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A PRELIMINARY ANALYSIS OF REGIONAL GROUNDWATER MOVEMENT IN THE NIGER DELTA, NIGERIA*

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ABSTRACT

A preliminary analysis of regional groundwater movement has been done for the Niger Delta, Nigeria. The Niger Delta covers an area of about 75,000 km^2 in southern Nigeria. The Delta is underlain by clastic Tertiary sediments, from top to bottom: the Benin, Agbada, and Akata Formations. The Delta is one of the most hydrocarbon rich regions in the world, where petroleum has been produced from the Agbada Formation by several oil companies. Oil and gas production has resulted in environmental degradation of the delta. In this study, a preliminary analysis of groundwater movement in the delta is performed to determine groundwater flow pathways, discharge and recharge areas, and average residence time of water movement through the flow systems. The USGS three-dimensional finite-difference code, MODFLOW, was used to simulate steady-state flow. No regional flow system occurred, and flow was concentrated in intermediate and local systems. A major discharge area was found that collects water from local flow systems in the coastal plains and from intermediate systems that originate from the mid topographic elevations. The depth to length ratio of the Niger Delta, its low regional slope, and its significantly undulating surface relief make the delta a hydrogeologically shallow basin.

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INTRODUCTION

Groundwater evaluation is increasingly tilting toward a watershed approach due to large-scale contamination, resulting from urban development, rapid population growth, and land use changes. The origin and trend of regional groundwater flow studies may be attributed to Hubbert (1940), Tóth (1962, 1963), and Freeze and Witherspoon (1966, 1967, 1968). The general properties of regional groundwater flow have been studied extensively in the last few decades (Boronina, Balderer, Renard, & Stichler, 2005; Boronina, Renard, Balderer, & Christodoulides, 2003; Bredehoeft, Back, & Hanshaw, 1982; D'Agnese, Faunt, Hill, & Turner, 1999; Márquez, de Pablo, Oyarzun, & Viedma, 2005; Ophori, 2004; Ophori & Tóth, 1989a, 1989b; Scanlon, Mace, Barrett, & Smith, 2003; Tóth, 1984; Varni & Usunoff, 1999). This topic is also routinely treated in modern texts on hydrogeology (e.g., Domenico & Schwartz, 1998; Fetter, 1994; Freeze & Cherry, 1979; Schwartz & Zhang, 2003; Sen, 1995).

Tóth (1962) defined three hydraulically different regions (recharge, discharge, and throughflow or midline) of groundwater movement in drainage basins. In recharge areas, usually under topographically high regions, water moves downward, or away from the water table. Beneath topographically low areas as, for instance, stream valleys or lake basins, water moves upward or toward the water table in discharge areas. The midline areas occupy medium elevations between mounds and valleys where water flow is parallel to the water table. Tóth (1963) described groundwater flow systems from his solution to the Laplace equation for an undulating water table, which was described by a sine-wave function. A flow system is a family of flow lines originating in a given recharge area and terminating in a given discharge area. A flow system that terminates in a discharge area which is immediately adjacent to its recharge area is a local system, whereas a system that connects the principal recharge area with the principal discharge area of a topographic basin is a regional system (Figure 1). An intermediate system may straddle one or more local systems without extending from the principal watershed to the main valley. Drainage basins may possess complex flow patterns in which different hydraulic regions of local, intermediate, or regional systems may spatially coincide. For example, a local discharge area may overlie a regional recharge area, and a local recharge area may overlie a regional discharge area (Figure 1). Whether or not a regional system will form in a drainage basin is determined by several factors, including the ratio of the depth to the width of the basin (e.g., compare Figures 1 and 2). Other factors are described by Tóth (1963), and they include regional slope and the amplitude of the surface relief. Additional complications in the flow pattern may be introduced by permeability variations (Tóth, 1962; Freeze & Witherspoon, 1967). Heterogeneities such as fault zones and fractures, and high-conductivity aquifers in low-conductivity aquitards affect flow patterns based on their position in the

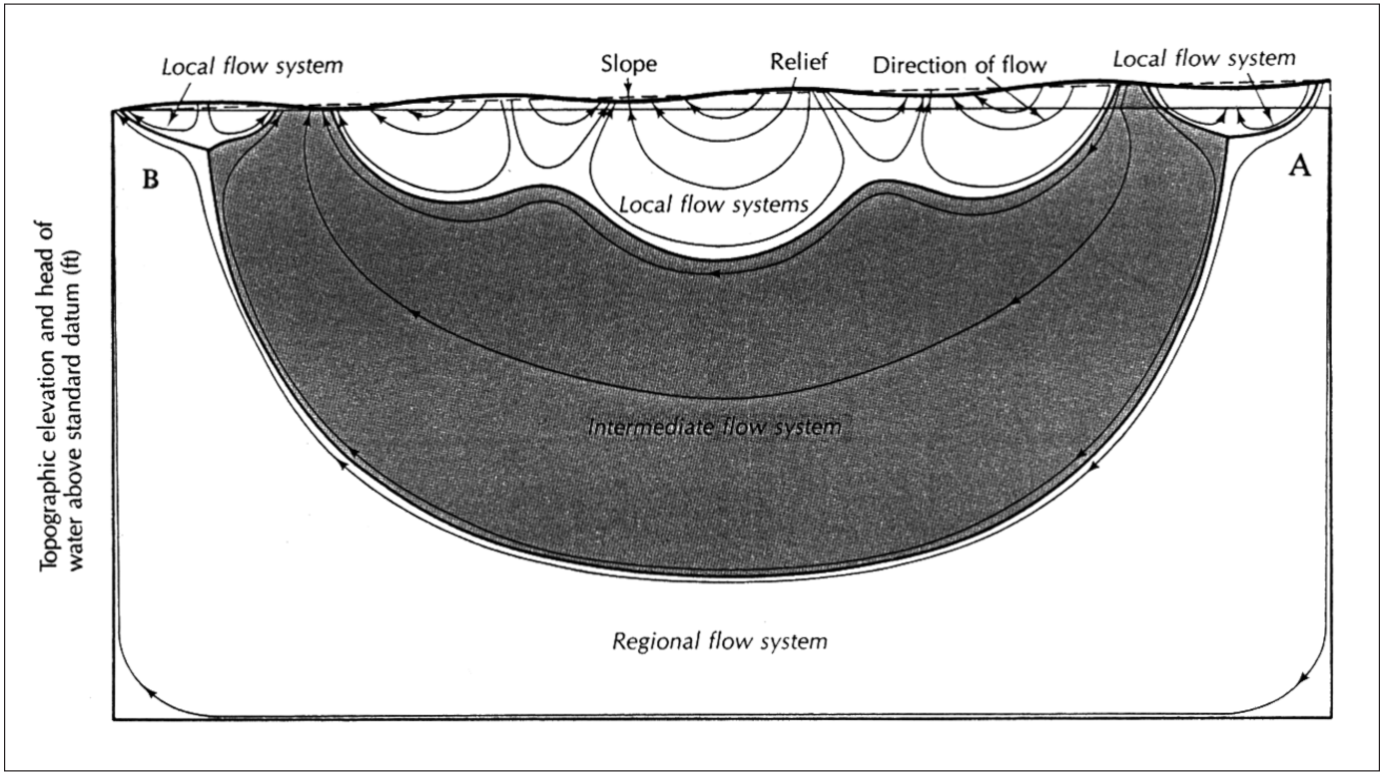

Figure 1. Flow systems of regional groundwater flow in a “deep” drainage basin (i.e., depth-to-length ratio of 1:2, after Tóth, 1963).

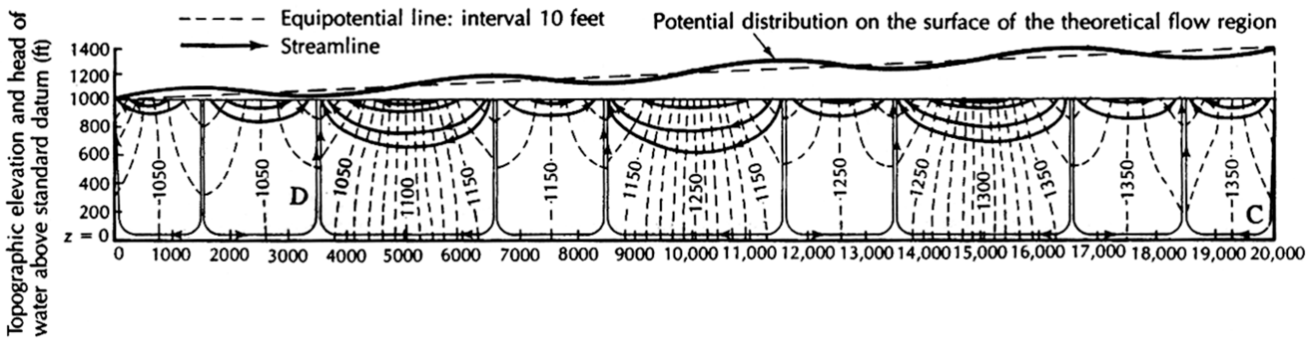

Figure 2. Flow systems of regional groundwater flow in a “shallow” drainage basin (i.e., depth-to-length ratio of 1:20, after Tóth, 1963). Locations where arrows point toward or away from ground surface are “discharge” or “recharge” areas, respectively, of the exclusively local systems. Dimensions are in (× 0.3 m).

system, degree of heterogeneity, areal extent, and orientation with respect to flow directions. In some cases, a high-conductivity lenticular body may convert a recharge area to a discharge area.

Groundwater flow systems are so complex that it would appear to be impossible to organize our understanding of regional groundwater flow into a useful tool for waste and environmental management and in water resources management. However, several studies have utilized a knowledge of regional groundwater flow in these areas. For example, it is possible to expect water from points A and B in Figure 1 to have some similarity in chemistry, but that will not be true for water from points C and D in Figure 2. This is because points A and B are part of the same regional flow system, while C and D are in two different local systems. This idea has been applied in studies such as Chebotarev (1955), Winter (1976, 1978), Tóth (1978), and Ophori and Tóth (1989a, 1990), to mention a few. In environmental management, Tóth and Sheng (1994) and Sheng and Tóth (2000) have developed a "Regional Recharge Concept" that uses groundwater flow to aid in nuclear waste disposal. Using several arguments and four key characteristics of groundwater flow that were calculated in a basin by numerical modeling, Tóth and Sheng (1994) concluded that:

1. regional groundwater flow can be exploited to play the role of the geosphere as a barrier to radioactive waste transport by judiciously selecting the basin and locating the repository near the basin's crest; and
2. that recharge areas are superior to discharge areas for the siting of high level nuclear waste repositories from the viewpoint of minimum travel-path lengths and return-flow times of contaminants transported by groundwater.

The preceding discussion shows that the analysis of regional groundwater flow systems has been applied in the solution of environmental problems including: a) the analysis of water chemistry; and b) waste disposal. In spite of this knowledge, several regions, such as the Niger Delta, Nigeria, to the author's knowledge, have not benefited from studies of large-scale groundwater flow. The Niger Delta is one of the world's most prolific oil producing areas. Oil and gas production by many multinational companies has resulted in widespread environmental pollution. A knowledge of the regional pattern of groundwater movement will aid in evaluating the pollution distribution.

In this study, the hydrogeologic environment is described for the Niger Delta, Nigeria. A hydrogeologic conceptual model is constructed and used to simulate steady-state groundwater flow. The primary objective is to develop a preliminary understanding of the groundwater flow pattern. Areas of recharge and discharge and flow systems of different scales are outlined. Average residence times and path lengths through these flow systems are determined. The distribution of flow velocity magnitudes is evaluated.

DESCRIPTION OF THE STUDY AREA

Location

The Niger Delta has an aerial extent of 75,000 km^2 and is located between longitude 4° 45'and 8° 15' E, and latitude 4° 15' and 6° 04' N (Figure 3). The delta is estimated to contain recoverable reserves of 51 Tcf of gas and 21 billion barrels of oil, making it one of the most hydrocarbon rich regions of the world. It is also one of the world's leading areas of petroleum production. Petroleum has been produced over the last three decades from the Agbada (geologic) Formation by several national and international oil companies. This, in addition to accelerated growth in urbanization, population, business, and industry, calls for attention on a systematic understanding of groundwater movement in the Niger Delta.

Topography and Geomorphology

The topographic map of the Niger Delta (Figure 4) was produced from Digital Elevation Model (DEM) data obtained from the Global Land Cover Facility (GLCF, 2005). Two main physiographic zones are present in the area—the coastal plains to the south and the hilly region to the north. The latter shows a complicated surface relief of isolated hills that are separated into two main parts by the Niger River. The topography reaches an elevation of 300 m with several peaks having amplitudes that are capable of influencing groundwater movement. The regional slope is sinusoidal and attains an average of 0.004. The coastal plains are generally flat, but local highs give it a gently undulating look. The regional slope is linear with an average of about 0.0005. The average topographic elevation is 15 m.

Precipitation and Evapotranspiration

The annual average temperature is 27°C with a small range of 3°C. The annual rainfall ranges from 2000 mm in the north to over 4000 mm in the coastal areas, with an average of 3000 mm. The average evapotranspiration is 1000 mm leaving an effective rainfall of 2000 mm. Of this effective rainfall, 37% or 750 mm is known to recharge the subsurface aquifers while the remaining 1250 mm flows directly overland into the streams (Akpokodje, Etu-Efeotor, & Mbeledogu, 1996). This recharge, which is 25% of the total precipitation, is on the high side of the range commonly reported for unconsolidated sediments (Leggette, Brashears, & Graham Inc., 1994; Vecchioli & Miller, 1973). However, it is reasonable for the coarse grains of the Benin Formation.

Geology

The geology of the Niger Delta is discussed by authors such as Reyment (1965), Short and Stauble (1967), Weber and Daukoru (1975), Avbovbo (1978),

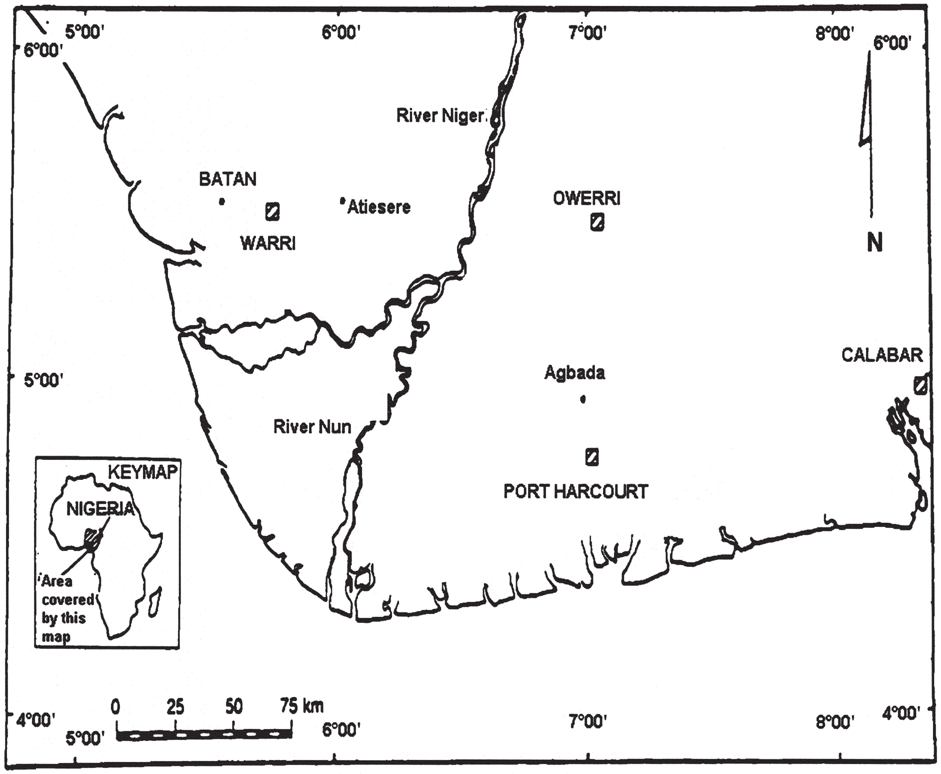

Figure 3. Map showing location of the Niger Delta.

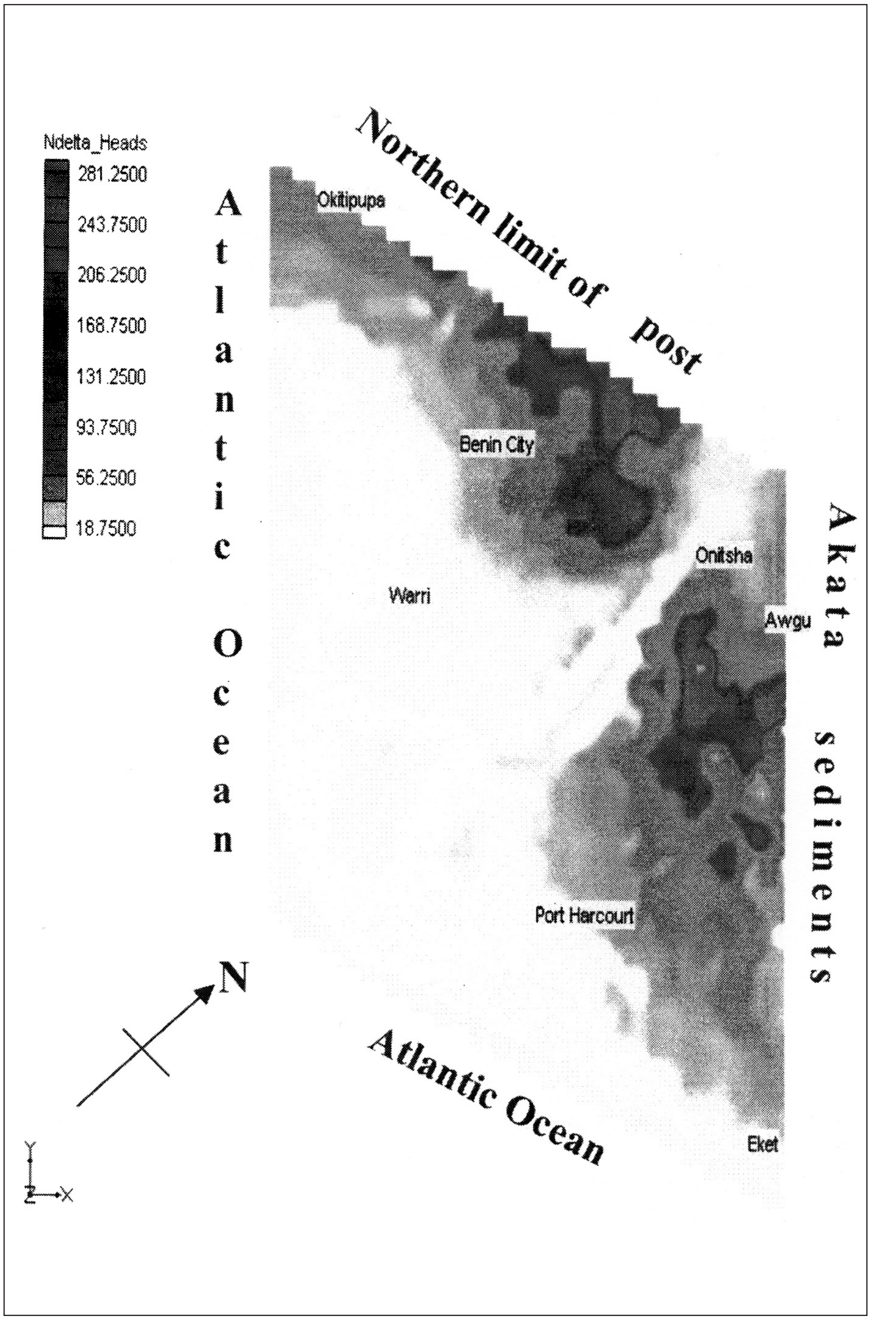

Figure 4. Topography (in meters) of the Niger Delta, Nigeria.

Agagu (1979), Whiteman (1982), Owolabi et al. (1990), and Koledoye et al. (2000, 2003). A tertiary sequence of three formations has been recognized in the Niger Delta complex, consisting, in ascending order, of the Akata, Agbada, and Benin Formations. The Akata Formation is a marine shale unit with horizons of sand. It is regarded as the major source rock of oil and gas in the Niger Delta. The Agbada Formation overlies the Akata, and is represented by a sequence of sandstones and shales. The Formation varies in thickness from 3000 to 3750 m, and it is the reservoir host rock for oil and gas in the Niger Delta complex. The Benin Formation rests comfortably on the Agbada Formation, and comprises a thick succession of unconsolidated sands with minor clay. The Formation is continental in origin. Many aquifers with potable water in the Niger Delta occur in this formation. It has a maximum thickness of 1970 m. The structural development of the Niger Delta sediments is characterized by extensive and densely distributed series of growth faults and the accompanying roll-over anticlines (Short & Stauble, 1967; Weber & Daukoru, 1975). A structural analysis of these sediments shows that individual fault blocks can be grouped into uniform megaunits in terms of time-stratigraphy, as well as hydrocarbon distribution (Evamy, Harremboure, Kammerling, Knapp, Malloy, & Rowlands, 1978). The treatment of these sediments as equivalent porous media (EPM) may be inferred from this statement.

Hydrogeology

Hydraulic Units

Akpokodje et al. (1996) have summarized the hydrostratigraphic units of the Benin Formation using information from various studies by Etu-Efeotor and Akpokodje (1990), Izeze (1990), Etu-Efeotor and Odigi (1983), Akpokodje (1987), and Lowden (1972). According to Akpokodje et al. (1996), there are four well defined aquifers in the upper 305 m that vary in thickness to over 120 m. The aquifers vary from unconfined conditions at the surface through semi-confined to confined conditions at depth. The aquifers are separated by highly discontinuous layers of shales, giving a picture of an interval that consists of a complex, non-uniform, discontinuous, and heterogeneous aquifer system. Although the majority of groundwater supply wells abstract water from these aquifers, there is evidence that industrial and municipal groundwater supply wells produce water from deeper aquifers in the Benin Formation. Thus, Akpokodje et al. (1996) used an eight-layer hydrostratigraphic unit model in their simulation of groundwater flow in the Benin Formation. At the large scale of the current study, it is assumed that the Benin Formation is heterogeneously homogeneous. Similarly, the Agbada Formation is treated as a homogeneous mix of sand and clay units.

Hydraulic Parameters

The required hydraulic parameters for modeling in this study are hydraulic conductivity and porosity. Although there is substantial hydraulic conductivity data on geologic materials of the Niger Delta, most of the data have been obtained from relatively shallow water wells in the upper part of the Benin Formation. Raw field data, from which hydraulic conductivities may be deduced for the deeper Agbada Formation, are not easily accessible from the files of the multinational oil companies. For the Benin Formation, several researchers have reported hydraulic conductivities (Table 1) using techniques such as pump test analysis, and grain size and statistical analysis.

Owolabi et al. (1994) developed an empirical statistical expression between permeability, porosity, and irreducible water-saturation for unconsolidated sands of the Niger Delta. They used this expression to obtain hydraulic conductivities in the range of 2.0×10^{-6} to 4.5×10^{-5} m/s. In the current study, 200 sets of field-measured data on porosity and water saturation were collected from an oil company for both the Benin and Agbada Formations, and used with the expression of Owolabi et al. (1994). The resulting hydraulic conductivities ranged from 3.0×10^{-6} to 4.1×10^{-5} m/s. In similar geologic materials outside the Niger Delta, hydraulic conductivities have also been estimated to range from 2.8×10^{-7} to 6.3×10^{-4} m/s (Okagbue, 1989), and 4.4×10^{-5} to 1.5×10^{-4} m/s (Onuoha & Mbazi, 1989), for the Ajali sandstone aquifer north of the Niger Delta.

Like hydraulic conductivity, porosity has been evaluated for geologic materials of the Niger Delta by many researchers (e.g., Akpokodje, 1987; Etu-Efeotor & Akpokodje, 1990; Etu-Efeotor & Odigi, 1983; Garcia-Bengochea, 1983; Izeze, 1990; Lowden, 1972; Ngah, 1990). Akpokodje et al. (1996) determined porosity for these materials solely from sonic logs using the Raymer-Hurt method after correcting for compaction effects. The porosity values obtained ranged from 20-36%, and compared very well with those reported in the earlier studies.

Table 1. Hydraulic Conductivity Values Reported by Various Authors for the Benin Formation

Hydraulic conductivity (m/s)	Author
7.2×10^{-5} to 2.4×10^{-3}	Okagbue, 1989
3.9×10^{-4} to 4.1×10^{-4}	Amajor and Ofoegbu, 1989
1.2×10^{-4} to 3.5×10^{-4}	Umar, 1984
4.2×10^{-7} to 4.1×10^{-4}	Etu-Efeotor and Akpokodje, 1990; Izese, 1990; Etu-Efeotor and Odigi, 1983
4.0×10^{-6} to 1.0×10^{-4}	Akpokodje et al., 1996
2.0×10^{-6} to 4.5×10^{-5}	Owolabi et al., 1994
3.0×10^{-6} to 4.1×10^{-5}	This current study

MODELING OF GROUNDWATER MOVEMENT

Model Conceptualization

For the entire Niger Delta, the conceptual model used to construct the groundwater flow model consists of the topography, climate, geology, groundwater domain geometry, physical hydrologic characteristics, and hydrologic boundary conditions. The region considered covers an area of about 75,000 km^2 and is bounded by the Atlantic Ocean to the west and south, and by the basement complex and the northern limit of the post Akata sediments to the north and east. The preceding discussion on the geology and hydrogeology have aided in simplifying the geology and hydraulic units for inclusion in the model. The Benin and Agbada Formations are treated as two separate homogeneous equivalent porous medium (EPM) layers of sediments. This assumption is considered appropriate for the Niger Delta given the scale of the regional model, the high frequency and even distribution of normal faults and roll-over anticlines, and the objectives of this modeling study. Such an assumption may also be found in Evans et al. (1996) and Scanlon et al. (2003). Available hydraulic data indicate that the Benin Formation may be assigned a higher value of hydraulic conductivity than the Agbada Formation since permeability usually decreases with depth. The topography has a regional slope that varies from sinusoidal to linear with values of 0.0005 to 0.004, and a surface relief that is highly to gently undulating. A recharge from precipitation of 750 mm maintains the water table at a relatively steady position.

Simulation

The conceptual model was converted to a numerical model with the Groundwater Modeling System (GMS) Package (Engineering Computer Graphics Laboratory, 1996), and the U.S. Geological Survey finite-difference code, MODFLOW (McDonald & Harbaugh, 1988) in the GMS Package was used to simulate the flow. A grid of 80 rows and 50 columns that were approximately 4.5 km by 4.5 km in size was used. The Benin Formation was divided into seven layers, each with a thickness of 250 m. Similarly, the Agbada Formation was split into 13 layers to produce a total of 20 model layers. The Akata Formation of marine shales was considered to be impermeable relative to the Agbada Formation, thus its top was made a no-flow bottom boundary of the model. In total, the model had 50,000 active cells. The vertical boundaries of the model were chosen to be impermeable because they were selected to coincide with the coastline to the south and west, and with the boundary between the Tertiary sediments of the Niger Delta and the basement complex rocks to the north and east. The boundaries were tested and found to be appropriate in a separate simulation run. The top boundary was the water table, which was assumed from field evidence to resemble the surface topography (Akpokodje et al., 1996; Amajor & Ofoegbu, 1989; Onuoha & Mbazi, 1989; Uma & Onuoha, 1989). The water table elevation was specified at every node at the ground surface to generate the flow. As discussed previously, average hydraulic conductivity values of 1.0×10^{-4} m/s and 1.0×10^{-6} m/s were assigned to the Benin and Agbada Formations, respectively.

Several simulations were performed using the MODFLOW code. After each simulation, the average discharge of groundwater from the system was calculated and was assumed to equal the recharge rate. This calculated recharge rate was then compared with the groundwater recharge rate of 750 mm which had been independently estimated as discussed earlier. The hydraulic conductivity of the top model layer was adjusted and simulations repeated until the simulated recharge rate was close to 750 mm. A close match was obtained with a surface hydraulic conductivity of 8.0×10^{-5} m/s, for which the simulated recharge rate was 746 mm. Ophori (1999), Evans et al. (1996), Vogel and Schelkes (1996), and Gorokhovski and Nute (1996) argue that calibration of large-scale groundwater flow model should be refined beyond the use of surface hydraulic conductivity because such results are not unique. However, a detailed analysis of this topic for the Niger Delta is beyond the scope of this current study.

DISCUSSION OF RESULTS

Groundwater Flow

The equipotentials in Figure 5 show a line of potentiometric mounds that trend from north of Benin City across the Niger River valley to south of Onitsha and Awgu. These mounds form a groundwater divide from which groundwater flow diverges southward toward the Atlantic Ocean on one hand, and northward into the hinterland on the other. This simple southward flow pattern has been reported by many earlier researchers, including Okagbue (1989) and Akpokodje et al. (1996). However, this simple flow pattern is complicated by a series of many local and intermediate flow systems, as shown by the velocity vectors in Figure 5. Areas of divergence or convergence of these vectors are recharge (R) or discharge (D) areas of the local and intermediate systems, some of which have been marked as R or D in Figure 5. A typical SW-NE hydraulic flow section through the Niger Delta is shown in Figure 6. This figure depicts a flow pattern that is dominated by local flow systems with recharge areas alternating with their adjacent discharge areas as illustrated earlier in Tóth's shallow basin (see Figure 2). There is no regional flow system, as the highest topographic point (T, Figure 6) is not connected by a flow line to the lowest point (B, Figure 6). It may be concluded from these findings that the depth to length ratio of 0.02, the low regional slope, and the significantly undulating surface relief make the Niger Delta a hydrogeologically shallow watershed as described by Tóth (1963).

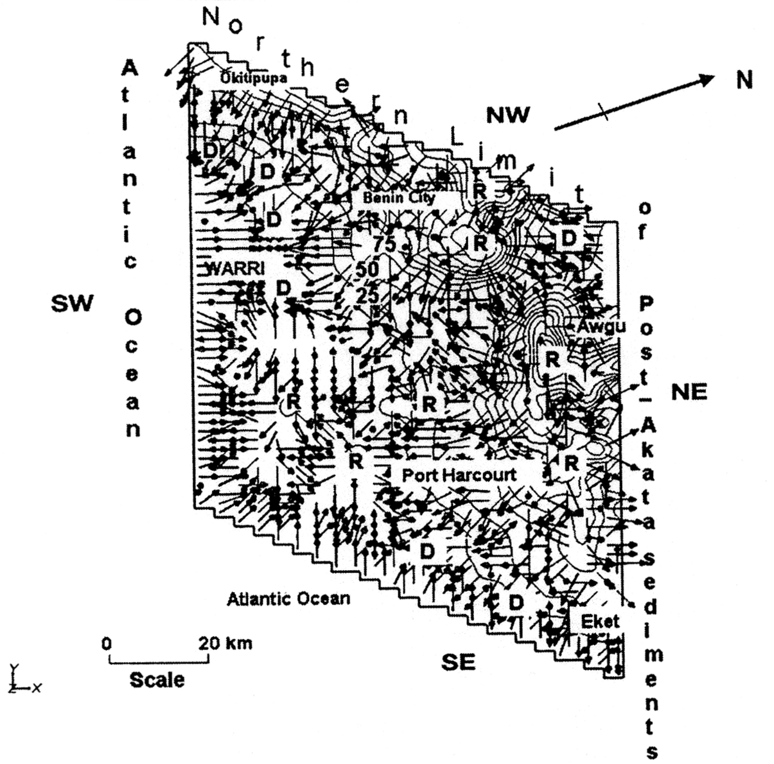

Figure 5. Simulated flow pattern in the horizontal plane (labeled solid lines are equipotentials, arrows are velocity vector showing flow direction, sample recharge "R" and discharge "D" areas are shown).

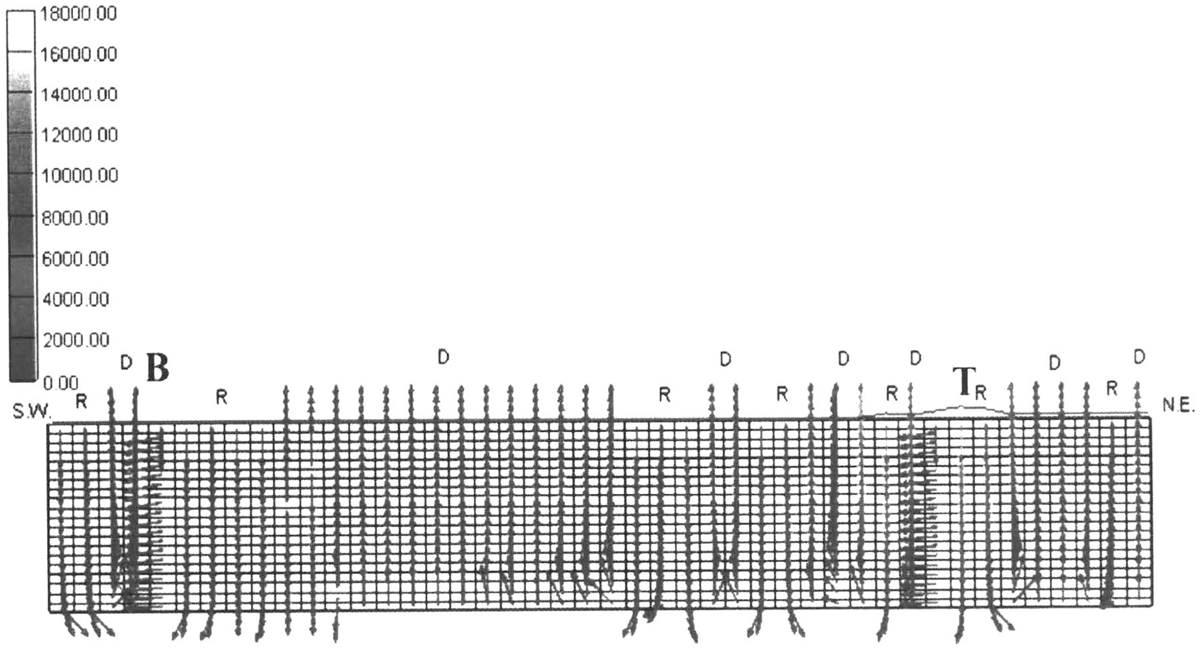

Figure 6. Simulated flow pattern along a typical in the vertical SW-NE section (see trace of section on Figure 5.

Flow Tracking

In order to gain a more detailed understanding of the flow pattern in the Niger Delta, a particle tracking analysis of flow was conducted to trace the flow pathways, path lengths, and travel time through typical flow systems. In this analysis, particles were located in strategically selected model cells and tracked from their entrance to exit locations, using the MODPATH module (Pollock, 1994) of the GMS Package. Thus, it was possible to determine whether particles moved through local or intermediate flow systems. This tracking revealed the following:

1. The sinusoidal regional slope of the hilly region to the north has high enough amplitude to dominate the effects of the regional slope, thereby driving water deep in predominantly local systems that discharge back to surface in the immediate vicinity in the areas marked "H" in Figure 7.
2. Further downslope at the mid-topographic elevations (marked "M" in Figure 7), the regional slope becomes more linear to promote the formation of relatively long intermediate flow systems that discharge into the coastal plains to the south.
3. Water discharged from these intermediate systems, together with that from local systems within the plains (marked "L" in Figure 7), form a "major discharge area" that trends east-west from point A, south of the town of Okitipupa through Warri and Port Harcourt to point A' near Eket (Figure 7).

Furthermore, the particle tracking analysis produced average path lengths and travel times of 86,908 m and 1.8×10^8 days for this major discharge area relative to shorter lengths and times of 20,257 m and $1.6 \text{ x } 10^6$ days for the discharge areas of the predominantly local systems. This is a further evidence of the existence of the major discharge area.

CONCLUSION

A conceptual hydrogeological model was constructed and used to simulate groundwater flow in the Niger Delta. The aim is to develop a preliminary understanding of the groundwater flow pattern, and to provide a first attempt of gaining some insights on the complex hydrogeologic system.

Results show that, on the regional scale, groundwater is recharged along a line of potentiometric mounds that trend from north of Benin City across the Niger River valley to south of Onitsha and Awgu. From the mounds, groundwater diverges southward toward the Atlantic Ocean on one hand, and northward into the hinterland on the other. This simple flow pattern, commonly reported by most researchers, is complicated by a series of many local and intermediate systems that occur anywhere from the southern coastal plains to the northern hills. There is no regional flow system that connects the highest topographic point to the lowest valley bottom. The configuration of the region (i.e., the surface

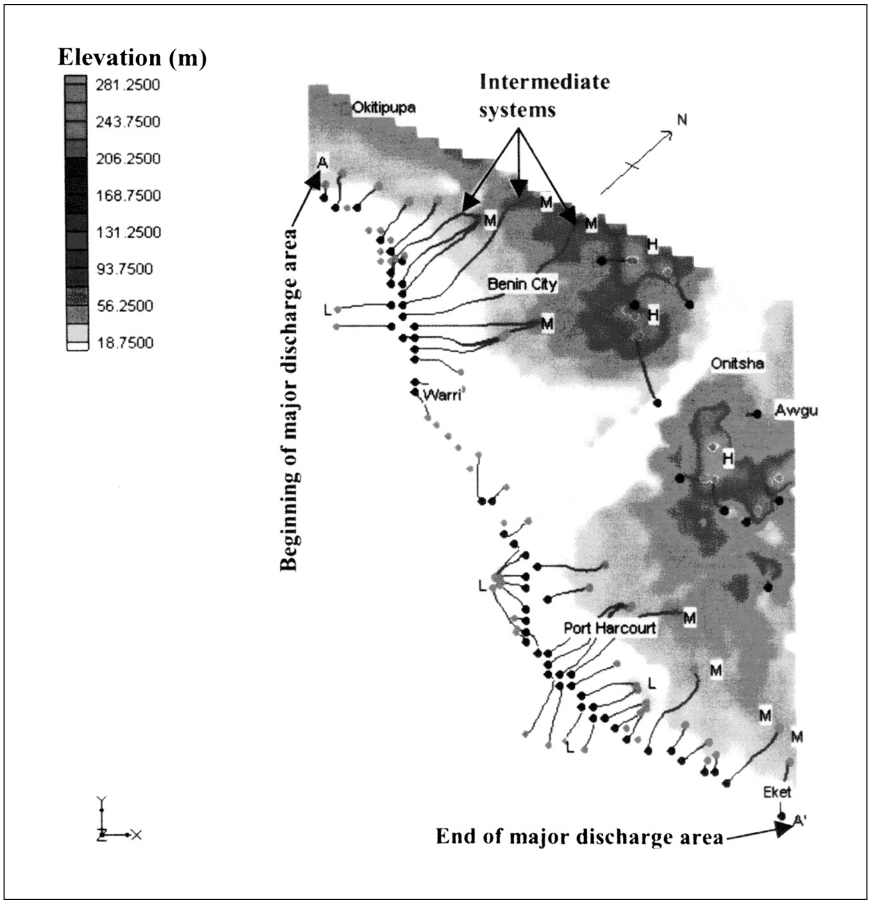

Figure 7. Sample particle tracks illustrating intermediate and local flow systems (dots are recharge and discharge points, note that only short local systems are shown in the northern hills, and long intermediate systems originate from mid-topographic elevations "M").

relief, regional slope, and depth to width ratio) characterizes the Niger Delta as a shallow basin. Particle tracking indicates that the high amplitudes of topographic peaks in the northern hills favor the formation of predominantly local systems. From the mid topographic elevations to the southern coastal plains, the regional slope becomes more linear. This enhances the development of intermediate systems that discharge, along with local systems within the plains, into a major east-west discharge zone that runs from the area south of the town of Okitipupa through Warri and Port Harcourt to Eket. This discharge zone appears to coincide with a known oil-rich belt. More research work may be needed to confirm the existence of the major discharge zone in the future.

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