

GROUNDWATER MODELLING WITH LIMITED DATA: A CASE STUDY OF YOBE RIVER BASIN, NORTH EAST NIGERIA

Hassan, M.¹, R.C. Carter² and K.R. Rushton²

Abstract

An exploratory numerical groundwater model of a shallow aquifer interacting with a river in a semi-arid zone was developed using MODFLOW. The model simulated field data adequately as well as the physical processes presented in its conceptual framework. The conceptualization of the aquifer to exist under both confined and unconfined conditions can be adequately described in the model. Water balance from the model shows that river to aquifer flow dominates aquifer recharge processes, and its magnitude is limited not only by relative head difference, but also by the transmissivity and hydraulic gradient of the aquifer.

1. Introduction

Groundwater models are tools that are aimed at predicting the consequences of a proposed action. They are also used in an interpretive sense to gain insight into the controlling parameters in a site-specific setting or as a framework for assembling and organising field data and formulating ideas about system dynamics. The techniques of groundwater modelling are well documented in Wang and Anderson (1982), Anderson and Woessner (1992) and Spitz and Moreno (1996).

The modelling of groundwater is primarily of value when adequate extensive data exist. In such situations, conventional calibration and validation approaches may be possible. But detailed measurements throughout a site are both impractical and expensive. In such cases, the model is constrained to represent the site to those that are acceptably realistic. The inherent scarcity of data is particularly relevant in developing countries where there is limited information about soil and aquifer properties, and where monitoring and record keeping may be poor. Therefore, models which display economy of complexity, but which are based on sound conceptual frameworks are needed. The models must reflect those features of the groundwater system, which really matter. They must also be credible and reliable.

1.1 Study area and background

The area under study is located in the semi-arid zone of north-east Nigeria (Figure 1), which is characterised by low rainfall and reduced river flow. In the last three decades, rainfall has decreased by about 30% (Hess *et al.*, 1995) and annual discharge by the major headwaters of rivers Hadejia and Jama'are has decreased by almost 60%. The reduction in the discharge from these rivers to the Yobe Basin is due to construction of dams across them in addition to low rainfall. As a result of these changes in the hydrology of the area, both the Federal and State governments in the North East Arid Zone (NEAZ) have made tremendous efforts towards developing and managing the existing water resources. Reports of various professional water consultants, such as Schultz (1975), IWACO (1985), Water Surveys

¹ Department of Physics, University of Maiduguri, Maiduguri, Nigeria

² Institute of Water and Environment, Cranfield University, Silsoe, Bedford, MK45 4DT UK.

(1986), Diyam (1987) and NEAZDP (1990) with various terms of reference were engaged for two decades (1975-1995) with the mandate to develop the groundwater in the river basin.

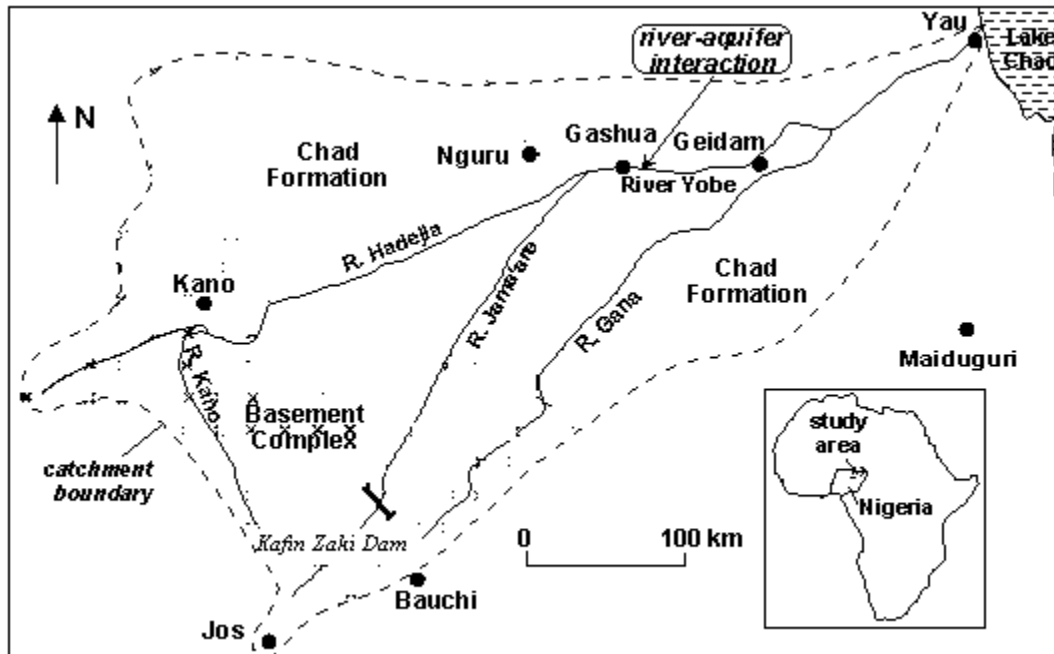


Figure 1: Map of the study area

These previous works have identified four natural features that limit opportunities for the development of water resources in the area. They include aridity, highly seasonal climate, climates that have shown major changes or trends in recent decades and poor aquifer (Carter, 1998). These studies did not address the state of the groundwater in the area or state possible management strategies based on water availability. Studies by Alkali (1995) as well as Carter and Alkali (1996) suggested that the shallow aquifer in the Yobe Basin has complex hydrogeologic features. For example, it was discovered that the aquifer is covered extensively with low permeability clay that hinders vertical infiltration of water. According to them, the dominant factor in the recharge of the aquifer is the river and that the aquifer is capable of converting from unconfined to confined conditions. Another desk study that consists of photo-interpretation of the geomorphological features of the Yobe floodplain by Marinof-Petkoff (1994) and hydrogeological and geophysical studies by Hassan (2002) have shown that some areas of the Yobe River Basin are covered by permeable deposits.

In all the studies carried out in the area, there was difficulty in assessing the aquifer potential based on the existing field data. There was complete lack of historical data in some cases. For example, data on groundwater level fluctuation, recharge estimates, aquifer parameters and lithology are not readily available. In the cases where some data, such as river stage variation and discharge exist, there were problems of missing records. Carrying out “conventional” modelling in such cases is difficult.

Some or all of the problems discussed above need to be addressed in the context of existing data. This limitation of data has constrained the development of a 'full-scale' model where calibration, verification, validation and prediction are possible. In view of this, an exploratory groundwater model was developed using MODFLOW to assess the aquifer potential based on the existing data.

2. Methodology and model preparation

MODFLOW is a computer program, which was developed by the United States Geological Survey, Reston, Virginia, for modelling groundwater flow. It uses a block-centred finite difference approach to solve the three-dimensional equations for groundwater flow in porous media. A detailed description of MODFLOW can be found in McDonald and Harbaugh (1987).

The idealized conceptual model was used to design and simulate various scenarios using the MODFLOW model. A combined pre- and post-processor, model independent graphical interface called *Groundwater Vistas* was used for data input and for interactive modelling with MODFLOW.

2.1 Description of the conceptual model

The River Yobe system as conceptualised in Hassan (2002) is shown in Figure 2. It consists of the following:

- The aquifer geometry and the boundary show that the aquifer is 10 m thick and 4 km wide with the river almost in the middle. It has clay cover in some places whose thickness varies from 0.5 to 3 m. A no flow boundary condition in the north and a constant head in the south that allows small seepage to the upland bound it.
- The landforms show that the Yobe floodplain consists of areas that could allow vertical recharge. The flow processes in the aquifer are vertical recharge from rainfall, overland flooding and river to aquifer flow.
- Aquifer parameters such as storage coefficient and hydraulic conductivity cover a range of values.
- The river-aquifer interaction is represented with a varying river coefficient; the magnitude of flow between the river and the aquifer depends on relative head difference between water in the river and groundwater in the aquifer

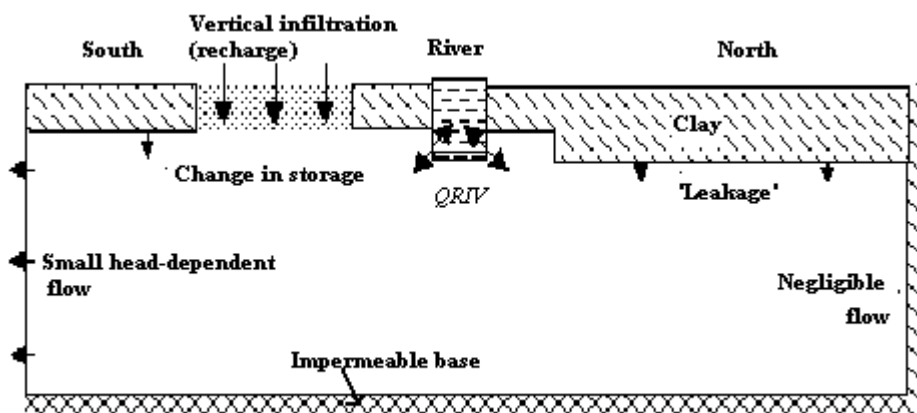


Figure 2: Conceptual model of the Yobe river system

The modelled area was discretized three-dimensionally. The size of the grid blocks were 500 m in the x-direction and variable in the y-direction with the smallest being 35 m and the largest 150 m. Each grid consists of 3 columns and 50 rows with row25 containing the river. In the vertical direction, the model consists of a 16 m thick layer. Figure 3 shows the finite difference grid of the study area.

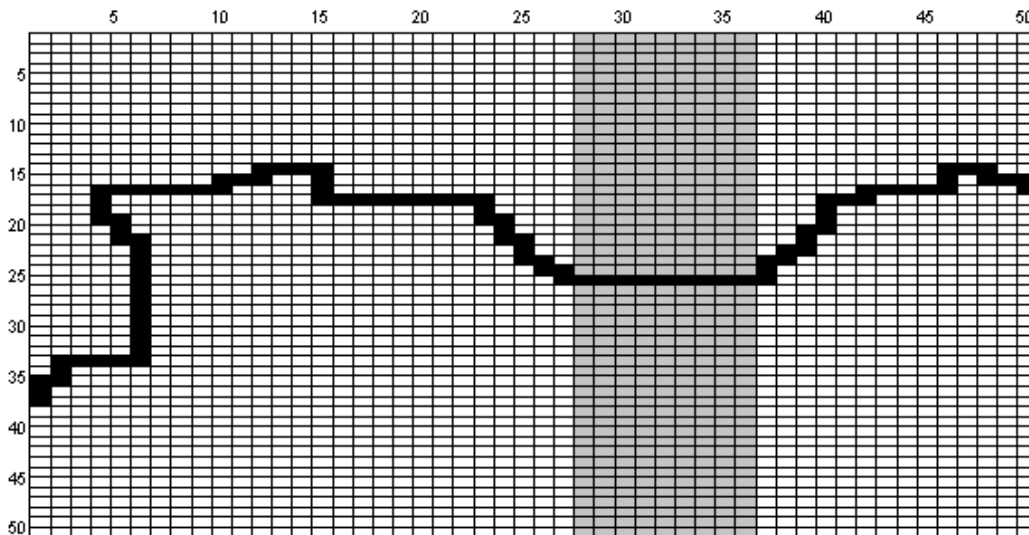


Figure 3: Finite difference grid of area of study showing River Yobe and the area of interest (shaded)

2.2 Data requirements

Input data to the model consists of the three major external stresses: river stage time series with a varying river coefficient, vertical recharge and 'leakage'. The methods and procedures for obtaining these data include both geophysical and hydrogeological investigations as discussed in Hassan and Carter (2004). Figures 4, 5 and 6 show the starting conditions and time series of the input data respectively. The input for one year consists of 36 stress periods each with a length of 10 days and a single time step. This was repeated for 2.4 years (86 stress periods) with stress period one starting from 30th October. The choice of the number and length of stress periods and time steps was dictated by the rapid change in the river stage.

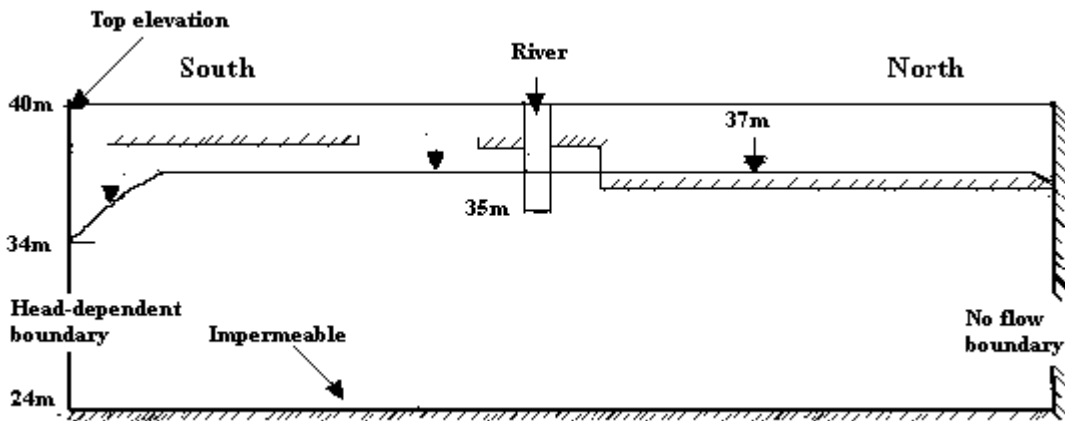


Figure 4: Starting conditions

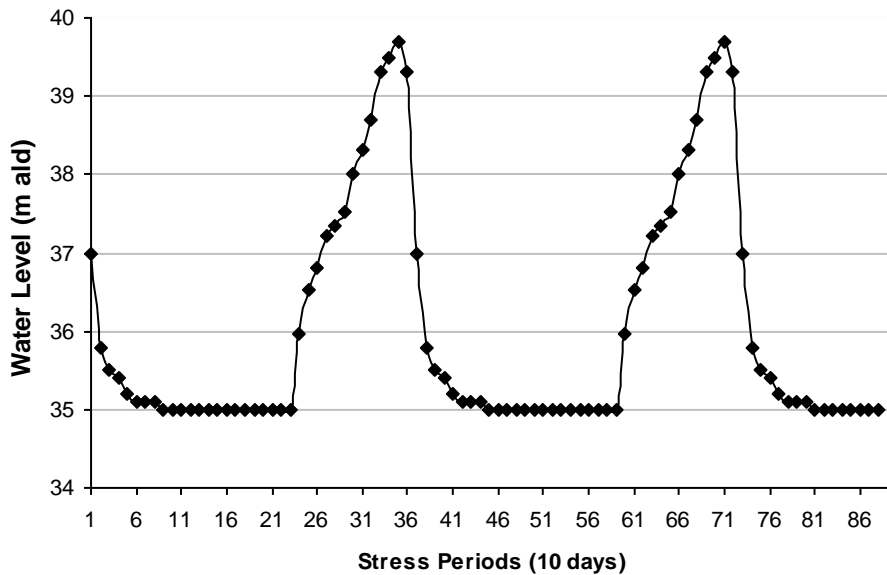


Figure 5: River stage variations with time

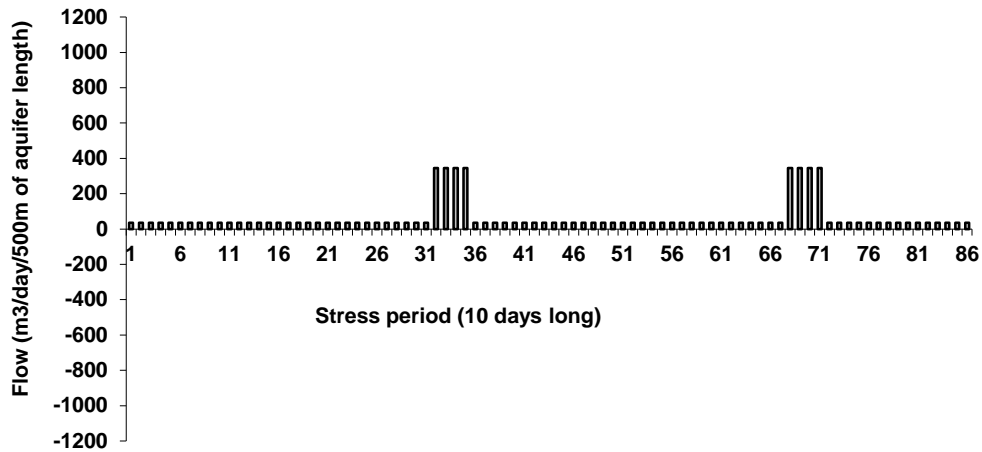


Figure 6: Recharge and ‘leakage’ input

Sensitivity analysis was carried out on the wide range of aquifer parameters to arrive at acceptable values. These parameters and their values are as follows:

- i) $K_h = 0.1$ m/day (unconfined); and $K_h = 15$ m/day (confined region)
- ii) $SC_c = 0.001$ (confined); and $SC_u = 0.05$ (unconfined)
- iii) $VL = 1.5 \times 10^{-5}$ m/day (the clay cover was modelled as a ‘leakage’ factor that allows water to seep continuously into the aquifer).

Where, K_h is hydraulic conductivity, SC_c and SC_u are storage coefficients for the confined and unconfined conditions respectively and VL is vertical leakage.

A recharge value of 1.25 mm/day was estimated using a water balance model (Hess, 1997). This is equivalent to 50 mm of recharge per annum. This amount is consistent with independent estimates by Carter et al. (1994) and Edmonds *et al.* (2002). The recharge was applied to rows 29 to 33 and in stress periods 32 to 35 inclusive. Figure 7 shows an extract of the finite difference grid area of interest and the recharging zone. These stress periods correspond to 10th –19th September to 10th –19th October respectively when recharge is believed to occur.

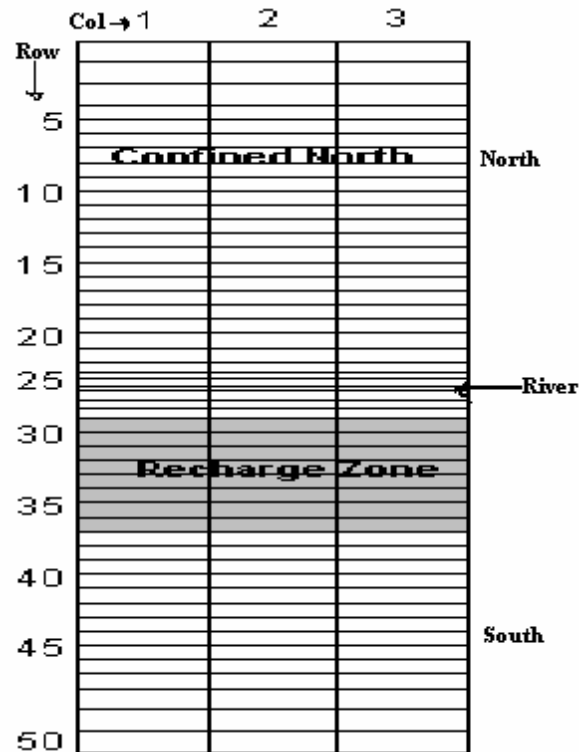


Figure 7: Finite difference grid of area of interest showing recharge area

The outputs from the model consisting of groundwater heads for each of the 86 stress periods were used for calculation of the various flow processes. The river to aquifer flow is calculated using Equation 1.

$$Q_{riv} = C_{riv} \times HDIFF \quad (1)$$

where C_{riv} is the river coefficient and $HDIFF$ is the relative head difference between water level in the river and the groundwater head in the aquifer.

3. Results and discussion

3.1 The groundwater hydrographs

The modelled groundwater hydrograph for node (27, 2) compared with a field observed groundwater head variation from piezometer P7 is shown in Figure 8 for an area located near and to the south of the river. This area was conceptualized to be largely unconfined. The figure suggests a strong influence of the river on the groundwater compared with heads far away from the river node. The plot also suggests a good measure of representation of the groundwater level fluctuation taking place in the vicinity of the river. A side-by-side comparison of the modelled groundwater heads far from the river with piezometers located at similar distances is indicated in Figure 9, but in the largely confined north, the modelled groundwater hydrographs show little variation near or far from the river.

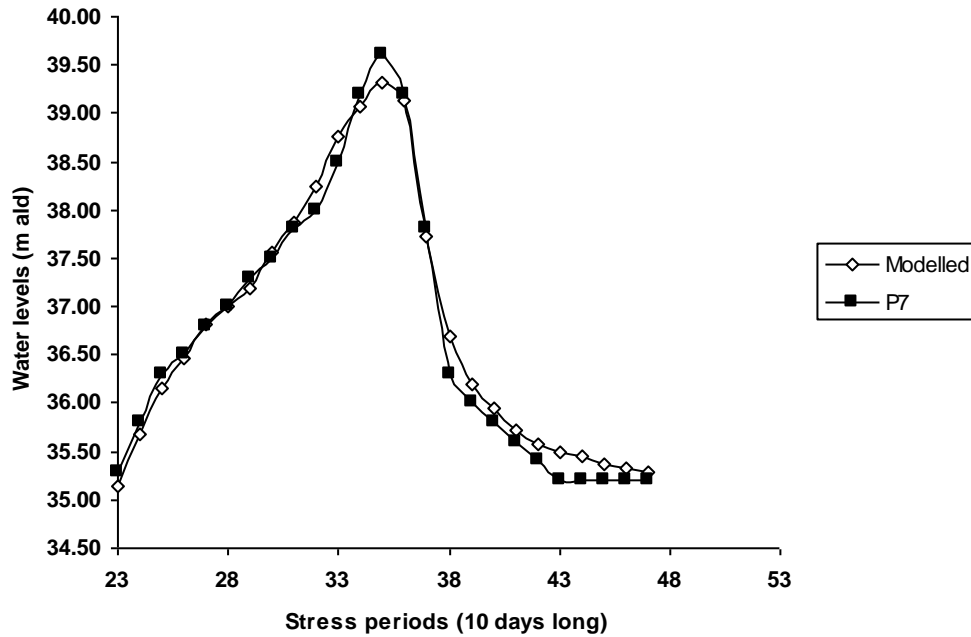


Figure 8: Observed and modelled groundwater heads for node (27, 2)
mald = meters above local datum

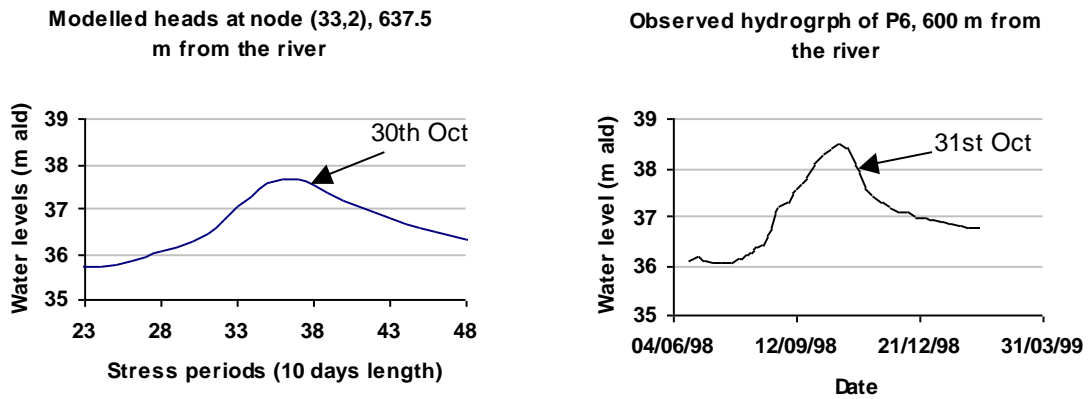


Figure 9: Groundwater heads at 600 m south of the river; (a) modelled, (b) observed
mald = meters above local datum

3.1 Groundwater flow in the aquifer

The various groundwater flows in the aquifer were calculated from the groundwater heads using Darcy's law and the Richard's continuity equation. Figure 10 shows the flow from the

aquifer (node 25, 2) beneath the river to adjacent nodes north and south of the river. The results show that the flow to the confined north is much smaller than the flow to the unconfined south. Similar results are shown in Figure 11 where nodes (17, 2) and (32, 2) are located 637.5m away from the river in both directions. The figure suggests that the model has the ability to exhibit the rapidity and inertia of the confined and unconfined conditions obtained in the north and south of the basin respectively.

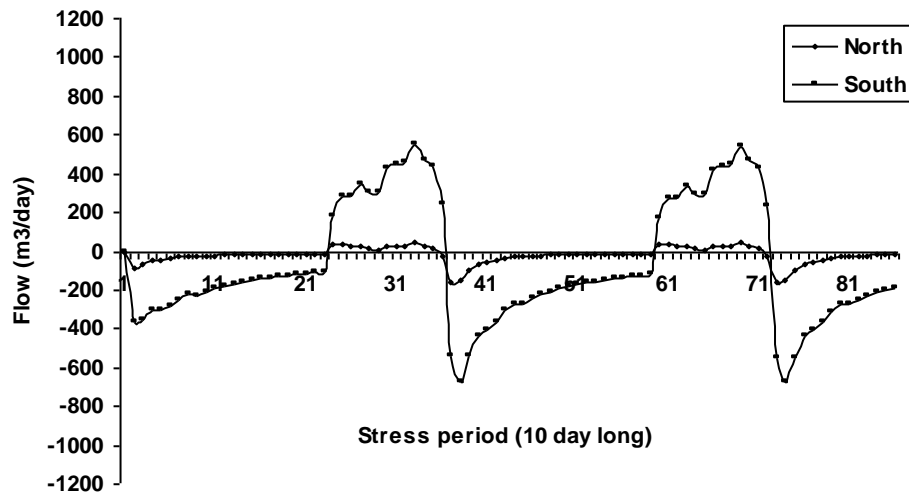


Figure 10: Groundwater flow from the aquifer to the north and south of the river node (25, 2)

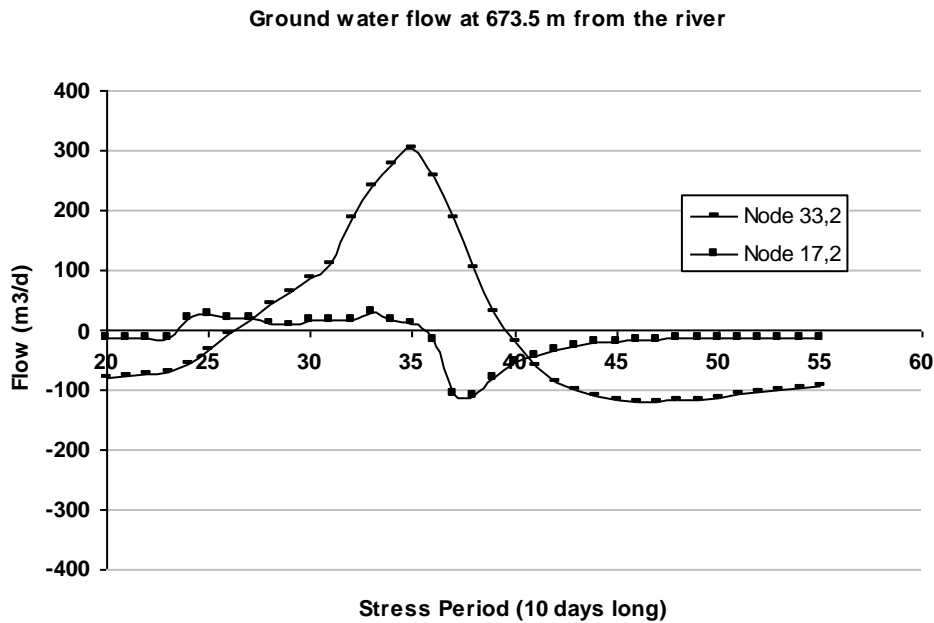


Figure 11: Groundwater flow from the aquifer to nodes (17, 2) and (32, 2), 637.5 m away from the river

3.3 River-aquifer flow

The modelled groundwater heads at the river node together with the input river stage and river coefficient were used to calculate the river to aquifer flows. Figure 12 shows the flow with positive values indicating flow from river to aquifer. The result indicates that the river is adequately represented because the aquifer responded to changes in the river level. It also shows that during recharge, the flow to the aquifer decreases even at high river level. This suggests that Q_{riv} is limited both by the ability of the aquifer to transmit water and the magnitude of HDIFF.

3.4 The water balance

The water balance consists of the difference between the total water flowing into the aquifer and the total water coming out of it. This is in turn equal to the change in storage. The inflow consists of recharge (the 'leakage' through low permeable surfaces) and the river to aquifer flow. The outflow consists of the flow from the aquifer to river during low river stage and the boundary outflow. Figure 13 shows the time series plot of the water balance for one year. It indicates that the river to aquifer flow dominates all inflows (about 70%) to the model area.

4. Conclusion

The basic and exploratory single layer model has demonstrated the ability to simulate adequately the observed field data. It also reflected the physical processes presented in its conceptualization. Despite uncertainties in the estimates of some parameters such as river coefficients and aquifer parameters, the similarity between the model results and observed

data is encouraging. The model was able to demonstrate that in confined areas, less water enters the aquifer and there is immediate response to changes in the application of stress when compared to the unconfined areas. The results from the model are plausible and represent to some extent the understanding incorporated in its conception.

References

- Alkali, A.G. (1995). *River-Aquifer Interaction in the middle Yobe River Basin, Northeast Nigeria*. Unpublished PhD thesis. Silsoe College.
- Anderson, M.P. and W.W. Woessner (1992). *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*. Academic Press, Inc., San Diego, CA. 381pp.
- Carter, R.C., E.D. Morgulis, J. Dottridge and J.U. Agbo (1994). Groundwater modelling with limited data: a case study in a semi-arid dunefield of northeast Nigeria. *Quarterly Journal of Engineering Geology*, 27: S85-S94.
- Carter, R.C. (1998). Prospects for Sustainable Water Management Policy in Sub-Saharan Africa, with Special Reference to the Northeast Arid Zone of Nigeria. In *Water Resources Management, A Comparative Perspective*. Ed. Dharendra K. Vajpeyi.
- Carter, R.C. and A.G. Alkali (1996). Shallow Groundwater in the Northeast Arid Zone of Nigeria. *Quarterly Journal of Engineering Geology*. 29: 341-355.
- Diyam Consultants. (1987). *Kano State Shallow Aquifer Study*. Final reports Vol. 1. Kano, Nigeria.
- Edmunds, W.M., E. Fellman, I.B. Goni and C. Prudhomme. (2002). Spatial and temporal distribution of groundwater recharge in northern Nigeria. *Hydrogeology Journal* 10: 205-215.
- Hassan, M. (2002). *Exploratory groundwater modelling in data-scarce environments: The shallow alluvial aquifer of River Yobe Basin, North East Nigeria*. Unpublished PhD Thesis Cranfield University UK.
- Hassan, M. and R.C. Carter (2004). Development of Conceptual Model: Towards Developing a Numerical Groundwater Model of a River-aquifer Interaction. *Nigerian Journal of Physics*. 16(1) 117-125
- Hess, T.M. (1997). *BALANCE - A soil water balance model manual*. Unpublished, Cranfield University, UK.
- Hess, T.M., W. Stephens and U.M. Maryah. (1995). Rainfall Trends in the North East Arid Zone of Nigeria, 1961-1990. *Agricultural and Forest Meteorology*, 74: 87-97.
- IWACO (1985). *Study of the Water Resources in the Komadougou Yobe Basin*. Report No. 5. Groundwater Resources. International water supply consultants. Rotterdam, Netherlands.
- Marinof-Petkoff, M.N. (1994). *A Geomorphological study of the Yobe River Floodplain: Implication for Groundwater Recharge*. Unpublished MSc. Thesis. Cranfield University.
- McDonald, M.G. and A.W. Harbaugh, (1987). *A modular three-dimensional finite-difference groundwater flow model. Techniques of water resources investigations*. 06-A1, US Geological Survey, Reston, Virginia, 576p.
- NEAZDP (1990). Groundwater Resources Report. PMU, Northeast Arid Zone Irrigation Project. Garin Alkali, Gashua. Yobe State, N.E. Nigeria.
- Rushton, K.R. and L.M. Tomlinson (1979). Possible mechanisms for leakage between aquifers and rivers. *Journal of Hydrology*. 40: 49-65.

- Shultz International Limited. (1975). *Hadejia River Basin Study*. Water Resources Vol. E. Vancouver, Canada.
- Spitz, K. and J. Moreno (1996). *A practical Guide to Groundwater and Solute Transport Modeling*. John Wiley and Sons, INC. New York.
- Wang, H.F. and M.P. Anderson (1982). *Introduction to Groundwater Modelling: Finite Difference and Finite Element Methods*. Academic Press. San Diago
- Water Surveys Group (1986). *Investigation of the Shallow Aquifers for Lowland Irrigation in Bauchi State. N.E. Nigeria*. Main Report, Vol. 1. Kaduna Nigeria.