Integration of aquifer resistivity and hydrogeochemical data for groundwater quality assessment in a basement complex terrain of Osogbo metropolis, Southwest Nigeria

Oyelowo Gabriel BAYOWA[1,*], Gbenga Olakunle OGUNGBESAN[1], Akinola Bolaji ELUWOLE[2], Kehinde Francis AKINLOYE[3], Isaiah Oluwadara ADELERE[1], Hussain Olanrewaju ABUBAKAR[4], Segun Adebayo BABATUNDE[1]

[1] Department of Earth Sciences, Ladoke Akintola University of Technology, P.M.B. 4000, Ogbomoso, Nigeria

[2] Department of Geophysics, Federal University Oye-Ekiti, Oye-Ekiti, Nigeria

[3] Department of Geography, University of Ilesa, Ilesa, Nigeria

[4] Department of Geophysics, University of Ilorin, P.M.B. 1515, Ilorin, Nigeria

Abstract: In this paper, one hundred and nine vertical electrical sounding data were acquired and quantitatively interpreted to delineate the subsurface sequence and determine the geoelectric parameters. One hundred and eighteen shallow wells with measured depths to the water table were sampled and thirty-five ground-water samples were analysed for physicochemical parameters, in a view to assessing the groundwater quality in Osogbo metropolis, Southwest Nigeria. The delineated subsurface layers included the topsoil/laterite, weathered layer; partly weathered/fractured basement and the basal fresh basement with respective resistivities and thicknesses: $13-4727$ Ωm and $0.2-8.9$ m; $70-641$ Ωm and $0.8-32.0$ m; $18-826$ Ωm and $1.8-27.9$; and $349-\infty$ Ωm and ∞ m. The main aquifer unit identified was the weathered layer which was classified into ≤ 100 Ωm (low), $101-350$ Ωm (moderate) and $350-750$ Ωm (high) resistivity zones. Depths to the water table ranged from $3.1-40.7$ m. The analysed physicochemical parameters included the pH ($5.31-7.33$), Electrical Conductivity (EC) ($90-1709$ μs/m); Total dissolved Solid (TDS) ($89-1227$ mg/L); Ca^{2+} ($1.9-93$ mg/L); Na^+ ($9.2-349$ mg/L); K^+ ($0.8-60$ mg/L); and NO_3^- ($0.9-4.9$ mg/L). The central district of the study area with relatively shallow water table (< 12 m) and cluster of ancient waste dumpsites fell within the low resistivity zone having physicochemical characteristics of high TDS ($623-1227$ mg/L) and EC ($903-1709$ μs/m) and elevated concentrations of Na^+ ($120-349$ mg/L), Ca^{2+} ($48-93$ mg/L) and K^+ ($25-60$ mg/L) relative to *WHO (2022)* and *SON (2015)* thresholds for potable

*corresponding author, e-mail: obayowa@lautech.edu.ng; phone: +2348030820291

doi: 10.31577/congeo.2025.55.2.3

water and adjudged a poor groundwater quality zone. The pollutant is suspected to be leachates from waste dumpsites and pit latrines. From the point of view of geoelectric and physicochemical parameters, the other areas of the metropolis are considered to be of good groundwater quality.

Key words: aquifer resistivity, basement complex terrain, Osogbo metropolis, physicochemical parameters, shallow wells, water quality

1. Introduction

The demand for groundwater for drinking and domestic usages in developing nations of the world is on the increase (*Jeihouni et al., 2018*). However, groundwater must occur in sufficient quantity and quality as a prerequisite to achieving a sustainable development in the developing nations of the world (*SEG, 2025*). Groundwater experiences variations in chemistry as it moves from one point to another below the ground surface (*Tijani and Onodera, 2009*). Such variations in chemistry could lead to groundwater quality compromise as its chemical parameters may change to concentration levels greater or less than a certain worldwide acceptable threshold (*Bayowa et al., 2014*). Variations in groundwater chemistry may arise due to rock-water-interaction and anthropogenic activities. The antropogenic activities could include indiscriminate disposal of refuse and toxic waste materials (*Adepelumi et al., 2001; Ariyo and Enikanoselu, 2007; Bayowa et al., 2015, 2023a*) and discharge of domestic wastes and industrial effluents directly on open or excavated ground (*Adepelumi et al., 2005; Bayowa et al., 2012, 2014*). Leachates from wastes could percolate through the soil or through geological features such as faults and fractures into the groundwater system to contaminate and constitute contamination plumes within the aquiferous unit(s) (*Bernstone and Dahlin, 1997; Buselli and Lu, 2001* and *Bayowa et al., 2012*).

Osun State, in southwestern Nigeria, was created in 1991 with Osogbo as the capital. Since the State creation, the town has witnessed astronomical increase in population and significant infrastructural, industrial and urban agricultural activities. The demand for water supply has understandably increased. The public water supply scheme has been grossly inadequate leaving the inhabitants to significantly depend on groundwater from wells and boreholes. However, the groundwater is under serious threat of pollution. Being an ancient city, Osogbo has many abandoned and active indiscriminately located waste dumpsites with leachate generating capacities. Within the central district characterised by old houses, pit latrines are still being used. Wastes are continuously being generated from existing plants and fertiliser-aided dry season irrigation farming within the flood plains.

Several authors (e.g. *Oyelami et al., 2013; Ojo et al., 2014* and *Igboama et al., 2021*) had carried out investigations on the groundwater quality in some selected parts of Osogbo metropolis. The authors identified dumpsites and landfills as a major threat to the quality of groundwater resource in Osogbo metropolis. However, their studies are isolated and far in between with limited geophysical and/or hydrogeochemical data points within parts of Osogbo metropolis which do not give a representative regional overview of the groundwater quality of the metropolis. Again, none of these earlier studies address the usual interpretational pitfall that classifies all low resistivity weathered layer aquifer as indicative of pollution.

In this study, representatives larger volume of electrical resistivity (vertical electrical sounding (VES)), and physicochemical data were acquired over the entire metropolis between October 2021 and May 2022 to assess the hydrogeologic characteristic, groundwater flow and quality of the groundwater in the shallow weathered basement aquifers. Weathered basement aquifers are very important sources of potable groundwater in basement rock underlain areas of the world (*Macdonald et al., 2005; Bayowa et al., 2023b*).

The electrical resistivity method is a veritable tool in mapping resistivity variations in the aquifer system within basement complex or sedimentary terrain (*Zume et al., 2006*). Electric current is injected into the ground through two current electrodes while the resulting potential is measured across another pair of potential electrodes to enable the estimation of the ground resistance to the flow of current. The method is fast, inexpensive and environment non-invasive (*Zonge et al., 2005* and *Lowrie, 1997*). *Freeze and Cherry (1979)* showed that there is correlation between ion concentration in the groundwater and the electrical resistivity (or conductivity). Very low aquifer resistivities could be an indication of potential contamination of groundwater within an aquifer system in the presence of high concentrations of Total Dissolved Solids (TDS) (*Frohlich and Urish, 2002; Bayode et al., 2012; Bayowa et al., 2023a*). However, the resistivity of clay-sized particles in an aquifer could overlap significantly with that of contaminant plumes making it difficult for resistivity alone to be used as index of pollution. This informed the incorporation of physicochemical data analyses of groundwater samples with aquifer resistivity in this study (*Senos Matias et al., 1994; Ebraheem et al., 1997; Kayabalıet al., 1998; Bayowa et al., 2014* and *Olla et al., 2015*).

The study objectives include to: (i) delineate the subsurface sequence and generate the geoelectrical parameters (ii) develop the groundwater flow map (iii) determine the physicochemical properties of the groundwater samples from shallow wells (iv) assess the impact of waste dumpsites and pit latrines on the quality of the groundwater, and (v) use the aquifer resistivity and physicochemical characteristics of the groundwater samples to assess its quality.

2. The study area

Osogbo lies within latitudes 7.72° N and 7.84° N and longitudes 4.5° E and 4.62° E (Fig. 1a,b). It is located in the tropical rain forest with the wet and the dry climatic seasons between the months of April and October and November and March respectively (*Olayiwola and Olaitan, 2019*). The average annual temperature and rainfall of the area are 26.1 °C and 1241 mm respectively (*Adejuwon and Jeje, 1975*). The tropical deciduous rain forest type dominates the study area.

The topographic elevation is over 243 metres (800 feet) above the mean sea level. River Osun and its numerous tributaries dendritically drain the metropolis (*Faniran and Jeje, 1983; Osun State Government, 2025*). The area is accessible through numerous tarred and untarred roads and foot paths as highlighted in the google image of the environment (Fig. 1b).

The metropolis is underlain by the Precambrian Basement Complex rocks which include schist, banded gneiss, amphibolite schist and pegmatites (Fig. 1a). The schist is medium grained rock that is composed of mica (muscovite and biotite), quartz and feldspar. The rock unit underlies Oreniwon, Owode, Olupona, Woru and Igbona area. The banded gneiss is made up of alternating mafic (dark hornblende) and quartzo-feldspathic (light) minerals which define banding with gradational contact (*Rahaman, 1989*). This lithologic unit is found in the area around Oke Bale, Forest Reserve, Testing Ground and Akogun. The strongly foliated amphibolite schist underlies the northwestern edge of the study area. It is composed of amphiboles, mica and hornblende.

Pegmatites are coarse grained intrusive rocks that are composed mainly of feldspars, mica and quartz with accessory minerals such as tourmaline and garnet. This rock type occupies the northern flank of the metropolis.

In their fresh state, with extremely low (< 3%) porosity and virtually zero permeability, the basement rocks are poor hydrogeological units. Weathering and stress induced fractures and faults enhance porosity and permeability to improve water retaining and transmitting capacities of the basement rocks. The weathered basement and fractured basement columns constitute the aquifer units. In most areas and for shallow wells (depths < 35 m), the weathered layer constitutes the main aquifer. The aquifer system is recharged by surface precipitation (rain water) and base flow while it is discharged through wells, tubewells, boreholes and springs and, evapotranspiration.

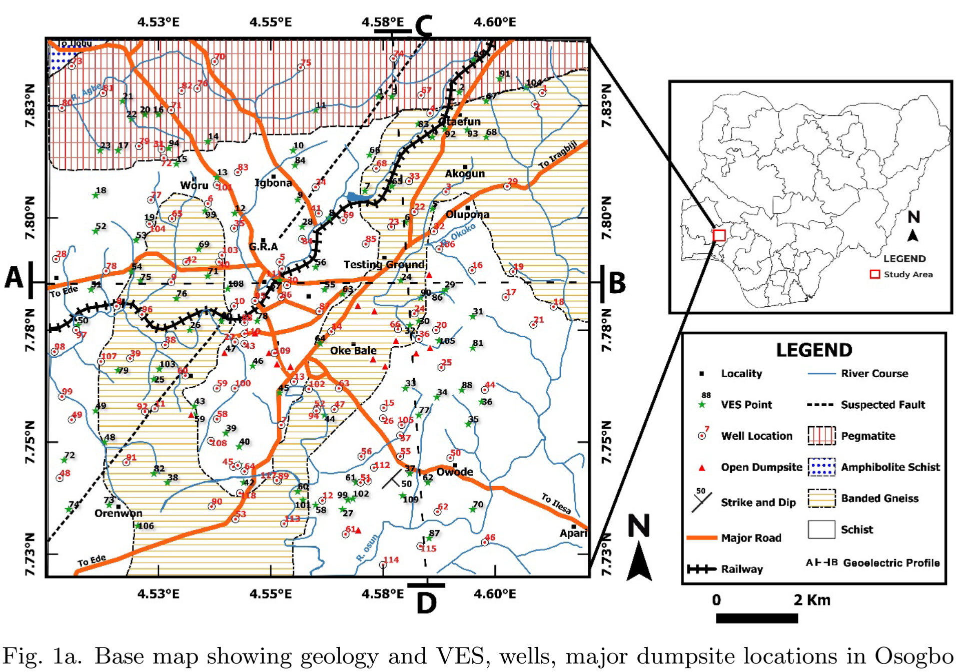

Fig. 1a. Base map showing geology and VES, wells, major dumpsite locations in Osogbo metropolis and geoelectric section profiles A – B and C – D (inset is the Administrative map of Nigeria). Modified from *Bayowa, et al. (2023b)*.

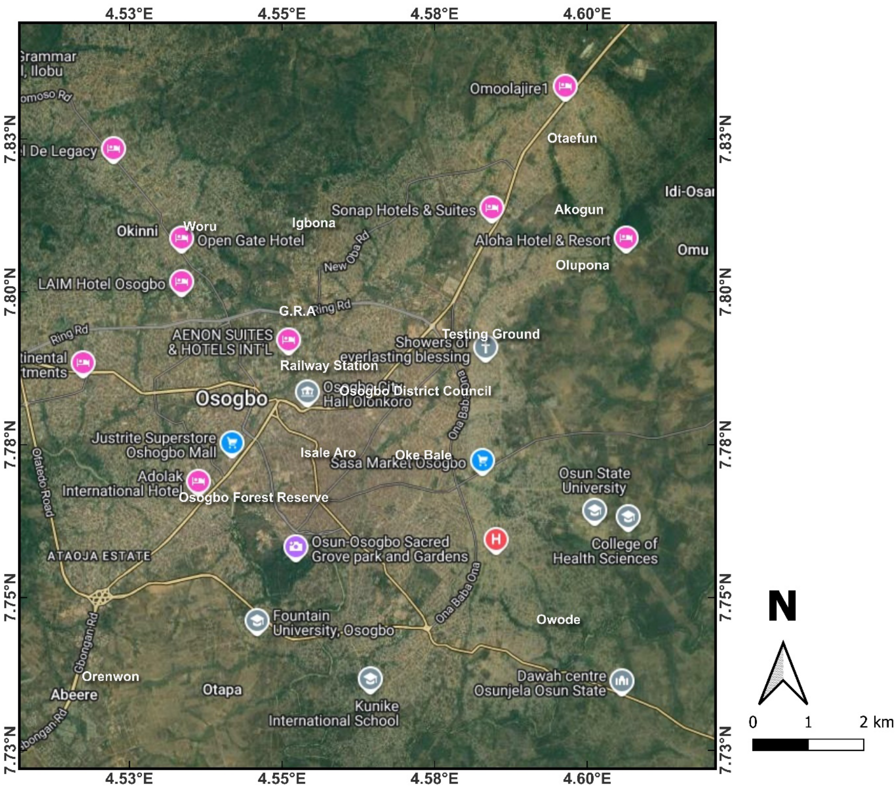

Fig. 1b. Google image of the environment of the study area (*Google Maps, n.d.* – `https://mapsplatform.google.com/maps-products/earth/capabilities/`.

3. Methodology

This study involved georeferencing of active and abandoned waste dumpsites around Osogbo metropolis using the Garmin Geographic Positioning System (GPS) and field-based data acquisition/laboratory data analyses. The field data involved (i) acquisition of VES data around the study area (ii) measurement of static groundwater levels (iii) in situ measurements of the physical parameters of the groundwater directly from shallow wells and groundwater sampling and subsequent analyses in the laboratory for cations and anions concentrations. The details of the data acquisition and analyses are discussed below.

3.1. Geoelectrical investigation

The ABEM Signal Averaging System (SAS) 1000C Terrameter was used to acquire one hundred and nine (109) VES data within the study area (Fig. 1). The Schlumberger array was used with maximum half current electrode spacing (AB/2) of 100 m. The acquired data were presented as VES curves whose interpretation involved partial curve matching with 2-Layer model curves and auxiliary curves. The resulting geoelectrical parameters (layer resistivities and thicknesses) were refined using WinResist 1-D forward modelling software. The interpretation procedures are well documented in *Zohdy et al. (1980), Telford et al. (1990), Lowrie (1997)* and *Sharma (2004)*. The VES geoelectrical interpretation results were classified in terms of subsurface lithology and an iso-resistivity contour map developed for the weathered layer aquifer unit.

3.2. Hydrological investigation

Depths from the ground level to the static water level (SWL) in one hundred and eighteen (118) Garmin Geographic Positioning System (GPS) georeferenced shallow wells were measured with GAMICOS 100 m water level meter and the water table elevation (groundwater head) at each well site determined by subtracting the depth to the SWL from the well head elevation. The SWL and water table elevation data were used to generate water table and groundwater elevation contour maps using Kriging gridding and Surfer 11 software. Contour intervals of 2 m and 5 m respectively were used to avoid overcrowded contour lines.

3.3. Hydrogeochemical investigation

Thirty five (35) of the referenced wells were sampled for groundwater and analysed for physicochemical parameters. Temperature, hydrogen potency (pH), total dissolved solids (TDS) and electrical conductivity (EC) of the groundwater were measured in-situ using XL830L KPY Origin Handheld Digital Multimeter. Groundwater samples were collected in 1litre polyethylene bottles that had been pre-washed with detergent and de-ionized water and finally rinsed with the groundwater. All water samples were collected without pre-pumping because all the sampled wells were actively in use. Water samples were collected in duplicate bottles at each station – one set for cations and the other for anions. Those that were meant for cation analysis were acidified to pH < 2 with 10% nitric acid. The samples were then labelled and appropriately packed before they were taken to the laboratory within 24 hours of sampling. All samples were later stored in the refrigerator prior to analyses. Major ions (K^+, Na^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-, CO_3^{2-}) concentrations of 35 samples were analysed at SMO Laboratory Services in Ibadan, Nigeria. All water samples were first filtered through a 0.43 μm membrane and then analysed for major cations using Atomic Absorption Spectrometer (AAS); HCO_3^- and CO_3^{2-} (by acid titration); Cl^- (by $AgNO_3$ titration); NO_3^- (phenol-disulphuric acid colorimetric method) and SO_4^{2-} (by $BaCl_2$ titration). The standard procedures as outlined in *Eaton et al. (1995)* and *USEPA (1983)* were ensured during the analyses. All the analyses were replicated for each sample and the average and standard deviation computed. Those results with standard deviation greater than 5% were rejected.

The hydrochemical data were processed for univariate (range, mean, standard deviation, coefficient of variation) statistical analysis and co-variations plots. Using the RockWorks16 software, the hydrochemical data were plotted on trilinear Piper diagram (*Piper, 1994*) which was used to determine the hydrochemical facies of the groundwater. Spatial geochemical maps of the hydrochemical parameters were generated using Kriging gridding method and Surfer 11 software.

The potability of the groundwater was ascertained based on compliance of measured parameters with World Health Organisation (*WHO, 2022*) and Standard Organization of Nigeria (*SON, 2015*) standards.

4. Results

4.1. Geoelectrical investigation

The VES curves vary from simple 3-Layer A and H types to complex $4-6$ Layer KH, QH, HKH, KHK, HAKH and KHKH types (Fig. 2) depending on the subsurface geology and the spread length of the electrode array. The H and the KH types account for over 50% of the total. The VES interpretation results were displayed on W–E and and N–S geoelectric setions (Fig. 3) which show that areas underlain by schist are characterised by $3-4$ Layer H and KH curves while the banded gneiss and pegmatite underlain areas are typified by 3 – 6 Layer H, AKH, KHK, HKH, KHKH and HAKH curves.

The 3 – 6 geoelectric layers delineated identified four geologic layers which are the topsoil/laterite, weathered layer, partly weathered/fractured basement and the fresh basement (Fig. 3). The geoelectric parameters (layer resistivities and thicknesses) are respectively 13 – 4727 Ωm and 0.2 – 8.9 m; 70 – 641 Ωm and 0.8 – 32.0 m; 18 – 826 Ωm and 1.8 – 27.9 m and 349 – ∞ Ωm. The two identified aquifer units are the weathered layer and the partly weathered/fractured basement.

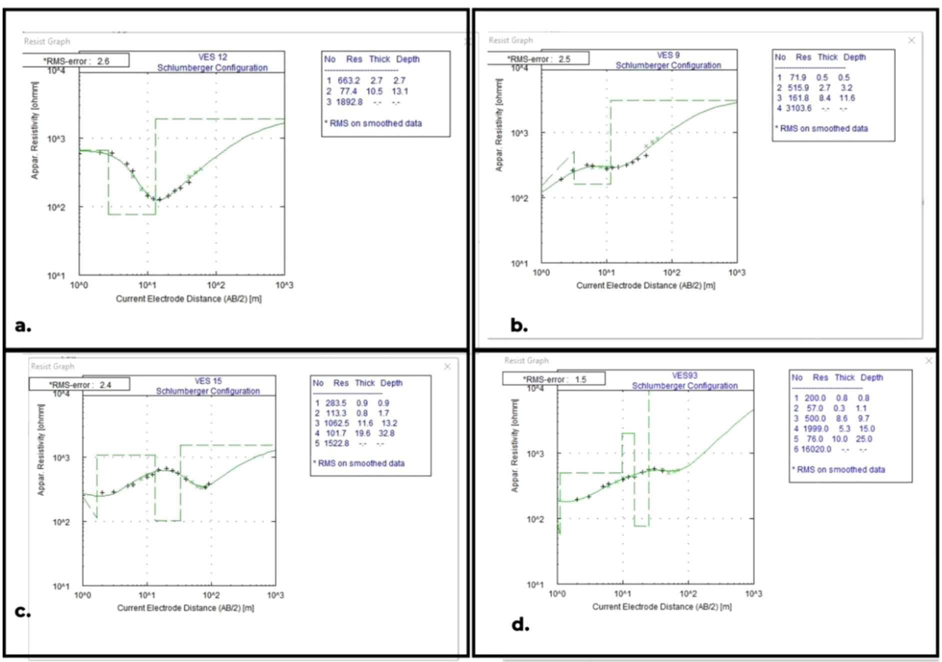

Fig. 2. Vertical Electrical Sounding (VES) resistivity type curves from the study area (a) H type (b) KH type (c) HKH type and (d) HAKH type.

Figure 3 shows that the weathered basement layer is thicker (up to 22 m) over the schist and thinner (< 12 m) over the banded gneiss and pegmatite. The partly weathered/fractured basement aquifer unit was majorly identified within the banded gneiss and pegmatite. This aquifer unit occurs as confined aquifer (*Olorunfemi and Fasuyi, 1993*) and beneath the fresh basement rock (see Fig. 3).

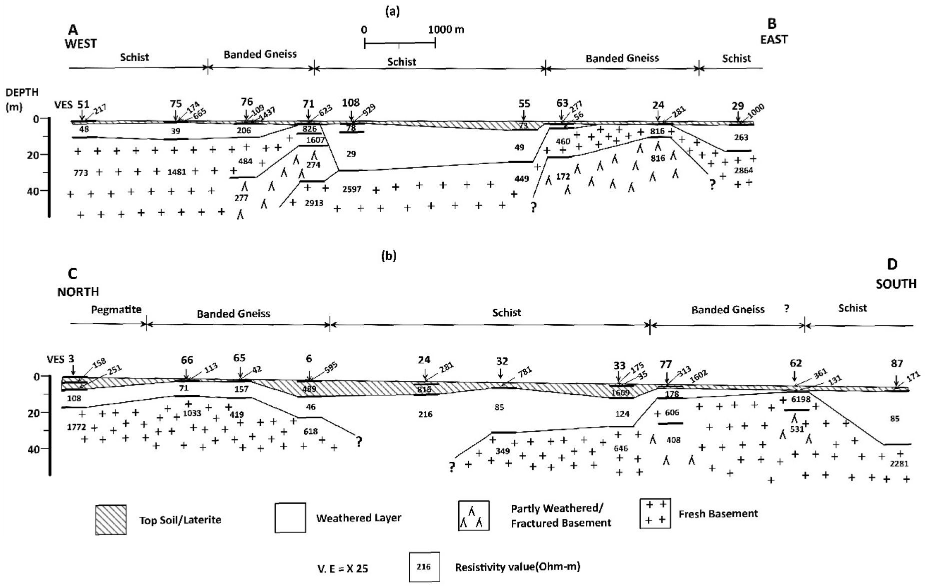

Fig. 3. 2D Subsurface geoelectric sections along (a) West – East Profile (A – B) and (b) North – South Profile (C – D) (see Fig. 1a).

The depths of the wells adopted in this study generally range from 6.0 – 50.7 m but are generally < 35 m and hence must have terminated at the bottom of the weathered layer. Hence the aquifer unit that is most relevant to groundwater quality assessment in this study is the weathered layer aquifer. The relevance of this aquifer resistivity to groundwater quality evaluation is in the fact that the measured resistivity values are significantly influenced by the chemical composition (ionic concentrations and hence chemical quality) of the saturating groundwater, as expressed by the Archie's formula:

$$R_r = a\,\phi^{-m} R_w\,, \qquad (\mathit{Sheriff,\ 1991}) \tag{1}$$

where R_r is the resistivity of a fully saturated formation, ϕ is the formation porosity, R_w is the resistivity of the saturating water (determined by the ionic concentration) and a and m are constants.

4.2. Hydrological investigation

The drilled depths of the wells used in this study range from 6.0 – 50.7 m while the depths to the SWL in the wells within the study area vary from

3.1 to 40.7 m below the ground level (Appendix 1). The SWL contour map (Fig. 4) reveals pockets of shallow (< 12 m) water level in the southwest (close to Orenwon and Forest Reserve), central (around Railway Station and Osogbo District Council) and north/northeastern part. Areas with moderate to deep (> 12 m) water levels are located in the southeastern (Owode/Oke Osun) and northwestern part, and are sandwiched between areas with shallow water table in the central, north central and northeastern part (Fig. 4). The groundwater head (water level elevation) generated from the SWL and well head elevation ranges from 287.5 to 356.7 m (Appendix 1). The groundwater head map (Fig. 5) reveals pockets of converging groundwater flow in the northcentral, central (around Isale Aro, Oke Bale and Osogbo District Council), southeastern (around Oke Oshun and Owode) and west of Woru while groundwater diverging zones characterise Igbona/GRA, Ota Efun, Testing Ground and southwest of Owode (Fig. 5). This complex groundwater flow pattern is characteristic of the basement

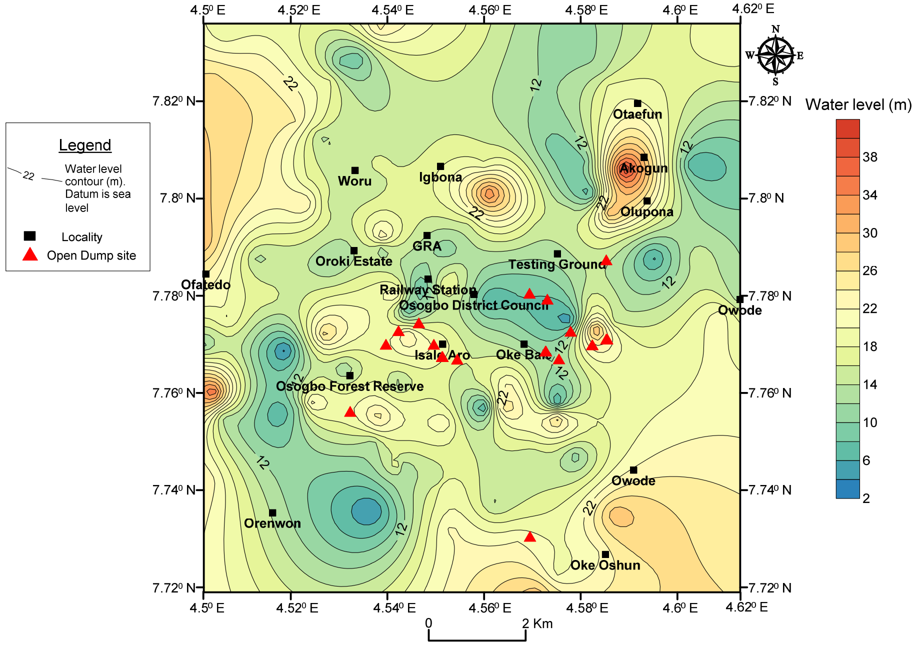

Fig. 4. Water table contour map of Osogbo metropolis showing areas of shallow water level (coloured in blue) and areas of deep water level (coloured in brown).

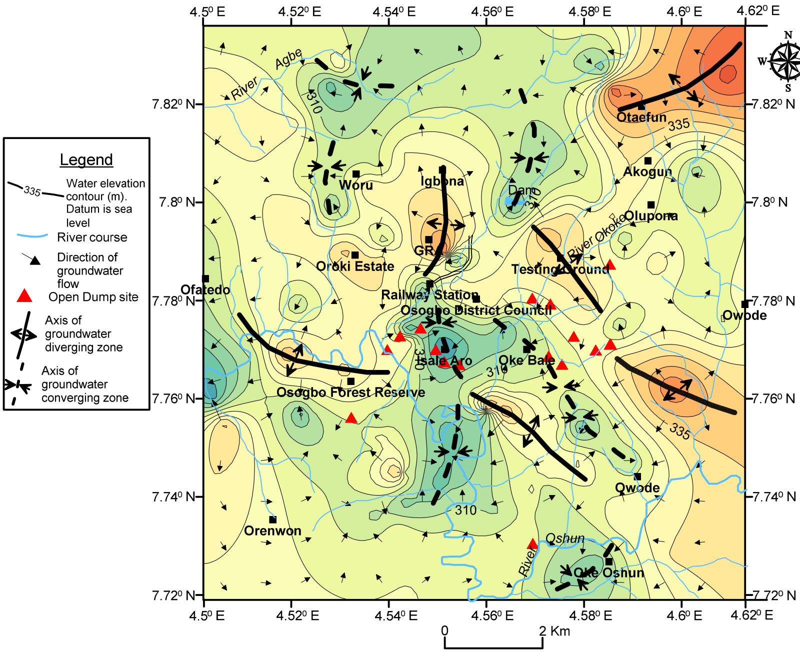

Fig. 5. Groundwater elevation contour map of Osogbo metropolis showing directions of water flow including axes of groundwater convergence and divergence.

complex terrain and a consequence of localised and discontinuous aquifer system (*Satpathy and Kanungo, 1976*) and undulating basement bedrock topography.

4.3. Hydrogeochemical investigation

The physicochemical parameters of the analysed groundwater samples as well as permissible limits of *WHO (2022)* and *SON (2015)* are contained in Table 1. The water temperature ranges from 21.60 to 34.30 °C with a mean of 29.83 °C. The pH values vary from 5.31 − 7.33 with a mean of 6.33.

The EC, TDS and salinity range from 90.2 to 1709.0 μS/cm, 59.0 to 1227.4 mg/L and 0.04 to 0.85 ppt, respectively. The concentration ranges of the anions and cations are contained in Table 1. Iso-concentration maps were generated for the physical (Fig. 6) and major anions and cations (Fig. 7) that could be relevant in the assessment of groundwater quality.

Table 1. Descriptive statistics for physicochemical parameters of groundwater samples collected from Osogbo metropolis between October 2021 and May 2022.

Parameters	No	Min	Max	Ave	STD	CV (%)	*WHO (2022)*	*SON (2015)*
Temp. (°C)	35	21.6	34.3	29.83	1.6	5.36	–	–
pH	35	5.31	7.33	6.33	0.56	9.93	6.5 – 8.5	6.5 – 8.5
EC (s/m)	35	90.20	1709.01	396.75	310.82	78.34	2500	1000
TDS (mg/l)	35	59.00	1227.36	269.87	221.33	82.01	600	500
Salinity (ppt)	35	0.04	0.85	0.19	0.15	79.99	–	–
TH (mg/L)	35	7.36	299.88	11.02	88.19	76.68	–	–
Ca^{2+} (mg/l)	35	1.91	92.56	27.27	23.71	86.93	75	75
Mg^{2+} (mg/l)	35	0.32	36.24	11.4	9.35	81.96	50	20
Na^{+} (mg/l)	35	9.24	348.94	45.39	56.34	124.12	200	200
K^{+} (mg/l)	35	0.83	60.02	12.22	13.76	112.63	12	–
Cl^{-} (mg/l)	35	0.89	36.20	14.40	8.52	59.15	250	250
HCO_3^{-} (mg/l)	35	*ND*	0.44	0.04	0.09	120.99	120	–
SO_4^{2-} (mg/l)	35	0.08	31.04	5.11	7.61	148.82	250	100
NO_3^{-} (mg/l)	35	*ND*	4.91	2.57	1.17	45.37	50	50
WQI	35	14.39	109.05	31.44	18.27	58.11	–	–

ND – not detected; Temp. – Temperature; EC – Electrical Conductivity; TDS – Total Dissolve Solid; TH – Total Hardness; WQI – Water Quality Index; WHO – World Health Organisation; SON – Standard Organization of Nigeria.

5. Discussion of results

5.1. Resistivity attribute

An aquifer resistivity can be used as an index of its groundwater quality since the said resistivity is majorly determined by the resistivity of the groundwater contained in the aquifer, as demonstrated in Eq. (3). For the present study, the weathered layer resistivity values range from 7.0 – 641 Ωm which fall within the observed weathered layer resistivity values for similar basement complex environment (*Idornigie et al., 2006* and *Olorunfemi, 2020*). The weathered layer aquifer resistivity map (Fig. 8) was therefore generated using the litho-classification by *Idornigie et al. (2006)* of low $\leq$ 100 Ωm (clay), moderate 101 – 350 Ωm (sandy clay) and high 351 – 750 Ωm (clayey sand).

The low resistivity zones occur in the far north, extreme west, southeast of Owode and the central district (including Osogbo District Council, Oke Bale, Isale Aro). Areas with moderate to high resistivities are characterised

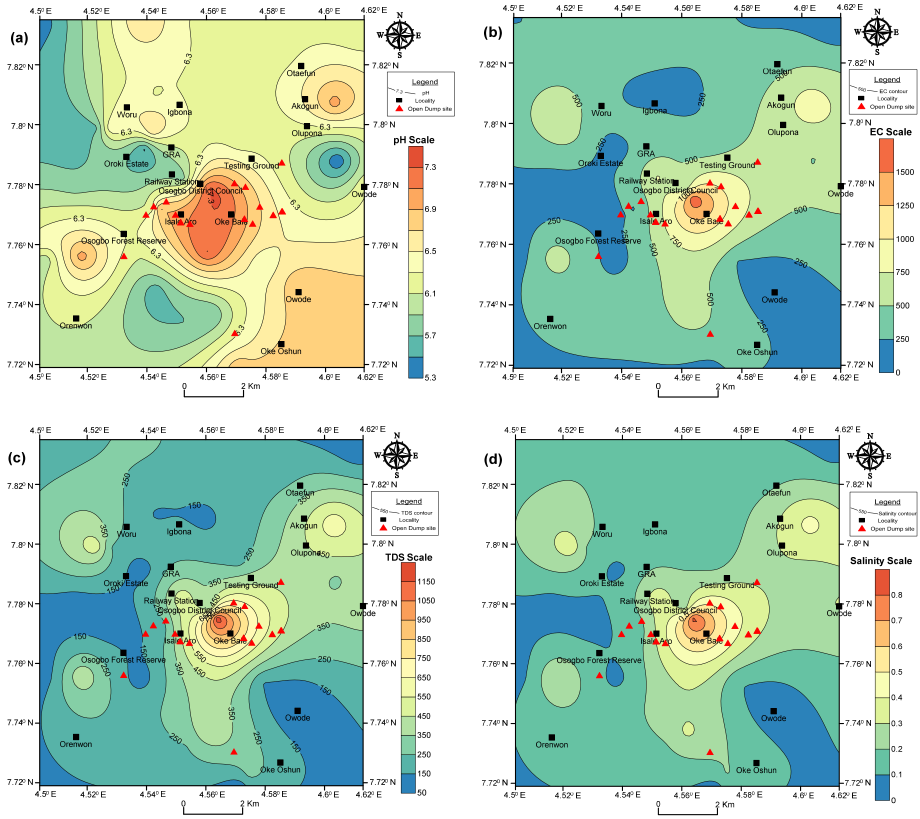

Fig. 6. Hydrochemical maps (a) pH, (b) EC (c) TDS and (d) salinity distributions in groundwater of Osogbo metropolis.

by resistivity closures that surround the low resistivity central district which include Woru, Igbona, Testing Ground, GRA, West of Railway Station, Osogbo Forest Reserve in the west, Orenwon, Ota Efun, Akogun and Olupona in the northeast and the eastern flank. These areas are developing (modern) districts of the metropolis.

Dumpsite-generated-leachate-impacted basement complex environment are characterised by relatively low ($< 100\ \Omega$m) topsoil/weathered basement resistivity (*Bayode et al., 2012, Odipe et al., 2018* and *Bayowa et al., 2023a*) which overlap with the resistivity of clay. This demonstrates the limitation of the resistivity attribute as an index of pollution in basement complex

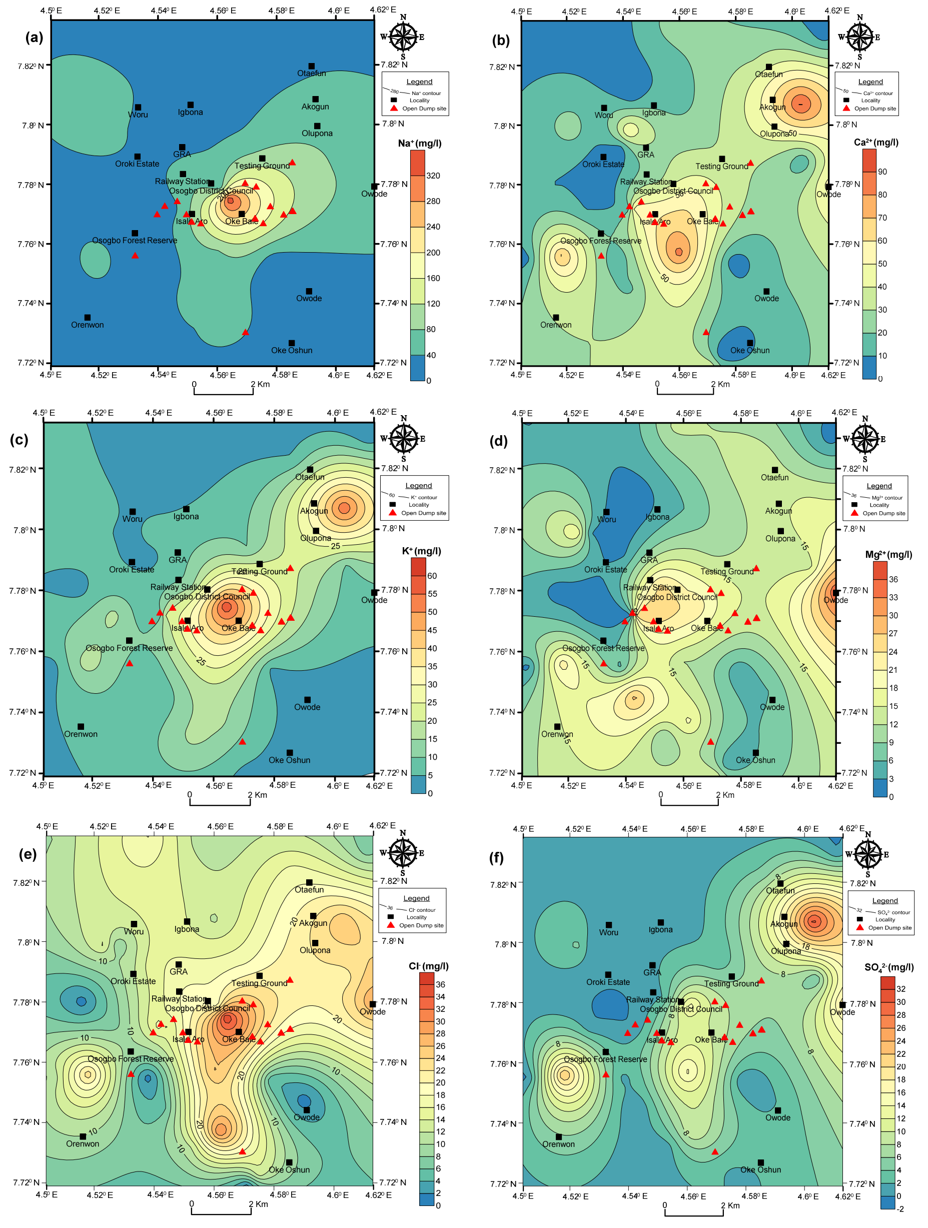

Fig. 7. Hydro-chemical maps of (a) Na^+, (b) Ca^{2+}, (c) K^+, (d) Mg^{2+}, (e) Cl^- and (f) SO_4^{2-} contents of groundwater in Osogbo metropolis.

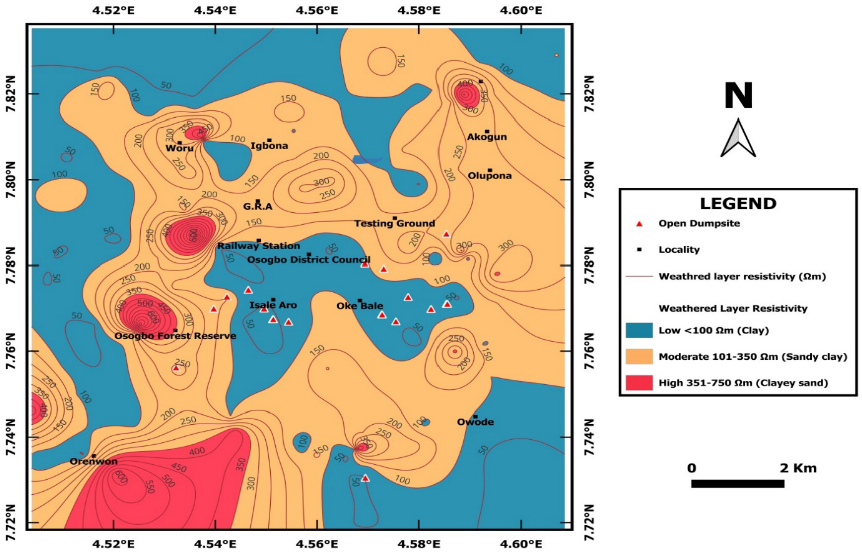

Fig. 8. Weathered layer aquifers resistivity map of the study area.

environment and the necessity to integrate geoelectric attribute with other attributes including constraining geoelectrical interpretations with georeferenced locations of existing waste dumpsites. In this study, twelve (12) of the sixteen georeferenced waste dumpsites (constituting 75% of the total) fall within the central metropolitan district and the low resistivity zone. This could indicate that leachates from these waste dumpsites could have impacted the weathered basement aquifer resistivity values. The remaining four dumpsites are located within the moderate resistivity ($101-350$ Ωm) zone.

Based on the above, areas with weathered basement resistivity >350 Ωm such as Ota Efun, Akogun, lupona, Orenwon, Woru, west of Railway Station and Osogbo Forest Reserve have tendency for groundwater devoid of pollution while the groundwater in the low resistivity zone most especially in the central district of Oke Bale, Isale Aro and Osogbo District Council may have been polluted by leachates from the waste dumpsites. Similarly low soil/subsoil resistivity values (<100 Ωm) of $12-71$ Ωm; $13-40$ Ωm and < 78 Ωm were observed within basement complex underlain waste dump sites at Akure (*Ojo et al., 2023*), Ijemikin (*Odipe et al., 2018*) and Ile-Oluji (*Oni et al., 2023*) in southwestern Nigeria.

5.2. Hydrology and groundwater flow

The large variation (3.1 – 40.7 m) in the depth to the water table is typical of the basement complex terrain (as similarly observed by *Olorunfemi et al., 1999* and *Akinwumiju and Olorunfemi, 2016*) where such depths depend on the geology, the land surface slope (geomorphology) and the basement bedrock relief. The water table is generally shallow in the valley, deep on the hilltop and intermediate on the slope (*Olorunfemi, 1990*), and is often said that the water table virtually mirrors the surface topography.

The variability in depth gives rise to a complex water table map (Fig. 2) (as also observed by *Olorunfemi et al., 1999*) with several isolated shallow and deep depth closures. Because the depths are not normalised against any topographic reference, the map is very rarely of any hydrogeologic significance beyond giving an idea of depth at which groundwater is likely going to be encountered. Water table map could however be relevant in pollution study (and hence groundwater quality assessment) since areas with shallow water table are more susceptible to pollution through interaction of waste dumpsite generated leachates and groundwater. This makes the central district, most especially, Oke Bale, south of Testing Ground and areas around Osogbo District Council/Railway Station with clusters of waste dumpsites potential poor groundwater quality zones.

The groundwater table (head) map (Fig. 5) is referenced against the mean sea level and is hence compensated for topographic variation and therefore hydrologically and geologically relevant (*Olorunfemi and Okhue, 1992* and *Olorunfemi et al., 1999*). Figure 5 displays a complex multi-directional groundwater flow pattern (as similarly observed by *Akinwumiju and Olorunfemi, 2018*) due to discontinuos (isolated) aquifer system with limited lateral and vertical extents. The map identifies basement depressions in the areas around Oke Aro, Oke Bale – Owode, Oke Osun and Woru with axes of groundwater convergence and, basement ridges around Otaefun, Igbona – GRA, Osogbo Forest Reserve and Testing Ground with axes of groundwater divergence which give a regional picture of the groundwater flow system. The basement depressions are characterised by relatively thick overburden and hence potential zones for groundwater accumulation while the basement ridges have relatively thin overburden, low storativity and are groundwater diverging (radiating) zones with limited promise for groundwater development.

The relevance of the groundwater head map to groundwater quality evaluation is in the assessment of the influence of groundwater flow on pollution migration. However, because the flow pattern in the basement complex area is multi-directional (*Olorunfemi et al., 1999*), the influence on pollution migration will be difficult to assess except at localised level.

5.3. Hydrogeochemistry and groundwater quality

The closeness of the mean water temperature of 29.83 °C with the average local mean annual temperature of 28.30 °C suggests a shallow active water circulation (*Mazor, 1991*). About 83% of the sampled groundwater has pH values of < 7 which makes the groundwater generally slightly acidic. Also, about 63% of the water samples display pH values less than the minimum permissible level (6.5 – 8.5) for both *WHO (2022)* and *SON (2015).* The pH values greater than 7 were recorded for alkaline groundwater at the central part of the study area and around Osogbo District Council, Oke Bale and Isale Aro (Fig. 6a) with shallow water table and clustered waste dumpsites that display low resistivity values ($< 100\ \Omega$m) typical of leachate polluted area. Relatively high values of EC (750 – 1709 μs/m), TDS (450 – 1227 mg/L) and salinity (0.4 – 0.85 ppt) were observed in the central part of Osogbo (Figs. 6b,c,d) which could be attributed to the effect of leachate from the dumpsites ubiquitous around Osogbo District Council, Oke-Bale and Isale Aro area.

Groundwater samples around the north, west, east, northeast, southeast, southwest, northwest and southern parts of the study area which include locations such as Igbona, Ota-Efun, Akogun, Olupona, Owode, Oke-Osun, Orenwon and Woru show TDS values lower than the *WHO (2022)* and *SON (2015)* standards of 500 & 600 mg/L for drinking water and are therefore classified as freshwater zones (*FMHSW* – `https://health.gov.ng/`). However, groundwater samples from around Oke Bale and Isale Aro areas show TDS and EC values of 623 – 1227 mg/L and 903 – 1709 μs/m which are above permissible level of 500 & 600 mg/L and 1000, respectively (Figs. 6b,c) and hence not potable. Interaction of leachates from the ancient wastes dumpsites with groundwater around the central part of the study area is most likely responsible for the high TDS and EC values.

The results of the analysed groundwater samples show that Na^+ dominates the cations followed by Ca^{2+} with less abundance in K^+ and Mg^{2+}.

The anions are dominated by Cl^-, followed by SO_4^{2-} and NO_3^-, with lower concentrations of HCO_3^- (Table 1). Most of the samples show cations and anions contents lower than *WHO (2022)* and *SON (2015)* limits for drinking water while Ca^{2+}, K^+ and Na^+ concentrations exceeded the permissible limits of 75, 12 and 200 mg/L, respectively for both standards. Magnesium ion content is below the WHO permissible limit but higher than the *SON (2015)* recommended limit of 20 mg/L for water samples collected around Osogbo District Council, Isale Aro, Railway Station and Owode (Fig. 7). The Osogbo central district comprising of Osogbo District Council, Isale Aro and Oke Bale are typified by enhanced anion and cation concentration closures of Na^+ (120 – 349 mg/L), Ca^{2+} (48 – 93 mg/L), K^+ (25 – 60 mg/L), Mg^{2+} (15 – 36 mg/L), Cl^- (18 – 36 mg/L) and SO_4^{2-} (8 – 31 mg/L) relative to the adjoining areas (Figs. 7a-f). The strong spatial variability expressed by high coefficient of variation (CV) values were recorded for all the ions, and in particular for those of Na^+, K^+, HCO_3^- and SO_4^{2-} which are greater than 100% (Table 1). The vertical variation plots show higher distribution of EC, TDS, Ca^{2+}, K^+, SO_4^{2-} and Cl^- at shallower depths than deeper depths (Fig. 9) suggesting that their concentrations in the analysed water samples derived mostly from surface-originated processes especially anthropogenic sources.

Chloride and sulphate content in groundwater is usually used as an indicator of surface contamination sources because they are conservative in natural environment. Chloride and sulphate in groundwater are likely to be influence by Cl/SO_4 salts such as NaCl (cooking salt), $CaSO_4$ (cement material), $MgSO_4/K_2SO_4$ (fertilizers) and $CaCl_2$ (deicing salt). In the case of the study area, the vertical distribution of Cl^- and SO_4^{2-}, whose concentrations are exactly balanced by Ca^{2+} and K^+ suggest that cement materials and fertilizers possibly influence the concentrations of these ions (*Panigrahy et al., 1996*).

5.3.1. Geochemical facies

The evolving groundwater types were identified by plotting major ions chemistry in the *Piper (1994)* diagram. The Piper plot (Fig. 10) classifies Osogbo groundwater samples mainly as Na+K-Cl (zone 7) with minor Na+K-Cl-SO_4 (zone 6) water types. In terms of cationic concentrations, 71% of the sampled groundwater plotted in alkali-rich water zone while 26% plotted in

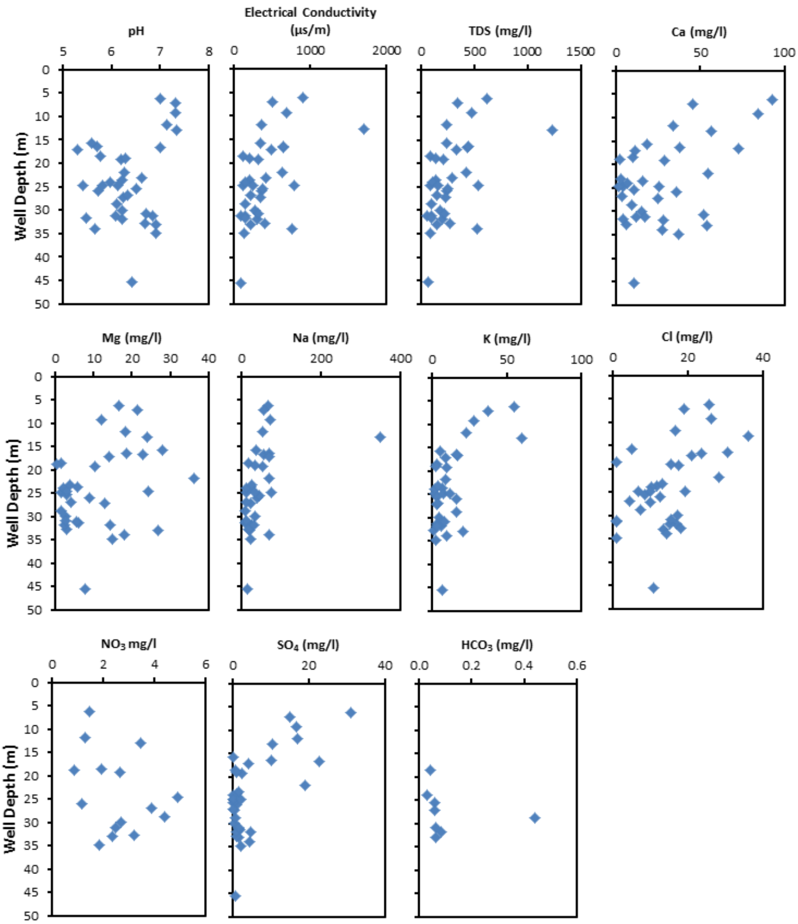

Fig. 9. Co-variation plots of well depth (m) vs. physicochemical parameters of groundwater samples from Osogbo metropolis. Note the negative correlations of EC, TDS, Na^+, Ca^{2+}, K^+, SO_4^{2-} and Cl^- with well depth suggesting input possibly from shallow sources.

calcium-rich water zone. In term of anionic contents, the analysed samples are dominated by chloride water type (81%) while the remaining 9% plotted in sulphate water zone. Various processes among which are anthropogenic contamination, rock-water interaction, biogeochemical processes and solution kinetics can control the evolving groundwater chemistry (*Kim et al., 2005; Srinivasamoorthy et al., 2014*). The hydrochemical composition, vertical variation with depth and the water types (Na-Cl and Ca-Cl) suggests that water chemistry is regulated mainly by two processes; mineral weathering through rock-water interaction and anthropogenic contamination.

Chloride and sulphate are essentially conservative in natural environment and originate mostly from land surface contaminations. Although, Cl^- and SO_4^{2-} concentrations in the groundwater of Osogbo metropolis are within the permissible and safe limit of WHO standards, they are however high (>30 mg/L) around Osogbo District Council (most urbanised with residential buildings) and Akogun (agricultural area) respectively. The high Cl^- and SO_4^{2-} contents in groundwater of these areas could be from household sewage and fertilizer inputs respectively. The concentrations of Na and K in the groundwater, on the other hand, may be controlled by weathering of minerals, which generally regulates the contents of the major cations in groundwater (*Kim et al., 2005*).

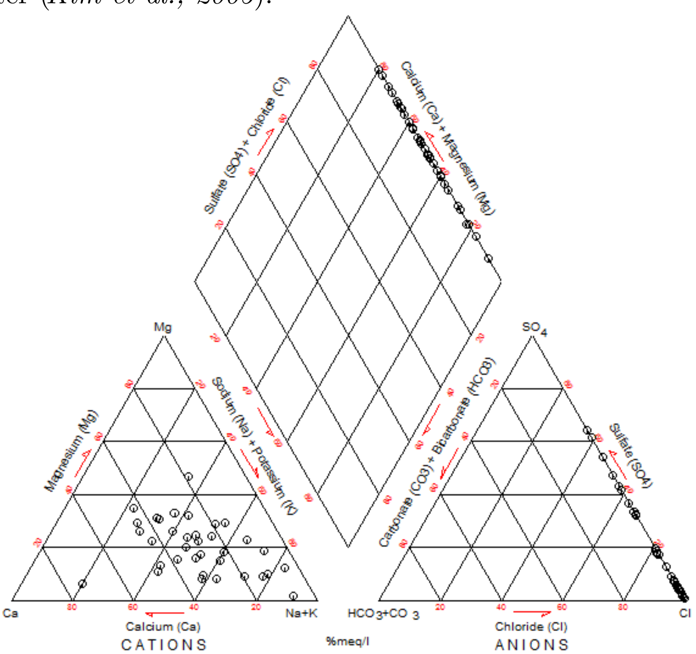

Fig. 10. Piper plot of major ion chemistry of groundwater in Osogbo metropolis two main water types; Na-Cl and Ca-Cl.

Sodium- and potassium-bearing minerals are abundant in the silicate rocks of the study area. Therefore, the evolution and spatial variability of these major ions (Na^+, K^+, Cl^- and SO_4^{2-}) in the groundwater of Osogbo metropolis can be used to infer the geochemical processes taking place in the area.

5.4. Synthesis of results and groundwater quality assessment

The integration of the results obtained from geoelectrical and physicochemical data gives an insight into the groundwater quality of different zones in the study area. The weathered layer aquifer isoresistivity map classifies the study area into three geoelectric zones with resistivities in the range of $\leq 100\ \Omega$m (low), $101-350\ \Omega$m (moderate) and $> 350\ \Omega$m (high). Majority of the georeferenced waste dumpsites fall within one of the low resistivity zones which is suspected to be conductive-leachate-induced and around Osogbo District Council, Isale Aro and Oke Bale whose groundwaters are characterised by relatively high TDS ($450-1227$ mg/L), EC ($750-1709$ μs/m), and elevated concentrations of Na^+ ($120-349$ mg/L), Ca^{2+} ($48-93$ mg/L), K^+ ($25-60$ mg/L), Mg^{2+} ($15-36$ mg/L), Cl^- ($18-36$ mg/L) and SO_4^{2-} ($8-31$ mg//L) with respect to *WHO (2022)* and *SON (2015)* permissible levels for potable water and hence can be rated as of poor quality. This central district has tendency for groundwater contamination due to the relatively shallow water table depths and leachates from ancient dumpsites and pit latrines situated around this ancient part of the metropolis. The Na+K-Cl and Na+K-Cl-SO_4 groundwater facies suggest that contamination in the area is controlled by rock-water interaction and anthropogenic activities. However, the anthropogenic contamination is probably more severe in the area.

The integration of aquifer resistivity with hydrochemical attributes enables the differentiation of unpolluted weathered layer aquifers from the polluted ones (in spite of overlapping low resistivity values) with the former characterised by physicochemical elemental concentration levels that are within the *WHO (2022)* and *SON (2015)* permissible levels for potable water, thereby resolving the resistivity pitfall.

6. Conclusions

In this study, aquifer resistivities, physicochemical parameters, and static groundwater level data were used to evaluate hydrologic characteristic, groundwater flow and quality in Osogbo metropolis. The study concludes as follows:

1. Based on integrated aquifer resistivity and physicochemical parameters constrained by permissible thresholds of *WHO (2022)* and *SON (2015)*, the groundwater within Osogbo metropolis is of good quality save the central district area comprising of Osogbo District Council, Oke Bale and Isale Aro whose groundwater shows evidence of pollution.
2. The polluted central district is characterised by relatively low aquifer resistivity (< 100 Ωm), high TDS (623 – 1227 mg/L) and EC (903 – 1709 μs/m) and elevated concentrations of Na^+ (120 – 349 mg/L), Ca^{2+} (48 – 93 mg/L) and K^+ (25 – 60 mg/L). Other areas are characterised low-medium-high (up to 641 Ωm) aquifer resistivity and groundwater whose physicochemical parameters fall below the *WHO (2022)* and *SON (2015)* thresholds for potable water.
3. The pollution of the central district groundwater is suspected to be associated with relatively shallow water table and leachates from the ancient waste dumpsites and pit latrines common within the core of the ancient city.
4. The groundwater flow pattern is complex and multi-directional as is typical of a basement complex terrain. This makes it difficult to assess the influence of the groundwater flow pattern on pollution movement.
5. The integration of aquifer resistivity with hydrochemistry enables the differentiation of polluted weathered layer aquifers from the unpolluted ones in spite of their overlapping resistivity values.

Acknowledgements. The authors wish to appreciate Prof. M. O. Olorunfemi, formerly of the Department of Geology, Obafemi Awolowo University, Ile-Ife, Nigeria, for spending his time to edit the draft manuscript and enhance its quality. We are also grateful to anonymous reviewers for their suggestions, constructive criticism and invaluable remarks that added value to the quality of the paper.

Author contributions. OGB designed and supervised the study. OGB and GOO formulated suitable methods used for the study. OGB, GOO, IOA, KFA, ABE, HOA and SAB anchored the data acquisition. OGB, KFA and HOA handled the literature review. GOO, ABE, and IOA analysed and interpreted the data. KFA, IOA, ABE produced the figures. OGB prepared the final manuscript draft. All authors read manuscript and approved the final draft of the manuscript for submission.

Funding. This work does not receive financial support in form of funds or grants during the preparations of the manuscript.

Data availability. Data would be made available on request.

Conflict of interest declaration. Authors have no relevant financial or non-financial interest to disclose.

References

Adejuwon J. O., Jeje L. K., 1975: Land element of the environmental system of Ife Area. In: Ojo A. (Ed.): Environment Resource Base Project, No. 2, Department of Geography, University of Ife, Ile-Ife.

Adepelumi A. A., Ako B. D., Ajayi T. R., 2001: Groundwater contamination in the basement complex area of Ile-Ife Southwestern Nigeria: a case study using electrical resistivity method. Hydrogeol. J., **9**, 6, 611–622, doi: 10.1007/s10040-001-0160-x.

Adepelumi A. A., Ako B. D., Afolabi O., Arubayi J. B., 2005: Delineation of contamination plume around oxidation sewage-ponds in Southwestern Nigeria. Environ. Geol., **48**, 8, 1137–1146, doi: 10.1007/s00254-005-0056-5.

Akinwumiju A. S., Olorunfemi M. O., 2016: Shallow aquifer characteristics, borehole yield and groundwater resource sustainability assessment in the Osun drainage basin, southwestern Nigeria. Ife J. Sci., **18**, 2, 305–314.

Akinwumiju A. S., Olorunfemi M. O., 2018: Modeling groundwater flow system of a drainage basin in the basement complex environment of southwestern Nigeria. In: Proceedings of the International Cartographic Association (ICA), **1**, 1–7, doi: 10.5194/ica-proc-1-2-2017.

Ariyo S. O., Enikanoselu E. M., 2007: Integrated use of geoelectrical imaging and geochemical analysis in the environmental impact assessment of Egbe dumpsite in Ijebu-Igbo area, Southwestern Nigeria. Cont. J. Earth Sci., **1**, 3, 11–17.

Bayode S., Olorunfemi M. O., Ojo J. S., 2012: Integrated geoelectrical and hydrochemical investigation for environmental impact assessment of the area around some ancient dumpsites in Akure metropolis, southwestern Nigeria. Pac. J. Sci. Technol., **13**, 1, 700–713.

Bayowa O. G., Falebita D. E., Olorunfemi M. O., Adepelumi A. A., 2012: Groundwater contamination prediction using finite element derived geoelectric parameters constrained by chemical analysis around a sewage site, southwestern Nigeria. Int. J. Geosci., **3**, 2, 404–409, doi: 10.4236/ijg.2012.32045.

Bayowa O. G., Akinfotire O. Y., Onipede O. K., 2014: Electrical resistivity investigation for the assessment of groundwater contaminant plume flow direction around a sewage pond in Ile-Ife, Southwestern Nigeria. Sci. Focus, **19**, 1, 11–23.

Bayowa O. G., Falebita D. E., Adegboyega R. O., 2015: Surface DC resistivity survey of contamination beneath Ido-Osun dumpsite, southwestern Nigeria. Geofís. Int., **54**, 4, 343–352, doi: 10.22201/igeof.00167169p.2015.54.4.1700.

Bayowa O. G., Afolabi O. A., Akinluyi F. O., Oshanaiye A. O., Adelere I. O., Mudashir A. W., 2023a: Integrated geoelectric and hydrochemistry investigation for potential groundwater contamination around a reclaimed dump site in Taraa, Ogbomoso, Southwestern Nigeria. Int. J. Energy Water Resour., **7**, 1, 133–154, doi: 10.1007/s42108-021-00167-9.

Bayowa O. G., Ogungbesan G. O., Adelere I. O., Olasunkanmi N. K., Olatunbosun A. S., Alagbe A. O., 2023b: Groundwater potential assessment of shallow aquifers in the basement complex underlain Osogbo metropolis, Southwest Nigeria, using geo-electric attributes, Environ. Earth Sci., **82**, 9, 239, doi: 10.1007/s12665-023-10907-1.

Bernstone C,. Dahlin T., 1997: DC resistivity mapping of old landfills: Two case studies. Eur. J. Environ. Eng. Geophys., **2**, 121–136.

Buselli G., Lu K., 2001: Groundwater contamination monitoring with multichannel electrical and electromagnetic methods. J. Appl. Geophys., **48**, 1, 11–23, doi: 10.1016/S0926-9851(01)00055-6.

Eaton A. D., Clesceri L. S., Greenberg A. E., (Eds.), 1995: Standard methods for the examination of water and wastewater. 19th Ed., American Public Health Association (APHA), New York.

Ebraheem A. M., Senosy M. M., Dahab K. A., 1997: Geoelectric and hydrogeochemical studies for delineating ground-water contamination due to salt-water intrusion in the northern part of the Nile Delta, Egypt. Groundwater, **35**, 2, 216–222, doi: 10.1111/j.1745-6584.1997.tb00077.x.

Faniran A., Jeje L. K., 1983: Humid Tropical Geomorphology. Addison-Wesley Longman Ltd., London, 414 p.

Federal Ministry of Health & Social Welfare, Nigeria (FMHSW), n.d.: https://health.gov.ng/.

Freeze R. A., Cherry J. A., 1979: Groundwater. 1st Ed., Prentice-Hall, 604 p.

Frohlich R. K., Urish D. W., 2002: The use of geoelectrics and test wells for the assessment of groundwater quality of a coastal industrial site. J. Appl. Geophys., **50**, 3, 261–278, doi: 10.1016/S0926-9851(02)00146-5.

Google Maps, n.d.: Google Maps platform. https://mapsplatform.google.com/maps-products/earth/capabilities/.

Idornigie A. I., Olorunfemi M. O., Omitogun A. A., 2006: Electrical resistivity determination of subsurface layers, subsoil competence and soil corrosivity at an engineering site location in Akungba-Akoko, southwestern Nigeria. Ife J. Sci.,, **8**, 2, 159–177.

Igboama W. N., Hameed O. S., Fatoba J. O., Aremu I. E., Aroyehun M. T., 2021: Geo-electric and hydro-physicochemical investigations of Osogbo Central Dumpsite, Osogbo,Southwestern Nigeria. Arab. J. Geosci., **14**, 1361, doi: 10.1007/s12517-021-07766-0.

Jeihouni M., Toomanian A., Alavipanah S. K., Hamzeh S., Pilesjöb P., 2018: Long term groundwater balance and water quality monitoring in the eastern plains of Urmia Lake, Iran: A novel GIS based low cost approach. J. Afr. Earth Sci., **147**, 11–19, doi: 10.1016/j.jafrearsci.2018.06.017.

KayabalıK., Yüksel F. A., Yeken T., 1998: Integrated use of hydrochemistry and resistivity methods in groundwater contamination caused by a recently closed solid waste site. Environ. Geol., **36**, 3-4, 227–234, doi: 10.1007/s002540050339.

Kim K., Rajmohan N., Kim H., Kim S., Hwang G., Yun S., Gu B., Cho M. J., Lee S., 2005: Evaluation of geochemical processes affecting groundwater chemistry based on mass balance approach: A case study in Namwon, Korea. Geochemical Journal, **39**, 4, 357–369, doi: 10.2343/geochemj.39.357.

Lowrie W., 1997: Fundamentals of Geophysics. Cambridge University Press, United Kingdom, 368 p.

MacDonald A., Davies J., Callow R., Chilton J., 2005: Developing Groundwater: A guide for rural water supply. ITDG Publishing, UK, 384 p.

Mazor E., 1991: Applied Chemical and Isotopical Groundwater Hydrology. Open University Press, Milton Keynes, Bucks, Wiley, UK, 274 p.

Odipe O. E., Ogunleye R. A., Suleiman M., Abubakar S. S., Olorunfemi M. O., 2018: Integrated geophysical and hydrochemical investigations of impact of the Ijemikin waste dump site in Akure, southwestern Nigeria, on groundwater quality. J. Health Pollut., **8**, 18, 180604, doi: 10.5696/2156-9614-8.18.18060.

Ojo A. O., Oyelami C. A., Adereti A. O., 2014: Hydro-geochemical and geophysical study of groundwater in the suburb of Osogbo, South Western Nigeria. J. Earth Sci. Clim. Change., **5**, 6, 205, doi: 10.4172/2157-7617.1000205.

Ojo B. C., Osotuyi A. G., Olaiya B. T., Salako A. O., John S. J., Omoniyi A. R., 2023: Geoelectric signatures from a Leachate Plume mapped from a Basement Complex Terrain in Akure, Nigeria. Open J. Phys. Sci. (OJPS) (ISSN: 2734-2123), **4**, 2, 13–29, doi: 10.52417/ojps.v4i2.519.

Olayiwola A. M., Olaitan A. A., 2019: Spatial preference of urban residential location in Osogbo, Nigeria. Ghana J. Geogr., **11**, 1, 140–158, doi: 10.4314/gjg.v11i1.9.

Olla T. A., Akinlalu A. A., Olayanju G. M., Adelusi A. O., Adiat K. A., 2015: Geophysical and hydrochemical investigation of a municipal dumpsite in Ibadan, Southwest Nigeria. J. Environ. Earth Sci., **5**, 14, 99–112.

Olorunfemi M. O., 1990: The hydrogeological implication of topographic variation with overburden thickness in basement complex area of S.W. Nigeria. J. Min. Geol., **26**, 1, 145–152.

Olorunfemi M. O., 2020: Groundwater exploration, borehole site selection and optimum drill depth in basement complex terrain. NAH 2009 Special Publication Series 1, Revised Version, 43 p.

Olorunfemi M. O., Fasuyi S. A., 1993: Aquifer types and the geoelectric/hydrogeologic characteristics of part of the central basement terrain of Nigeria (Niger State). J Afr. Earth Sci., **16**, 3, 309–317, doi: 10.1016/0899-5362(93)90051-Q.

Olorunfemi M. O., Ojo J. S., Akintunde O. M., 1999: Hydro-geophysical evaluation of the groundwater potential of the Akure metropolis, southwestern Nigeria. J. Min. Geol., **35**, 2, 207–228.

Olorunfemi M. O., Okhue E. T., 1992: Hydro-geologic and geologic significance of a geoelectric survey at Ile-Ife, Nigeria. J. Min. Geol., **28**, 2, 221–229.

Oni A. G., Agunbiade O. J., Oluwawemimo M. A., Kolawole S. I., Ayowole-Obi A. O., 2023: Resistivity measurement and water quality analysis for the assessment of the impact of Ile-Oluji waste dumpsite in Ondo State, Southwestern Nigeria, on the environment. Research Square, preprint, doi: 10.21203/rs.3.rs-2665887/v1.

Osun State Government, 2025: Major Towns: Osogbo. The Official Website of the State of Osun. https://www.osunstate.gov.ng/h0me/, accessed 26 June, 2025.

Oyelami C. A., Ojo O. A., Aladejana J. A., Agbede O. O., 2013: Assessing the effect of a dumpsite on groundwater quality: case study of Aduramigba Estate within Osogbo metropolis. J. Environ. Earth Sci., **3**, 1, 120–130.

Panigrahy P. I. C., Sahu S. D., Sahu B. K., Sathyanarayana D., 1996: Studies on the distribution of calcium and magnesium in Visakhapatnam harbour waters, Bay of Bengal. In: Procedings, International Symposium on Applied Geochemistry, Osmania University, Hyderabad, pp. 353–340.

Piper A. M., 1994: A graphic procedure in the geochemical interpretation of water-analyses. Trans. Am. Geophys. Union, **25**, 6, 914–923, doi: 10.1029/tr025i006p00914.

Rahaman M. A., 1989: Review of the basement geology of southwestern Nigeria. In: Kogbe C. A. (Ed.): Geology of Nigeria (2nd Ed.), Rock View, pp. 39–56.

Satpathy B. N., Kanungo D. N., 1976: Groundwater exploration in hard-rock terrain: A case history. Geophys. Prospect., **24**, 4, 725–736, doi: 10.1111/j.1365-2478.1976.tb01569.x.

Senos Matias M., Marques da Silva M., Ferreira P., Ramalho E., 1994: A geophysical and hydrogeological study of aquifers contamination by a landfill. J. Appl. Geophys., **32**, 2-3, 155–162, doi: 10.1016/0926-9851(94)90017-5.

Sharma P. V., 2004: Environmental and engineering geophysics. Cambridge University Press, 475 p.

Sheriff R. E., 1991: Encyclopedic dictionary of exploration geophysics (3rd Ed.). Geophysical References Series 1, Society of Exploration Geophysicists (SEG), Tulsa, USA.

Srinivasamoorthy K., Gopinath M., Chidambaram S., Vasanthavigar M., Sarma V. S., 2014: Hydrochemical characterization and quality appraisal of groundwater from Pungar subbasin, Tamilnadu, India. J. King Saud Univ. Sci., **26**, 1, 37–52, doi: 10.1016/j.jksus.2013.08.001.

Standards Organisation of Nigeria (SON), 2015: Nigerian Standard for Drinking Water Quality (NIS-554-2015). SON Publication, Abuja, Nigeria, 28 p., retrieved from https://africacheck.org/sites/default/files/Nigerian-Standard-for-Drinking-Water-Quality-NIS-554-2015.pdf.

Sustainable Development Goals (SDG), 2025: Sustainable Development Goal 6: Ensure availability and sustainable management of water and sanitation for all, targets and indicators. Available at https://sdgs.un.org/goals/goal6#targets_and_indicators, accessed 13 June 2025.

Telford W. M., Geldart L. P., Sherif R. A., 1990: Applied geophysics (2nd Ed.). Cambridge Univ. Press, pp. 553–770.

Tijani M. N., Onodera S., 2009: Hydrogeochemical assessment of metal contamination in an urban drainage system: A case study of Osogbo township, SW-Nigeria. J. Water Resour. Prot., **1**, 3, 164–173, doi: 10.4236/jwarp.2009.13021.

United State Environmental Protection Agency (USEPA), 1983: Methods of chemical analysis of water and wastes. Environmental Monitoring and Support Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, Ohio 45268.

World Health Organization (WHO), 2022: Guidelines for Drinking-Water Quality. (4th Ed., incorporating first and second addenda). World Health Organisation, Geneva, Switzerland.

Zohdy A. A. R., Eaton G. P., Mabey D. R., 1980: Application of surface Geophysics to Groundwater Investigations: Techniques of Water-Resources investigations of the United States Geological Survey, pp. 1-3.

Zonge K., Wynn J., Urquhart S., 2005: Resistivity, Induced Polarization and Complex Resistivity (chapter 9). In: Butler D. K. (Ed.): Near Surface Geophysics. Society of Exploration Geophysics, pp. 265–300, doi: 10.1190/1.9781560801719.ch9.

Zume J. T., Tarhule A., Christenson S., 2006: Subsurface imaging of an abandoned solid waste landfill site in Norman, Oklahoma. Groundw. Monit. Remediat., **26**, 2, 62–69, doi: 10.1111/j.1745-6592.2006.00066.x.

Appendix 1

Table A1. Well location, depth and water level data.

Well No	Latitude (N)	Longitude (E)	Elevation (m)	Well Depth (m)	Static Water Level (m)	Water Level Elevation (m)
1	07°49.67′	04°36.63′	374	24.80	20.10	353.90
2	07°49.52′	04°36.53′	373	18.70	16.27	356.73
3	07°48.35′	04°35.34′	371	50.70	40.69	330.31
4	07°49.40′	04°35.13′	372	31.87	18.60	353.40
5	07°47.41′	04°33.12′	362	14.24	10.80	351.20
6	07°48.19′	04°32.16′	345	16.80	13.90	331.10
7	07°47.92′	04°31.38′	354	33.90	24.30	329.70
8	07°46.82′	04°30.94′	341	18.50	16.90	324.10
9	07°47.14′	04°31.67′	339	22.20	12.10	326.90
10	07°46.82′	04°32.51′	351	25.20	22.10	328.90
11	07°45.45′	04°31.45′	334	23.80	23.00	311.00
12	07°44.22′	04°33.69′	323	16.40	13.70	309.30
13	07°45.81′	04°33.31′	324	23.40	15.20	308.80
14	07°46.48′	04°33.81′	311	12.90	10.40	300.60
15	07°45.46′	04°34.51′	320	8.95	5.30	314.70

Table A1. Continued from the previous page.

Well No	Latitude (N)	Longitude (E)	Elevation (m)	Well Depth (m)	Static Water Level (m)	Water Level Elevation (m)
16	07°47.30′	04°35.69′	334	12.50	5.20	328.80
17	07°46.94′	04°36.14′	331	20.40	14.60	316.40
18	07°46.81′	04°36.78′	337	21.90	11.80	325.20
19	07°47.28′	04°36.24′	332	17.10	15.40	316.60
20	07°46.50′	04°35.21′	326	17.70	14.95	311.05
21	07°46.57′	04°36.51′	335	24.50	21.20	313.80
22	07°48.08′	04°34.92′	323	11.20	6.60	316.40
23	07°47.88′	04°34.61′	345	28.20	14.60	330.40
24	07°46.72′	04°34.92′	350	29.80	17.30	332.70
25	07°46.00′	04°35.28′	354	28.20	19.70	334.30
26	07°45.32′	04°34.50′	348	30.80	27.30	320.70
27	07°46.34′	04°32.52′	339	30.00	20.30	318.70
28	07°47.45′	04°30.13′	341	34.50	30.00	311.00
29	07°46.51′	04°34.70′	329	16.80	4.65	324.35
30	07°47.10′	04°33.22′	342	18.00	16.10	325.90
31	07°48.92′	04°31.54′	329	19.30	17.80	311.20
32	07°47.82′	04°35.18′	362	42.60	30.20	331.80
33	07°48.49′	04°34.85′	325	12.80	9.80	315.20
34	07°48.41′	04°33.60′	340	23.60	18.40	321.60
35	07°47.86′	04°32.51′	345	30.80	17.20	327.80
36	07°46.38′	04°34.98′	353	42.60	31.50	321.50
37	07°45.45′	04°33.62′	354	12.50	8.40	345.60
38	07°46.30′	04°31.59′	352	28.70	27.20	324.80
39	07°46.12′	04°31.12′	343	6.00	3.10	339.90
40	07°47.41′	04°32.31′	343	17.10	13.20	329.80
41	07°48.06′	04°33.64′	350	42.10	34.80	315.20
42	07°47.41′	04°31.87′	350	14.80	13.00	337.00
43	07°46.32′	04°32.65′	351	33.00	25.20	325.80
44	07°45.70′	04°35.86′	370	21.00	19.10	350.90
45	07°44.67′	04°32.50′	356	21.40	17.20	338.80
46	07°43.66′	04°35.86′	357	34.80	26.30	330.70
47	07°45.44′	04°33.85′	366	29.80	25.90	340.10
48	07°44.52′	04°30.18′	353	30.70	23.40	329.60
49	07°45.30′	04°30.34′	350	24.00	13.30	336.70
50	07°44.79′	04°35.40′	331	31.30	20.40	310.60
51	07°44.46′	04°34.20′	337	22.80	15.40	321.60
52	07°45.45′	04°33.62′	343	34.70	30.40	312.60
53	07°43.97′	04°32.53′	330	16.30	10.20	319.80

Table A1. Continued from the previous page.

Well No	Latitude (N)	Longitude (E)	Elevation (m)	Well Depth (m)	Static Water Level (m)	Water Level Elevation (m)
54	07°43.16′	04°34.27′	342	34.90	29.30	312.70
55	07°44.81′	04°34.73′	337	27.90	10.60	326.40
56	07°44.81′	04°34.21′	334	15.20	14.10	319.90
57	07°45.09′	04°34.73′	343	32.40	19.70	323.30
58	07°45.31′	04°32.28′	337	31.20	25.30	311.70
59	07°45.72′	04°32.28′	339	24.80	18.40	320.60
60	07°45.89′	04°31.86′	343	19.50	11.70	331.30
61	07°43.77′	04°34.00′	342	32.50	21.80	320.20
62	07°44.07′	04°35.23′	354	38.10	29.70	324.30
63	07°45.72′	04°33.91′	339	29.20	22.50	316.50
64	07°44.61′	04°32.65′	329	17.20	13.20	315.80
65	07°47.99′	04°31.68′	319	25.40	15.40	303.60
66	07°48.42′	04°36.16′	314	6.20	6.00	308.00
67	07°49.64′	04°35.01′	314	16.20	12.50	301.50
68	07°48.66′	04°34.41′	315	17.10	9.00	306.00
69	07°47.97′	04°33.97′	323	32.80	24.70	298.30
70	07°50.09′	04°32.25′	333	32.80	24.70	308.30
71	07°49.44′	04°31.67′	315	24.70	18.50	296.50
72	07°48.80′	04°31.57′	327	23.00	13.60	313.40
73	07°50.03′	04°30.34′	334	24.70	18.50	315.50
74	07°50.13′	04°34.64′	330	17.60	10.40	319.60
75	07°50.01′	04°33.40′	327	27.20	17.60	309.40
76	07°49.73′	04°32.02′	315	19.00	8.50	306.50
77	07°48.24′	04°31.40′	334	27.80	18.30	315.70
78	07°47.29′	04°30.80′	337	28.40	13.30	323.70
79	07°48.96′	04°31.24′	351	36.10	24.10	326.90
80	07°49.47′	04°30.21′	355	34.40	26.60	328.40
81	07°49.67′	04°30.76′	343	28.90	23.10	319.90
82	07°49.70′	04°31.81′	335	18.70	9.50	325.50
83	07°48.61′	04°32.56′	340	18.90	14.80	325.20
84	07°47.72′	04°33.42′	343	18.50	16.20	326.80
85	07°47.65′	04°34.27′	353	19.20	15.10	337.90
86	07°46.94′	04°33.14′	344	24.70	18.70	325.30
87	07°46.75′	04°33.65′	334	7.10	5.80	328.20
88	07°46.60′	04°32.65′	322	13.30	7.20	314.80
89	07°44.48′	04°33.10′	327	20.80	20.10	306.90
90	07°44.14′	04°32.21′	312	11.80	3.50	308.50
91	07°44.73′	04°31.07′	317	16.60	6.00	311.00

Table A1. Continued from the previous page.

Well No	Latitude (N)	Longitude (E)	Elevation (m)	Well Depth (m)	Static Water Level (m)	Water Level Elevation (m)
92	07°45.41′	04°31.32′	311	15.70	12.70	298.30
93	07°44.69′	04°32.56′	328	15.70	12.70	315.30
94	07°45.42′	04°33.61′	308	9.30	5.60	302.40
95	07°46.89′	04°32.79′	307	9.30	7.10	299.90
96	07°46.71′	04°31.28′	325	27.10	15.30	309.70
97	07°46.50′	04°30.40′	333	29.10	20.20	312.80
98	07°46.21′	04°30.11′	310	14.60	10.90	299.10
99	07°45.61′	04°30.21′	329	45.40	36.90	292.10
100	07°45.72′	04°32.52′	330	15.30	13.00	317.00
101	07°48.44′	04°32.28′	331	28.00	16.90	314.10
102	07°45.71′	04°33.51′	333	21.60	16.30	316.70
103	07°47.50′	04°32.35′	335	31.70	24.00	311.00
104	07°45.23′	04°33.14′	319	32.50	21.60	297.40
105	07°45.23′	04°34.75′	321	26.90	20.70	300.30
106	07°47.58′	04°35.25′	329	24.30	18.40	310.60
107	07°46.08′	04°30.73′	322	13.70	11.50	310.50
108	07°45.02′	04°32.20′	327	16.20	13.20	313.80
109	07°46.19′	04°33.05′	307	20.80	19.50	287.50
110	07°46.45′	04°32.65′	309	19.40	17.20	291.80
111	07°47.32′	04°33.15′	311	15.10	11.10	299.90
112	07°44.66′	04°34.38′	336	18.30	15.20	320.80
113	07°43.91′	04°33.18′	339	25.90	22.40	316.60
114	07°43.36′	04°34.50′	324	23.20	19.30	304.70
115	07°43.61′	04°35.00′	324	31.90	21.30	302.70
116	07°44.48′	04°34.30′	324	19.60	15.50	308.50
117	07°44.49′	04°33.08′	311	21.20	15.00	296.00
118	07°44.32′	04°32.59′	315	18.80	12.60	302.40