Electric log interpretation for the evaluation of salt water intrusion in the eastern Niger Delta

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Abstract The Niger Delta (75,000 km$^2$) comprises a thick (up to 9000 m) sequence of clastic sediments subdivided into the Akata, Agbada and Benin Formations in ascending order. Sands of the Benin Formation constitute aquifers which have been exploited for water supply, although in parts of the delta many of them have been abandoned due to high salinity. Interpretation of 267 oilwell logs for delineating the fresh water-bearing aquifers is reported here. While fresh water sands occur at the upper zone of the Benin Formation in most places, saline water sands were found at the upper zone at depths (ranging from 30 to 947 m) in two well-defined areas, underlain by fresh water sands. The saline water is thought to be connate. The fresh water/saline water interface has been mapped throughout the eastern Niger Delta and is found to be deepest (2237 m) 44 km west-southwest of Port Harcourt.

Interprétation des logs électriques dans l'évaluation de l'intrusion de l'eau salée dans la partie orientale du Delta du Niger

Résumé Le Delta du Niger (75 000 km$^2$) est composé d'une épaisse couche (environ 9000 m) de sédiments élastiques comprenant par ordre croissant les formations d'Akata, d'Agbada et du Benin. Les sables de la formation du Benin constituent des aquifères qui ont été exploités pour l'approvisionnement en eau, bien que dans certaines parties du Delta, un bon nombre de ces aquifères aient été abandonnés en raison d'une salinité élevée. Cette étude propose une interprétation des logs de 267 puits pétrolifères peu profonds en vue de délimiter les aquifères d'eau douce. Tandis que les sables imbibés eau douce s'observent en amont de la formation du Benin dans la plupart des cas, on a trouvé des sables imbibés d'eau saline en amont à des profondeurs comprises entre 30 et 947 m en deux endroits bien déterminés qui reposent sur des sables renfermant de l'eau douce. Nous pensons que l'eau saline est innée. Une carte de l'intéférence entre eau douce et eau saline a été tracée dans toute la partie orientale du Delta du Niger et il a été contaté que la profondeur maximale est de 2237 m, à 44 km ouest-sud-ouest de Port Harcourt.
INTRODUCTION

The Niger Delta is a coastal arcuate delta of the River Niger (Fig. 1), covering an area of about 75 000 km$^2$, and comprises a 9000 m thick overall clastic sequence (Evamy et al., 1987). Over 95% of Nigeria's oil and gas is produced from reservoirs in both onshore and offshore areas of the delta.

Salt water intrusion in coastal aquifers is a subject that has been intensively studied all over the world as a scientific understanding of saline intrusion in a particular area is essential for the management of coastal water resources (Van Dam & Meulenkamp, 1967; De Breuck & De Moor, 1969; Shata & El-Fayoumy, 1970; Oteri, 1983; Mandel & Goldenberg, 1986). Salt water intrusion into aquifers in the Niger Delta has resulted in the abandonment of many water wells in parts of the delta, e.g. Buguma, Bille, Kulama and Aiyetoro. Despite the large number of published articles on the Niger Delta (Short & Stauble, 1967; NEDECO, 1961; Weber, 1971; Allen, 1965; Avbovbo, 1978; Evamy et al., 1978; Opara, 1981; to mention a few), very little work has been done on the fresh water/saline water relationships in aquifers there. Avbovbo (1978) drew an isopach map of fresh water sands.
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from interpretation of oilwell logs. This, however, was based on the wrong assumption that the sands in the youngest formation (Benin Formation) were all fresh water-bearing. BRGM & Metals and Minerals (1979) catalogued the existing water well information in coastal areas of Nigeria but apart from remarking on the occurrence of saline intrusion, the report provided little data on the depth to the fresh water/saline water interface anywhere. It actually recommended a depth of 200-300 m for all water wells in coastal areas of Nigeria in order to obtain fresh water. Etu-Efeotor (1981) and Amajor (1986) have discussed the hydrochemistry of groundwaters in the eastern Niger Delta.

Since the first oil well, Ihuo-1, was drilled in 1951 in the Niger Delta, thousands of other wells have been drilled both onshore and offshore. In this study, oilwell logs have been interpreted in terms of water quality, thereby mapping the fresh water/saline water distribution in aquifers of the eastern Niger Delta (Fig. 1). It is hoped to extend this study eventually to the western Niger Delta where similar conditions are known to exist (Oteri, 1984).

GEOLOGY

The Niger Delta is made up of thick clastic sedimentary rocks with ages ranging from Eocene to Recent. It consists, in ascending order, of the Akata, Agbada and Benin Formations (Short & Stauble, 1967) which occur throughout the delta. The Akata Formation is characterized by a uniform marine shale development while the Agbada Formation consists of sandstone and sand beds alternating with shale layers. The sands are generally salt water-bearing with formation resistivities up to 2 Ω m except in those sands containing hydrocarbons. The Benin Formation consists of predominantly massive highly porous sands and gravels with locally thin shale interbeds. Sand percentage ranges between 70 and 100%. The shales range from impermeable to semipervious. Consequently there is not a single water-bearing formation but many (artesian) aquifers. This is characteristic of most deltas (Huisman, 1966).

METHOD OF STUDY

Two hundred and sixty seven oilwell logs run by Shell Petroleum Development Company of Nigeria Ltd and Gulf Oil Company of Nigeria Ltd in the eastern Niger Delta and whose top log depth (shallowest depth logged with a resistivity tool) was shallower than 609 m have been interpreted during the study. For the vast majority of well logs run in the delta, resistivity logging starts at depths of 1000 m or more as sands of the Agbada Formation are the reservoirs of interest in oil exploration.

The well logs interpreted are resistivity logs run in combination with spontaneous potential (SP) and/or gamma ray (GR) logs, the SP and GR logs being used to interpret the lithology. The data obtained were in the form of depth interval, lithology and formation resistivity. These were taken from the
top log depth to a depth within the Agbada Formation. The top log depth varied between wells. Analysis showed that in 56% of the wells studied, the top log depth did not exceed 61 m while 85% were shallower than 152 m. A comparison with water wells drilled by Shell for its operations in the eastern Niger Delta revealed that of the 233 wells drilled as at December 1984, 77% were shallower than 61 m while 97% were shallower than 152 m. The shallowest well was 30 m deep with the deepest being 506 m. The well logs can be said to be covering the critical depth range for water wells in the area.

Relationship between formation resistivity and water quality in the Niger Delta aquifers

The author is not aware of any work that has been carried out relating water quality parameters to formation resistivities within aquifers of the Benin Formation. This is because for the vast majority of water wells in the area, no well logs were run, while systematic water sampling was not undertaken in wells that were logged.

<table>
<thead>
<tr>
<th>Well</th>
<th>Depth (m)</th>
<th>Chloride (mg L⁻¹)</th>
<th>Conductivity (25°C) (10⁻⁶ S cm⁻¹)</th>
<th>Formation resistivity from oilwell log (Ω m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buguma</td>
<td>259</td>
<td>2269</td>
<td>2300</td>
<td>4—6</td>
<td>a</td>
</tr>
<tr>
<td>Kula</td>
<td>151</td>
<td>NG</td>
<td>362</td>
<td>150</td>
<td>b</td>
</tr>
<tr>
<td>Bille</td>
<td>188</td>
<td>2940</td>
<td>13300</td>
<td>7</td>
<td>a</td>
</tr>
<tr>
<td>Forcados</td>
<td>6</td>
<td>42.5</td>
<td>263</td>
<td>96</td>
<td>c</td>
</tr>
<tr>
<td>Forcados</td>
<td>1-8</td>
<td>60</td>
<td>200</td>
<td>50</td>
<td>c</td>
</tr>
<tr>
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<td>12</td>
<td>180</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>Escravos Terminal</td>
<td>105</td>
<td>551</td>
<td>2000</td>
<td>15—20</td>
<td></td>
</tr>
</tbody>
</table>

a — from BRGM & Metals and Minerals (1979);
b — from Etu-Efeotor (1981);
c — from surface electrical resistivity soundings (Oteri, 1984);
NG = not given.

Chloride and conductivity of water samples obtained from a very few logged water wells or those wells close to logged oilwells have been assembled in Table 1. A linear logarithmic regression analysis of the aquifer resistivity with chloride ion concentration and electrical conductivity gave the following relationships:
chloride ion:

\[ [\text{CL}] = 54 \, 133 \, [\text{RESIST}]^{-1.69} \]
\[ r = -0.98 \] (1)

conductivity:

\[ [\text{COND}] = 29 \, 425 \, [\text{RESIST}]^{-1.03} \]
\[ r = -0.87 \] (2)

where:
- \([\text{CL}]\) = chloride ion concentration in mg l\(^{-1}\);
- \([\text{COND}]\) = electrical conductivity of water in \(10^{-6}\) S cm\(^{-1}\);
- \([\text{RESIST}]\) = aquifer resistivity in \(\Omega\) m;
- \(r\) = correlation coefficient.

A better (inverse) correlation was found to exist between chloride ion concentration and aquifer resistivity than between the electrical conductivity and aquifer resistivity. In using the above relationships for the Benin Formation, extreme caution needs to be exercised as the sample points were very few (seven or less) and water samples were not obtained from specific intervals in logged wells.

It is perhaps worth noting that Guo (1986) found a linear logarithmic relationship between total dissolved solids \([\text{TDS}]\) and aquifer resistivity of the form:

\[ [\text{TDS}] = 45.3 \, [\text{RESIST}]^{-1.2} \]
\[ r = -0.936 \] (3)

in sand aquifers of the North China Plain.

An aquifer resistivity of 40 \(\Omega\) m which from equations (1) and (2) corresponds to water with a chloride ion concentration of 120 mg l\(^{-1}\) and electrical conductivity of \(680 \times 10^{-6}\) S cm\(^{-1}\) respectively has been chosen as the boundary between fresh water and brackish/saline water in this study. Aquifers having resistivity of 40 \(\Omega\) m and above are termed fresh water aquifers while those with formation resistivities less than 40 \(\Omega\) m are termed brackish/saline water aquifers.

RESULTS AND DISCUSSION

Based on the depth of occurrence of the first saline water sands, the wells could be divided into two major categories: those wells in which shallow saline water sands are encountered at top log depth underlain by fresh water sands and saline water sands successively (Group S); and those wells in which fresh water sands were encountered at top log depth underlain by saline water
Fig. 2. (a) Schematic diagram showing characteristics of Group S and Group F wells. (b) Electric logs of Well-1 and Well-2, examples of Group S and Group F wells respectively (Rm = resistivity of mud; Rmf = resistivity of mud filtrate; DFE = derrick floor elevation). Resistivity in Ω m.
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sands (Group F). Figure 2(a) is a schematic diagram illustrating the two categories while Fig. 2(b) shows electrical logs of Well-1 and Well-2 illustrating aspects of Group S and Group F wells respectively. In a few of the wells studied, the formation resistivity of all sands encountered was lower than 40 Ω m.

Figure 3 shows the locations of the well logs for the study and distribution of the various categories. It is seen that the vast majority of the wells belong to Group F, a fact that must have led the previous authors (Avbovbo, 1978; Opara, 1981) to describe the Benin Formation as fresh water-bearing. Group S wells are concentrated in two zones marked S1 and S2 in Fig. 3, and in two isolated wells east of Zone S2 shown in the figure. Some wells, especially those on the west margin of Zone S2, showed multiple wedge structure (Collins & Gelhar, 1971), where aquifers separated by shale beds have their separate fresh water/saline water interfaces. Figure 4 illustrates the phenomenon with the interval 64–406 m having fresh water-bearing sands. Within the interval 406–779 m the aquifers separated by thin shale beds have their separate fresh water/salt water interfaces as shown in the figure. Thick fresh water-bearing sands occur again from 796 m to the base of fresh water sands at 2030 m depth (not shown in Fig. 4).
Contour lines of depth to the fresh water/salt water interface [c in Fig. 2(a)] are also shown in Fig. 3. These indicate that the interface is deepest in the centre of the delta reaching a maximum depth of some 2200 m about 44 km west southwest of Port Harcourt. The depth to the interface decreases rapidly offshore and less rapidly eastwards and northwards.

Zones with shallow saline water sands (Group S)

The characteristic feature of all Group S well logs is an intervening shale layer separating the denser salt water above from the less dense fresh water below. The thickness of this shale layer varies from one well to another with some as thin as 2.4 m. The Maestrichtian aquifer in Senegal is similarly separated from the upper brackish water-bearing Eocene aquifer above it by clays (Fleurova & Marinov, 1978).

Of the areas where shallow saline water sands were found, that in Zone S2 is the most extensive and well-defined. The wells in this zone form a "structure" with an estimated length of 110 km; it is 50 km wide at the present-day coastline tapering at its northernmost extremity inland. The depth to the top of the fresh water sands underlying the saline water sands varies as
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Fig. 5 Depth (measured) to top of fresh water sands underlying saline water sands in Zone S2 in m.

shown in Fig. 5, to a maximum value of some 950 m. It was found to be shallowest at the coastline, deepening steeply inland but gently offshore. Figure 6 shows cross sections along profiles XX' and YY' which illustrate the variations in thickness of the fresh water-bearing sands. Along the strike direction XX', the thickness of the fresh water sands was found to be less in areas with shallow saline water sands than in areas without. Offshore, the thickness of the fresh water sands decreases to a minimum value. The east-west cross section along profile YY' showed that the shallow water sands were thicker in the west of the Zone S2 "structure", thinning rapidly eastwards. The fresh water aquifers were more uniform in thickness along this profile than along the XX' profile.
Source of the saline water

Even though much investigation still needs to be done before definite conclusions can be made about the source and mechanism of the salt water intrusion in the Niger Delta, it is deemed essential to make some projections. Groundwater resources development in the Niger Delta is still in its infancy. There is therefore no overdevelopment of the aquifers that could have led to recent salt water intrusion. The Niger Delta was formed on a subsiding basement with minor transgressions occurring from time to time during the main regressive phase (Evamy et al., 1978; Oomkens, 1974; Weber, 1971). It is thought that the saline water delineated from this study are connate with the sands deposited during some of the transgressive phases of delta formation.

CONCLUSION

This regional study using shallow oilwell logs has shown that thick fresh
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Water-bearing aquifers occur in the eastern Niger Delta, even in areas where many water wells were abandoned due to high salinity. Salt water intrusion, which is thought to be connate, has been delineated. The well logs have provided a much more cost effective method of delineating the fresh water aquifers and mapping the fresh water/saline water interface compared with the more usual surface geophysical techniques in this area. This is partly because of the fact that well logs are already available owing to the oil exploration activity and partly because of the deteriorating resolution with depth in the case of surface electrical resistivity particularly with the preponderance of clayey overburden in riverine areas of the delta. Finally, by mapping the depth to the top of fresh water aquifers and the interface between fresh and saline waters, the results of this study have provided an effective strategy for minimizing the incidence of abandoned wells as a result of high water salinity in the eastern Niger Delta.

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