SIMULATION OF HEAVY METALS MOVEMENT AND CHANGE IN CONCENTRATION IN SHALLOW UNCONFINED AQUIFER IN NORTH CENTRAL NIGERIA USING VISUAL MOFLOW AND MT3DMS

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ABSTRACT

Shallow groundwater is a major water source for rural people in Minna, a rapidly growing city in North-central Nigeria. However, indiscriminate dumping and poor poultry waste management in and around the city have threatened the quality of this water source. Visual MODFLOW was used to study the loading, dynamics fate and transport of some heavy metals in Minna shallow aquifer while MT3DMS was used to predict the concentration of the heavy metals in one, three and five years' time. Conceptual model approach was employed for the simulation with the model domain discretized into 50cells each in *x* and *y* directions. Results showed that the whole aquifer was strongly contaminated with arsenic, copper and Zinc. This was presented as colour shading by visual MODFLOW. Initial concentrations of arsenic copper and zinc were 0.74mg/L, 8.43mg/L and 11.63mg/l respectively as against 0.01mg/l, 2.00mg/L and 5.00 mg/L recommended as maximum allowable contamination (MAC) for drinking water by WHO. MT3DMS predicted a progressive reduction in heavy metals concentration. For instance, a reduction in value to 0.60 mg/L, 7.51 mg/L and 4.20 mg/l were predicted for arsenic, zinc and copper respectively over five-years period. The study also revealed that the polluted shallow aquifer in Minna can be cleaned up of these heavy metals after some years.

Keywords: Contamination, prediction, shallow aquifer, heavy metals, concentration change and visual MODFLOW

INTRODUCTION

Numerical modeling technique has become an important tool in groundwater quality assessment in recent times. As a result, many visual numerical modeling softwares for groundwater have been developed and used. For instance, Finite Element Subsurface Flow system (FEFLOW), Groundwater Modeling System (GMS) and Uncertainty Analysis Visualization software package (UNCERT) have been developed and used in different parts of the globe by researchers (Wang et al., 2008). Use of software becomes imperative because water monitoring in groundwater and tracing of contaminant migration are very complicated. Researchers have observed that groundwater investigation and monitoring are difficult exercise and attention is then shifted to modeling and software techniques since the modeling

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methods are more reliable and easier to handle, though it employs mathematical equation and was also based on reasonable assumptions (Ghoraba et al., 2013).

Visual Modflow, a groundwater monitoring software which has a separate package to resolve special hydro geologic problem was developed using FORTRAN 77 language environment with the finite difference method to describe movement of groundwater and contaminant migration within aquifers (Ghoraba et al., 2013). Modflow is able to simulate a wide range of flow in porous media while MT3DMS, a 3-dimentional multi-species contaminant transport interfaced on Modflow monitors solute transport process and concentration change in the subsurface (Saghravani, 2010). Both are based on the advection-dispersion relationship to study and predict change in concentration of contaminants as they travel through a porous media. Visual Modflow uses cell-by-cell data which are computed by MODFLOW to establish results (Saghravani and Mustapha, 2011). While visual MODFLOW deals with flow hydrodynamics through porous media, MT3DMS, a solute transport model solves the problem of contaminant transport and change in concentration in the subsurface (Ghoraba et al., 2013). It simulates movement and fate of any miscible contaminant in groundwater after taking into account the advection, digestion, diffusion and other basic chemical reaction and equation (Zamri et al., 2013).

Groundwater quality monitoring is an important practice in environmental studies. It has been observed that once groundwater is contaminated, it may remain so for many years before it can be cleaned (Lautz & Siegel, 2006). Groundwater contamination sources are many; they vary from human activities and can be categorized as domestic, agricultural and industrial. Even if the sources of groundwater contamination are difficult to trace because they may come from either point or non-point sources, monitoring the contaminant movement to be able to design clean up measures is as important as groundwater treatment. Recent studies have showed that anthropogenic activities can impact natural composition of groundwater. Indiscriminate disposal of animal waste that contains harmful chemical components and microbial matter overland can have harmful effect on groundwater. Many activities have been reported (Lerner & Harris, 2009) to have the potential to increase heavy metals concentrations in groundwater if indiscriminate animal waste dumping and poor waste management process continue to be unchecked.

In Minna, a semi-arid town in North central Nigeria, for instance, importance of shallow groundwater cannot be overemphasized. Chukwu et al., (2004) research on water sources in Minna metropolis revealed that on an average, 21.67 % of Minna inhabitants use bore hole, 50.83 % use shallow wells, 14.67 % use tap, 3.5 % still depends on surface water from rivers while 9.3% use springs which dry up in the dry season and are forced to join the percentage using the shallow wells. Water consumption is high, climate being tropical, and people using shallow wells engage in manual work and crop and animal production. Therefore, it is expected that their water consumption rate will be as high as about 5-6 litres per day (Sanusi & Akinbile, 2013). Moreover, they still use water from these shallow wells to prepare food for themselves and their family members. These people therefore ingest more of these contaminants than expected and are therefore at the risk of water - borne diseases.

Arsenic and other heavy metals are metalloid element toxic to humans even at low concentration. Nickel, chromium, zinc and manganese though have good affinity for soil, there have been evidences of their presence in shallow groundwater where waste materials that are rich in heavy metal concentrations are dumped very close to shallow wells and are then released at quantities far greater than what the soil can sorb at that particular time (Pitt et al., 1999). Removal of these heavy metals by soil is also pH-dependent and their solubility increases as the solution pH decreases. It is therefore common to detect traces of heavy metals in groundwater where the overlying soil is acidic in nature (Arnade, 1999).

Epidemiological studies have shown that consumption of water containing 500μg/L of arsenic may cause internal cancer like lung and liver cancers. Smith and Smith, (2004) reported that consumption of inorganic arsenic may cause multiple illnesses in different organ of the body but the most documented are bladder, kidney and liver cancer. It is therefore reasonable to focus on cancer for the long-term risks resulting from arsenic in drinking water. Though nutritional zinc deficiency was reported in a number of countries, acute toxicity arises from ingestion of excessive zinc in water as it leads to fever, nausea, vomiting, stomach cramp and diarrhea. In some cases, acute toxic effects of cancer and cardiovascular diseases have been linked to the consumption of zinc in water above guideline value. The acute lethal dose of copper for adult is between 4 and 400 μg per kilogram of body weight after which it may lead to gastrointestinal bleeding, intravascular heamolysis, hepatocellular toxicity and renal failure. At lower dose, it may just cause nausea, vomiting, diarrhea and abdominal pain (Araya et al., 2003). Buschmann et al., (2008) assessed the quality of drinking water resources in Mekong Delta floodplain and listed the health effect of heavy metals that are present at concentrations higher than the WHO recommended value including cancer and skin damage, neurological disorder, haematological and kidney damage.

To meet nutritional requirements of the birds, several metals are supplemented in poultry feeds. It includes, iron, copper, manganese, zinc, iodine and chromium. These metals are also excreted and form major component of poultry manure. Because of mobility (though slow) of these metallic ions in the subsurface, they can also migrate into groundwater and lead to pollution though their environmental risk is a function of the ability of the soil to absorb and desorb the metals and leachability of the metals. Arsenic and chromium are often included in poultry diets because of their coccidiostatic properties. They are added in the form of 3-nitro-4-hydroxy-phenylarsenic acid (roxarsone). Average broiler feed contains about 45kg of roxarsone per one ton of feed. Arsenic is also added to the feed to increase the bird weight gain and improve feed efficiency. Consequently, arsenic and chromium are largely excreted in poultry manure. Arsenic in poultry litter is easily mobilized but strongly absorbed by most soil, thus the leaching rate into groundwater appears to be slow except in a soil with high hydraulic conductivity. Preliminary results of heavy metals analysis conducted on the poultry manure samples in Minna (Adeoye et al., 2014) revealed that arsenic in poultry manure in Minna ranged between 3.50 and 45.6mg/l, copper ranged from 19.3 to 116.3mg/l, while zinc ranged from 52.6 to 396.2mg/l. Personal interview conducted revealed uniformities in the dosage of all the trace elements addition to the feeds in all the farms visited. However, from the analysis, it was discovered that there is a wide variation in composition of these metals in the manure analyzed. Within species, farms and age of the birds and this has been attributed to a number of factors like environmental conditions and the management systems on the farms. The major concern of the heavy metals in manure which are dumped or are applied to agricultural land is loading of heavy metals in the receiving soil.

MATERIALS AND METHODS

The study area for this research is Minna, capital of Niger State, a semi – arid town in North central Nigeria, (Figure 1). The city lies in latitude 90 36' 50''N and longitude 60 33'25''. Minna has two local Governments, *Chanchaga* Local Government which has its headquarter in Minna and Bosso Local Government with headquarter in *Maikunkele*, a peri-urban slum in Minna. The population of Minna as in 2012 was 613,246 (NPC 2012). River *Chinchaga* is the major river in Minna which drains into River Kaduna at about 45km in the Northwestern side. Geology of Minna belongs to central portion of Nigerian basement complex rock of Precambrian in age though some of them are found in the early Paleozoic. The rocks have been grouped into four lithological units by Shekwolo & Brisbe (1999) as gneiss-quartzite complex, schist belts, granitoids and metamorphosed basic rocks. Aquifers in Minna are either confined or semi-confined or unconfined. The unconfined aquifer has generally a shallow water table of about 20meters in thickness though, perched conditions exist in some places, (Alabi, 2011). Minna aquifer is recharged through rainfall. Other climatic conditions in

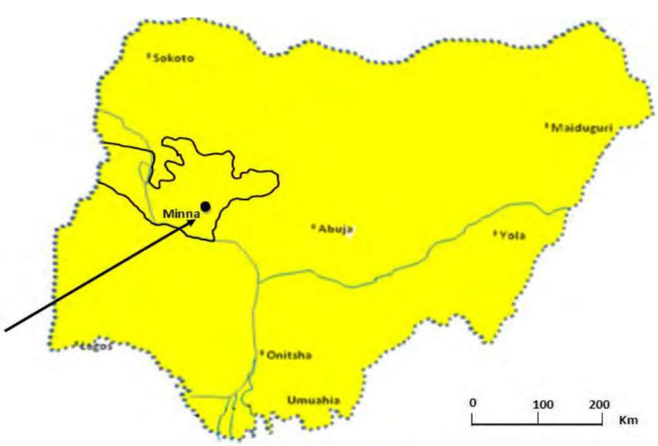

FIGURE 1
Map of Nigeria Showing Location of Niger State

Minna are presented in Table 1.

Recharge to the shallow aquifer based on soil-moisture balance approach conducted by Adesiji & Jimoh, (2012) on dynamics of groundwater flow in Minna revealed that rainfall is the major source of recharge to Minna aquifer and the recharge is estimated to be 22% of the total annual precipitation. The major source of groundwater supply in Minna is shallow open wells (depth usually less than 15m) because of their high yield and relatively cheaper method of construction. The average static water level in Minna has been found to be 5.86m by Idris-Nda, (2010) when he conducted an aquifer test in Minna metropolis to assess the hydraulic properties of the shallow aquifer using Cooper-Jacob method.

Groundwater Quality in Minna

Many groundwater quality assessments have been carried out in Minna and the shallow aquifer of Minna has been discovered to be vulnerable to pollution from agricultural, domestic and industrial wastes. This was attributed to high permeability of the top soil which offers little protection to underlying aquifer. Shekwolo & Brisbe, (1999) and Alabi, (2012), reported poor bacteriological quality of groundwater close to domestic and industrial waste dumps in Niger State. Also, Jimoh et al., (2003) found high concentration of electrical conductivity (EC) and total dissolved solids in shallow groundwater in Minna peri-urban environments and the concentrations were attributed to various industrial effluents and concentration of abattoir activities in the area. Salami et al., (2008) attributed high concentration of lead, arsenic, and chromium in Minna shallow groundwater to contamination from petrol chemical industries which directly release their effluents to soil without any treatment. Seasonal variations of all these parameters have been recorded by all the researchers.

During the course of this research, information and available data were sought from the archives of Niger State Ministry of Health and Minna General Hospital on the prevalence of water borne diseases in Minna. The result showed a high trend in water borne diseases, the prevalence of which were high at present and will rise if water quality of these shallow wells is allowed to worsen further. There is a sharp increase in prevalence of typhoid, diarrhea and cholera, the three most deadly water borne diseases with few records of Amoebiasis, blue baby and giardiasis. Findings from the hospital also showed that the out-patient and in-patient in the hospital increased by almost 33 % during the wet season. This may likely confirm the linkage of diseases in Minna hospitals to poor water supply since research has confirmed poorer water quality from Minna shallow wells in the wet season (Adeoye et al., 2012). It is believed that one tenth of the diseases in Minna, Nigeria can be prevented by improved water supply and efficient management of water resources and animal wastes.

Simulation with Visual Modflow

To be able to simulate contamination of groundwater and

TABLE 1
Climatic and Aquifer Conditions in Minna

Climatic Factors	Minimum	Maximum
Annual Precipitation	1100mm	1300mm
Daily Sunshine Hours	6.4	9.2
Average temperature	19^0C	40^0C
Evapotranspiration	25mm	90mm
Aquifer Permeability	0.44m/day	0.6m/day
Aquifer Transmisivity	$55m^2$/day	$185m^2$/day
Storage coefficient	2.6 X 10^{-3}	4.4 X10^{-3}

Source: Edoga & Suzzy, 2008, and Adesiji & Jimoh, 2012.

to determine groundwater movement in Minna, the following data were used as input parameters into visual MODFLOW to study the conditions of Minna shallow aquifer with respect to heavy metals concentration and movement.

- The elevation of each of the well sampled above mean sea level (AMSL)
- The initial concentrations of the chemical parameters under consideration.
- Soil and aquifer characteristics of the area like thickness of the soil layer, hydraulic conductivity, dispersitivity, bulk density specific storage, evapotranspiration, specific yield, effective and total porosity (Table 2).

Apart from soil properties, other input parameters into the model are concentration of the contaminant, groundwater level above mean sea level, evapotranspiration and groundwater recharge. The visual MODFLOW 4.2 was used to develop the loadings, dynamics, fate and transports of all these chemical parameters in shallow groundwater of Minna. It gives a better understanding and quantification of fate and transport of these chemical parameters in shallow groundwater.

Conceptual Model Development

Table 3 presents the initial aquifer parameters used in conceptual model development. The conceptual model approach was used because the geometry of the model domain is very complex.

The Sampling points in Table 3 are the poultry farms where the shallow wells from which samples were collected are located. The coordinates of the farms were employed to develop the base map used for the conceptual model.

This approach represents the essential part of the groundwater system by mathematical terms. Because of the way the shallow wells are pumped, steady- state condition occurs around the wells and cone of depression is assumed to be constant. The geological and geographical map of the study area was

TABLE 2
Soil Properties Used in Visual Modflow

Properties	Values
Soil Type	Sand
Hydraulic Conductivity K (m/s)	9.91E-6
Total Porosity	0.47
Effective Porosity	0.36
Specific Yield	0.24
Specific Storage	2.7E-3
Dispersivity (m)	0.19

TABLE 3
Heavy Metal Values in the Shallow Wells Sampled

Parameters	Arsenic (mg/L)	Copper (mg/L)	Chromium (mg/L)
	MAC = 0.01 mg/L	MAC = 2.00 mg/L	MAC = 5.00mg/L
SAMPLING POINTS	*Average values obtained*	*Average values obtained*	*Average values obtained*
ABD	0.64* ± 0.00	2.96 ± 0.29	5.21 ± 0.98
ABT	0.52 ± 0.00	3.03 ± 0.08	0.00 ± 0.00
ALA	0.06 ± 0.00	1.61 ± 0.00	0.00 ± 0.0
BAC	0.72 ± 0.01	3.61 ± 0.32	6.69 ± 1.03
ELK	0.69 ± 0.03	5.61 ± 0.15	3.21 ± 0.07
FUT	0.00± 0.00	0 .00± 0.00	5.21 ± 0.21
IK	0.71 ± 0.07	3.64 ± 0.92	8.29 ± 0.68
JAM	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
JML	0 .00± 0.00	0.00 ± 0.00	0.00 ± 0.00
JOE	0 .29± 0.00	3.34 ± 0.20	0.00 ± 0.00
JUM	0.66 ± 0.10	3.91 ± 0.03	7.64 ± 1.04
JMR	0.00 ± 0.00	0.96 ± 0.04	1.48 ± 0.00
LIM	0.74 ± 0.03	6.96 ± 1.02	8.48 ± 0.42
MIL	0.61 ± 0.02	8.43 ± 0.68	11.63 ± 1.02
NAD	0.62 ± 0.09	3.43 ± 0.57	4.21 ± 0.11
NAB	0.00± 0.00	0 .00± 0.00	0 .00± 0.00
NAN	0.04 ± 0.00	0.00 ± 0.00	0.90 ± 0.03
NAT	0.00 ± 0.00	4.21 ± 0.11	0.00 ± 0.00
NGS	0 .05 ± 0.00	0.71 ± 0.08	2.36 ± 0.00
SRY	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Values are means of Triplicate reading ± standard deviation. MAC- Maximum Allowable Concentration

imported and registered and they were used to develop the conceptual model. The three-dimensional groundwater flow equation for confined and unconfined aquifer that assumes the groundwater movement occurs in heterogeneous and anisotropic medium was used, (Equation 1)

$$S\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)-Q \qquad (1)$$

Where K_x, K_y and K_z are hydraulic conductivities to x, y and z orientation (m/d), h is the water head (m), S is the storage coefficient of the aquifer (1/m) and Q is the source and sink items (1/d). This equation was combined with the three-dimensional equation to describe the rate of contaminants transport, equation 2.

$$\frac{\partial c}{\partial t}=-\frac{\partial}{\partial x_i}(cv_i)+\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right)+R_c \qquad (2)$$

Where c is the concentration of the solute (mg/l), R_c is the radius of sinks, D_{ij} is the dispersion coefficient tensor and V_i is the velocity tensor.

Boundary Conditions

Boundary conditions are necessary when running a MODFLOW program to describe the exchange of flow between the model area and external system. For this particular study, the boundary conditions considered are Constant Head Boundary (CHB) conditions and Wall Boundary (WB) Conditions. CHB act as an infinite source of water entering the aquifer system while the WB is material of low permeability features which obstruct the movement of groundwater. The domain was discretized into 50 cells each in x and y direction. The modeling domain was selected according to natural hydrogeological boundaries, over an area with *x* coordinate 222222 – 245000 m, and *y* coordinate 1052400 – 1071000m. The base map that was super-imposed on the model was digitized map of the study area. The conceptual model receives lateral infiltration recharge from *Chanchaga* River from the east side. In the west, Tagwai dam was defined as CHB and below is the river *chanchaga* as another boundary. The model also receives recharge from precipitation and the only discharge from the model is through evapotranspiration. Figure 2 shows the model domain and the coordinates. The conceptual model was developed based on the following assumptions that the groundwater flow directions and head are constant during the period of simulation for steady state modeling condition.

It is also assumed that the aquifer is homogenous unconfined aquifer and that hydraulic head is constant (Saghravani et al., 2011). K_y in equation 3.6 is assumed to be 10% of K_x and K_z is assumed to be 10% of K_y (Ghoraba et al., 2013).

Calibration of the Model

The developed conceptual model was run under steady-state condition with a 1 day simulation period as starting point. The calibration process is a process whereby the model input parameters are adjusted until the observed data matched the computed data. For model suitability, the calibration exercise was done with the real historic data and adjusting the model until it produced results within a reasonable error to determine which factors of the model is sensitive to understand better the real system and practically to evaluate the worth of the data collection (UPM Hydrogeological Research Team, 2012). The output parameters expected from the models are predicted concentration of selected heavy metals in Minna shallow aquifer for 1, 3, and 5 years. These outputs are expected to be presented in form of colour shading in the aquifer.

RESULTS AND DISCUSSIONS

Visual MODFLOW Simulation

The summary of simulation results is presented in Table 4. The overall simulation results for each contaminant considered is presented in form of colour shading for 365days, 1095 days and 1825 days. From Figures 3 -11 which are results for copper, zinc and arsenic, it was revealed that the whole aquifer under investigation is contaminated with heavy metals. The predicted concentrations of the contaminants are higher than MCL even after five years though with decreased values if compared with initial concentrations. There are zones of zero contaminants (Blue zone) very close to Constant Head Boundary (CHB) that was very distinct after one year but there is migration of the contaminant towards the CHB after 3 and 5 years. This may mean that the contaminant plume is also migrating towards the lake and as a result, leading to reduction in concentration in the main aquifer. A sharp reduction in concentration of nitrate was also observed between 3 and 5 years. This may be as a result of fast subsur-

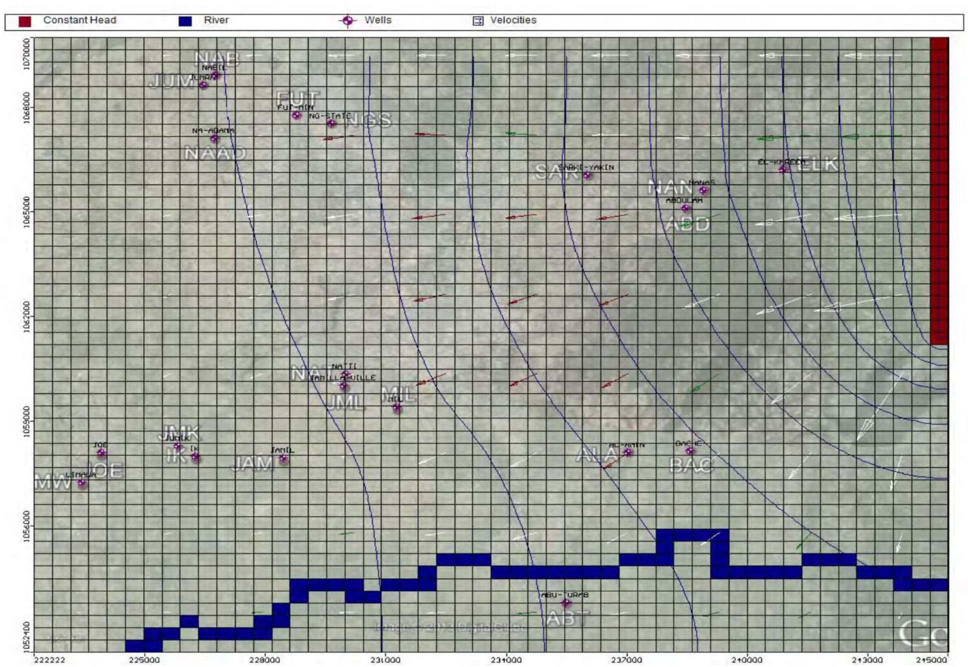

FIGURE 2
The Conceptual Model Domain Showing Flow Direction and Boundaries

TABLE 4
Summary of Observed and Predicted Contaminants Concentrations

Contaminants	MAC* (mg/L)	Initial (mg/L)		Predicted(mg/L)					
				365 Days		1095 Days		1825 Days	
		Min	Max	Min	Max	Min	Max	Min	Max
Arsenic	0.01	0.00	0.74	0.00	0.63	0.00	0.61	0.00	0.60
Zinc	0.05	0.00	11.63	0.00	7.64	0.00	7.64	0.00	7.51
Copper	2.00	0.00	8.43	0.00	7.02	0.00	4.41	0.00	4.20

**MAC- Maximum Allowable Concentration*

face nitrate migration into deep aquifer or dispersion into reservoirs adjacent the study area. The reduced concentration may also be as a result of decay function because MT3DMS model incorporate a first order decay reaction and sorption of the solute to predict what the concentration would be in the specified days.

Generally, Visual MODFLOW predicted the concentrations of the five contaminants considered based on the as-

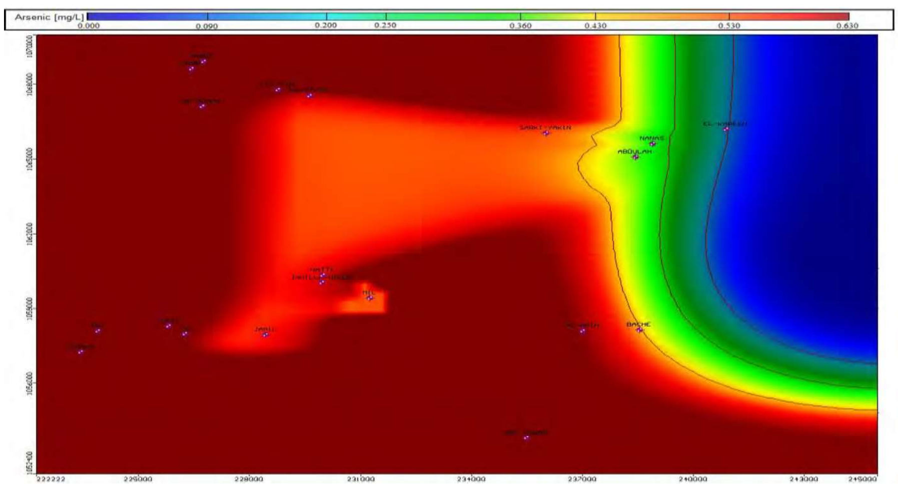

FIGURE 3
Predicted Arsenic Concentration after 365 Days

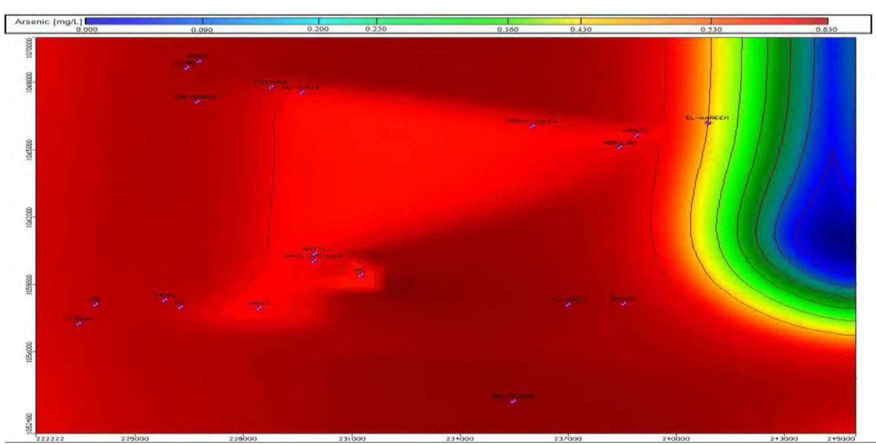

FIGURE 4
Predicted Arsenic Concentration after 1095 Days