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Integrated Modeling of Water Table Depth Using Controlled-Source Electromagnetic Sounding (ADMT-200S) and SRTM-Derived Terrain Data: A Case Study of Ile-Ife, Southwestern Nigeria

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Abstract: This study investigated the integrated modeling of water table depth in the Ile-Ife region of Southwestern Nigeria, addressing the critical need for precise groundwater mapping in a rapidly urbanizing environment characterized by water scarcity and reliance on costly private boreholes. The research employed a synergistic approach combining Controlled-Source Electromagnetic Sounding (ADMT-200S) for subsurface resistivity, Shuttle Radar Topographic Mission (SRTM) data for terrain analysis, and interpolated borehole records. Methodologies included Ordinary Kriging interpolation of 20 borehole depths to generate a continuous water table surface, followed by GIS-based overlay analysis to integrate ADMT-200S resistivity maps (identifying fracture zones and low-resistivity regions, typically <30 ohm-m, indicative of water presence) with SRTM-derived elevation data. Key findings revealed significant spatial variability in water table depths across the study area. Higher elevations generally corresponded to deeper water tables, as demonstrated by the comparison of modeled depths with SRTM topography. Observed depths ranged from 80m to 100m in high overburden areas, for instance, Ede road (20m overburden, 100m depth) and Olugbodo (15m overburden, 80m depth). The integrated model successfully classified high groundwater potential areas where low resistivity overlapped with shallower interpolated depths. This research provides crucial, localized insights into the complex interplay of surface terrain and subsurface hydrogeology, enhancing the predictive accuracy for borehole siting. The findings underscore the potential for such integrated approaches to inform sustainable land and water management practices in Ile-Ife and similar regions to ensure long-term water security.

Keywords: *Water Table Depth, Groundwater Modeling, Electromagnetic Sounding (ADMT-200S), Geographic Information Systems (GIS), Ile-Ife.*

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I. INTRODUCTION

Groundwater, often concealed beneath the Earth's surface, remains an indispensable resource for sustaining environmental resilience, especially in regions grappling with rising population densities and escalating water demands [1, 2, 3]. Beyond its critical function in securing domestic and agricultural water supply, groundwater plays a pivotal role in construction engineering—where consistent availability helps mitigate project delays due to water scarcity [4, 5]. While climatic variables and human activity undeniably influence groundwater dynamics, the contributions of surface topography and subsurface soil properties are frequently underexplored, despite their profound impact on aquifer distribution and accessibility.

Efficient and precise delineation of groundwater table levels is essential for sustainable resource planning,

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especially in rapidly urbanizing landscapes [6, 7, 8]. In this regard, the city of Ile-Ife, Nigeria, provides a compelling case study. Rapid demographic growth—driven by the expansion of tertiary institutions and commercial development—has spurred a dramatic rise in water demand [9]. Yet, with municipal water infrastructure falling short, residents increasingly rely on self-initiated borehole drilling to meet their water needs [10, 11, 12]. The high cost of drilling underscores the importance of accurate pre-drilling assessments to avoid failed attempts and optimize resource allocation [13]. Moreover, understanding how terrain configuration correlates with groundwater depth is crucial for predicting subsurface conditions at unsampled locations and supporting informed site selection.

Historically, groundwater exploration has relied on a range of traditional geophysical techniques, including electrical resistivity, electromagnetic profiling, seismic refraction, gravity, magnetic, and radiometric surveys [13]. Among these, electromagnetic (EM) and electrical resistivity methods have emerged as preferred tools due to their effectiveness in penetrating diverse geological conditions. Nevertheless, these surface-based techniques often involve labor-intensive deployment, require specialized and delicate equipment, and may offer limited spatial resolution over large areas—especially when used without integration [14, 15]. Similarly, while borehole logs provide accurate point-scale information on aquifer depths, they are localized and lack the spatial coverage needed for regional-scale modeling [14].

Recent advances in remote sensing and Geographic Information Systems (GIS) have opened new pathways for spatial groundwater analysis and terrain modeling [16, 17]. Integrative methods, such as combining electrical resistivity imaging with GIS or using satellite-based DEMs for surface-groundwater interaction studies, have yielded valuable insights [18, 19, 20]. However, these approaches frequently lack direct, real-time subsurface feedback, which is essential for resolving localized aquifer complexities.

This study introduces a novel, integrated approach to modeling groundwater table depth through the synergistic combination of complementary datasets. Central to this approach is the use of controlled-source audio-frequency electromagnetic (AFEM) data, acquired using the ADMT-200S Frequency System, which enables real-time subsurface resistivity mapping. This is further enhanced by electromagnetic profile sounding, derived from the same system but interpreted using a profile-based framework to detect lateral anomalies and fracture zones. These geophysical datasets are integrated with high-resolution topographic information obtained from Shuttle Radar Topographic Mission (SRTM) elevation data, allowing for a comprehensive assessment of the relationship between surface terrain configuration and subsurface water distribution.

Unlike traditional passive electromagnetic methods, the ADMT-200S system operates as an active-source device, transmitting low-frequency signals into the subsurface to measure apparent resistivity [21]. This approach enables rapid, high-resolution mapping of groundwater-bearing layers in real-time during field campaigns. The electromagnetic profile method provides a complementary interpretation strategy, helping to identify lateral variations and refine fracture zone detection [22]. Combined with SRTM-derived elevation models, this integrated methodology allows for the investigation of how terrain features influence groundwater occurrence and depth distribution.

The core innovation of this research lies in the synergistic integration of real-time subsurface resistivity data with high-resolution terrain modeling to produce an accurate, spatially continuous model of groundwater potential in a hydrogeologically complex urban setting. The study not only enhances the predictive accuracy of borehole siting but also contributes a scalable framework applicable to other data-sparse regions with similar hydrogeological challenges.

II. MATERIALS AND METHODS

To achieve the stated objectives of integrated water table depth modeling, a rigorous and multi-pronged methodological approach was adopted, leveraging diverse geospatial and geophysical datasets. This section delineates the study area, data acquisition protocols, subsequent processing techniques, the analytical framework employed for water table level modeling, and the procedures for model validation. The overall water level mapping procedure is conceptually illustrated in Figure 1.

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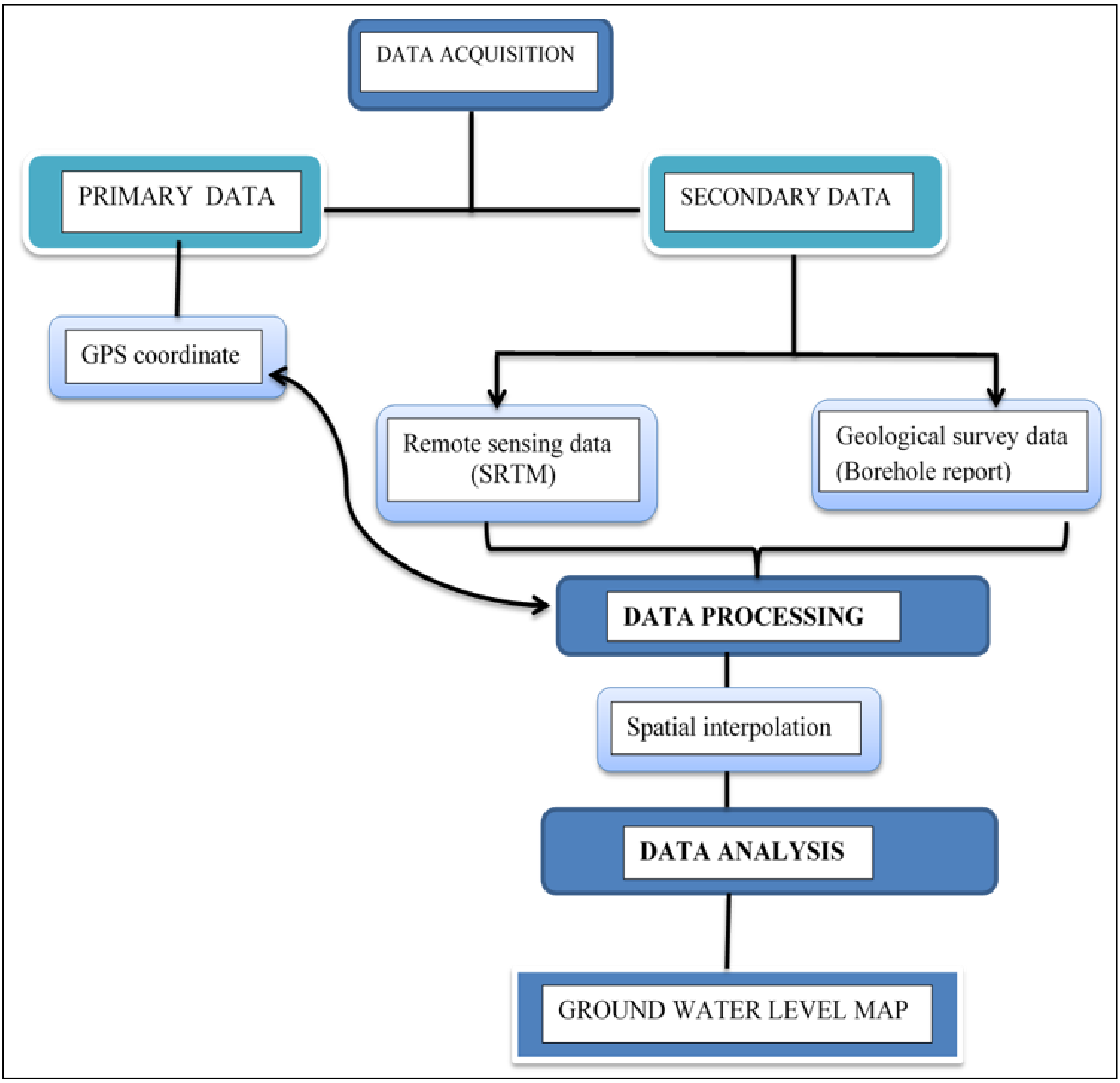

Fig 1 Showing Water Level Mapping Procedure

A. Study Area

The geographical scope of this investigation encompasses Ile-Ife and its immediate environs, specifically comprising the Ife Central and Ife East Local Government Areas, situated in Southwestern Nigeria. The historic Yoruba city of Ile-Ife is geographically located around 7.4905° N latitude and 4.5521° E longitude. This region is characterized by rapid urbanization, driven by the presence of tertiary educational institutions and burgeoning commercial activities, leading to increased water demand [9]. Consequently, residents largely rely on expensive, privately-sunk boreholes for their domestic and agricultural water needs, due to insufficient municipal supply. This pressing societal challenge in a complex hydrogeological setting underscores the imperative for advanced integrated modeling efforts to accurately map groundwater resources [23]. The locations of Ife Central and Ife East Local Government Areas used in this study are shown in Figure 2.

The underlying geology of the Ile-Ife area is predominantly composed of metamorphic rocks, quartzites, and granite gneiss, characteristic of the Precambrian Basement Complex, part of the Yoruba Hills. These lithologies exhibit varying degrees of weathering and fracturing, which fundamentally control groundwater occurrence and movement within the aquifer systems. Surface topography within the study area presents a variable elevation profile, with the highest point, Oke-Atapa Hill, reaching 351 meters above sea level. The area is drained by numerous rivers and streams, such as the Opa River and the

Ogun River, exhibiting meandering patterns due to the hilly terrain, and it also features numerous springs that serve as important water sources. This intricate interplay of geological features and surface topography creates a heterogeneous environment, making it an ideal case study for applying and testing the predictive capabilities of an integrated modeling approach that combines diverse geospatial and geophysical datasets to resolve complex groundwater dynamics.

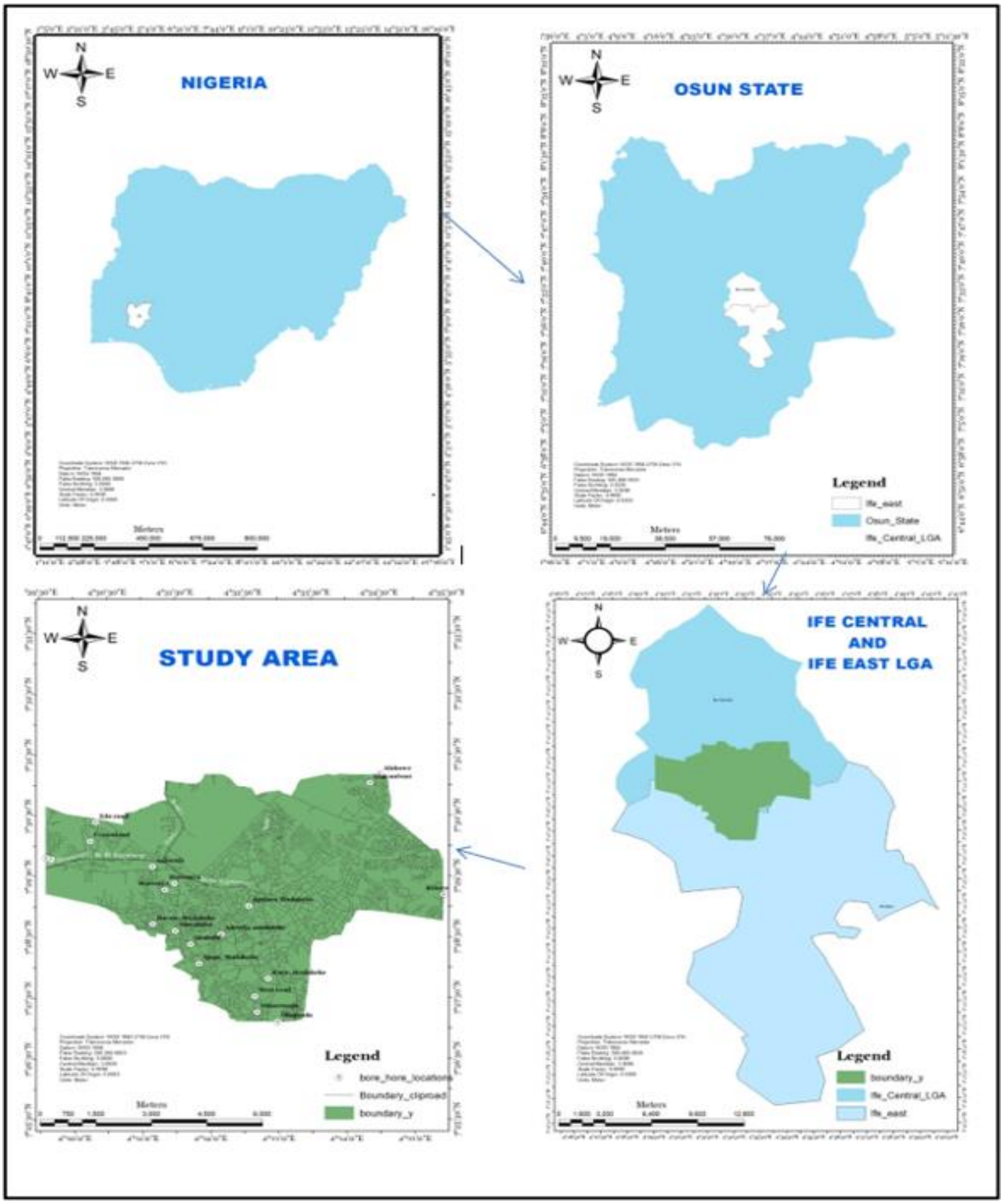

Fig 2 Study Area Maps of Ife Central and Ife East Local Government Areas

B. Data Acquisition

Both primary and secondary data were meticulously acquired to support the groundwater potential mapping process. This comprehensive data collection strategy is summarized in Table 1, providing details on data types, sources, reference systems, and acquisition years.

Table 1 Description of Datasets, their Sources, and Purpose

Type of Data	**Data Source**	**Reference System / Datum**	**Purpose**	**Year**
GPS Coordinates	Hand-held GPS & DGPS with CORS (Osogbo)	UTM WGS 84	To determine spatial (X, Y) and elevation (Z) positions	2024
DEM (SRTM)	USGS Earth Explorer	UTM WGS 84	Surface elevation and terrain analysis	2024
Borehole Geological Data	Skashtec Integrated Ltd., Al-AQQ Hydrological Services	—	Groundwater depth and aquifer structure	2020–2024
Shapefile (Boundary Layer)	Grid_3 site / Google Earth digitization	UTM WGS 84	Define spatial extent of the study area	2024

➢ *Borehole Data and Georeferencing*

Primary geographic coordinates for selected borehole locations within the study area were acquired using both Hand-held Global Positioning System (GPS) units and a Differential GPS (DGPS) system. The DGPS was precisely connected to a Continuously Operating Reference Station (CORS) situated in Osogbo, ensuring high precision (WGS 84 UTM system) for ground control points and accurate spatial data acquisition. Borehole geological data, providing critical empirical information on the observed depth to the water table from the earth surface, were obtained from prior geophysical survey reports, notably compiled by Skashtec Integrated Ltd. and Al-AQQ Hydrological Services. These reports, covering the period from 2020 to 2023, offered essential measurements of groundwater depth and preliminary insights into aquifer structures. A total of 20 borehole points was extracted and utilized for water level mapping and subsequent comparative analyses. The Easting and Northing, depth and overburden data of the bore hole of the selected locations in Ile Ife and its environment is depicted in table 2.

Table 2 Showing Easting and Northing, Depth and Overburden Data of the Bore Hole of the Selected Locations in Ile Ife and its Environment

S/N	**Location**	**Easting**	**Northing**	**Height**	**Overburden**
1	Olugbodo	671033	824006	-80	-15
2	Asherifa	667651	828690	-80	-15
3	Modomo 1(complex)	664923	828923	-80	-15
4	Modomo 2(coach)	664781	828962	-90	-10
5	Kosere	675531	827858	-75	-8
6	Ede road	666119	830035	-100	-20
7	Crownland	665971	829467	-80	-15
8	Alakowe	673792	831489	-90	-10
9	Adelola, modakeke	669516.992	826653.281	-45	-15
10	Ajape, modakeke	668906.565	825764.644	-55	-15
11	Apalara modakeke	670250.343	827508.41	-80	-15
12	Olorunfemi	673525.812	831242.801	-55	-15
13	Barale, modakeke	667660.901	826953.77	-60	-20
14	Oke otubu	668267.401	826745.121	-55	-15
15	Olanrewaju	670472.97	824289.582	-95	-10
16	Gbalefef	668680.651	826343.401	-40	-15
17	Moremi 1	667992.203	827998.591	-70	-20
18	Moremi 2	668244.782	828188.661	-60	-20
19	Toro road	670418.383	824765.872	-40	-15
20	Iraye, Modakeke	670777.502	825303.481	-40	-15

➢ *Controlled-Source Electromagnetic Sounding (ADMT-200S) Data Collection*

For direct subsurface water detection, a primary geophysical investigation was conducted using the ADMT-200S Frequency System. Although referred to by the manufacturer as the Automatic Depth Measurement Technique (ADMT), the system operates based on a controlled-source audio-frequency electromagnetic (AFEM) method. This portable geophysical exploration instrument functions by transmitting low-frequency electromagnetic (EM) waves (typically within the 1 Hz to 1 kHz range) into the subsurface and analyzing the resulting resistivity variations to delineate groundwater-bearing formations. Water-bearing zones, due to their inherently higher electrical conductivity, manifest as distinct lower resistivity signatures, which the ADMT-200S is designed to accurately detect. It is

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crucial to emphasize that, contrary to some general terminology or earlier interpretations, this system does not employ a passive electromagnetic source akin to traditional magnetotelluric (MT) or audio-magnetotelluric (AMT) methods; it is fundamentally a controlled-source technique, enabling direct control over the transmitted signal.

In this investigation, a wireless magnetic base sensor was employed, selected based on prevailing site conditions. Measurements were systematically acquired along linear traverses using 1-meter intervals, with resistivity data collected at each midpoint. The ADMT-200S offers a non-invasive, rapid, and highly mobile alternative to traditional resistivity methods, facilitating real-time mapping of aquifers, fracture zones, and other groundwater-bearing structures. Data collected on-site were immediately processed to generate preliminary 2D and 3D subsurface resistivity maps using the AIDU-APP software, which were subsequently analyzed and interpreted to delineate subsurface conditions and identify optimal locations for borehole drilling. The profile curve and structural map from an ADMT survey is illustrated in Figure 3.

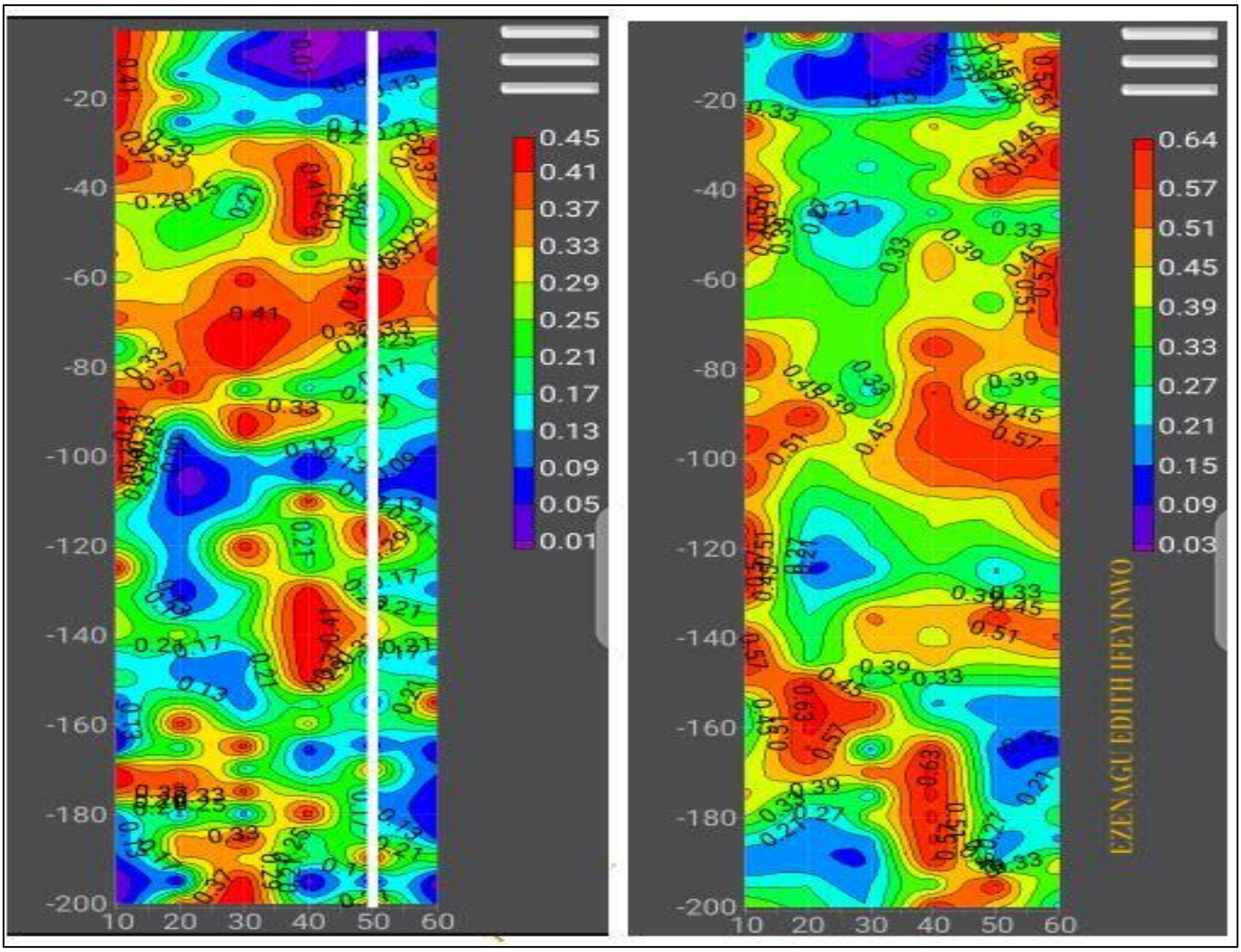

Fig 3 Showing Profile Curve of a Particular Geological Survey of Ezenagu Edith Ifeyinwo Residence Phase 5 Olugbodo, Ondo Road, Ile- Ife.

➢ *Shuttle Radar Topographic Mission (SRTM) Data Acquisition*

Secondary remote sensing data, specifically Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs) from the Shuttle Radar Topographic Mission (SRTM), were acquired from the USGS Earth Explorer platform. These datasets served as a critical input for comprehensive surface terrain analysis. The SRTM data utilized maintained a UTM WGS 84 reference system, consistent with the acquired ground coordinates, to facilitate seamless integration and comparison of surface configuration. The SRTM DEMs were instrumental in providing a comprehensive understanding of the topographic variations across the study area, which are hypothesized to influence groundwater depth.

C. Data Processing and Analysis

The heterogeneous datasets acquired from the Controlled-Source Electromagnetic Sounding (ADMT-200S), borehole geological reports, and SRTM satellite imagery underwent rigorous processing and analysis to facilitate the integrated modeling of water table depth.

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➢ *Controlled-Source Electromagnetic Sounding (ADMT-200S) Data Processing and Interpretation*

Data acquired using the ADMT-200S Frequency System were subjected to a multi-stage processing and interpretation workflow. On-site, the collected resistivity data were immediately processed using the AIDU-APP software to generate preliminary 2D and 3D subsurface resistivity maps. These initial visualizations aided in the real-time identification of potential water-bearing zones and suitable borehole drilling points. The geophysical survey profile curve is shown in Figure 4.

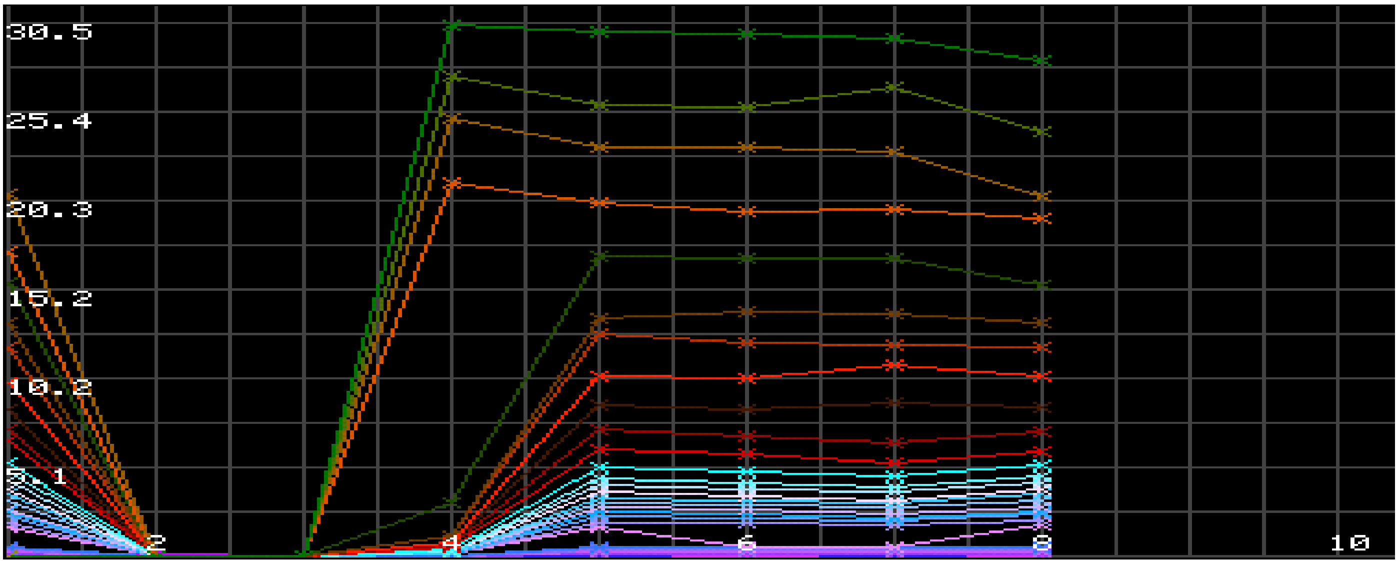

Fig 4 Showing Profile Curve of the Particular Geophysical.

For a more comprehensive and quantitative interpretation, the frequency data were then analyzed through a three-stage approach:

- Profile Curve Analysis: This initial stage involved visualizing the apparent resistivity variations along the acquired linear traverses. The generated profile curves illustrate the field records and computed resistivity values along the traverse for various frequency selections. These were instrumental in detecting lateral variations in subsurface properties.
- Structural Mapping: Subsequent to profile analysis, structural maps were generated. These maps provide a spatial representation of the subsurface, highlighting zones of contrasting resistivity that correspond to different geological formations or fluid content. The generated maps from AIDU-APP software were analyzed to identify suitable borehole drilling points. The plotted structural map is provided in Figure 5.

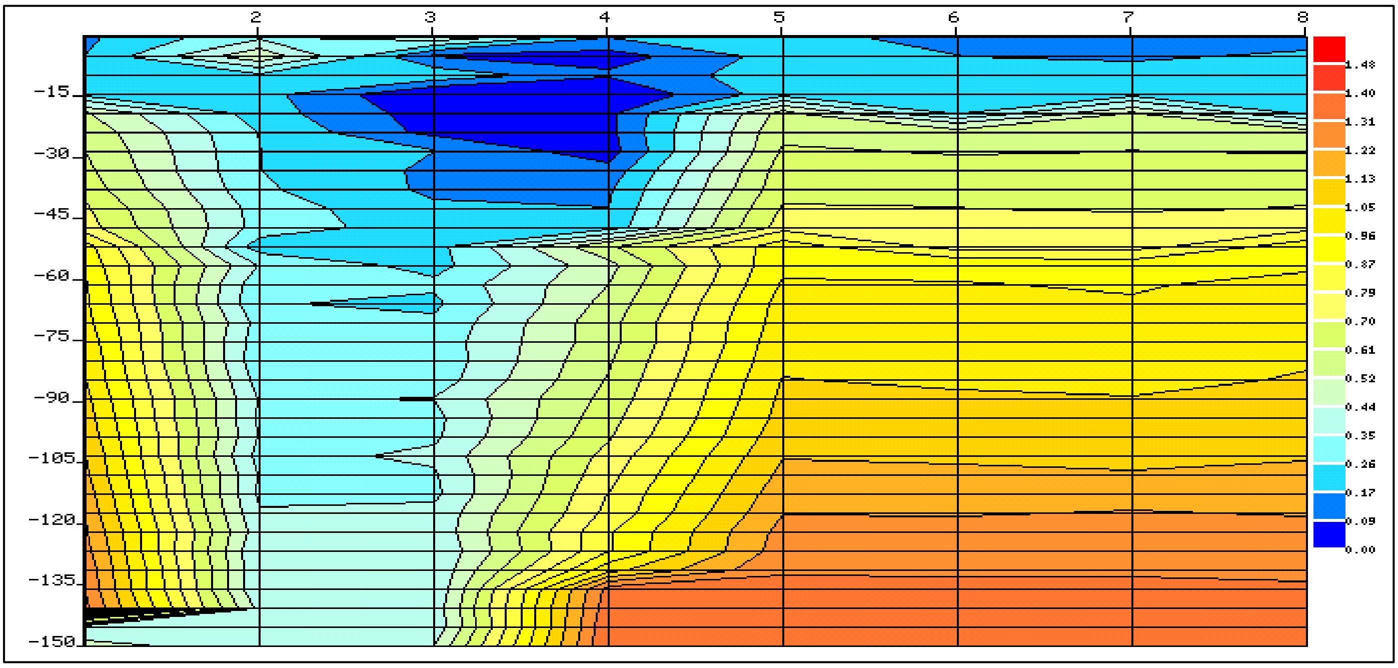

Fig 5 Showing Plotted Structural Map of the Study Area

- *Computer-Based Inversion:*

For final quantitative interpretation and the derivation of geo-electric layers, the profile curves and structural map frequency data were input into specialized inversion software, namely EMIGMA and Earth Imager. This advanced processing step allowed for the creation of geoelectric models, revealing the true resistivity distribution with depth and delineating subsurface stratigraphy. Sounding results typically revealed a system of four to five geo-electric layers for the probed locations.

Through this rigorous interpretation, the study identified that while topsoil and overburden exhibited variable saturation (e.g., overburden saturated from 15m), the deeply seated fractured zones were interpreted as potential confined aquifers.

These fracture zones, characterized by moderate to fairly moderate groundwater content, were deemed the most suitable targets for increasing borehole yield. The process also aimed to determine the pattern of subsurface geological features in relation to frequency values with depth, identify bedrock discontinuities and mineralized veining, and observe voids and solution features in soil/rock, providing professional guidance for engineering construction and water prospecting.

➢ *SRTM Data Processing and Terrain Analysis*

The downloaded SRTM data, comprising Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs), served as the foundation for surface terrain analysis. The area of interest was precisely clipped from the larger SRTM dataset using clipping tools within ArcGIS 10.x. The observed ground coordinates from the DGPS survey were utilized in conjunction with the SRTM data to accurately define the boundary of the study area, which was subsequently digitized using Google Earth and managed as a shapefile.

The SRTM-derived DEM served as the foundation for characterizing surface configuration and its potential influence on water table depth. Specifically, the DEM was used to generate various topographic attributes relevant to hydrological processes, such as slope and aspect maps, which provide insights into surface runoff and potential groundwater recharge zones. The surface elevation data derived from SRTM were prepared for comparison with the modeled groundwater levels to investigate the relationship between terrain and water table depth. The Digital Elevation Model of the surface terrain is shown in Figure 6.

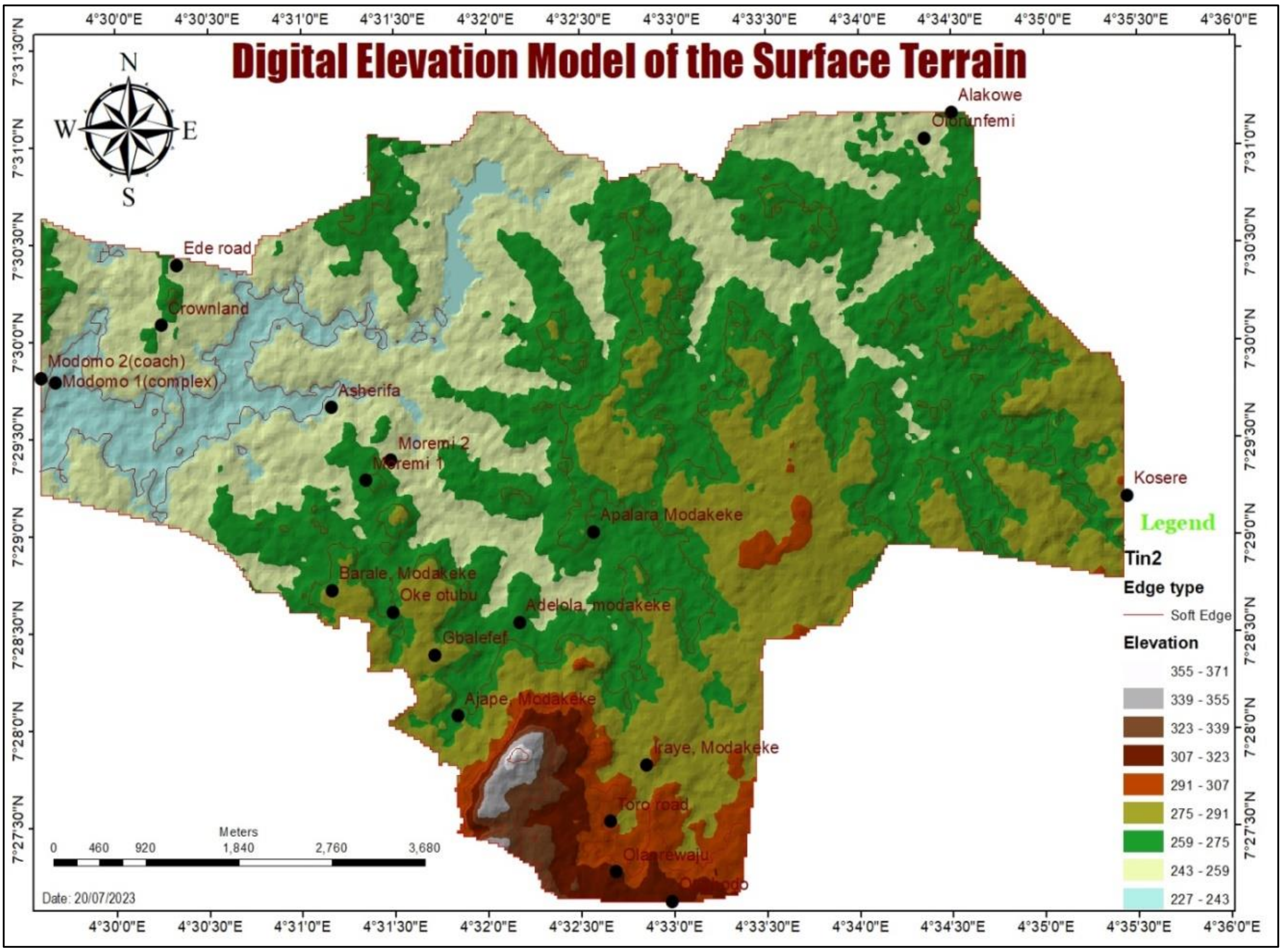

Fig 6 Showing Digital Elevation Model of Surface Terrain or Surface Configuration

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➢ *Spatial Interpolation of Water Table Levels*

To generate a continuous spatial model of water table depth across the study area from the discrete borehole and geophysical data points, Kriging interpolation was performed. This geostatistical method, implemented using the 3D Analyst tools in ArcGIS 10.8.2, was chosen for its ability to provide optimal, unbiased estimates of spatial variables while accounting for spatial autocorrelation. The borehole depths acquired at each location served as the primary input for the Kriging algorithm, allowing for the classification and visualization of water table depths (i.e., how deep and close water can be found from the subsurface) across the entire study area. Ordinary Kriging was specifically employed, with variograms and covariance functions prepared to estimate statistical dependence values.

Furthermore, for comparative analysis of surface and subsurface configurations, Digital Elevation Models (DEMs) were generated from two distinct sources: one derived from the processed SRTM satellite data, and another from the Kriging-interpolated borehole XYZ data. These raster layers were subsequently converted to Triangulated Irregular Network (TIN) surfaces, allowing for enhanced 3D visualization and comparison of height differences within ArcScene. Additional comparative analyses were conducted using Microsoft Excel 2016 for height plotting and interactive profile curves within ArcGIS, enabling a detailed examination of areas with varying elevations from SRTM data and ground coordinate data. This comprehensive comparative analysis aimed to ascertain the influence of surface configuration on the detection of subsurface water, while also acknowledging the interplay of other factors such as overburden soil type and the borehole depth acquisition method. The water level map deduced from borehole depth is presented in Figure 7, TIN derived from bore-hole depth is depicted in Figure 8, interactive profile curve in Figure 9 and Figure 10 showing the interactive elevation profile for surface and underground depth.

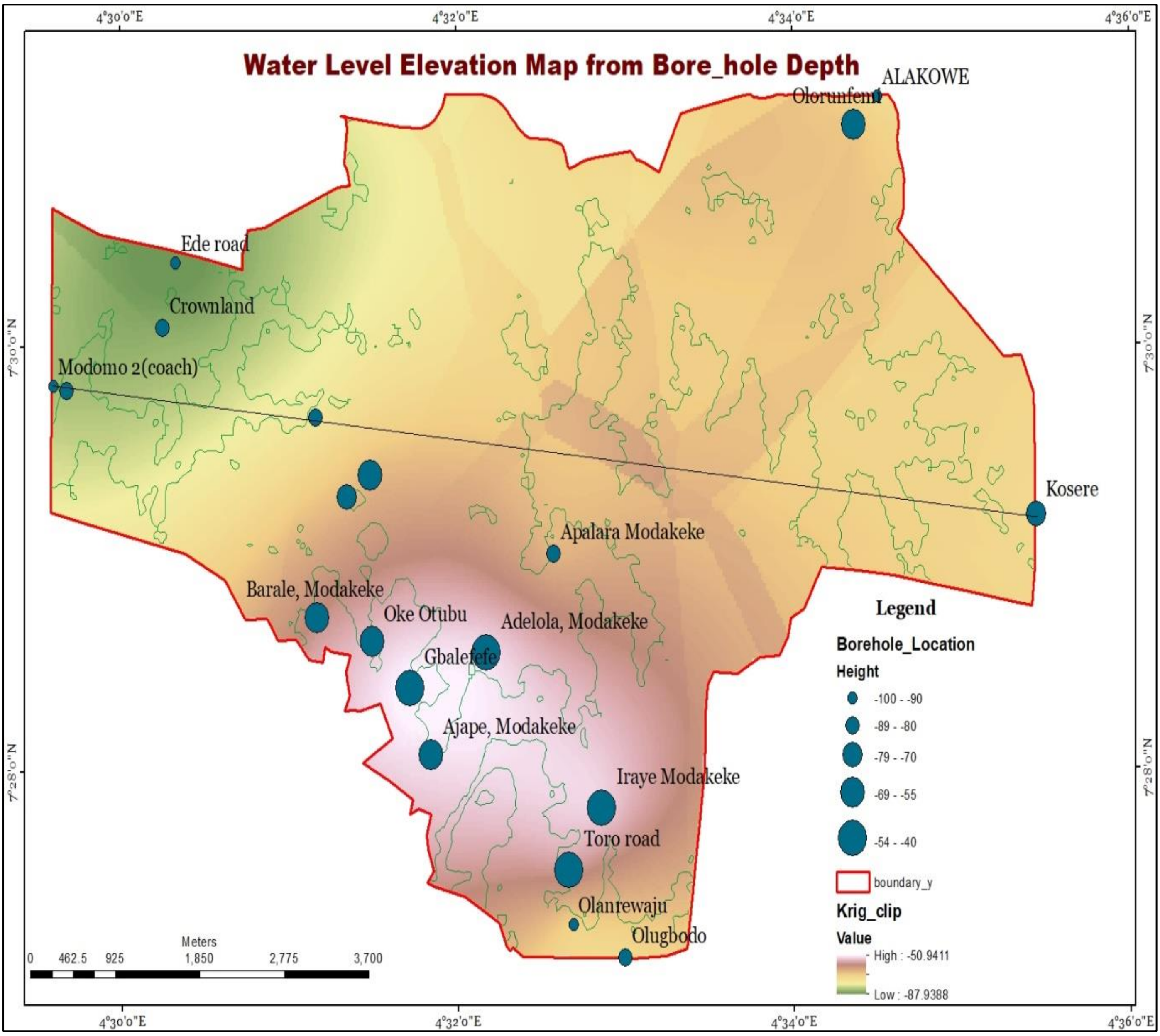

Fig 7 Water Level Map Deduced from Bore Hole Depth

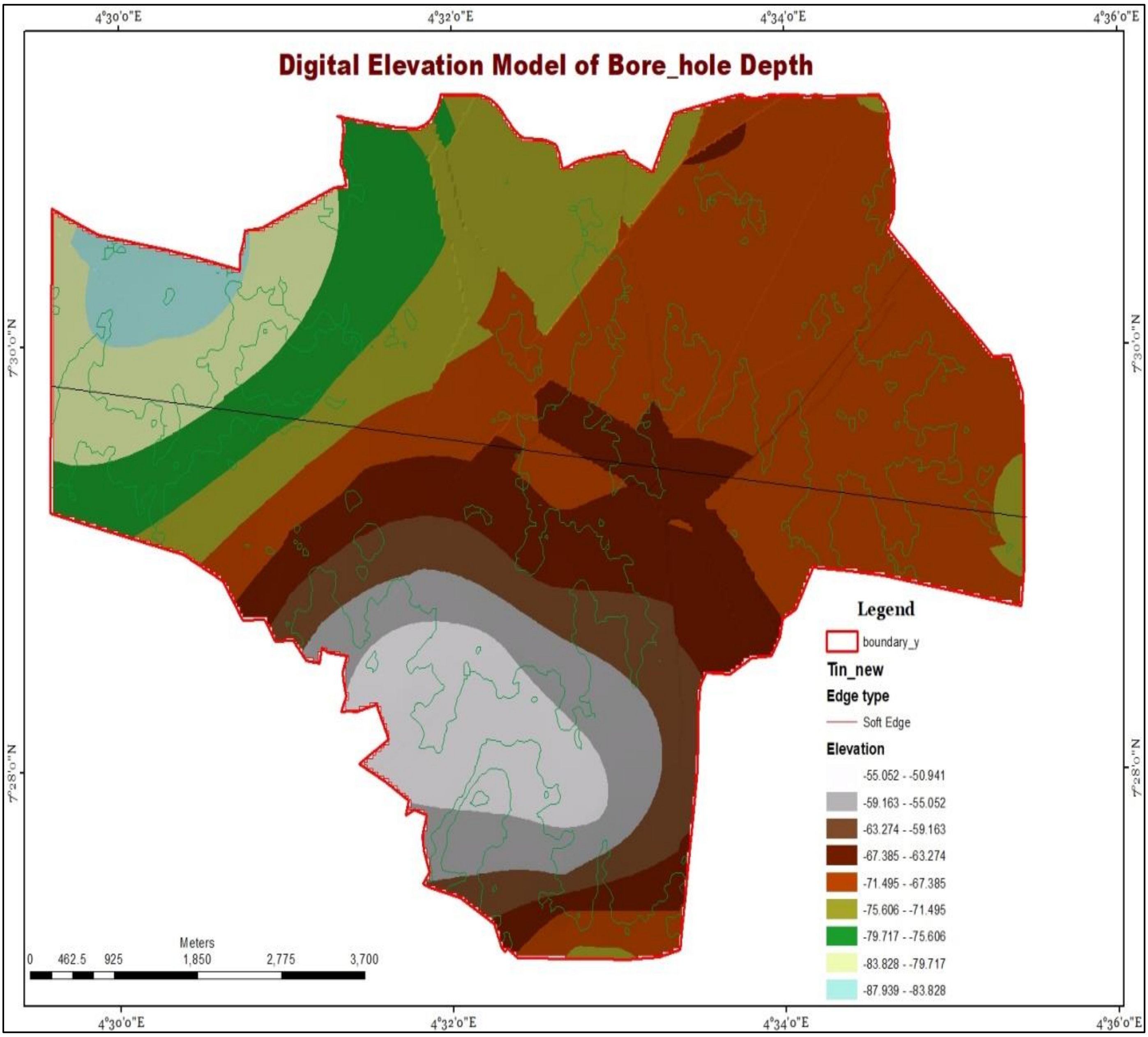

Fig 8 TIN Derived from Bore-Hole Depth

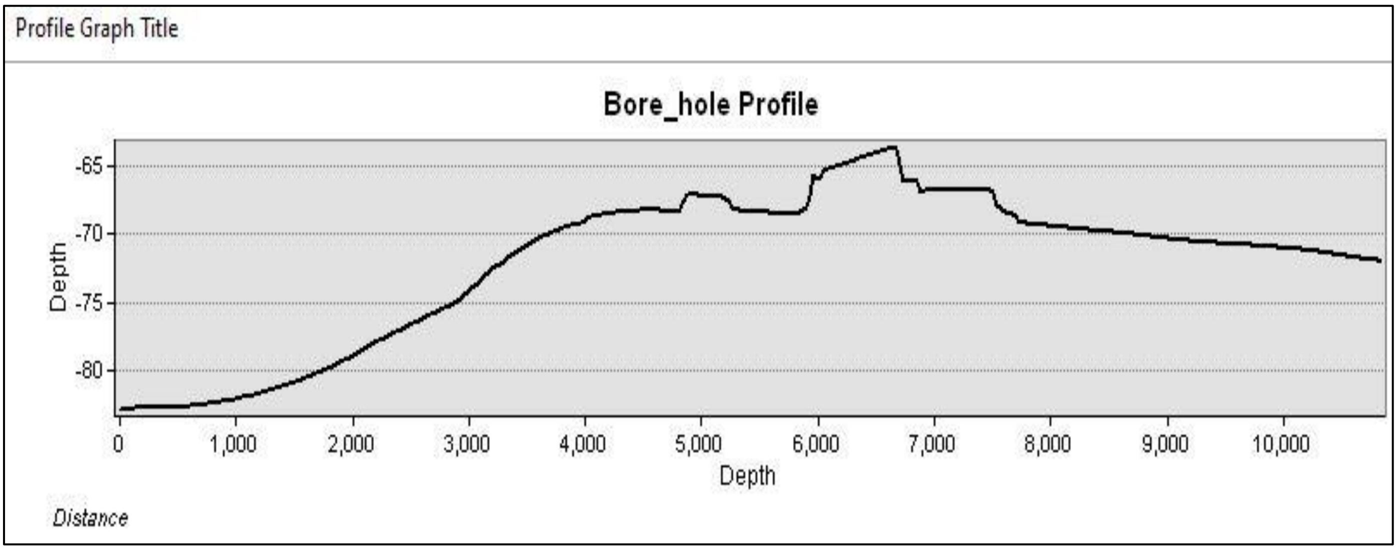

Fig 9 Interactive Profile Curve Deduced from Bore Hole Depth

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Profile curve plotted from 3D analysist on ARC GIS interface, two point is interpolated from bore hole height data on interface, this point was interpolated from west to east, it shows the frequency range of height difference which correspond with the kriging above in range

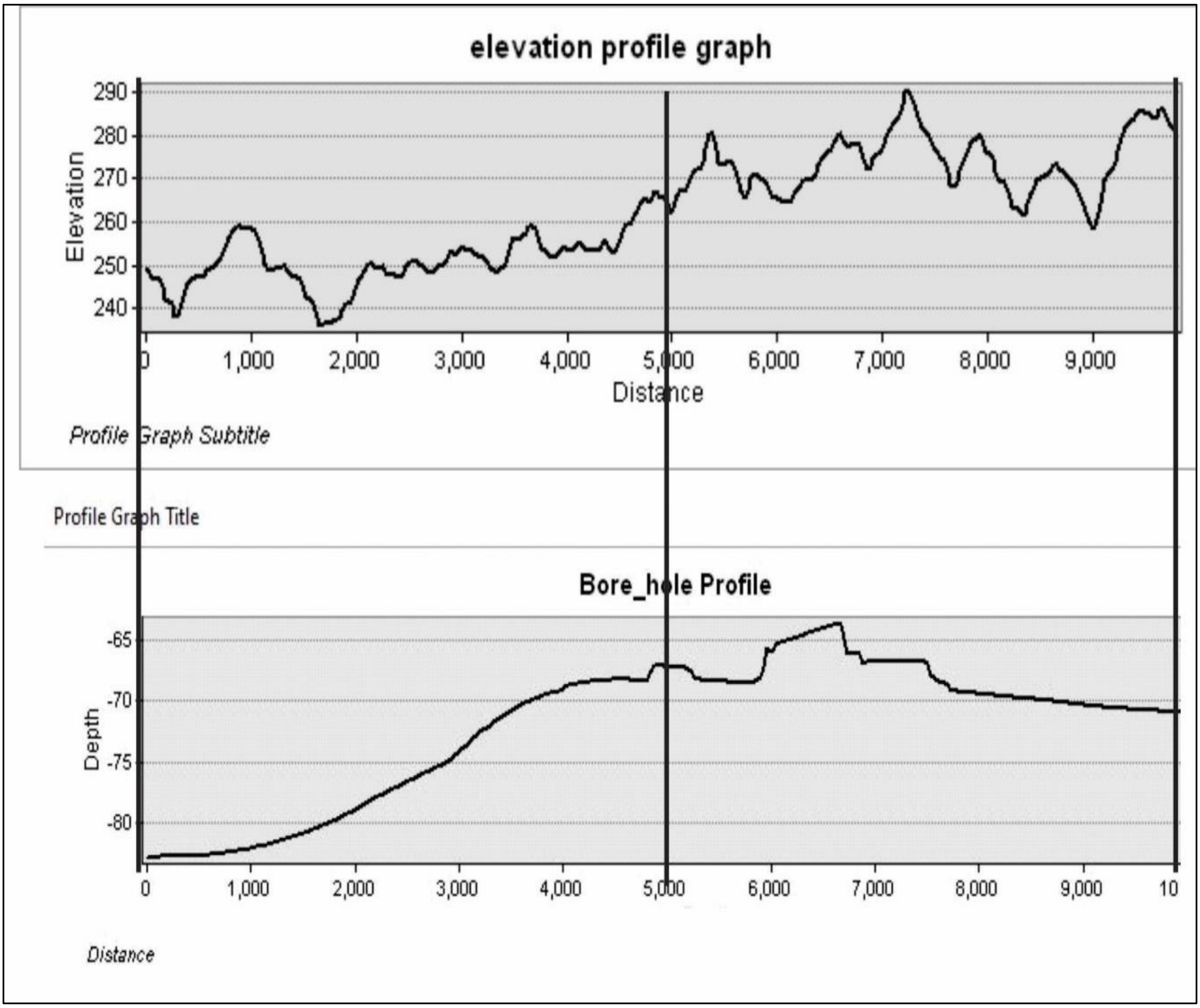

Fig 10 Showing Interactive Elevation Profile for Surface and Underground Depth

D. Overburden

It is the thickness of soil from top to the basement rock, Overburden is the collective term for all the materials (soil, sediments, rocks) that lie above the zone of interest in the borehole. These materials might include loose soil, gravel, sand, clay, and various types of rock formations. The borehole overburden from selected bore-hole locations as soil test for the area was represented in figure 11.

Overburden can be examined from geophysical investigation of soil samples which can be characterized with poor graded soil with high Clay content, its referred as immediate soil to encounter before drilling which have the capacity of carrying loads for engineering construction or infrastructure development, it combined application of geophysical and geotechnical method in evaluating the soil stability, overburden in construction foundation case must be found competent underlying bedrock, which can be close to the surface in the area since the near surface lithology can reveal the occurrence of high plastic classic and clayey materials.(Festus Olusola Eebo *et al.* 2022)

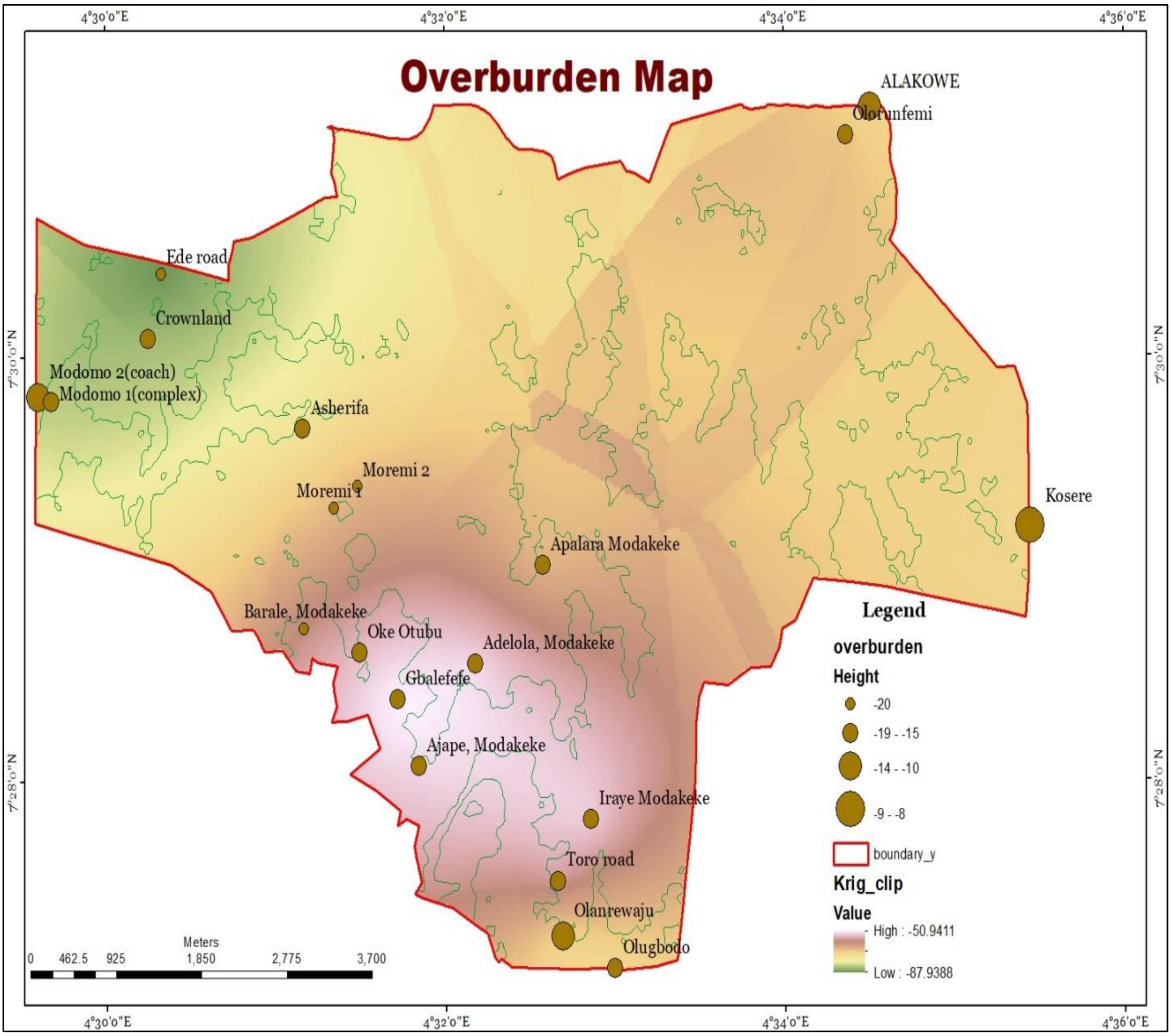

Fig 11 Showing Borehole Overburden from Selected Bore-Hole Locations as Soil Test for the Area

E. Integrated Water Table Level Modeling

The final integrated water table level model for the Ile-Ife study area was developed by synergistically combining three independent yet complementary datasets: (i) resistivity-derived subsurface interpretations from the ADMT-200S Frequency System, (ii) digital elevation data derived from Shuttle Radar Topographic Mission (SRTM), and (iii) interpolated water table depths based on borehole records.

The integration followed a GIS-based overlay analysis framework within the ArcGIS 10.x environment. First, spatial interpolation of borehole water depths was performed using ordinary Kriging, resulting in a continuous raster surface representing estimated groundwater table depths across the study area. Simultaneously, 2D and 3D subsurface resistivity maps generated from the ADMT-200S were georeferenced and overlaid to highlight fracture zones and low-resistivity regions, which are indicative of saturated or water-bearing layers.

To capture the influence of topography on subsurface hydrology, SRTM-derived elevation maps were used to delineate surface drainage patterns, slope gradients, and potential recharge zones. Areas with moderate elevation and gentle slopes were hypothesized as favorable for recharge and groundwater accumulation. The DEM was compared directly with the interpolated water table model to analyze elevation–depth relationships and identify topographically controlled aquifer zones.

The resistivity anomaly maps from ADMT-200S were then spatially correlated with the interpolated water table surfaces. Zones where low resistivity (typically <30 ohm-m) overlapped with shallower interpolated depths were classified as high groundwater potential areas. Conversely, zones with high resistivity and deeper water levels were designated as low groundwater potential zones. This classification was implemented through weighted map overlay using a binary

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decision logic: areas were flagged as high potential only when both low resistivity and favorable depth conditions were met.

The final output is an integrated groundwater potential map and water table depth surface, combining electrical, geological, and topographic evidence. This integrated model not only improved the prediction of suitable drilling zones but also enhanced understanding of how terrain and subsurface resistivity jointly influence groundwater availability. The model provided a scientifically robust basis for borehole siting and can be adapted for similar geologic settings in Southwestern Nigeria and beyond.

F. Model Validation

To ensure the robustness and reliability of the developed water table level model, a rigorous validation process was undertaken. While a dedicated independent validation dataset was not explicitly reserved for quantitative statistical evaluation, the model's accuracy was assessed through extensive comparative analyses as described in the results and discussion.

Specifically, the interpolated water table depth map (derived from borehole data via Kriging) was visually and spatially compared with the SRTM-derived Digital Elevation Model. This comparison involved overlaying the two DEMs in ArcGIS ArcScene to observe their spatial alignment and identify areas of congruence or divergence. Further qualitative validation was conducted through graphical comparisons using Microsoft Excel 2016, plotting ground height (from DGPS and SRTM) against borehole depths to visually inspect correlations and trends across various locations. An example of this correlation analysis is shown in Figure 12. These comparative analyses provided insights into how surface elevation correlates with observed and modeled water table depths, thereby qualitatively supporting the model's accuracy and its ability to reflect the influence of terrain on groundwater occurrence. The analysis of specific locations and their corresponding depths and overburden also served as a form of localized verification of the model's predictions.

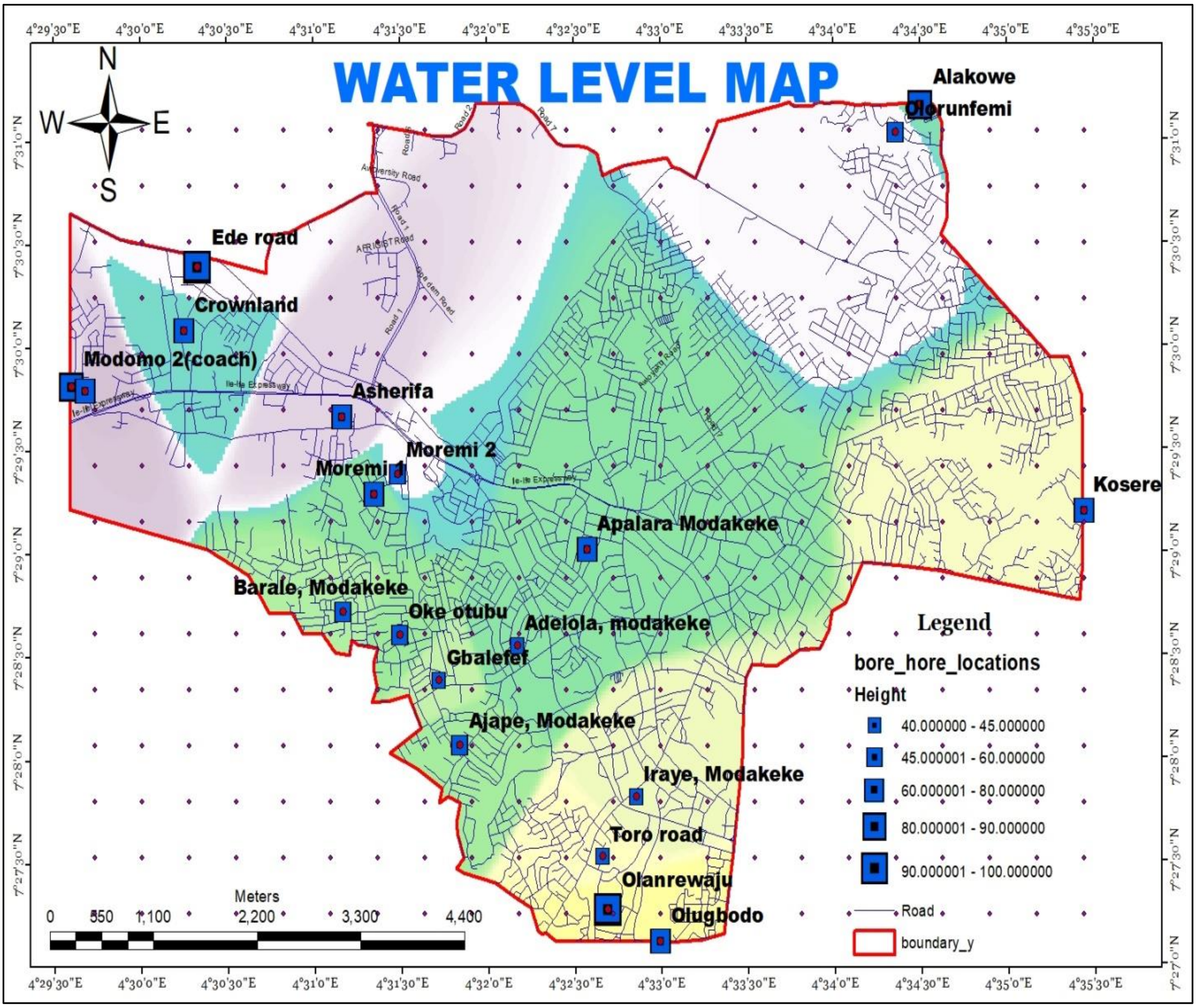

Fig 12 Showing Water Level Map

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G. Software and Hardware

The computational aspects of this study were facilitated by a personal computer operating relevant software. Geographic Information System (GIS) operations, including spatial analysis, interpolation, 3D terrain modeling, clipping, and geocoding, were primarily performed using ArcGIS 10.x. Base map digitization and shapefile creation were also conducted utilizing Google Earth Pro. Statistical analyses and charting for comparative evaluations were carried out using Microsoft Excel 2016. For the processing of resistivity data and geoelectric layer modeling from the ADMT-200S, specialized software packages including EMIGMA and Earth Imager were employed. Additionally, the AIDU-APP software was used for in-field visualization and mapping of 2D/3D resistivity sections, allowing for immediate data assessment. The primary geophysical instrument utilized was the ADMT-200S Frequency System (Hunan Puqi Geoelectric Technology). GPS coordinates were acquired using both Hand-held GPS units and a DGPS connected to the Osogbo CORS station.

III. DISCUSSION

The integrated modeling approach, combining Controlled-Source Electromagnetic Sounding (ADMT-200S) data, SRTM-derived terrain information, and borehole records, provides valuable insights into the complex hydrogeological dynamics of Ile-Ife, a rapidly urbanizing environment facing significant water resource challenges. This approach addresses the limitations of relying solely on traditional geophysical methods or remote sensing data, as highlighted in the introduction.

The application of the ADMT-200S system proved effective in delineating subsurface resistivity variations. The three-stage interpretation process, encompassing profile curve analysis, structural mapping (as indicated in Figure 5), and computer-based inversion, allowed for the identification of geo-electric layers and fracture zones that are critical for groundwater occurrence. Observations from the geophysical surveys, such as those shown in Figure 4., consistently revealed systems of four to five geo-electric layers. Critically, the deep-seated fractured zones were identified as the most promising targets for high-yield boreholes, even where overburden saturation might be moderate. This aligns with hydrogeological principles in basement complex terrains, where groundwater accumulation often depends on secondary porosity created by weathering and fracturing, as discussed in the introduction. For instance, a traverse point 4 exhibited an overburden of 8-10 meters and was drilled to 90 meters, suggesting the need for deep penetration into fractured zones for optimal yield. The ADMT's ability to provide 2D and 3D subsurface maps in real-time, as seen in Figure 4, directly supports efficient drilling operations by guiding the identification of suitable drilling points, a capability not readily available with traditional methods.

The spatial interpolation of borehole data using Kriging provided a continuous water table depth map, enhancing the regional understanding beyond discrete measurement points. This approach, as noted in the introduction, addresses the limitation of mapping unobserved quantities in groundwater resources. The resultant water level map Figure 7 visually demonstrated significant spatial variability in water table depths.

A key aspect of this study involved comparing the modeled water table depths with the SRTM-derived surface terrain configuration. As illustrated in Figure 7 for surface terrain and Figure 8 (labelled as TIN derived from borehole depth) for modeled subsurface, there is a discernible relationship where areas with higher surface elevations tend to correspond to deeper water tables, and conversely, low-lying regions exhibit shallower water tables. This relationship is further supported by the correlation analysis presented in Figure 10, which graphically plots ground height against water depth. For example, locations like Kosere, Toro, and Olugbodo, despite having relatively high ground heights (e.g., 290.13m, 295.64m, 311m), correlated with borehole depths of 75m, 40m, and 80m respectively , indicating that while higher elevation generally implies deeper water, local geological conditions (e.g., presence of fractured zones or specific lithologies) and overburden thickness play a critical role. This highlights the importance of integrating ADMT data, as it provides crucial subsurface information that is not captured by SRTM data alone, addressing the limitation of relying solely on remote sensing as noted in the introduction. The observation that areas with low porosity (green areas in Figure 11) are highly prone to water highlights the influence of soil type and overburden on groundwater accumulation , a factor that is often overlooked when using only surface geophysical methods.

The integrated modeling approach, which combines geophysical interpretations with interpolated borehole data and terrain analysis, offers a more robust framework for groundwater potential mapping than relying on individual methods. The weighted map overlay approach, classifying high potential areas based on the overlap of low resistivity zones and shallower interpolated depths, directly enhances the precision of identifying suitable drilling locations. This is particularly valuable in a context like Ile-Ife, where economic considerations necessitate accurate siting to reduce drilling costs and ensure water availability. The model's ability to predict unobserved quantities based on observed patterns is a significant step towards more efficient groundwater resource management in the region, consistent with the objective of providing practical tools for cost-effective borehole siting as stated in the introduction.

IV. LIMITATIONS OF THE STUDY

While this research presents a novel integrated modeling approach for water table depth and groundwater potential in Ile-Ife, it is imperative to acknowledge certain inherent limitations that warrant consideration for future refinements and applications of the model.

Firstly, the spatial resolution and accuracy of the integrated model are inherently influenced by the density of the primary borehole data, which serves as the direct empirical measurement of water table depth. With only 20

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discrete borehole locations utilized for spatial interpolation, the accuracy and reliability of the continuous water table surface generated by Kriging may exhibit localized deviations, particularly in areas with sparse data coverage. This constraint affects the granularity of the model's predictive capability in highly heterogeneous subsurface environments.

Secondly, although the integrated model's coherence was qualitatively assessed through visual comparisons with SRTM-derived Digital Elevation Models and graphical correlation analyses in (Figure 6 and 7), a dedicated, quantitatively withheld independent dataset was not explicitly reserved for rigorous statistical validation. Consequently, the predictive accuracy and robustness of the model could not be precisely quantified using standard metrics such as Root Mean Squared Error or Coefficient of Determination, which are typically expected for hydrological modeling studies in high-impact journals.

Furthermore, while Controlled-Source Electromagnetic Sounding (ADMT-200S) effectively delineates resistivity contrasts indicative of water-bearing fracture zones, it is pertinent to note from geophysical survey reports that such methods primarily indicate the presence of liquid or potential formations rather than providing a direct measure of sustainable yield or flow rate for prospective boreholes. This distinction implies that the integrated model, while highly effective for siting based on water presence, does not directly predict long-term extraction viability without further hydrological testing.

Finally, the developed integrated model primarily represents a static spatial snapshot of water table conditions. It does not explicitly account for the dynamic temporal fluctuations in groundwater levels that are driven by seasonal precipitation variability, evapotranspiration rates, or anthropogenic pumping activities. While factors like specific soil composition and detailed lithological variations beyond those inferred from resistivity were acknowledged as influential, their granular integration into the final quantitative model was limited by available data resolution and the cross-sectional scope of this initial integrated assessment. Future research could enhance the model's predictive capabilities by incorporating time-series groundwater level data and more detailed lithological mapping.

V. CONCLUSION

This project has successfully demonstrated the efficacy of an integrated modeling approach for characterizing groundwater resources in Ile-Ife, Southwestern Nigeria, by synergistically combining Controlled-Source Electromagnetic Sounding (ADMT-200S) data, SRTM-derived terrain information, and borehole records. The study's innovative methodology, which integrates high-resolution subsurface resistivity data with comprehensive topographical analysis and spatial interpolation, significantly enhances the ability to accurately model water table depths and identify potential groundwater zones, addressing a critical need for efficient water resource management in the region.

The research revealed significant spatial variability in water table depths across the study area. A key finding is the consistent inverse correlation observed between surface terrain elevations and subsurface water levels: areas with higher surface terrain elevations generally corresponded to deeper water tables, while low-lying regions exhibited shallower ones. This relationship, supported by graphical correlations (e.g., Figure 6 and 7) and spatial overlays, aligns with fundamental hydrogeological principles governing groundwater flow in relation to topography and geological structure. Furthermore, the study underscores the critical role of geological formations, particularly fractured zones identified by ADMT-200S, as preferential conduits for groundwater distribution. The integrated model, by incorporating these diverse datasets, offers a more robust and reliable prediction of groundwater potential than relying on any single method in isolation.

The derived integrated groundwater potential map (Figure 12) provides a scientifically robust and practical basis for informed decision-making regarding borehole siting, optimizing water extraction, and ensuring long-term resource sustainability in Ile-Ife. This knowledge is crucial for sustainable water resource management, especially in regions where groundwater is a primary water source. It is anticipated to assist local authorities, water managers, and stakeholders in formulating effective strategies for responsible groundwater management, thereby safeguarding this essential natural resource for future generations and promoting sustainable water use. The study also underscores the importance of continuous monitoring and analysis of water level data to ensure adaptable water management procedures sensitive to changing hydrological conditions. The methodology and findings can be adapted for similar geologic settings in Southwestern Nigeria and beyond, offering a valuable framework for integrated groundwater assessment and management in other urbanizing regions facing water scarcity.

➢ *Declaration of generative AI and AI-assisted technologies in the writing process*

During the preparation of this work the author(s) used GEMINI 2.0 Flash Service in order to improve the readability of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

➢ *Author Contribution:*

- Caleb Olutayo Oluwadare: Conceptualization, Writing-Review & Editing, Supervision.
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- Segun Isaac Olonade: Writing- Original draft preparation, Visualization.
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