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Full Paper

SIMULATION OF GROUNDWATER CONTAMINANT TRANSPORT IN THE AMEKI AQUIFER DOMAIN OF ANAMBRA STATE, SOUTH EASTERN NIGERIA

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ABSTRACT

About 95% of water schemes located within the Ameki aquifer domain of Anambra State depend on groundwater exploitation. Provision of potable water to the generality of communities within the domain was grossly inadequate, based on reliable community population statistics. Dependence on untreated surface water in some places gave rise to water borne diseases. Groundwater flow and contaminant transport models were developed to evaluate the movement of hypothetical contaminants within the Ameki aquifer in Anambra State. Hypothetical particle-tracking simulations revealed that water high in dissolved solids concentration moved from the designed contaminant source, Ogbakuba community in Ogbaru Local Government Area, toward the nearest pumped well situated at Nza Community in Ekwusigo Local Government Area. Introduced contaminant particles moved a distance of 950m from 1979 to 1999. Results of the hypothetical simulation for the 1979-2050 period showed that by 2050 most of the particles introduced in Ogbakuba Community would have moved about 1200m, reaching the nearest well at Nza Community. The results indicated that with continued pumping the hypothetical contaminant particles will eventually extend to reach more production wells as cone of depression of well fields increases. The paper preliminarily assessed the implication of exploiting groundwater reserve, without recourse to the effects of sustained pumping on the aquifer system. Other factors governing the transport of solute in groundwater such as dispersion and chemical reaction were not considered.

KEYWORDS: Groundwater flow, simulation, contaminant transport, particle-tracking

1. INTRODUCTION

The project area covering the Ameki domain in Anambra State is situated within latitudes $6^0 15^I$N and $5^0 40^I$N and longitudes $6^0 35^I$E and $6^0 55^I$E. The problem domain is situated within the South Eastern part of the Anambra Basin. The domain has a boundary with the famous Niger River on its entire Western borderline. Figure 1 depicts the map of Nigeria with the boundaries of Anambra State indicated.

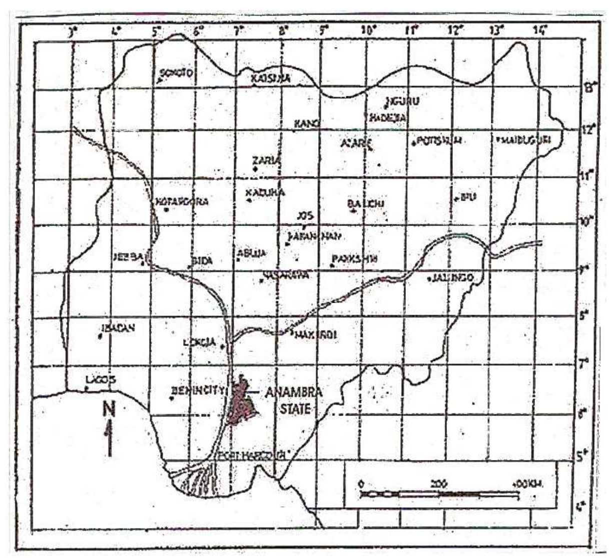

Figure 1: Map of Nigeria with the boundaries of Anambra State indicated

The problem domain is drained mainly by the Anambra River and its main tributaries such as Oyi, Ezochie and Igbariam. Most of the rivers traversing the entire project area have small catchments which are highly seasonal. The basin climate is tropical wet and dry seasons, with less than 5^0C temperature range. The average annual precipitation is about 200.5cm (Tokun, 2003). Offodile, 1992, described generally the climate in the entire Anambra Basin area as hot and humid, with mean annual rainfall of 152.4cm to 203.2cm in the Enugu area to 101.6cm to 228.6cm in Idah area to the north of the Basin. The dry season is relatively short from about November to March. Maximum temperature is 34^0C.

According to literatures (Ezeigbo, 1987; Nwakwor and Eche, 1987), the most important aquiferous formation within the project area are the Ameki, Alluvium and Nanka. A small portion of the Ajalli Formation extends to parts of Ayamelum Local Government Area (LGA) of Anambra State.

2. HYDROGEOLOGY

The generalized geological map of the Anambra Basin is presented in Figure 2. The geological map of Anambra State, with the location of the problem domain, is shown in Figure 3. The existing water supply system in Anambra State comprises mainly boreholes – both shallow and deep, and in some places fully reticulated to serve the residents/villages within the catchment area; hand dug wells – mostly provided through communal efforts and fully developed impounded lakes.

The peculiar geology of the Anambra State has not made open wells feasible in most of the LGA's or communities, except in the riverine areas and a few upland communities (Emenike, 2001). The water bearing aquifer within the study area is the Ameki. Overlying the Imo Shale to the south eastern part of the study area, according to Offodile, 1992 and Ezeigbo, 1987, lies the Ameki Formation. This extends far south beyond the boundaries of Anambra State, up to Okigwe. The Ameki Formation, which is the main aquifer covering Onitsha, Ogbaru, Nnewi and Nnobi areas, is underlain by a series of sandstones interbedded with shales and thin limestones.

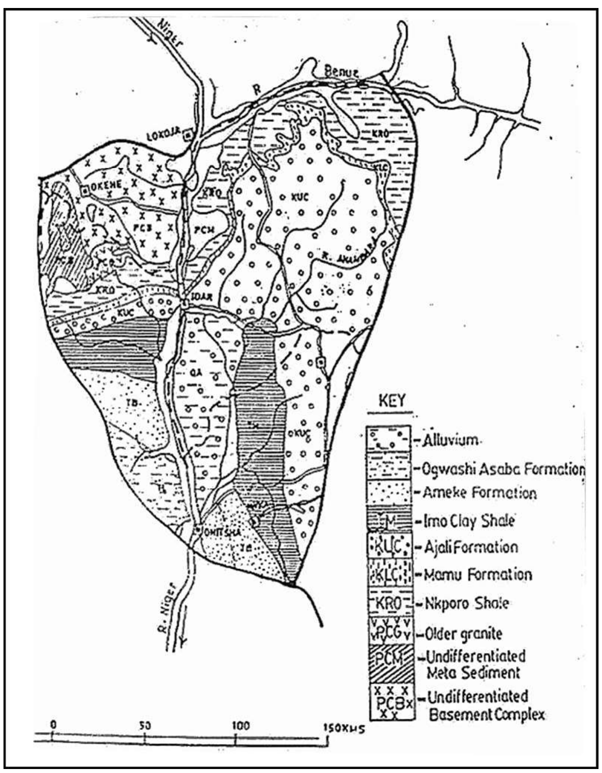

Figure 2: The generalized geological map of the Anambra Basin (after Offodile, 1992)

3. METHODOLOGY

The Ameki model was represented by a rectangular finite difference grid discretized into rows and columns that formed model cells where the ground-water flow equation was solved numerically at nodes at the center of each cell. The Ameki aquifer problem domain was discretized into a finite difference grid of 20 rows and 15 columns, with the origin at the upper left corner. The origin of the

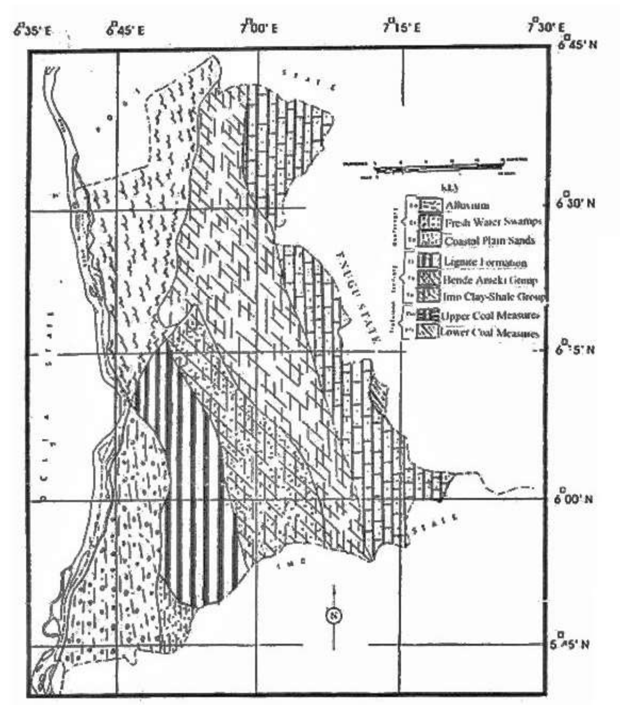

Figure 3: The geological map of Anambra State with the location of the problem domain (after Badafash Nig. Ltd., 1994)

grid (that is, the upper left corner of the grid; row 1, column 1) is at a coordinate of 6035'E and 6017'N (Figure 4). The Ameki domain is idealized as a water table aquifer with an average bottom elevation of 50m below sea level. All the model cells formed by the grid for the Ameki domain have dimensions of 26,000m by 26,000m along the x and y axes respectively. The boundaries of the Ameki aquifer, in each case, are approximated in a stepwise fashion, making some of the nodes within the model grid to be outside the aquifer areas. By assigning zero transmissivities to such nodes outside the boundaries, they are excluded from the calculations. The governing equation for the three-dimensional movement of ground water of constant density through the study area was described by the partial-differential equation:

$$\frac{\partial}{\partial x}\left\{K_{xx}\frac{\partial h}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{K_{yy}\frac{\partial h}{\partial y}\right\}+\frac{\partial}{\partial z}\left\{K_{zz}\frac{\partial h}{\partial z}\right\}-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where:

K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (LT^1); h is the potentiometric head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1}); S_s is the specific storage of the porous material (L^{-1}); and t is time (T).

The MODFLOW codes used in this model included Basic (BAS), Block-Centered Flow (BCF), Well (WEL), River (RIV), Recharge (RCH), Discretization (DIS), and Strongly Implicit Procedure (SIP) [BAS, BCF, WEL, RIV, RCH, DIS and SIP] by (McDonald and Harbaugh, 2004; Pollock, 1994; Ahlfeld, 2005; Smith et al, 1996; Guiger and Franz, 2003). The model boundaries for the Ameki aquifer domain was determined from the hydrogeological map of Anambra State part of the Anambra Basin, and cross-sections

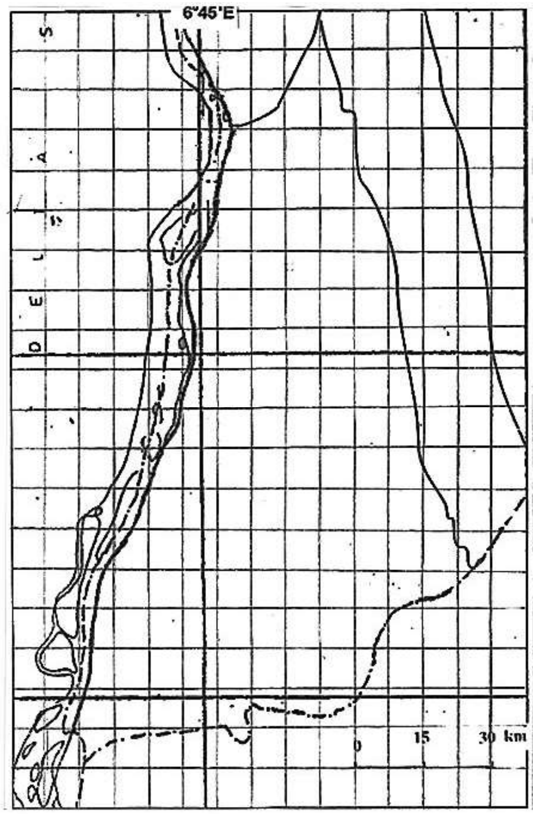

Figure 4: Model grid of the Ameki Aquifer domain

through the aquifer domains. The top boundary of the model, the water table, was simulated in each case as a free-surface boundary (unconfined) to allow it to move vertically in response to changes between inflow and outflow. No-flow boundaries were used below the modeled area to represent contact with aquicludes and ground-water divides.

The surface area of each model array as initially generated had the form of a rectangular box. Where the limits of the study area (problem domain) did not coincide with this rectangular shape, inactive cells were used to delete portions of the model array which fell outside the aquifer boundaries. Out of the many rivers and streams traversing the model domain, only Rivers Niger and Anambra were considered as contributing water to the ground-water system or draining water from it, depending on the head gradient between the river and the ground-water regime. Others were identified and treated as dry washes having relevance mostly at the peak of the wet season. The calibrated ground water flow model was used to preliminarily simulate groundwater flow direction and traveltimes for hypothetical contaminants introduced in the Ogbaru Local Government Area (LGA). Advection by the ground water flow system is one of the main processes controlling the fate and transport of solutes in groundwater. The partial differential equation describing conservation of mass in the Ameki steady-state, three dimensional ground-water flow system was expressed as:

$$\frac{\partial}{\partial x}\{nv_x\} + \frac{\partial}{\partial y}\{nv_y\} + \frac{\partial}{\partial z}\{nv_z\} = W \qquad ......(2)$$

where: vx, vy, and vz are the principal components of the average linear ground-water velocity vector; n is porosity and W is the volume rate of water created or consumed by internal sources and sinks per unit volume of aquifer.

Equation 2 expressed the conservation of mass for an infinitesimally small volume of the aquifer domain. The finite difference approximation of Equation 2 presented a mass balance equation for a finite-sized cell of the Ameki aquifer that accounted for water flowing into and out of the cell, and for water generated or consumed within the cell. Figure 5 shows a finite-sized cell of aquifer and the components of inflow and outflow across its six faces. The six cell faces were referred to as x_1, x_2, y_1, y_2, z_1, and z_2. Face x_1 is the face perpendicular to the x direction at x-x_1. Similar definitions hold for the other five faces. The average linear velocity component across each face in cell (i, j, k) was obtained by dividing the volume flow rate across the face by the cross sectional area of the face and the porosity of the material in the cell, as follows:

$$v_{x_1} = \frac{Q_{x_1}}{(n\Delta y\Delta z)} \quad , \qquad v_{x_2} = \frac{Q_{x_2}}{(n\Delta y\Delta z)} \qquad (3)$$

$$v_{y_1} = \frac{Q_{y_1}}{(n\Delta x\Delta z)} \quad , \qquad v_{y_2} = \frac{Q_{y_2}}{(n\Delta x\Delta z)} \qquad (4)$$

$$v_{z_1} = \frac{Q_{z_1}}{(n\Delta x\Delta y)} \quad , \qquad v_{z_2} = \frac{Q_{z_2}}{(n\Delta x\Delta y)} \qquad (5)$$

where Q is a volume flow rate across a cell face, and Δx, Δy, and Δz are the dimensions of the cell in the respective coordinate directions. If flow to internal sources or sinks within the cell is specified as Qs, the following mass balance equation for the cell is:

$$\frac{(nv_{x_2} - nv_{x_1})}{\Delta x} + \frac{(nv_{y_2} - nv_{y_1})}{\Delta y} + \frac{(nv_{z_2} - nv_{z_1})}{\Delta z} = \frac{Q_s}{(\Delta x\Delta y\Delta z)} \qquad (6)$$

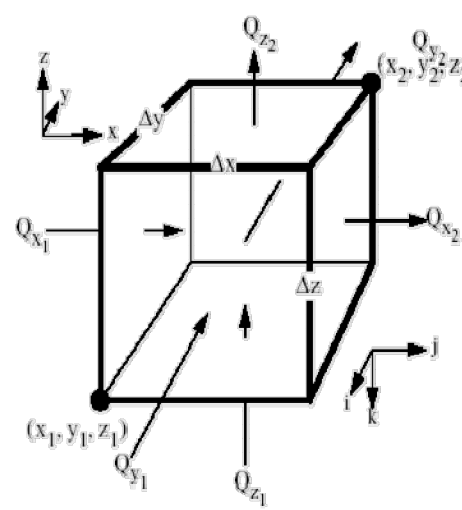

Figure 5: Finite-difference Cell showing definitions of x-y-z and i-j-k.

The left side of equation 6 represented the net volume rate of outflow per unit volume of the cell, and the right side represented the net volume rate of production per unit volume due to internal sources and sinks. Substitution of Darcy's law for each of the flow terms in equation 6 resulted in a set of algebraic equations expressed in terms of heads at nodes located at the cell centers. The solution of that set of algebraic equations yielded the values of head at the node points. Once the head solution had been obtained, the inter-cell flow rates was computed from Darcy's law using the values of head at the node points. The U. S. Geological Survey modular three-dimensional finite-difference ground-water flow model, (MODFLOW), would then solve for head and calculate inter-cell flow rates. In order to compute path lines, a method was established to compute values of the principal components of the velocity vector at every point in the flow field based on the inter-cell flow rates from the finite difference model.

Linear interpolation was used to compute the principal velocity components at points within a cell. Using simple linear interpolation, the principal velocity components was expressed in the form:

$$v_x = A_x(x - x_1) + v_{x_1} \quad (7)$$

$$v_y = A_y(y - y_1) + v_{y_1} \quad (8)$$

$$v_z = A_z(z - z_1) + v_{z_1} \quad (9)$$

where A_x, A_y, and A_z are constants that corresponded to the components of the
velocity gradient within the cell:

$$A_x = \frac{(v_{x_2} - v_{x_1})}{\Delta x} \quad (10)$$

$$A_y = \frac{(v_{y_2} - v_{y_1})}{\Delta y} \quad (11)$$

$$A_z = \frac{(v_{z_2} - v_{z_1})}{\Delta z} \quad (12)$$

Linear interpolation produced a continuous velocity vector field within each individual cell that identically satisfied the differential conservation of mass equation (equation 2) everywhere within the cell. In considering the movement of a particle, p, through a three-dimensional finite-difference cell, the rate of change in the particle's x-component of velocity as it moved through the cell would be given by:

$$\left\{\frac{dv_x}{dt}\right\}_p = \left\{\frac{dv_x}{dx}\right\} \left\{{}_z\frac{dx}{dt}\right\}_p \quad (13)$$

To simplify notation, the subscript, p, was used to indicate that a term was evaluated at the location of the particle [denoted by the x-y-z coordinates (x_p, y_p, z_p)]. For example, the term, $(dv_x/dt)_p$ is the time rate of change in the x-component of velocity evaluated at the location of the particle. In equation (13), the term $(dx/dt)_p$ is the time rate of change of the x-location of the particle. By definition,

$$v_{x_p} = \left\{\frac{dx}{dt}\right\}_p \quad (14)$$

where is the x-component of velocity for the particle. Differentiating equation (7) with respect to x yields the additional relation:

$$\left\{\frac{dv_x}{dx}\right\} = A_x \quad (15)$$

Substituting equations (14) and (15) into equation (13) gives,

$$\left\{\frac{dv_x}{dt}\right\}_p = A_x v_{x_p} \quad (16)$$

Analogous equations are obtained for the y and z directions,

$$\left\{\frac{dv_y}{dt}\right\}_p = A_y v_{y_p} \quad (17)$$

$$\left\{\frac{dv_z}{dt}\right\}_p = A_z v_{z_p} \quad (18)$$

Equations (16) through (18) can be rearranged to the form,

$$\left\{\frac{1}{v_{x_p}}\right\} d(v_{x_p}) = A_x dt \quad (19)$$

Equation (19) can be integrated and evaluated between times t_1 and t_2, (t_1 and t_2) to give,

$$\ln\left\{\frac{v_{x_p}(t_2)}{v_{x_p}(t_1)}\right\} = A_x \Delta t \quad (20)$$

where $\Delta t = t_2 - t_1$. By taking the exponential of each side of equation (20), substituting equation (7) for $v_{Xp}(t_2)$, and rearranging, we obtain,

$$x_p(t_2) = x_1 + \left\{\frac{1}{A_x}\right\}\left\{v_{x_p}(t_1)\exp(A_x \Delta t) - v_{x_1}\right\} \quad (21)$$

Analogous equations can be developed for the y and z directions, as:

$$y_p(t_2) = y_1 + \left\{\frac{1}{A_y}\right\}\left\{v_{y_p}(t_1)\exp(A_y \Delta t) - v_{y_1}\right\} \quad (22)$$

$$z_p(t_2) = z_1 + \left\{\frac{1}{A_z}\right\}\left\{v_{z_p}(t_1)\exp(A_z \Delta t) - v_{z_1}\right\} \quad (23)$$

The velocity components of the particle at time t_1 are known functions of the particle's coordinates. Consequently, the coordinates of the particle at any future time (t_2) could be computed directly from equations (21) through (23). For the steady-state flow, the direct integration method described above was imbedded in a simple algorithm that allowed a particle's exit point from a cell to be determined directly given any known starting location within the cell. Transient finite-difference flow simulations consist of a series of discrete time steps during which flow rates are constant and storage changes within cells contribute an additional component to the internal source/sink term on the right side of equation 6. The particle tracking algorithm described previously for steady-state flow systems was extended to transient finite-difference simulations by taking advantage of the fact that transient simulations behave as a series of steady state flow periods. For each time step, particle paths were computed just as for the steady state case until the end of the time step was reached. A new velocity distribution was then calculated for the next time step and the computation of particle paths was resumed. The computation of paths forward or backward, boundary conditions, and the path line termination criteria were handled the same as for steady state flow.

The computer code MODPATH, developed by Pollock, 1994, was used to simulate advective transport for this research work. Modpath used particle-tracking techniques to compute path lines and travel times based on the results of MODFLOW simulations (McDonald and Harbaugh, 2004). Results of the calibrated simulations of the ground water flow model developed for the Ameki model domain were used in the application of MODPATH. Other processes controlling the fate and transport of solutes in ground water, for example dispersion, diffusion, adsorption and chemical reactions were not included in the MODPATH simulation exercise.

The effect of pumping on ground water flow and travel times were demonstrated by introducing hypothetical particles into mode cells under transient (1979-99) ground water conditions. The particles tracking simulations were used to assess the potential for poor quality water to migrate into the main pumping areas. Ground water flow direction and distances traveled were shown by tracking particles through time. Particles were introduced in the Ogbakuba community in Ogbaru Local Government Area. Particles were released to the top face for a single time period, 1979, assumed to be the base year representing the state of predevelopment in the Ameki aquifer domain. MODPATH simulated the path along which the particles were advected under the transient conditions (1979-1999), and the predictive conditions (1979 – 2050).

4. RESULTS AND DISCUSSION

The study area map and topographical elevations for the Ameki domain is presented in Figure 6. The contours represent the Natural Ground Level (N.G.L.), Above Mean Sea Level (A.M.S.L.), while the locations represent the positions of observation wells in the aquifer domain. The idealization exercise is similar to that developed by Agbede, 1989; Bear and Verruijt, 1992; Harbaugh and McDonald, 1996; Bouwer, 1999; Olowofela and Akinyemi, 2001; Asiwaju-Bello and Oladeji, 2001; Agbede and Adegbola, 2005; and Bexfield and McAda, 2003, for simplification of model aquifer domains prior to numerical simulation. The values of initial and final transmissivities in m^2/sec for the Ameki ground water flow model domain are 1.5×10^{-4} and 1.25×10^{-4} , while the storage coefficients have initial and final values of 1.0×10^{-4} and 4.5×10^{-3} . The procedure for deriving the final hydraulic parameter is consistent with the approach adopted by Carrera and Neuman, 1986; Busari and Agbede, 1992; Christensen, 1997; Cooley, 1979; and D'Agnese et al, 1996.

The calibrated transient state model for the Ameki Domain was used to carry out a preliminary assessment of the movement of hypothetical contaminants within the aquifer. Hypothetical particle-tracking simulations revealed that water high in dissolved solids concentration moved from the designed contaminant source (Ogbakuba community in Ogbaru LGA) toward the nearest pumped well situated at Nza Community in Ekwusigo Local Government Area (Figure 7). Hypothetical contaminant particles introduced in the Ogbakuba community in Ogbaru LGA moved a distance of 950m between 1979 and 1999.

Results of the hypothetical simulation for the 1979-2050 period showed that by 2050 most of the particles introduced in Ogbakuba Community in Ogbaru LGA would have moved about 1200m, reaching the nearest well at Nza Community in Ekwusigo LGA. The results indicated that with continued pumping the

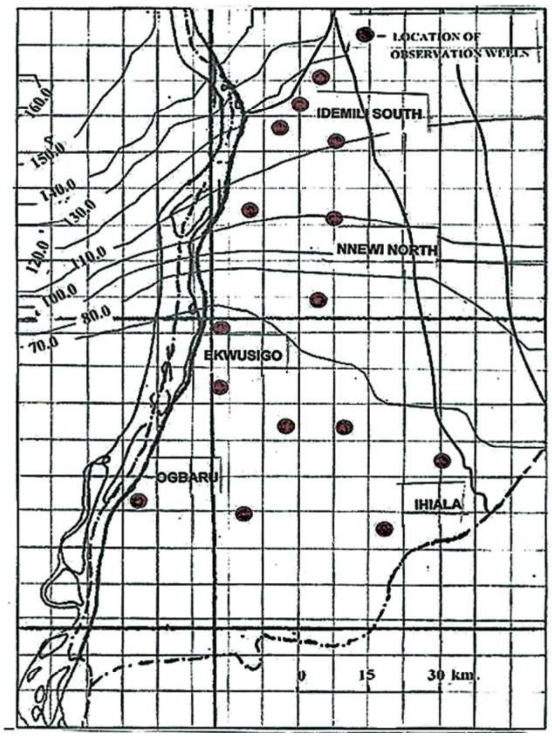

Figure 6: Study Area Map showing positions of observation wells and topographical elevations of the Ameki Domain

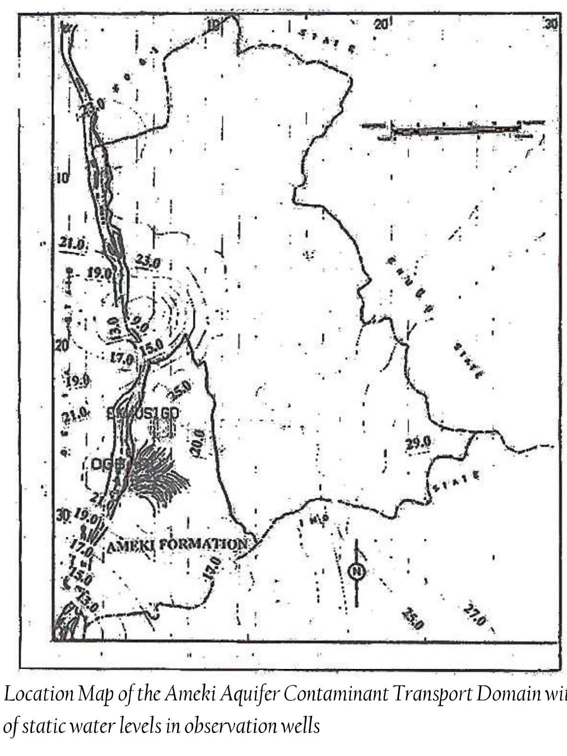

Figure 7: Location Map of the Ameki Aquifer Contaminant Transport Domain with contours of static water levels in observation wells

hypothetical contaminant particles will eventually extend to reach more production wells as cone of depression of well fields increases. The exercise was carried out purely to assess and demonstrate the application of the Ameki calibrated model to analyse transport of contaminants in groundwater flow within a domain.

5. CONCLUSIONS

Preliminary particle tracking simulation was carried out within the Ameki aquifer domain to demonstrate the potentials of the calibrated model to investigate advective transport of contaminants in groundwater. Introduction of hypothetical contaminants in the Ogbakuba Community in Ogbaru LGA moved a distance of 950m between 1979-99 while results of the hypothetical simulation for the 1979-2050 showed a movement of about 1,200m, reaching the nearest well at Nza community in Ekwusigo LGA. Other factors governing the fate of transport of solutes in groundwater such as dispersion and chemical reaction were not considered in the present study. The accuracy of the Ameki ground water model is limited by the assumptions made in formulating the governing flow equations and in the assumptions made during model construction. The model was also limited by the availability of data and the interpolations and extrapolations of available data. In future, with the availability of additional data, further refinement of the model should be carried out, which could improve the accuracy of model prediction of the effects of additional stresses on the aquifer system, such as increased withdrawals or drought.

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