Impacts of Urban Growth on Surface Water and Groundwater Quality (Proceedings of IUGG 99 Symposium HS5, Birmingham, July 1999). IAHS Publ. no. 259, 1999.

Dynamics and quality of water resources in the Niger Delta

T. K. S. ABAM

Institute of Geosciences and Space Technology, Rivers State University of Science and Technology, PMB 5080, Port Harcourt, Nigeria

Abstract The Niger Delta is a large and ecologically sensitive region, in which various water species (including surface and groundwater, saline and fresh waters) are in a dynamic equilibrium. Physical environmental attributes of these waters and the nature of their changes as well as the resultant adjustments in hydrodynamic and ecological boundaries are described. Groundwater over-abstraction in the urban coastal areas has resulted in increased aquifer salinity. The inland incursion of tidal waters has been strengthened by the reduction of freshwater discharge due to impoundment in upstream dams and reservoirs.

INTRODUCTION

The Niger Delta, a 70 000 km^2 sedimentary basin of global ecological significance, is located in the southern most part of Nigeria. The delta is dissected by a dense network of rivers and creeks, which maintain a delicate but dynamic equilibrium between saline, estuarine and freshwater surface bodies with complex underground extensions. The region, which is ecologically fragile, is presently inhabited by about seven million people. This large resident population is influenced mainly by the rapid growth in the oil and gas industry.

Increased population instigated an increase in the demand for usable water. This has led to heavy investments in the development of surface and underground water resources by both government and private citizens. Consequently, several boreholes have been drilled especially in the urban areas of Port Harcourt and Warri. At present a combined total of over 750 boreholes are operational in the two cities. However as noted by Etu-Efeotor & Akpokodje (1990), groundwater development and abstraction has been undertaken indiscriminately without regard to the safe yield of aquifers and possibly deterioration of water quality.

Although detailed stratigraphic analyses of the various geologic/geomorphic and aquifer systems (Etu-Efeotor & Akpokodje, 1990) have yielded a better understanding of the groundwater potential, they have not addressed the crucial question of over-abstraction and its consequences, particularly the possibility of large scale saline water intrusion and the general issue of sustainable supply of potable water in the region.

Other studies such as Amadi & Amadi (1990), investigated the chemistry of streams and shallow well waters and compared the Port Harcourt and Degema areas for both dry and wet season. As relevant as this study may be, it deals with only a small fraction of the resident population, and may be considered inconsequential. Earlier, Etu-Efeotor & Odigi (1983) carried out surface resistivity surveys around Degema, a sandy island in the mangrove swamp, and identified saline water intrusion into coastal aquifers as a problem. No sharp fresh water-saline water interface was found however, as mixing of the fresh-salt water resulted in a transitional brackish water zone. This suggested a complex interaction between surface and underground saline and fresh water bodies. Such an interaction ought to be understood for strategic planning of sustainable water management. This paper investigates the hydrodynamics of surface and underground water and its effects on the water quality in the Niger Delta.

PHYSICAL CHARACTERISTICS OF THE NIGER DELTA

The main sedimentary environments typical of most delta environments are observable in the Niger Delta. These include the continental, transitional and marine environments. The continental zone comprises sandy alluvial environments, including the braided stream and meander belt systems of the upper deltaic plain. The transitional environment comprises the brackish water lower deltaic plain and the coastal area with its mangrove swamps, barrier bars and lagoons. The marine environment includes the sub-marine part of the delta, the fringe with its fine sand, silt and clay, and the associated marine fauna.

The drainage system of the Niger delta region comprises a dense network of distributory rivers, creeks and estuaries formed by the movement and interactions of the predominant river systems among which are the Niger, Forcados, Nun, Ase, Imo, Warri and Sombrero rivers. The dense river network of creates a condition of delta-wide hydrological continuity. Developments in one part of the delta, such as pollution or oil spills, can readily be felt in other parts.

As the receptacle of all the flood waters of the Niger and its tributaries, the delta experiences severe water inundation during the wet season (July–October). During this period an average of about $118\,758 \times 10^6$ m^3 of water is discharged into the delta (FEPA/World Bank/NDES, 1998), and constitutes the principal source of surface water supply.

DYNAMICS OF SURFACE WATERS

Three distinct flow components can be distinguished from a typical upstream river hydrograph: a period of high water discharge between August and October, followed by recession and relatively low discharge lasting up to March, and then a period of very low discharge about April and May. In the coastal area the flow is tidal, with constant daily variations in water level and flow velocity. At peak discharge, the flow is competent with a very high sediment load, which increases the inherent turbidity. During flood recession, the competency of the flow is reduced, sediment load is reduced and turbidity is correspondingly reduced.

Investigations by IGST (1988) indicate that there is an overwhelming net drift of flow and sediments to the coast. This is facilitated by the higher fresh water discharge in comparison to the upstream directed flood tidal flux, the higher ebb tide velocity and duration compared to equivalent flood tide attributes. Most estuarine rivers are contaminated during high tide by the influx of sea water upstream to distances which depend on discharge, river bed slope, channel shape, tidal level and fluctuations in wind velocity and direction. The distances contaminated upstream may range from less than a kilometre to tens of kilometres and could be accentuated by subsidence.

Comparison of water level records in locations on interconnected river systems show upstream areas, e.g. Patani, having a lower water level during the freshwater discharge period, compared to a tidal area such as Forcados, possibly due to subsidence. The relatively higher water in the coastal area indicates a reversed river bottom gradient and implies the presence of a sustained hydraulic head driving sea water and extending saline contamination to locations far upstream. Tidal fluctuation is accompanied by a cyclic diurnal change in water quality, due to the mixing in continuously varying proportions of original river water with sea water. In the lower reaches of the estuary, the water quality approaches that of sea water and at the farthest point inland, that of primary river water. The damming effect of sea water causes a freshwater tide in the upper reaches, where although the river stage responds to tidal effects, the quality remains essentially unaffected. This scenario is illustrated at Peremabiri where seasonal fluctuations occur in the hydrographs throughout the year, but water quality is essentially fresh with only a 4% increase in the conductivity of the wet season value.

Within the tidal reach, the change in water quality depends on the composition of the original river water and sea water and the relative quantities involved in the mixing. A zone of mixing and diffusion migrates up and down the river, the maximum saline contamination occurring during high tide and the minimum during low tide. During the high water stage (August–October), in the rainy season, the tidal effect on quality is minimal, because of the large discharge of freshwater. In the lean months (November–June) when the river stage is at its lowest, the quality is most adversely affected by tides, due to the predominant influence of sea water.

UNDERGROUND WATER, AQUIFER CHARACTERISTICS AND RECHARGE

Lithologs of boreholes in selected communities spread across the various geomorphic sub-environments have been prepared by Etu-Efeotor & Akpokodje (1990). An important observation is the identification of the Benin Formation (2100 m) consisting of massive porous coarse sands with localized clay/shale interbedding, as the most prolific aquifer in the region. The Quaternary deposits (40–150 m) overlying the Benin Formation are the superficial sediments making up the present day surface geomorphic zones in the delta and consist of alternating sequences of sand, silt and clay with the latter becoming increasingly more prominent seaward.

Using mainly lithologs from boreholes in the region, aquifer frequency with depth were derived (Fig. 1). These frequencies reflect in broad terms aquifer vertical distribution and probable persistence and the likelihood of success in encountering aquifers at particular depths in the different sub-environments. Aquifer parameters such as transmissivity, storage coefficient and hydraulic conductivity can be derived from calculations with physical tests on retrieved samples, or from pumping tests as demonstrated by Etu-Efeotor & Odigi (1983). The water table is generally high in the region, varying from the ground surface at the Atlantic coast to 15 m towards the apex

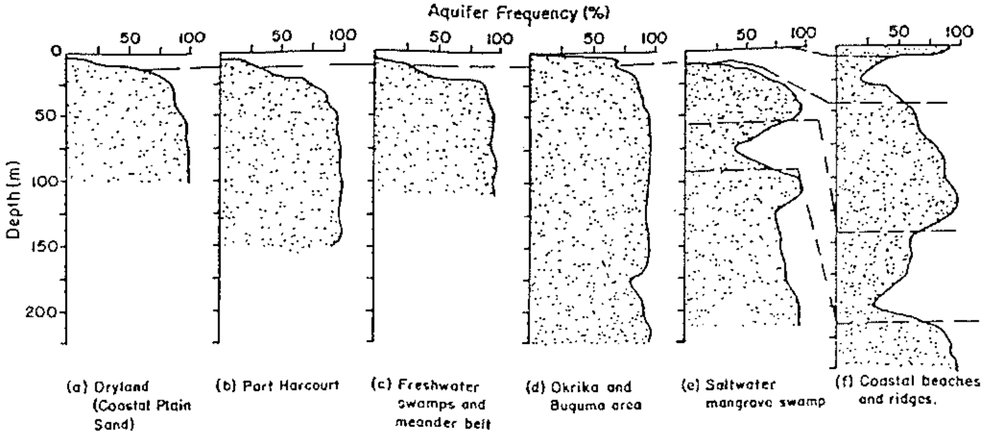

Fig. 1 Variation of aquifer frequency with depth. Aquifer frequency at a given depth = (number of logs with aquifer materials/total number of logs in the area) × 100. After Etu-Efeotor & Akpokodje, 1990).

of the delta (Fig. 2). The water table also fluctuates in response to daily tidal cycles in the coastal area, and to seasonal rainfall in the coastal plain sands and upstream recharge areas as typified by a water monitoring programme in the Port Harcourt area. As expected there is an initial lag in the response curve explained by the time taken up by infiltration up to full saturation. The response pattern in this case (coastal plain sand) is suggestive of a reasonably permeable material. Higher permeability values have been reported in the upstream recharge areas (Enoch George Associates, 1989–1998). Although infiltration may be faster in this case, the water table takes longer to respond because of the relatively depressed level of the groundwater surface. With an extensive recharge area, coupled with a reasonably high rainfall amount, groundwater recharge in the Niger Delta region is considered to be satisfactory.

GROUNDWATER QUALITY

Groundwater quality was evaluated from tests on samples from boreholes spread around the Niger Delta; borehole depths varied from 40 m to 100 m. The groundwater quality evaluated thus encompasses groundwater recharge areas, transitional zones, freshwater swamps, mangrove swamps, estuaries and sandy islands. Because these tests covered a period spanning over many years in which pumping rates have varied, they also provided a basis for exploring the influence of pumping or abstraction rates on water quality in the delta.

The physical quality comprising colour, odour, appearance and taste are acceptable in aquifers within the coastal plain sands. In the freshwater swamps, occupied largely by Bayelsa State, the groundwater physical qualities are objectionable. Groundwater in this area is characterized by high incidences of turbidity, high Hazen units of colour and objectionable taste. Interestingly, the areas with objectionable physical quality also recorded high iron content. The reason for this association is not clear. Usually, iron occurs in groundwater in the form of ferrous hydroxide in concentrations less than

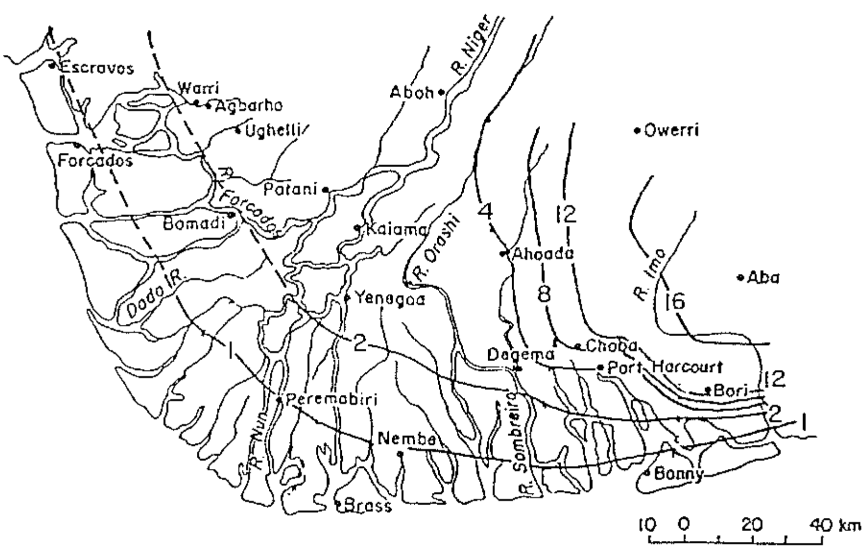

Fig. 2 Depth to groundwater table (metres below ground level). After Etu-Efeotor & Akpokodje, 1990).

0.5 mg l^{-1}. Higher concentrations are attained by water with low pH and by water derived from swamps and peat bogs.

There is a wide distribution of slightly acidic water in the region. Consistently high chloride content is also indicated in boreholes within coastal areas, especially mangrove swamps, sandy islands and estuaries. In Port Harcourt for example, chloride content in boreholes at the boundaries between the coastal plain sands and the mangrove swamps are above 35 mg l^{-1} while those on mangrove swamp proper are in excess of 150 mg l^{-1}. In the coastal islands, chloride content is variable depending on the depth of the borehole. In Bonny, a community less than 500 m from the Atlantic ocean, a shallow well was sampled with very low chloride content of 2.5 mg l^{-1}. In contrast, chloride content in deeper boreholes at Ogbolomabiri in the mangrove swamp was 94 mg l^{-1}. In Okrika and Buguma, both in the mangrove swamp sub-environment, chloride concentrations were intermediate.

INFLUENCE OF HEAVY ABSTRACTION ON WATER QUALITY

Increased industrial activity and resident population have resulted in increased abstraction rates and volumes in recent times. The delicate balance in the salt water–freshwater interface is maintained only when abstraction is not excessive. However, if extraction rate and volumes are increased, chloride concentrations are expected to be increased in neighbouring inland aquifers. Figure 3 presents the influence of abstraction in coastal aquifers on chloride concentration in the Moscow Road Pumping Station at Port Harcourt. Chloride concentration in groundwater increased from 11 mg l^{-1} in 1995 to 37 mg l^{-1} in 1996 and then dropped to 17 mg l^{-1} in 1997. In the same period, groundwater abstraction from the major pumping station in Port Harcourt

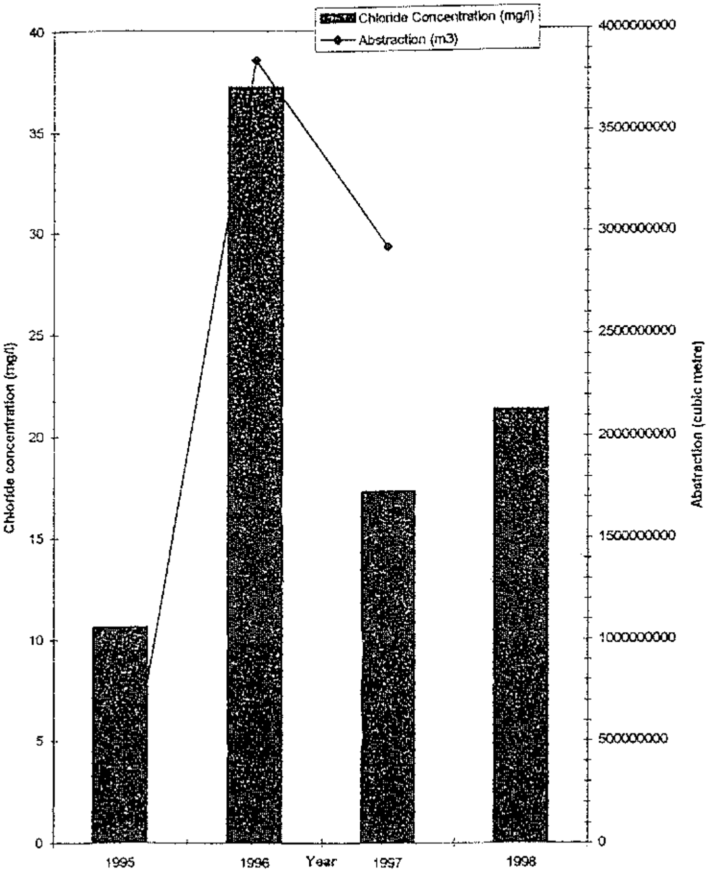

Fig. 3 Influence of abstraction in coastal aquifers on chloride concentration (Moscow Road Pumping Station, Port Harcourt).

increased from 18.8 × 10^6 l in 1995 to 3857 × 10^6 l in 1996 (Table 1) due to a programme of World Bank intervention for water rehabilitation. In 1997 abstraction dropped to 2926 × 10^6 l.

In a sense, the increase in chloride concentration can be linked to increased saline contamination occasioned by increased groundwater abstraction in the Port Harcourt area. This trend in chloride concentration is observed in other coastal locations within the urban area.

Over-abstraction in coastal/estuarine aquifers may result in the reversal of the hydraulic gradient of groundwater. When this happens, the saline water–freshwater

Table 1 Groundwater utilization in the Port Harcourt urban area.

	1995	1996	1997
Total volume of groundwater extracted (l)	18 796 851	3 857 521 238	2 926 053 780
Volume used for domestic consumption (l)	11 278 111	2 314 212 743	1 755 632 268
% of total volume for domestic consumption	60	60	60
Volume for industrial use (l)	7 518 740	1 553 008 495	1 170 421 512
% of budget for water supply	0.27	0.63	0.02

interface moves towards a freshwater zone, thereby extending the zone of saline contamination. A similar effect is readily created by a rise in the head of saline water relative to that of freshwater, for example during high tide.

SURFACE AND GROUNDWATER INTERACTIONS IN THE COASTAL AREA

The freshwater–salt water interaction in the coastal aquifer is not merely that of hydrostatic equilibrium, but one involving movements of freshwater and saline water adjusting to a hydrodynamic equilibrium (Sanling, 1963). Moreover, the interface fluctuates due to tidal potentiometric level changes, causing a sympathetic fluctuation in the interface. As a result, in a limited zone close to the interface, mixing of saline water and freshwater occurs mainly due to dispersion and less significantly, due to molecular diffusion (Subramanian, 1972). The interface is therefore a transitional zone and not one of sharp contact. The diffuse interface can also be indicated in geo-electric profiles in the region, although saline contamination may sometimes be confused with the presence of iron water.

In spite of the non-comparability of the hydrostatic and hydrodynamic models of the interface, for purposes of predicting approximate location of the hydrodynamic boundary, it may be assumed that the interface is determined by hydrostatic equilibrium in an aquifer of homogenous materials in which flow is one-directional and the vertical velocity component negligible. This proximal approach has been reinforced by Subramanian (1972) who showed that the depth of the interface is larger than the depth computed by the Ghyben-Herzberg relation in situations where groundwater flow is discharged into the sea with an upward motion through a zone constricted between the downward sloping water table and upward sloping interface. Although, in general, the Ghyben-Herzberg relationship can easily be simplified to $h_s = 40h_f$, there are modifications to accommodate the peculiar hydrodynamic scenarios observed in oceanic islands, which are approximated by the preponderant sandy islands of the Niger Delta such as Okrika, Buguma, Brass, Nembe, and Bonny. The depth of the freshwater–saline water interface in these islands is determined by the groundwater mound, the size of the island and the permeability of the underlying soils (Sanling, 1963). Groundwater recharge, which is mainly through precipitation, distends the mound. Consequently, the determination of depth requires the combination of Dupuit assumptions and the Ghysen-Herberg relation. A schematic illustration of groundwater flow in various scenarios typical of the coastal region of the Niger Delta is presented as Cases 1 to 4 (Fig. 4):

Case 1: shows the regional flow direction which is intercepted at the coast by the sea. The mixing boundaries at the coastal interface and in the shallow estuaries surrounding sandy islands such as Okrika.

Case 2: shows the regional groundwater flow in the shallow estuaries with sandy islands.

Case 3: illustrates the broad geohydrological conditions in circumstances where the estuaries are deeper with broader and deeper mixed zones.

Case 4: illustrates the chain of sandy islands with their interconnected geohydrology.

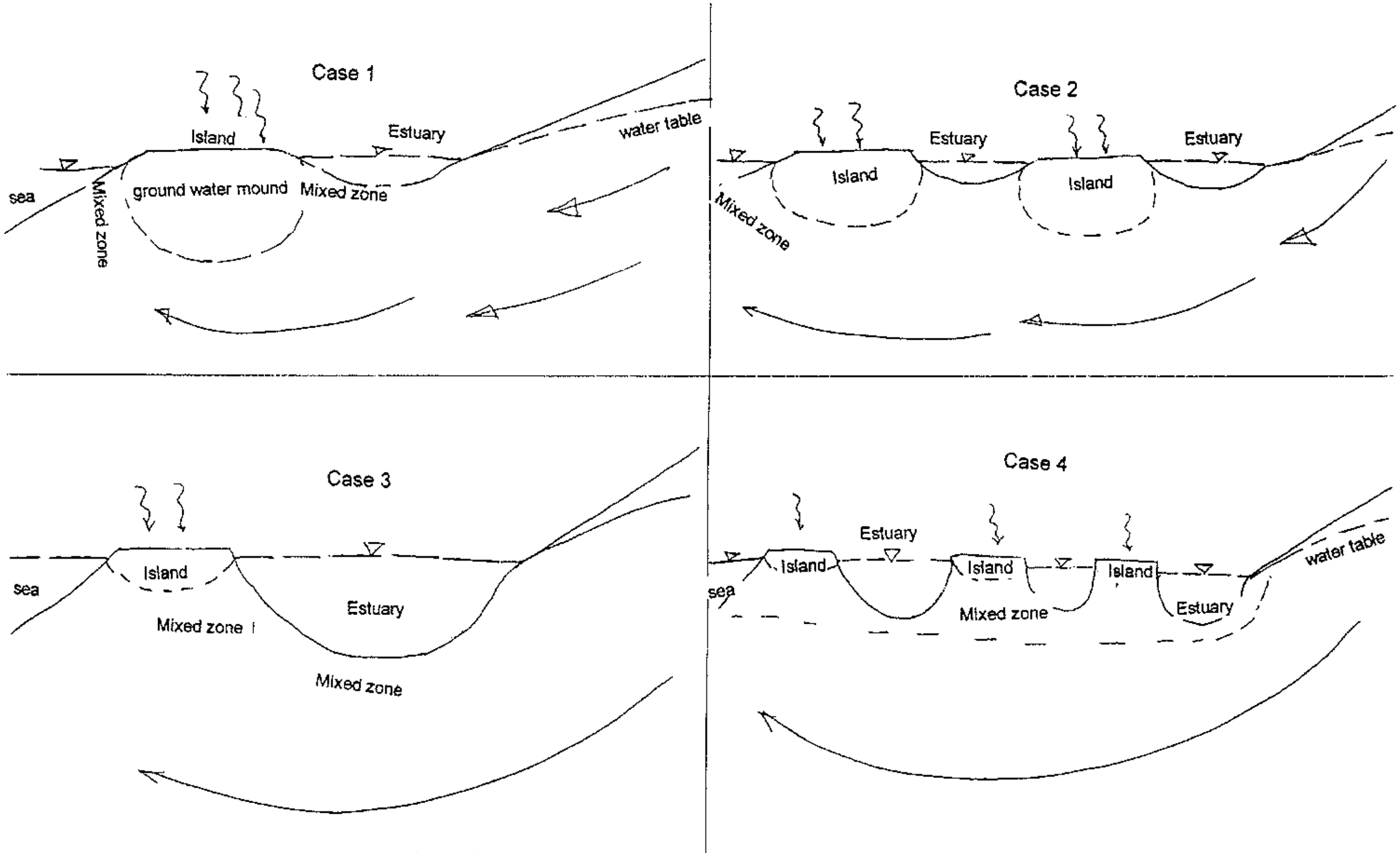

Fig. 4 Scenarios of water interaction in coastal island areas.

Analysis of these scenarios indicated at least three types of freshwater within the mixing zone of the Niger Delta. These are sourced from:

(a) direct precipitation on the island producing a freshwater mound;
(b) water flowing from upland recharge sources; and
(c) connate water trapped during sedimentation.

The waters of the rivers and creeks of the estuaries are dominated by saline sea water. At the interfaces of these waters with fresh groundwater, some mixing takes place leading to some hydrodynamic adjustments. Within the estuarine reach of the stream, saline water may encroach into the underlying freshwater aquifers in a variety of ways, depending on the relative positions of the water table, the river stage and the degree of interconnection between the stream and the aquifer.

CONCLUSION

Disturbing the hydrodynamic equilibrium between salt water and freshwater in the coastal aquifers by heavy pumping results in the invasion and contamination of the freshwater aquifer by saline water. There is a potential threat to surface freshwater resources in the Niger Delta from enhanced upstream movement of sea water due to reversal of the riverbed gradient produced by subsidence.

REFERENCES

Amadi, U. M. P & Amadi, P. A (1990) Saltwater migration in the coastal aquifers of Southern Nigeria. *J. Mining Geol.* **26**(1), 35–44.

Enoch George Associates (1988–1988) Reports of Soil Investigation.

Etu-Efeotor, J. O. & Akpokodje, E. G. (1990) Aquifer systems of the Niger Delta. *J. Mining Geol.* **26**(2), 279–285.

Etu-Efeotor, J. O. & Odigi, M. I. (1983) Water supply problems in the eastern Niger Delta. *J. Mining Geol.* **20**(1,2), 183–193.

IGST (1988) Interim Report for the Hydrographical and Hydrological Survey of Rivers and Lakes, for the NNPC-EIA Project.

Sanling, G. (1963) *Salt Water–Freshwater Relationships in the Development of Groundwater Resources with Special Reference to Deltaic Areas*, 52–62. Water Resources Series no. 24, UNESCO, Paris.

Subramanian, A. (1972) Studies of tidal effects on the River Zuari, India. *Geohydrol.* **8**, 79–85.