Hydrology in the Humid Tropic Environment (Proceedings of a symposium held at Kingston, Jamaica, November 1996). IAHS Publ. no. 253, 1998.

Salinization of shallow sandy coastal aquifers: a case study from parts of the Niger Delta region of Nigeria

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Abstract The Niger delta is the main oil producing region of Nigeria. The shoreline of the delta is arcuate shaped with a length in excess of 300 km. Behind the belt of beaches and sand ridges at the shore is a mangrove swamp from 5 km to over 50 km wide. This zone is traversed by a network of creeks with numerous small ponds and swamps. The creek density ranges from about one creek per 3 × 3 km of the land surface to over one creek per 1 × 1 km, and the widths range from less than 20 m (inland) to over 1000 m at the shoreline. This paper focuses mostly on the effects of this creek network on the quality of water in the adjacent aquifers. It is clear from the study that the creeks, especially within the mangrove zone, are saline with electric conductivity (EC) ranging up to 40 000 $\mu S\ cm^{-1}$ and chloride concentrations ranging up to 13 000 $mg\ l^{-1}$. The high salinity is generally the result of daily flushing of this zone by ocean tides. Despite the dense network of saline creeks, the groundwater in adjacent shallow aquifers is generally fresh with EC less than 1000 $\mu S\ cm^{-1}$ and chloride concentrations less than 200 $mg\ l^{-1}$. However, there is clear evidence of seawater presence in the shallow aquifers and some locations have up to 18% saline seawater. The low level of seawater encroachment seems to arise from the nature of the hydraulics in the area. Most of the aquifers are essentially undeveloped, in many of the rural settlements sampled, and the general flow of the groundwater is towards the creeks. It is projected that heavy groundwater withdrawal from the many water boreholes in Oil Corporation Campsites may have stimulated a more intense saline water encroachment than was observed in this study.

Salinización de los acuíferos costeros arenosos poco profundos

Resumen El delta del Níger es la principal región productora de petróleo de Nigeria. La costa del delta tiene forma arcuate con una extensión de más de 300 km. Detrás del cinturón de playas y riscos arenosos costeros hay manglares de entra 5 y 50 km de ancho. La zona es atravesada por una red de riachuelos con numerosos estanques pequeños y pantanos. La densidad de los riachuelos va desde uno por cada 3 × 3 km de superficie terrestre hasta más de uno por cada 1 × 1 km, y su anchura desde menos de 20 m (tierra adentro) hasta 1000 m en la costa. Este trabajo se centra principalmente en los efectos de esta red de riachuelos sobre la calidad del agua en los acuíferos adyacentes. Queda evidenciado en el estudio que los riachuelos, especialmente dentro de la zona de manglares, son salinos con una conductividad eléctrica (EC) de hasta 40 000 $\mu S\ cm^{-1}$ y concentraciones de cloruro de hasta 13 000 $mg\ l^{-1}$. La elevada salinidad es generalmente resultado de la descarga diaria de esta zona por las mareas oceánicas. A pesar de la densa red de riachuelos salinos, el agua subterránea en los acuíferos adyacentes poco profundos es generalmente dulce, con EC menor a 1000 $\mu S\ cm^{-1}$ y concentraciones de cloruro inferiores a 200 $mg\ l^{-1}$. Sin embargo, hay una clara evidencia de la presencia de agua de mar en los acuíferos poco profundos y algunos sitios tienen hasta 18% de agua de mar salina. El bajo nivel de intrusión de agua de mar parece surgir de la naturaleza de la hidráulica del área. Los acuíferos están en su mayor parte inexplotados en muchos de los asentamientos rurales tomados como muestra, y el flujo general del agua subterránea es hacia los riachuelos. Se ha proyectado que la fuerte extracción de agua subterránea de muchos de los pozos de agua en las estaciones de la corporación petrolera pueden haber estimulado una más intensa intrusión salina que la que se pudo observar en el presente estudio.

INTRODUCTION

Salinization of coastal aquifers arises mainly from two natural mechanisms: (a) the intrusion of saline seawater into adjacent coastal aquifers as governed generally by the Ghyben-Herzberg equation and aided by artificial withdrawal of fresh groundwaters in the aquifers; and (b) the intrusion of saline seawater into inland channels, embayments, creeks, and other surface water sources and the subsequent lateral and vertical movements of the saline water into adjacent aquifers. The first process is very common and is frequently documented in the literature (De Breuck, 1991). The second is prominent especially where the hydraulic activities of the coast (tides, currents, etc.) have developed a belt rich in saline water bodies adjacent to the coastline.

The shoreline of the Niger Delta is arcuate shaped with a length in excess of 300 km. Behind the belt of beaches and ridges (0–2.5 km wide) is a mangrove swamp, 5 km to over 50 km wide. This zone is traversed by a network of creeks with numerous small ponds and swamps. The creek density for example ranges from about one creek per 3 × 3 km of the landsurface to over one creek per 1 × 1 km. The creeks range in width from less than 20 m to over 3 km with the greater widths occurring as embayments at the shoreline.

Over 50% are, however, less than 100 m wide especially at the contact with the dry land bordering the delta. The water in the creeks is saline with electric conductivity (EC) ranging between 15 000 and over 30 000 $\mu S\ cm^{-1}$. This paper focuses mostly on the effect of this creek network (including the associated ponds, swamps, etc.) on the quality of the water in adjacent aquifers.

PHYSIOGRAPHY AND CLIMATE

The present day Niger Delta is an elongate triangle shaped region with an inland apex at Onitsha and bases at the coasts—Opopo in the east of the Delta and Forcados in the west. The delta may be subdivided into five physiographic units (Shell, 1962; Allen, 1965) comprising:

(a) meander belts;
(b) wooded backswamps and freshwater swamps;
(c) mangrove swamps;
(d) lagoonal marshes; and
(e) abandoned beach ridges.

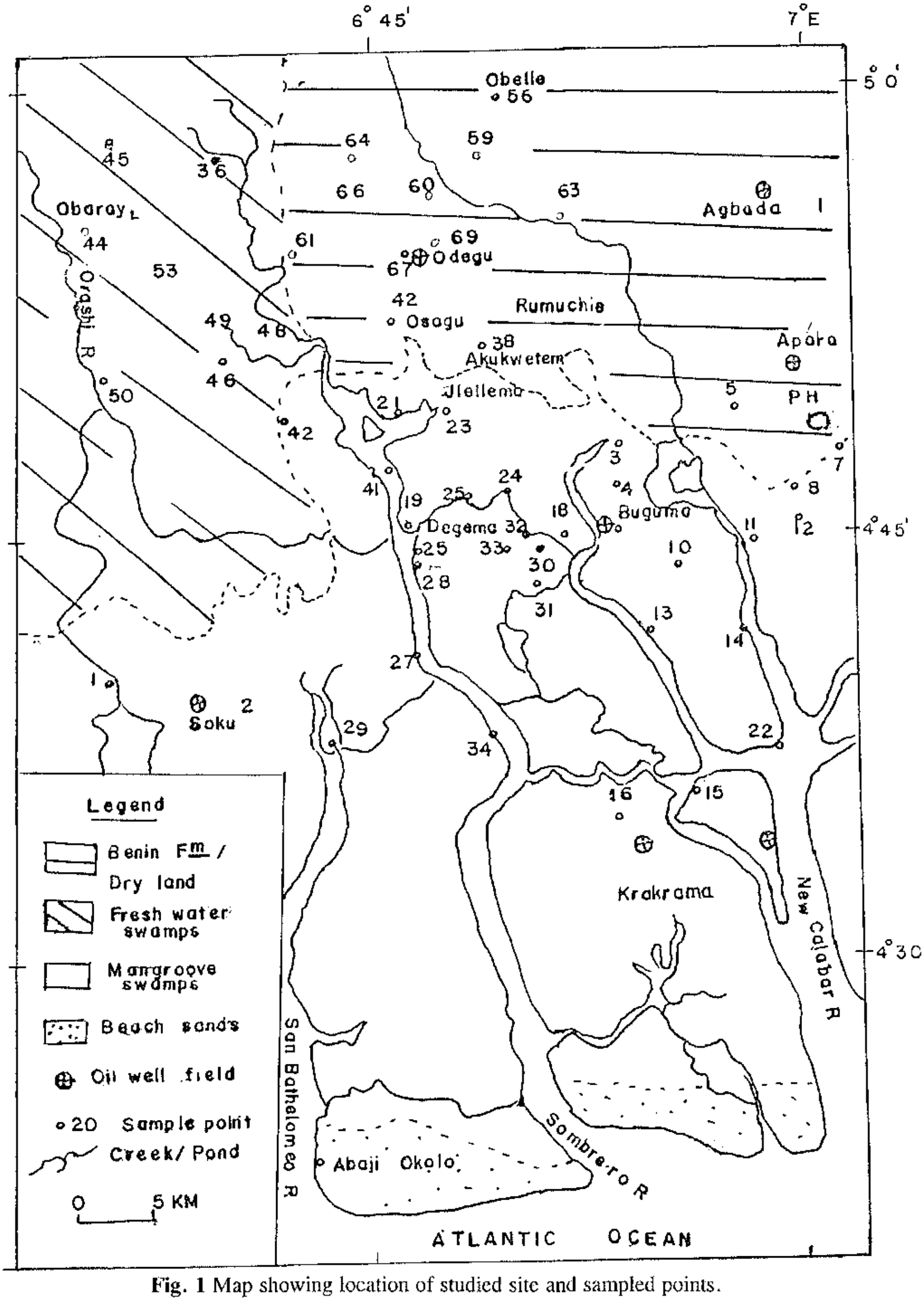

Fig. 1 Map showing location of studied site and sampled points.

The distribution of these geomorphic units is fairly well known and is summarized in Fig. 1. The main region of study—the mangrove belt—extends throughout the delta and is a few hundred metres to about 3 km behind the shoreline.

The region is, however, less developed (generally less than 15 km wide) at the central and western zones where the bulk of the water of the Niger River is discharged to the sea but prominent (ranging over 50 km) at the eastern margin with less freshwater distributaries. The area selected for detailed investigations—the Degema/Buguma area—is within the eastern margin where the mangrove zone is distinctly developed.

There are no highlands, but the creeks and marshes form depressions which are 2–10 m below adjacent lands. Locally, there is a slow but persistent rise in the in the relief away from the creeks and the farthest points are generally the most elevated. The localized relief, as described above, is superposed on a regional seaward slope in the range of 1 m/km.

The climate is equatorial with many rainy days and relatively fewer dry days. The rainy season lasts from March to November while December–February are more or less dry. However, only the month of January is—in some years—completely rainless. The average annual rainfall is over 3000 mm and, as the area is flat and vegetated, much of the rain is available to recharge the groundwater regime.

GEOLOGIC AND HYDROGEOLOGIC FRAMEWORK

The modern delta is a depression carved on an earlier (Tertiary) delta (Allen, 1965). The depression is infilled by late Quaternary (late Pleistocene to Holocene) deposits. The thickness of the materials increases from the delta edge towards the centre. For instance, at Okirika, at the eastern edge of the delta, the Quaternary deposit is less than 5 m thick whereas at Brass, at the axial region, the thickness is over 50 m. The stratigraphy of the deposits including those of the underlying bedrock is given in Etu-Effetor & Akpokodje (1990) and Amajor & Ngerebara (1990). The sequence is characterized by dominantly argillaceous beds (silts and clays) near the top and more sandy beds towards the base. The details appear to vary with specific geomorphic units. For instance, sandy beds are generally more common within the freshwater swamps while clays and silts appear to dominate the mangrove swamps. The top horizon (0–1.0 m) of the mangrove swamp is usually a dark grey silty clay with abundant organic matter.

In the principal area of investigation, sandy beds dominate over argillaceous layers and the general stratigraphy is similar to that of the freshwater swamps. A typical section is given in Fig. 2. The clay–silt layers actually contain pockets of sands and the sandy beds are frequently interlayered with clays. Typical columnar sections are given in Etu-Effetor & Akpokodje (1990), Mbipom & Archibong (1989) and Oteri (1990). The presence of numerous shallow dug wells (generally less than 10 m below ground surface) in the Degema-Buguma area also support the dominance of sandy layers over clays and silts.

The generalized picture of the hydrogeologic framework may be obtained from the geology. The sandy beds and the numerous dug wells confirm the presence of a shallow sandy aquifer throughout the study area. The water table in the dug wells varies from 10 to 20 m in inland areas and from 2.0 to 10 m in the near shoreline areas. Reliable contoured maps could not be obtained and a water table map was not prepared, but evaluation of the topography and groundwater level data suggests a general local flow toward the creeks.

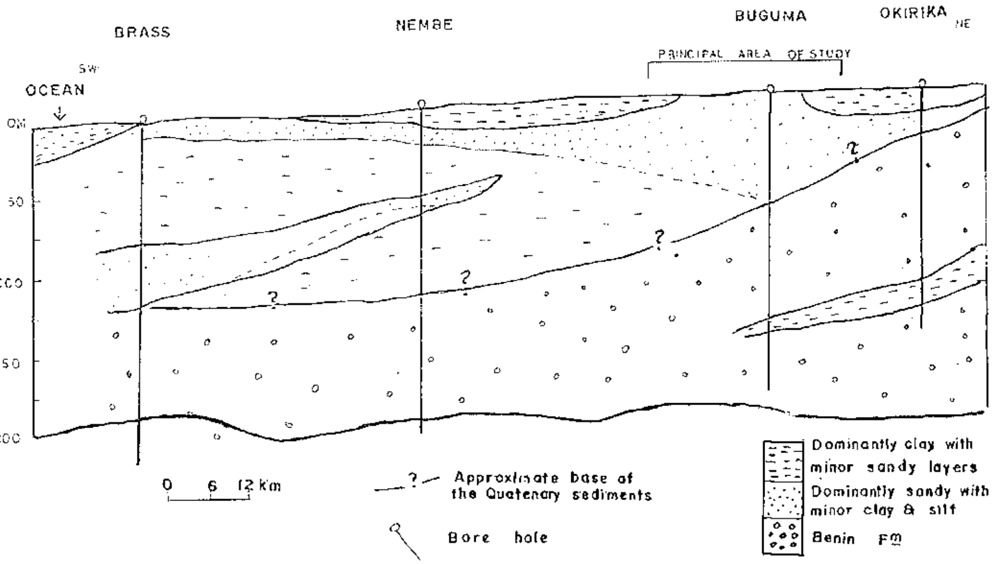

Fig. 2 Geological section across the Niger Delta.

METHOD OF INVESTIGATION

The high salinity of the creek waters was first observed from a casual (non geological) trip to the Degema area. A follow-up study was subsequently planned and involved boat trips to a number of communities around the Degema-Buguma area of River State, Nigeria (Fig. 3). The salinity of the creeks at each village was measured *in situ* with the help of Wissenschaftlich Technische Werkstaetten (WTW) field conductivity and pH meters. Other water sources—dug wells, boreholes and springs—were similarly investigated. The water table in the dug wells and the lithology at the visible section of the unlined wells were observed. Distances from the dug wells and boreholes to the nearest creeks were obtained by estimation with the help of 1:50 000 planimetric maps of the area (the Degema and Kilo sheets published by the Federal Survey of Nigeria).

For logistic reasons, it was not possible to follow a pre-planned network of observation points. Many strategic villages, especially toward the coast, were not visited for crew safety reasons (prevailing inter-community clashes in this oil rich region). All the measurements were done in the peak of the dry season (January 1995) when freshwater influx is least and salinity is highest. Many of the creeks were over 50 m wide and a representative sample could not be taken. The electric conductivity was thus taken at every 5 m across such streams and the average was taken as the average value for the point of measurement. Such values do not take into account the actual volume of flow of the creek but the representative values so obtained appear reasonable for this study. Moreso, individual values at each cross section rarely deviated more than 10% from the mean.

Water samples were taken from each measurement point in one litre plastic containers and were subsequently analysed using Merk Field Kits (Aquamerk 11106 for chlorides and 8048 for carbonates). Because of laboratory and cost constraints only Cl and HCO_3 which could be obtained with the available Merk kits were measured. These parameters are believed to be very helpful in investigating the salinization process in the area, since the two water source end members—saline and freshwater—can easily be identified.

RESULTS

Surface waters

The sample points are given in Fig. 1 while Table 1 displays the hydrochemical parameters measured. The pH of the water sources (not included in the table) ranges from 5.7 to 9.3 but over 75% of the samples had pH values of 6.7 to 8.4 and it is clear that the dominant form of carbonates is bicarbonate (HCO_3). Table 1 reveals that the salinity of the creeks (in terms of electric conductivity) ranges from about 18.8 $\mu S\ cm^{-1}$ to about 39 100 $\mu S\ cm^{-1}$. The salinity of the seawater around the inlet of the creeks ranges 35 000 $\mu S\ cm^{-1}$ at Abaji Okolo (mouth of San Bartholomeo Creek) to about 42 000 $\mu S\ cm^{-1}$ at Elem Ifoko (new Calabar River). Based on this, it was assumed that samples with salinity values over 30 000 $\mu S\ cm^{-1}$ are mostly seawater while those with values less than 200 $\mu S\ cm^{-1}$ represent fresh (unmixed) water from the inland rivers. Samples with values ranging within these extremes, i.e. 200–30 000 $\mu S\ cm^{-1}$, represent various levels of mixing of saline seawater and fresh inland waters.

A generalized salinization pattern of the surface water sources appears distinct. The inland streams and rivers remained fresh (with electric conductivity, EC, less than 200 $\mu S\ cm^{-1}$ until they enter the mangrove zone which is flushed by inland surging seawater under tidal influence. The distance from the shoreline at which the saline water is encountered varies from creek to creek and appears to depend both on the volume of freshwater flowing down the creek and on the strength of the tide. For instance, at the western border of the studied area (Fig. 1) where the bulk of the Orashi River is discharged through San Bartholomeo and Sta Barbara creeks, the mean distance is about 40 km from the shoreline, whereas at the middle region and eastern boundary where the relatively small Sombreiro River is discharged, the average distance from the coast is over 50 km.

The transition from freshwater (EC $< 200\ \mu S\ cm^{-1}$) to relatively saline water (EC $> 10\ 000\ \mu S\ cm^{-1}$) varies widely being narrow at some locations and much wider at others. The EC at Harry's Town (21) and Ile-ilema (23) beaches (separated by about 6 km on an east–west line, Fig. 1) were 16 800 and 16 700 $\mu S\ cm^{-1}$ respectively, but the values at Osogu (42) and Akukwatere (38) were 8000 and 14.0 $\mu S\ cm^{-1}$ respectively. These later stations are both about 7 km away from Harry's Town and Ile-ilema and connected to them by creeks of similar magnitude. While Osogu is northwest of Harry's Town, Akukwatere is northeast of Ile-ilema. In general, intermittent EC values in the range 600–5000 $\mu S\ cm^{-1}$ were rare, whereas many values were either less than 200 $\mu S\ cm^{-1}$ or more than 5000 $\mu S\ cm^{-1}$ (either fresh or significantly mixed).

In the middle region of the mangrove belt, the salinity of the creeks also fluctuated rapidly from about 16 000 $\mu S\ cm^{-1}$ to over 30 000 $\mu S\ cm^{-1}$. For instance,

Table 1 Some hydrochemical properties of the surface and groundwater samples.

			SURFACE WATER				GROUND WATER			
	S/N	LOCATION	RX	EC µS/cm	Cl⁻ mg/l	HCO_3 mg/l	EC µS/cm	Cl⁻ mg/l	HCO_3 mg/l	RX
10/1/96	1	Sama	121.7	27,800	10,705	152	775	142	220	1.1
,, ,, ,,	2	Ikukiri	77.3	28,800	9,300	205	610	88	189	0.8
,, ,, ,,	3	Tombia	113.9	29,100	9,600	145	849	150	230	1.1
,, ,, ,,	4	Bukuma	123.6	28,900	9,470	132	748	96	205	0.8
,, ,, ,,	5	Iwofe	97.7	28,000	9,200	162	460	36	160	0.4
,, ,, ,,	6	Chiba	23.5	1,153	380	28	136	17	42	0.6
,, ,, ,,	7	Port Harcourt	62.7	27,100	8,800	187	480	41.3	150	0.5
,, ,, ,,	8	Okirika	134.5	28,700	9,400	120	632	56.1	217	0.4
,, ,, ,,	9	Odirogu	132.5	28,120	9,250	120	95	12.4	29.5	0.7
11/1/95	10	Omungukiri	139.4	27,600	8,900	110	763	120	210	1.0
,, ,, ,,	11	Bakana	96.4	25,800	8,450	151	341	33	106	0.5
,, ,, ,,	12	Isaka	30.6	28,700	8,200	460	761	55	195	0.7
,, ,, ,,	13	Gogokiri	117	26,000	8,300	122	417	85	110	0.5
,, ,, ,,	14	Opuekwekokoo	147.7	28,400	9,100	106	418	52	109	0.9
,, ,, ,,	15	Kala tuma	147.7	27,500	9,000	105	629	2.7	182	0.8
,, ,, ,,	16	Bille	161.6	27,700	9,100	97	495	32	126	0.7
,, ,, ,,	17	Buguma	219.8	35,700	13,400	105	38	20	10.5	0.4
,, ,, ,,	18	Ido	233.8	39,700	13,000	100	220	95	58	0.9
,, ,, ,,	19	Degema	188.7	19,900	6,500	59	193	48	56	0.6
12/1/95	20	Kala Degema	146.4	16,900	5,700	67	570	110	135	1.2
,, ,, ,,	21	Harry's Town	189.0	16,800	5,500	50.0	453	3200	120	0.7
,, ,, ,,	22	Ochokorocho	177.6	27,000	8,450	82	625	21	190	1.0
,, ,, ,,	23	Ile-ilema	205	16,700	5,600	47	10400	10	416	3.3
,, ,, ,,	24	Abalama	219.1	36,500	12,200	96	178	31	45	0.8
,, ,, ,,	25	Abonema	223.5	20,400	6,750	52	80	10	22	0.8
,, ,, ,,	26	Obonnoma								
,, ,, ,,	27	Lelekiri	203.0	34,100	11,800	100	300	15	78	0.7
,, ,, ,,	28	Erisokiri	197.7	39,000	12,400	108	114	6.0	34	0.5
,, ,, ,,	29	Opukiri	222	39,100	12,900	100	187	45	53	0.4
,, ,, ,,	30	Angulama	311	23,100	9,240	51	85	30	23	0.6
,, ,, ,,	31	Omekwe Tariama	212	32,100	11,200	91.0	431	22	129	0.6
,, ,, ,,	32	Omekwe Ama	171	22,700	7,000	70	293	58	85	0.5
,, ,, ,,	33	Minima	184	23,200	9,200	85	251	10	75	0.9
,, ,, ,,	34	Idama	166	19,200	6,300	65	516	10	125	0.5
,, ,, ,,	35	Abonema II	209	17,100	5,500	45	134	6	40	0.4
13/1/95	36	Osugbogo	3.59	650	200	95	153	2	48	0.8

Table 1 continued

	S/N	LOCATION	SURFACE WATER				GROUND WATER			
			RX	EC µS/cm	Cl^- mg/l	HCO_3 mg/l	EC µS/cm	Cl^- mg/l	HCO_3 mg/l	RX
13/1/95	37	Ogolokiama	0.75	18.5	2.0	5.0	55	2	15	0.3
,, ,, ,,	38	Akukwatere	0.08	25	0.5	7.5	154	12	17	0.4
,, ,, ,,	39	Obelle	2.13	558	150	120			45	
,, ,, ,,	40	Egbema I	0.10	20	0.5	6.0				
,, ,, ,,	41	Degema Hulk	197	20,100	7,000	60				
,, ,, ,,	42	Osogu	159.6	11,700	3,230	35	32	0.5		0.0
,, ,, ,,	43	Ahoada	0.07	130	1.2	26	57	6	9	7
,, ,, ,,	44	Obarayi	0.05	18.4	< 0.2	6.0	22	1.0	17	0.6
,, ,, ,,	45	Amanigboko					298	5.0	6.5	0.3
,, ,, ,,	46	Okama							8.9	0.1
,, ,, ,,	47	Emelego	0.60	20	20	6.0	153	3		
14/1/95	48	Omokwa	0.5	601	52	180	29	1.5	57	0.0
,, ,, ,,	49	Abua					109	5	8	9
,, ,, ,,	50	Engenni	0.19	65	2.2	19	164	3.4	33	0.3
,, ,, ,,	51	Abessa	1.11	72	1.5	22	600	75	50	0.3
,, ,, ,,	52	Egbema II	0.07	85	1.2	27	679	122	168	0.1
,, ,, ,,	53	Okobo					120	2.3	190	0.8
,, ,, ,,	54	Ndelle I					79	1.5	33	1.09
,, ,, ,,	55	Ndelle II					106	2.5	20	0.1
,, ,, ,,	56	Obelle I					108	2.5	27	0.1
,, ,, ,,	57	Obelle II		14	< 0.2		13	<	30	0.2
,, ,, ,,	58	Ibaa I		13	< 0.2		31	0.2	3.2	0.1
,, ,, ,,	59	Ibaa II		79	2.0	3.5	171	0.5	8.5	
,, ,, ,,	60	Rumuji		18.6	< 0.2	3.5		0.4	51.0	0.1
,, ,, ,,	61	Agba Ndelle				23				
,, ,, ,,	62	Obaku				5.0	251	23	70	
,, ,, ,,	63	Oduoha					116	9	31	
,, ,, ,,	64	Omofo					211	17	55	
,, ,, ,,	65	Ogamini I					314	28	85	
,, ,, ,,	66	Ogamini II					115	12	31	
,, ,, ,,	67	Rumuafo					201	18	56	
,, ,, ,,	68	Rumuodogo					37	4	9.0	
,, ,, ,,	69	Rumuodogo II					214	19	58	

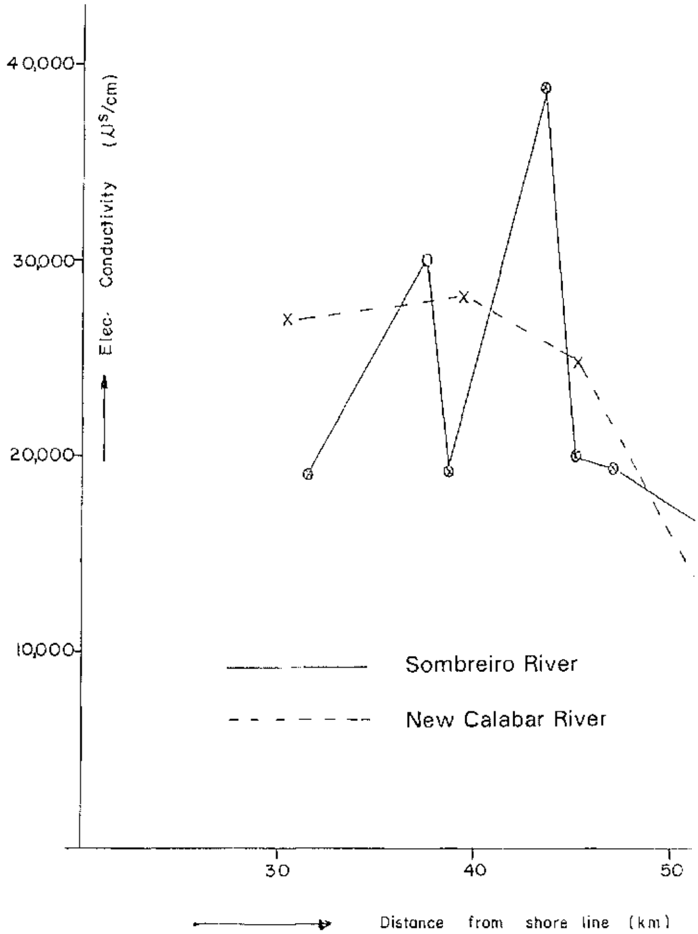

Fig. 3 Plot of variation of electrical conductivity *vs* distance from the coastline.

measurements on the Sombreiro and New Calabar creeks gave the values displayed in Fig. 3. These values were obtained on two alternate days but within the same time range (1100–1700 h) to reduce the effects of tide. The fluctuations shown on the figure reveal the complex mixing process operating in the region. Whereas the values obtained along the Sombreiro creek fluctuated significantly as the coastline was approached, those on the New Calabar creek showed a more or less steady increase in salinity toward the coastline. Some measurements taken at different times at the same location often differed up to 10%. For instance measurements at Buguma beach taken at about 0900 h was about 35 700 µS cm^{-1}, but the value for the same spot at about 1800 h (on the same day) was about 32 500 µS cm^{-1}. These were taken to reflect the effect of tide.

Chloride and bicarbonate concentrations in the creeks are given in Table 1. The chlorides range from less than 10 mg l^{-1} in the freshwater creeks to over 13 000 mg l^{-1} in the mangrove belt. The bicarbonates range from 4 mg l^{-1} to over 100 mg l^{-1} with the relatively higher values also within the mangrove zone. A clearer

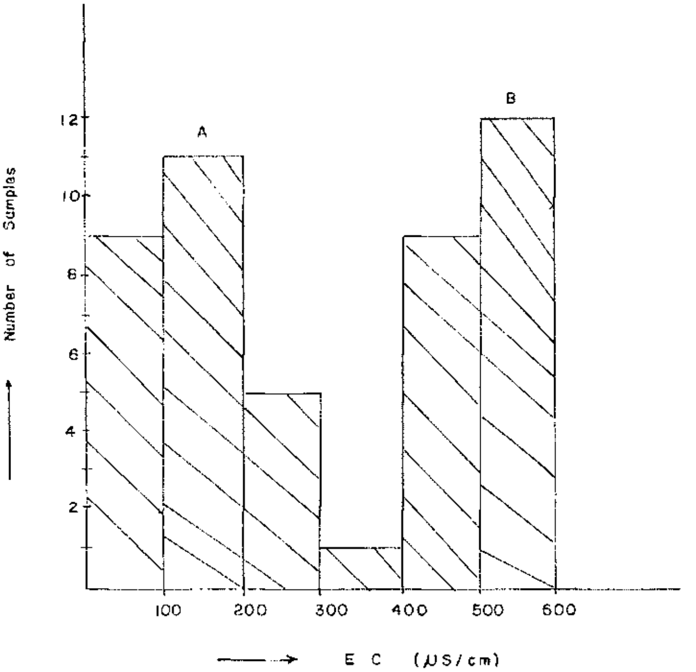

Fig. 4 Histogram showing the spread of electrical conductivity in the groundwater samples.

picture of the enrichment pattern of these ions is shown by the Revelle coefficient [$Rx = r\text{Cl}/(\text{HCO}_3 + \text{CO}_3)$]. It is shown by Revelle (1941) that values of *Rx* over 10 are indicative of saline seawater while values less than 1.0 represent fresh waters. The values obtained from the mangrove zone ranged from 30 to over 200 with most values falling above 100. These values are close to the value of 230 for seawater and thus suggest that the creeks are seawater, perhaps, with varied degrees of mixing with fresh inland waters. The *Rx* values for samples with EC less than 500 $\mu S\ cm^{-1}$ were generally less than 1.0, again confirming their freshwater origin.

Groundwater

As shown in Table 1, the electric conductivities (EC) of the groundwater in the shallow aquifers penetrated mostly by dug wells are generally two orders of magnitude less than those of surface water of corresponding locations. EC values ranged from less than 50 to about 1000 $\mu S\ cm^{-1}$. However, at Ilellema, a dug well located about 200 m from the beach had an EC value of about 10 400 $\mu S\ cm^{-1}$. Two groups of ground waters were recognized: those that are very fresh with EC less than 300 $\mu S\ cm^{-1}$ and those that are relatively more enriched in dissolved constituents and have EC values over 400 $\mu S\ cm^{-1}$. The spread is displayed as a histogram in Fig. 4.

In the first group (EC $< 300\ \mu S\ cm^{-1}$), bicarbonate ions (HCO_3) were significantly more than chlorides (Cl) (*Rx*: 0.07–0.5). This group was encountered in upland areas near the border with the dry land. The streams and other surface water outcrops in this zone (e.g. swamps, ponds, marshes etc.) are fresh, and saline creeks are absent. The depth to the water table ranges from about 7 m below the ground surface to over 17 m. Depths in excess of 20 m are rare.

The second group (EC > 400 $\mu S\ cm^{-1}$) had prominent chloride concentrations (*Rx* over 0.5) and this was clearly in excess of bicarbonates in situations where the EC was over 700 $\mu S\ cm^{-1}$ (and *Rx* greater than 1.0). The group was more frequently encountered towards the shoreline and dominated the region of the saline creeks and swamps. The depth to the water table was generally less than 10 m below the surface and mostly ranged between 3.5 and 6 m. The distances from the sampled dug wells to the nearest creek varied from about 50 m to about 1500 m. The salinity of the water in the dug wells could not be empirically related to either the distance to the creeks or to the salinity of the creeks, but there was a general tendency for higher EC values near relatively more saline creeks and *vice versa.*

In locations where relatively deep boreholes (greater than 50 m below ground surface) and dug wells were sampled (e.g. Akukwatera, sample nos 33–35; Abalama, nos 47–49; Tombia, nos 73–75; and Port Harcourt, nos 83–85), the dug wells were relatively more conductive than the boreholes, 849 *vs* 37 $\mu S\ cm^{-1}$ at Tombia, and 480 *vs* 160 $\mu S\ cm^{-1}$ at Port Harcourt. However at Odirogu (nos 88–90), the order was reversed with the borehole being more conductive (95 *vs* 330 $\mu S\ cm^{-1}$). The indication is that the aquifer is fresher at the deeper horizons than at the near surface horizons. A generally similar observation was made by Oteri (1990) on the western flank of the Niger Delta.

The chloride values ranged from less than 0.2 mg l^{-1} to about 15 mg l^{-1} in upland areas and from about 20 mg l^{-1} to over 200 mg l^{-1} in the mangrove belt. Corresponding bicarbonate (HCO_3) values are about 3 mg l^{-1} to about 60 mg l^{-1} in the upland areas and 50 mg l^{-1} to about 400 mg l^{-1} in the mangrove belt. The sample from Ilellema has a chloride value of about 3200 mg l^{-1} and bicarbonate of about 416 mg l^{-1}. The Revelle coefficient, *Rx*, indicated values ranging from less than 0.1 to about 1.0. In the freshwater zone (upland areas), the values were generally less than 0.5, whereas in the mangrove belt, the values were close to 1.0 and, in a few places, over 1.0. In the places where *Rx* was around the critical value of 1.0, the indication is that seawater is already present, perhaps, at very low concentrations. At Ilellema, the *Rx* value was 13.3 and thus suggesting significant seawater presence.

To obtain a more quantitative indication of seawater salinization of the aquifers, the simple mixing equation of Mazor (1991) was applied assuming two end member water source types—seawater: EC = 58 000 $\mu S\ cm^{-1}$, Cl = 19 000 mg l^{-1}; and fresh groundwater: EC = 200 $\mu S\ cm^{-1}$, Cl =10 mg l^{-1}. The equation is of the form:

$$Ax = C[1 - x] = B$$

where *A* and *C* are saline and freshwater end members, respectively; *B* is the mixed water; and *x* is the fraction of saline end member in the mixed water.

Using the above equation, the fraction of seawater in the aquifers having about 600 $\mu S\ cm^{-1}$ of electric conductance is 0.7% while those with conductance of about 1000 $\mu S\ cm^{-1}$ is 1.4%. The Ilellema sample with EC of 10 400 $\mu S\ cm^{-1}$ has a seawater fraction of about 18%.

DISCUSSION AND CONCLUDING REMARKS

It is clear from the data that the creeks within the mangrove swamps are saline with electric conductivity up to 40 000 μS cm^{-1} and chloride concentrations up to 13 000 mg l^{-1}. The salinity is a result of the daily flushing of this zone by ocean tides. The tidal effect is not uniform, however, and produces a variation in the salinity that appears to depend both on the time of measurement as well as on location. Generally, locations at inland areas are less affected than more coastal points but there is no predictable pattern of creek salinity with distance from the coast.

Despite the dense network of saline creeks, the groundwater in adjacent shallow aquifers (50–1000 m from the creeks) is generally fresh with electric conductivity less than 1000 μS cm^{-1} and chloride concentrations less than 200 mg l^{-1}. However, there is a clear evidence of seawater presence especially in aquifers within the mangrove zone. The Revelle coefficient of 0.7 to over 1.0 in many of the samples suggests contact with saline seawater. As the locations are relatively far from the shoreline (over 10 km) and as the groundwater in deeper horizons of the aquifer (in deep boreholes) is relatively fresh, the contact could not have been through direct intrusion of the seawater from the coast. Rather, the adjacent saline creeks are the likely source.

Already, information from geology suggests a hydraulic connectivity between the shallow aquifers and the creeks. The low level of seawater influence on the shallow aquifers (less than 1% in most cases) probably arises from the nature of the hydraulics properties in the area. Projections based on the local topography and water levels in the dug wells suggests that the local groundwater flows are towards the creeks. Thus mixing can only arise from diffusion or at high tide when the water level in the creeks is more than in the adjacent aquifers. There could also be mixing if the water level in the aquifer is lowered (as during intensive use of dug wells) relative to the water levels in the creeks. The significant presence of seawater (18%) at the Illellema dug well probably resulted from such a drop in the local water table around the well. The well at this point is located in a high density zone and is open at all times to the public. Moreso, it is only about 100 m from the nearby creek.

The general conclusion is that the shallow aquifer is susceptible to contamination with saline seawater (in the creeks). At present, there is little or no mixing between the freshwater in the aquifers and the saline seawater in the creeks. This arises mostly because the shallow aquifer is not extensively exploited and if large-scale withdrawals are carried out (as with motorized boreholes), the equilibrium may be disturbed and more seawater could be introduced into the shallow aquifers.

Acknowledgements Field work was assisted by M. Angala, W. Briggs, C. Akpodono and B. Lott of the Department of Geology, University of Nigeria, Nsukka. Chemical analyses, including the field chemical kits were made possible through a research grant of the Volkswagen Foundation, Hannover, Germany. Mr Eze of Department of Geology, University of Nigeria, Nsukka drafted the figures. These are gratefully acknowledged.

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