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Modelling Seawater Intrusion into Multi-layered Aquifer System of Lagos Area, Nigeria

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Abstract

Investigation as indicated that in the immediate vicinity of Lagos metropolitan, four separate aquifers are tapped. Over-exploitation of these aquifers through boreholes for both domestic and industrial water supply has resulted in salt water intrusion occurring in the confined aquifers. Monitoring and management of salt water intrusion is not done in Nigeria hence there is a need to study and ascertain the extent of sea water intrusion along the coastal region of Nigeria.

Data were collected from the boreholes within the studied area to model a two-dimensional advection-dispersion problem. The basic differential equation was solved for two-dimensional transport in an incompressible porous medium and transport in the absence of sources. The velocity flow was solved as a separate problem, independent of the solution for the concentration. A computer program was developed to solve the two dimensional dispersion problems by the finite element method. The model was calibrated in two steps, with the transient runs modelling Chloride concentration for the three aquifers. The runs simulated the 1982 and 1996 chloride concentration and predicted what condition it will be in 2010.

The result indicated that the area of chloride concentration increased from 13km^2 in 1996 to 38km^{2}for upper coastal plains sands while the concentration increases from 68mg/L to 83mg/L. Comparing the simulated chloride for all the three aquifers Abeokuta formation has the lowest value of chloride concentration. This confirms that Abeokuta formation is freshwater aquifer. Generally the results obtained for chloride concentration agrees with report of Coode Blizard Ltd.

Key words: Seawater intrusion, Aquifer, Chloride concentration, Coastal plain sands, Model

Introduction

Groundwater extraction is required in many coastal areas where the freshwater supply from surface sources is not adequate. However, excessive groundwater extraction may lead to seawater intrusion into the aquifer, and hence excessive salinity. Seawater intrusion refers to the replacement of fresh water in coastal aquifers by salt water due to the motion of saltwater body into the freshwater aquifer. At present, many coastal aquifers in the world, especially shallow ones, experience an intensive saltwater intrusion caused by both natural and human-induced processes (Abd-Elhamid & Javadi, 2008; Bastani *et al*., 2008; Papadopoulou *et al*., 2005). There is a need to predict the location and movement of the possible danger of contamination fronts. Practical management requires knowledge of not only the possible immediate or short term responses, but also of the long-term responses. For these managerial purposes, a numerical model can assist in estimating the location of the freshwater/saltwater interface for given sets of hydrological conditions. Use of coastal aquifers as operational reservoirs in water resource systems requires the development of tools that facilitate the prediction of the aquifer behaviour under different conditions. Quantitative understanding of the patterns of movement and mixing between freshwater and saltwater, as well as the factors that influence these processes, are necessary to manage the coastal groundwater resources (Ranjan, 2007). Monitoring and management of salt water intrusion is not done in Nigeria hence there is need to study and ascertain the extent of seawater intrusion along the coastal region of Nigeria.

In the past, several numerical models have been proposed to simulate the problem of saltwater intrusion into aquifers. For saltwater intrusion in multi-layered systems, few modelling studies have been reported and these are mostly limited extensions of single-layer models (Mulaem & Bear, 1974; Sa da Costa & Wilson, 1979; Bear & Kapuler, 1981). Huyakorn *et al.* (1996) developed a two-phase formulation of saltwater intrusion problems in multi-layered coastal aquifer. Numerous other researchers, such as Frind (1982), Huyakorn *et. al*. (1987), and Cheng *et. al.* (1998) have implemented numerical models for simulating saltwater intrusion problems using different methods. In addition, Sivapragasam *et. al.* (2010) used artificial neural network to model the spatial variation of electrical conductivity to determine the extent of seawater intrusion in the coastal area of Brisbane, Australia. This paper presents the result of the study to ascertain the extent of seawater intrusion into the aquifers of Lagos State.

Study Area

The coastal aquifer of Lagos metropolis area consists of four major aquifers (Figure 1). The uppermost located in Ewekoro formation is phreatic and it is connected to the adjoining lower confined aquifer by a semi-pervious stratum through which it communicates with the middle aquifer (Lafe & Imala, 1985). Investigation has indicated that the second and the third aquifer (i.e. in Ilaro formation) provide substantial quantities of water for the public and industries in the metropolis. The fourth aquifer (located in Abeokuta Formation) is deep and highly productive.

The modelled aquifers are the Upper Coastal Plains sands and the Lower Coastal Plains Sand which outcrop in the North-West and South-East line intersecting the towns of Abeokuta and Ijebu-Ode. The northern margin of the model is the outcrop of Abeokuta Formation and the southern boundary is the coastal line of Lagos State. Inputs to the system are recharge from rainfall on the outcrop of areas both the Coastal Plains Sands and Abeokuta Formation, juvenile water entering the Abeokuta Formation via deep faults and more recently, as saline intrusion to the Coastal Plains Sands from flow reversals close to the coast. Output from the system are from abstraction boreholes concentrated in Ikeja, Ilupeju, Apapa and Victoria Island, Epe and Badagry. Output is also by aquifer flow to the south presumably as submarine fresh water springs on the continental shelf.

Methodology

The study employs the two-dimensional Solute-transport in an incompressible porous medium and transport in the absence of sources, decay reactions etc. (see equation 1).

$$\frac{\partial c}{\partial t} = -V_i \frac{\partial c}{\partial x_i} + \frac{\partial}{\partial x_i}\left(D_{ij} \frac{\partial c}{\partial x_i} \right) \qquad (1)$$

where c is a concentration, v is the average velocity and D_{ij} is the coefficient of dispersion.

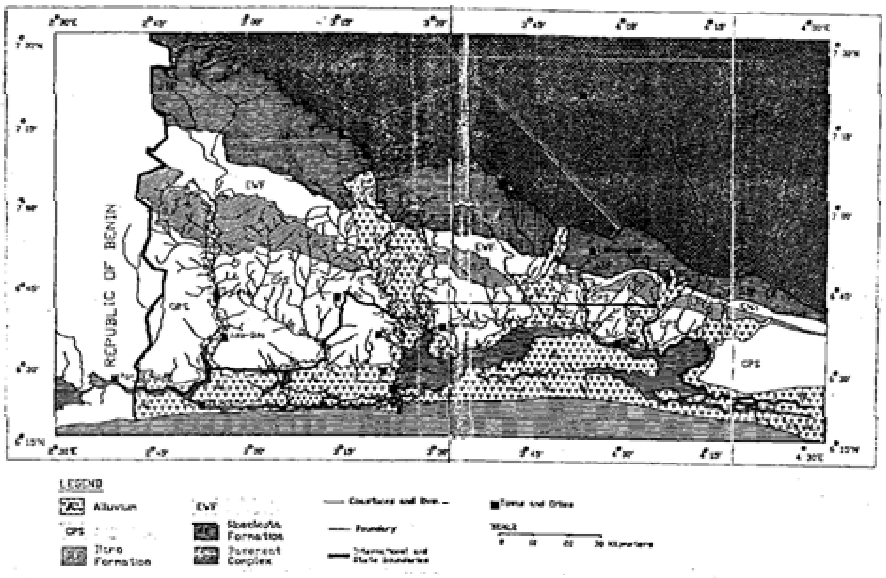

Figure 1: Geological Map of Lagos State

The first term on the right hand side of equation1 represents the advective transport component and the second term, dispersive transport. The porous medium is assumed to be isotropic; the components of the dispersion tensor D may be expressed by:

$$D_{ij} = a_T V \delta_{ij} + (a_L - a_T) V_i V_j / V \tag{2}$$

where a_L and a_T are the longitudinal and transverse dispersivities respectively.

Considering the case of uniform flow in the x-direction, in a two dimensional domain R in the x-y plane. only non-zero coefficient of the dispersion tensor D are:

$$D_{xx} = a_L V \qquad D_{YY} = a_T V \tag{3}$$

The basic differential equation for this case is

$$\frac{\partial c}{\partial t} = -V\frac{\partial}{\partial x} + \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_{yy}\frac{\partial c}{\partial y}\right) \tag{4}$$

The time derivative is now approximated by denoting the initial value, at the beginning of a time step of magnitude Δt, by c_0 and the value at the end of the interval by c^1. The average is assumed to be given by the interpolation formula

$$c = \varepsilon c_0 + (1 - \varepsilon) c^1 \tag{5}$$

where ε is an interpolation parameter, with $\varepsilon = 1/2$ corresponding to linear interpolation, $\varepsilon = 0$ to backward interpolation and $\varepsilon = 1$ to forward interpolation. With Equation 5, Equation 4 becomes

$$\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial x}\left(D_{yy}\frac{\partial c}{\partial y}\right)-V\frac{\partial c}{\partial x}-\frac{c-c_0}{(1-\varepsilon)\Delta t}=0 \tag{6}$$

This is the differential equation for which a finite element approximation is presented.

Modelling of the Seawater Intrusion

The solute transport model did not couple the groundwater flow equation with the equation for dispersion and advection, it was solved separately. Also, the modelling of the solute transport was done on the basis of each of the aquifers. The solute transport model was calibrated in two steps. First, head guesses and several adjustments of hydraulic parameters calibrated the velocity flow portion of the model until the computed parameters agreed with measured field values by trial and error method. The second step involves the variation of aquifer dispersivity to calibrate the solute transport portion of the model. It was found that the most reasonable match was obtained with a dispersivity of longitudinal and transversal being 30m and 1m respectively.

The input data are interactively, with the program asking for some general data the number of nodes, the number of elements, the value of longitudinal dispersivity, the value of transverse dispersivity, the time step, number of time steps, interpolation parameter, number of gauss-seidel iteration and the relaxation factor. Then the data of all nodes must be entered: the two coordinates, concentration of the known chloride; value of a type – indicator (IP) whether 0 or 1, the velocities of the coordinates. The grid selected was a quadrangular, grid composed of 84 elements and 53 nodes (see figure 2). The nodal spacing in the x,y direction were kept constant and equal to 16km. The simulation was performed for 5.1 time steps with $\Delta t = 1000$days.

Chemical analyses of borehole water samples data were collected. Values of the physical parameters used in the simulation are presented in Table 1. Transient simulations were run using 1982 data as initial condition. The transient runs modelled chloride of the three confined aquifers. The run simulated the 1982 and 1996 chloride concentration and predicted what condition it will be in 2010, if abstraction continues at the present rate from coastal plains sands and Abeokuta formation. The model was considered calibrated when the area of simulated chloride plume matched area within 10 percent.

Simulations of Future Chloride Movement

After calibration, the solute transport model was used to simulate the concentration of the chloride for the year 2010.

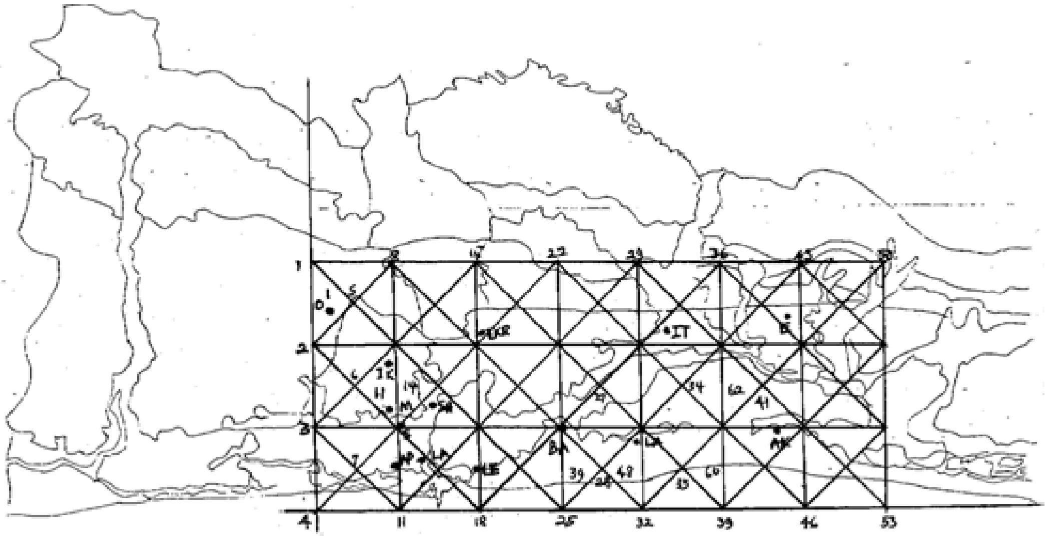

Figure 2: The modelled area

Upper Coastal Plains Sands

The total area of chloride concentration in 1996 was about 13km^2, at the end of 14years simulation, the area of chloride concentration increased to 38 km^2. The result of the simulation is shown in Table 2. The concentration increases from 68mg/l to 83mg/l this is caused primarily by radial flow to the pumping areas in the upper coastal plains sands and being in the coastal zone.

Lower Coastal Plains Sands

Table 3 showed the simulated results for areas under the Lower coastal plains sands aquifer. The chloride concentration increases from 29mg/l to 34mg/l at the end of 14 years simulation. The range of chloride concentration for this aquifer is about 50mg/l, this is so because over 95% of all the boreholes in Lagos State obtained their water from this aquifer. The result obtained agreed with the report of Coode Blizard Ltd. i.e. the occurrence of the salt water zone varies from west to east, being very thin in areas west of Apapa but very thick between Apapa and Akodo.

Abeokuta Formation

The chloride concentration increases from 21mg/l to about 31mg/l by 2010. Comparing the simulated chloride for all the three aquifers, Abeokuta formation have the lowest value this confirms that Abeokuta formation is a freshwater aquifer (see Table 4).

Conclusion

This present work has demonstrated that finite element formulation is suitable for 2-dimensional simulation of solute transport in multi-layer aquifer systems. The velocity flow was solved as a separate problem, independent of the solution for the concentration. The model was calibrated in two steps, with the transient runs modelling chloride concentration the three aquifers. The runs simulated the 1982 and 1996 chloride concentration and prediction was made for 2010. The result indicated that the area of chloride concentration increases from 13km^2 in 1996 to 38km^{2}for upper coastal plains sands while the concentration increases from 68mg/L to 83mg/L. Comparing the simulated chloride for all the three aquifers Abeokuta formation has the lowest value of chloride concentration. This confirms that Abeokuta formation is freshwater aquifer. Generally, the results obtained for chloride concentration agreed with the report of Coode Blizard Limited.

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Table 1: Values of Physical Parameters of the Solute Transport Model.

Parameter	Assigned Values
Porosity of aquifer	0.25
Longitudinal dispersion coeff. D_{xx}	0.750m/d
Transverse dispersion coeff. D_{yy}	0.025m/d
Velocity of flow	0.025m/d
Transmisivity	2200m^2/d
Hydraulic conductivity	15.17m/d
Hydraulic head	15m

Table 2: Simulated Chloride for Upper Coastal Plain Sands

Town	Days	Concentration (mg/l)	Town	Days	Concentration (mg/l)
Mushin	0	67.89	Eredo	0	17.99
	1000	70.78		1000	20.46
	2000	73.66		2000	22.93
	3000	76.55		3000	25.39
	4000	79.44		4000	27.86
	5110	82.64		5110	30.60
Ikeja	0	54.30	Surulere	0	47.99
	1000	57.52		1000	49.35
	2000	60.73		2000	50.70
	3000	63.95		3000	52.07
	4000	67.17		4000	53.43

5110	70.74	5110	54.94

Table 3: Simulated Chloride for Lower Coastal Plain Sands

Town	Days	Concentration (mg/l)	Town	Days	Concentration (mg/l)
Apapa	0	10.00	Ota	0	8.00
	1000	10.31		1000	8.930
	2000	10.61		2000	9.861
	3000	10.92		3000	10.79
	4000	11.23		4000	11.720
	5110	11.57		5110	12.750
Akodo	0	28.99	Ikeja	0	4.50
	1000	29.84		1000	4.767
	2000	30.69		2000	5.033
	3000	31.54		3000	5.300
	4000	32.39		4000	5.566

	5110	33.34		5110	5.862
Badore	0	12.50	Lekki	0	16.500
	1000	12.93		1000	16.980
	2000	13.37		2000	17.460
	3000	13.80		3000	17.930
	4000	14.24		4000	18.410
	5110	14.72		5110	18.940
Shomolu	0	10.42	Victoria Island	0	13.500
	1000	11.00		1000	13.930
	2000	11.59		2000	14.350
	3000	12.17		3000	14.780
	4000	12.76		4000	15.200
	5110	13.40		5110	15.670
Ikorodu	0	6.50			
	1000	6.998			
	2000	7.497			
	3000	7.995			
	4000	8.493			
	5110	9.046			

Table 4: Simulated Chloride for Abeokuta formation

Town	Days	Concentration (mg/l)	Town	Days	Concentration (mg/l)
Ikeja	0	6.500	Ikorodu	0	20.900
	1000	6.890		1000	22.500
	2000	7.281		2000	24.100
	3000	7.671		3000	25.710
	4000	8.061		4000	27.310
	5110	8.495		5110	29.090
Ota	0	19.240	Eredo	0	14.000
	1000	21.480		1000	22.260
	2000	23.710		2000	23.630
	3000	25.950		3000	24.990
	4000	28.190		4000	26.360
	5110	30.670		5110	27.880
Itoikin	0	10.000			
	1000	10.810			
	2000	11.610			
	3000	12.420			
	4000	13.220			
	5110	14.110			