

Integrated GIS–AHP and 2-D Electrical Resistivity Tomography for Environmental Assessment of Solid-Waste Dumpsites in Gombe Metropolis, Nigeria

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ABSTRACT

Open dumping of municipal solid waste can expose surface water and groundwater to leachate, yet surface environmental constraints and subsurface conditions are often assessed separately. This study aimed to integrate the GIS-based Analytic Hierarchy Process (AHP) with two-dimensional electrical resistivity tomography (2-D ERT) to assess the environmental setting and potential subsurface contamination pathways of existing solid-waste dumpsites in Gombe Metropolis, northeastern Nigeria. Sixteen dumpsites were mapped, ten spatial criteria were weighted by AHP, and ten dumpsites were surveyed with Wenner–Schlumberger 2-D ERT profiles of 100 m and 5 m electrodes spacing. Distance from wells/boreholes (27.65%), distance from rivers (19.52%), geology (13.41%) and land use/land cover (10.84%) received the highest weights (consistency ratio = 0.0362). About 80.28% of the analysed area lies within 500 m of rivers/streams and 15.30% within 500 m of wells/boreholes. Very low resistivities (<10 Ω m) occurred at seven of the ten surveyed dumpsites, whereas Bypass Doma House was comparatively resistive (mostly >200 Ω m). Combining both lines of evidence, Bagadaza GRA Bypass, Bui Road WD2, Liji WD1 and Yalanguruza, where extensive low-resistivity zones lie within 500 m of mapped boreholes, emerged as the highest priorities for hydrochemical verification. The integrated framework shows that water-resource protection, lithological and structural pathways, and subsurface conductivity should be evaluated together when assessing urban dumpsites. Because low resistivity can also reflect clay-rich or saturated materials, the conductive zones indicate possible leachate influence rather than confirmed groundwater contamination. The final GIS-AHP suitability map was mapped and the suitability classes as the outcome of the weighted spatial analysis.

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INTRODUCTION

Rapid urban growth and inadequate waste-management infrastructure have increased reliance on open or poorly controlled dumpsites in many developing cities (Kaza et al., 2018). The environmental concern is not limited to the visible accumulation of waste. Rainfall infiltrating decomposing waste can generate ion-rich leachate that may migrate through soil, weathered material, fractures, and aquifer units, while contaminated runoff may reach nearby streams. Consequently, the environmental

condition of a dumpsite depends on both its surface setting and the physical properties of the subsurface. GIS-based multi-criteria decision analysis (MCDA) provides a transparent way to combine environmental, hydrogeological, terrain, and infrastructure factors in waste-disposal assessment. AHP is particularly useful for assigning relative importance to criteria that differ in units and environmental significance (Saaty, 1980). Previous studies have used GIS–AHP or related MCDA approaches to evaluate landfill suitability in Nigeria and elsewhere (Ajibade et al., 2019; Rane et al., 2024; Tella

et al., 2025). Recent work continues to show that proximity to water resources, geology, land use, slope, and accessibility are among the important controls in landfill-suitability models (Bhowmick et al., 2024; Tella et al., 2025).

Surface suitability, however, does not establish what is occurring beneath an existing dumpsite. Electrical resistivity tomography provides continuous lateral and vertical information on subsurface electrical properties (Loke et al., 2013). Because dissolved ions increase pore-fluid conductivity, leachate-affected materials may produce conductive anomalies. Nigerian studies have demonstrated the usefulness of resistivity imaging for dumpsite investigations (Agu et al., 2023; Alao et al., 2024; Kamilu et al., 2026; Okpoli, 2013; Ugbor et al., 2021). Nevertheless, low resistivity is not diagnostic of leachate because clay-rich or naturally saturated materials can produce similar responses. Independent geological and hydrochemical evidence is therefore important for interpretation (Alao et al., 2024; Osifo & Ogumeyo, 2026).

Within Gombe and the wider Upper Benue Trough, previous hydrogeological and geoelectrical studies have focused mainly on groundwater occurrence and aquifer potential (Iyoriobhe & Ako, 1986; Kwami et al., 2019; Oniku et al., 2025; Rauff et al., 2025); in the Yola area, GIS-based weighting has been combined with resistivity sounding, but for groundwater prospecting rather than waste-disposal assessment (Oniku et al., 2025). Dumpsite investigations elsewhere in Nigeria have generally applied geoelectrical and geochemical methods to individual sites (Alao et al., 2024; Okpoli, 2013; Ugbor et al., 2021), and GIS-based studies have mainly addressed the siting of new landfills (Ajibade et al., 2019; Tella et al., 2025). To our knowledge, the existing dumpsites of Gombe Metropolis have not yet been assessed within a single framework that combines city-scale environmental screening with site-scale subsurface imaging; this is the research gap addressed

here. Combining the two approaches is scientifically justified because each compensates for a weakness of the other: the receptor and pathway setting derived from GIS–AHP constrains the interpretation of non-unique resistivity anomalies, while 2-D ERT tests whether the subsurface beneath each dumpsite is consistent with the vulnerability implied by the surface criteria.

This study aims to integrate GIS-based Analytic Hierarchy Process and two-dimensional electrical resistivity tomography to assess the environmental suitability and potential subsurface contamination pathways of existing solid-waste disposal sites in Gombe Metropolis, Nigeria.

Study Area

Gombe Metropolis is located in northeastern Nigeria between approximately 10°15'–10°21' N and 11°07'–11°15' E (Fig. 1a). The area has a tropical continental climate with distinct wet and dry seasons and lies within the Sudan Savannah zone. The geological succession includes the Kerri-Kerri Formation, Gombe Sandstone, Pindiga Formation, Yolde Formation, Bima Formation, and locally occurring Basement Complex rocks (Carter et al., 1963; Obaje, 2009; Zaborski et al., 1997). The Bima Formation consists mainly of coarse fluvial sandstones, the Yolde Formation of transitional sandstones and shales, the Pindiga Formation of marine shales and limestones, the Gombe Sandstone of sandstones, siltstones, shales and ironstones, and the Kerri-Kerri Formation of continental sandstones and claystones (Obaje, 2009). These units differ in lithology, permeability, weathering, and structural characteristics, which influence groundwater occurrence and the potential movement of contaminants; the hydrogeology of the Gombe sub-catchment is described by Iyoriobhe and Ako (1986). Sixteen existing waste-disposal sites were located by GPS and incorporated into the GIS database (Fig. 1b).

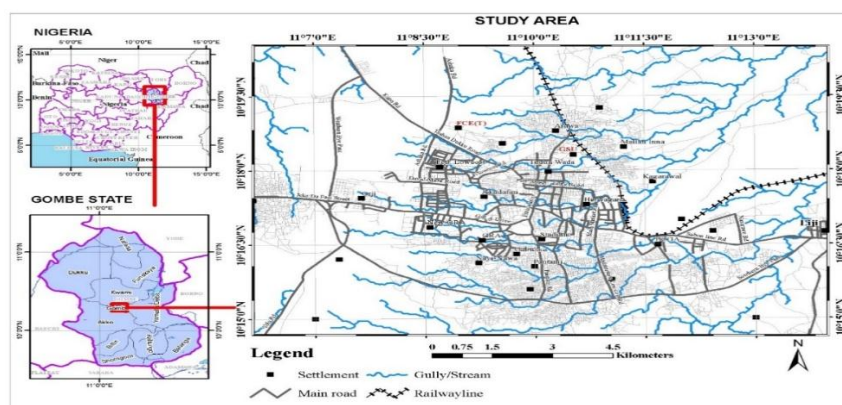


Figure 1(a): Location Map of the Study Area, Gombe Metropolis, Nigeria

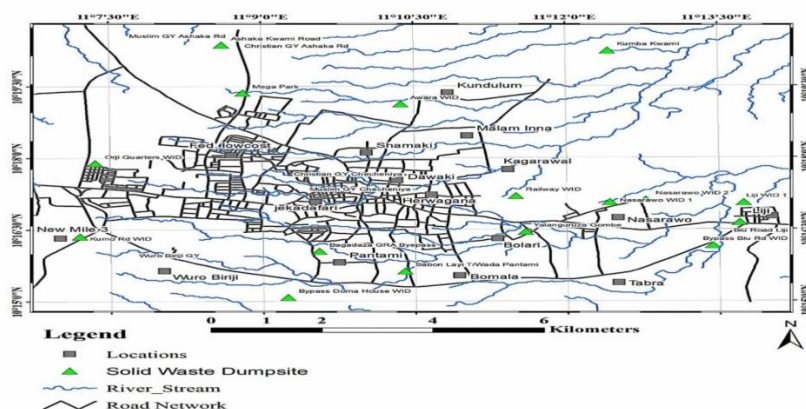


Figure 1(b): Map of Existing Solid-Waste Dumpsites in Gombe Metropolis

MATERIALS AND METHODS

Remote Sensing and GIS Datasets

Landsat satellite imagery was performed at 30 m spatial resolution, dated 24/05/2025 and used for Land Use and Land Cover classification and visual interpretation of surface features were gotten from USGS Earth explorer. The spatial database combined Landsat imagery, a digital elevation model (DEM), geological and soil maps, road and river/stream networks, field-mapped well/borehole locations, lineaments, and GPS coordinates of existing dumpsites. Landsat imagery was used for land-use/land-cover (LULC) classification, while the DEM was used to derive elevation, slope, and aspect. All spatial datasets were projected to WGS 84/UTM Zone 32N, clipped to the analysis boundary, rasterized where necessary, and standardized to a 30 m spatial resolution. The ten criteria were selected from the factors commonly used in GIS-based landfill and dumpsite assessments in relation to groundwater

contamination (Ajibade et al., 2019; Bhowmick et al., 2024; Rane et al., 2024; Tella et al., 2025), subject to the availability of data for Gombe Metropolis. Proximity to roads, rivers/streams, wells/boreholes and lineaments was represented by distance/buffer classes, and each criterion layer was reclassified into the classes shown in Figs. 2a–2j and assigned suitability scores before weighting. Lineaments were extracted from geological information and enhanced imagery, and distance to the nearest mapped lineament was used as an indicator of possible preferential subsurface pathways. Because the soil units in the available soil map follow the geological boundaries closely (Figs. 2i and 2j), the soil and geology layers are not fully independent, and their combined weight (18.66%) is interpreted as a single lithology-related control. Table 1 summarizes the spatial criteria, rank, their data sources, environmental roles and AHP weights.

Table 1: Spatial Criteria used in the GIS–AHP Assessment

Criterion	Rank	Data/derivation	Environmental role	AHP weight (%)
Well/borehole distance	1	Field GPS; proximity analysis	Groundwater receptor protection	27.65
River/stream distance	2	Hydrological network; proximity analysis	Surface-water protection	19.52
Geology	3	Geological map	Permeability/attenuation and lithological control	13.41
LULC	4	Landsat supervised classification/USGS	Land-use conflict and exposure	10.84
Slope	5	DEM	Runoff, erosion and engineering feasibility	8.39
Road distance	6	Road network; proximity analysis	Access versus nuisance/exposure	6.96
Soil	7	Soil map	Initial infiltration/attenuation	5.25
Lineament distance	8	Imagery/geology; proximity analysis	Potential fracture-controlled pathways	3.60
Elevation	9	DEM	Terrain/drainage context	2.52
Aspect	10	DEM	Secondary terrain/microclimatic context	1.85

AHP Weighting and Spatial Integration

The ten criteria were compared pairwise using Saaty's 1–9 scale (Saaty, 1980), giving the comparison matrix in Table 2. Each element of the matrix was divided by

its column sum (last row of Table 2), and the criterion weights were obtained as the row means of this normalized matrix, which approximate the principal eigenvector. Consistency was evaluated using the

consistency ratio (CR), with $CR < 0.10$ adopted as acceptable. The principal eigenvalue ($\lambda_{\max}$) of the matrix was used to calculate the consistency index (CI) using Equation 1:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (1)$$

The consistency ratio (CR) was then computed using Equation 2:

$$CR = \frac{CI}{RI} \quad (2)$$

Where $\lambda_{\max}$ is the principal eigenvalue of the pairwise comparison matrix, n is the number of criteria ($n = 10$) and RI is the random index for a matrix of order n (RI = 1.49 for $n = 10$). For the matrix in Table 2, $\lambda_{\max} = 10.485$, $CI = 0.0539$ and $CR = 0.0362$, well below the 0.10 threshold, which indicates acceptably consistent judgments (Saaty, 1980, Okereke et al., 2026).

Table 2: Pairwise Comparison Matrix of the Ten Criteria

Criteria	Well	River	Geology	LULC	Slope	Road	Soil	Lin.	Elev	Aspect
Well	1	2	3	4	4	5	5	6	7	8
River	0.50	1	2	3	3	4	4	5	6	7
Geology	0.33	0.50	1	2	2	3	3	4	5	6
LULC	0.25	0.33	0.50	1	2	2	3	4	5	6
Slope	0.25	0.33	0.50	0.50	1	2	2	3	4	5
Road	0.20	0.25	0.33	0.50	0.50	1	2	3	4	5
Soil	0.20	0.25	0.33	0.33	0.50	0.50	1	2	3	4
Lin.	0.17	0.20	0.25	0.25	0.33	0.33	0.50	1	2	3
Elevation	0.14	0.17	0.20	0.20	0.25	0.25	0.33	0.50	1	2
Aspect	0.13	0.14	0.17	0.17	0.20	0.20	0.25	0.33	0.50	1
Sum	3.17	5.18	8.28	11.95	13.78	18.28	21.08	28.83	37.50	47.00

Principal Eigen value $\lambda_{\max} = 10.485$; consistency index $CI = 0.0539$; random index $RI = 1.49$; consistency ratio $CR = 0.0362$. Note: A value greater than 1 indicates that the row criterion is more important than the column criterion, 1 indicates equal importance, and reciprocal values indicate lesser importance. Sum = column sum, calculated from the exact reciprocals (e.g., $1/3$ rather than 0.33). Lin. = lineament; Elev = elevation.

To represent the relative significance of each layer in the decision-making process, each reclassified thematic layer was multiplied by its AHP-derived weight, and the suitability index (SI) was computed by weighted linear combination (Equation 3):

$$SI = \sum_{i=1}^n W_i R_i \quad (3)$$

Where W_i is the AHP-derived weight of criterion i (Table 1; the weights sum to 1), R_i is the reclassified suitability score of criterion i , and $n = 10$ is the number of criteria.

This operation produced a composite raster layer representing cumulative suitability scores across the study area.

2-D Electrical Resistivity Tomography

Ten of the sixteen dumpsites were investigated using an ABEM Terrameter, the remaining six were not considered because of their age, distance from water source and geographical conditions that cannot warrant 100 m profile. Each profile was 100 m long, with 21 electrode positions arranged in the Wenner–Schlumberger configuration at a basic electrode spacing (a) of 5 m, and measurements were acquired for increasing separation factors (n) to obtain depth information; the resulting inverse models extend to about 15.9 m depth. The measured resistances (R) were converted to apparent resistivity (ρ_a) using Equations 4 and 5:

$$\rho_a = kR \quad (4)$$

$$k = \pi n(n + 1)a \quad (5)$$

Where ρ_a is the apparent resistivity (Ωm), R is the measured resistance (Ω), k is the geometric factor (m) of the Wenner–Schlumberger array, a is the basic electrode spacing (5 m), n is the separation factor ($n = 1, 2, 3, \dots$) and $\pi \approx 3.142$.

The data was computed using excel spreadsheet and saved to *.Dot file. The apparent-resistivity data were inverted with RES2DINV (64-bit), which uses a smoothness-constrained least-squares inversion (Loke & Barker, 1996; Loke et al., 2013), to generate two-dimensional subsurface resistivity models. All ten inversions were stopped at the fourth iteration; RES2DINV (Table 3). Interpretation focused on the magnitude, depth, and lateral continuity of conductive anomalies. Conductive zones were treated as possible leachate-affected materials only where the dumpsite setting made such an interpretation plausible; the non-uniqueness of resistivity was retained as a central limitation.

Integration Framework

The integrated interpretation followed a source–pathway–receptor logic. Existing dumpsites represent potential contaminant sources; soils, permeable or weathered geological materials, fractures/lineaments,

and terrain-related drainage form potential pathways; and wells/boreholes, rivers/streams, settlements, and productive land represent receptors. GIS-AHP was used to characterize the surface environmental setting, while 2-D ERT provided site-scale evidence of subsurface electrical heterogeneity. The two datasets were integrated quantitatively: with numerical index combining the suitability index and resistivity values in tables. For each surveyed site, the distance classes to the nearest mapped well/borehole and stream and the mapped geological unit were read from the thematic layers (Figs. 2e, 2f and 2j) and compared with the 2-D ERT evidence. Each site was then assigned an indicative follow-up priority: high, where a very low-resistivity zone (lowest resistivity value below 15 Ωm) occurs within 500 m of a mapped well/borehole; elevated, where such a zone occurs farther from mapped wells/boreholes; and lower, where no zone below 15 Ωm was imaged. This threshold matches the <15 Ωm level interpreted as leachate accumulation at the Kurata dumpsite, southwestern Nigeria (Kamilu et al., 2026). The priority expresses the need for confirmatory investigation and is not a classification of contamination.

RESULTS AND DISCUSSION

Spatial Environmental Constraints

The GIS analysis mapped sixteen existing solid-waste disposal sites across Gombe Metropolis (Fig. 1b). Water-resource protection emerged as the strongest spatial constraint. Approximately 54.45 km² (80.28%) of the 67.8 km² analysis area lies within 500 m of rivers or streams (Fig. 2e). For groundwater abstraction points, 10.37 km² (15.30%) lies within 500 m of wells/boreholes, whereas 35.39 km² (52.18%) lies more than 2,000 m away (Fig. 2f). These results show that a large part of the urban area is strongly constrained by surface-water proximity, while groundwater-receptor risk is more spatially variable. Because the mapped wells and boreholes are concentrated in the central,

southern and eastern settlements, the >2,000 m class partly reflects the coverage of the field inventory rather than an absence of groundwater users.

Land-use and terrain conditions further constrain disposal. Built-up land accounts for 26.59 km² (41.40%) of the 64.3 km² classified LULC area and agricultural land for 17.88 km² (27.80%), indicating substantial potential conflict between waste disposal, settlement, and productive land (Fig. 2g). Bare/open land represents 11.80 km² (18.34%), but open land cannot be considered environmentally suitable without considering water resources, geology, soil, and structural controls. Slope analysis indicates that 23.81 km² (35.12%) occurs at 0–5°, while 11.26 km² (16.61%) exceeds 15° (Fig. 2h). Gentle terrain can reduce engineering difficulty and erosion risk, but low slope alone does not provide hydrogeological protection. Elevation ranges from about 340 to 700 m, with the highest ground (>550 m) in the west, on the Kerri-Kerri Formation, and an isolated ridge in the east (Fig. 2c); outside this ridge, aspect shows no dominant orientation (Fig. 2b). Most of the built-up area lies within 500 m of a road (Fig. 2d).

The structural analysis also has hydrogeological implications: about 55.07% of the analysed area lies within 1 km of mapped lineaments (Fig. 2a). This does not demonstrate that every mapped lineament is an open or hydraulically connected fracture, but it identifies areas where structural controls deserve additional field verification. The Kerri-Kerri Formation underlies the western part of the area, while the Gombe Sandstone, Pindiga, Yolde and Bima formations, with a small inlier mapped as Basement Complex, occur in NNE–SSW-trending belts to the east (Fig. 2j); the soil units largely follow these geological boundaries (Fig. 2i). Geological and soil classes should therefore be interpreted as spatial proxies for permeability rather than direct measurements of hydraulic conductivity. The spatial percentages and corresponding areas differences in thematic classifications was due to no data cell.

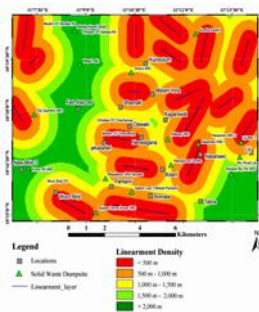


Figure 2(a): Distance from Lineaments

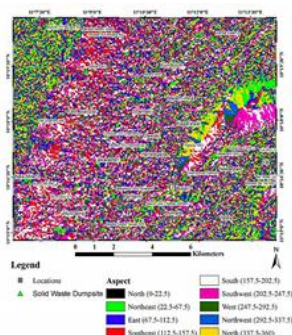


Figure 2(b): Aspect

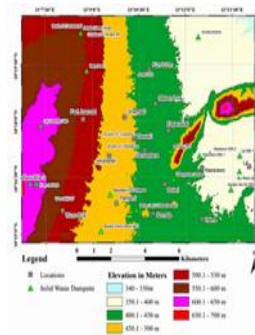


Figure 2(c): Elevation

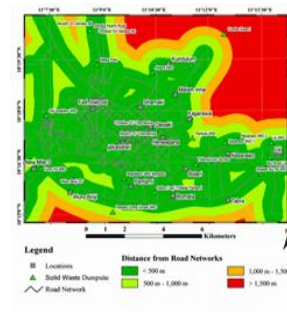


Figure 2(d): Distance from Road Network

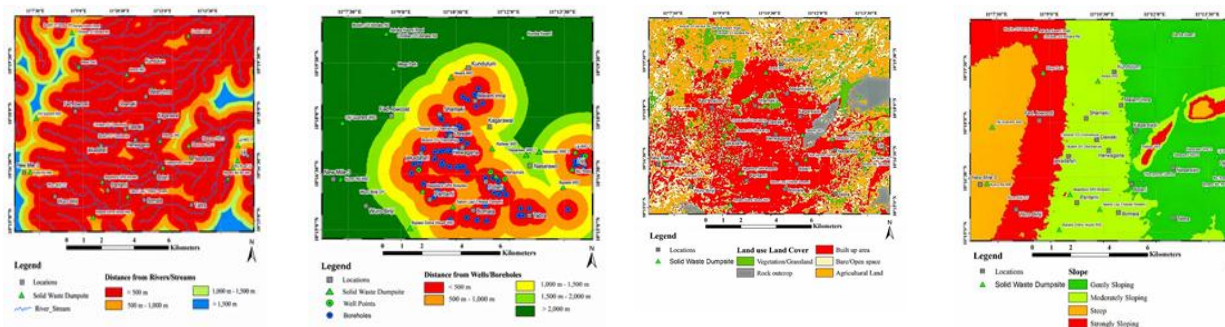


Figure 2(e): Distance from River/Stream

Figure 2(f): Distance from Well/Borehole

Figure 2(g): Land Use/Land Cover

Figure 2(h): Slope

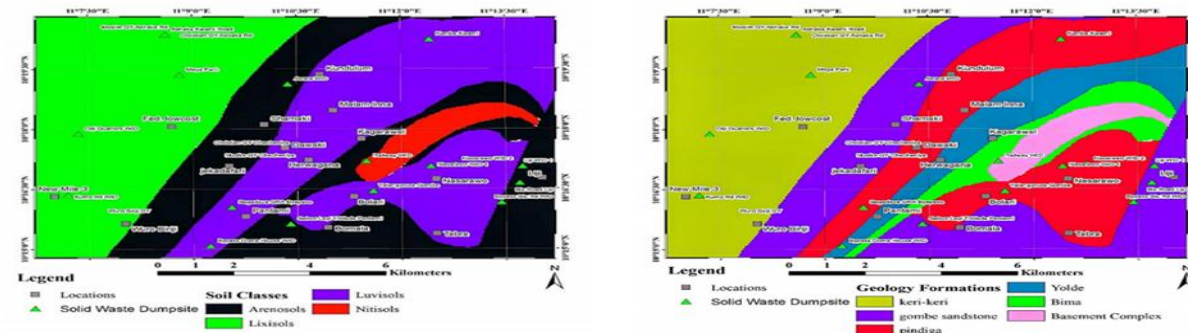


Figure 2(i): Soil Classes

Figure 2(j): Geology

Figure 2: Criterion Maps used in the GIS–AHP Assessment of Gombe Metropolis.

AHP Criterion Priorities

The AHP weights (Table 1) place well/borehole distance first (27.65%), followed by river distance (19.52%), geology (13.41%) and LULC (10.84%); the remaining six criteria together account for 28.57%. Together, well and river distance account for 47.17% of the total weight, demonstrating that the decision structure is dominated by protection of water receptors. The priority structure is environmentally defensible because operational accessibility should not compensate for a serious threat to groundwater or surface water. Because weighted linear combination is fully compensatory, however, high scores on secondary criteria can partly offset proximity to a receptor; for the siting of any new landfill, minimum separation distances from wells/boreholes and streams should therefore be applied as exclusion constraints before the weighted overlay. Comparable GIS-MCDA studies have likewise given substantial importance to water

resources, lithology, land use, and terrain (Ajibade et al., 2019; Rane et al., 2024; Tella et al., 2025).

Subsurface Resistivity Characteristics of the Dumpsites

The 2-D ERT results show marked spatial variability among the ten surveyed dumpsites (Figs. 3a–3j). Very conductive materials ($<10 \Omega\text{m}$) occur at Ashaka–Kwami Road, Mega Park, Bagadaza GRA Bypass, Liji WD1, Kumo Road, Kurba Kwami, and Biu Road WD2. Yalanguruza and Railway show their lowest contour values in the 10–50 Ωm range, whereas Bypass Doma House is distinctly more resistive, with a colour scale of 103–670 Ωm . The contrast demonstrates why surface GIS screening alone is insufficient for evaluating existing dumpsites: sites that occupy broadly similar urban settings can have different subsurface electrical signatures. Table 3 summarizes the resistivity classes represented in each inverse model section.

Table 3: Summary of 2-D ERT Resistivity Classes across the Ten Surveyed Dumpsites

Dumpsite (Fig.)	$<10 \Omega\text{m}$	10–50 Ωm	50–400 Ωm	$>400 \Omega\text{m}$	Interpretive note
Ashaka–Kwami Road (3a)	3.83–6.25	12.9–26.7	55.2–235	486	Deep, broad conductive zone below ~6 m; possible leachate-affected materials
Bagadaza GRA Bypass (3b)	6.85–9.85	13.5–45.3	67.8–101	–	Broad shallow conductive zone (near surface to

Dumpsite (Fig.)	<10 Ω m	10–50 Ω m	50–400 Ω m	>400 Ω m	Interpretive note
Biu Road WD2 (3c)	6.06–8.08	10.8–45.4	–	–	~9 m) Shallow (west) and deeper (east) conductive zones
Bypass Doma House (3d)	–	–	103–392	513–670	Comparatively resistive; no extensive low-resistivity zone
Kumo Road (3e)	6.30–8.74	12.1–45.0	62.5	–	Extensive conductive zone in central–eastern part
Kurba Kwami (3f)	3.25–9.96	14.5–44.4	–	–	Strong conductive body at ~4–11 m
Yalanguruza (3g)	–	13.1–41.5	60.9–193	–	Uniformly low resistivity throughout
Railway (3h)	–	25.3	51.6–215	438–3712	Lower-resistivity zone below ~10 m beneath highly resistive cover
Mega Park (3i)	9.88	14.3–41.9	58.5–119	–	Predominantly shallow conductive anomaly
Liji WD1 (3j)	3.49–7.31	10.6–46.2	–	–	Strong conductive layer below ~10 m

Note: Values are the contour (colour-scale) limits of each inverse model section that fall within each class; they show which resistivity classes are represented in the model and approximate its range. The lowest and highest colour bins are open-ended.

At Ashaka–Kwami Road (Fig. 3a), the inverse model contains prominent conductive anomalies of approximately 3.83–26.7 Ω m, particularly around 20–30 m, 35–55 m, and 60–75 m along the profile. The most pronounced conductive zone extends from roughly 6 m to the maximum investigated depth of about 15.9 m, beneath a more resistive near-surface layer. At Bagadaza GRA Bypass (Fig. 3b), low resistivity ($\approx$ 6–13.5 Ω m) occupies the upper 6–9 m along almost the entire profile, above more resistive material, particularly east of about 60 m. At Biu Road WD2 (Fig. 3c), where most of the section lies below about 45 Ω m, the lowest values ($\approx$ 6–11 Ω m) occur in the upper 5–6 m between about 10 and 45 m and in a deeper body ($\approx$ 7–15.9 m) between about 60 and 85 m.

Bypass Doma House (Fig. 3d) is the clearest geophysical contrast: most of the section lies between about 240 and 600 Ω m, and lower values (below 180 Ω m) are confined to small zones at the start of the profile and at its base between about 62 and 75 m. These higher resistivities may reflect coarser, drier or more indurated materials beneath the site, a thinner waste deposit or limited leachate generation. They show only that no extensive conductive zone was imaged to about 16 m depth along this profile; this does not establish environmental safety, because leachate could migrate below the investigated depth or away from the profile, and suitability still depends on proximity to receptors, geology, groundwater conditions, waste

characteristics, and confirmatory chemical data. At Kumo Road (Fig. 3e), low resistivity ($\approx$ 6–17 Ω m) occupies the central and eastern parts of the profile (about 32–85 m) from near the surface to depth, with the lowest values ($\leq$ 9 Ω m) between about 60 and 80 m. At Kurba Kwami (Fig. 3f), a pronounced sub-horizontal conductive body ($\approx$ 3–7 Ω m) extends from about 15 to 50 m along the profile at about 4–11 m depth beneath a thin, more resistive near-surface layer.

Yalanguruza (Fig. 3g) is uniformly conductive (mostly $\approx$ 13–35 Ω m), with the lowest values ($\leq$ 16 Ω m) at about 7–12 m depth between about 40 and 60 m; no resistive unit was imaged within the investigated depth.

The Railway profile (Fig. 3h) differs from many other sites: the upper 8–9 m is highly resistive (mostly >1,000 Ω m) and is separated by a sharp, nearly horizontal transition at about 9–11 m from a lower-resistivity zone ($\approx$ 25–105 Ω m) that extends to the base of the section. Its absolute error (4.8%) is the lowest of the ten inversions, although geological ambiguity remains. At Mega Park (Fig. 3i), low resistivity of approximately 9.88–28.7 Ω m is concentrated mainly between about 30 and 80 m along the profile and from the near surface to approximately 6–8 m depth, and is underlain east of about 45 m by a resistive layer ($\geq$ 84 Ω m). At Liji WD1 (Fig. 3j), a laterally continuous low-resistivity layer ($\approx$ 3.5–11 Ω m) occurs below about 10–11 m between about 35 and 78 m, beneath moderately resistive material ($\approx$ 22–46 Ω m).

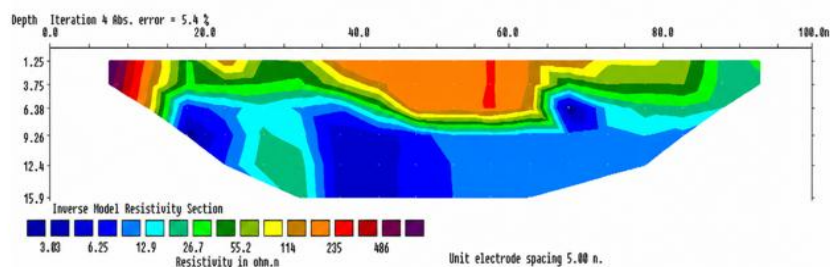


Figure 3(a): 2-D Inverse Resistivity Model of the Ashaka–Kwami Road Dumpsite (distance and depth in metres)

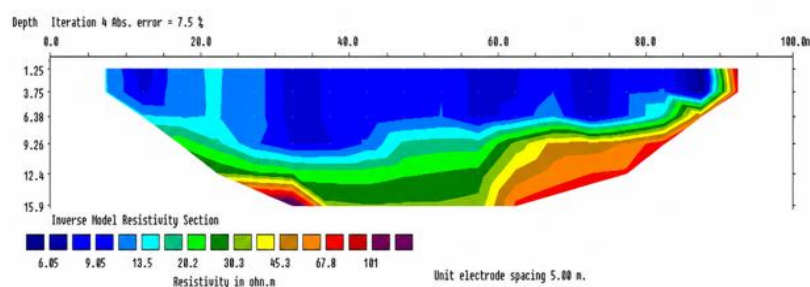


Figure 3(b): 2-D Inverse Resistivity Model of the Bagadaza GRA Bypass Dumpsite (distance and depth in metres)

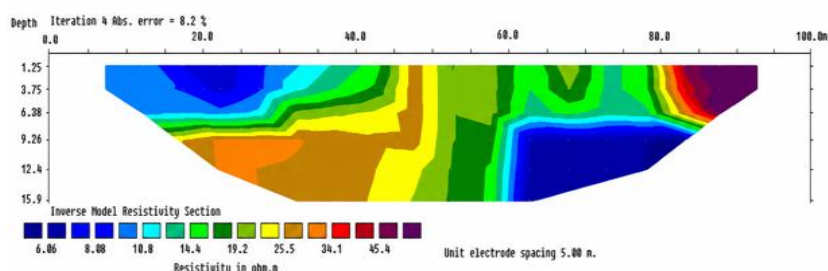


Figure 3(c): 2-D Inverse Resistivity Model of the Bui Road WD2 (Liji) Dumpsite (distance and depth in metres)

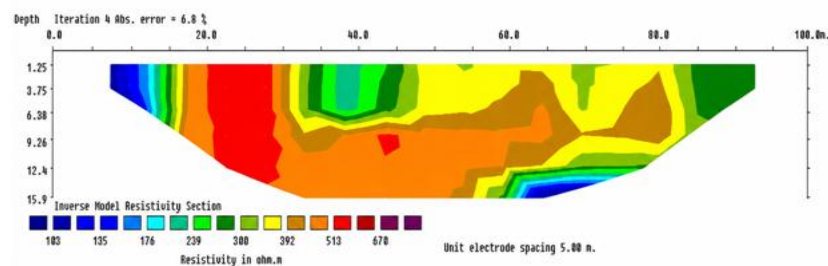


Figure 3(d): 2-D Inverse Resistivity Model of the Bypass Doma House Dumpsite (distance and depth in metres)

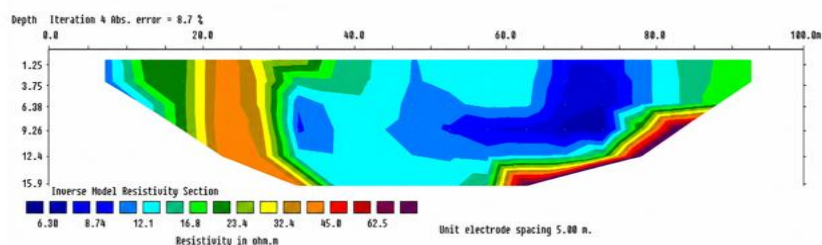


Figure 3(e): 2-D Inverse Resistivity Model of the Kumo Road Dumpsite (distance and depth in metres)

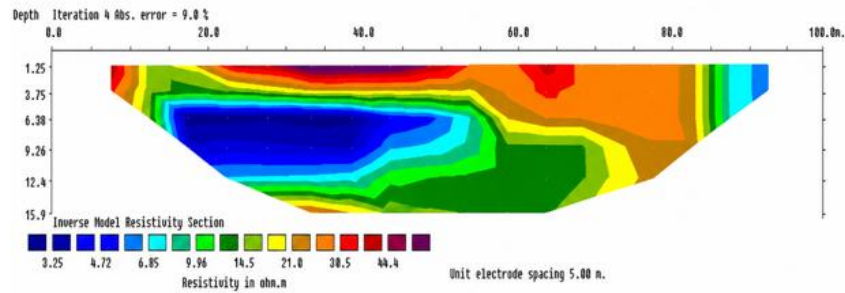


Figure 3(f): 2-D Inverse Resistivity Model of the Kurba Kwami Dumpsite (distance and depth in metres)

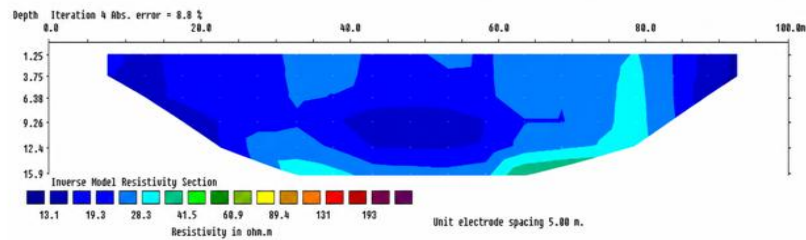


Figure 3(g): 2-D Inverse Resistivity Model of the Yalanguruza Dumpsite (distance and depth in metres)

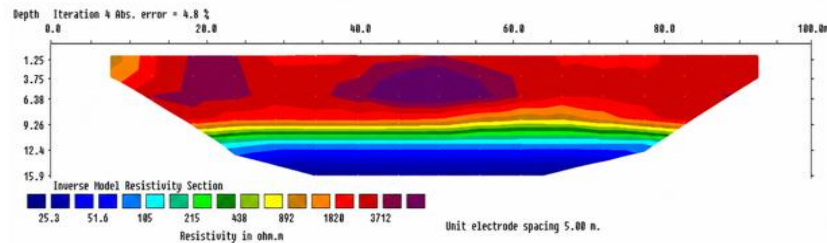


Figure 3(h): 2-D Inverse Resistivity Model of the Railway Dumpsite (distance and depth in metres)

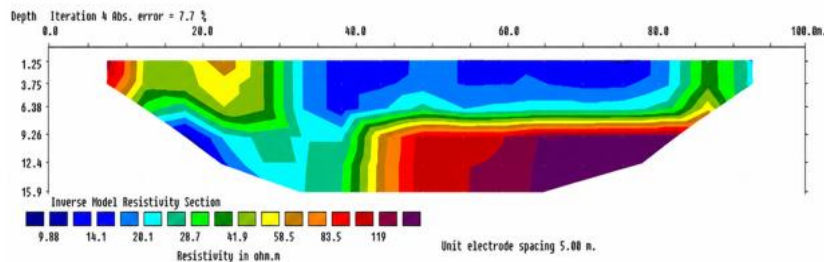


Figure 3(i): 2-D Inverse Resistivity Model of the Mega Park Dumpsite (distance and depth in metres)

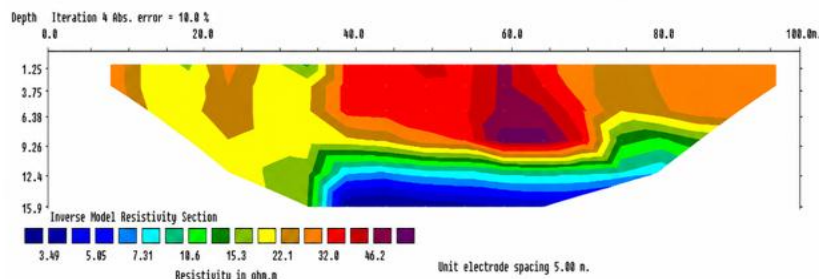


Figure 3(j): 2-D Inverse Resistivity Model of the Liji WD1 Dumpsite (distance and depth in metres)

Integrated Environmental Interpretation

The combined evidence supports a two-scale assessment. At the metropolitan scale, GIS–AHP identifies where receptors and potential pathways make waste disposal environmentally constrained. At the dumpsite scale, 2-D ERT shows whether conductive subsurface anomalies are present and how they vary with depth and lateral position. The approaches are therefore complementary rather than interchangeable

and they were interpreted quantitatively. A site may be relatively distant from a mapped well yet remain vulnerable if permeable or fractured materials provide a migration pathway; conversely, a conductive 2-D ERT anomaly should not be labelled as contamination without considering lithology, saturation, and pore-water chemistry. Table 4 combines the receptor and lithological setting of each surveyed site with its 2-D ERT evidence.

Table 4: Integrated Source–Pathway–Receptor Summary for the Ten Surveyed Dumpsites

Dumpsite	Mapped geology	Nearest stream	Nearest mapped well/borehole	Lowest Resistivity (Ωm)	Main low-resistivity zone	Priority
Bagadaza GRA Bypass	Pindiga Formation	<500 m	<500 m	6.85	Near surface to ~9 m along most of the profile	High
Biu Road WD2	Gombe Sandstone	500–1,000 m	<500 m	6.06	Upper ~6 m (10–45 m) and ~7–15.9 m (60–85 m)	High
Liji WD1	Gombe Sandstone	500–1,000 m	<500 m	3.49	Below ~10–11 m (35–78 m)	High
Yalanguruza	Pindiga Formation	<500 m	<500 m	13.1	Whole section; lowest at ~7–12 m	High
Ashaka–Kwami Road	Kerri-Kerri Formation	500–1,000 m	>2,000 m	3.83	Below ~6 m (15–85 m)	Elevated
Kumo Road	Kerri-Kerri Formation	500–1,000 m	>2,000 m	6.30	Near surface to depth (32–85 m)	Elevated
Kurba Kwami	Pindiga Formation	<500 m	>2,000 m	3.25	~4–11 m (15–50 m)	Elevated
Mega Park	Kerri-Kerri Formation	<500 m	>2,000 m	9.88	Near surface to ~7 m (30–80 m)	Elevated
Railway	Basement Complex–Bima contact	<500 m	500–1,000 m	25.3	Below ~10 m (20–80 m)	Lower
Bypass Doma House	Pindiga–Yolde contact	500–1,000 m	1,500–2,000 m	103	Small, localized zones only	Lower

Note: Geology and distance classes were read from Figs. 2j, 2e and 2f at the dumpsite locations; contour values and zones are from Figs. 3a–3j (positions along the profile in brackets). High: lowest contour value <15 Ωm with a mapped well/borehole within 500 m; Elevated: lowest contour value <15 Ωm with the nearest mapped well/borehole >500 m; Lower: lowest contour value $\geq 15 \Omega\text{m}$.

The strongest integrated concern arises where low-resistivity anomalies coincide with sensitive receptors and plausible pathways. On this basis, Bagadaza GRA Bypass, Biu Road WD2, Liji WD1 and Yalanguruza are the highest priorities (Table 4): each lies within 500 m of mapped boreholes and contains extensive low-resistivity material, which at Bagadaza GRA Bypass and Biu Road WD2 begins close to the surface. Ashaka–Kwami Road, Kumo Road, Kurba Kwami and Mega Park contain pronounced conductive zones but lie

more than 2 km from the mapped wells/boreholes; they remain of concern because all four lie within 1 km of streams and because the well inventory may be incomplete, and they should not be considered for expansion without detailed hydrogeological and hydrochemical assessment. Lithology must also be considered. Bagadaza GRA Bypass, Yalanguruza and Kurba Kwami lie on the shale-dominated Pindiga Formation (Obaje, 2009; Zaborski et al., 1997), which can be conductive without leachate, while the sharp,

laterally continuous resistive-over-conductive boundaries at Railway ($\approx 9\text{--}11$ m), Liji WD1 ($\approx 10\text{--}11$ m) and Ashaka–Kwami Road (≈ 6 m) may mark a water table or lithological contact rather than a leachate plume. Railway contains a deeper lower-resistivity zone beneath a highly resistive cover, at a site mapped on the Basement Complex–Bima contact. Bypass Doma House is geophysically distinct and may warrant further feasibility investigation, but the available data do not justify designating it as a confirmed landfill site.

The very low resistivities measured here ($\approx 3\text{--}10$ Ωm) fall within the ranges attributed to leachate-affected materials at other Nigerian dumpsites, for example $3.12\text{--}8.7$ Ωm near Onitsha (Ugbor et al., 2021), $1.5\text{--}19$ Ωm at a landfill near Kaduna, where leachate geochemistry supported the interpretation (Alao et al., 2024), and below 15 Ωm at the Kurata dumpsite in southwestern Nigeria (Kamilu et al., 2026); this agreement supports the possibility of leachate influence at the conductive Gombe sites (see also Okpoli, 2013). There are, however, important differences. Near Onitsha and Kaduna the conductive zones were confined to depths of about 7 m and 12 m, respectively, whereas in Gombe several low-resistivity zones form laterally continuous layers beneath more resistive cover and extend to the base of the models (about 16 m). Deeper leachate migration is possible, as shown by conductive zones of $9.0\text{--}33.0$ Ωm extending to about 25 m around dumpsites in Minna (Agu et al., 2023), but continuous layers of this kind can also be lithological. Conversely, where hydrochemistry confirmed leachate infiltration into a shallow aquifer at Oghara, the affected zones had

resistivities of $20.3\text{--}95$ Ωm (Osifo & Ogumeyo, 2026), showing that resistivity ranges for leachate are site-specific and cannot be transferred between settings without local calibration.

Geology is the most likely explanation for these differences. Most of the Gombe sites, by contrast, lie on sedimentary formations, several of them shale-dominated or clay-bearing, and clay-rich sediments can have intrinsically low resistivities (Telford et al., 1990). In the Yola area of the Upper Benue Trough, which is also underlain by the Bima and Yolde formations, resistivities of 20 Ωm or less were attributed to clay or water-saturated sediments (Oniku et al., 2025), and even a control profile about 1 km from the Onitsha dumpsite, on the sedimentary Ameki Formation, contained zones of $14.6\text{--}44.3$ Ωm (Ugbor et al., 2021). The contrast between leachate-affected and background is therefore likely to be weaker in Gombe, which makes background profiles and hydrochemical data more important. Alao et al. (2024) also showed that the resistivity of leachate-affected zones decreases in the wet season, so the survey season must be considered when comparing sites. The present study adds a broader environmental context by combining subsurface imaging with water-resource proximity, LULC, geology, soil, terrain, and structural information. Figure 4 is the final suitability map for Gombe metropolis, where Kurba Kwami, Ashaka Kwami Road and Bypas Doma House waste dumpsites were classified as moderately suitable while Sabon Layi T/Wada Pantami, Liji WD 1, Biu Road Liji WD 2 and Arawa waste dumpsites were classified unsuitable for solid waste dumpsites.

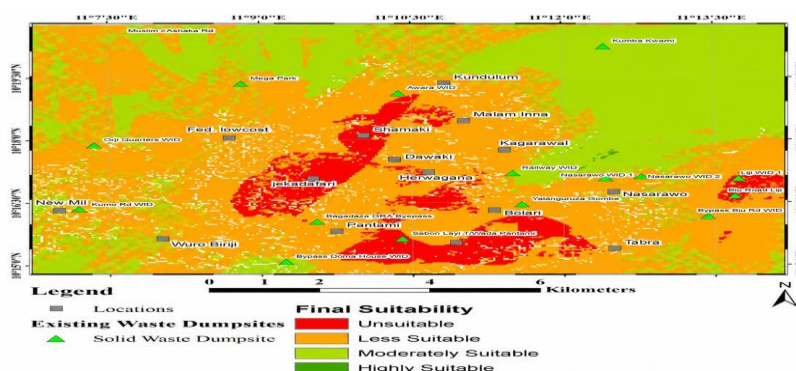


Figure 4: Final Suitability Map of Gombe Metropolis

Limitations

No water or soil samples were analysed, so the conductive zones remain possible rather than confirmed leachate-affected materials. Each site was surveyed once along a single 100 m profile reaching about 16 m depth, which may not include the aquifers tapped by nearby boreholes, and without background profiles on each formation the effects of lithology and leachate cannot be

fully separated. The well/borehole inventory is concentrated in the central, southern and eastern settlements, so distances to groundwater receptors may be overestimated elsewhere. In addition, the soil and geology layers are partly dependent, and criteria derived from regional-scale maps were resampled to 30 m, which does not increase their inherent accuracy. Future work should combine hydrochemical sampling of

nearby wells and boreholes, depth-to-water measurements and repeated (time-lapse) 2-D ERT monitoring (Dimech et al., 2022) at the high-priority sites.

CONCLUSION

An integrated GIS–AHP and 2-D ERT framework was applied to existing solid-waste dumpsites in Gombe Metropolis. Protection of water resources is the dominant environmental constraint: wells/boreholes and rivers received 27.65% and 19.52% of the AHP weight (CR = 0.0362), and 80.28% of the analysed area lies within 500 m of rivers/streams. The ERT surveys show marked site-to-site variability, with very low resistivities ($\approx 3\text{--}10\ \Omega\text{m}$) at seven of the ten dumpsites and comparatively high values (mostly $>200\ \Omega\text{m}$) at Bypass Doma House, Bagadaza GRA Bypass, Biu Road WD2, Liji WD1 and Yalanguruza, where extensive low-resistivity zones lie within 500 m of mapped boreholes, are the highest priorities for investigation. The main limitation is the absence of hydrochemical validation, so the conductive zones indicate possible leachate influence rather than confirmed contamination. Groundwater-quality testing of nearby wells and boreholes and detailed hydrogeological investigation are therefore recommended at the priority sites, and the integrated GIS–AHP and ERT approach, with minimum separation distances from water sources applied as exclusion constraints, should be adopted in future waste-disposal planning in Gombe. For waste-management planning in Gombe, expansion of sites with strong conductive anomalies should be avoided pending detailed investigation, while any future candidate landfill should be selected from GIS-derived favourable areas and then subjected to geophysical, hydrogeological, geotechnical, and water-quality verification.

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