

A PRACTICAL APPLICATION OF COMPUTATIONAL MODELLING TO PREDICT OPTIMAL PUMPING CONDITIONS FOR FUTURE GROUNDWATER EXPLOITATION: CASE STUDIES

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ABSTRACT

This paper presents the results of case studies using the Modular Three-Dimensional Finite Difference Ground Water Flow Model (MODFLOW), compiled using the Lahey Fortran 95, to model and predict optimal groundwater pumping conditions in three aquifer domains.

Aquifer parameters used for the models were determined from existing hydrogeological data. Each aquifer system was discretized into an appropriate finite difference grid. Results of the steady-state simulation were used as initial conditions for the transient-state model, which was made up of 22 annual stress periods, with each stress period having 5 time steps of daily units.

Hydraulic heads for steady state conditions were within 0.3 to 20.0m, 0.94 to 25.42m, and 5.58 to 15.54m of measured water levels for 1979-83, for the Ameki, Nanka and Alluvium model domains respectively. Transient-heads were within 2.77 to 6.00m, 4.90 to 26.21m and 0.22 to 5.59m of measured water levels for Year-1999, for the Ameki, Nanka and Alluvium domains. The Root Mean Square Errors (RMSE) for steady state calibration for the Ameki, Nanka and Alluvium domains were 7.79m, 15.53m and 11.04m, respectively, and the Mean Errors (ME) were 1.85m, 3.62m and -4.91m, respectively. For transient verification, the RMSE's were 4.09m, 12.86m and 3.35m for the Ameki, Nanka and Alluvium domains, respectively, while the ME's were -2.49m, -7.07m and -0.20m, respectively.

The accuracy of the ground water models is limited by the availability of data and the interpolations and extrapolations of available data. The model could be used as a prevision tool to optimize groundwater extraction within the domains.

INTRODUCTION

Groundwater reservoirs accept water; filter it to remove sediments and disease-causing organisms; store it in quantities vastly exceeding those which are, or conceivably could be stored in all natural (and artificial) surface water bodies put together, and eventually transport it from areas of replenishment to areas of needs. The efficiency of these processes is however a function of the aquifer parameters.

In order to achieve maximum development of groundwater for beneficial

use, it requires thinking in terms of an entire groundwater basin. By visualizing a basin as a large natural underground reservoir, it is clear that utilization of groundwater by one landowner affects the water supply of all other landowners. To maintain the resource indefinitely, a hydrologic equilibrium must exist between all water entering and leaving the basin.

As groundwater development intensifies, well owners become more interested in the response of aquifers to heavy pumping, whereas initially they were concerned with the delineation and

exploration of aquifers. Competition for available resources has therefore brought about the theory of modeling, numerical simulation and optimization of aquifer-potentials and their response to development, as inevitable tools for effective groundwater exploration and exploitation. Thus, quantitative techniques have been introduced into groundwater hydrology to aid the accurate prediction of the effect of various hydrologic stresses on aquifer systems.

This paper presents several case studies illustrating how the numerical model, United States Geological Survey (USGS) Modular Three-Dimensional Finite

Difference Ground-Water Flow Model (MODFLOW) code developed by McDonald and Harbaugh (2004), and associated universal modified packages were assembled to simulate flow in the Anambra Basin. In addition to approximating the actual groundwater flow system, the model was used to determine gaps and potential anomalies in data and in understanding the aquifer system.

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:

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

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 ($L T^{-1}$);

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).

In general, S_s , K_{xx} , K_{yy} and K_{zz} are functions of space ($S_s = S_s(x,y,z)$, $K_{xx} = K_{xx}(x,y,z)$,

$K_{yy} = K_{yy}(x,y,z)$ and $K_{zz} = K_{zz}(x,y,z)$) and W is a function of space and time ($W = W(x,y,z,t)$).

MODELLING PROCESS AND ASSUMPTIONS

A conceptual model for the study area and the aquifer domains was carefully developed. The conceptual model was composed of a set of assumptions that reduced the real problem and the real

domains to simplified versions of reality. The assumptions involved such items as: the geometry of the boundaries of the investigated aquifer domain; the kind of material comprising the aquifer (with reference to its homogeneity and isotropy); the mode of flow in the aquifer (three dimensional, or two dimensional); the relevant state variables and the area, or volume, over which the averages of such variables were taken; sources and sinks of water within the domain and on its boundaries (with reference to their approximation as point sinks and sources, or distributed ones) and the conditions on the boundaries of the considered domain that expressed the way the latter interacted with its surrounding.

The boundaries of the aquifers, in each case, were 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. All the model cells formed by the grid for the Ameki, Nanka and Alluvium study areas have dimensions of 26,000m by 26,000m along the x and y axes

respectively.

Under the assumption that the density of ground water is constant, the continuity equation expressing the balance of flow for a cell is:

$$\sum Q_i = SS \Delta h - \Delta V \quad \dots\dots\dots 2$$

where:

Q_i is flow rate into the cell (L^3T^{-1});

SS has been introduced as the notation for specific storage in the finite-difference formulation. Its definition is equivalent to that of S_s in equation (1), which is the volume of water which can be injected per unit volume of aquifer material per unit change in head (L^{-1});

V is the volume of the cell (L^3); and h is the change in head over a time interval of length t .

MODEL GRID

The boundaries to the case study areas were extracted from the map of Anambra State, Nigeria, on a scale of 1:2,000,000, as compiled by the Federal Surveys, Lagos. The areal extent of the map covers a land distance of 779,000m on the X-axis and 971,000m on the Y-axis. Figure 1 depicts the boundaries of the study areas and problem domains. The correlated lithological logs across the domains are presented in Figure 2. Spot heights derived from topographical maps on a scale of 1:50,000, were extrapolated to generate the topographical map for the entire study area (Anambra State) on a base map (Figure 3). A FORTRAN program source-code was developed for the preparation of input data for the Visual MODFLOW and SURFER contour plotting softwares. The topographical map was superimposed on the Anambra State Grid, as presented by Figure 3. The origin of the study area is at the upper left corner of the grid at a coordinate of 6°35'E and 6°45'N.

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 (McDonald and Harbaugh, 2004)], MODPATH/MODPATH PLOT (Pollock, 1994), GWM (Ahlfeld et al, 2005), SURFER (Smith et al, 1996) and VISUAL MODFLOW (Guiger and Franz, 2003).

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 entire 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.

HYDROGEOLOGIC PROPERTIES

Aquifer properties, such as hydraulic conductivity, transmissivity, specific yield, and storage coefficient, control the rate at which water moves through the aquifer, the volume of water in storage, and the rate and areal extent of water-level declines caused by ground-water development.

The aquifer system properties across the study area were

initially estimated from well logs, specific capacity tests and the published literature (Table 1). Final estimates of these properties were made using a trial-and-error approach during steady state and transient state model simulations. The aquifer property values could vary considerably spatially because of the heterogeneity of the aquifer system material.

Ground-water pumpage is the main discharge from the basin. Ground-water pumpage in the study area began during the colonial era, in the fifties. There was however, no record of daily, monthly or yearly groundwater pumpage for the entire study area. The distribution of pumpage for the simulation exercise was therefore estimated as a percentage of water based on well-capacity data from pumping tests.

CASE STUDY 1

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.

The origin of the grid (that is, the upper left corner of the grid; row 1, column 1) is at a coordinate of 6°35'E and 6°17'N.

The Ameki domain is idealized as a water table aquifer with lowest elevation of 50m below sea level. 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.

Model Calibration

The steady state calibration involved matching the simulated hydraulic heads to

measured water levels from wells in the Ameki aquifer domain between 1979-83. The measured water levels for ten wells, ranging from 8.64m to 102.00m Above Mean Sea Level (AMSL), were assumed representative of the hydraulic heads of the domain prior to groundwater development. The assumption is consistent with the works of previous modelers on various model domains as outlined among others by Bear and Verrujt (1992), Bouwer et.al (1999) and Bexfield and McAda (2003). The works of Busari and Agbede (1992), Asiwaju-Bello and Oladeji (2001) and Olowofela and Akinyemi (2001), were also based upon available historical and reliable sequence of data. The simulated hydraulic heads for steady state conditions generally were within 0.33 to 20.00m of the measured water levels for 1979-83, of ten observation wells.

The Root Mean Square Error (RMSE) for steady state calibration was 7.99m. The Mean Error (ME) was 1.85m, which indicated a model bias toward under-estimating head values. The accuracy of the calibration is within ranges obtained from previous similar exercise elsewhere, as outlined by Agbede (1989), Bouwer et al (1999) and Bexfield and McAda (2003), with RMSE ranging from 6.25 to 28.95.

Model Prediction

Upon achieving a satisfactory steady-state calibration, transient groundwater conditions were modeled for the 22-year period between 1979 and 1999. The transient-state model consisted of 22 annual stress periods. Each stress period had 5 time steps. The time units were days.

For the transient-state calibration, the quantity and distribution of pumpage, storage coefficient, hydraulic conductivity and the boundary conditions were assumed to be the same as those calibrated for the steady-state simulation. Estimates of ground-water pumpage from the Ameki aquifer formation were not modified for the

model simulations because it was assumed that the estimates were fairly accurate.

The calibration procedure for transient conditions consisted of adjusting the natural recharge during 1979-1999. Calibration was achieved when the adjustments resulted in simulated hydraulic heads that approximated measured water levels in five observation wells. After calibration, the simulated heads were within about 2.77 to 6.00m of measured water levels for the entire domain. For the transient verification, the RMSE was 4.09m, and the ME was 2.49m.

In general, the differences between simulated and measured values were perhaps due to an inaccurate distribution of pumpage to the individual wells, an inaccurate estimation of the quantity and distribution of natural recharge, and/or inaccuracies in the reported water-level measurements. The positions of observation wells are plotted on the map. The transient state calibration contour for the water levels (1979-99) is depicted in Figure 4. The positions of observation wells are plotted on the map. Results of the model simulations showed that in the steady-state simulation, the total recharge, was about 261,259,280m³. All the recharge during steady state conditions resulted from infiltration of precipitation runoff. The simulated water budget for the end of the transient-state simulation (1999) showed that, for 1999, about 317,224,756,864m³ of water recharged the aquifer system and about 317,225,313,864m³ discharged from the system. The 557,000m³ of outflow in excess of inflow in 1999 resulted in a decrease in storage to the system. The lowering water levels in the domain are indicative of this negative change in storage.

CASE STUDY 2

The second case-study aquifer domain is the Nanka Formation. Offodile (1992) and Nwajide (1980)

equivalent of the Ameki Formation. Njumbe and Onuoha (2002) reported that the Agulu, Nanka and Oko areas are underlain by the Nanka Sands. Emenike (2001) described Nanka Formation as being thinly overlain by the lignite-clay seams of the Oligocene Ogwashi-Abasa Formation and underlain by the Imo Formation. The problem domain of Nanka Formation covers Nanka, Idemili, Oko, Agulu, Aguata and Nkpologwu areas of Anambra State. Ezeigbo (1987) described the Nanka Sands as a prolific aquifer of high yield, while Offodile (1992) concluded that in the Nanka Sands, around Nanka, Idemili and Oko, the water table is generally low, ranging from 30 to 300m. It was observed that the development of the Nanka Sands aquifer could be achieved by means of deep boreholes. The Nanka domain is idealized as a water table aquifer with lowest elevation of 50m below sea level. The Nanka aquifer problem domain was discretized into a finite difference grid of 25 rows and 15 columns, with the origin at the upper left corner.

Model Calibration

The steady state calibration involved matching the simulated hydraulic heads to measured water levels from wells in the Nanka aquifer domain between 1979-83. The measured water levels for nine wells, ranging from 31.00m to 235.30m AMSL, were assumed representative of the hydraulic heads of the domain prior to groundwater development. The simulated hydraulic heads for steady state conditions generally were within 0.94 to 25.42m of the measured water levels for 1979-83, of nine observation wells.

The RMSE for steady state calibration was 15.53m. The ME was 3.62m, which indicated a model bias toward under-estimating head values.

Model Prediction

Transient groundwater conditions

between 1979 and 1999. The transient-state model consisted of 22 annual stress periods. Each stress period had 5 time steps. The time units were days. For the transient-state calibration, the quantity and distribution of pumpage, storage coefficient, hydraulic conductivity and the boundary conditions were assumed to be the same as those calibrated for the steady-state simulation.

Estimates of ground-water pumpage from the Nanka aquifer formation were not modified for the model simulations because it was assumed that the estimates were fairly accurate.

The calibration procedure for transient conditions consisted of adjusting the natural recharge during 1979-1999. Calibration was achieved when the adjustments resulted in simulated hydraulic heads that approximated measured water levels in five observation wells. After calibration, the simulated heads were within about 4.90 to 26.21m of measured water levels for the entire domain. For the transient verification, the RMSE was 12.86m, and the ME was 7.07m.

The simulated water budget for the end of the transient-state simulation (1999) showed that, for 1999, about 316,468,560,000m³ of water recharged the aquifer system and about 316,468,560,200m³ discharged from the system. The transient state calibration contour for the water levels (1979-99) is depicted in Figure 5. The positions of observation wells are plotted on the map. The simulated water budget for the end of the transient-state simulation (1999) showed that, for 1999, about 316,468,560,000m³ of water recharged the aquifer system and about 316,468,560,200m³ discharged from the system.

CASE STUDY 3

The third case study aquifer domain is represented by the Alluvium

of the study area, adjacent to the Niger River. Borehole log records show that the area is fairly permeable and is readily recharged by the adjacent Rivers Niger and Anambra. Ezeigbo (1987) described the Alluvium as consisting of friable sands that are pebbly in some places. Intercallations of clay and sandy clay also occur. It was concluded that the formation is of quite significant groundwater promise in the North-Western part of Anambra State. The Alluvium domain is idealized as a water table aquifer with an average bottom elevation of 90m below sea level. The alluvium aquifer problem domain was discretized into a finite difference grid of 22 rows and 10 columns, with the origin at the upper left corner.

Model Calibration

The steady state calibration involved matching the simulated hydraulic heads to measured water levels from wells in the Alluvium aquifer domain between 1979-83. The measured water levels for five wells, ranging from 10.00m to 105.00m AMSL, were assumed representative of the hydraulic heads of the domain prior to groundwater development. The simulated hydraulic heads for steady state conditions generally were within 5.58 to 15.54m of the measured water levels for 1979-83, of five observation wells.

The Root Mean Square Error (RMSE) for steady state calibration was 11.04m. The Mean Error (ME) was -4.91m, which indicated a model bias toward over-estimating head values.

Model Prediction

Upon achieving a satisfactory steady-state calibration, transient groundwater conditions were modeled for the 22-year period between 1979 and 1999. The transient-state model consisted of 22 annual stress periods. Each stress period had 5 time steps. The time units were days.

For the transient-state calibration,

the quantity and distribution of pumpage, storage coefficient, hydraulic conductivity and the boundary conditions were assumed to be the same as those calibrated for the steady-state simulation. The calibration procedure for transient conditions consisted of adjusting the natural recharge during 1979-1999. Calibration was achieved when the adjustments resulted in simulated hydraulic heads that approximated measured water levels in five observation wells. After calibration, the simulated heads were within about 0.22 to 5.59m of measured water levels for the entire domain. For the transient verification, the RMSE was 3.35m, and the ME was 0.20m. The transient state calibration contour for the water levels (1979-99) is depicted in Figure 6. The positions of observation wells are plotted on the map.

Results of the model simulations showed that in the steady-state simulation, the total recharge, was about 138,899,472m³. All the recharge during steady state conditions resulted from infiltration of precipitation runoff. The simulated water budget for the end of the transient-state simulation (1999) showed that, for 1999, about 4,310,566,654m³ of water recharged the aquifer system and about 4,310,579,200m³ discharged from the system.

CONCLUSIONS

It is observed that for the three case study scenarios, hydraulic heads for steady-state conditions were sensitive to the amount of water that recharged to, and discharged from, the ground-water system and the transmissivity of the aquifer system. Changes in hydraulic heads during the transient state simulation were sensitive to natural recharge and discharge, the storage coefficient of the model layers, the hydraulic conductivity of model layers and the boundary conditions.

In order to decrease the number of assumptions in the model, parameters

should be measured whenever and wherever possible. This will only be possible by obtaining reliable data. An improved understanding of the properties of the aquifer will be useful in the possible future development domains as veritable water sources.

The present models could be effectively used for various groundwater management scenarios within the Ameki, Nanka and alluvium aquifer domains.

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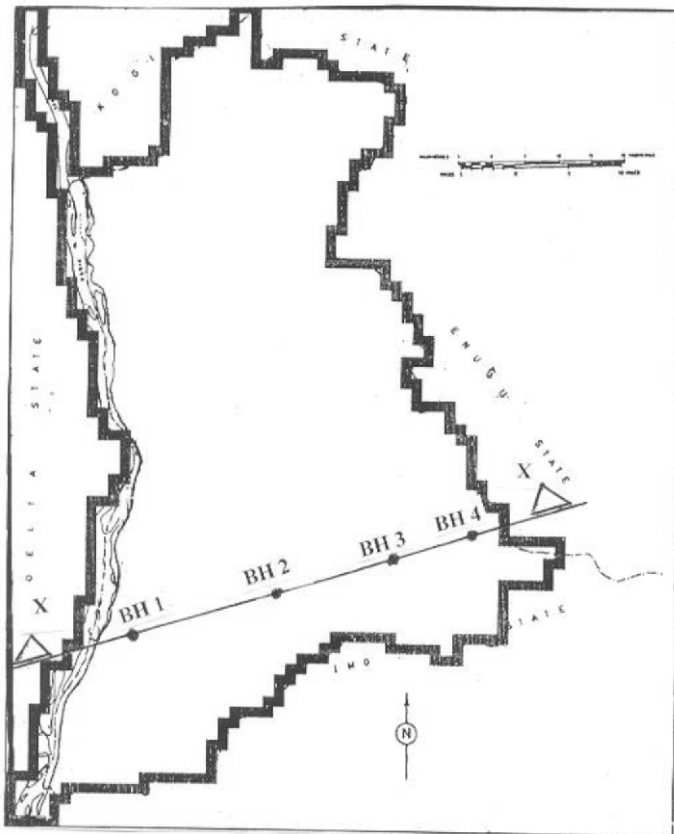


Figure 1: Boundaries of Study Area

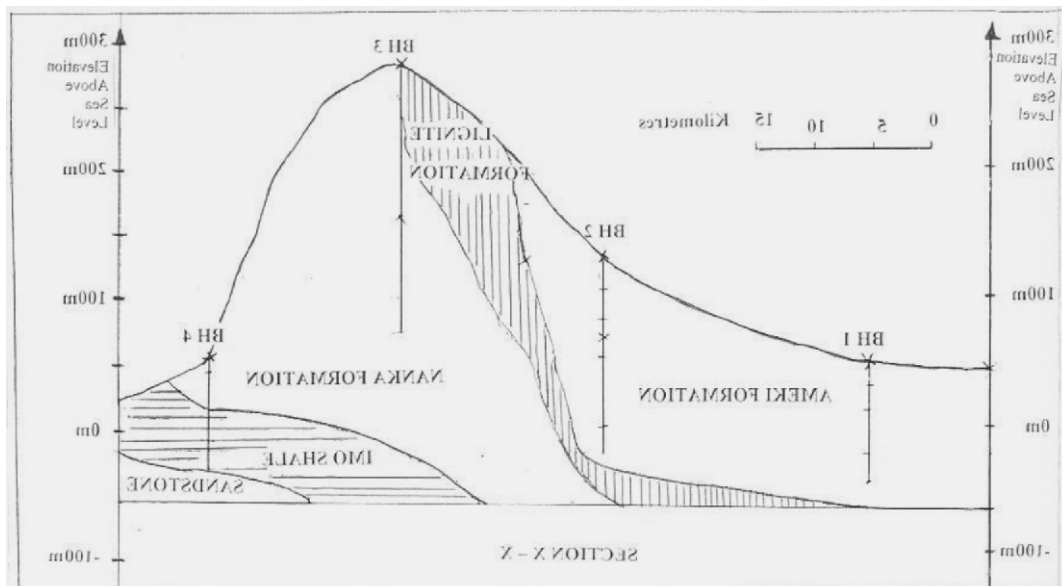


Figure 2: Cross-Section X X through the Study Area

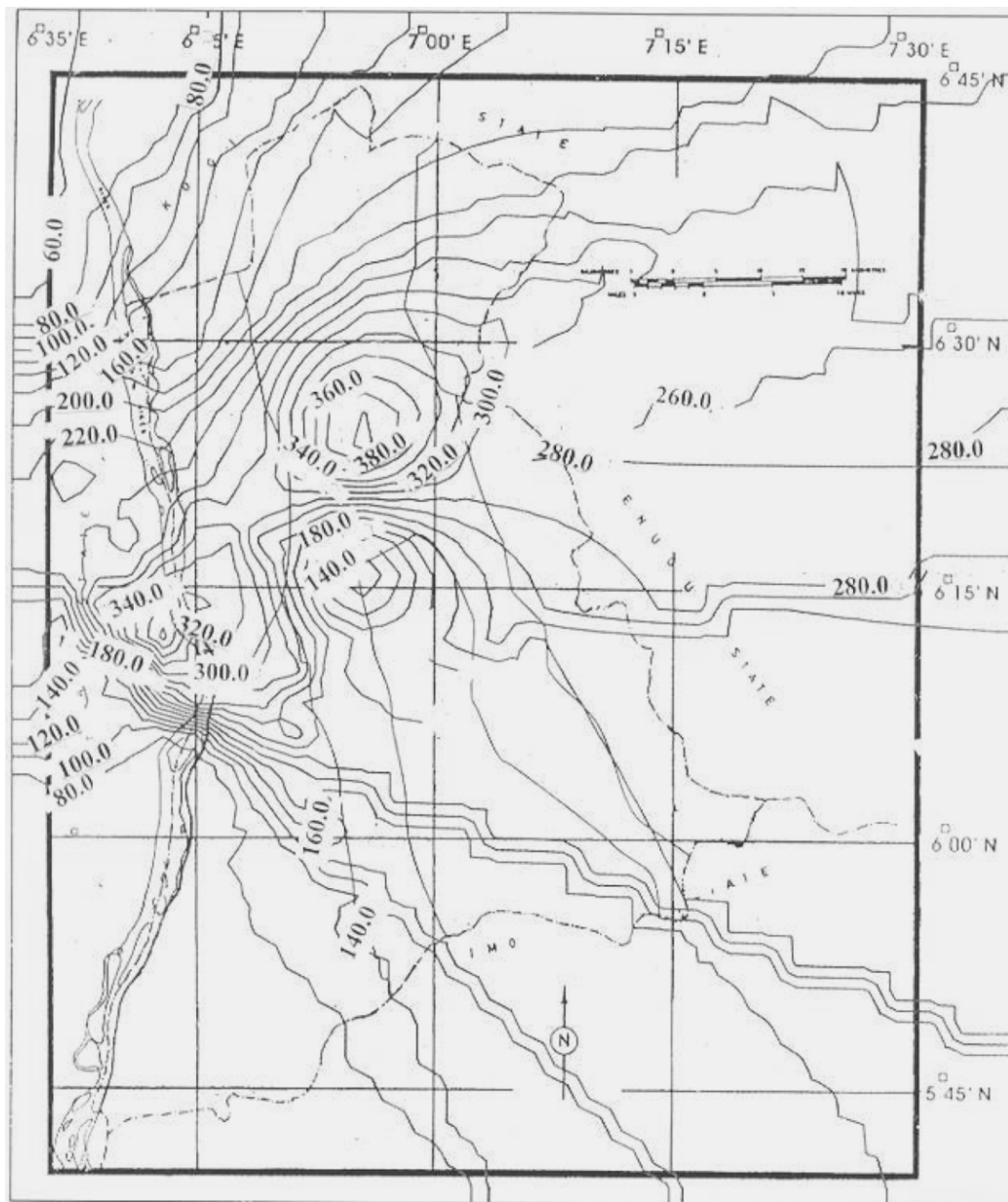


Fig. 3: Topographical Map of Anambra State on Base Map

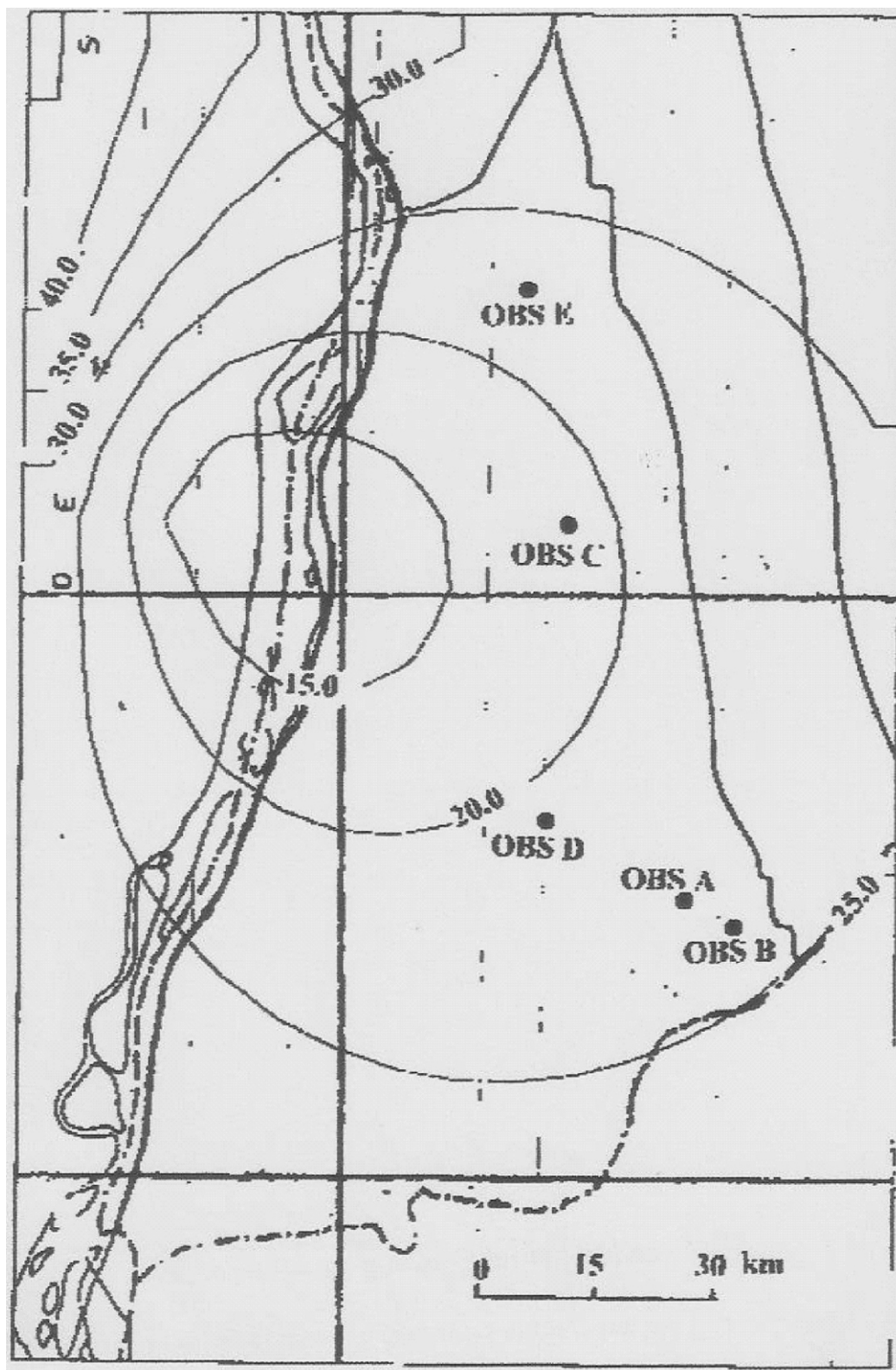


Figure 4: Transient State Calibration Contour for the Water Levels (1979-99) for the Ameki Aquifer Domain.

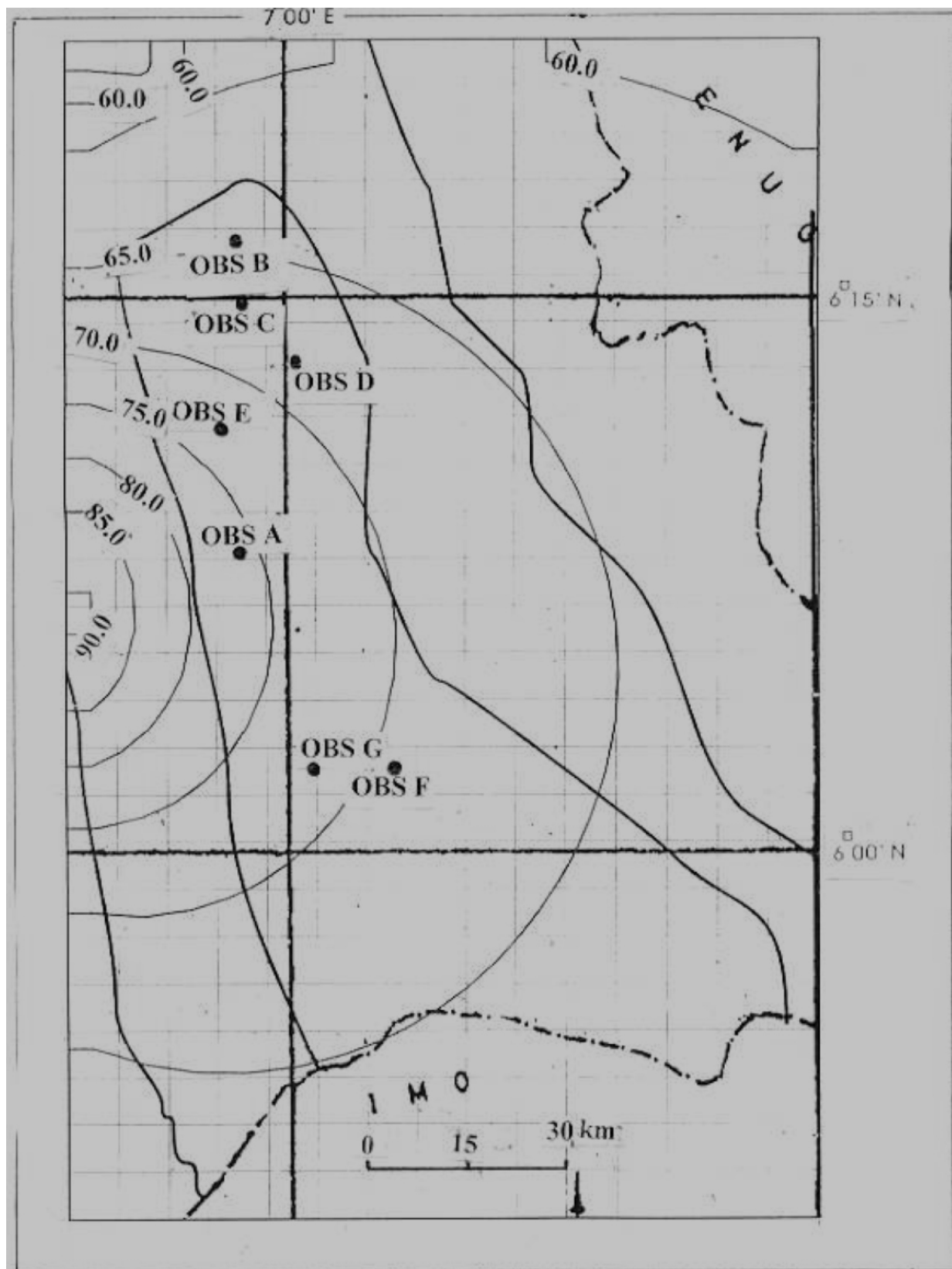


Figure 5: Transient State Calibration Contour for the Water Levels (1979-99) for the Nanka Aquifer Domain

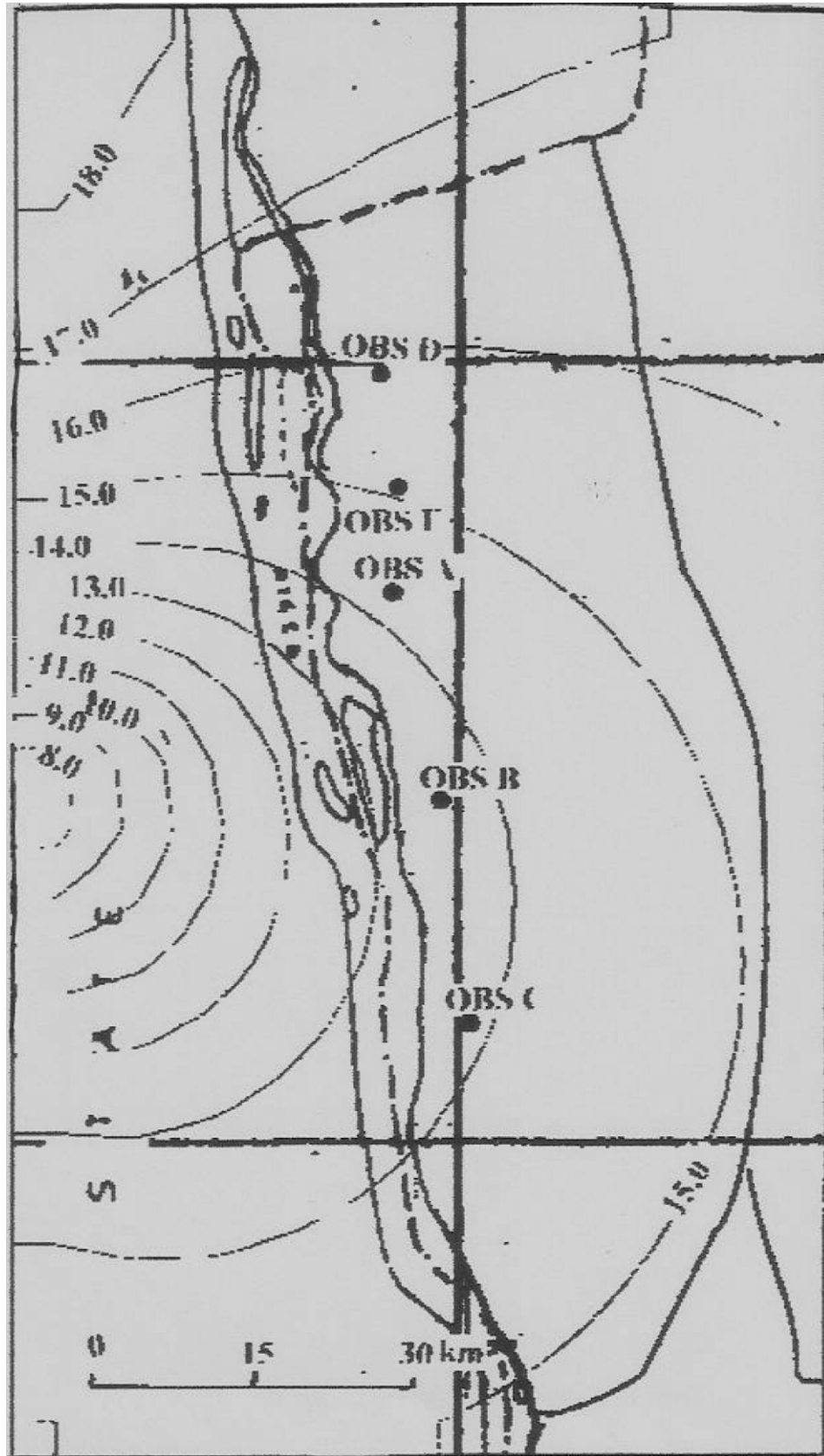


Figure 6: Transient State Calibration Contour for the Water Levels (1979-99) for the Alluvium Aquifer Domain

Borehole Zone	Average Drawdown (m)	Average Yield (m)	Average Static Water Level (m)	Average Transmissivity (m ² /day)	Average Specific Capacity (m ³ /day/m)	Average Storage Coefficient (x 10 ⁻²)
<i>Ameki</i>	12.90	23.89	51.36	12.71	69.43	0.01
<i>Nanka</i>	10.78	13.14	38.07	38.16	208.55	0.12
<i>Nanka</i>	10.41	13.20	72.94	4.39	24.00	0.05
<i>Nanka</i>	15.26	7.63	76.13	10.54	57.60	0.10
<i>Alluvium</i>	13.43	16.07	41.76	13.96	76.32	0.06
<i>Alluvium</i>	10.60	19.44	8.20	29.00	158.49	0.11

Table 1: Aquifer System Properties Across the Study Area