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Full Length Research Paper

Modeling the transport of suspended particulate matter by Kwa Ibo River, Umudike, South-eastern Nigeria: Implications for pollutant dispersion

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Modeling the transport of suspended particulate matter by the Kwa Ibo River, Umudike, south-eastern Nigeria is the focus of this paper. The model solves the 3D hydrodynamic equations and the suspended matter equations including advection/diffusion of particles, settling and deposition. It is aimed at assessing the extent of the interaction between the Kwa Ibo River and the viable groundwater wells located within the premises of Michael Okpara University of Agriculture, Umudike (MOUAU). In addition, it ascertains the degree of pollutant and contaminant migration from the river to the wells in question. The geology of the area comprises the "quaternary" to recent Benin Formation. Potential aquifer zones delineated earlier using the geo-electric resistivity surveys and well inventory in the area forms the basis for transport modeling. The watershed is modeled with a grid of (50 rows by 40 columns) and with two layers. Lateral in-flow from the north is simulated with constant heads at Government College, Umuahia and outflow at Umuariga in the south.

Key words: Modeling, suspended matter, dispersion, permeability, groundwater, Kwa Ibo River.

INTRODUCTION

The last quarter of the century has recorded remarkable technological development in groundwater studies. One area that this has occurred is in the investigation of deterministic, distributed parameter, computer simulation models for analyzing flow and solute transport in groundwater systems. Suspended particulate matter (SPM) is "--- sediment carried in suspension by the turbulent components of the fluid or Brownian movement" (Wilber, 1983). In recent years, there has been an increasing interest in modeling suspended matter since this is essential for water quality models. First, when sediment is stirred up nutrients, trace metals and organic contaminants are released into the water column. In turn, as suspended sediment settles out the dissolved chemicals may be scavenged. Secondly, since the light intensity at depth depends inversely on suspended sediment load in the water column above, suspended matter impacts on primary productivity (Morris and Howarth, 1998). Thus mathematical models have been developed to simulate the suspended matter distributions in different aquatic environments and under different approaches, from relatively simple box models (Puls and Sundermann, 1990; Abril and Garcia-Leon, 1994) to more complex dynamic approaches in which advection, diffusion and settling of particles are computed from calculated current fields (Clarke and Elliott, 1998; Cancino and Neves, 1990; Perianez, 2002; Lumborg and Windelin, 2003). By convention, particulate matter (PM) in suspension is defined as the material that is retained on a 0.4 to 0.5 µm pore size filter. Smaller material is considered to be dissolved. Muddy sediments consist of clays with some variable silt content and particle diameter (Pugh, 1987) is < 62.5 µm. Larger particles such as sands settle much more rapidly out of suspension in water than mud particles and bed load transport is the most important mechanism in moving these coarse

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sediments (Pugh, 1987; Morris and Howarth, 1988). Usually, only particles with diameters < 62. 5 µm are considered when modeling suspended matter dynamics. Indeed, it has been pointed out (Eisma, 1981) that for all practical purposes mud can be regarded synonymous of suspended matter (Perianez, 2005).

A water body suspended load is a component of the total turbidity. Suspended particulate matter (SPM) regulates the transport of all types of water pollutant in dissolved and particulate phases in Lakes, river and coastal areas; regulates water clarity, sedimentation etc (Hausstein, 2008). There also exists a relationship between water discharge and SPM in rivers. Groundwater flow modeling is generally defined as the quantity of groundwater available or direction of dissolved contaminant migration. It is also used to define the limit of a capture zone for a contamination recovery well (or well field), or for delineating a water well protection area (or recharge area) for a water supply.

The objective of this paper is to develop a suspended matter model (SMM) to simulate the transport of sediments by the Kwa Ibo River watershed, Umudike in Abia State –Nigeria. This is an interesting problem since a complex intrusion process occurs when a freshwater input runs into marine waters. It mainly depends upon the interaction between the buoyancy induced momentum fluxes; which spread the freshwater offshore, and the turbulent dilution and dissipation mechanisms, that reduce density differences between the two water masses. To achieve this objective, characterization of the geological formations within the area through interpretation of geophysical data; hydrogeological analysis for aquifer characteristics and groundwater flow modeling of the area have been carried out.

Location

Kwa Ibo River – Umudike lies within the Ikwuano and Umuahia South Local Government Areas and was selected for detailed aquifer characterization and hydrogeological investigations. The watershed is located between latitudes 5°19’ and 5°30’N and longitude 7°30’ and 7°31’E. It covers a rectangular area of about 180 km^2, which is bounded by Government college Umuahia, Ariam, Usaka Eleogu and Umuobia Olokoro (Igboekwe, 2008).

Rainfall

Southeastern part of Nigeria in which Abia State forms a part is where the research location is situated. This area enjoys a copious rainfall during the rainy season. The mean monthly rainfall during the season is 335 mm and falls to 65 mm during the dry season (Ebillah-Salmon, 1993). The annual rainfall is between 2000 and 2250 mm (Jalon consultants, 1980). There are about 225 rain days per year in this area.

Drainage pattern

This study area is drained by the Kwa Ibo River, which rises near Umuahia and flows in a southeastern direction. Its main tributary, the Anya Rivers, cuts across the premises of the Michael Okpara University of Agriculture and the National Root crops Research Institute both in Umudike. This river, also called the Great Kwa River in Cross River state, also drains the Easter part of Calabar, and finally empties into the Atlantic Ocean. It is popularly known as its Waterfall (called Kwa falls) and well-exposed Schist’s near Aningeye and Abbiati in the Calabar Flank (Ekweme et al., 1995). The eastern part of the study area is uplifted and forms an undissected upland, whereas the western part of the study area comprises a combination of various terrain elements. Within the study area, the Kwa Ibo River flows between the undissected upland the dentritic lowland. The general slope of the study area is from northwest to southeast. The drainage is also observed to follow the topography, which has an average value of 120 m (a.m.s.l).

Geology

The geology of the area comprises cretaceous to recent deltaic marine sediments. There are two principal geological formations in the area, the Bende – Ameki and the Coastal Plain sands, the latter are otherwise known as the Benin Formation. The late Tertiary to early Quaternary Benin Formation is the most predominant (Mbonu et al., 1991), and uncomfortably overlies the Bende – Ameki Formation, with a southwestward dip. At Umudike, the formation is about 200 m thick. The lithology is unconsolidated fine- medium-coarse grained cross- bedded sands, occasionally pebbly with localized clays and shale.

Hydrology

The principal geological formations have a comparative groundwater regime. They both have reliable groundwater that can sustain regional borehole production. The Bende-Ameki Formation has less groundwater when compared with the Benin Formation.

The high "permeability" of the Benin formation, the overlying Lateritic earth, and the weathered top of this formation as well as the underlying clay-shale member of the Bende-Ameki series, provide the hydrological conditions favouring aquifer formation in the area.

LITERATURE REVIEW

Flow and transport process

The process of groundwater flow is generally assumed to be governed by the equations expressed in Darcy's Law and the conservation of mass. Darcy's Law does have limits on its range of applicability; however, the limits must be evaluated in any application. The purpose of a model that simulates transport in groundwater is to compute the concentration of a dissolved chemical species in an aquifer at any specified place or time. The theoretical basis for the equation describing solute transport has been well documented in the literature (Bear, 1997; Domenico and Sebwartz, 1998). Reilly et al. (1987) provide a conceptual framework for analyzing and modeling physical solute transport process in groundwater. The changes in chemical concentration occur within a dynamic system primarily due to four district processes.

(i) Advective transport, in which dissolved chemical are moving with the flowing water.

(ii) Hydrodynamic dispersion in which molecular and ionic diffusion and small – scale variation in the flow velocity through the porous media cause the path of dissolved molecules and ions to diverge or spread from the average direction of groundwater flow.

(iii) Fluid sources, where water of one composition is introduced into and mixed with water of a different composition.

(iv)Reaction, in which some amount of a particular dissolved chemical species may be added to or removed from the groundwater and the solid aquifer material or other separate liquid phases. The subsurface environment constitutes a complex three dimensional, heterogeneous hydrogeologic setting. This variability strongly influence groundwater flow and transport, and such a reality can be described accurately only through careful hydrogeologic practice in the field.

Governing equation

The development of mathematical equations that describe the groundwater flow and transport process may be developed from the fundamental principle of conservation of mass of fluid or of solute. Given a representative volume of porous medium, a general equation for conservation of mass for volume mass is expressed as:

$$(Rate\ of\ mass\ in\ flow) - (rate\ of\ mass\ outflow + \frac{rate\ of\ mass\ production}{consumption} = (Rate\ of\ mass\ accumulation) \qquad (1)$$

This statement of conservation of mass (or continuity equation) may be combined with a mathematical expression of the relevant process to obtain a different equation describing flow or transport (Bear, 1997; Domenico and Schwartz, 1998; Freeze and Cherry, 1979).

Groundwater flow equation

The rate of flow of water through a porous media is related to the properties of the water, the properties of the porous media and the gradient of the hydraulic head, as represented by Darcy's law which can be written as:

$$q_i = -K_{i,j}\frac{\delta h}{\delta_{xi}} \qquad (2)$$

where q_i = specific discharge, LT^{-1}, K_{ij} = hydraulic conductivity of the porous medium, LT^{-1} and h = Hydraulic head, L.

A general form of the equation describing the transient flow of a compressible fluid in a non- homogeneous anisotropic aquifer may be derived by combining Darcy's law with the continuity equation. A general groundwater flow equation may be written in Cartesian coordinates as:

$$\frac{\delta}{\delta xi}\left\{Kij\frac{\delta h}{\delta_{xi}}\right\} = Ss\frac{\delta h}{\delta t} + W^* \qquad (3)$$

Ss is the specific storage, L^{-1}; T is the time, T; X_i are Cartesian coordinate, L.

An expression similar to Equation (3) may be derived for the two dimensional areal flow of a homogenous fluid in a confined aquifer and written as:

$$\frac{\delta}{\delta xi}\left\{T_{i,j}\frac{\delta h}{\delta_{xi}}\right\} = S\frac{\delta h}{\delta_{xi}} + W - \qquad (4)$$

Where T_{ij} in the transmisivity, LT-^{1} and $T_{ij} = K_{i,j}$ b; B= Saturated thickness of the aquifer, L; S=Coefficient (dimensionless) and W = W* b in the volumetric flux per unit area.

When the Equation 4 is applied to an unconfined (water table) aquifer system, it must be assumed that the flow is horizontal and equipotential lines are vertical, that the horizontal gradient equals the slope of the water table and Coefficient is equal to specific yield (S_y) (Anderson and Woessner, 1992).

Solute transport equation

An equation describing the transport and dispersion of a dissolved chemical in flowing groundwater may be derived from the principle of conservation of mass, Equation 1, just as the general flow equation was derived (Bear, 1979; Domenico and Schartz, 1998; Konikow and Groove, 1977; Bear, 1972; Bredehoef and Pinder, 1973; Reddell and Sunada, 1970). A generalized form of the solute transport equation is represented by Groove (1976), in which terms are incorporated to represent chemical reaction and solute concentration both in the pore fluid and on the solid surface as:

$$\frac{\delta(\varepsilon C)}{\delta t}=\frac{\delta}{\delta xi}\left\{\varepsilon D_{ij\frac{\delta c}{\delta X_i}}\right\}-\frac{\delta}{\delta xi}\left(\varepsilon C V_i\right)-C^I W^*-+CHEM \qquad (5)$$

Where CHEM equals $-\rho_b {}^{\delta\bar{C}}/_{\delta t}$ for linear equilibrium controlled sorption or ion exchange,

$\sum_{k=1}^{c} R_k$ for S chemical rate controlled reaction and or - λ (εC+ ρ_b C) for decay and where:

D_{ij} is the co-efficient of hydrodynamic Dispersion, L^2 T^{-1}, C is the concentration of the solute in the source or sink fluid, $\bar{C}$ is the concentration of the species absorbed on the solid (mass of solute/mass of solid, ρ_b is bulk density of the sediment, ML^3, R_k is the rate of production of the solute in reaction K, ML^3T^{-1}, λ is the decay constant (equals to ln $2/T_{½}$), T^{-1} (Groove, 1976).

The term on the right of Equation 6 represents the change in concentration due to hydrodynamic dispersion. The second term represents advective transport and describes the movement of solutes at average seepage velocity of the flowing groundwater. The third term represents the effects of mixing with a source fluid that has different concentration from the groundwater at the location of the recharge or injection. The fourth term lumps all the chemical, geochemical and biological reactions that cause transfer of mass between the liquid and solid phases or conversion of dissolved chemical species from one form to another. The chemical attenuations or inorganic chemicals can occur by sorption/desorption, precipitation/dissolution, or oxidation/reduction; organic chemicals absorb or degrade by microbiological processes. If the reactions are limited to equilibrium- controlled sorption or exchange and first-order irreversible rate (decay) reactions, then the general governing Equation 6 can be written as:

$$\frac{\delta c}{\delta t}+\rho_b\frac{\delta\bar{C}}{\varepsilon\delta t}=\frac{\delta}{\delta x_i}\left[D_{i,}\frac{\delta c}{\delta x_i}\right]-\frac{\delta}{\delta x}\left(CV_i\right)\frac{CW}{\varepsilon}-\lambda C\frac{\rho_b}{\varepsilon}\lambda\bar{C} \qquad (6)$$

The temporal change in sorbed concentration in Equation 7 can be represented in terms of the solute concentration using the drain rule of calculus as follows:

$$\frac{d\bar{C}}{dt}=\frac{d\bar{C}}{dC}\;\frac{\delta C}{\delta t} \qquad (7)$$

For equilibrium sorption and exchange reaction,

$\frac{d\bar{C}}{dC}$ as well as C, is a function of C alone. Therefore, the equilibrium reaction for C and $\frac{d\bar{C}}{dC}$ can be substituted into the governing equation to develop a partial differential equation in terms of C only. The resulting single transport equation is solved for solute concentration sorbed concentration can be calculated using the equilibrium reaction. The linear sorption reaction considers that the concentration of solute sorbed to the porous medium is directly proportional according to the reaction.

$\bar{C} = K_d C$ (8)

Where k_d is the distribution coefficient L^3M^{-1}. This reaction is assumed to be instantaneous and reversible the curve relating sorbed concentration to dissorbed concentration is known as an Isotherm. If that relation known as the equilibrium distribution coefficient, k_d. Thus, in case of a linear Isotherm.

$$\frac{d\bar{C}}{dt}=\frac{d\bar{C}}{dC}\;\frac{dC}{dt}\quad=K_d\,\frac{dC}{dt} \qquad (9)$$

After substituting this relation into Equation 7, we can then rewrite Equation 7 as:

$$\frac{\delta C}{\delta t}+\frac{\rho_b K_d}{\varepsilon}\frac{\delta C}{\delta}-\frac{\delta}{\delta x_i}\left[D_{i,}\frac{\delta c}{\delta x_j}\right]-\frac{\delta}{\delta x}\left(CV_i\right)\frac{CW}{\varepsilon}-\lambda C\frac{\rho_b K_d}{\varepsilon}\lambda\bar{C} \qquad (10)$$

Factorizing out the term $(1+\Delta_b K_d/\varepsilon)$ and defining of retarding factor R_f, (dimension less), as:

$$R_f = 1 + \frac{\rho_b K_d}{\varepsilon} \tag{11}$$

and substituting the relation into Equation 10, result in

$$R_f \frac{\delta c}{\delta t} = \frac{\delta}{\delta x_i}\left[D_{i,j} \frac{\delta c}{\delta x_j}\right] - \frac{\delta}{\delta x_i}(CV_i) + \frac{c' W^*}{\varepsilon} - R_f \lambda C \tag{12}$$

Because R_f is constant under these assumptions, the solution to these governing equations is identical to the solution for the governing equation with no sorption effects, except that the velocity, dispersive flux and source strength are deduced by a factor R_f. The transport process thus appears to be "retarded" because of the instantaneous equilibrium sorption into the porous medium. In the convection formulation the solute-transport Equation 6, the coefficient of hydrodynamics dispersion is defined as the sums of mechanical dispersion and molecular diffusion (Bear, 1997).

METHODOLOGY

Previous geophysical investigations carried out in the Kwa Ibo River watershed provided insight into the aquifer geometry for development of a groundwater flow model. Igboekwe (2005) used the schlumberger resistivity configuration for 11 vertical electrical sounding (VES) points to show that the watershed in underlain by a thick sandy aquifer. Geophysical data from Igboekwe (2005) and the well inventory collected from the area (Igboekwe and Adindu, 2011) formed the initial data set for the groundwater flow modeling. The hydraulic conductivity has been determined from pumping tests at three locations, namely Umuobia Olokoro (8.65 m day^{-1}), Ndoro (7.5 m day^{-1}) and at Umudike (8.0 m day^{-1}) (Igboekwe, 2005). The remaining values in the study area were estimated using a grid map and by the use of the formula derived by Uma et al (1989):

$$K = A(d_{10})^2 \tag{13}$$

Where K is the hydraulic conductivity, A, the grain size constant and d_{10} the permeability. The aquifer permeability varied from 3.15 to 14.4 m day^{-1} in the water shed. Higher permeability prevailed along the Kwa Ibo River course. The groundwater recharge at the rate of 85 mm year^{-1} has been simulated in the first layer by deploying the recharge package. Groundwater recharge increased from 85 mm year^{-1} in the southern boundary to 125 m year^{-1} in the north.

RESULTS AND DISCUSSION

The groundwater recharge during the rainy season, the abstraction (pumping rates) and the groundwater flux to the Kwa Ibo River controlled the hydrodynamics of groundwater flow condition in the Kwa Ibo River water shed (Igboekwe, 2008). Natural recharge to the aquifer system is 44 6683 m^3 day^{-1} and groundwater abstraction is 24211 m^2 day^{-1}. This the groundwater balance indicated that the net contribution from Kwa Ibo River to the groundwater system as about 20472 m^3 day^{-1}.

Groundwater quantity reflects substances that are dissolved or suspended in the water. Suspended materials are not transported far in most subsurface materials, but it is usually filtered out. In general, groundwater is very slow and depends on the permeability (water transmitting ability) of the subsurface material, as well as the hydraulic gradient for artesan conditions. Groundwater usually contains higher concentrations of natural dissolved material than surface water the materials dissolved in the water reflect the composition and solubility of the earth materials (soil and rock) that the groundwater is in contact with and time that it has been in the subsurface.

Lateral inflow entering the confirmed aquifers from the northern boundary also goes out as lateral outflow through the southern boundary. The perennial flow in the Kwa Ibo River is maintained by the flow from the aquifer system. The magnitude of velocity field vectors is 0.44 m day^{-1} or 160 m year^{-1} generally, under certain conditions some dissolved organic chemicals adsorb to the aquifer material. This absorption causes the contaminant to move slower than the groundwater (Figure 1 and Table 1). Under the transient state simulations, it is seen that water level fluctuations correlate with changes in rainfall within the 10 years period. The fluctuations may be attributed to distinct litho logical controls, whereby less fluctuation is associated with predominance of granular zones. It may be attributed to run off and recharge.

Conclusion

Hydrogeological and groundwater modeling has been carried out in the Kwa Ibo River watershed with the aim of determining the aquifer- river interaction within the study area as to access the degree of solute contaminant migration from the river to the aquifer. The aquiferous zone had been delineated by carrying out geophysical investigation at 14 locations. Depths to water levels are greater in upland areas (recharge areas) than in valley bottoms (discharge areas). The groundwater model has been prepared based on lithological information and vertical cross-section intervals from resistivity interpretation. The hydraulic connection between the river and aquifer was assumed to be 100 m day^{-1} (Igboekwe, 2008).

The permeability values were initially taken from pumping test data. The flow model has been used to compute the groundwater balance of (55274 m^3 day^{-1}) in the watershed using zone budgets. The computed hydraulic head and effective porosity values have been

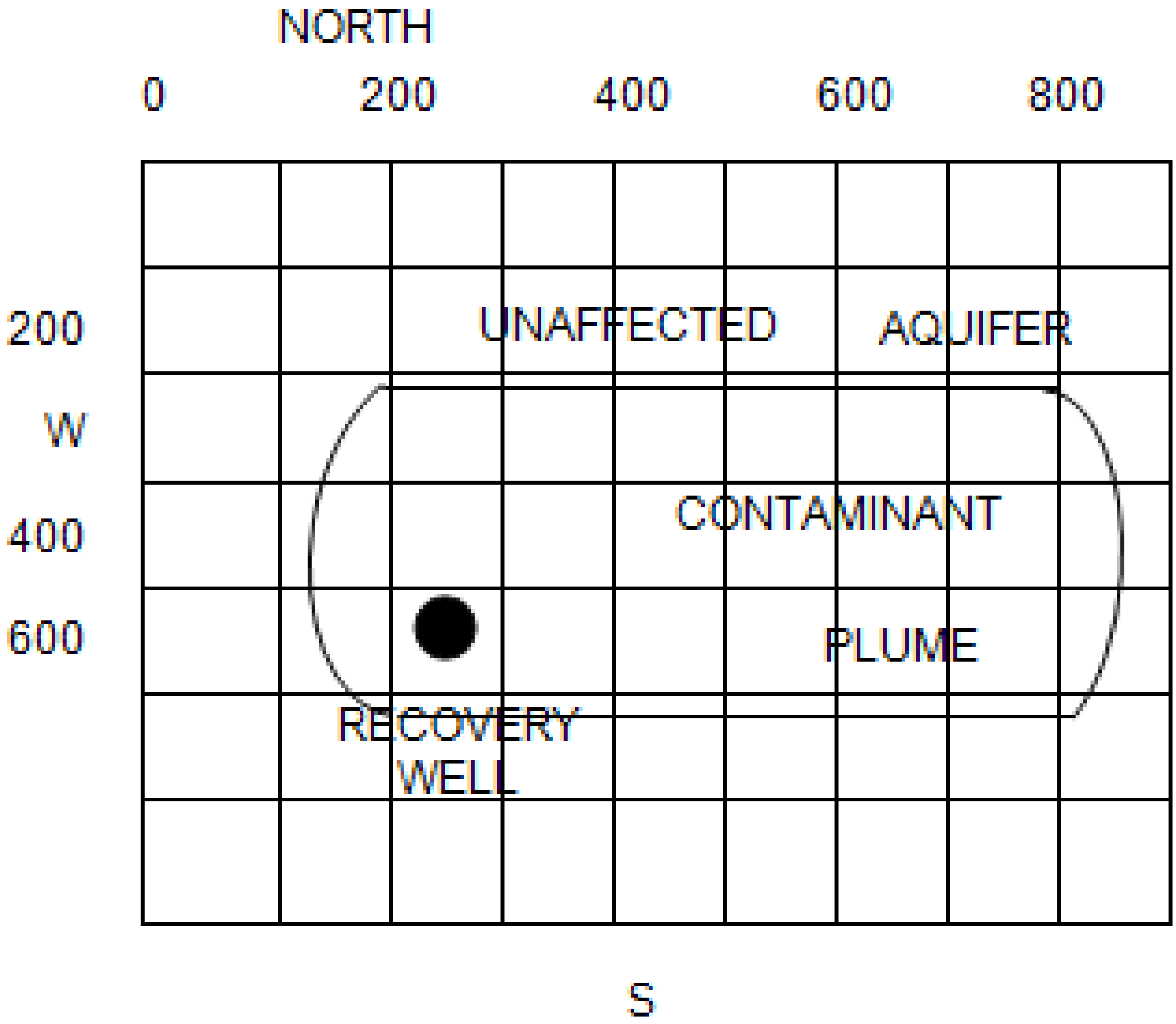

Figure 1. Solute transport modelling (typical modeling layout) north.

Table 1. Groundwater balance in Kwa Ibo River watershed.

Variable	Input (m^3 day^1)	Output (m^3 day^1)
Recharge	44683	-
Pumping	10591	24211
River leakage	-	-
Groundwater to river	-	5139
Lateral outflow	-	25924
Total	55274	55274

used for computation of groundwater velocity. The maximum groundwater velocity has been 0.44 m day^{-1} or 160 m $year^{-1}$ along the Kwa Ibo River, where higher permeability values exist. The groundwater recharge of 85 to 125 mm $year^{-1}$ seems to be about 10% of annual rainfall. The predominant groundwater flow is towards south, but it is mostly towards Kwa Ibo River on both sides. Generally, the net contribution of Kwa Ibo River to

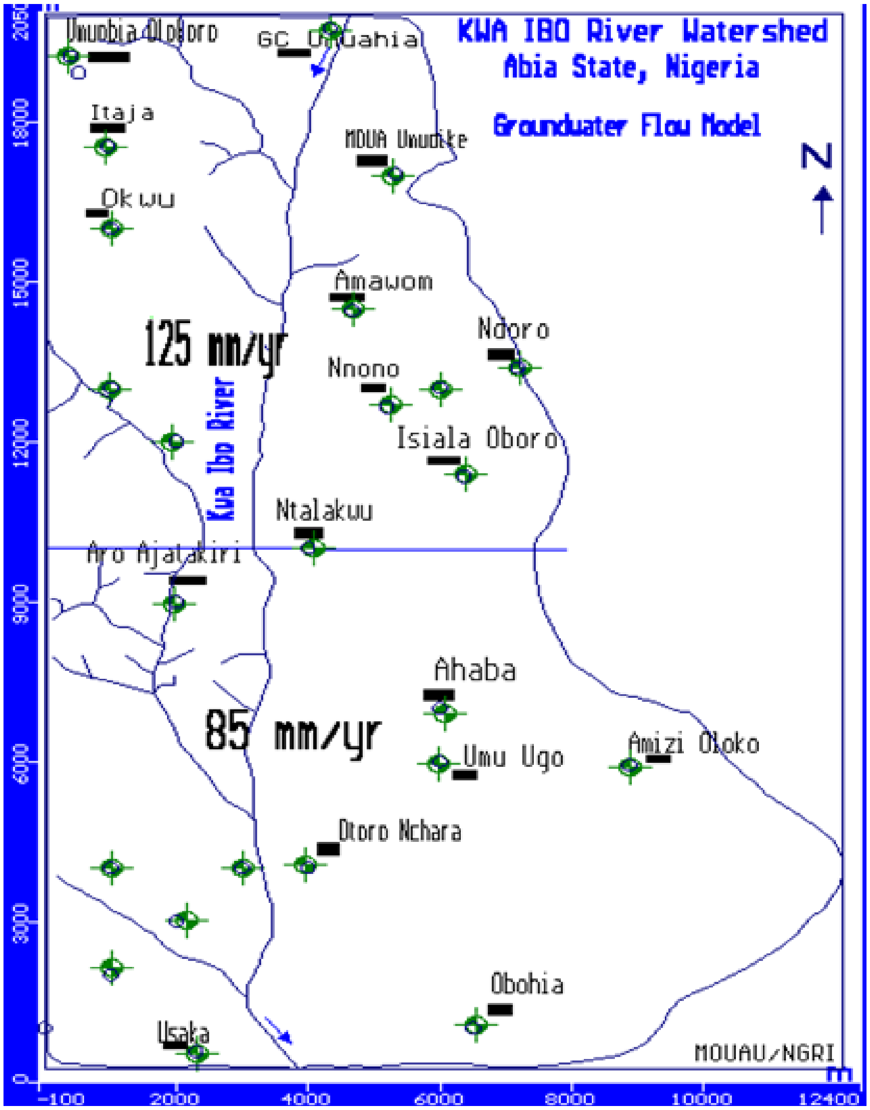

Figure 2. Location map of the study area.

the groundwater is high, above 20472 m^3 day^{-1}, indicating continuous recharge. Figure 2 shows the location map of the study area.

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