GLOBAL JOURNAL OF GEOLOGICAL SCIENCES VOL. ~~4~~ 3, NO. 2, 2005: 169 - 177
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GROUNDWATER FLOW MODELING OF KWA IBO RIVER WATERSHED, SOUTHEASTERN NIGERIA.

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(Received 16 May 2005; Revision accepted 6 September 2005)

ABSTRACT

Groundwater flow modeling of Kwa Ibo River Watershed in Abia State of Nigeria is presented in this paper with the aim of assessing the degree of interaction between the Kwa Ibo River and the groundwater regime of the thick sandy aquifer. The local geology of the area, called Benin Formation, is of Quaternary to Recent age. Potential aquifer zones earlier delineated using the geoelectrical resistivity soundings and well inventory in the area formed the basis for groundwater flow modeling. The watershed has been modeled with a grid of 65rows x 43columns and with two layers Lateral inflow from the north has been simulated with constant heads at the Government College Umuahia and outflow at Usaka Elegu in the south. The Kwa Ibo River traverses the middle of the watershed from north to south. The river stage data at Umudike, Amawom, Ntalakwu and Usaka Elegu have been used for assigning surface water levels and riverbed elevations in the model. Permeability distribution was found varying from 3 to 14.5 m/day. Natural recharge due to rainfall formed the main input to the aquifer system and abstraction from wells, the output. A steady-state groundwater flow simulation was carried out and calibrated against the May 1980 water levels using 26 observation wells. The model computations have converged after 123 iterations. Under the transient-state calibration, the highest rainfall (and hence groundwater recharge) over the ten-year study period was recorded in 1996, while the lowest was recorded in 1991. The computed groundwater balance of 55274m^3/day was comparable to that estimated from field investigations. Results from the modeling show that abstraction is very less compared to groundwater recharge. Hence there is the possibility for additional groundwater exploitation in the watershed through drilling of bore holes.

KEYWORDS: Groundwater, Modeling, Permeability, Recharge, Kwa Ibo River,

INTRODUCTION

The increasing population in Umudike area of southeastern Nigeria with a population of about 35,000 (Igboekwe, 2005) and demand for potable water to cater for the needs of the educational and research institutions within the area has prompted the present search for favorable groundwater potential zones in the area. Much of the wells drilled in different places in the area, have become abortive or dried up because of lack of prior systematic scientific investigation. Some of the existing shallow wells reflect high draw down during the dry season (mainly, November through February) each year.

The result of the draw down or outright failure of wells as well as the inadequacy of water supply from improved schemes is the intake of poor drinking water by the people. It therefore has become necessary to study the groundwater resource potentials in the Kwa Ibo River watershed in other to meet the projected water demand of the communities within a time frame. Thus the main objective of the present study is to assess the Kwa Ibo River – aquifer interaction using groundwater modeling technique. In order to achieve the above objective, the following tasks have been carried out: Characterization of the geological formations within the area through interpretation of geophysical data; Hydrogeological data analysis for aquifer characteristics; Groundwater flow modeling of the area.

Physiography, Geomorphology, Geology And Hydrogeology.

Kwa Ibo River Watershed was identified within the Ikwuano and Umuahia South local government areas for detailed aquifer characterization and other hydrogeological investigations. Figure1 shows the location map of the study area. The watershed is located between latitudes 5^{0}19$^/$ and 5^{0}30$^/$N and between longitudes 7^{0}30$^/$ and 7^{0}37$^/$E. It covers a total area of about 180 sq. km represented by an oblong terrain, which comprises of Government College Umuahia, Ariam,Usaka Elegu and Umuobia Olokoro on its borders (Igboekwe 2005).

Southeast of Abia State within which the watershed is found, enjoys a copious rainfall during rainy (monsoon) season. The mean monthly rainfall during this season is 335 mm and falls to 65 mm during the dry season (Ebilah et al, 1993). The annual rainfall is between 2000 mm and 2250 mm (Jalon Consultants and Engineers ltd, 1980). There are about 255 rain days per year in this area.

The study area is drained by the Kwa Ibo River, which rises near Umuahia and flows in a southeastern direction. Its main tributary, which is the Anya River, 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 eastern part of Calabar and finally empties into the Atlantic Ocean. It is popularly known for its waterfall (called Kwa Falls) and well-exposed schists near Aningene and Abbiati in the Calabar Flank (Ekwueme et al 1995). The eastern part of the study area is uplifted as shown by the elevation contour. So it is undisected upland. The western part of the study area is much influenced by the combination of various terrain elements such as slope, physiography, geology and geomorphology. It shows a dentritic drainage pattern. With this drainage pattern within the study area, it is concluded that the Kwa Ibo River is flowing in-

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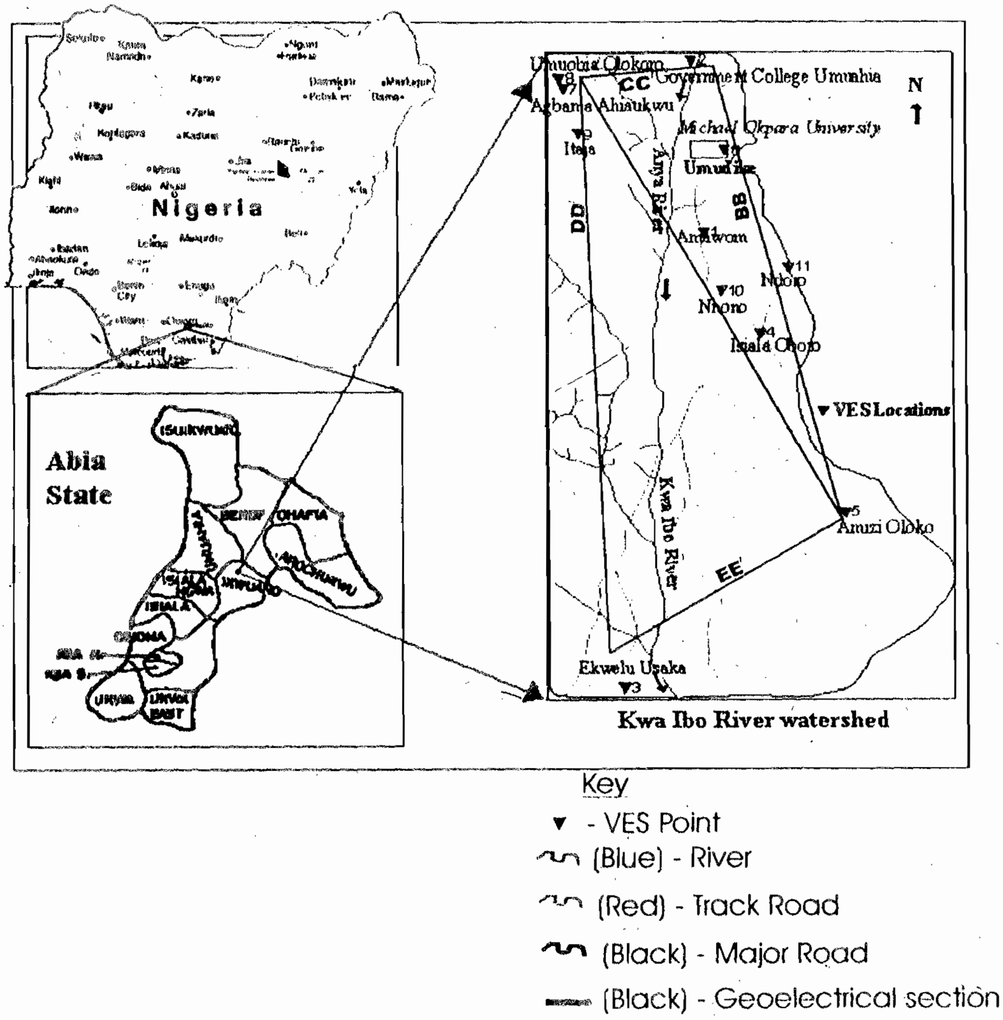


Fig 1a: Map of Kwa Ibo River watershed showing VES points

between the undisected upland and 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 120m (amsl).

The Geology of the area falls within the Deltaic marine sediments of Cretaceous to Recent age. There are two principal geological formations in the area namely: Bende-Ameki and the Coastal Plain Sands otherwise known as the Benin Formation. The most predominant, however, is the Benin Formation, whose sediments were deposited during the late Tertiary–early quaternary period (Mbonu et al 1991). The formation overlies the Bende–Ameki formation uncomformably and dips southwestwards. At Umudike, the formation is shallow. The expected thickness is about 200m. The lithology consists of unconsolidated loosely fine-medium-coarse grained cross–bedded sands occasionally pebbly with localized clays and shale.

The two principal geological formations have comparative groundwater regime. They both have reliable groundwater that can sustain regional borehole production. The Bende–Ameki Formation has little groundwater when compared to 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 hydrologic conditions favoring aquifer

LITERATURE REVIEW

In the modern world of science and technology, modeling has emerged as a major tool in all branches of science. With the onset of the new millennium, more and more areas of study have adopted computer aided modeling techniques. In this work, groundwater modeling is done by numerical solution using the Visual Modflow Software (Guiger and Franz, 1996). This software has been developed by Waterloo Hydrologic Inc. Version 2.0 © 1995-1999. Under the numerical solution, finite difference block centred technique is used. To solve the equations the Waterloo Hydrogeologic Solver (WHS) method is employed. In the study area, water table contours and well hydrographs are constructed for steady and transient state conditions using the software.

For the purposes of this review, it should be recalled that numerical methods are divided into two: Finite Difference Method (FDM) and Finite Element Method (FEM). Bredehoeft and Hanshaw (1968) and Trescott and Larson (1976) have described extensively the Finite Difference Method (FDM) while Neumann and Witherspoon (1970) as well as Desai and Abel (2002) have equally described the Finite Element Method (FEM). For the groundwater flow model, the flow equation is given by:

formation in the area.

$$V_i = -(K_{ii} / \Phi)\, dh/dx_i \qquad \ldots 1$$

where

Φ = the porosity

K_{ii} = a principal component of the hydraulic conductivity tensor

h = hydraulic head

The hydraulic head is obtained from solution of three dimensional groundwater flow equation through Modflow software (McDonald and Harbaugh, 1988)

$$\frac{\partial}{\partial x_i}\left[K_{ii}\frac{\partial h}{\partial x_j}\right] + q_s = S_s\frac{\partial h}{\partial t}\ldots\ldots\ldots\ldots\ldots\ldots(8) \qquad \ldots 2$$

where S_s is the specific storage of the porous material.

It should be noted that for a rectilinear grid with variable size spacing, Prickett and Lonnguist (1971) derived the following finite difference form for the non-steady state, two -dimensional flow of groundwater in an artesian non-homogeneous aquifer thus:

$$T_{i-1,j,2}\frac{(h_{i-1,j} - h_{i,j})}{\Delta x^2} + T_{i,j,2}\frac{(h_{i+1,j} - h_{i,j})}{\Delta x^2} + T_{i,j,1}\left(\frac{h_{i,j+1} - h_{i,j}}{\Delta y^2}\right) + T_{i,j-1,1}\frac{(h_{i,j-1} - h_{i,j})}{\Delta y^2}$$

$$= S_{i,j}\frac{(h_{i,j} - h_{\varphi i,j})}{\Delta t} + \frac{Q_{i,j}}{\Delta x\,\Delta y} \qquad \ldots.3$$

$S_{i,j}$ = storage coefficient in the volume centred around i,j.

$h_{\varphi i,j}$ = calculated head at node i,j at the end of the previous time increment.

Δt = time increment elapsed since last calculation of heads.

Groundwater Flow Model Case Studies

The simulation of regional groundwater flow system has traditionally been treated as a problem in steady state flow (Hubert, 1940; Toth, (1963), Freeze and Witherspoon, 1966). In recent years, largely under the influence of Toth, (1978) and Toth and Miller, (1983), it has been recognized that non-cyclical, long term transient changes in groundwater flow systems can be produced by changes in topographic relief caused by tectonic and geomorphological events.

Bredehoeft and Hanshaw (1968) presented a one-dimensional analytical solution to the problem of transient flow in a thick homogenous and sedimentary sequence under the influence of a fixed sedimentary rate.

Kent *et al*, (1982) carried out model studies using finite difference technique in Wasishta River basin covering 284 square kilometres. The objective of the study was to demonstrate the application of a predictive groundwater potentiometric head model to estimate the probability of irrigation in contrast to that of dry land farming.

Recent studies by Forster and Smith (1988a, 1988b and 1989) have improved the understanding of regional groundwater movement in mountain terrain characterized by high relief and low hydraulic conductivity of the rock.

Narasimha Reddy and Gurunadha Rao, (1991) carried out model studies in Dulapally basin, a granite terrain in Andhra Pradesh, India with the objective of groundwater resource evaluation and suggestion for construction of additional water harvesting structures for augmenting the water supply.

Amitabha M. *et al*, (1994) have studied the numerical modeling of groundwater resource management options in Kuwait. A regional numerical model calibrated under both steady and unsteady conditions has been used to investigate the hydrodynamic impacts of different groundwater management options on the potentiometric heads of the aquifers. The model is a three-dimensional aquifer system. Reynolds and Spruill (1995) have equally shown that groundwater models can be used to prepare or evaluate impact assessments required for water use in a regulated aquifer system. The model used in this study could be employed to substantiate the amount of water required for mining operations based on hydrogeologic conditions and ore location. The geographic extent and the degree of impacts on the potentiometric surface are estimated using this model. This case study supports the assertion that groundwater models can be used by regulatory agencies to predict the potential impacts on a regulated aquifer.

Lately, researchers such as Jim Yeh *et al*, (1996) have developed a two-dimensional, quasi-transient resistance network analogue in which the time variance of the groundwater flow in a regional sedimentary basin is approximated by a series of steady state simulation.

Bradley, (1996) has conducted model studies of Yuma basin in Arizona covering an area of 900 square kilometres with the objective of assisting local agencies in evaluating remedial water management alternative to mitigate the shallow groundwater level problems. The model contains four layers and simulates groundwater pumpage and percolation from agricultural irrigation. The model predicted that the water management alternative of pumping wells and lining, four miles east of main canal, would have the greatest impact on lowering groundwater levels. In addition, reducing percolation from agricultural irrigation within the Yuma Valley and Yuma Mesh had significant impacts on groundwater levels.

A four-layered groundwater flow model by Amar *et al* (1997) was constructed using Modflow software. Modeling indicated that groundwater recharge was required to prevent soil desaturation, minimize the recontamination of groundwater due to rebounding water levels and to provide continuous flushing of the soils. Model results were used to successfully modify the existing record of decision design.

From the above literature review, one thing has been established namely: The Finite Difference block centred technique is very effective in groundwater flow modeling. These days, the Visual Modflow software version 4.0 has been very useful in prosecuting the groundwater flow modeling studies in many parts of the world.

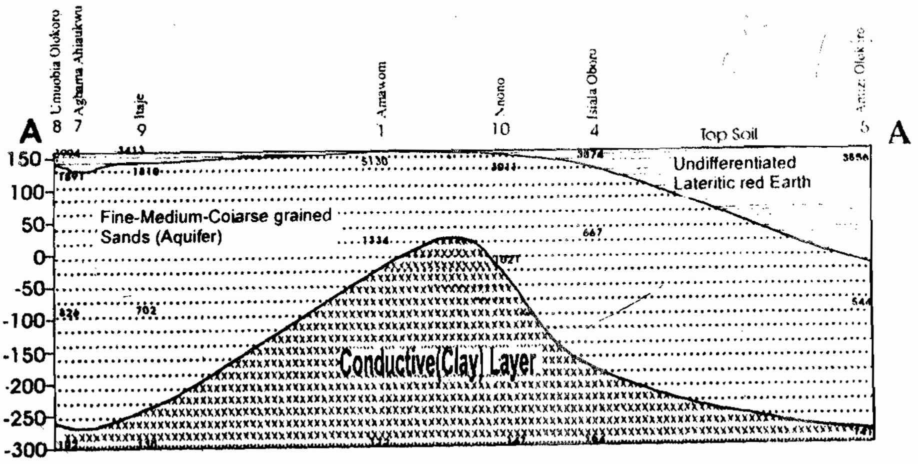


Fig 1b Geoelectrical Section along section AA'
(including depths obtained by Mbanu *et al*, 1991).

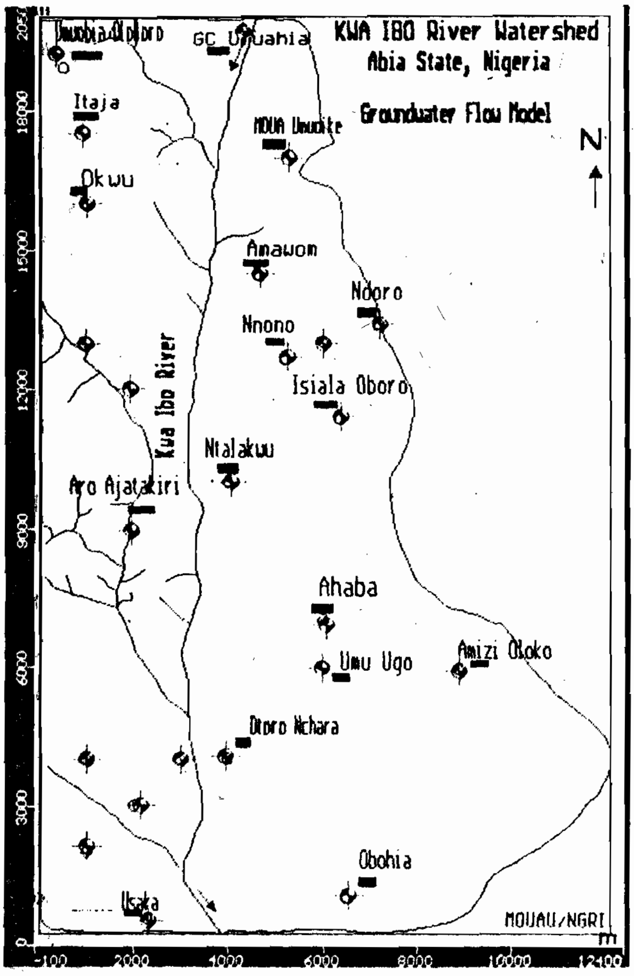


Fig 2: Location of Observation wells

METHODOLOGY AND DATA ACQUISITION

The geophysical investigations carried out in the Kwa Ibo River watershed had provided the insight into the aquifer geometry for development of a groundwater flow model. Igboekwe, (2005) had used the Schlumberger resistivity configuration for eleven VES points (Fig 1a) to show that the watershed is underlain by a thick sandy aquifer (Fig 1b). The geophysical data arising from his findings and the well inventory collected in the present study formed the initial data set for the groundwater flow modeling. Groundwater level monitoring and water sample collection for the modeling process have been carried out at 26 observation wells in the watershed (Fig.2). The water level data were collected during May 1980 (Jalon et al, 1980). All the observation wells were connected to mean sea level through a topographic survey. Static water level contours have been prepared to ascertain the general groundwater hydraulic gradient and stream aquifer interaction in the area, (Fig.3). The hydraulic conductivity has been determined from pumping tests at three locations namely Umuobia Alokoro (8.65 m/d), Ndoro (7.8) and at Umudike (8.0), (Igboekwe 2005). The remaining values in the study area were estimated using a grid map and by use of the formula derived by Uma *et al* (1989) viz:

$$K = A\,(d_{10})^2 \qquad \ldots 4$$

where K = hydraulic conductivity and A = grain-size constant.

It has been accepted that d_{10} is the most important parameter among those governing permeability of a granular medium (Marsily, 1986); Ala Edin et al (2000)). The grain size of the aquifer material ranges between 0.07 to 1.25 mm indicating that the sand size ranges between fine to medium.

The following information was used during conceptualization of the groundwater flow regime: the Kwa Ibo river is an ephemeral stream and is influent throughout its course and is thus simulated by river package; groundwater recharge due to rainfall takes place from the top layer; the continuous groundwater pumping for irrigation and drinking is prevalent in the absence of surface water sources; groundwater abstraction was based on village-wise well inventory.

The water table elevation in the watershed along northern boundary was defined by 97 m (amsl) equi-potential line at Government College in the north and lowest water table elevation by 34 m at Usaka Elegu in the south. The simulated model domain of the watershed consists of 65 rows and 43 columns and 2 layers covering an area of 12190 m x 20000 m (Fig.4). The number of nodes is large enough to include all the existing wells. The top layer mostly consists of 5-120 m top soil/laterite underlain by 68-325m thick sandy zone. The blocks in the grid were chosen as sufficiently small a rectangle as

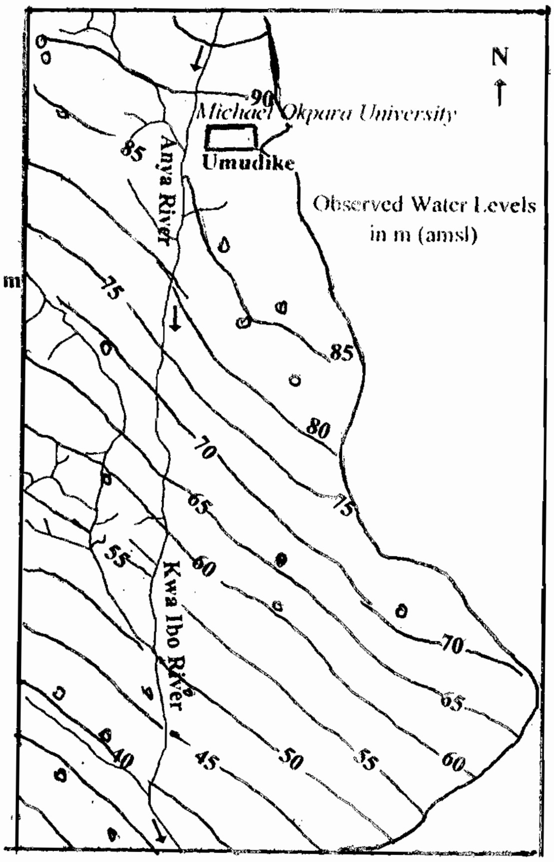


Fig 3: Contour map of observed water levels.

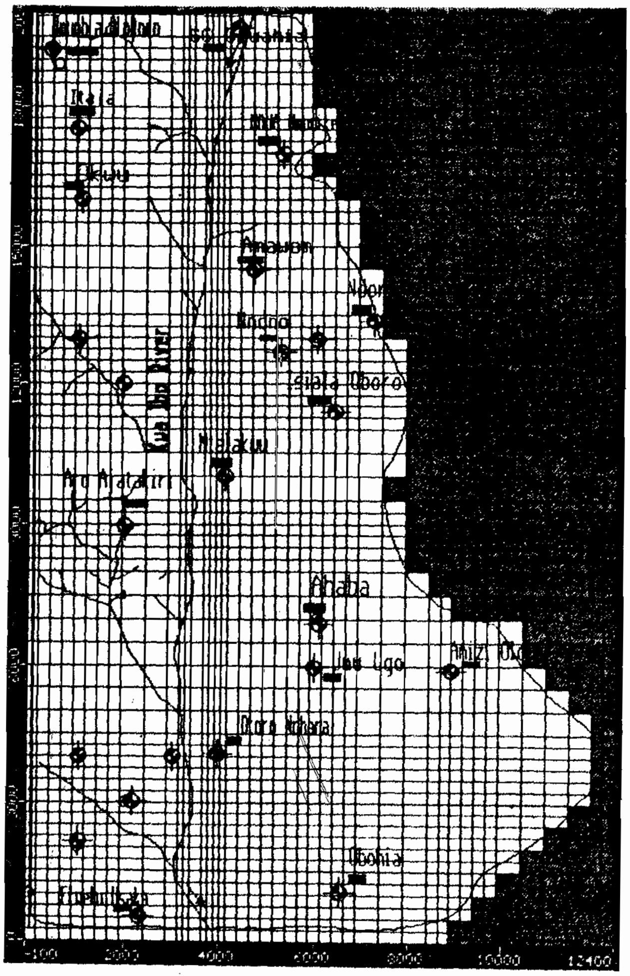


Fig 4: Grid map of the simulated model domain.

possible to ensure good connection between cells represented by various hydraulic characterizations. The aquifer permeability varied from 3.15 m/d to 14.4m/d in the watershed (Fig.5) Higher permeability prevailed along the Kwa Ibo River course.

The groundwater recharge at the rate of 85 mm/year has been simulated in the first layer by deploying the recharge package. Groundwater recharge increased from 85 mm/yr in the southern boundary to 125 mm/yr in the north (Fig.6). Minor variation from recharge area to the discharge areas have been taken care of while assigning recharge. The groundwater draft has been assigned through well package. Groundwater is the only resource available for irrigation and drinking in the area and groundwater-pumping (abstraction) rates are varying from 100 m^3/day to 150 m^3/day.

Steady–State Calibration

The groundwater flow model has been constructed for computation of hydraulic head distribution. The water level in the area indicate that hydraulic gradients do not change significantly with time. Thus groundwater flow was assumed to be in steady state representing the groundwater conditions of May 1980.

The groundwater head in the aquifer model was computed by using visual Modflow (Guiger and Franz, 1996). WHI Solver package of Modflow has been used. The solver checked for the maximum change in the solution at every cell after completion of every iteration. If the maximum change in the solution was below a set convergence tolerance then the solution had converged

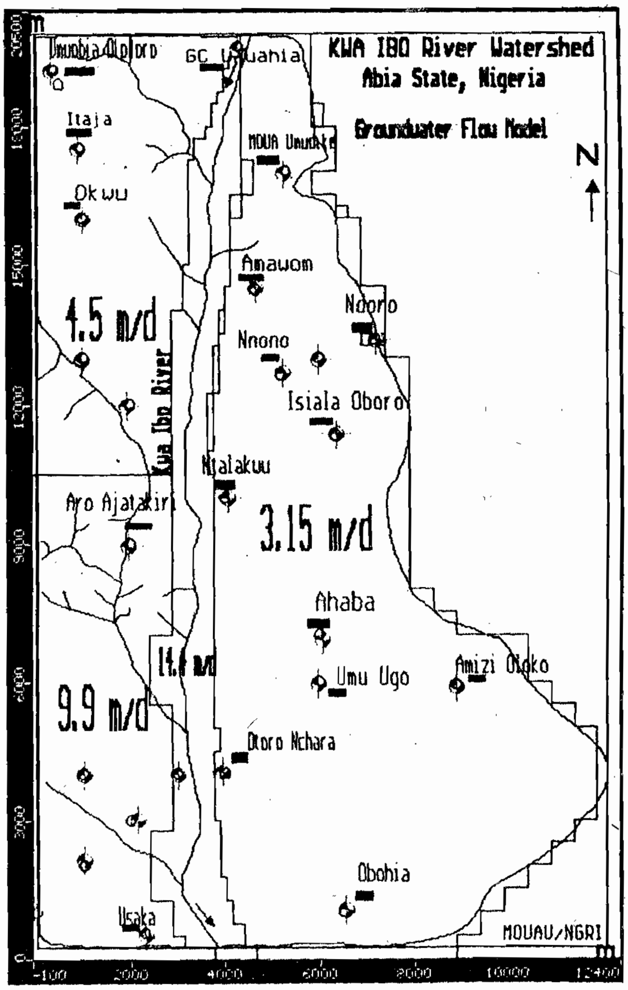


Fig 5: Simulated Permeability Distribution in the Study Area

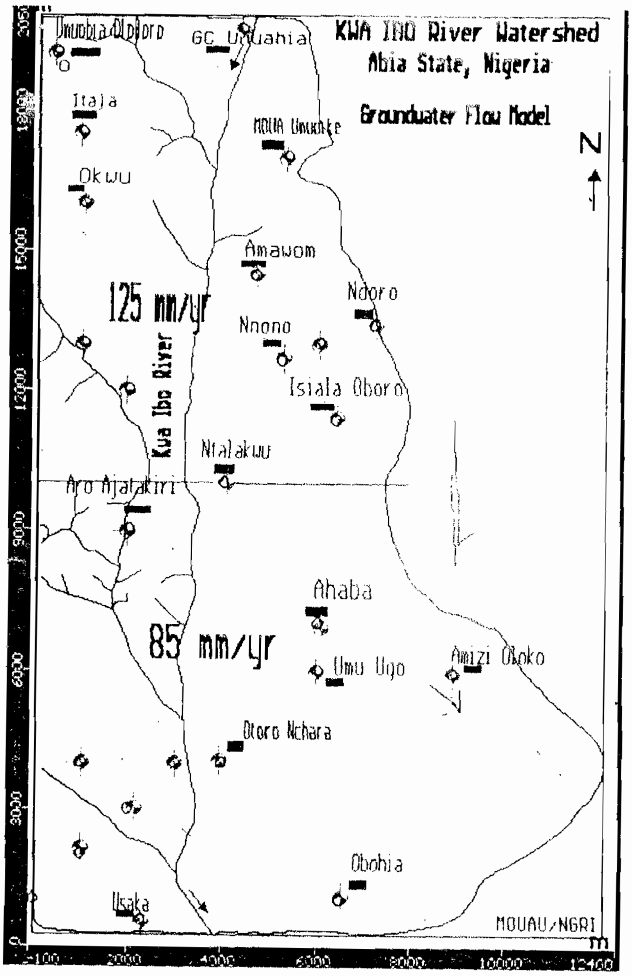


Fig. 6: Simulated Recharge Distribution of the Study Area

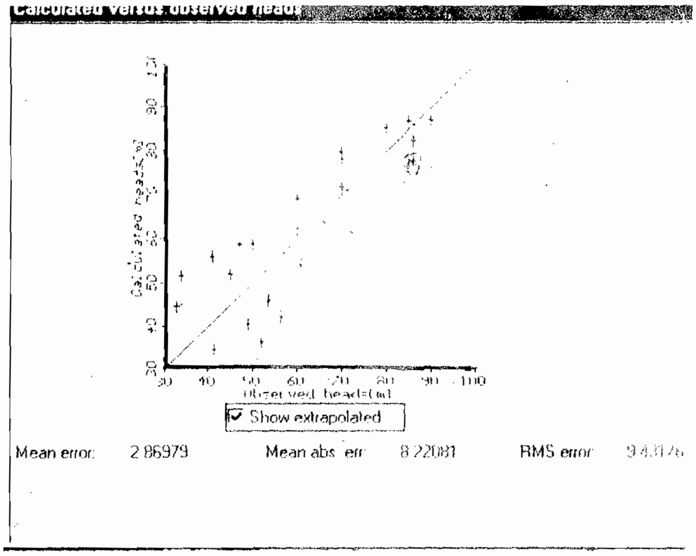
and the solver stopped, otherwise new iteration was started (McDonald and Harbaugh, 1988). The model computations have converged after 123 iterations.

The flow model was calibrated by adjusting several parameters (permeability, recharge and river stage) within a narrow range of values until a best fit was obtained between observed heads (m) and simulated heads (m), Fig.7. The accuracy of the computed water levels was judged by a mean error, mean absolute error and root mean squared error of computed values of points on the graph (Anderson and Woessner, 1992) for ten runs of the model. For steady state simulation, 26 observation wells are included on the calculated versus observed heads graph. The computed water level contours have been compared with the observed water level contours (Fig.8). The computed and observed water level contours replicate the trends and are found matching ±2-3 m at individual wells. Nevertheless, by keeping the hydraulic conductivity close to the estimated value, it was expected that simulated hydraulic heads and resulting velocity field represented the flow system reasonably well. The maximum groundwater velocity in the watershed is along Kwa Ibo River and is 0.44 m/day (~160 m/yr).

Sensitivity Analysis

Sensitivity analysis helps in the understanding of the significance of individual variables in the computation of model simulation output. In this part of the model, permeability and recharge were varied in order to assess their impact on model output. Initially the permeability value was increased by 5% of the preliminary calibrated model. It was later reduced slightly to give the mean error as 1.57547, observed mean absolute error as 9.4819 and rms error as 10.7961. The watershed was then divided into four zones with different permeability per zone. The permeability was doubled at this stage and later reduced by 10% in the tenth run to give e = 2.86979, obs e_{abs} = 8.22081 and e_{rms} = 9.43196. Increasing and decreasing the permeability helped the observed and computed hydraulic heads get aligned along the line of best fit. Further modifications of permeability did not improve the model accuracy.

Similarly, the sensitivity of recharge was also carried out. The initial recharge parameters were taken as 100 mm/yr. Later this value was reduced to 95 mm/yr. For better response to recharge modifications, the watershed was divided into two zones. The northern part of the watershed was assigned 120 mm/yr and the southern part, 80 mm/yr. This resulted in the improvement of the error margins on the 8th run thus e = 1.72513; obs e = 8.30321 and e_{rms} = 9.58159. Again, further modifications of the recharge did not improve the model accuracy. On the whole, the set of input parameters simulated in the model and the hydrogeological set-up evolved through the sensitivity analysis seem to be a best fit under steady-state condition.


Calculated versus observed heads

☑ Show extrapolated

Mean error: 2.86979 Mean abs err 8.22081 RMS error 9.43196

Fig.7 Comparison of Computed and Observed Water Levels

Table 1. Water level fluctuations in relation to rainfall at Umudike

YEAR	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Fluctuation (m)	36.6	25.0	25.0	30.0	30.0	23.2	29.1	27.0	25.0	20.0
Rainfall(mm)	17.89	15.84	14.66	13.70	16.47	13.76	14.47	17.91	19.24	14.67

Transient-State Calibration

After obtaining the steady state results, the dynamic run or transient state model was calibrated for Umudike, a community within the Kwa Ibo River Watershed. A comparison of the hydrographs drawn for the observed heads and rainfall for a ten-year period (between January 1988 and December 1997), are shown on figure 9 and in Table1. It is easily seen that the crests and the troughs for the two graphs synchronize. This means that water table rises and falls as rainfall increases and decreases during the ten-year period. Groundwater fluctuation is therefore a function of rainfall duration and consequently of recharge. The detailed rainfall data for Umudike (not shown), was given courtesy of National Roots Crops Research Institute (NRCRI), Umudike.

RESULTS AND DISCUSSION

The hydrodynamics of groundwater flow condition in the Kwa Ibo river watershed was controlled by three factors: the groundwater recharge during the rainy season, the abstraction (pumping rates) and the groundwater effluence to the Kwa Ibo River. The groundwater balance has been calculated in different zones under steady state condition (Table 2).

Natural recharge to the aquifer system is 44683 m^3/day and groundwater abstraction is 24211 m^3/day. Thus the groundwater balance indicates that net contribution from Kwa Ibo River to the groundwater system is about 5452 m^3/day. Much of the effluence is however taking place during the rainy season and very little takes place during the dry season. Lateral inflow entering the confined 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 effluence from the aquifer system. The magnitude of velocity field vectors is 0.44m/day or 160m/year. In the eastern farms of Michael Okpara University of Agriculture, Umudike, the direction of the velocity field vectors is due southeast. At Obohia and Itaja the direction is due southwest whereas at Aro-Ajatakiri and Usaka Elegu the direction changes to the south.

Under the transient state simulation, it is seen that water level fluctuations synchronize yearly with changes in rainfall within the ten-year period. The fluctuations may be attributed to the distinct lithological control, whereby less fluctuation is associated with predominance of impermeable zones and high fluctuations with predominance of granular zones. It may also be attributed to runoff and recharge. Runoff is high and recharge is less north of study area while southward, runoff is low and recharge, high.

CONCLUSION

The foregoing hydrogeological, and modeling studies have been carried out in the Kwa Ibo river watershed with the sole aim of determining the aquifer–river interaction within the study area. The surface water flow direction is from north to south. The aquifer geometry had earlier been delineated by carrying out geophysical investigations at 11 locations. The subsurface lithology was deciphered from cross-sections drawn from three profiles covering the watershed. The average depth to water level ranged from 72-97 m in recharge areas (uplands) and from ground level to about 34m in valley bottoms in the south. Generally water table has a configuration similar to that of land surface; however, depths to water levels are greater in upland areas (recharge areas) than in valley bottoms (discharge arrears).

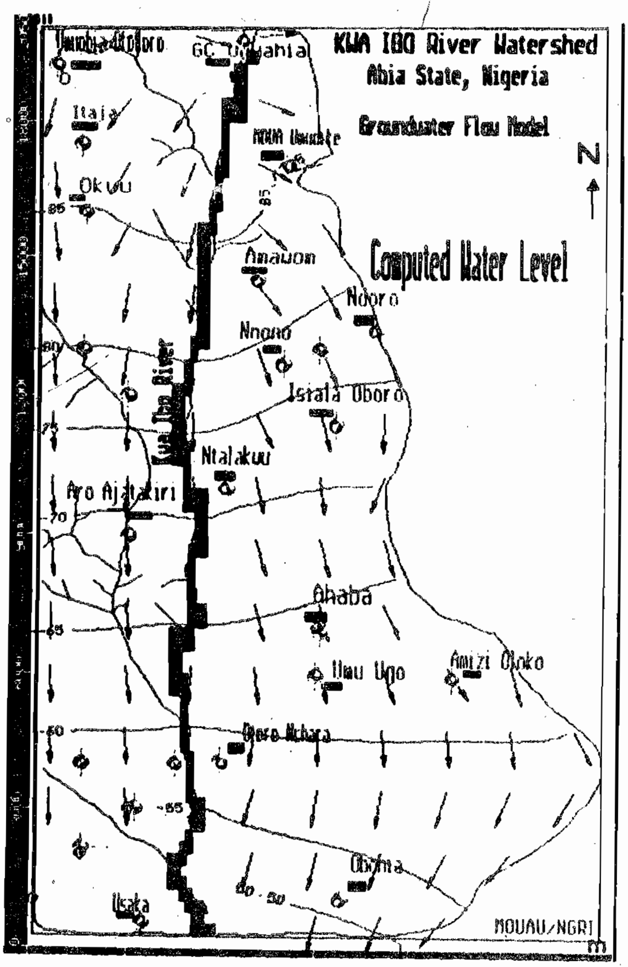


Fig. 8 Computed Water Levels and Direction of Water flow Map

Groundwater model has been prepared based on lithologic information and vertical cross-section interval from resistivity interpretation. River boundary condition has been utilized based on actual river level and streambed elevation at three locations. The hydraulic connection between the river and aquifer was assumed to be 100 m^2/day.

The permeability values have been initially taken from pumping test data. During the flow model calibration the values

Table 2: Groundwater balance in Kwa Ibo River watershed

Input (m^3/day)		Output (m^3/day)	
Recharge	44683	Pumping	24211
River Leakage	10591	Groundwater to River	5139
		Lateral outflow	25924
Total	**55274**		**55274**

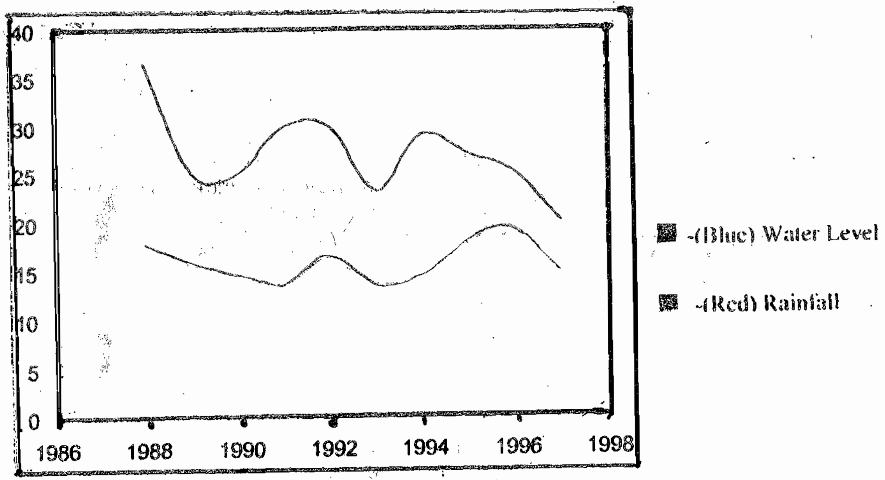


Fig 9 Hydrographs of Rainfall and Water Levels at Umudike

have been slightly modified to achieve a good match between computed and observed water levels. The comparison of computed and observed water levels graph helped in deciding the goodness of fit. It was found that the deviations are less than 2-3 m at almost all the observation wells.

The flow model has been used to compute the groundwater balance of (55274m^3/day) in the watershed using zone budget. The computed hydraulic heads and the effective porosity values have been used for computation of groundwater velocity. The maximum groundwater velocity has been 0.44 m/day or 160m/year along the Kwa Ibo River where higher permeability values exist. The groundwater balance is a preliminary one since the accurate groundwater withdrawal information is not available. However the estimate serves as a first order value for groundwater balance. The groundwater recharge of 85-125 mm/yr 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.

Under the transient state calibration, the hydrographs had maxima in the year 1988, 1995 and 1996 and their minima in the year 1991 and 1993 at Umudike. The highest rainfall (and hence groundwater recharge) over the ten-year study period was recorded in 1996, while the lowest was recorded in 1991.

In general, the net contribution of Kwa Ibo River to the groundwater is high, about 5452m^3/day, indicating less abstraction and continuous recharge. Hence, there is the possibility for more pumping wells in the area.

ACKNOWLEDGEMENTS

The authors wish to thank TWAS-CSIR for providing the research fellowship that made it possible for the research to be undertaken in India. Our thanks also go to the Vice-Chancellor, Michael Okpara University of Agriculture Umudike, Nigeria, Prof. O.C.Onwudike, for approving that the fellowship be taken. We also appreciate the opportunity offered by the Director, National Geophysical Research Institute (NGRI) India, Dr. V.P.Dimri, for granting access to the computer facilities. The assistance of Dr. A. Selemo, Messrs A. Kanu, N. Agbo, and Miss B. Ezebuiro are deeply appreciated.

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