

INTEGRATED USE OF GEOELECTRICAL IMAGING AND HYDROCHEMICAL METHODS IN DELINEATING LIMITS OF POLLUTED SURFACE AND GROUND-WATER AT A LANDFILL SITE IN IBADAN AREA, SOUTHWESTERN NIGERIA

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ABSTRACT

The impact of solid waste disposal at the Ring Road district of Ibadan metropolis, southwestern Nigeria, on the adjoining surface and ground-water sources, has been investigated. The basement rocks include Precambrian quartzites and quartz-schists that have been extensively weathered. In this study, the geophysical survey involved 5 electrical imaging lines, while the hydrochemical database comprised 4 samples of surface water and 6 samples of groundwater from dug wells. The samples were analysed for turbidity, pH, conductivity, total hardness, total dissolved solids (TDS), alkalinity, Cl⁻, NO₃⁻, SO₄²⁻, PO₄³⁻, Na⁺, K⁺, Mg²⁺ and Fe²⁺.

The results show that water bodies located in a down gradient direction and in close vicinity of the landfill, has received significant inputs of inorganic pollutants. Statistical analyses indicate positive correlation ($p < 0.05$) between the following pairs of parameters: Ca²⁺ and Mg²⁺ ($R = 0.83$); Na⁺ and K⁺ ($R = 0.95$); (Na⁺+Mg²⁺) and Cl⁻ ($R = 0.92$); (Na⁺ + K⁺) and Ca²⁺ ($R = 0.96$); pH and Cl⁻ ($R = 0.87$). Moreover, the electrical conductivity shows a positive correlation ($p < 0.05$) with the concentrations of K⁺ ($R = 0.97$); Na⁺ ($R = 0.96$); Ca²⁺ ($R = 0.93$); Mg²⁺ ($R = 0.82$); Fe²⁺ ($R = 0.85$); Cl⁻ ($R = 0.91$) and TDS ($R = 0.98$). On the other hand, the conductivity shows a negative correlation with SO₄²⁻ ($R = -0.78$).

Corroborating evidence was provided from the geoelectrical imaging data which indicate that the thickness of the waste dump ranges between about 2m to 17m, while its resistivity is low at between 4 and 8ohm-m. The low resistivity is due to the presence of leachate emanating from the site and this has also polluted the surface and ground-waters in the immediate delineation of the limits of the probable polluted zone.

INTRODUCTION

Research on groundwater contamination by solid waste disposal sites, has focused largely on the chemistry of groundwater (Hussain *et al.* 1989; Booth and Vagt, 1990; Assmuth and Stranberg, 1993). The majority are aimed at defining the spatial extension of groundwater contamination, based on the results of chemical analyses. One other technique for conducting groundwater contamination studies is the geophysical method. Geophysical methods that can be applied include seismic refraction (Cardarelli and Bernabini, 1997), VLF (Benson *et al.*, 1997), and resistivity (Carpenter *et al.*, 1990). Of these, the resistivity method is most preferred geophysical surveying technique for such types of investigations because it can clarify the subsurface structure, delineate contaminated zones of groundwater, and is inexpensive (Mazak *et al.* 1987). The integrated use of hydrochemical and geophysical methods is often recommended (Benson *et al.* 1983; Matias *et al.* 1994; Kayabali *et al.* 1998).

In the present work, hydrochemical and geoelectrical imaging methods were employed to study the groundwater contamination due to a solid waste disposal facility at Ibadan, southwestern Nigeria. The hydrochemical analyses involved

sampling of stream water and groundwater (from large diameter wells) while the resistivity survey comprised geoelectrical imaging and vertical electrical sounding.

SITE CHARACTERIZATION

The problem of solid waste management within Ibadan metropolis, southwestern Nigeria, is of considerable magnitude, and has been the subject of several studies (Maclaren, 1970; Oluwande, 1974; FMHE, 1982; Egunjobi, 1986). Among the health hazards that have resulted from the lack of an effective disposal system are certain cases of epidemics of communicable disease (Adesina, 1986). The peculiar problem of Ibadan results from the combined effect of the large population (put at 1.7 million by the 1991 census), lack of proper planning of the indigenous areas, and the scarcity of resources and facilities for effective waste disposal. It has been estimated that by 1990, up to 508,000 tonnes of domestic solid waste would be generated within the city (FMHE, 1982; Filani and Abumere, 1986). Fig. 1 shows the waste disposal sites in the metropolis.

Disposal of the waste involves dumping at the two recently abandoned landfills at Aperin and Ring Road districts of the city. Both landfills are poorly

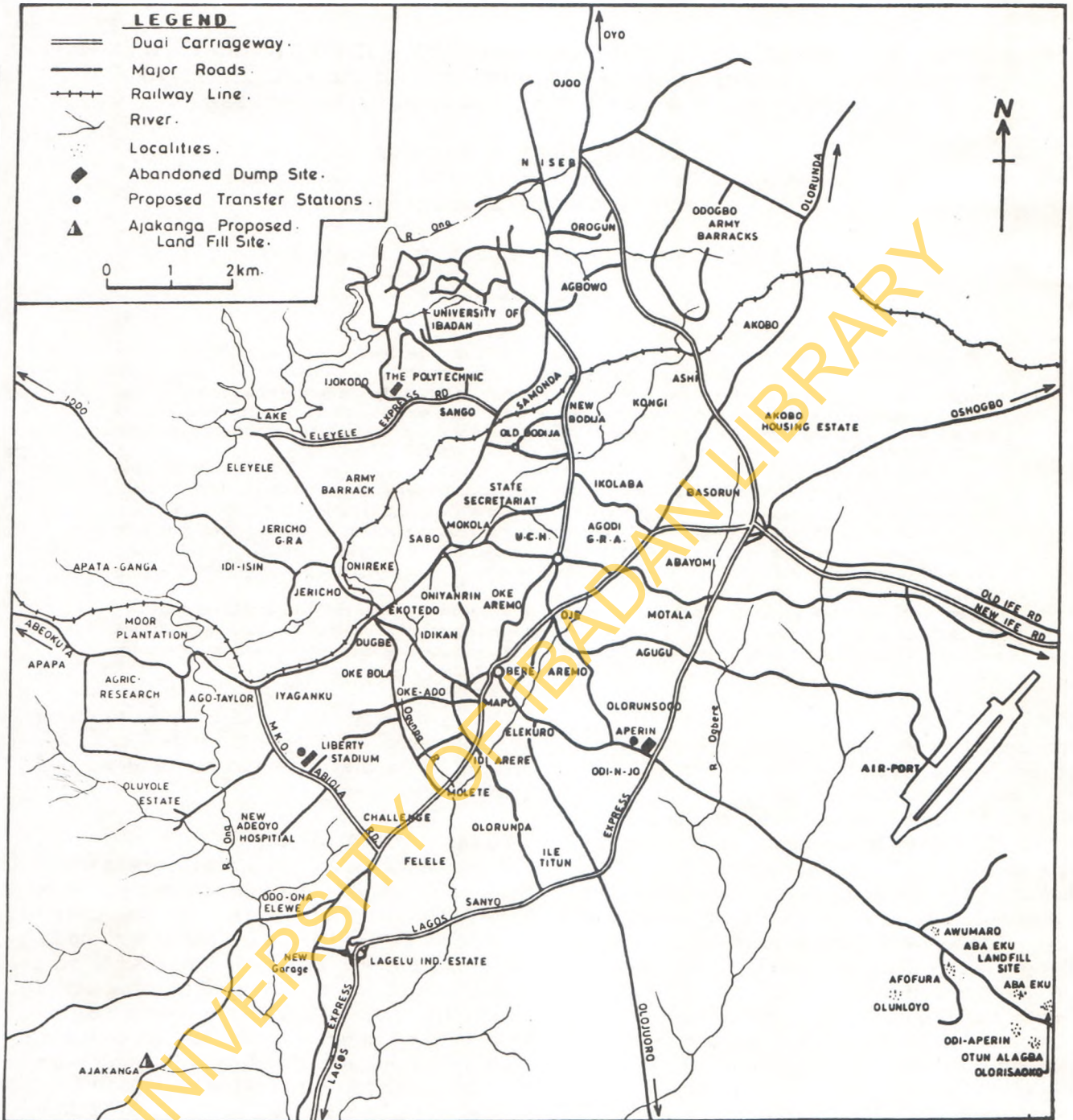


Fig. 1. Map of Ibadan showing the waste disposal sites

conceptualised in terms of location and operation. The Aperin and Ring Road districts are now densely populated, and no safeguard for the protection of surface and ground water was incorporated into the designs. The landfills are in fact operated

mainly as open dumps, although some amount of open-air incineration is unofficially carried out. Onianwa et. al. (1995) investigated the Aperin landfill site and their results indicated pollution of the surface and ground waters by the landfill.

The areal extent of the Ring Road waste disposal site, which is the subject of this paper, is about $0.5 \times 0.3 \text{ km}^2$. Owned and maintained by the Ibadan Solid Waste Management Authority, this dump site was in operation from 1960-1992. It is bordered to the east by the Liberty Stadium, to the south by a major highway, and to the north and west by streams.

GEOLOGY AND HYDROGEOLOGY

The dominant rock types in Ibadan are quartzites of the metasedimentary series, and banded gneisses, augen gneisses and migmatites constituting the gneiss-migmatite complex (Fig. 2).

The dump site is underlain by quartzite and quartz schist, with outcrops in the south-eastern part as well as towards the northern margin. The rock is extensively weathered and fractured. Foliation planes are well developed and strike between 340° and 352° , with a consistent easterly dip of between 28° and 36° . Two prominent joint directions are observed: (i). A set of joint trending about 256° , essentially oblique to the strike direction of the foliation plane in the quartz schist and with vertical dip. (ii) a second set of joints trending about 84° and 100° ; this later set of joints appears to be more widely distributed and have field with quartz veins (Fig. 3a).

The weathered profile developed above crystalline basement rocks in low latitude regions comprises, from top to bottom, the soil layer, the saprolite (product of *in situ* chemical weathering

of the bedrock), the saprock (fractured bedrock) and the fresh bedrock. However, in the disturbed environment constituting the waste dump, the overburden consists of a thin soil cover and the leachate-saturated refuse. A vertical section through the refuse dump and adjoining area is shown in Fig. 3b.

MATERIALS AND METHODS

Geoelectric Survey

Five electrical image lines were measured using the Wenner array and a manual technique, as an automated, computer-controlled, multi-electrode system was not available for the survey. The position and orientation of the survey lines are shown in Fig. 3a. It may be noted that the lines were aligned along approximately NW-SE azimuths. An alternative procedure in which the direction of traversing is SW-NE could probably have been suitable in measuring the maximum apparent resistivity anomalies; however, the effect of surface topography (Fig. 3b) would have led to generation of false anomalies and, consequently, erroneous interpretation (Fox *et al.* 1980). A minimum spacing of 10m was used. Measurements commenced at one end of the line with the electrodes at positions 1, 2, 3 and 4. The spacing is then doubled without moving the first electrode, the active electrode positions being 1, 3, 5 and 7. At each measurement, spacing is increased by one unit until a maximum spacing of 60m is reached. This should provide information down to depths of more than 40m. Three traverses (L1-L3) were measured directly on the waste dump site, with L2 being the longest at 350m. Two additional traverses, L4 and L5, each of which is 230m long, were measured outside the dump site in order to serve as a control for the former set. It was not possible to extend these two lines north-westwards as the area was waterlogged.

In order to supplement the 2-D apparent resistivity data, especially in providing near-surface information, two Wenner soundings were made. VES 1 was conducted at a point between L1 and L2 while VES 2 was made at the 160m - position along L3.

The subsurface resistivity distribution can often be approximated by 2D models for features having a consistent strike direction whose length is much longer than the depths of interest. In this work, the apparent resistivity field caused by such structures has been computed by using finite-difference solutions of Poisson's equation (Dey and Morrison, 1979). A commercially available algorithm, RES2DINV (Loke and Barker, 1996), was

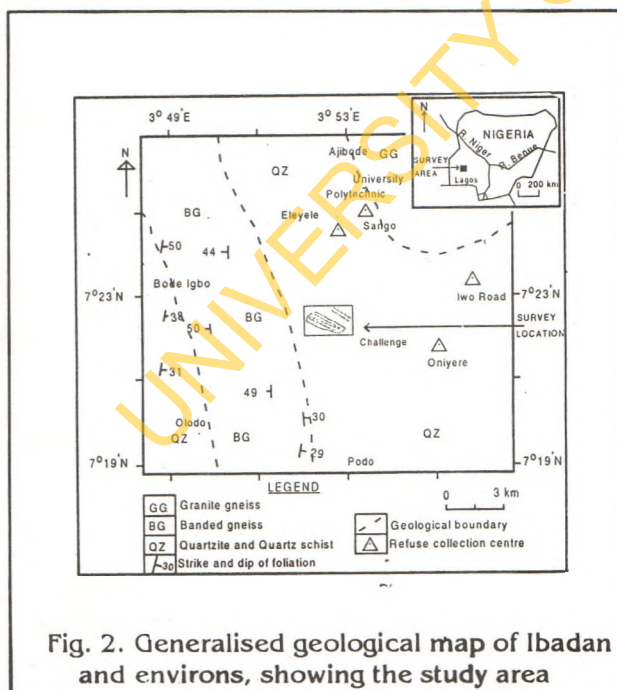
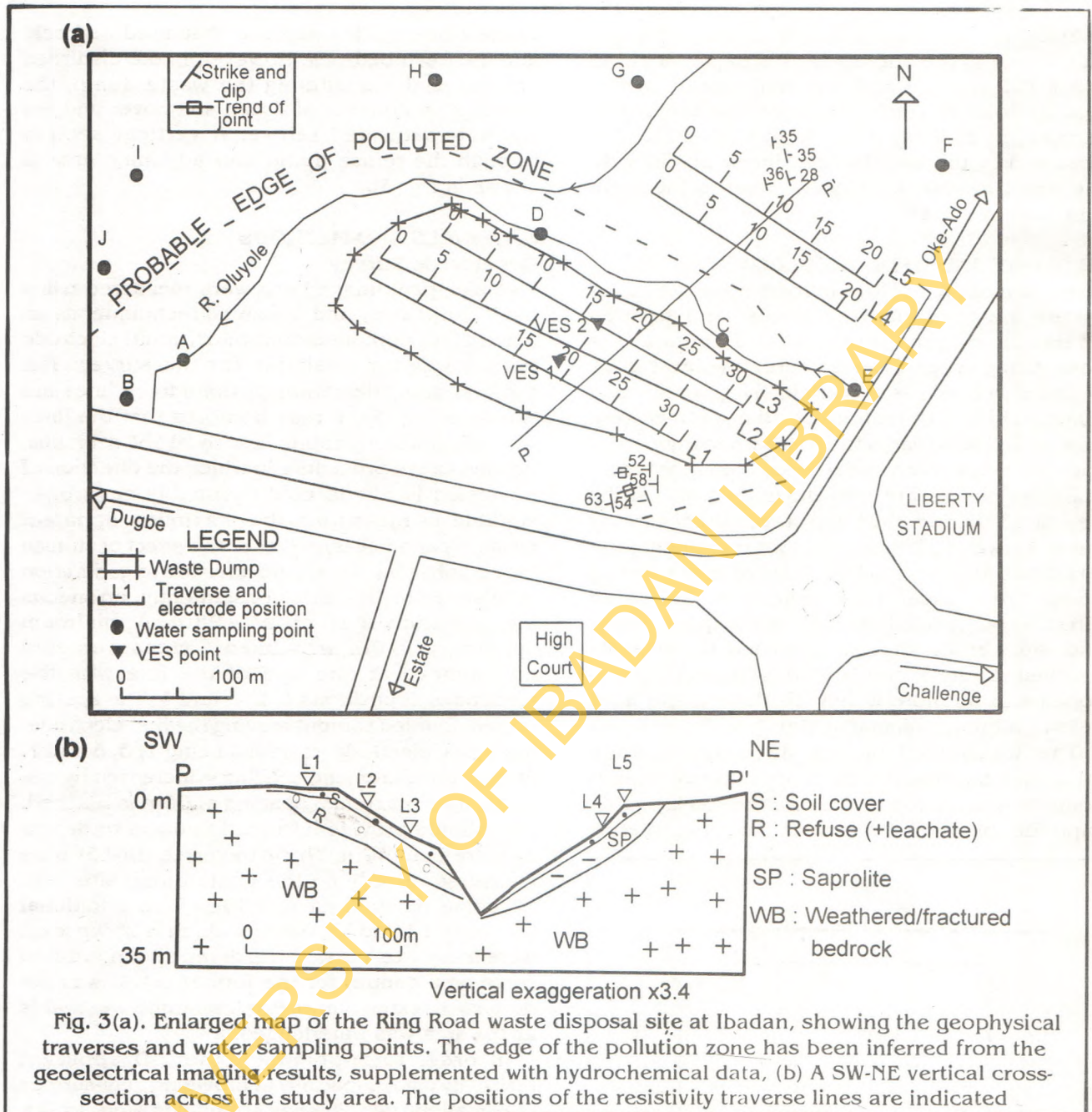


Fig. 2. Generalised geological map of Ibadan and environs, showing the study area



used for the inversion of the data. It is based on the smoothness-constrained, non-linear least squares optimisation technique. A data rms misfit, D_{rms} , is used to represent the fit between the observed and calculated apparent resistivity. A 1D inversion algorithm (Koefoed, 1979) was employed in processing the vertical sounding data. Details of the geoelectrical interpretation have been presented in Ojayinka and Yaramanci (1999, 2000) and only the aspects that are relevant to the hydrochemical investigation are summarised in the

presented work.

Since the pseudosection data contain information on both the vertical and the lateral variations in resistivity, the vertical gradient of the apparent resistivity pseudosection data between successive levels of the pseudosection data was calculated. The basis for computing the pseudo sounding data is that, theoretically, the slope of the rising segment of a resistivity sounding curve should not exceed +1. Slopes greater than this are often attributed to strong lateral contrasts. For

electrode position k , the vertical gradient V between two levels n and $n+1$ is given as

$$V(k,n+0.5) = \frac{\log \rho(k,n+1) - \log \rho(k,n)}{\log a(n+1) - \log a(n)} \dots (1)$$

where $\rho(k,n)$ is the apparent resistivity 'beneath' electrode position k at the n th level of the pseudosection,

$\rho(k,n+1)$ is the apparent resistivity 'beneath' electrode position at the $(n+1)$ th level of the pseudosection,

$a(n)$ is the Wenner electrode spacing for the n th level, and

$a(n+1)$ is the Wenner electrode spacing for the $(n+1)$ th level.

The respective values at the different data points were subsequently contoured as a space section. Similarly, the lateral variation in the apparent resistivity between two adjacent points on the same level was determined as:

$$L(k+0.5) = \frac{|\rho(k) - \rho(k+1)|}{(\rho(k) + \rho(k+1))/2} * 100\% \dots (2)$$

Hydrochemical Techniques

An inventory of stream, hand-dug wells and boreholes in the immediate vicinity of the waste dump was carried out. Water samples were taken from 10 points, labelled A to J. Four of these (A, C, D and E) are for surface water and the remaining 6 (B, F, G, H, I and J) ground water. Measurements

of the temperature, total dissolved solids (TDS) and pH were taken in the field using a portable Hach DR/EL/4 laboratory kit. Standard laboratory methods, involving wet analysis, were employed for determination of the anion and cation. A total of 15 parameters were determined, comprising turbidity, pH, conductivity, total hardness, total dissolved solids, alkalinity, chloride, nitrate, sulphate, phosphate, Na, K, Ca, Mg and Fe.

DISCUSSION

The results of the chemical analyses of the water samples are summarised in Table 1, while the spatial variation of some of the parameters along two selected traverses, namely J-I-D-C-E and B-A-H-G-F, are presented in Figs. 4 to 6. These traverses cut across both the impacted and the unimpacted areas. There is no lithological variation in the study area. Consequently, under natural conditions there should be no occurrence of anomalous values of ionic constituents in the water samples. Instead, systematic variation in the ionic constituents along the flow paths of the groundwater would be expected. Elevated values of ionic constituents can be interpreted as being due to contamination. The depth to water table is generally shallow at between 2.1 and 4.0m below the ground surface, except for water point F where it was slightly deeper at 7.6m.

The conductivity, alkalinity (ALK), total dissolved solids (TDS), total hardness, Calcium hardness, Fe^{2+} , Ca^{2+} , Na^{2+} , Mg^{2+} and K^+ , as well as Cl^- are higher

Table 1. Analysis of water samples from the Ring Road Waste Dump Site, Ibadan, Nigeria
(See Fig. 2a. for locations).

| Sample No | σ (mS/cm) | TH (mg/l) | TDS | ALK | Ca^{2+} | Mg^{2+} | Fe^{2+} | Na^+ | K^+ | NO_3^- | PO_4^{3-} | SO_4^{2-} | Cl^- (mg/l) | pH | Temp (°C) |
|-----------|------------------|-----------|-----|-----|-----------|-----------|-----------|--------|-------|----------|-------------|-------------|---------------|-----|-----------|
| A* | 0.70 | 172 | 390 | 65 | 39 | 8 | 1.1 | 53.7 | 50.8 | 0.06 | 7.4 | 41 | 76 | 6.8 | 30.0 |
| B** | 0.85 | 145 | 500 | 260 | 44 | 13 | 3.2 | 70.8 | 49.4 | 0.0114 | 6.6 | 6.5 | 29.0 | | |
| C* | 0.90 | 176 | 487 | 270 | 40 | 19 | 2.3 | 57.5 | 51.2 | 0.00 | 1.2 | 12 | 77 | 6.4 | |
| D* | 0.75 | 186 | 490 | 250 | 43 | 24 | 1.0 | 60.5 | 45.0 | 0.02 | 1.5 | 15 | 78 | 6.5 | 30.7 |
| E* | 0.15 | 87 | 78 | 48 | 16 | 4 | 0.6 | 21.3 | 5.2 | 0.01 | 3.5 | 41 | 39 | 5.9 | 30.0 |
| F** | 0.28 | 74 | 138 | 70 | 15 | 6 | 0.3 | 22.0 | 4.9 | 0.02 | 5.0 | 68 | 31 | 6.4 | 30.1 |
| G** | 0.25 | 50 | 145 | 22 | 28 | 8 | 0.2 | 21.5 | 12.8 | 0.001 | 4.5 | 67 | 19 | 5.9 | 30.5 |
| H** | 0.27 | 98 | 150 | 100 | 15 | 5 | 0.1 | 20.5 | 10.0 | 0.01 | 4.7 | 41 | 14 | 5.7 | 29.5 |
| I** | 0.15 | 85 | 140 | 70 | 18 | 4 | 0.3 | 21.5 | 13.1 | 0.06 | 4.8 | 43 | 14 | 5.9 | 29.0 |
| J** | 0.28 | 100 | 135 | 54 | 16 | 3 | 0.21 | 5.0 | 14.3 | 0.02 | 4.9 | 67 | 20 | 5.9 | 29.0 |

*Surface water, ** Ground water
TH = Total Hardness; TDS = Total Dissolved Solids; ALK = Alkalinity; σ = conductivity.
NB: Samples A to D are influenced by leachate from the waste dump, while samples E to J represent background values

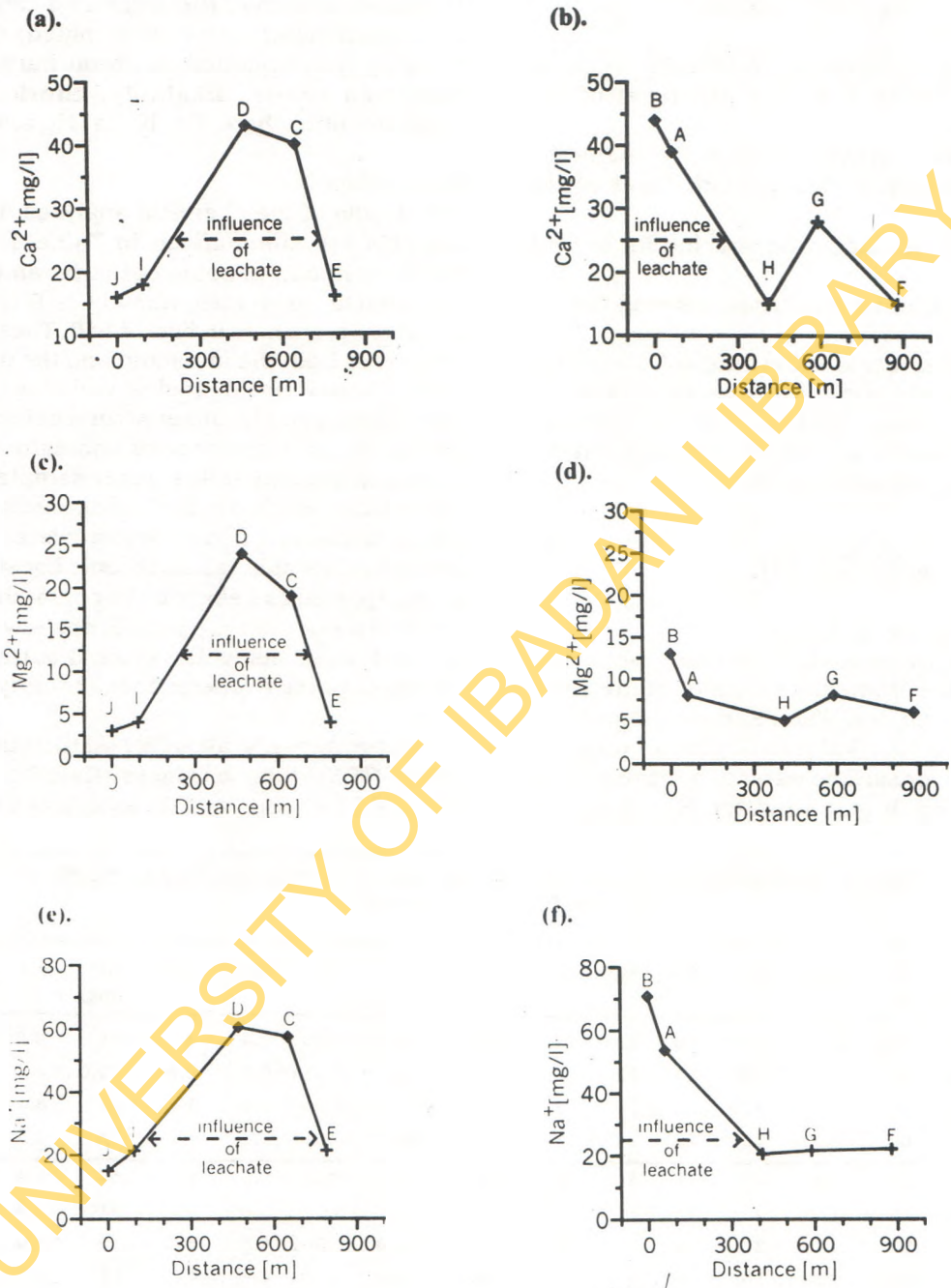


Fig. 4. Spatial variation in selection hydrochemical parameters at the waste disposal site. The left-hand plots are for the section J-I-D-C-E while those on the right hand are along the section B-A-H-G-F. See Fig. 3a for the positioning of the traverses. (a) and (b) Ca²⁺; (c) and (d) Mg²⁺; (e) and (f) Na⁺. The rectangles are data affected by leachate while the crosses are the background values

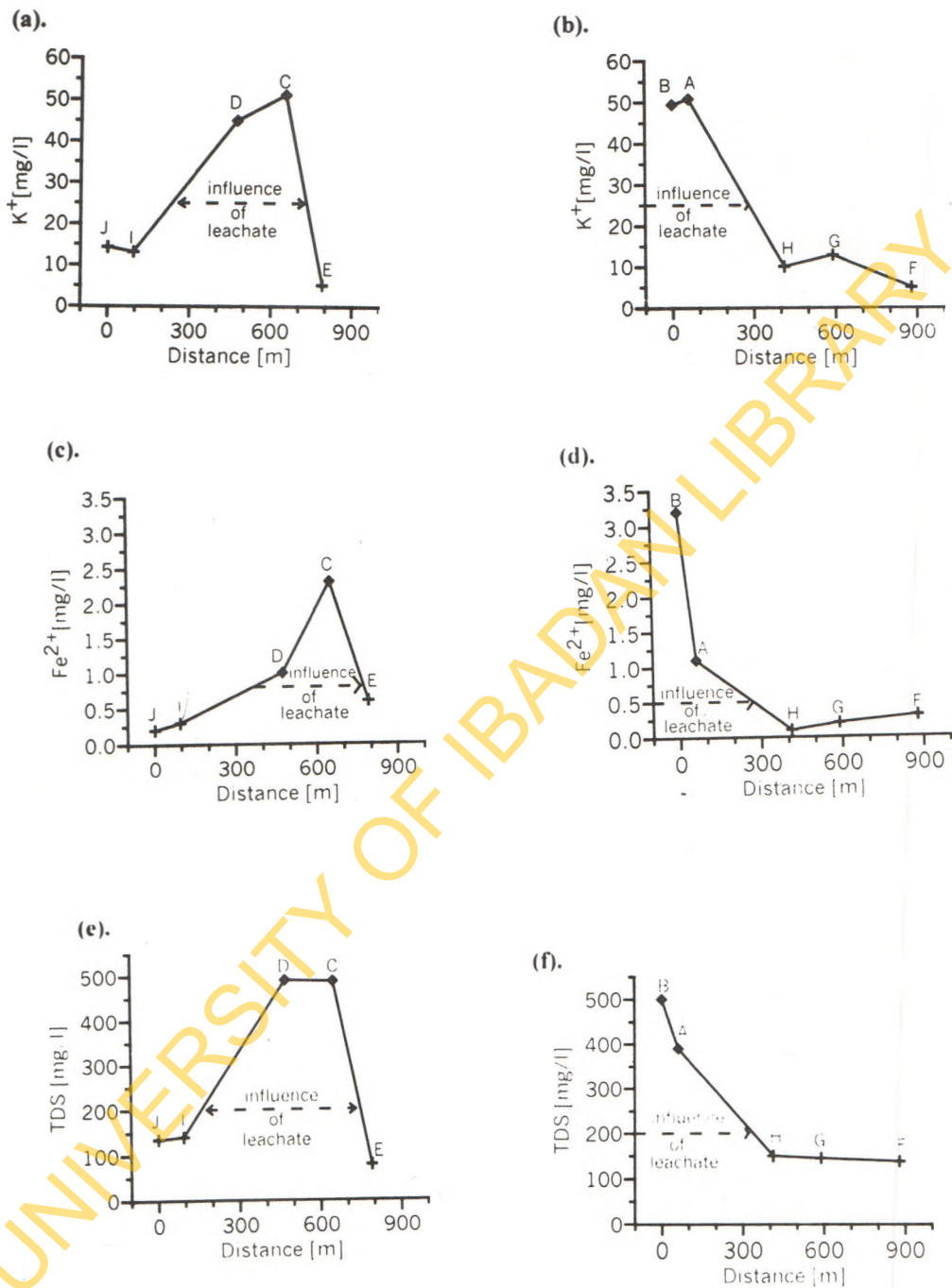


Fig. 5. Spatial variation in selected hydrochemical parameters at the waste disposal site. The left hand, plots are for the section JIDCE while those on the right hand are along the section BAHGF. (a) and (b) K⁺; and (c) and (d) Fe²⁺; (e) and TDS (i.e. total dissolved solids)

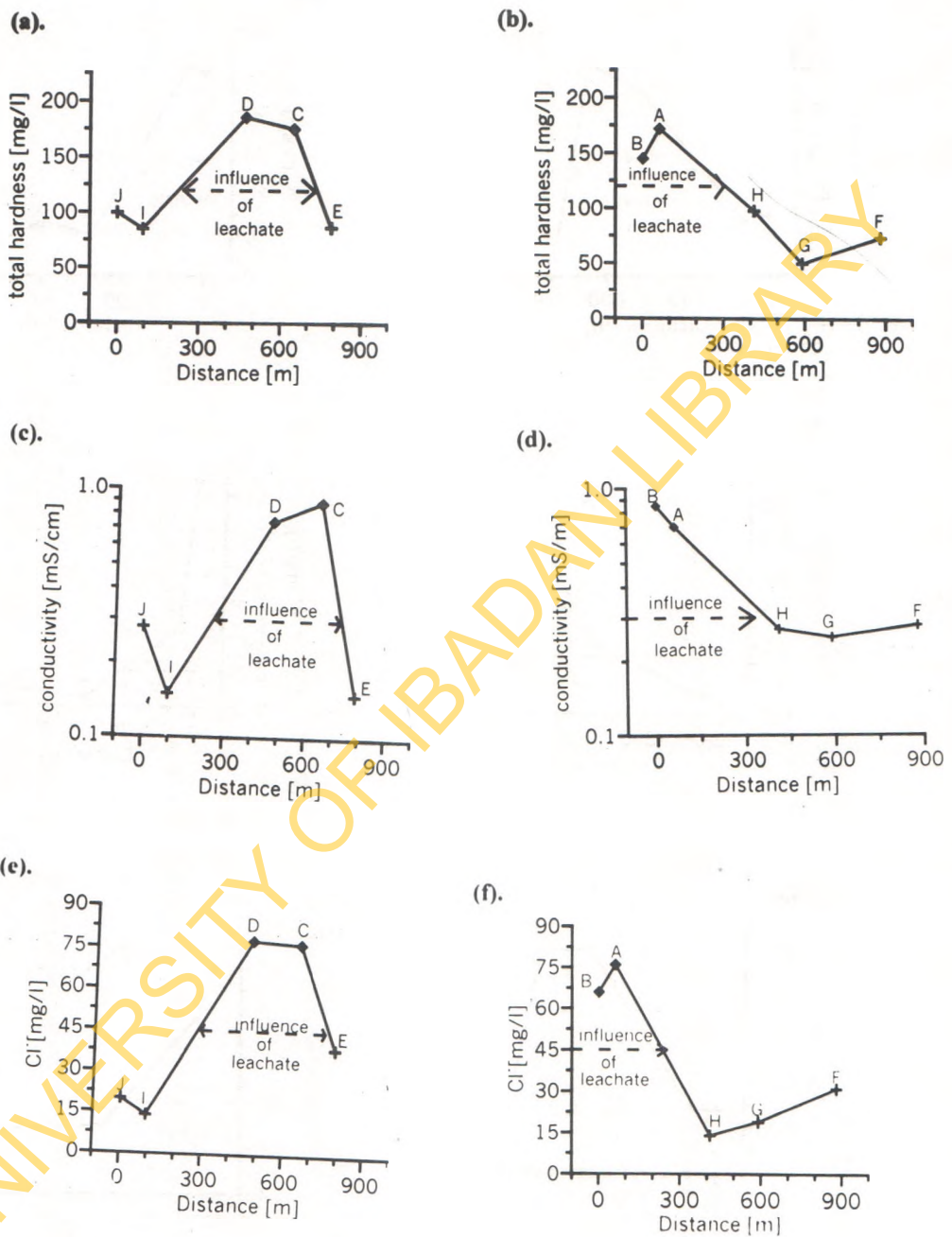


Fig. 6. Spatial variation in selected hydrochemical parameters at the waste disposal site. The left-hand plots are for the section JIDCE while those on the right hand are along the section BAHGF. (a) and (b) total hardness; (c) and (d) conductivity; (e) and (f) Cl⁻

at the locations immediately adjacent to the waste dump (A, B, C and D) than those locations far removed and unlikely to have been affected by any leachate from the dump (locations, E, F, G, H, I, and J). Organic matter decomposing under aerobic conditions produces carbon dioxide which combines with the leaching water to form carbonic acid. This, in turn, acts upon metals in the refuse and the calcareous materials in the soil and rocks resulting in increased hardness of water.

The TDS values for samples from the immediate vicinity of the dump site and those downstream vary between 390mg/l and 500mg/l. This can be compared to the background values of between 77.5mg/l and 150mg/l. The pH is also slightly higher at over 6.4, probably because of generation of ammonia and methane as a result of refuse decomposition. This is to be expected if the decomposition of organic refuse took place by fermentation reaction whereby hydrogen and carbon dioxide are consumed and methane released. The high concentrations of Fe and Mg can be attributed to reduction of oxide cement and coatings from the degradation of organic matter. The main source of bicarbonate is from organic degradation with mineral carbon dioxide from the soil zone. The origin of the major cations

in the leachate is probably from inorganic compounds in the refuse, alteration of silicate minerals and desorption from clays. On the other hand, the concentrations of PO_4^{3-} and SO_4^{2-} are generally lower in the locations (i.e A to D) thought to have been influenced by the leachate. That of NO_3^- has no readily discernible pattern. These water samples were classified as sodium bicarbonate type (NaHCO_3). On the other hand, samples E to J are unaffected by the leachate and can be classified as Calcium-Magnesium type with chloride as the main anion. Rainfall is the main source of the chloride. The shallow depth to the water table at 2.1m might have aided pollution of the ground water at point B (see Fig. 3a).

Statistical analysis using the product-moment coefficient of correlation indicated positive correlation ($p < 0.05$) between some pairs of parameters namely Mg^{2+} vs Ca^{2+} ($R = 0.83$); K^+ vs Na^+ ($R = 0.95$); Cl^- vs $(\text{Na}^+ + \text{Mg}^{2+})$ ($R = 0.92$); Ca^{2+} vs $(\text{Na}^+ + \text{K}^+)$ ($R = 0.96$); Cl^- vs pH ($R = 0.87$) (Fig. 7). The corresponding regression equations are presented in Table 2.

Moreover, the electrical conductivity shows a positive correlation ($p < 0.05$) with the concentrations of K^+ ($R = 0.97$); Na^+ ($R = 0.96$); Ca^{2+} ($R = 0.93$); Mg^{2+} ($R = 0.82$); Fe^{2+} ($R = 0.85$); Cl^-

Table 2. Results of regression analysis relating concentrations of some of the hydrochemical parameters

| Regression equation | Correlation coefficient (R) | SD of the fit | p-value |
|---|-----------------------------|---------------|-------------|
| $\text{Mg}^{2+} = 0.45859\text{Ca}^{2+} - 3.16549$ | 0.82621 | 4.23649 | 0.00322 |
| $\text{K}^+ = 0.91559\text{Na}^+ - 7.48464$ | 0.9503 | 6.7575 | <0.0001 |
| $\text{Cl}^- = 0.93498(\text{Na}^+ + \text{Mg}^{2+}) + 0.56879$ | 0.92145 | 11.44612 | 0.000151361 |
| $\text{Ca}^{2+} = 0.29788(\text{Na}^+ + \text{K}^+) + 8.90763$ | 0.96309 | 3.6471 | <0.0001 |
| $\text{Cl}^- = 65.20749\text{pH} - 360.234$ | 0.86747 | 14.6572 | 0.00115 |

p-value = Probability (that R is zero).

SD = standard deviation

The concentrations are in mg/l.

($R = 0.91$) and TDS ($R = 0.98$) (Fig. 8). On the other hand, the conductivity shows a negative correlation with SO_4^{2-} ($R = -0.78$). It may be noted that the correlation coefficient between conductivity and the concentration of NO_3^- is not statistically significant ($p > 0.05$).

The regression equations are shown in Table 3. The average values of the ionic ratios for the water samples influenced by leachate (A to D) and the background (E to J) are presented in Table 4. Samples A to D have higher $\text{Na}^+/\text{Ca}^{2+}$. Pawar *et al.* (1998) have reported similar results from a sugar-mill effluent in India.

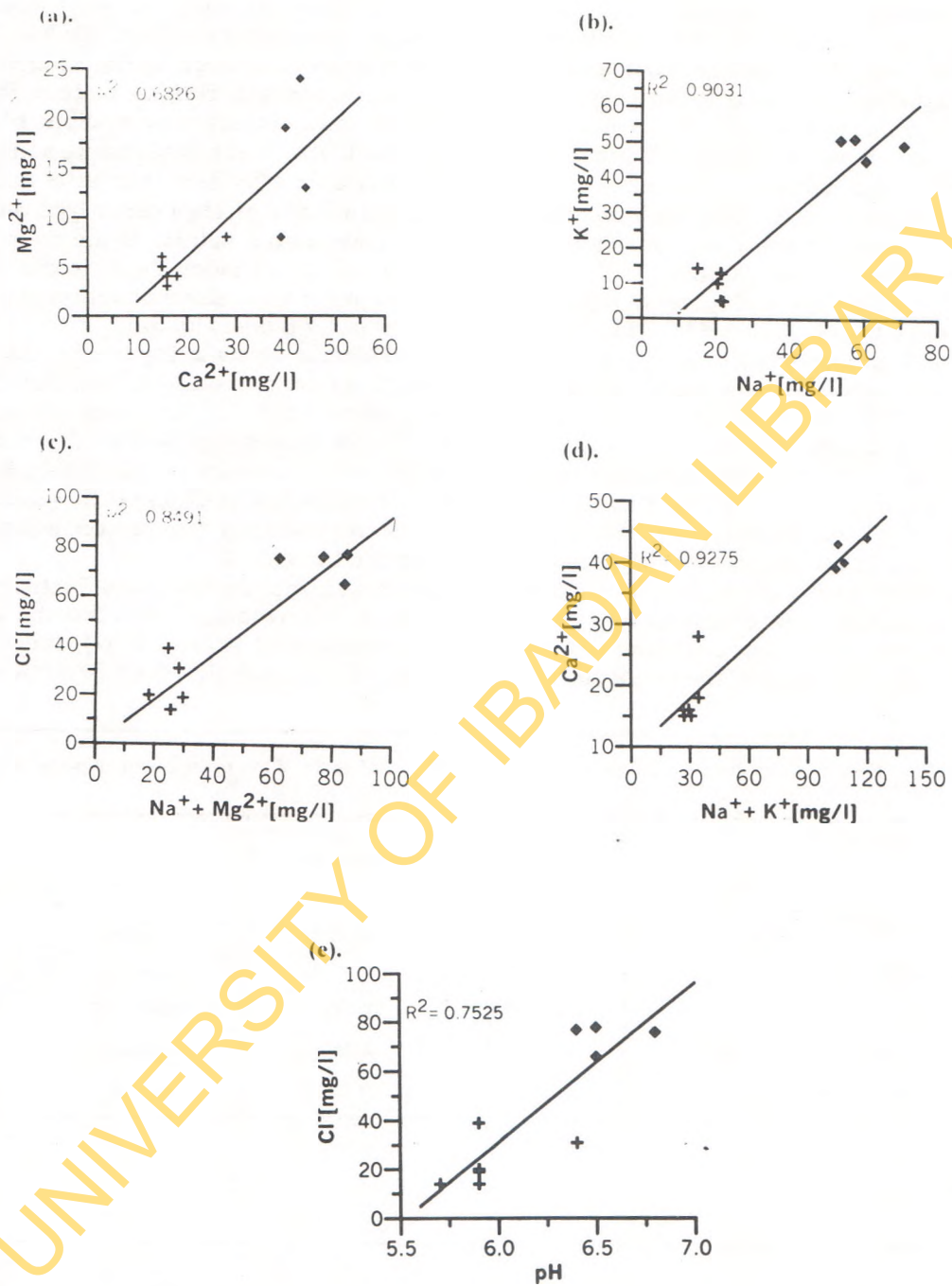


Fig. 7. Correlation between some of the hydrochemical parameters at the waste disposal site. (a) Mg^{2+} and Ca^{2+} , (b) K^+ and Na^+ , (c) Cl^- and $(Na^+ + Mg^{2+})$, (d) Ca^{2+} and $(Na^+ + K^+)$, (e) Cl^- and pH

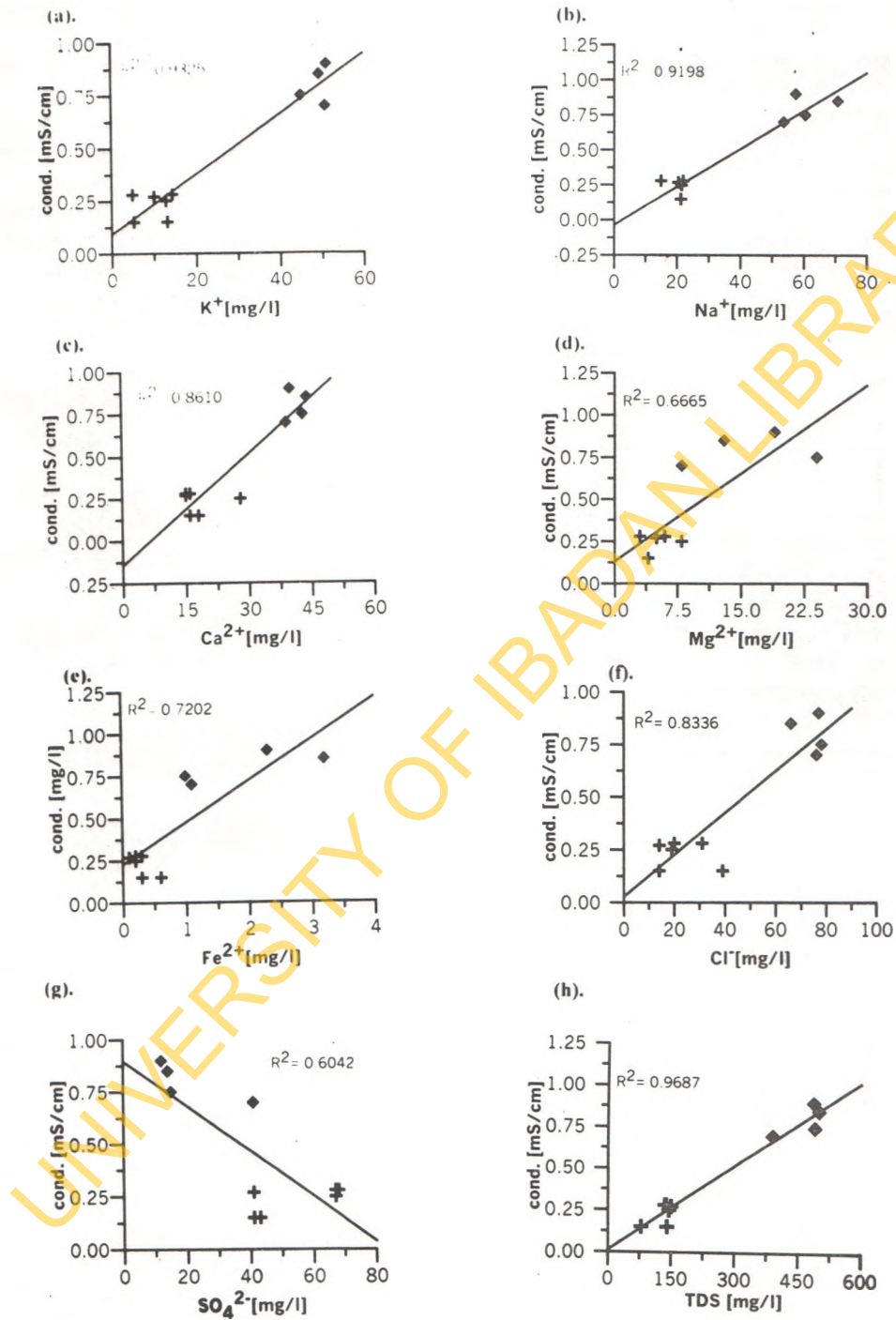


Fig. 8. Correlation between concentrations of ions and the electrical conductivity

Table 3. Results of regression analyses relating concentrations of ions and conductivity.

| Regression equation | Correlation coefficient (R) | SD of the fit | p-value |
|--|-----------------------------|---------------|-------------|
| cond. = 0.01428K ⁺ + 0.09135 | 0.96566 | 0.08541 | <0.0001 |
| cond. = 0.01359Na ⁺ - 0.03692 | 0.95908 | 0.0909 | <0.0001 |
| cond. = 0.02199Ca ²⁺ - 0.14449 | 0.92791 | 0.11968 | 0.000108219 |
| cond. = 0.03485Mg ²⁺ - 0.13037 | 0.8164 | 0.1854 | 0.00396 |
| cond. = 0.24716Fe ²⁺ + 0.22815 | 0.84862 | 0.16983 | 0.00191 |
| cond. = 0.00995Cl ⁻ + 0.02622 | 0.91501 | 0.13097 | 0.000225341 |
| cond. = 0.01073SO ₄ ²⁻ + 0.89668 | -0.77733 | 0.20197 | 0.00814 |
| cond. = -1.46387NO ₃ ⁻ + 0.48874 | -0.10559 | 0.319925 | 0.77158 |
| cond. = 0.00168TDS + 0.0115 | 0.98424 | 0.05677 | <0.0001 |

p-value - Probability (that R is zero);
 SD - standard deviation
 Cond. is the electrical conductivity (ln mS/cm) while the concentrations are in mg/l.

Table 4. Averages ionic ratios for the water samples.

| Group | Na ⁺ /Ca ²⁺ | Ca ²⁺ /Mg ²⁺ |
|--------|-----------------------------------|------------------------------------|
| A to D | 1.4576 | 3.039 |
| E to J | 1.1755 | 3.8055 |

A plot of the TDS against the Na/(Na+Ca) ratio (Fig. 9) shows that the samples plot in the centre of the Gibb's (1970) boomerang; this indicates that the water samples may have acquired their chemistry from the weathered materials derived from the underlying (parent) rocks.

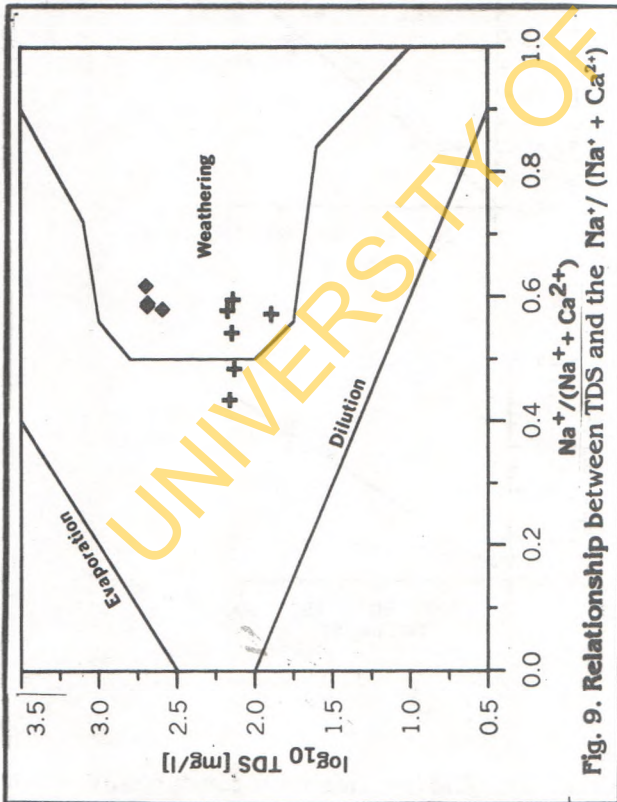


Fig. 9. Relationship between TDS and the Na⁺ / (Na⁺ + Ca²⁺)

The apparent resistivities in the 2D geoelectrical survey are relatively very low, at between about 4ohm-m and 90ohm-m for the three traverses (lines L1-L3) measured on the waste dump (Fig. 10). This is in agreement with the results of the water analyses, which indicate presence of high electrical conductivities. There is a low apparent resistivity anomaly at about the 200-m position along L2 and at about the 150-m position on L3. The mean apparent resistivities for the respective levels of the pseudosection are presented in Fig. 11. It can be observed that the apparent resistivities for the more recently deposited waste along L1 and L2 are lower than those at corresponding electrode spacings on line L3.

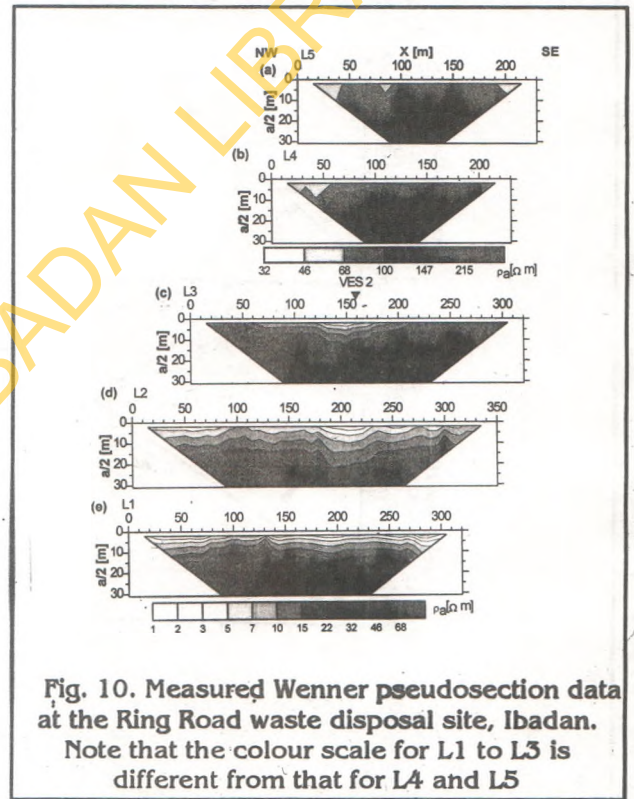


Fig. 10. Measured Wenner pseudosection data at the Ring Road waste disposal site, Ibadan. Note that the colour scale for L1 to L3 is different from that for L4 and L5

An examination of vertical sets of apparent resistivities (for successive electrode spacings) beneath each electrode position, as calculated from equation (1) (Fig. 12) shows that there is a very step vertical gradient, indicating a strong possibility of sharp, rather than gradational, vertical resistivity changes in the electrical imaging data measured over the waste dump. It may be noted that for L1, the vertical gradients are nearly always greater than 1. These subtle features are not very obvious from the iso-apparent resistivity contours. The lateral variations in the apparent resistivity data (Fig. 13) are larger for L4 and L5.

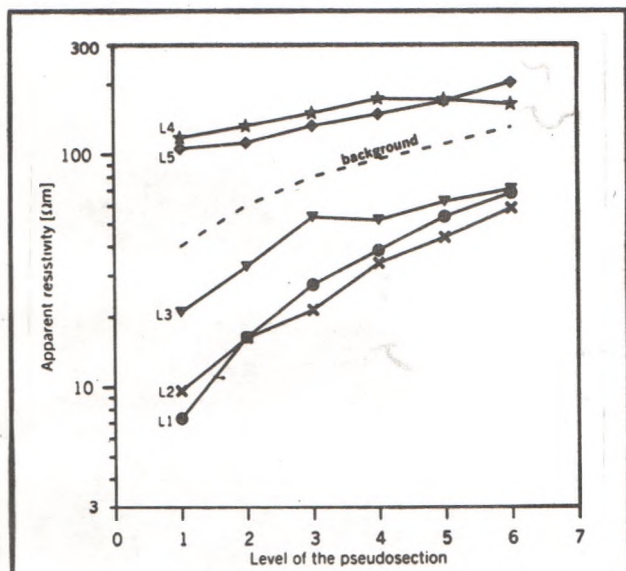


Fig. 11. Mean apparent resistivities measured for the respective levels of the pseudosection. Values below the background have been affected by leachate from the dump site

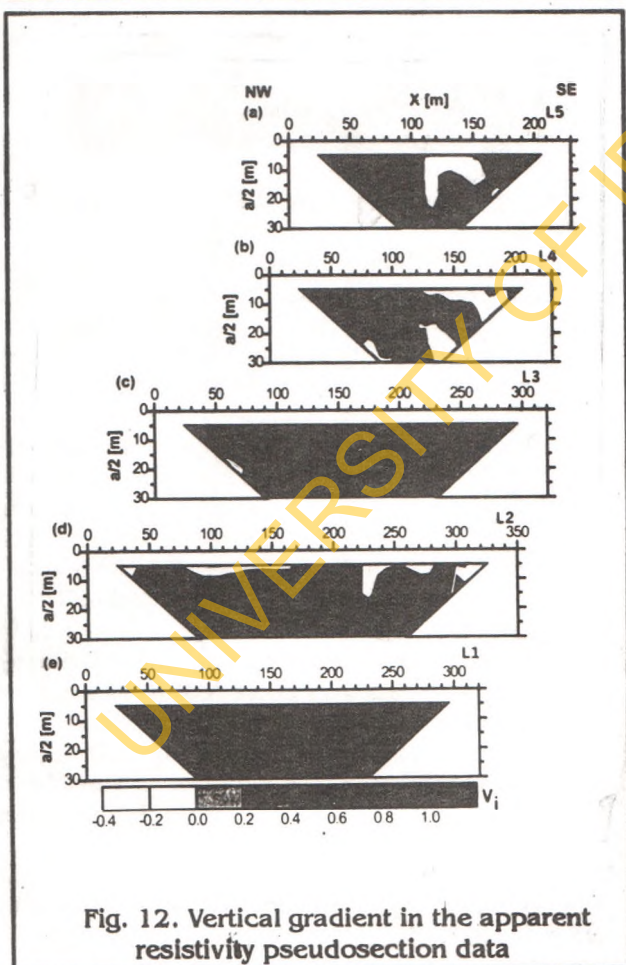


Fig. 12. Vertical gradient in the apparent resistivity pseudosection data

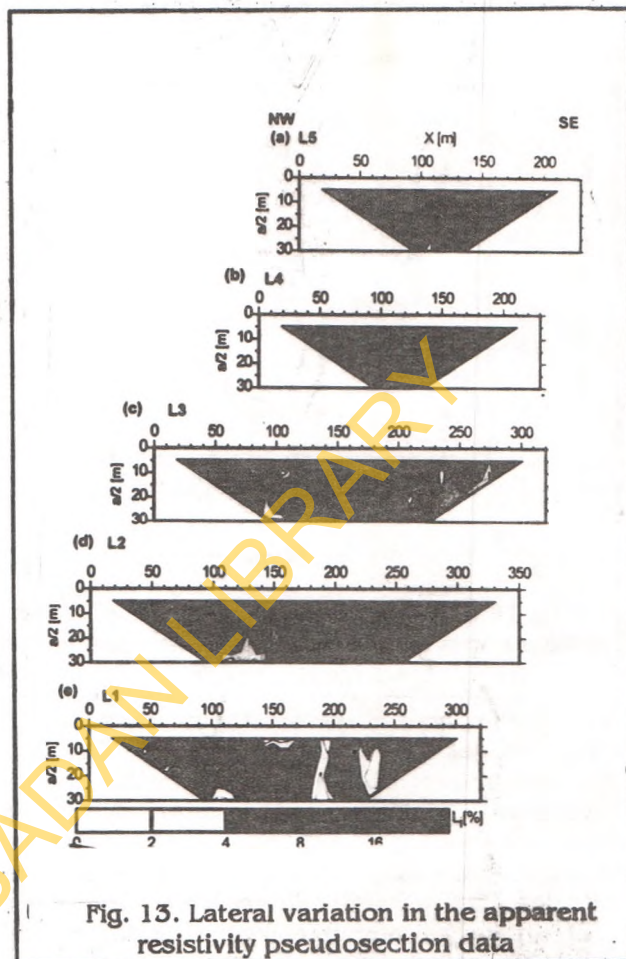
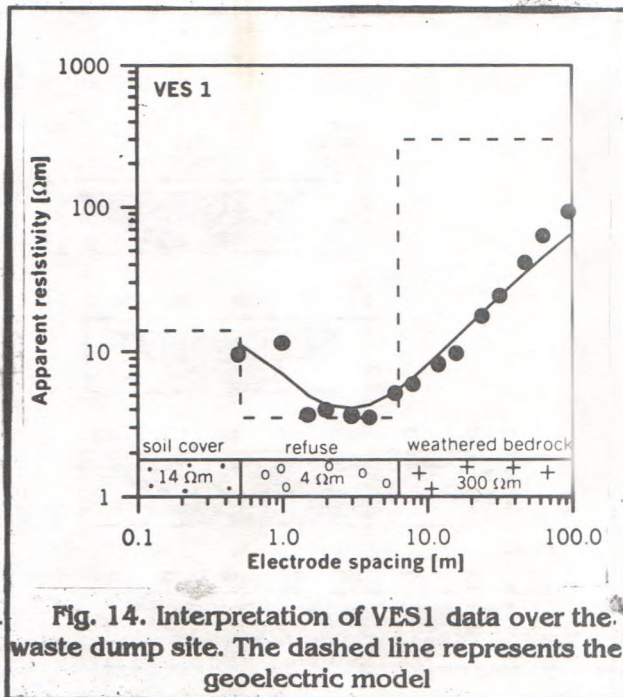


Fig. 13. Lateral variation in the apparent resistivity pseudosection data

Due to the lateral variations in resistivity, it was observed that the right hand side of the two Wenner soundings measured over the dump site show a steeply-rising terminal branch sounding data rises at an angle of over 45° for spacings greater than 16m. A three-layer model was used in fitting the field data. The first layer is the thin soil cover, while the second layer represents the refuse dump. The bedrock constitutes the last layer. The interpretation of VES 1 is shown in Fig. 14.

In comparison, the apparent resistivities for L4 and L5 are much higher at between 35ohm-m and 253ohm-m. In addition, high apparent resistivity structures are very prominent between the 120- and 180-m positions along L4 and between 110- and 160-m along L5; these coincide with outcrops of weathered basement materials.

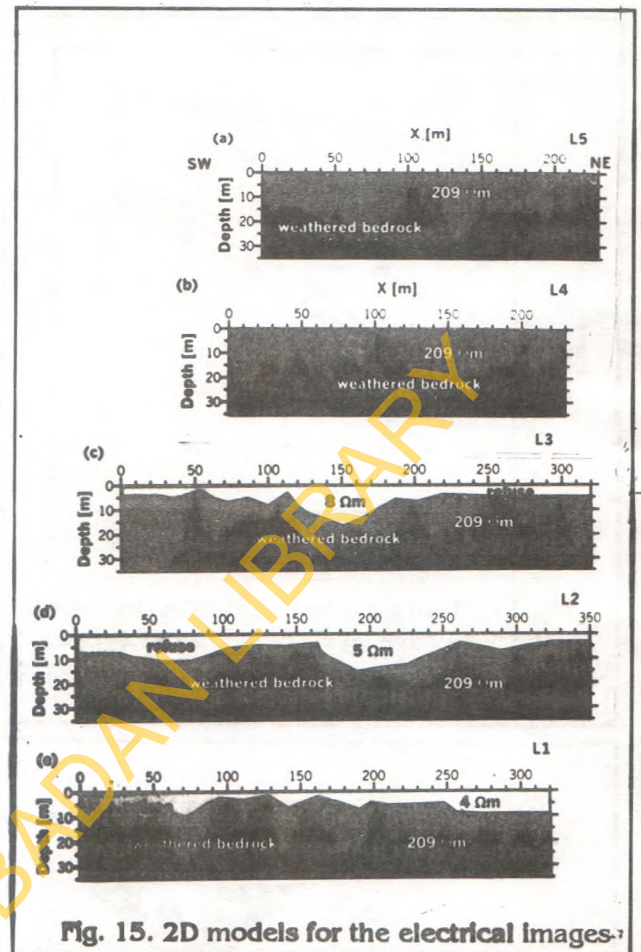
As noted above, there is evidence for a large vertical resistivity change within the waste dump. Hence, in order to produce a final interpretation of the landfill resistivity images, a simplified model in terms of 2 layers has been used to explain the data. The upper layer is the refuse and the second



layer (half-space) is the weathered bedrock. An initial model was compiled for each line, the optimum model obtained from the 2D smooth inversion and the supplementary sounding information serving as a guide. Then, the apparent resistivity pseudosection from this model was calculated using a finite different algorithm. After comparing the computed section with the field data, appropriate adjustments were made to the model parameters and a further computation made. The bedrock resistivity was fixed at 209 ohm-m. The result of the modelling is very sensitive to the resistivity of the upper layer. A satisfactory fit to the field data was reached after about 6 iterations (Fig. 15), with a slightly lower resistivity for the more recently deposited waste along L1 and L2 (4 to 5ohm-m), compared to the older waste below L3 (about 8ohm-m). This interpretation is consistent with the measured data (see Fig. 11). The thickness of the refuse dump varies between about 2m to about 17m.

The low resistivity of the refuse is due to the presence of leachate, which has also polluted the surface- and groundwaters in the immediate vicinity of the site. From a consideration of the surface topography, and the probable groundwater flow direction, it can be expected that there would be a high concentration of leachate, towards the bottom of the valley.

On the other hand, the model overburden resistivities are much higher for L4 and L5 which are not underlain by refuse ; here, the 2D models



are merely a reflection of the lateral variations in the thickness of the regolith derived from the chemical weathering of the crystalline bedrock. The regolith resistivity is between 50 and 60ohm-m while the depth to bedrock ranges between 2 and 27m.

A comparison between the apparent resistivity pseudosection data calculated from the geoelectric model of Fig. 15 and the respective observed data indicates that most of the features in the field data are accurately modelled. These include the low resistivity anomalies towards the centres of L1-L3 and high resistivity structures along L4 and L5. As would be expected, the best agreement between the two sets of data was recorded in L4 which is probably the least noisy. However, the models are not necessarily unique as other models (more complex or less complex) could probably be found that would equally produce acceptable fits to the observed data. It should be noted that the edge of the polluted zone in Fig. 3a was inferred from the geoelectrical imaging results, supplemented with hydrochemical data.

CONCLUSIONS

This paper has demonstrated that the integrated use of geoelectrical imaging and hydrochemistry can be employed to investigate a landfill structure. The probable limit of the polluted zone was defined from the combined use of the two techniques. On basis of the chemical analysis of surface and ground water samples, it has been possible to establish that leachate from the Ring Road waste disposal site in Ibadan, southwestern Nigeria, is a source of pollution of surface and groundwater in the area. In several parts of Nigeria underlain by crystalline basement rocks, a large percentage of the population is dependent on water from shallow wells (often less than 20m deep), as the major source of drinking water supply. Quite commonly, efforts are focused on locating the aquifers to satisfy drinking water needs while the quality aspect is often neglected. Continued operation of waste disposal facilities, near urban centres, without environmental precautions, may lead to serious health problems.

Water-quality management is an issue that must be given top priority. Some of the measures that can be taken for the protection of groundwater

include: (a) waterproofing the base of the leachate stream and the stream bed to prevent infiltration of the effluent, (b) continuous monitoring using geoelectrical imaging to provide early warnings as to the presence of potential pollution, (c) treating the effluent to meet the standards established by both the Oyo State Environmental Protection Agency and the Federal Environmental Agency (FEPA), (d) launching public-awareness campaigns and convincing the relevant authorities at the local, state and federal levels as to the need to undertake groundwater protection measures.

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