

Full Length Research Paper

Groundwater flow modelling in the upper Anga'a river watershed, Yaounde, Cameroon

A. Fouépé Takounjou^{1*}, V. V. S. Gurunadha Rao², J. Ndam Ngoupayou³, L. Sigha Nkamdjou¹
and G. E. Ekodeck³

¹Institute for Geological and Mining Research-Hydrological Research Centre, P. O. Box 4110, Yaounde, Cameroon

²National Geophysical Research Institute, Hyderabad- 500 606, India

³Department of Earth Sciences, University of Yaounde I, P. O. Box 812, Yaounde, Cameroon

Accepted 8 September, 2009

The Anga'a River watershed is located within the Yaounde IV district, South-east of Yaounde City, Cameroon. The groundwater flow and particle tracking modelling was carried out to determine in detail the groundwater flow and particle migration in the shallow unconfined aquifer of the Upper Anga'a river watershed. The watershed was modelled with a grid of 106 columns x 68 rows with two layers viz., unconfined and semi-confined aquifers extending up to 50 m depth. The Anga'a river traverses in the central part of the watershed and generally flows North-South. Lateral inflows and outflows were simulated with constant head. The Anga'a river heads and the Lake levels were simulated using a river package. Natural recharge due to rainfall formed the main input to the aquifer system and the output was made of abstraction from pumping wells, base flow to Anga'a River, lake, springs and Evapotranspiration. A steady state groundwater flow simulation was carried out using Visual MODFLOW software and calibrated for the February, 2008 groundwater levels at 18 observation wells. The model computation has converged after 170 iterations with a convergence criterion of 0.01 m. The computed groundwater level contours have been following the trend of observed ones. The computed groundwater balance indicated that the Anga'a river base flows come from the groundwater regime. Groundwater Flow model results indicated that the topography controls groundwater flow in the watershed and that base flow to river is an important factor moderating groundwater movement in the Anga'a river watershed.

Keys words: Groundwater, modelling, modflow, modpath, latrine, unconfined aquifer.

INTRODUCTION

The pipe-water supply is presently catering the needs of only 35% of cities and towns in Cameroon. In Yaounde, the capital city of the country, less than 50% of households have direct access to pipe drinking water. This rate falls to 30% in suburban areas (Tanawa et al., 2002). Less than 20% of households have access to the drinking water network in urban centres with less than 100,000 inhabitants and since the supply is erratic, most people at some points use springs and wells (Leseau, 1998; Nola et al., 1998).

A forgotten fringe of the population of African cities mainly made up of those living in suburban areas and

small urban centres mostly rely on groundwater from springs and wells to meet the domestic needs. For instance, in the Yaounde IV district (with 250,000 inhabitants), 330 water supply points have been found in 2002 (Tanawa et al., 2002). These traditional water points cover about 80% of water supply through 95 springs and 167 dug wells. The availability of groundwater is therefore crucial to ensure that the population has enough water in quantity and quality. Bemmo et al. (1999) showed that 55% of water consumed in poor neighbourhoods of the city of Yaounde comes from groundwater. Djeuda et al. (1999) argued that water captured from wells and springs is young, under saturated, periodically replenished and belong to a hydrochemical-opened system in contact with the atmosphere and this is why it is very vulnerable to pollution. Dumoutier (2003) rightly showed that 87% of water supply

*Corresponding Author, E-mail: afouepe@yahoo.fr. Tel: (+237) 96240468, (+237) 79224908.

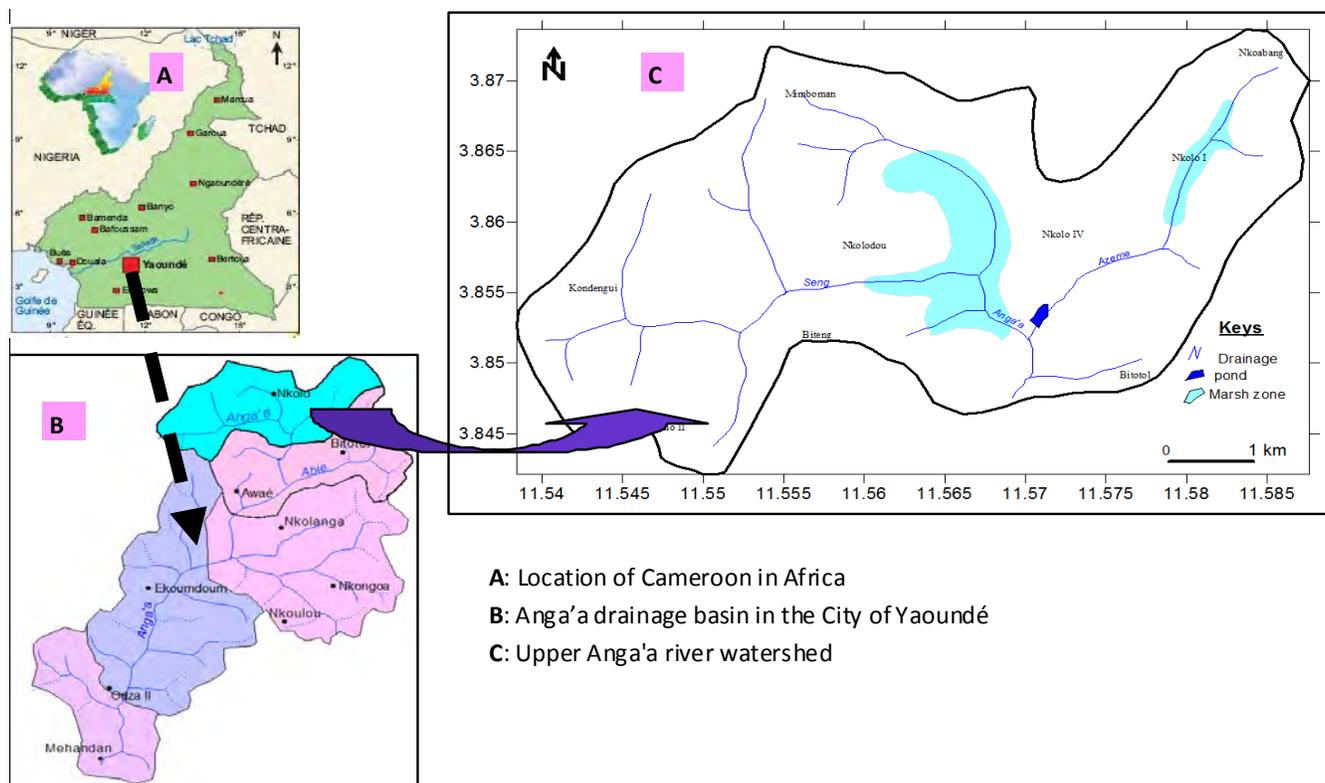


Figure 1. Location of the Upper Anga'a river watershed near Yaoundé City, Cameroon.

points in the city of Yaounde have an elevated risk of faecal contamination due to latrines situated upstream of water supply wells and springs. Another crucial issue is that within the urban environment, there are numerous potential sources of pollution due to various human activities, mainly the construction and use of pits and latrines (Zaporozec, 2004). At least one latrine is found on each plot while one out of three plots has a well. Statistics show that in all Cameroon cities, 86% of household use latrines and this figure increases to 94% when the entire country is considered. In the Anga'a river watershed in particular, these statistics depict the following configuration in terms of density: population 4545 inh/km²; groundwater supply points: 6 wells/km²; latrines 22 lat/km² (Tanawa et al., 2002). These figures clearly show the potential danger of groundwater pollution by latrines.

This paper is part of a study aimed to ascertain groundwater flow and mass transport modelling in the Anga'a river watershed. The overall objective of the present work is to determine in detail the groundwater movement and assess the interaction between the groundwater aquifer and the Anga'a River using a groundwater modelling tool. Examples of model applications to field problem include Igboekwe et al. (2008); Konikow and Bredehoeft (1974); Mondal and Sing (2009) and Thangarajan et al. (2008). The evaluation of the present situation is to provide answers to the following questions: Where does water

recharge the aquifer? Is groundwater discharging to the local stream, or is the stream losing water that is recharging the aquifer? This study will provide quantitative evidences to answer such questions by analyzing the results of relatively simple measurements, such as piezometric head survey and geophysical investigations. The case of the Anga'a watershed located in the city of Yaounde, Cameroon, is used to illustrate the threat to the underground water resource.

NATURAL CONDITIONS

Location

The city of Yaounde is located about 250 km from the Atlantic coast and the edge of the Congolese forest and covers an area of about 300 km² (Figure 1). Its population, estimated at 1,500 000 inhabitants in 2000 is experiencing a growth rate of between 5 and 7% per annum (Wéthé et al., 2003).

The watershed of the Anga'a River is located southeast of the city of Yaounde, between latitudes 3° 45' N and 3° 53' N and longitudes 11° 30' E and 11° 36' E. It has an area of 65 km². The upstream part that is the subject of this study covers an area of approximately 11 km². It is made of two areas: West Zone of 7.5 km², located in the Mfoundi division, an urban area and the Eastern zone of 3.4 km², located in a rural area, in the Mefou and Afamba division. Apart from the existence of many dug-wells (piezometers) and agricultural spaces, the rural zone of this site has the distinction of having benefited from several drinking water projects (mainly modern wells equipped with hand pumps).

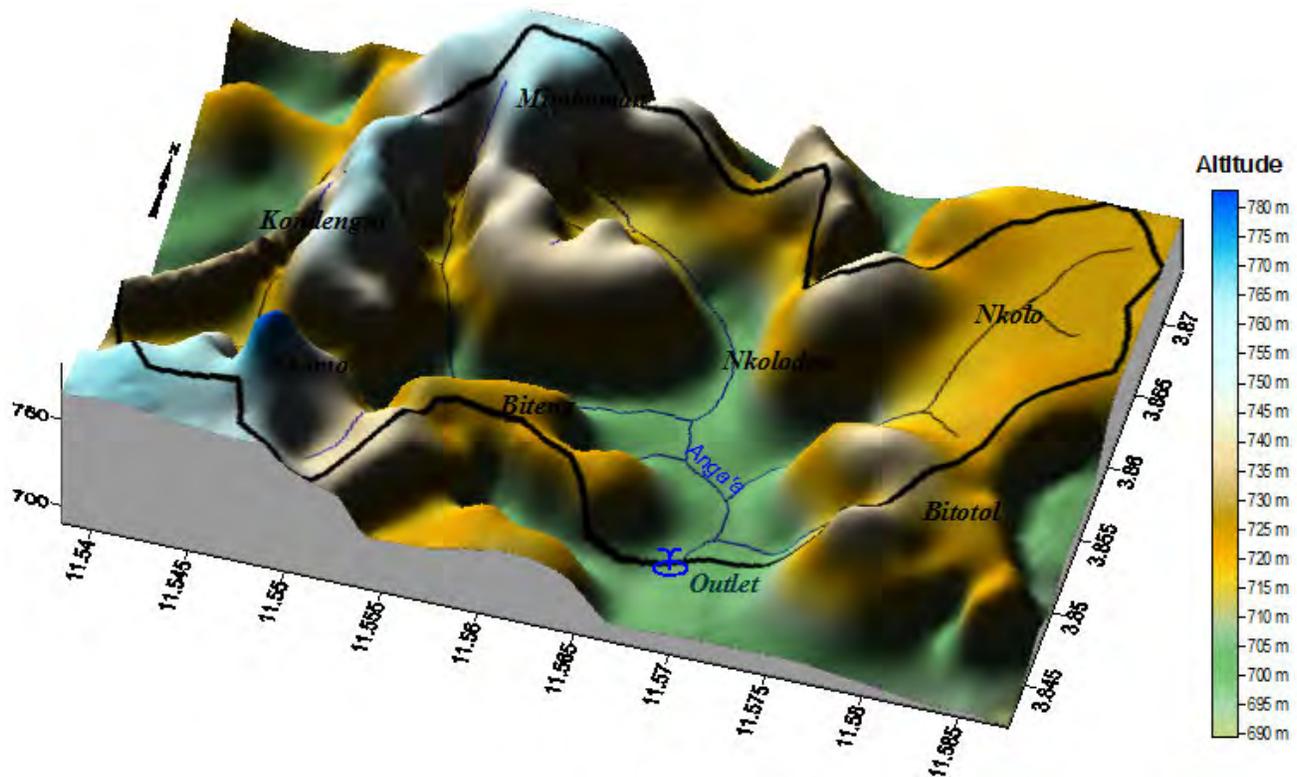


Figure 2. 3D morphology of the upper Anga'a river watershed showing the various hills and marsh areas.

Climate

The study area falls in a region of equatorial climate with four distinct seasons: a long dry season (mid-November to mid-March), a small rainy season (mid-March to mid-June), a small dry season (mid-June to mid-September) and a major rainy season (mid-September, mid-November) (Sighomnou, 2004). An abundance of precipitation (1600 mm / y), an average temperature of 24°C and evaporation of 800 mm / y characterize this climate.

Soil and vegetation

The south Cameroon plateau's soils are predominately ferric and lateritic, the result of decomposing sedimentary stone and crystalline rocks (granite, gneiss, schists, and michachists). The soil colour is red or reddish brown in the interior. The study of the pedologic cover in the Nyong watershed area generally shows two types of profile over the granitoidic bedrock (Onguene, 1993):

- On the hills and hills slopes, the cover, which thickness may reach 50 m at the highest points - gets progressively thinner towards the valley parts.
- In the swampy depression, the lateritic sequence seems to be truncated: the saprolites, or the mottled clays, are overlaid by a whitish clayey-sandy horizon, considered as colluvial. It is overlapped by a greyish clearly hydromorphic horizon, essentially constituted by kaolinite and residual quartz grains (Boeglin et al., 2003; Yongue, 1986).

The region belongs to the domain of the semi-deciduous Congo-Guinean forest, characterized by *Sterculiaceae* and *Ulmaceae*. This area is surrounded by the grass and shrub savannah. The forest in

the strict sense does not exist in the urban upper Anga'a because of its recent urbanization. In the rural part, hills and hills slopes are covered by secondary forest. Several areas have been deforested for growing traditional food crops like manioc, yams, banana, peanut and corn. The swampy depression is the domain of semi-aquatic plants like raphia or palm trees (Boeglin et al., 2003).

Geomorphology

The city of Yaounde is sited on a network of hills dominated by the Mont F  b   which rises to 1060 m above mean sea level (amsl). The different neighbourhoods, scattered in a chaotic way, give an important place to vegetation in the lowland. Yaounde is crossed by small rivers including *Mfoundi*, *Biyeme*, *Mefou* and *Anga'a*. The upper Anga'a watershed has a very rough relief which consists of a series of small hills intersected by marshy valleys where the tributaries of the *Anga'a* River flow (Figure 2). The hypsometric curve of the watershed shows that its average altitude is 726 m above sea level, with the highest two points being 782 m (at Biteng) and 784 m (at Mimboman Chateau) respectively. The lowest point is at an altitude of 693 m (at the fish pond of Nkolo IV). The slopes are steep, giving rise to rapid flow of surface runoff, and thus sustaining the development of many wetlands in the lowlands.

Geology and hydrogeology

Southern Cameroon, within which the study area is located is underlain by two rock units, namely: (i) the Neoproterozoic Yaounde Group, which is thrust onto the Congo craton, and (ii) the Bafia Group, which is classically assumed to be a (Palaeoprotero-

Groundwater Flow & Mass Transport Modelling in the Anga'a river Watershed, Yaounde City, Cameroon

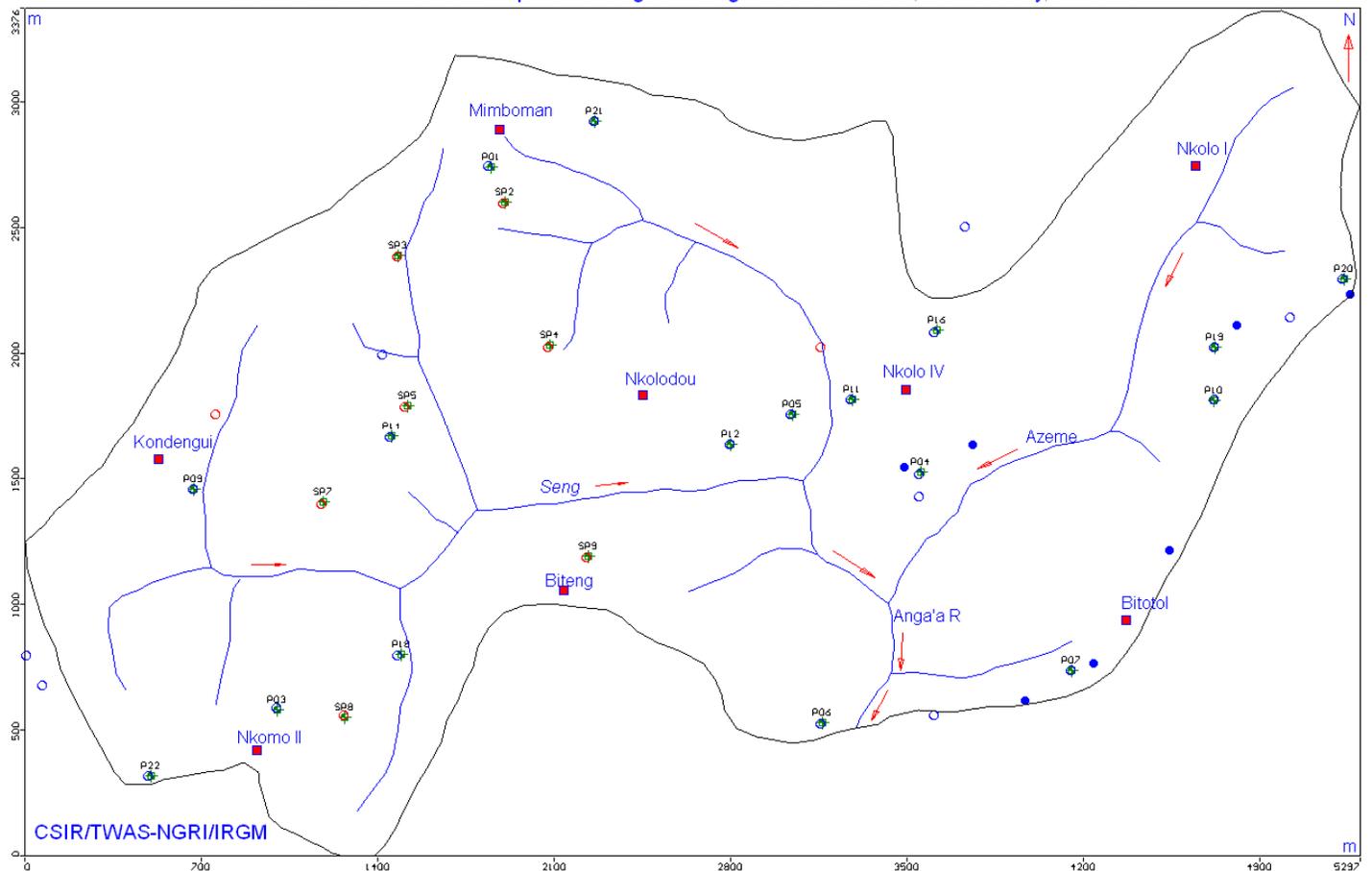


Figure 3. Anga'a river watershed and hydrographic network. Location of observed and pumped wells

terozoic) tectonic slice of basement that over-thrust the Yaounde Group to the north (Vicat et al., 2002; Tchakounte et al., 2007). Metamorphic rocks such as gneiss, mica, migmatites, and schists make up the South Cameroon Plateau's basement (Nzenti et al., 1998). Deposits of these rocks appear along fault lines south of Yaounde, where schists and quartzites are exposed. The region of Yaounde in gneissic rock is a strongly weathered and intensely fractured metamorphic zone. The weathered zone which is 15 - 20 m thick is clay and acidic (pH < 5.5). The hydrodynamic functioning of the coupled rock/soil system act as two layers system in which weathered zone has a capacitive role and fractures have a first-rate drainage role (Djeuda et al., 1999). The underground water may preferentially occur following the flow lines of major geological features (faults, lineaments). In these circumstances it is very important to know the routes of underground water to better protect the aquifer.

DATA ACQUISITION AND METHODOLOGY

Literature review helped to collect preliminary useful information about the geology and hydrogeology of the area. In-depth field works on geophysics and aquifer test are presently going on to gather relevant lithological data for the refinement of the study. The hydraulic conductivity and effective porosity data have been obtained from Kalla (2008) in the neighbour and adjacent watershed to Anga'a; Tanawa et al., 2002) on the water transfer speeds and equivalent conductivities of the Anga'a basin and;

Djeuda et al., 1999 on the characterization of the hydrodynamic properties of the lateritic layers in the entire River Anga'a watershed. Rainfall data was collected through a rain gauge installed in the watershed. This rainfall data was complemented by those obtained from the National Meteorological Commission located near the study field. Recharge was estimated by the water table fluctuation method. The value of specific yield of 0.15 and the specific storage of 10^{-6} were taken from Sekhar et al. (2008) in the forest zone of south Cameroon. Due to the unavailability of geophysical investigations in the area, lithology information was obtained from a single bore-well located in the watershed. The watershed conceptual model is simplified to 2-layered setup. A standard numerical modelling technique was used to develop a regional discrete model of the Anga'a River catchment.

WELL INVENTORY

The Anga'a river watershed

The upper Anga'a watershed is not very dissected and is drained by a river system not very dense. Its drainage density is 1.87. With 1.95 streams per square kilometre, the watershed has important surface water reserve. The main *Anga'a* is supplied by two tributaries: the *Azeme* on the left bank, which drains the rural part of the watershed and the *Seng* (Order 2) on the right bank, which drains the urban part of the watershed (Figure 3). Groundwater level monitoring was carried out since July, 2007 at 26 observation

points in the watershed.

The depths to water level measurement carried out have been reduced to the mean sea level and groundwater contours have been prepared to ascertain the general groundwater hydraulic gradient and stream aquifer interaction areas. In the absence of topographic survey to connect all the observation wells to the mean sea level, GPS equipment and Google Earth tool have been used. The inaccuracy of these methods has led to some discrepancy between observed and calculated water head.

Groundwater flow condition

Water table conditions exist in the top aquifer whereas in deeper zones, groundwater is semi-confined to confine. For the modelling purpose, aquifer is considered semi-confined. Comparison of water table and piezometric maps indicates an interconnection between the top aquifer (first layer) and the lower semi-confined aquifer. Groundwater level data for February 2008 has been used for steady state calibration (cf. Figure 3).

At the middle of the watershed (Nkolo), water table is shallower (~3 m) and fluctuates out of step with seasons by a little less than 1 m. Up North, East and south-west, in the highland of the study area, water table is deeper (~22 m) and fluctuation is more for the same amount of rainfall in the area. It may be attributed to the distinct lithological control, whereby less fluctuation is associated with the predominance of impermeable zones and high fluctuation with predominance of granular zone (Igboekwe et al., 2008). It may also be attributed to runoff and recharge. The general groundwater flow direction follows the topography.

GROUNDWATER FLOW MODELLING

Groundwater flow processes

Most groundwater models in use today are deterministic mathematical models. Deterministic models are based on conservation of mass, momentum, and energy and describe cause and effect relations. The underlying assumption is that given a high degree of understanding of the processes by which stresses on a system produce subsequent responses in that system, the system's response to any set of stresses can be predetermined. Deterministic groundwater models like MODFLOW generally require the solution of partial differential equations.

A general form of the equation describing the transient flow of a compressible fluid in a non-homogeneous anisotropic aquifer is derived by combining Darcy's law with the continuity equation. The three-dimensional movement of groundwater of constant density through porous medium may be described by the partial-differential equation (McDonald and Harbaugh, 1988):

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

Where; K_{xx} , K_{yy} , and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity [L/T]; h is the potentiometric head [L]; W is a volumetric flux per unit volume representing sources and/or sinks of water, with $W < 0.0$ for flow out of the ground-water system, and $W > 0.0$ for flow into the system [T⁻¹]; S_s is the specific storage of the porous material [L⁻¹]; and t is time [T].

Equation (1) describes groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium. Equation

(1) together with specification of flow and/or head conditions at the boundaries of an aquifer system and specification of initial-head conditions constitutes a mathematical representation of a groundwater flow system (McDonald and Harbaugh, 1988). MODFLOW uses iterative approach and integrated finite-difference approximation with block centred formulation to solve groundwater flow equation.

Conceptualization of the flow process in Anga'a river watershed

The geophysical investigations are currently being carried out in the watershed. As mentioned earlier, aquifer characteristics have been estimated in the watershed following literature review. The following information has been used during conceptualisation of groundwater flow regime:

- The Anga'a River is a perennial stream and is influent throughout its course, except at the north-east and south-west.
- The *Nkolo IV* fish pond (Lake) is assumed to be maintaining a level and is sustained through base flow from the river
- The Dirichlet boundary condition is applied in northern part of watershed, at *Mimboman*, which allows entry of lateral flow
- The same conditions are applied in the western and south-western areas, at *Biteng*; and in the south-eastern area at *Bitotal*
- Groundwater leaves the watershed at various places: in the southern area through Anga'a River, and in the south-west and north-east.
- Groundwater recharge due to rainfall enters the aquifer from the top layer.
- Springs discharge are considered as groundwater withdrawal through stream-aquifer interaction

Groundwater flow model

The water table elevation in the watershed along the South-western boundary was defined by 745 m (amsl) equipotential line and lowest water table elevation by 690 m in the downstream of Nkolo IV fish pond on Anga'a River outlet. The simulated model domain of the watershed consists of 106 columns x 68 rows with two layers (Figure 4). The size of the cells in the model is 50 x 50 m, covering an area of 5298 x 3440 m and the model is represented with more than 4370 active cells. The first layer is an unconfined while the second layer is assumed to be semi-confined one. The top layer mostly consists of 2 - 18 m top soil clay/sandy weathered zone underlain by 15 - 25 m fractured zone. The aquifer permeability varied from 1 m/d to 2 m/d in the watershed. Higher permeability has been prevailed in the valley parts saturated with groundwater.

As regards boundary conditions, the outflow from groundwater flow model was estimated in term of few constant head nodes and Anga'a River was simulated with river package in the Visual MODFLOW (Figure 5). The groundwater recharge at the rate of 30 mm/year has been simulated in the first layer by deploying the recharge package. Groundwater recharge has been increased from 30 mm/yr in the lowland to 40 mm/year in the highland (Figure 6). Natural vegetation may sustain with an average evapotranspiration of 10 mm/yr and the same has been assigned to all cells in the watershed. Even though groundwater is the only available resource for drinking water in the area, just few pumping wells can be found in the watershed. People are depending on traditional dug well for household laundry. Drinking water comes from few traditional sealed dug wells with hand pump in the rural area, and piped water network in the urban area. Vegetable are grown in the swampy zone during pre-monsoon and Anga'a River is used to sprinkle the crops. Groundwater pumping rates was assumed to be varying from 10 m³/day to 18 m³/day.

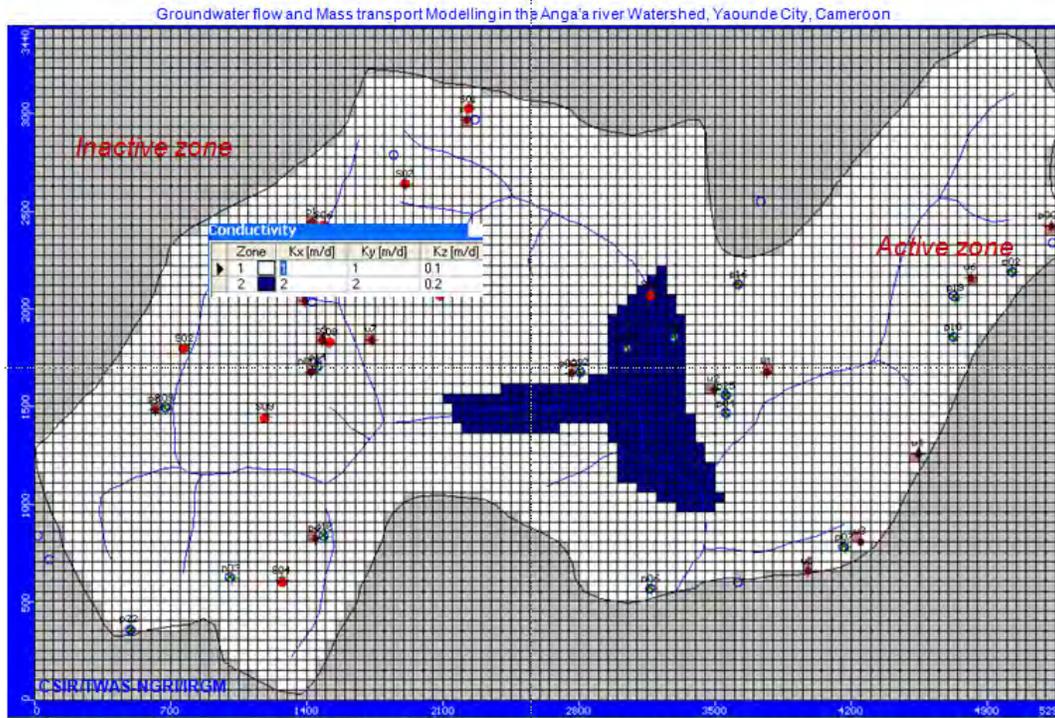


Figure 4. Discretization of the simulated Model domain, Active and Inactive Flow Zones and Simulated Hydraulic Conductivity distribution (in m/day) in Groundwater Flow Model.

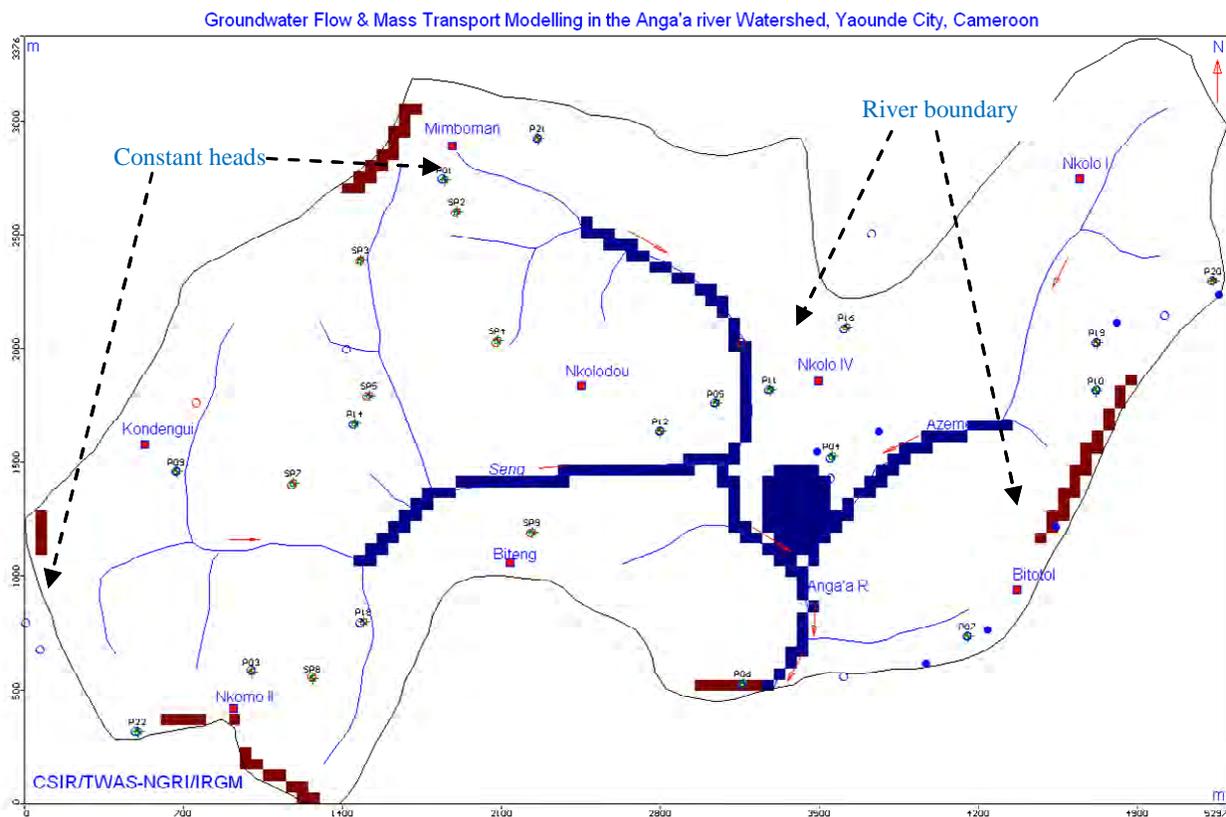


Figure 5. Constant head and river boundary conditions in the flow model.

Groundwater Flow Modelling in the Anga'a river watershed, Yaounde-Cameroon

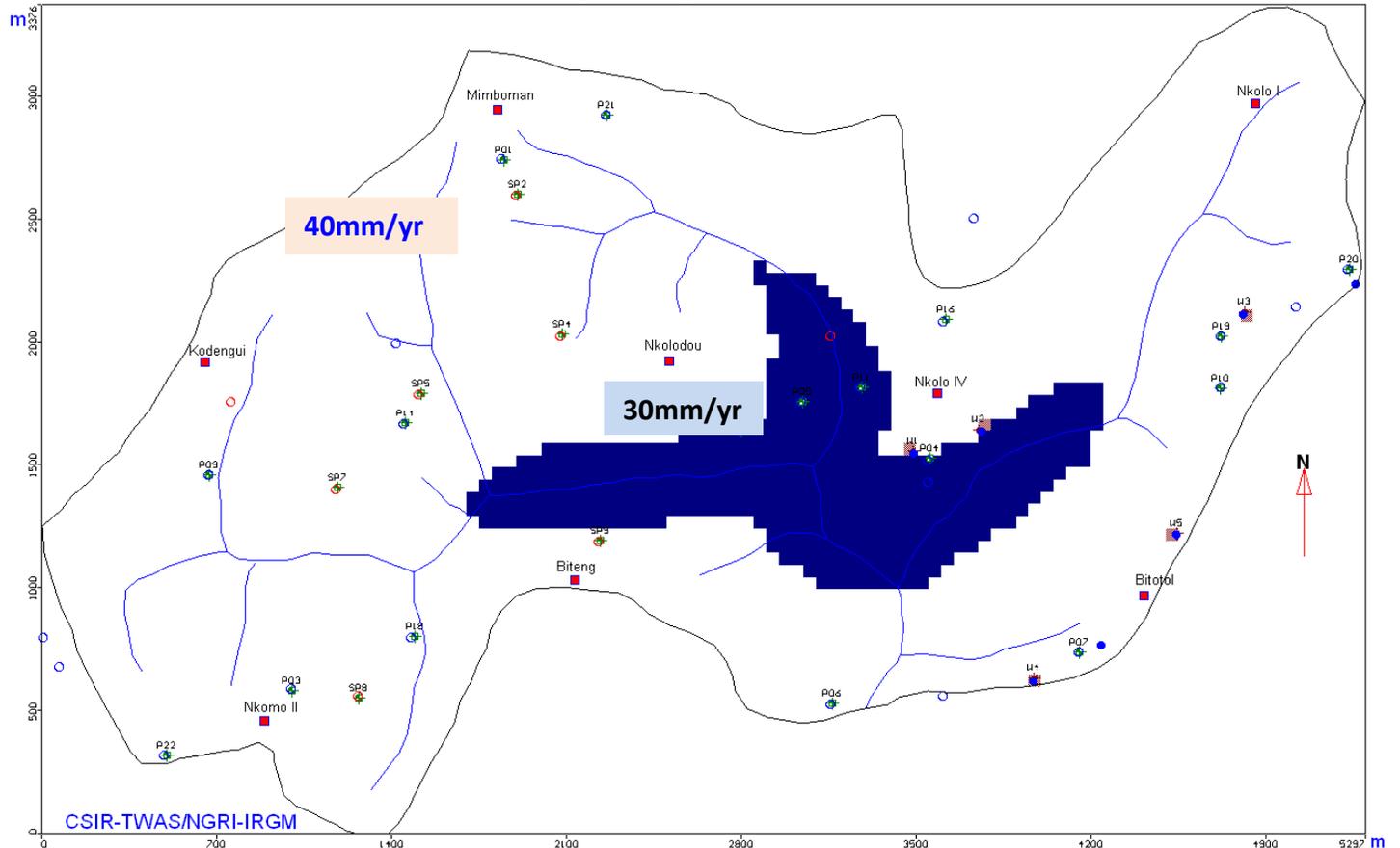


Figure 6. Block-wise Groundwater Recharge (mm/yr) due to average annual Rainfall

Steady state calibration

The groundwater flow model has been constructed for computation of hydraulic head distribution. As minor fluctuation is observed in groundwater level in the area, this indicates that hydraulic gradients do not change significantly with time (Hani et al., 2007). Thus groundwater flow was assumed to be under steady state condition represented by groundwater condition of February, 2008. For steady state simulation, 17 observation wells were included on the calculated versus observed heads graph (Figure 7). The groundwater levels measured during February, 2008 were used as initial water level configuration for the Anga'a watershed groundwater flow model. The groundwater head in the aquifer model was computed by using Visual MODFLOW (Guiger and Franz, 1996). Waterloo Hydrogeologic Software (WHS) solver package of MODFLOW has been used for groundwater flow computation. This solver checked the maximum change in the solution at every cell after completion of each iteration. If the maximum change in the solution is below the set of convergence tolerance (here 0.01 m), then the solution has converged and the solver stops, otherwise, new iteration will start (McDonald and Harbaugh, 1988). The groundwater flow model has converged after 170 iterations.

The purpose of the calibration of a groundwater flow model is to demonstrate that the model can response field measured heads and flows. A trial and error calibration technique has been used. The flow model was calibrated by adjusting several parameters (permeability, recharge, river stage and aquifer thickness) within a

narrow range of values until the best fit was obtained between the observed heads and simulated heads (Mayer et al., 2007). The accuracy of the computed groundwater levels was judged by a mean error, mean absolute error and root mean square error of computed values for points on the graph (Anderson and Woessner, 1992).

PATHLINES MODELING IN ANGA'A RIVER WATERSHED

Particle tracking model are specifically designed to monitor the particle pathways and fate of contaminant sources. MODPATH is a particle tracking post-processing package that was developed to compute three-dimensional flow paths using output from steady-state or transient ground-water flow simulations by MODFLOW. MODPATH uses a semi-analytic particle tracking scheme that allows an analytical expression of the particle's flow to be obtained within each finite-difference grid cell. Output from steady-state or transient MODFLOW simulations is used in MODPATH to compute paths for imaginary "particles" of water moving through the simulated ground-water system. In addition to computing particle paths, MODPATH keeps track of the time of travel for particles moving through the system. By carefully defining the starting locations of particles, it is possible to perform a wide range of analyses such as delineating capture and recharge areas or drawing flow nets.

Particle tracking analysis was used to track lines of particles and

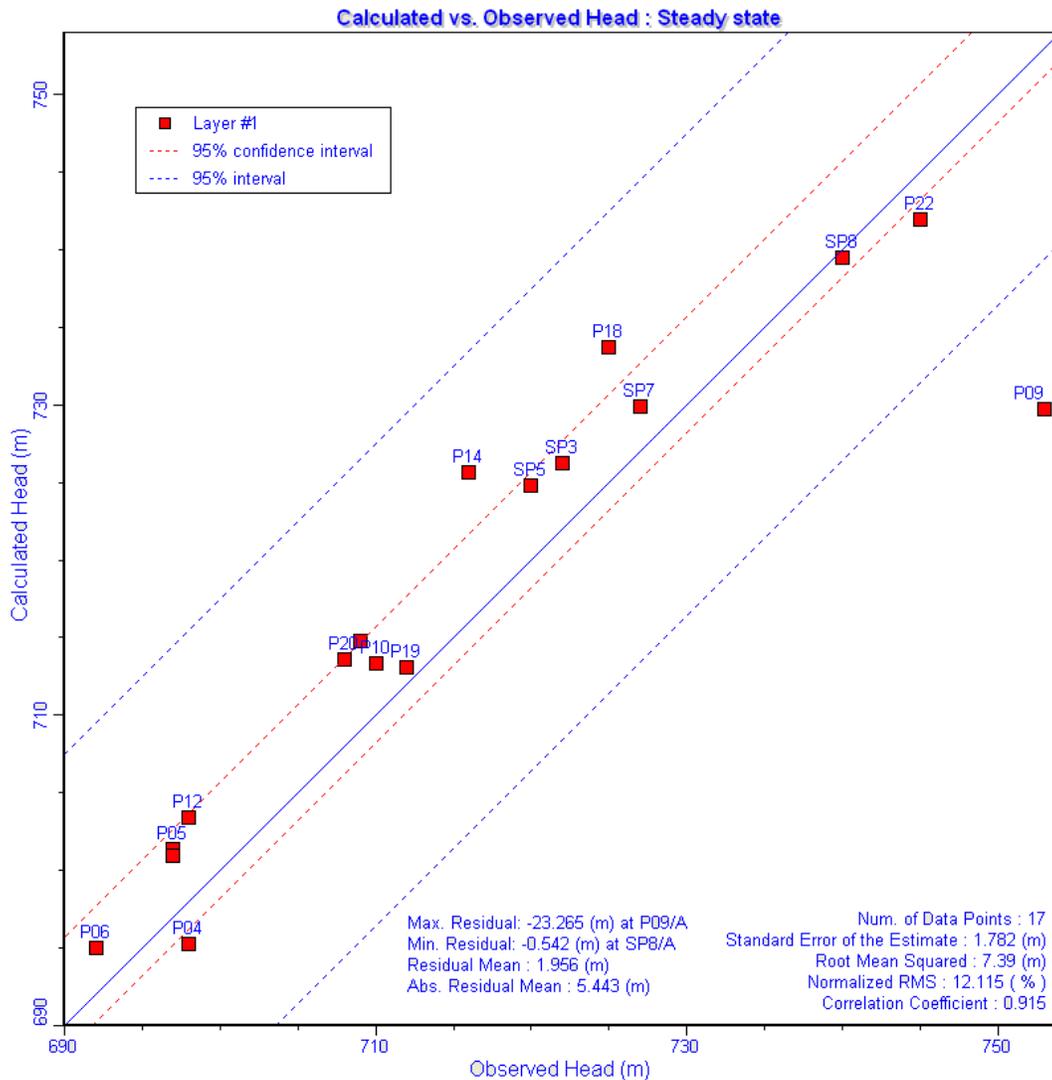


Figure 7. Comparison of computed vs. observed groundwater levels in the Anga'a river watershed (February 2008).

determine the preferred contaminant exposure pathways from recharge area near Nkomo II to Nkolo IV fish pond and discharge points of supply wells, and to evaluate particle travel times of the cycle.

SENSITIVITY ANALYSIS

Sensitivity analysis brings out and helps understand significant role played by individual parameters in the computation of the model simulation output and also aids determine which data must be defined most accurately (Mayer et al., 2007; Konikow, 1996). Initially, the conductivity value was increased by 10% of the preliminary calibrated model. The comparison between computed heads and observed heads for this modification has resulted in RMS error moving from 6.85 - 6.20. Further, a second sensitivity run was made with decrease in conductivity by 10% and little variation has been observed for RMS value. The second parameter changed during sensitivity analysis was recharge while keeping conductivity value unchanged. Recharge value was lowered by 10 mm/year in

the entire watershed. This modification provoked the RMS value to move from 6.20 - 6.18. Further modifications did not improve the model accuracy.

RESULTS AND DISCUSSION

The computed groundwater level contours are following the trend of observed groundwater levels during February, 2008 (Figures 8 and 9). The groundwater velocity vectors indicate the predominant flow towards the Anga'a River and present the maximum groundwater velocity in the watershed to be 0.19 m/day. This complies with results from Tanawa et al. (2002) in the same basin, who obtained the value of 2.6×10^{-6} m/s. The Computed Groundwater table cross section and the velocity vectors along Row 35 are rightly to show the major groundwater circulation route from high elevation points to lowlands

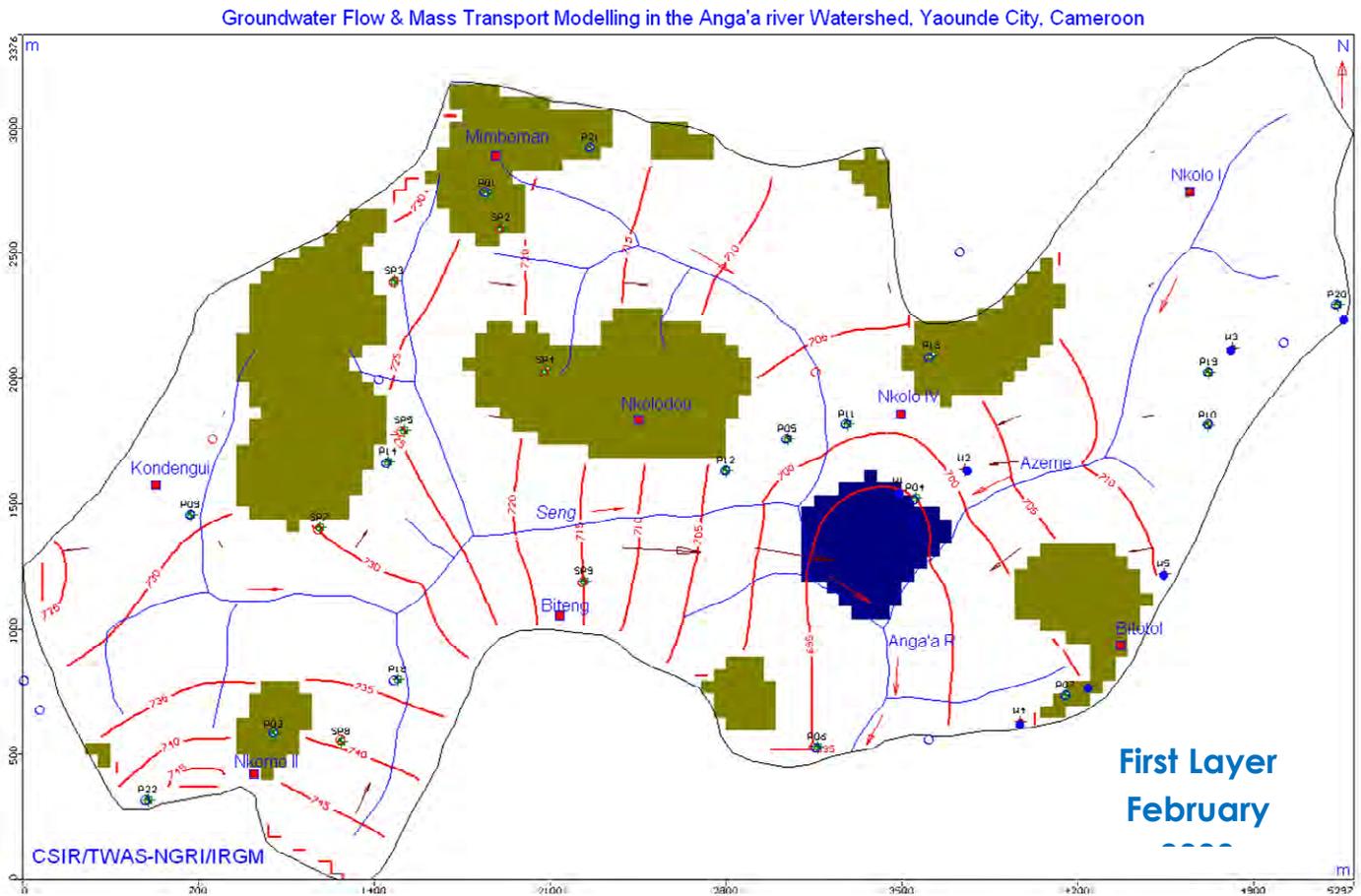


Figure 8. Computed groundwater level contours in m (amsl) and dry cells in the 1st layer – February 2008.

(Figure 10). The computed and observed water level contours replicate the trend of groundwater flow and are found generally matching (+/-) 3 - 4 m, even if at some particular point like P09, the discrepancy is very high (cf. Figure 7). Particle tracking analysis present that the contaminant exposure pathways generally follows the groundwater route. It helps to understand that the contaminant occurring near Nkomo II may take about 50 years travel time to reach the Nkolo IV fish pond (Figure 11).

The sensitivity analysis showed that the model is very little sensitive to the conductivity parameter and not sensitive to the recharge. It has been observed that only the topography has a major influence on the groundwater flow condition in the Upper Anga'a river watershed. This is observable by the presence of dry cells in the first layer model, due to the inaccuracy of the conceptual layers model establishment.

The groundwater balance has been worked out under steady state condition. The watershed has been divided in two zones (Zone II for the Nkolo pond area and Zone I for the rest of the watershed) to assess the contribution of the Nkolo IV pond to the groundwater flow process. The

groundwater budget indicates that river Anga'a is gaining river throughout the watershed. It is also observed that the Nkolo fish pond is replenished particularly by groundwater and that leakage to river is one of the major processes moderating groundwater movement in the Anga'a river watershed (Table 1). This appears to be particularly important because the availability of water in the pond is an important factor for the sustainability of the fishery in the area.

Conclusion

Ground Water Flow and particle tracking Modelling study have highlighted groundwater condition and particle migration in the shallow unconfined aquifer of the Upper Anga'a river watershed. Groundwater model has been conceptualized and developed using the lithologic information and similar aquifer parameters applicable for the region. The computed groundwater level contours have shown to replicate the trend of observed groundwater contours. It was found that the surface topography controls the groundwater flow conditions in the Anga'a river

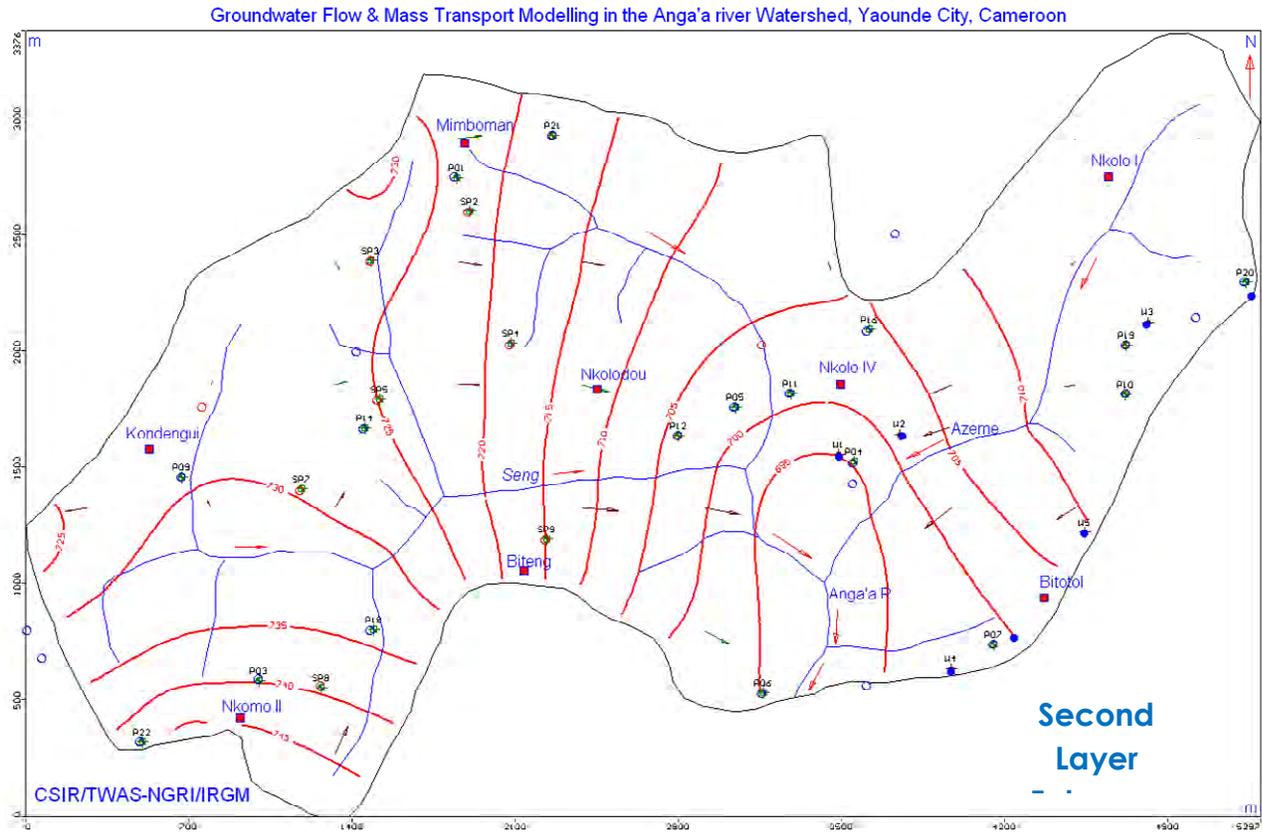
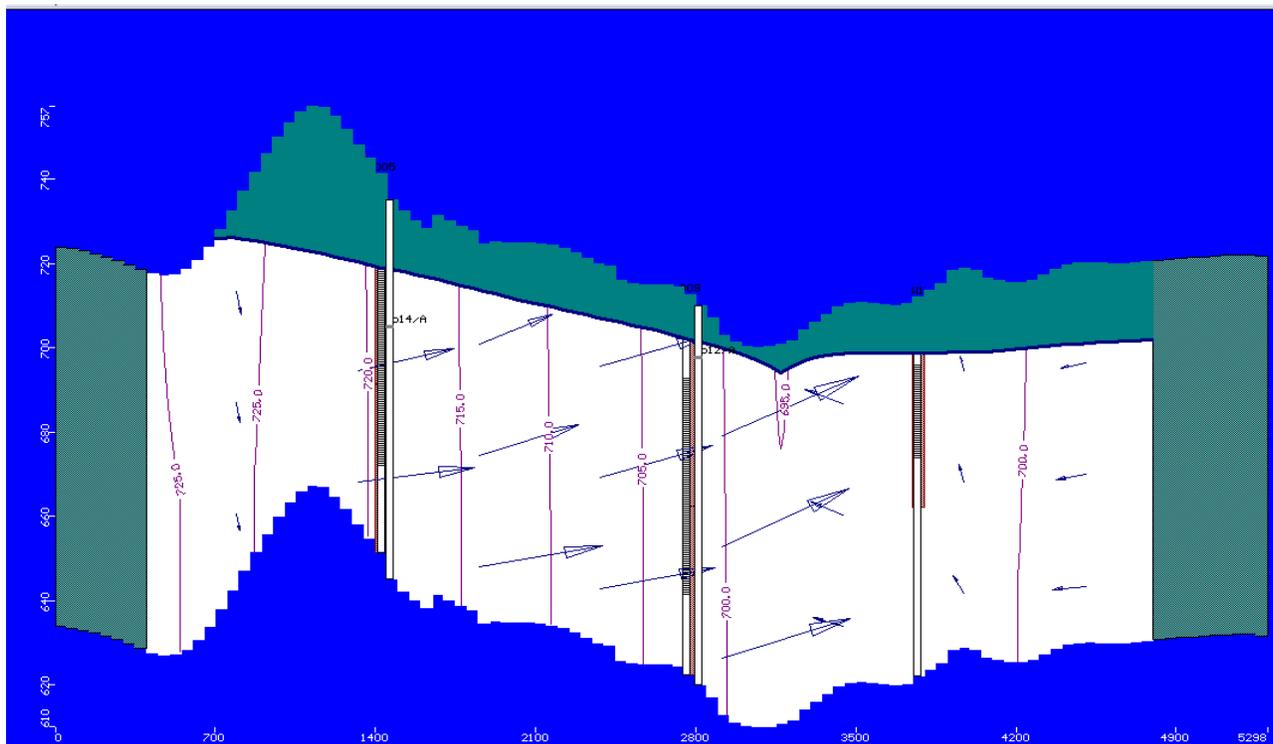


Figure 9. Computed groundwater level contours in m (amsl) and velocity vectors in the 2nd layer – February 2008



Groundwater Flow & Mass Transport Modelling in the Anga'a river Watershed, Yaounde City, Cameroon

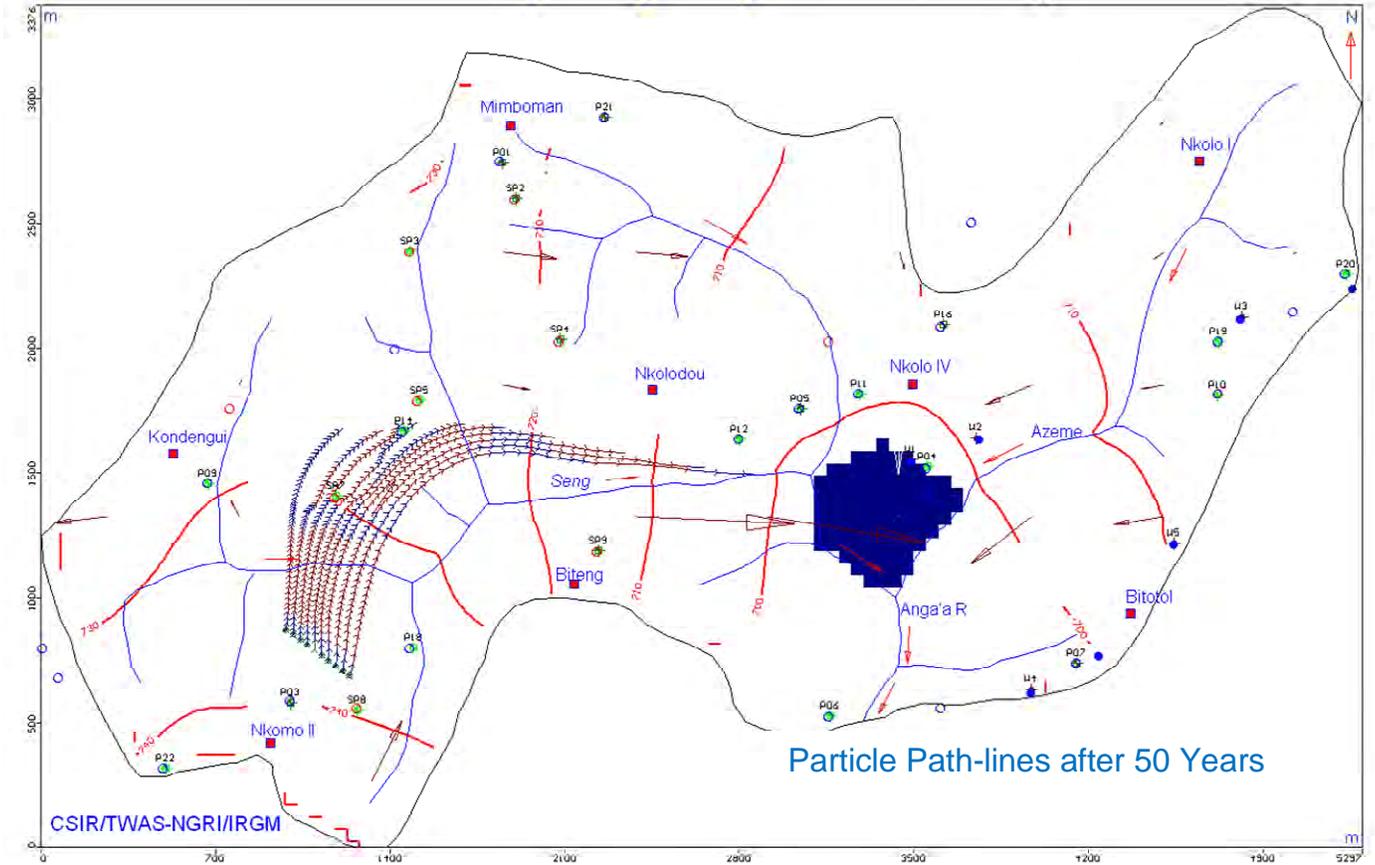


Figure 11. Path-lines of Forward particle tracking simulation in the first layer after 50 years. Preferential contaminant flow paths can be observed.

Table 1. Groundwater balance in the Anga'a river watershed.

Zone	Input m ³ /day		Output m ³ /day	
I	Constant head	1750	Constant head	580
	Recharge	830	Wells	40
	River leakage	1530	Evapotranspiration	60
			River leakage	1000
	Zone II to I	95	Zone I to II	2520
	Total	4205	Total	4200
II	Recharge	20	Wells	10
	River leakage	440	River leakage	2870
	Zone I to II	2520	Zone II to I	100
		Total	2980	Total

watershed and that the general groundwater flow direction is NW-SE along the valley parts of Anga'a River. The preliminary results present the maximum groundwater velocity observed in the watershed as 0.19 m/d. notwithstanding this very small value, it appears that if some contamination occurs around Nkomo II, it may take about 50 years travel time to reach the Nkolo IV fish pond.

The groundwater budget indicated that the Nkolo fish pond is replenished particularly by groundwater effluence and rainfall. This is particularly important because the availability of water in the pond is an important factor for the sustainability of the fishery in the area. The ongoing geophysical study will be added to additional hydrogeological data and chemical analysis to refine the groundwater flow model and built the mass transport model in the

future.

ACKNOWLEDGEMENTS

The present work was supported by grants from the International Foundation for Sciences (IFS) and the joint fellowship from the Academy of Sciences for the Developing World (TWAS) and Council for Scientific and Industrial Research India (CSIR). Sincere thank to Dimri V.P., and Hell J.V., respectively, Director of National Geophysical Research Institute (NGRI), Hyderabad, India and Director of Institute for Geological and Mining Research (IRGM), Yaounde, Cameroon for their professional assistances. We would also like to thank J.C. Tonga (IRGM/CRH), B.A. Prakash and L. Suri Naidu (NGRI) for their technical support.

REFERENCES

- Anderson MP, Woessner WW (1992). Applied groundwater modelling. Academic press, San Diego, California, U.S.A. p.381
- Bemmo N, Ngamga D, Kengni NY, Guetsa KF, Megno OL, Babakary H (1999). Assainissement autonome et impact sur la santé et l'environnement, choix des technologies adaptées : cas de Yaounde, Cameroun, Rapport.
- Boeglin JL, Ndam JR, Braun JJ (2003). Composition of the different reservoir waters in a tropical humid area: example of the Nsimi catchment (Southern Cameroon). *J. Afr. Earth Sci.* 37: 103–110.
- Djeuda Tchapnga H, Tanawa E, Temgoua E, Siakeu J, Ngo Massana B (1999). Mode de circulation, mécanismes de recharge et temps relatifs de séjour des eaux des nappes souterraines des altérites du milieu cristallin : cas du bassin versant de l'Anga'a, Yaounde, Cameroun. Press. Univ. Yaounde pp. 117-126.
- Dumoutier S (2003). Sources of contamination in springs and well used for drinking water in low-income communities of Yaounde, Cameroon. Master of Science thesis, University of Cranfield, Silsoe p.46.
- Guiger N, Frantz T (1996). Visual MODFLOW: Users guide. Waterloo Hydrogeologic, Waterloo, Ontario, Canada.
- Hani A, Djorfi S, Lamouroux, C, Lallahem S (2007). Impact of the industrial rejections on water of Annaba aquifer (Algeria). *European water* 19/20: 3-14.
- Igboekwe MU, Gurunadha Rao VVS, Okwueze EE (2008). Groundwater flow modelling of Kwa Ibo River watershed, southeastern Niger. *Hydrol. Process.* 22: 1523–1531.
- Kalla MF (2008). Comportement hydrodynamique d'un aquifère à nappe libre en zone urbaine de Yaounde. M.Sc thesis, Univ. Yaounde I, p.99 .
- Konikow LF (1996). Numerical models of groundwater flow and transport. In: Manual on Mathematical Models in Isotope Hydrogeol. Int. Atomic Energy Agency Rept. IAEA-TECDOC-910, Vienna, Austria: pp.59-112.
- Konikow LF, Bredehoeft JD (1974). Modeling flow and chemical quality changes in an irrigated stream-aquifer system. *Water Resources Res.* 10(3): 546-562.
- Leseau (1998). Gestion de l'eau et protection de la ressource. Rapport de recherche, ENSP de Yaounde p.187.
- Mayer A, May W, Lukkarila C, Diehl J (2007). Estimation of fault-zone conductance by calibration of a regional groundwater flow model: desert Hot Springs, California. *Hydrol. J.* 15(6): 1093-1106.
- McDonald MG, Harbaugh AW (1988). A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Techniques of Water-Res. Invests. of the U.S. Geol. Survey, Book 6, Ch. A1: p.586.
- Mondal NC, Singh VS (2009). Mass transport modeling of an industrial belt using visual MODFLOW and MODPATH: A case study. *J. Geography and Regional Planning* 2(1): 001-019.
- Nola M, Njine T, Monkiedje A, Sikati FV, Djuikom E, Tailliez R (1998). Qualité bactériologique des eaux de sources et puits de Yaounde, Cameroun. *Cahier Santé* 8(5): 330-336.
- Nzenti JP, Njankot T, Njiosseu EL, Tchoua FM (1998). Les domaines granulitiques de la chaîne panafricaine Nord-équatoriale au Cameroun. In *Géologie et Environnement au Cameroun*, Vicat et Bilong Ed, coll (Geocam) pp.255-264.
- Onguene M (1993). Différenciation pédologique dans la région de Yaounde (Cameroun) : Transformation d'un sol rouge ferrallitique en un sol a horizon jaune en relation avec l'évolution du modelé. These Doct. Univ. Paris 6: 254.
- Sekhar M, Braun JJ, Hayagreeva RKV, Ruiz L, Robain H, Viers J, Ndam JR, Dupre B (2008). Hydrogeochemical modelling of organo-metallic colloids in the Nsimi experimental watershed, South Cameroon. *Environ. Geol.* 54:831–841.
- Sighomnou D (2004). Analyse et redéfinition des régimes climatiques et hydrologiques du Cameroun : perspectives d'évolution des ressources en eau. Thèse doct. Etat. Univ. Yaounde I, Cameroun p.289.
- Tanawa E, Djeuda TH, Ngnikam E, Temgoua E, Siakeu J (2002). Habitat and protection of water resources in suburban areas in African cities. *Building Environ.* 37: 269-275.
- Tchakounte JN, Toteu SF, Van Schmus W, Penaye J, Deloule E, Ondoua JM, Houketchang M, Ganwa AA, White W (2007). Evidence of ca 1.6-Ga detrital zircon in the Bafia Group (Cameroun): Implication for the chronostratigraphy of the Pan-African Belt north of the Congo craton. *Geosci. J.* 339(2): 132-142.
- Thangarajan M, Singh VS, Sarma MRK, Mondal NC (2008). Regional characterization of groundwater flow regime in a weathered hard rock aquifer system: a case study in Kodaganar river basin, Tamilnadu, India. *Groundwater Resources Assessment, Recharge & Modeling* (Editors: Ranghaswami MV, Palaniswami, Mayilswami), Macmillan Advanced Res. Series, New Delhi pp.275-290.
- Vicat JP, Mvondo H, Willems L, Pouclet A (2002). Phénomènes karstiques fossiles et actuels au sein des formations métamorphiques silico-alumineuses de la nappe pan-africaine de Yaounde (Sud-Cameroun). *C. R. Geosci.* 334: 545–550.
- Wéthé J, Radoux M, Tanawa E (2003). Assainissement des eaux usées et risques socio-sanitaires et environnementaux en zones d'habitat planifié de Yaounde-Cameroun. *Vertigo* 4(1): 1-12.
- Yongue FR (1986). Contribution à l'étude pétrologique de l'altération des facies de cuirassement ferrugineux des gneiss migmatitiques de la région de Yaounde. Thèse Doct. 3e cycle, Univ. Yaounde p.214.
- Zaporozec A (2004). Groundwater contamination inventory. UNESCO IHP-VI series on groundwater 2: 160.