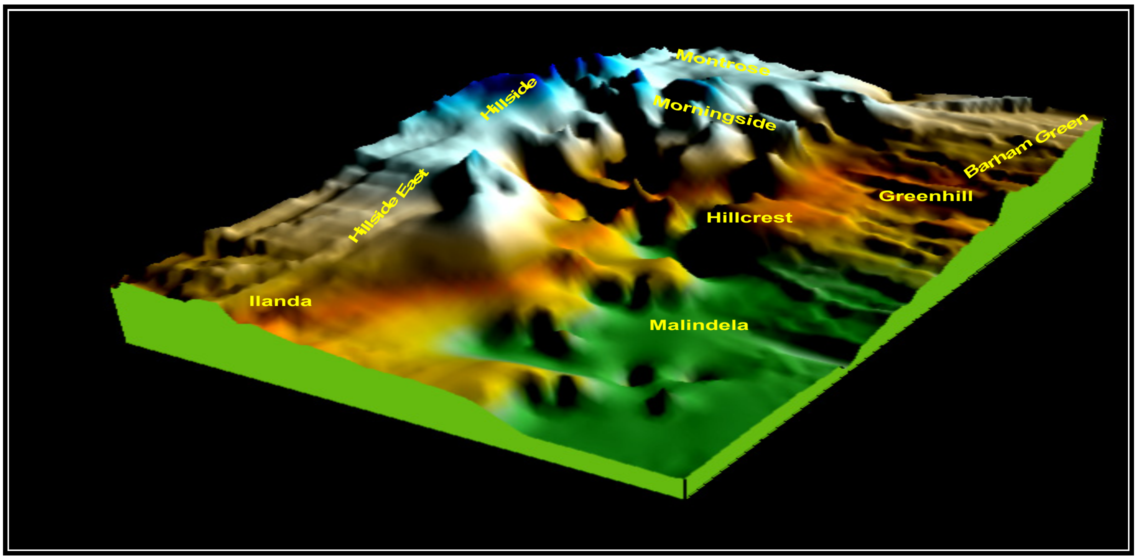

Figure 7. Surface topography and relief maps modelled using Surfer Version 8. The elevation is in the Z dimension and it represented in metres

4.2 Borehole Logging Analysis

Fractured rocks and soil samples collected from a borehole drilled in Greenhill, Hillcrest and Ilanda are shown in Figure 8. The top layer consists mainly of brownish rock and sandy soils mixed with clay and grass. The size of rock fragments increases with depth from 6 m to 24 m. This shows the presence of the regolith layer which is constituted by deposits of sediments and weathered parent rock (basalt). The high-magnesia metabasalts give rise to stony soils of a lighter brown colour, practically indistinguishable from andesite soils. Damp specimens showed that the watertable was intercepted at a shallow depth of 6 m. The degree of weathering of the basaltic rock is shown by the size of the rock fragments collected at each level. The drill bit gave large rock fragments in highly weathered zones and fine samples from an unbroken parent rock. From the samples, it could be seen that the samples became fine in size as the basement rock was approached. The colour of the rock turned from brownish to green-greyish from the top layer to the bottom layer. The analysis of the logs from the three sites is shown in Figure 9 and they indicate that the area is mainly composed of the greenstone formation. This forms a good component that is favourable for groundwater source. The greenstones invariably contain vesicles that make them susceptible to deep weathering.

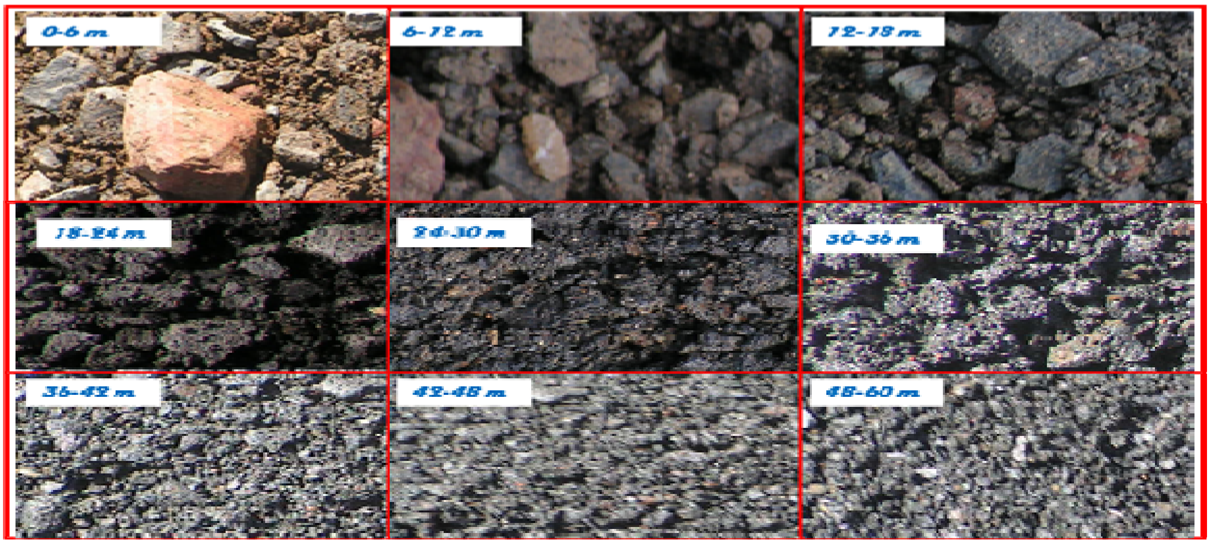

Figure 8. Specimen of soil and rocks collected from a borehole drilled in Greenhill

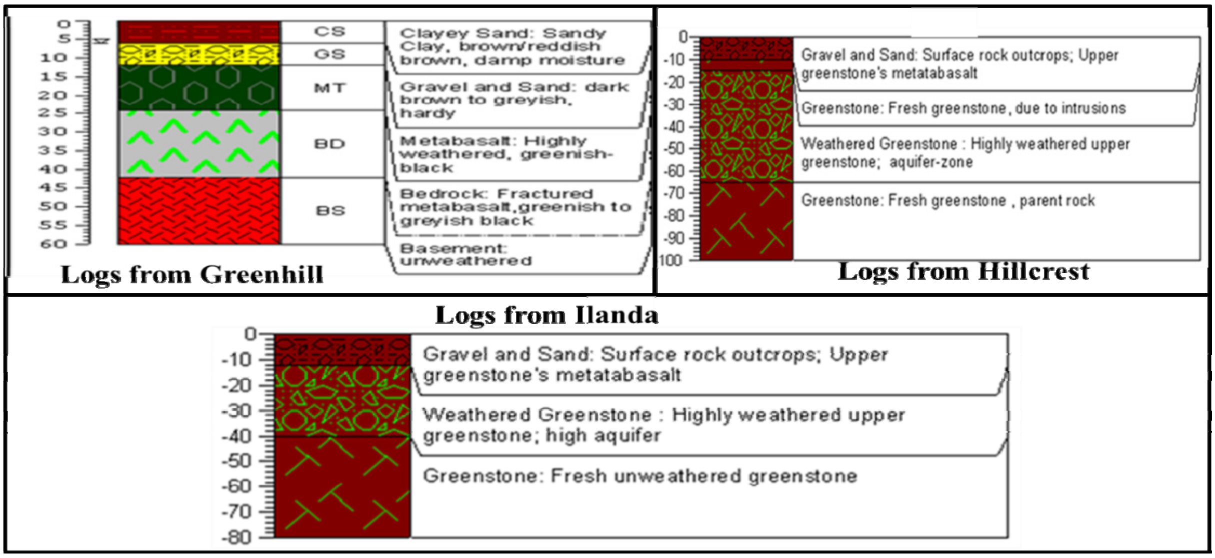

Figure 9. Borehole logs obtained from LogPlot 7. Three samples which were analysed were obtained from Greenhill, Hillcrest and Ilanda suburbs

4.3 Geophysical VES Analysis

Part of the results of the 36 VES surveys carried out in the low yield aquifer are presented by curves on a logarithm scale (Figure 10). The field values of the apparent resistivities are marked by circles and the curve is presented by a black line, which is a smoothing line on the field values. The red and blue lines show the model obtained from the inversion process, which was done using the IPI2Win modelling tools. The VES curves resemble those of A-type ($\rho_1<\rho_2<\rho_3$) and H-type ($\rho_1>\rho_2<\rho_3$) curves (Telford et al., 1990). A-type curves show an exponential increase of resistivities with increase in depth of penetration. H-type curves show that the first layer is heavily composed of outcrops from weathered metabasalt which is associated with high resistivities. The intermediate layer has low resistivity compared to the first layer which is an indication of highly weathered basement rock interacting with the watertable.

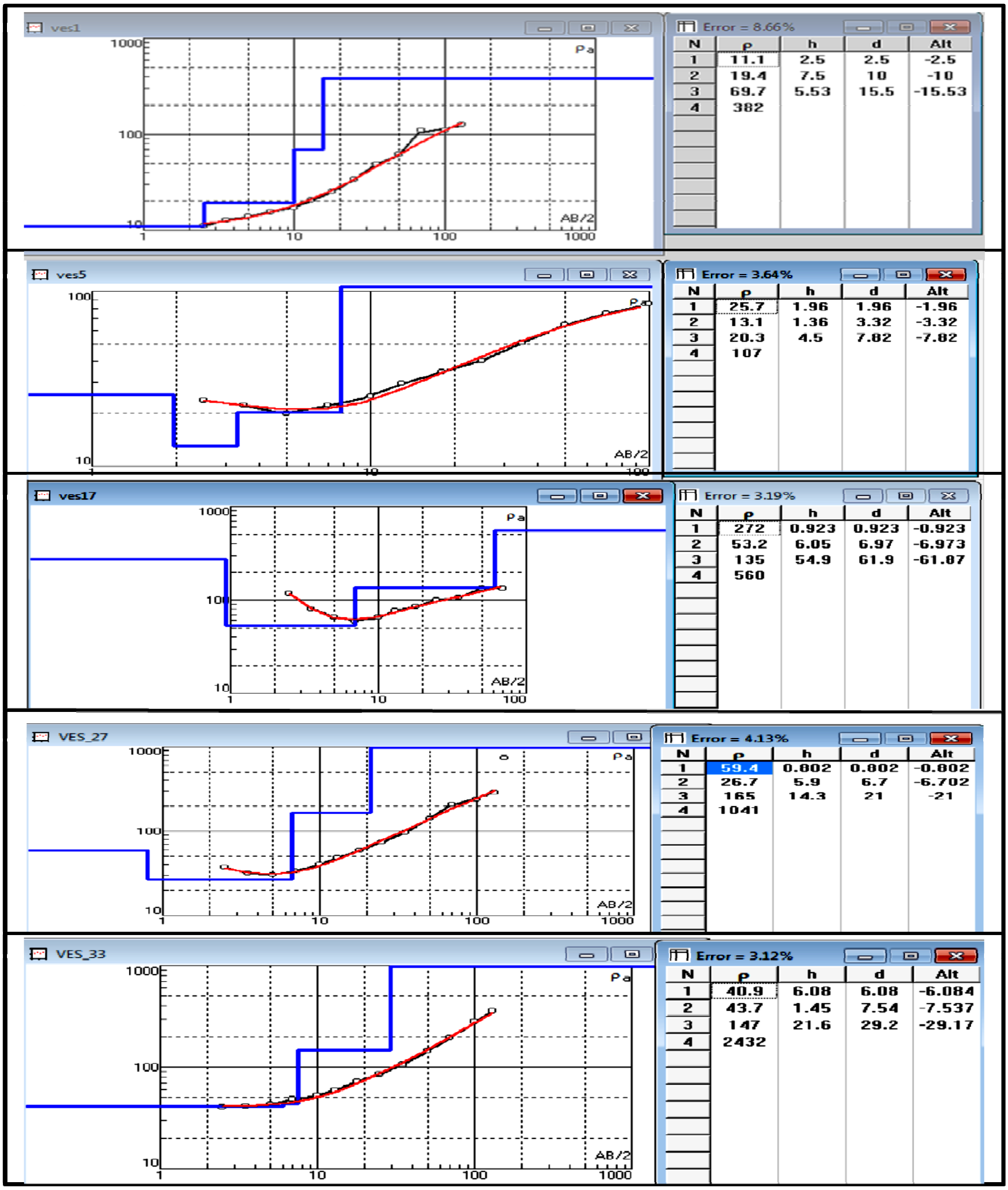

Figure 10. VES curves and data for stations 1, 5, 17, 27 and 33. Most the curves show three layer models consisting of the subdivided regolith layer and the basement rock

The geoelectrical pseudo sections produced from all VES stations are shown in Figure 11. The VES profiles were correlated and merged with respect to the direction of the profile line and the closeness of the individual VES stations. On the pseudo sections, the top horizontal scale represents the names of the sounding points, while the bottom horizontal ruler represents the coordinates of the sounding points. Vertical lines mark the sounding point given as *AO* being equivalent to half the current electrode spacing, *AB/2*. The sections covered by VES 1 to VES 5 represent the subsurface geology of Ilanda/Hillside area whilst VES 6 to VES 10 give an average overview of Malindela/Hillside area and VES 11 to VES 15 represent the underling subsurface of Hillcrest/Greenhill. The sections covered by VES 16 to VES 20 represent the subsurface of

Greenhill/Morningside area. VES 20 to VES 26 give an average overview of Morningside/Hillside West area and VES 28 to VES 36 representing the underling subsurface geology of Montrose/Barham Green. The geophysical results revealed that the low yielding aquifer is a shallow, heterogeneous unconfined aquifer with a good yielding potential in low lying areas which have thick overburden deposition of weathered metabasalt. The thickness of the regolith varies between 10 and 100 m. The average overburden layer in the study area is about 23 m which is less than the average thickness of the regolith of Matsheumhlope aquifer as reported by Martinelli and Hubert (1985).

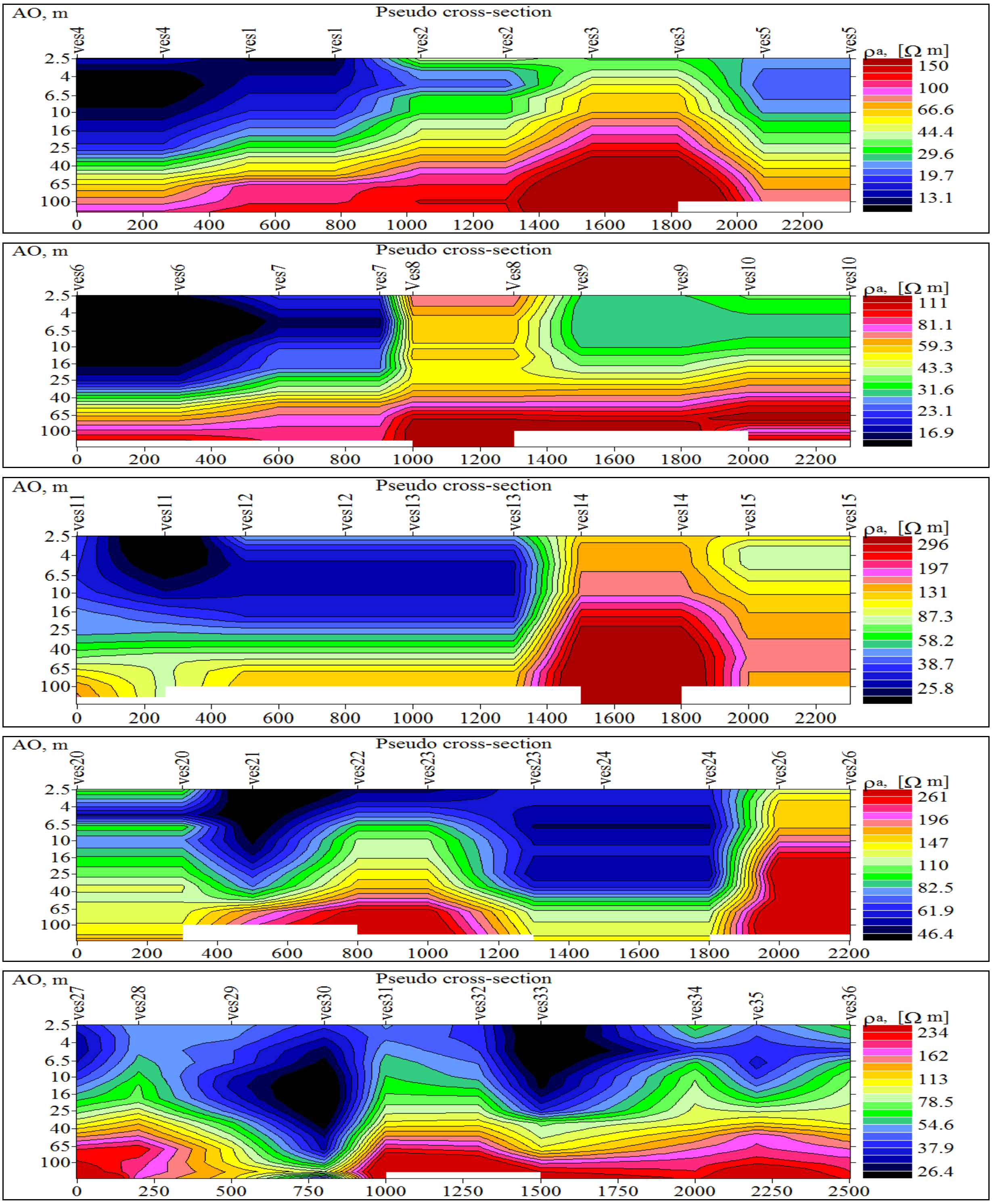

Figure 11. Pseudo sections of all the 36 VES carried out in the study area

Interpolation of the geospatial variation of the depth to the bedrock overlaid on a shaded relief is shown in Figure 12. The results show that the deep weathered rock underlay the central part of the study area. This could be attributed to geological lineaments which are highly populated in the area. The outskirts of the area are underlain by a shallow regolith which can be explained by the volcanic activities occurred (Amm, 1965). A better view of the subsurface was obtained by modelling the apparent resistivity results into a 3D surface map (Figure 13). The abrupt change in depth to the bedrock is an indicator of the degree of weathering that occurred in the study area. Deep weathering occurred in areas around Malindela, Greenhill and Hillcrest which is the same area that have a high density of lineaments. Most of the areas in the highlands (Montrose, Malindela, Hillside and Ilanda) show partial weathering. The auxiliary modelling of spatial variation of the depth to the basement rock in relation to water-potential generated a possible groundwater flow map within the aquifer (Figure 14). Groundwater is likely to move from shallow bedrock to deep bedrock. Areas at high elevations have high chances of losing water quickly, compared to areas that lie in the aquifer basin (Malindela and Hillcrest).

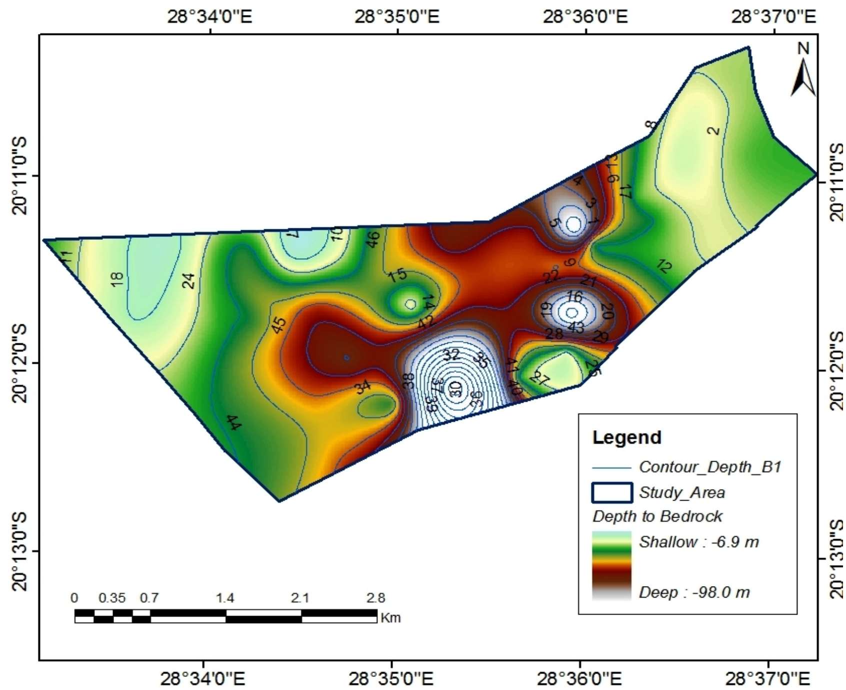

Figure 12. The geospatial variation of the depth of the regolith in the study area

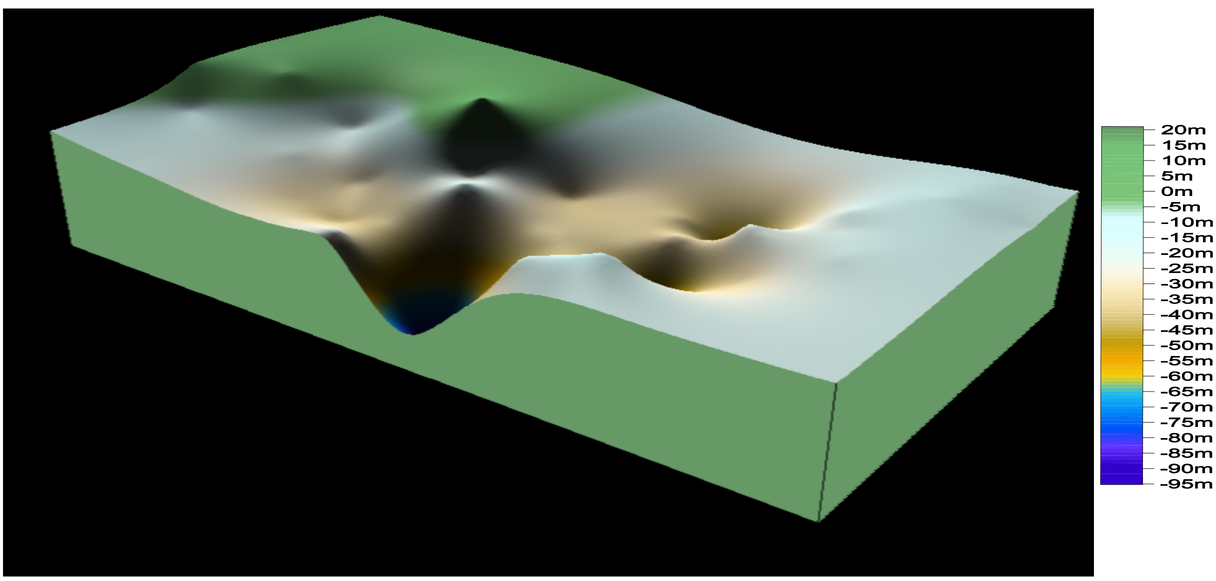

Figure 13. Model of the subsurface, showing depth of weathering in the area

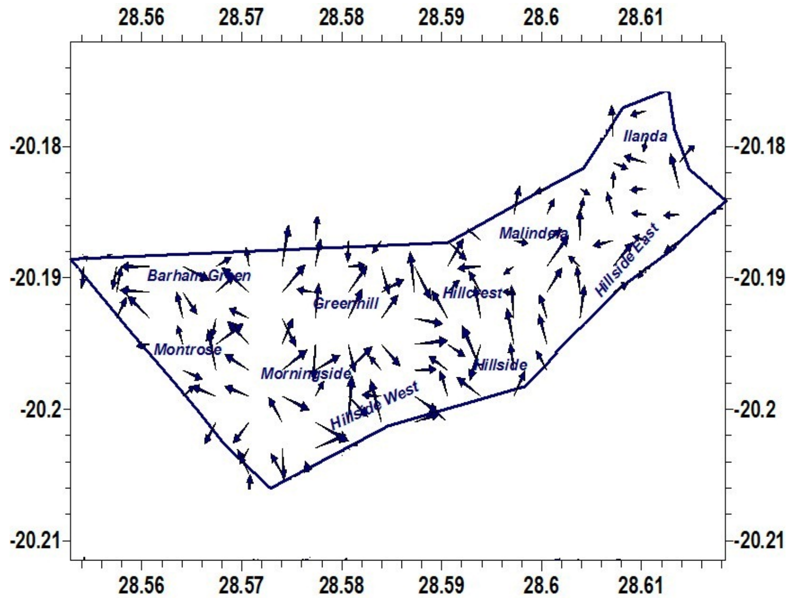

Figure 14. Potential groundwater flow in the low yield aquifer. The magnitude of the arrows shows the probable amount of flow that can be experience at a given area with respect to other areas

The spatial variation of the resistivity of the layers above the basement rock is interpreted by the use of a shade map as in Figure 15. Resistivity of the subsurface is normally used to characterise the aquifer. Very low resistivity is an indicator of immense weathering that has occurred in the area whilst very high resistivity shows less or no fractured rock. The results shows that the resistivities range between 16-600 Ωm. High values were recorded in areas close to Ilanda, Greenhill and Montrose, whereas low resistivities were recorded close to the streams and the central part of the study area. An overview of the variation of the resistivity shows an abrupt change in resistivities over short distances. This could be explicated by the nature of the geological pattern underlay Bulawayo Metropolitan, which is mainly crystalline basement rock in the form of metamorphosed basaltic rock. The columns of the geological sections obtained from borehole logging show a direct relationship with the geoelectrical sections obtained from the interpretation of the VES data.

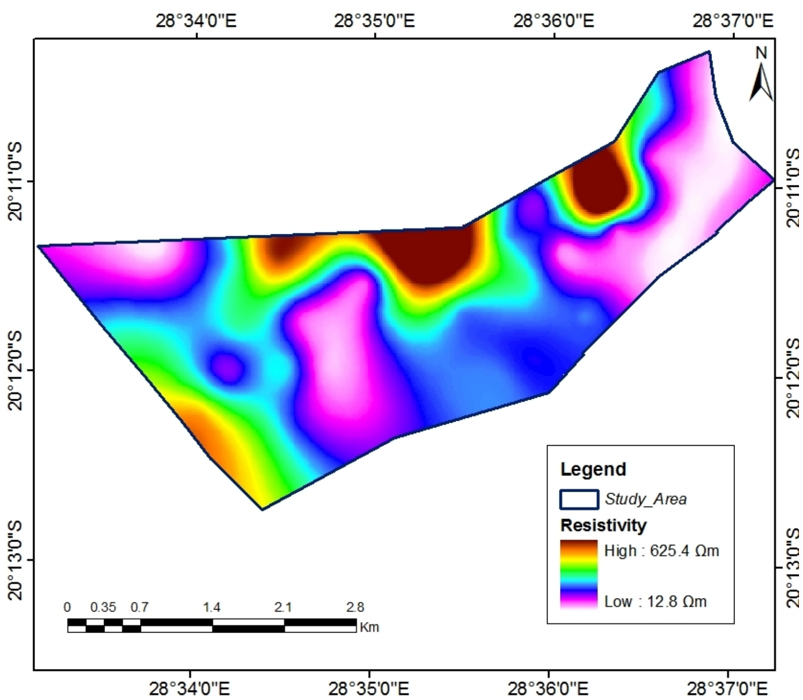

Figure 15. Variation of the resistivity of the subsurface in the area of study

4.4 Occurrence of Groundwater in the Area

The correlation of the resistivities of the geological stratigraphy and the thickness of the overburden sediments produced a model of the potential occurrence of groundwater. These geological characteristics were weighted in equal proportion in the ArcGIS environment to give the groundwater potential of the study area (Figure 16). High yielding areas are found in the central region of the study area whilst the other parts are low yielding. The gradual increase in apparent resistivities with depth of the subsurface resemble the basement aquifer occurrence. These geoelectrical characteristics are associated with volcanic and crystalline hard rocks (metabasaltic) of no primary porosity in the study area. Their aquifer properties depend on secondary fracturing that is either due to release joining or faulting. Long-term weathering and erosion of the joint systems generating subsurface porosity and permeability are undoubtedly the most important mechanisms for the aquifer development in this area. The influence of fracturing on the permeability of crystalline rocks depends very much on their petrography and mineralogy, as well as the type of faulting (Sami et al., 2002; UNEP, 2008). The more quartziferous the rocks the more brittle they are. As a result deep fractures could develop over wide areas. Tension faulting cutting across the aquifer gives higher permeability. The vesicular-amygdaloidal portions of simple and compound metabasalt flow/units, whenever sheet jointed, form the main aquifers in the area. Sometimes, the underlying compact metabasalt in hydraulic connection with these vesicular amygdaloidal portions also acts as a secondary portion of this basement aquifer. Variation in the thickness of the regolith at short distances in the area indicate that the crystalline basement rocks have generally been subjected to multiple tectonic events, under varying stress conditions, which resulted in complex patterns of ductile folding and brittle fracturing in the near-surface regions of the earth’s crust. The inverse modelling shows great possibility of high spatial and temporal variability of groundwater occurrence in the area. Shallow occurrence of the overburden material is likely to result in the low storage capacity of the aquifer.

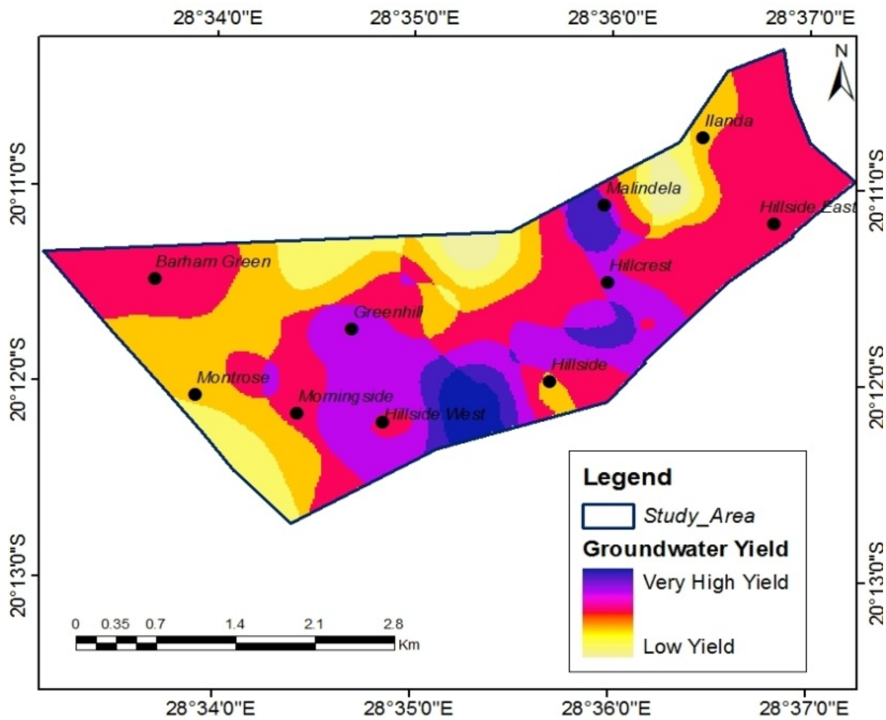

Figure 16. The map showing the potential groundwater yield obtained from the correlation of the resistivity of the geological sections and the depth of the overburden sediments

4.5 Borehole and Well Failure in the Matsheumhlope Aquifer

The geophysical and borehole logging results together with topographic and geomorphological analysis showed the complex occurrence of basement aquifers. They vary largely in groundwater potential over very short distances. Such aquifers have a secondary porosity due to weathering and fracturing which permit limited storage and limited flow of water. It is the weathered and often clayey overburden, known as the regolith, that provides the main groundwater storage and fractures that provide the main conduits for groundwater flow (Lloyd, 1999; Lovell, 2009). In his report, Wright (1992) described aquifers similar to low yielding aquifers as essentially phreatic in character. They however, respond to localized abstraction in a semi-confined fashion, if the rest water level occurs in a low permeability horizon. The results have shown that most of the areas that were considered to be 'flash points' in Mangore (2004) are underlain by shallow and fissure permeable basement rock. This makes them susceptible to borehole failure. For a borehole or well to be sustainable in crystalline basement aquifer it has to be drilled in well interconnected fractures that draw on sufficient water stored in the regolith. In addition the maximum depth of saturated weathering and the permeability of weathering should be reasonable.

In addition to this spatial complexity of the low yielding aquifer, is the temporal uncertainty of rainfall and recharge in Bulawayo. Whenever Zimbabwe receives low rainfall for an extended period (for instance, the 10 years period 1982-92, then 1992-2002, followed by 2002-2012) recharge fails to match natural recession and groundwater levels fall. This natural fall in rainfall normally causes sources to dry up if they were sited hastily or for convenience (say near to homesteads) rather than in optimum groundwater locations. Modelling catchment hydrology showed that low groundwater levels in Zimbabwe in the early 1990s were due to the extended period of low rainfall and were not due to human impact, either through abstraction or land use change (Butterworth et al., 1999). Water points failed, because they were inadequately sited to cope with the natural recession during the dry period. Therefore, employment of hydrogeophysical methods is important in discerning high yielding areas in crystalline basement aquifers since they have the ability to locate the deepest areas for borehole drilling.

5. Conclusion

The study has managed to identify and delineate the nature, extent and spatial distribution of the components of the low yield aquifer in the Matsheumhlope wellfield. This has invariably provided some preliminary data on the groundwater potential of the area that can be used for improvement and development of the water resources of Bulawayo Metropolitan. The correlation of geophysics and borehole logging have discovered the low yielding aquifer as a basement aquifer developed within the weathered and fractured crystalline, greenstone rocks of intrusive and metamorphic. Generally the aquifer has shallow occurrence and fissure permeability of the bedrock aquifer. Thus it has low storage capacity of groundwater. It is more susceptible to borehole failure because of the geomophological occurrence, shallow existence of the permeable bedrock, poor sitting of wells and boreholes, and low groundwater storage capacity. The long dry spells experienced in the region also contributed much to borehole failure. Considering the high demand for groundwater in the city due to erratic water supplies, borehole failure may worsen if proper management policies are not implemented. Therefore, intensive geophysical methods, remote sensing and geological maps should be used in sitting boreholes to identify the weathered, saturated fracture zone and to map its extent and eliminate negative sites that have hard rock at shallow depth.

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