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Groundwater and contaminant flow modelling in Olomoro area of Delta State

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Abstract

Geophysical investigation and hydrogeological information have been used with a steady state groundwater flow simulation model to describe the aquifer system and the flow rate of contaminants in the Olomoro area of Delta State. The area was modelled with a grid of* 100 *row* × 65 *columns. A conceptual model was developed from the results of the Electrical resistivity survey. The aquifer zones delineated from the Electrical resistivity sounding and the well inventory of the area formed the basis for the flow modelling. The model was simplified into three layers; the top soil, the clayey sand/laterite/clay layer and the sand layer. The first two layers of thickness* 2-10*m are assigned low hydraulic conductivity values while the third layer of thickness* 10 - 100*m is assigned high hydraulic conductivity value. The aquifer system is modelled as a single layer. The Groundwater Vistas software, version 4, from the Environmental Simulation International (ESI) containing the U.S. Geological Survey three dimensional finite difference code MODFLOW and MODPATH packages was used to simulate the conceptual understanding of the geology and hydrogeology of the area. The modelling results gave average groundwater flow velocity of the area to be about 388 m/year. This finding may provide baseline information during environmental impact assessment of the area.

Keywords
Model, thorium, progenies, intake, dose coefficients

1.0 Introduction

Groundwater flow and contaminant transport modelling has been used at many hazardous waste sites with varying degrees of success. Models may be used throughout all phases of the site investigation and remediation process. The ability to reliably predict the rate and direction of groundwater flow and contaminant transport is critical in planning and implementing groundwater remediation [3]. The elegant application of the finite difference method to the theory and application of transport in porous media have been extensively dealt with by various authors [1], [2], [4], [5], [7], [8], [9], [13] and [17 developed finite difference based computer programs to model the response of the first aquifer horizon to groundwater discharge rates under transient flow and unconfined condition in Lagos metropolis. Their model showed that the eastern part of the study area had the least drawdown values and therefore can best support future groundwater resources development. Similar studies were carried out by [6] to model the groundwater flow of Kwa Ibo River watershed in Southeastern Nigeria using the finite difference method.

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Results from the modelling showed that abstraction is less compared to groundwater recharge. Ophori [11] developed a large scale groundwater flow model for the Niger Delta covering an area of about 75,000km^2. The model results showed a major discharge area trending east-west which receives its water from local systems and from intermediate systems that originate at mid topographic elevations. Olomoro is an oil producing community with several oil fields, flow station and extensive network of pipe lines within the fields as well as small networks of flow lines that carry oil from wellheads to the flow station. The oil and gas related installations allow many opportunities for oil leaks and spills in the area which may contaminate the shallow water bearing aquifer. As a result of the peculiar nature of the study area, groundwater and contaminant flow modelling which from available literature have not been carried out in the area is necessary. In this study the groundwater flow and contaminant transport model have been developed to determine the groundwater flow velocity and predict the rate of contaminant flow in the event of hydrocarbon pollution in order to serve as a useful guide for groundwater remediation.

2.0 Physiography and geology

Olomoro community (Figure 2.1) lies within latitude 5˚ 23’ – 5˚ 27’N and Longitude 6˚ 7’ – 6˚ 11’N in the Western Niger Delta. The area is characterized by a seaward sloping plain terrain with elevation of less than 12*m* above mean sea level. The area is in the tropical rain forest area of the Niger-delta and experiences high rainfall most of the year. Most parts of the community get flooded during rainy season. The area forms a part of the featureless Sombreiro Warri deltaic plain with fresh water swamps. The study area is well drained by rivers and creeks.

The geologic sequence of the Niger Delta consists of three main tertiary subsurface lithostratigraphic units which are overlain by various types of quaternary deposits [14[. The base is the Akata Formation (Palaeocene to Eocene) comprising mainly of marine shales and sand beds. The Agbada Formation (Eocene to Oligocene) is the intermediate paralic sequence consisting of interbedded sands and shales. The top most unit is the Benin Formation which comprises of fluviatile gravels and sands. It is over 90% sandstone with shale intercalations. The unit is thickest in the central area of the Delta. The contact with the underlying Agbada Formation is defined by the base of sandstones which also corresponds to the base of the fresh water bearing strata. The local hydrogeological setting indicates that the study area is underlain by fine to medium and coarse grained unconsolidated Sombreiro - Warri deltaic plain sands. The hydraulic conductivity of the sands vary from 3.8×10^{-3} *cm*/*s* to 9×10^{-2}*cm*/*s*, which indicates potentially productive aquifer [10].

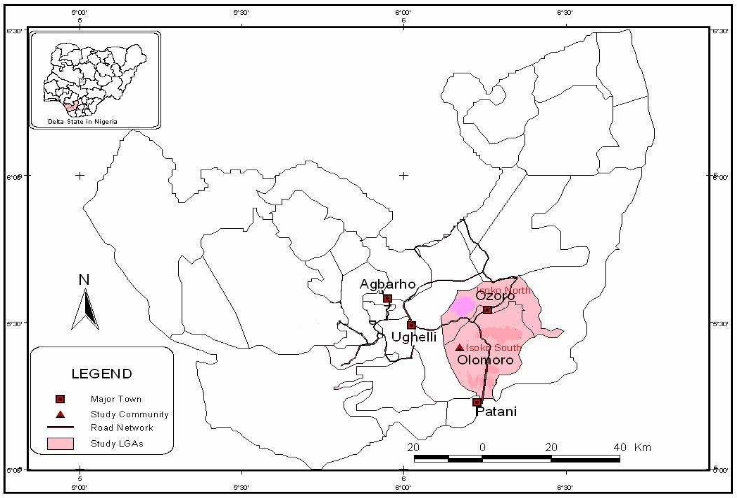


Figure 2.1: Map of Delta State, Nigeria showing the study area

3.0 Methodology and data acquisition

Comprehensive geophysical investigation was carried out in the Olomoro area to provide an insight into the physical configuration of the aquifer; the location, areal extent and thickness of all the confining layers for development of the groundwater flow model. A total of forty Vertical Electrical Soundings (VES) using the Schlumberger electrode array method was carried at preferred points in the study area. The ABEM SAS 1000 portable Terrameter having an inbuilt booster was used for the data acquisition. The maximum current electrode separation (AB) was 1000m. The data obtained from the electrical resistivity survey was plotted on a log-log graph paper with the electrode separation (AB/2) on the abscissa and apparent resistivity (ℓa) values as the ordinate. The partial curve matching technique using two layer standard curves and the corresponding auxiliary curves were used to obtain the initial resistivity and thickness of the subsurface layers delineated. The thickness and resistivity values obtained from the partial curve matching were then used as a starting model for the computer iterative techniques with the aid of the Resist Software based on the work of [15] to obtain the true resistivity and thickness of the layers delineated. The results of the geophysical investigation were used to delineate the aquifer geometry and construct the conceptual model (Figure 3.1).

The average values of the hydraulic properties; transmissivity, hydraulic conductivity and storage coefficient obtained for the study area are shown in (Table 3.1).

Table 3.1: Aquifer parameters values input into the model.

Location/layer		**Longitude**	**Latitude**	**Rock Matrix Porosity**	**Transmis-sivity m^2/d**
Olomoro	1	6.135	5.405	0.4	42
	2	6.135	5.405	0.4	792

Table 3.1: Aquifer parameters values input into the model. (contd.)

Location/ layer		**Specific yield**	**Storativity**	**Recharge m^3/day**	**Hydraulic conductivity *m/d***
Olomoro	1	0.01	0.01	0.000348	4.6
	2	0.02	0.02	0.000348	8.8

3.1 Model conceptualization

The conceptual model was developed based on data provided ranging from geophysical data, borehole logs alongside some assumptions made. The conceptual model of the study area is illustrated in Figure 3.1. The regional surface and groundwater flow is from north east to south west. The model is simplified into three layers; the top soil, the clayey sand/laterite/clay layer and the sand layer. The first two layers of thickness 2 - 10*m* are assigned low hydraulic conductivity values while the third layer of thickness 10 - 100*m* is assigned high hydraulic conductivity value. The aquifer system is modelled as a single layer.

3.2 Mathematical model and numerical solution

The fundamental equation is typically written as

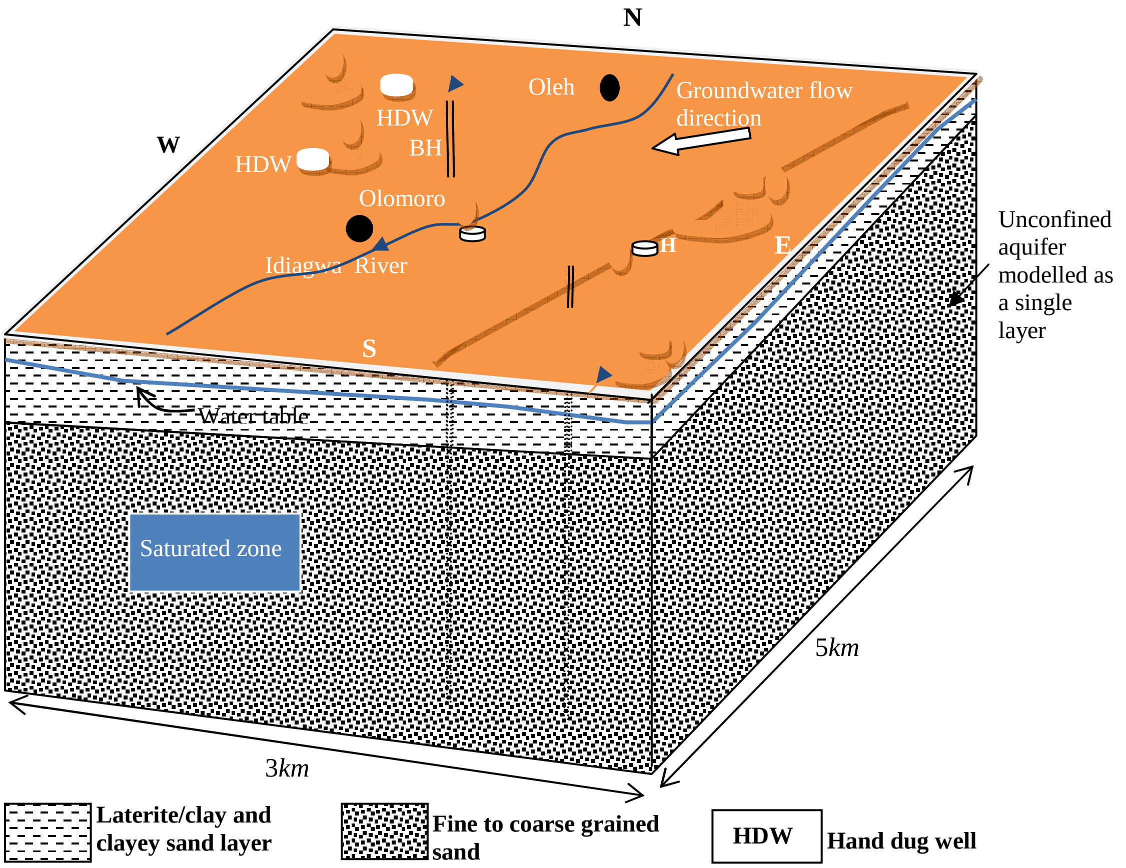


Figure 3.1: Conceptual model of study area

$$\frac{\partial}{\partial x}\left(\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\partial h}{\partial z}\right)=\frac{S}{T}\frac{\partial h}{\partial t}-R(x,y,z,t) \tag{3.1}$$

where T is the transmissivity ($T = Kb$, where K is the hydraulic conductivity and b the thickness of the aquifer), S = storage coefficient, R = recharge, h = potentiometric head, t is the time function, while x, y and z are position Cartesian coordinates. The governing equation for a two dimensional steady state flow in an unconfined homogeneous and isotropic aquifer is expressed by [16] as:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=-\frac{R}{T} \tag{3.2}$$

In the absence of recharge to the aquifer, the finite difference expression for the steady state case is [16];

$$h_{i-1,j}+h_{i+1,j}+h_{i,j-1}h_{i,j+1}-4h_{i,j}=0 \tag{3.3}$$

Solving for $h_{i,j}$ (1) becomes

$$h_{i,j}=\frac{1}{4}\left(h_{i-1,j}+h_{i+1,j}+h_{i,j-1}h_{i,j+1}\right) \tag{3.4}$$

where $h_{i,j}$ represents the average of the heads at the four closest nodes in the nodal mesh

If there is recharge to the aquifer, then the finite difference equation for the steady state case is,

$$\left(\frac{h_{i-1,j}-2h_{i,j}+h_{i+1,j}}{(\Delta x)^2}\right)+\left(\frac{h_{i,j+1}-2h_{i,j}+h_{i,j+1}}{(\Delta y)^2}\right)=-\left(\frac{R}{T}\right) \tag{3.5}$$

where Δx and Δy are the distances between the nodes in the x and y directions.

The Gauss-Seidel iteration method was used to solve the finite difference equations. The Gauss-Seidel equation for (3.3) is $h_{i,j}^{m+1}=\frac{1}{4}\left(h_{i-1,j}^{m+1}+h_{i,j-1}^{m+1}+h_{i+1,j}^{m}+h_{i,j+1}^{m}\right)$ (3.6)

The Gauss-Seidel equation for (3.5) where $\Delta x = \Delta y$ is

$$h_{i,j}^{m+1}=\frac{1}{4}\left(h_{i-1,j}^{m+1}+h_{i,j-1}^{m+1}+h_{i+1,j}^{m}+h_{i,j+1}^{m}+\Delta x^2 R/T\right) \tag{3.7}$$

In a transient problem the head is a function of time. The governing equation for a two dimensional transient flow in an unconfined homogeneous and isotropic aquifer is

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S}{T}\frac{\partial h}{\partial t}-R(x,y,,t) \tag{3.8}$$

The finite difference approximation without recharge is given by [16] as;

$$h_{i+1,j}^{n+1}+h_{i-1,j}^{n+1}+h_{i,j+1}^{n+1}+h_{i,j-1}^{n+1}-4h_{i,j}^{n+1}=\frac{1}{T}Sa^2\left(\frac{1}{\Delta t}\left(h_{i,j}^{n+1}-h_{i,j}^{n}\right)\right) \tag{3.9}$$

where S is Storativity, T is transmissivity, Δt is the length of time step, $a = \Delta x = \Delta y$ = the dimensions of the finite difference grid and n represents the nth time step.

3.3 Computer simulation

The simulated model domain of Olomoro area consists of 30 rows and 50 columns and three layers covering an area of 3000m × 5000m. The blocks in the grid were chosen as small as possible to ensure good connection between cells represented by various hydraulic characterizations. The hydraulic conductivity varied from 4.6 to 8.8*m/d*. The other aquifer parameters used for the model are shown in Table 3.1.

The Groundwater Vistas software, version 4, from the Environmental Simulation International (ESI) containing MODFLOW and MODPATH packages was used to simulate the conceptual understanding of the geology and hydrogeology of the area. The MODFLOW (modular three dimensional finite difference groundwater flow model, [7]) is a computer programme that solves the groundwater flow equation. Particle tracking is a form of transport modelling in which only the bulk movement of groundwater is investigated. Particle tracking neglects the effects of chemical reactions, dispersion, and diffusion. In the particle tracking analysis, the particles were located in strategically selected cells and tracked from their entrance to exit locations towards the southern boundary of the model domain using the MODPATH module [12] of the groundwater Vista Package in order to trace the flow pathways, path lengths and travel time through the flow system.

4.0 Results and discussion

The results of the simulated model domain consisting of a grid of 30 rows and 50 columns is shown in Figure 4.1.

Figure 4.2 shows the model groundwater steady state head distribution of the hydrogeological system of the area. An approximate head gradient of about 0.0004 towards the South was obtained using the model output head distribution data. The water level indicates that the hydraulic gradient does not change significantly with time. Thus the ground water flow is assumed to be in steady state and the computed groundwater flow direction is mainly in the northeast southwest direction.

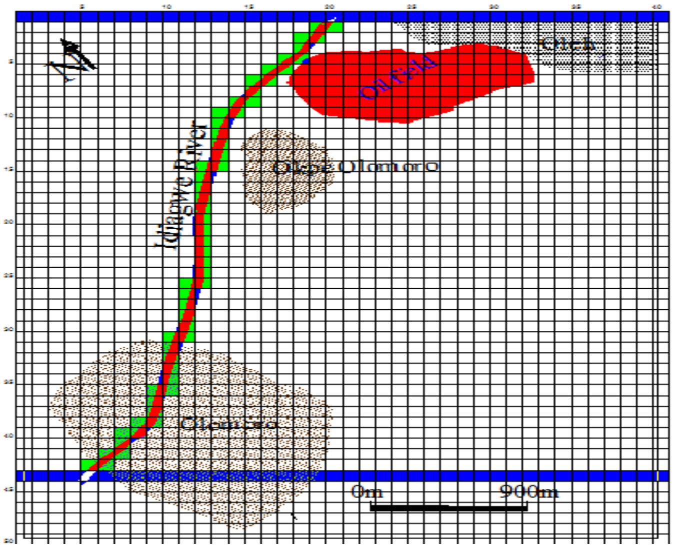


Figure 4.1: Model showing uniform grid spacing on the map of study area

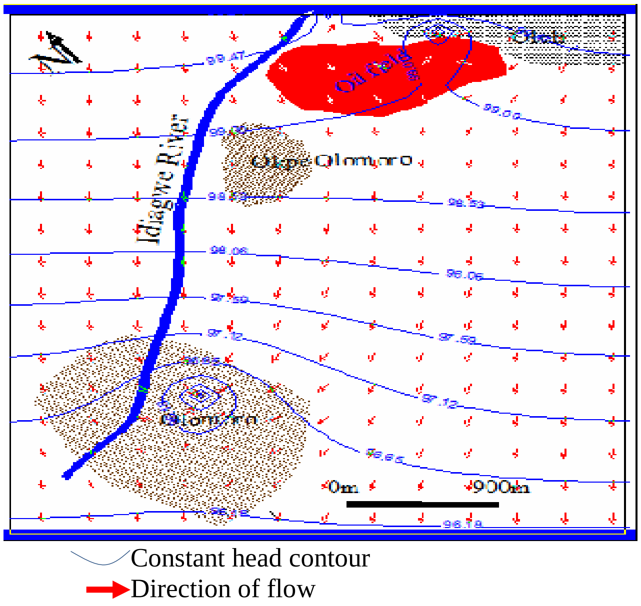
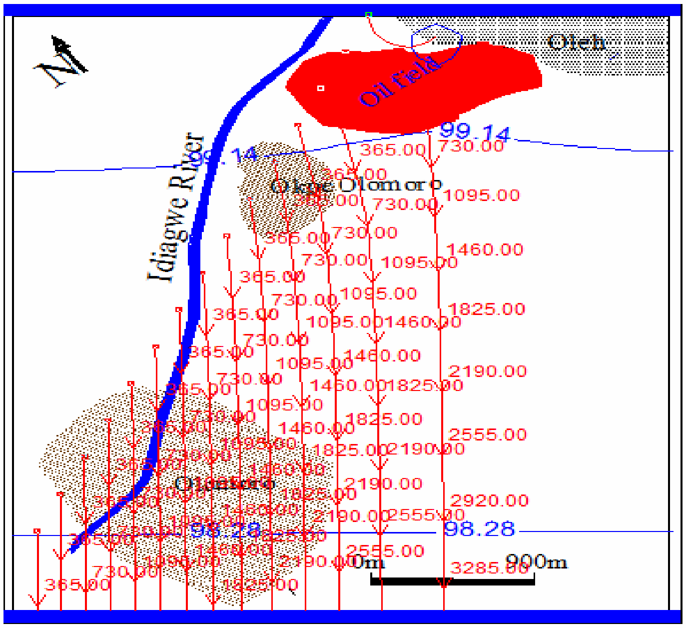


Figure 4.2: Model Showing steady state groundwater head distribution

The results of the particle tracking simulation are displayed by the plotted path lines through the aquifer system shown in Figure 4.3. The travel times in days are labeled on the path lines.

The particle tracking analysis produced a travel time of 3285 days along the longest path length in Figure 4.3 corresponding to a distance of 3500m measured from Okpe Olomoro to Olomoro. The groundwater flow velocity was calculated using the travel time and the path length to obtain 1.065 *m*/day or 388*m*/year. Advective flow was assumed therefore the contaminants would flow at this velocity.



Fiure 4.3: Particles track used to determine the flow direction and flow rate.
(Arrow line and numbers represent Particles tracks and estimated travel time in days.

5.0 Conclusion

The groundwater flow and transport model has been used in the present study to analyse the pathways of hydrocarbon pollution in Olomoro area. The surface water flow direction is in the northeast - southwest direction. Geophysical investigation was used to delineate the aquifer geometry and construct the conceptual model. The direction of groundwater and contaminant flow has also been shown from the model to be mainly in the northeast southwest direction. The groundwater flow velocity established from this model is 388 m/year. A similar study carried out by [6] where they modelled the groundwater flow of Kwa Ibo River watershed in Southeastern Nigeria using the finite difference method gave the groundwater flow velocity in the area as 160 *m*/year.

The high groundwater flow velocity (388*m*/year) in this model may be as a result of the high hydraulic conductivity values used in the model simulation [10]. Considering the nature of the study area which is prone to hydrocarbon pollution, this study provides reliable baseline information on the response time for remediation and a basis for environmental impact assessment. It is also recommended that more hydrogeological data be obtained by establishing monitoring wells in the area and performing aquifer tests in order to obtain improved models.

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