

Assessing Groundwater Nitrate Pollution in Yaoundé, Cameroon: Modelling Approach

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Abstract: Groundwater flow modelling and mass transport simulation were carried out to determine the Nitrate and Total Dissolved Solid (TDS) migration within the shallow unconfined aquifer of the upper Anga'a river watershed of Yaoundé city, Cameroon. The MODFLOW code calibrated for February 2008 groundwater levels was used to simulate the steady state distribution of hydraulic head. Simulated hydraulic heads were similar to observed values along the watershed in model validation. The nitrate and TDS transport were described by the convection equation and solved using MT3D. The pollutant fate and transport model (MT3D) reproduced the spatial pattern of observed nitrate concentrations in model calibration and validation. Groundwater and plume velocities were 0.26 and 0.21 m per day respectively. Simulating the contaminant migration from the recharge area shows that the plume may take more than 50 years travel time to reach the central part of the basin from which decision analysis can be made for generating key criteria to secure any water quality from contamination. The application of groundwater modelling tool in this study has shown excellent perspectives for monitoring and protecting aquifer system from spatial and temporal pollutant migration that addresses the concern of changing natural groundwater recharge, population growth and economic development in the study region.

Key words: Latrines • Modflow • Nitrate pollution • Simulation • Yaoundé

INTRODUCTION

Groundwater plays a fundamental role in the water supply in Yaoundé, where less than 50% of households have direct access to the drinking water delivered through pipelines. The erratic condition of the water supply obliges most people at some points to use springs and wells [1-3]. Another crucial issue is that within the urban environment, there are numerous potential sources of pollution due to various human activities, mainly including agricultural activities and the construction and use of latrines. At least one latrine is found on each plot of land while one plot out of three has a well. Statistics

show that in all Cameroon cities, 86 % of household use latrines and this percentage increases to 94% when the entire country is considered. [4] showed that 87 % of water supply points in the city of Yaoundé have an elevated risk of faecal contamination due to latrines that are situated upstream of water supply wells and springs. This statement was later confirmed by [5] who noted that many diarrheal diseases in Yaoundé were related to the poor sanitation resulting from urban waste coupled with stagnant waters. Nitrate pollution which is considered here as partly coming from the use of pit latrine, is a nationwide concern. [6] reported high nitrate concentrations ($50.8 - 72.6 \text{ mg} \cdot \text{L}^{-1}$) in springs in the town

of Foumbot during year 2005. [7] realised that 58 % of wells and 50 % of springs in Bafoussam contain nitrate concentration above the 50 mg/l of the World Health Organisation [8] standards. [9] studied nitrate content in groundwater samples in north Cameroon. They realised that NO_3^- amount were significantly decreasing with depth; so they concluded that NO_3^- species in most of the considered ground waters were of superficial origin. Still in northern Cameroon, [10] registered nitrate content ranging from 0.4 to 320 mg.l⁻¹ in borehole and shallow wells. [11] registered nitrate concentration (47.8 – 94.3 mg•L⁻¹) above the WHO standard from springs located in the informal settlements of Douala. Meanwhile, while [12] registered TDS concentrations varying from 200 to 2415 mg.l⁻¹ in groundwater from the hard rock aquifer system in the Maheshwaram watershed in India; related studies in Cameroon do not show such important quantity of dissolved solid in groundwater samples even though this chemical species is used here to simulate contaminant migration. [13] study in the volcanic area of mount Cameroon revealed a mean TDS value of 148 mg.l⁻¹; [11] registered values varying from 30 to 340 mg.l⁻¹ in the alluvial groundwater from springs and bore wells in semi-urban informal settlements of Douala. [14] reported a mean TDS value of 86 mg.l⁻¹ in well's water in Yaoundé.

To assist water-resources managers in areas that rely on groundwater for drinking, hydrogeologist has been using computer models for groundwater simulations to better understand local groundwater systems and impacts of human activities on water resources [15]. These models can be used to simulate geochemical reactions along flow paths and movement of contaminants within an aquifer. Modelling the transport of contaminants through groundwater flow systems plays a critical role in any hazardous waste management and disposal program. One of the purposes of solute fate and transport model in groundwater is to compute the concentrations of dissolved chemical species in an aquifer at any specified time and place [16]. Modelling of different kinds of contaminant was studied by different settings of initial and boundary conditions [17-22]. The first part of this study has built the groundwater flow model and ran the model for the steady state after calibration of February 2008 groundwater flow condition [15]. From the information collected in the catchment, a modelling approach for simulating flow and transport was constructed. This present study focuses on simulating the spatial and temporal distributions of nitrate concentrations in groundwater system with many drinking water wells and springs monitored in the river catchment.

The modelling approach was carried out to characterize the groundwater flow regime and the pathways of nitrate and Total Dissolved Solid (TDS) within the groundwater system and to provide a first-hand estimation of hydraulic head distribution and residence time of groundwater in the shallow unconfined aquifer of the Anga'a river watershed located in the outskirt of Yaoundé. These two species were chosen (i) due to the availability of data, (ii) because high levels of nitrate can cause methemoglobinemia or "blue-baby" disease in infants, (iii) nitrates can be used as a crude indicator of faecal pollution where microbiological data are unavailable and (iv) the possibility to compare the results to related studies in other river catchments.

MATERIAL AND METHODS

Study Area: The watershed of the Anga'a river is located southeast of the city of Yaoundé, between latitudes 3°45' N and 3°53' N and longitudes 11°30' E and 11°36' E and covers an area of approximately 11 km² (Fig. 1). Many agricultural and public institutions amongst which is the kodengui central prison (see figure 1) are situated in the river watershed, which is made of many convexo-concave hills surrounding large flat swamps drained by the upper Anga'a brook. 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) [23]. An abundance precipitation of (1600 mm / y), an average temperature of 24 °C and evaporation of 800 mm / y characterize this climate. The soils are predominately ferric and lateritic, the result of decomposing sedimentary stone and crystalline rocks (granite, gneiss, and schists). The area is surrounded by the grass and shrub savannah. The swampy depression is the domain of semi-aquatic plants like raphia or palm trees [24]. The region of Yaoundé is underlain by strongly weathered and intensely fractured gneissic rocks (Fig.2). The weathered zone is typically 15 to 20 m thick clay and acidic (pH < 5.5). The hydrodynamic rock/soil system act as two layers superimposed namely the weathered layer and the fractured layer [25].

Methodology: Approximately ten wells, five springs and the Anga'a river were sampled for physical-chemical analysis (Fig. 1). Groundwater sampling under this Plan was conducted semi-annually. The first round of sampling

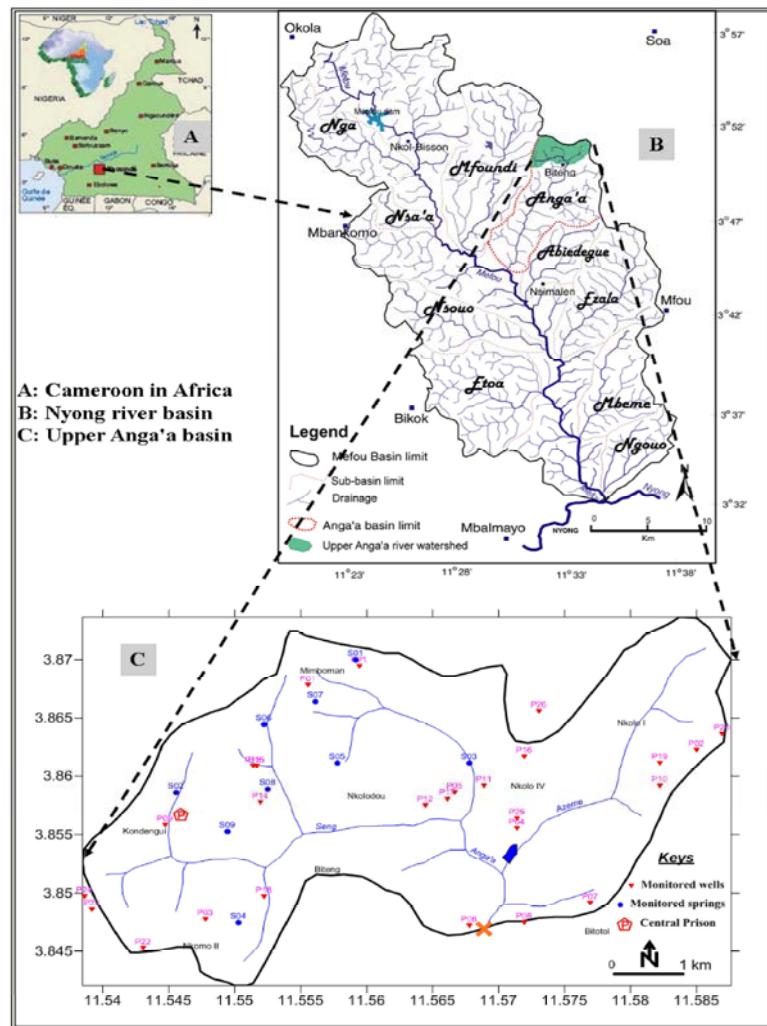


Fig. 1: Location of the Anga'a river watershed and monitored water points in Yaoundé city Cameroon

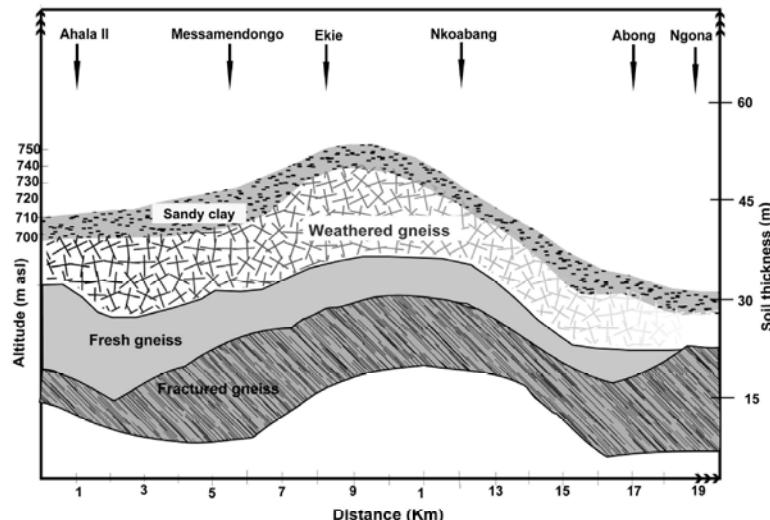


Fig. 2: Cross section of the soil profile along SW-NE in the Anga'a river watershed after information collected on drilled well's logs in the area.

was conducted in October 2007 and the other round was conducted in February 2008. To decipher the impact of localized source of pollution, a particular sampling was made on March 2009 at the contact point between the Kondengui central prison effluent and the Anga'a river. The wells, springs and points source of pollution selected for monitoring provides good geographic coverage of the study area. The groundwater flow and mass transport modelling were carried out using the Visual MODFLOW and MT3DMS codes to determine the groundwater direction and contaminant migration within the shallow unconfined aquifer of the Upper Anga'a watershed. Forward and backward particle tracks with MODPATH indicated the groundwater flow paths and a first estimation of the time scale of water transfer.

Groundwater level monitoring were carried out at 26 observation points in the watershed during the year 2008 (Fig.1). The depth to water level measurements were reduced to the mean sea level and groundwater contours were prepared to ascertain the general groundwater hydraulic gradient and the stream-aquifer interaction areas. Groundwater budget and vertical hydraulic gradient tests were realised and used for the refinement of the model output. Water level data for February 2008 were used for steady state calibration.

Groundwater Flow Model: Visual MODFLOW 4.2 software was used to determine the distribution of piezometric head and simulate groundwater flow. The model conceptualisation involved: (1) defining a simulation domain and the hydrogeological layers; (2) dividing this domain into zones, each of which possesses a unique set of hydraulic properties; (3) defining the outside boundary conditions along the six sides of the model domain; (4) determining the internal boundary conditions such as rivers, wells, recharge, evapotranspiration, drain and head dependant fluxes, which are also called stresses; and (5) collecting values of measured hydraulic head. A general form of the equation describing the transient flow of a compressible fluid in a non-homogeneous anisotropic aquifer may be derived by combining Darcy's law with the continuity equation. The three-dimensional movement of ground water of constant density through porous earth material may be described by the partial-differential equation:

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

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, 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 [26]. Detailed descriptions of the model configuration have been made earlier by [15, 27]. A brief description in regard to this study is made hereafter. The simulated model domain consists of 106 columns and 68 rows and is discretized into two layers; the first layer is unconfined while the second layer is assumed to be semi-confined after borehole logs [15]. The top layer mostly consists of 2 - 18 m clay/sandy weathered zone underlain by 15 - 25 m fractured zone. As regards boundary conditions, constant head values of 745 m and 698 m were respectively attributed at Mimboman chateau and at the Nkolo IV fish pond after analyses of piezometric maps [15, 27]. The aquifer permeability varied from $0.44 \text{ m} \cdot \text{d}^{-1}$ to $4.2 \text{ m} \cdot \text{d}^{-1}$ in the simulated domain while the distribution of the recharge value varied from 21.6 to 188 mm/y [27, 28]. Sixteen discharge points were simulated, amongst which were 8 springs with a total average discharge rate of $230 \text{ m}^3 \cdot \text{d}^{-1}$ for the simulated period of February 2008, and 8 pumping wells with a total average discharge rate of $292 \text{ m}^3 \cdot \text{d}^{-1}$. A value of $78 \text{ mm} \cdot \text{y}^{-1}$ was used for the evapotranspiration. Groundwater processes within the watershed was simulated for 10 years with stress period of 140 days. The hydraulic head for each unit was calibrated by trial and error. The parameters used for the calibration were: recharge; hydraulic conductivity, aquifer thickness and potential evapotranspiration.

Mass Transport Processes: Contaminants originating from human activities enter the subsurface environment through waste disposal practices, spills, and land application of chemicals. The establishment of effective disposal and isolation procedures for chemical wastes, the protection of public health, and the amelioration of subsurface contamination rely on the ability to predict the velocity at which contaminants move through the unsaturated and saturated zones. However, attempts to describe and predict contaminant transport cannot

succeed if major pathways and mechanisms for transport are not well defined [29]. The magnitude and direction of advective transport is controlled by the configuration of the water table or the piezometric surface, the presence of sources or sink, permeability distribution within the flow field and the flow domain [29].

Mass Transport Modelling

Governing Equations and Solution Techniques: The equation describing the transport and dispersion of a dissolved chemical in flowing groundwater is derived from the principle of conservation of mass. *This principle requires that the net mass of solute entering or leaving a specified volume of aquifer during a given time interval must equal the accumulation or loss of mass stored in that volume during that interval* [30]. The mathematical solute-transport model requires at least two partial differential equations. One is the equation of flow, from which groundwater flow velocities are obtained, and the second is the solute transport equation, whose solution gives chemical concentration in groundwater.

A generalised form of the solute-transport equation is presented by [31], in which terms are incorporated to represent chemical reactions and solute concentration both in the pore fluid and on the solid surface, as:

$$\frac{\partial C}{\partial x} = \frac{\partial}{\partial x_i} \left[D_{ij} \frac{\partial C}{\partial x_j} \right] - \frac{\partial}{\partial x_i} (v_i C) + \frac{q_s}{\theta} C_s + \sum_{k=1}^N R_k \quad (2)$$

Assuming that only equilibrium controlled linear or non-linear sorption and first order irreversible rate reactions are involved in the chemical reactions, the chemical reaction term can be expressed by [30] as:

$$\sum_{k=1}^N R_k = -\frac{\rho_b}{\theta} \frac{\partial \bar{C}}{\partial t} - \lambda \left[C + \frac{\partial \bar{C}}{\partial t} \right] \quad (3)$$

Rewriting and rearranging terms we get

$$R \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left[D_{ij} \frac{\partial C}{\partial x_j} \right] - \frac{\partial}{\partial x_j} (v_j C) + \frac{q_s}{\theta} C_s - \lambda \left(C + \frac{\rho_b}{\theta} \bar{C} \right) \quad (4)$$

where R is called the retardation factor, defined as

$$R = 1 + \frac{\rho_b}{\theta} \frac{\partial \bar{C}}{\partial C}$$

Equation (4) is the governing equation underlying the solute transport model.

where D_{ij} is the coefficient of hydrodynamic dispersion, [$L^2 T^{-1}$]; C_s is the concentration of the solute in the source or sink fluid, [ML^{-3}]; \bar{C} is the concentration of the species adsorbed on the solid (mass of solute/mass of solid); ρ_b is the bulk density of the sediment, [ML^{-3}]; R_k is the rate of production of the solute in reaction k, [$ML^{-3} T^{-1}$]; and λ is the decay constant (equal to $\ln 2 / T^{1/2}$), [T^{-1}]; t is the time [T]; λ is the porosity of the porous medium [-]; q_s is the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative) [31].

Conceptualisation of Mass Transport Modelling: MODFLOW and MT3DMS are used to make a wide range of predictions about the groundwater flow system including the distribution of solute concentration in a plume down gradient from a contaminant source, the time history of concentration at a point of interest, and much more [26]. MT3DMS can be used for modelling advection in complex anisotropic dispersion, steady-state and transient flow fields. This enables to do multi-species reactions and simulate or assess natural attenuation within a contaminant plume. It is assumed that nitrate and TDS transport in the groundwater is controlled by the advection-dispersion processes [32]. As the aquifer is shallow and the wells are generally partially penetrating ones, denitrification is considered as simplifying assumption to be absent [21]; this allowed our study to assume that nitrate is non-reactive and that retardation and absorption processes are negligible [33]. For nitrate and TDS transport modelling, advective fluxes are defined at flow sources/sinks, constant head and river boundaries [34]. During the simulation, Generalized Conjugate Gradient Solver is selected and the implicit finite difference method with upstream weighting is applied to the advection term. The dispersion package parameters assigned for the model are presented in Table 1.

The groundwater quality analysis has revealed high values of nitrate in two wells P01 and P03 located one at Nkomo II and another at Mimboman (Figure 1). Statistic on the concentrations of nitrate and TDS constituents in the water samples is displayed in Table 2. The mass

Table 1: Dispersion parameters assigned for the model

Parameters	Value
Longitudinal dispersivity	10 m
Horizontal/Longitudinal dispersivity	0.1
Vertical/Longitudinal dispersivity	0.01

Table 2: Statistic on the concentrations of nitrate and TDS constituents in the water samples

	Wells						Springs						river	Effluent rainfall	
Points	Dry			Wet			Dry			Wet			Dry	Dry	Wet
Element	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Mean	Mean	Mean
NO_3^{2-} (mg/l)	61	4.3	24.39	40	4.1	15.5	21	8.8	15.3	19	10.3	14.65	22.8	100	0.64
TDS (mg/l)	299	18.4	114.5	114	27	59.6	65	35.6	52	67.7	47.7	59.8	162	1255	60
Date	Feb 08			Oct 07			Feb 08			Oct 07			March 09		
n	9			7			5			3			1	1	3

Date: sampling date; n: number of samples

transport simulation was carried out by assigning a constant load TDS concentration of 2000 mg.l⁻¹, a hypothetical case entering the aquifer near Nkomo II and a real case of constant load nitrate concentration of 100 mg.l⁻¹ entering the aquifer at Kondengui from the Central prison sewage (Figure 1). The mean concentration for each grid block was calculated as the sum of the mass carried by all the particles located in a given block divided by the total volume of water in the block [35].

RESULTS AND DISCUSSION

The computed groundwater level contours follow the trend of observed groundwater levels during February 2008. The groundwater velocity vectors indicate the predominant flow towards the Anga'a river and present the maximum groundwater velocity in the watershed to be 0.26 m.day⁻¹ in the first layer and 0.23 m•day⁻¹ in the second layer. The groundwater velocity of 0.26 m.day⁻¹ around the fish pond is lower than the estimates

(0.37m.day⁻¹) based on the Darcy's law and higher than the estimates (0.22 m•day⁻¹) from [36]. The computed groundwater table cross section and the velocity vectors along Row 35 and Column 28 rightly showed the major groundwater circulation routes from the higher elevation points to the lowlands and the river channel. The computed and observed water level contours replicated the trend of groundwater flow and were found generally matching (+/-) 1.5 m (Fig. 3).

The sensitivity analysis during the previous modelling of the groundwater flow by the authors showed that the model was 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 was observable by the presence of dry cells in the first layer model, due to the inaccuracy of the conceptual layers model establishment [15]. Thus, calibration was improved just by adjusting the layer thickness.

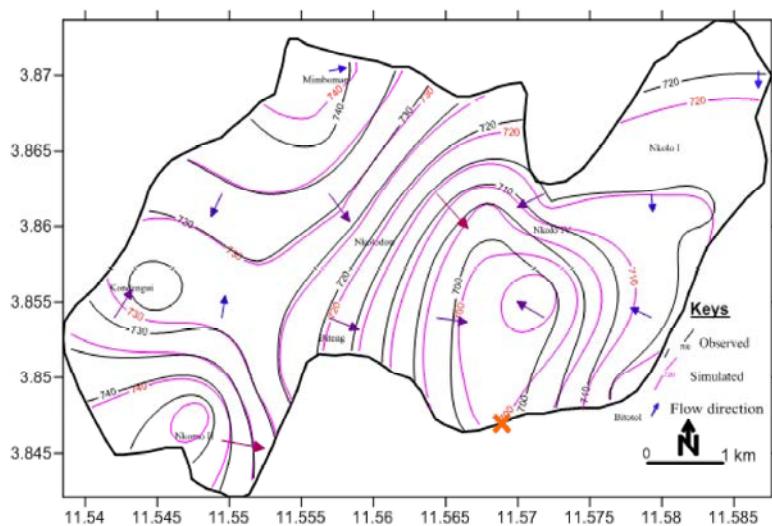


Fig. 3: Comparison of Computed vs. Observed groundwater levels in the watershed.

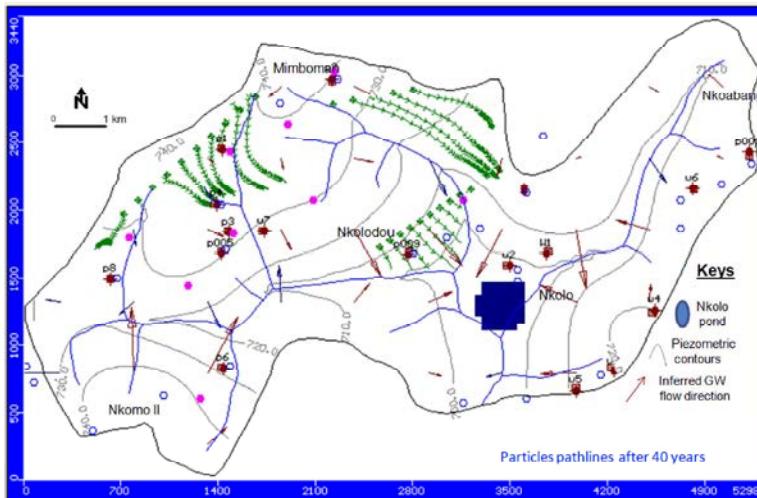


Fig. 4: Path lines of forward particles tracking simulation in the first layer after 40 years and delineation of recharge area for the fish pond in blue and the well P15.

Groundwater contours around Mimboman and Nkomo areas show a predominant flow towards river Anga'a and local flow towards Nkolo IV pond. Forward particle tracks originating from placement points extend down gradient, in the direction of groundwater flow were therefore indicative of groundwater flow paths (Figure 4). Groundwater hydraulic gradient on various sides of the stream indicates that the stream receives groundwater effluence as base flows. 40 years later after released of the particles, one can observe how far certain particles have moved (in the N and NW of the basin) while others were completely stopped. One can also observe that particles are passing throughout the river channel in the NW; this is because the water table is deeper than the river bed, and exchanges between the aquifer and the river are reduced to simple percolation of surface water to the aquifer. It is eventually observed in the North of the study area at Mimboman, a flow line of groundwater particles discharging into well P15, thus specifying the recharge area of the well. This situation is shown in Figure 4 where particles originating from the middle of the basin are intercepted by the river channel, contributing by the way to sustain the river base flow. This is a substantial proof of the aquifer-river interaction processes. Running backward particles by MODPATH enable to confirm that wells located in the North and central parts of the study area are recharged from Mimboman zone. It appears that the contaminant exposure pathways generally follow the groundwater route as exposed earlier by [15]. It helps to understand that the contaminant occurring near Nkomo II may take more than 50 years travel time to reach the Nkolo IV fish pond.

The distribution of horizontal solute concentration in the plume downgradient from contaminant entering the aquifer near Nkomo II and Mimboman zones is presented in Figure 5 after one year for the first and second layer and in Figure 6 after 20 years travelling time. The computed TDS and nitrate concentrations from the source locations indicate their migration as a plume down gradient towards the valley parts of Seng stream. It is observed that beside the advection effect, dispersion in another major process controlling the shape of the plume; this evidence gives credit to [32] assumptions. A decrease in nitrate content of groundwater samples along the groundwater flow lines is observed (Fig. 7). This is consistent with the mass transport model output which depicts the attenuation of the contaminant concentration along the groundwater flow route due partly to the anisotropic characteristic of the aquifer as revealed by [27]. To explain the strong spatial nitrate pattern in the watershed, the most likely hypothesis is a dilution with water containing a low level of nitrate [22] as reported in northern Cameroon by [10]. The simulated nitrate concentration around the stream at the outlet is 7.5 mg.L^{-1} . Thus, with 100 mg.L^{-1} in the recharge zone, some 92.5 mg.L^{-1} present in the groundwater recharge is diluted within the groundwater.

Despite the fact that basin wide nitrate pollution can be considered, the entire Nitrate values are significantly less than the 50 mg. L^{-1} drinking water standard [37] except for the prison effluent sample and the well P03. Nitrate pollution has not yet reached the admissible threshold for drinking water, but will worsen if nothing is done to prevent it. Nitrate pollution is a worldwide

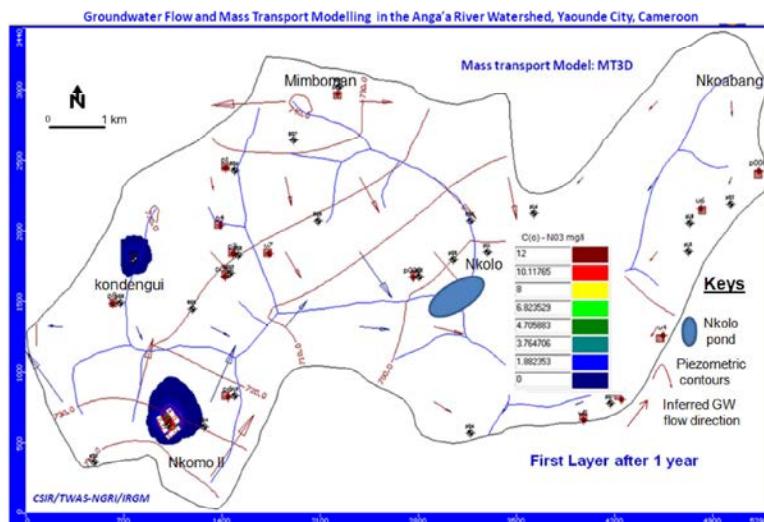


Fig. 5: Computed Lateral Migration of NO_3 Plumes at Nkomo and Kondengui sites after 1 Year

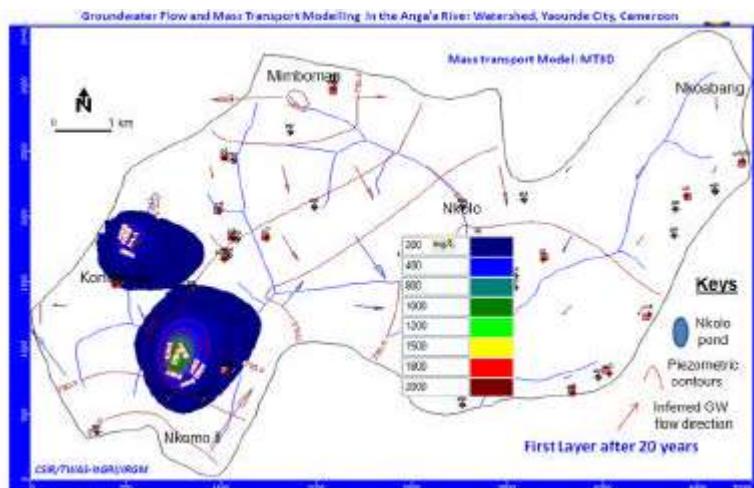


Fig. 6: Computed Lateral Migration of NO_3 Plumes at Nkomo and Kondengui sites after 20 Years

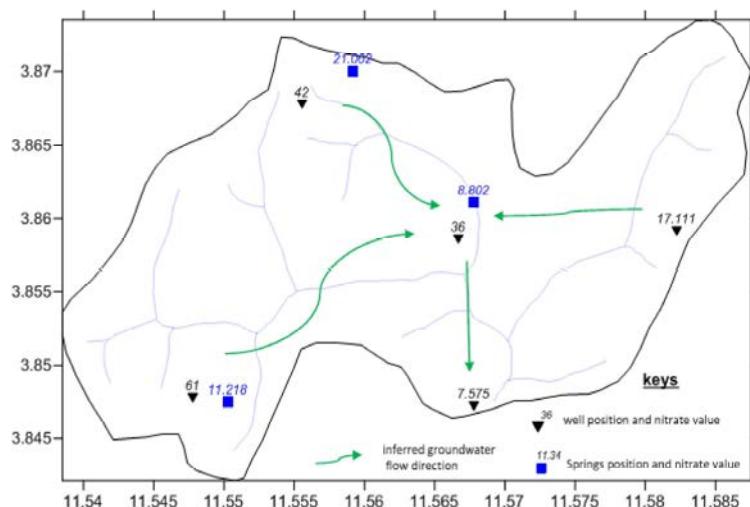


Fig. 7: Decrease in nitrate content along the inferred groundwater flow line

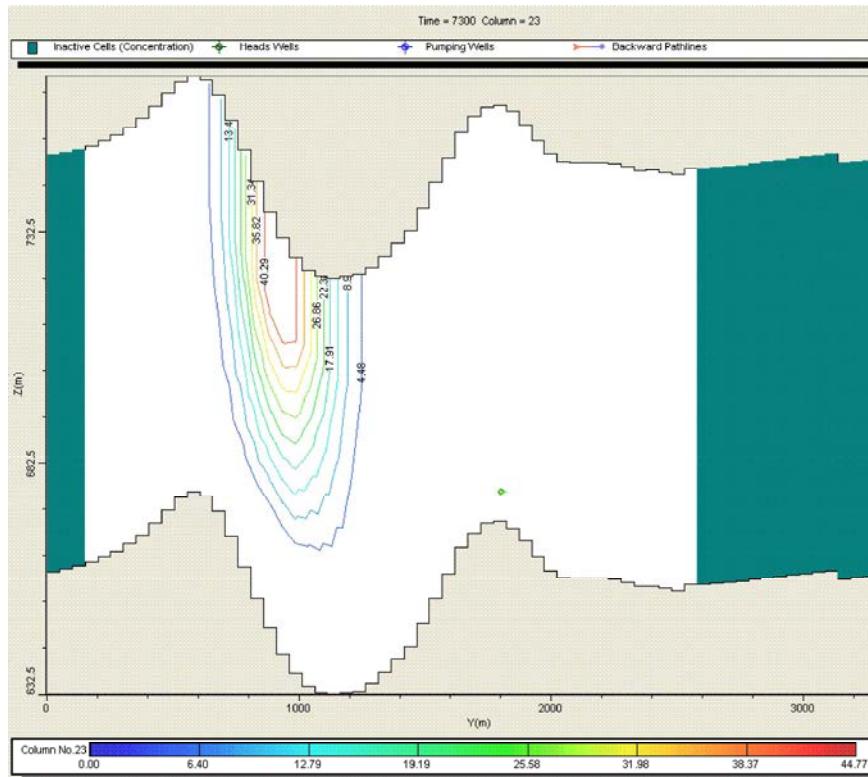


Fig. 8: Computed Vertical Migration of nitrate plume at Nkomo site, Column No 23- after 20 years

concern nowadays; high levels of nitrate can cause methemoglobinemia or “blue-baby” disease in infants. Levels of higher than 45 mg. L^{-1} (P03) may indicate excessive contamination of water supply by commercial fertilizers, organic wastes, septic systems or farm animal operations.

Vertical movement of groundwater is also important in the basin. The vertical flow of water is very important for the appraisal of pollutant transfer from the upper aquifers to the deeper ones. The cross-section view is clearly showing that the contaminant is moving slowly downwards (Fig. 8). This same model (streamline) was used for the extension of contaminant migration 50 years later. The plume shape indicates that pollutant may enter into the deeper aquifer with a velocity of $0.21 \text{ m}\cdot\text{day}^{-1}$. This cannot be considered as the diffusive effect because the groundwater velocity is not small. Therefore, the vertical movement of groundwater is responsible of the pollutant transport and the shape is due to advective processes. The chemical species plume shall travel up to about 800 m in the valley part after 50 years and the strength of the contamination will increased in terms of magnitude as well as spatially. However, simulations were realized under dry season conditions, which correspond to the lowest hydraulic gradients in the year and

consequently to the smallest groundwater velocity. Therefore, the simulated groundwater travel times obtained from the modelling must be regarded as an overestimate of the real ones. Furthermore, the model did not take into account non point pollution which may also contribute to groundwater pollution. The next step of this modelling would encompass the need to consider the dynamic state with a variable groundwater recharge in time and further to validate the model.

Mitigation of Groundwater Contamination: On-site sanitation in this study generally refers to as pit latrine, thus excluding septic tanks. They are economically attractive, but often entail groundwater pollution risk. Pit latrines are the most common on-site sanitation systems used in the Anga'a river watershed. Almost all the pit latrines used in the area are of the traditional unimproved type and do not meet the basic criteria of hygiene and accessibility to the children and disabled. Subsequently, “*flying toilets*” and spaces around the house are used for excreta disposal especially by the children. The interplay between the density of pit latrine and the population growth in the area exacerbate the magnitude of groundwater threat. Even though there is no real statistics about on-site sanitation pressure in the basin, literature

reveals 443 pit latrines per km² in the Anga'a basin [36], 957 pit latrines per km² in Manyatta-Mozambique [38]. In addition, sampling of nitrate and chloride in Manyatta has clearly shown the effect of the additional nutrient loading from pit latrines. These statistics provide clear evidence on how urbanisation can affect groundwater quality.

Pathogens do not travel farther or faster than the water in which they are suspended. The key factor that affects the removal and elimination of bacteria and viruses from groundwater used for drinking is thus the maximisation of the effluent residence time between the source of contamination and the point of water abstraction [39]. Because of the very low velocities flow within the unsaturated zone, this zone is the most important line of defence against faecal pollution of aquifers. This can be achieved by keeping the pit or infiltration surface well above the water table or by restricting the infiltration rate, which will occur naturally when the infiltration surface becomes congested.

In order to secure any water point from contamination, wellhead protection area must be clearly defined and secured for that particular point. Good design and construction of groundwater abstractions (boreholes, wells, and springs) is critical to the prevention of pollution, and key criteria include:

- Maximization of the residence time for water tapped by the borehole, well or spring, because it must be assumed that a proportion of the supply may contain water travelling from the base of a pit latrine to the water table and from there to the water supply. The travel time should exceed 25 days and where practical, exceed 50 days;
- Where aquifers are thin or where wells are the preferred water supply option, providing a 'safe' horizontal separation between pit latrines and wells will be critical;
- Improvement of the sanitary protection measures at the headworks of the water supply to limit the likelihood of localized pollution.

These measures should aim to keep sources of contamination as far away from the water supply as feasible and be as maintenance-free as practicable.

CONCLUSIONS

Groundwater flow and particle track modelling studies have highlighted groundwater conditions and particle migration in the shallow unconfined aquifer of the Upper

Anga'a river watershed. From the previous study, the computed groundwater level contours replicated the trend of observed groundwater contours. It was found that the surface topography controls the groundwater flow conditions in the Anga'a river watershed and that the general groundwater flow direction is NW-SE along the valley of river Anga'a. From the present study, the mass transport model has described the process of groundwater contamination and has simulated nitrate plume velocity of 0.21 m•day⁻¹. Particle tracks originating from points placed in selected model locations extending down-gradient from the placement point in the direction of groundwater flow indicated the groundwater flow paths. The groundwater budget indicated that the Nkolo fish pond is replenished particularly by groundwater effluence and rainfall. The model permitted to investigate the consequences of an accidental pollution allowing introduction of an amount of contaminant into the aquifer. For that, this model provides a useful framework of flow paths, a first estimation of the time scale of water and contaminant transfer; thus allowing ways for solutions. The application of groundwater modelling tool in this study has shown excellent promise for monitoring groundwater flow path, spatial and temporal pollutant migration within an aquifer system of a tropical forested area of developing countries. However, the model did not take into account non point pollution which may also contribute to groundwater pollution. The next step of this modelling would encompass the need to consider the dynamic state with a variable groundwater recharge in time and further to validate the model.

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