



Groundwater Flow Model and Particle Track Analysis for Selecting Water Quality Monitoring Well Sites, and Soil Sampling Profiles

Michael A. Nwachukwu, Huan Feng and Duke Ophori*

Abstract

Researchers often use only surface drainage (imperical method) as a tradition to locate sites for installation of water quality monitoring wells, and soil sampling profile for pollution studies in urban areas. They neglect that structural development may have altered the natural surface drainage. This paper demonstrates an advanced method; combining surface imperical method with a three-dimensional groundwater flow model and particle track analysis. This was performed using transient MODFLOW and MODPATH codes, as a first step in a pollution study of Owerri urban areas. Result was more reliable, showing diverging flows at Orji and Nekede auto-mechanic villages (MVs) due to relatively high elevation with the surroundings, and southward flow at the Obinze municipal waste dump (MWD). There were vertical flows at the sewage dumps (mangrove swamp areas) between Egbeda and Umuapu, and convergent flows along stream valleys. Particle tracking show an extended capture zone lying southeast. A total of eight water quality monitoring wells (WQ) was then recommended according to the directions of groundwater flow and particle releases from three tracking wells (ABC). WQ₁: SE of Orji MV, WQ₂: SE of Nekede MV, WQ₃: south of Obinze MWD, WQ₄: west of Egbeda, and WQ₅: east of Umuapu. WQ₆: NE of well A, WQ₇: SW of well B, and WQ₈: NE of well C. Soil sampling profiles; MVs: SE, MWD: South and sewage dumps: East and West. Distance of monitoring wells will vary according to the proximity of human settlements and shallow domestic wells (37m-55m) to the sites.

Keyword: Mechanic villages; heavy metals; modelling; pollution studies; Imo River basin

1. Introduction

A number of literature materials exist on different processes of proper sitting of monitoring wells based on the character of groundwater flow, and dimensions of the contaminated field. Hudak (1999) devised a graphical heuristic for locating up gradient groundwater monitoring wells near landfills, and observed that it can be adapted to no uniform flow fields, nonlinear migration boundaries, and irregularly shaped landfills oriented at various angles to the direction of groundwater flow. Moline et al. (1998) observed that the need for adequate characterization of spatial and temporal variations of groundwater flow are for appropriate placement and construction of monitoring wells, timing of ground water monitoring, and evaluation of exposure risk and contaminant flux in support of remedial decision-making. Hudak (2001), observed that in the non-linear network, groundwater monitoring wells clustered near the down-gradient corner of a landfill registered 100% detection efficiency. This strategy was effective because the cut-off wall induced convergent groundwater flow beneath the landfill. This study suggests that distorted hydraulic head fields induced by partial cut-off walls will be considered when designing detection monitoring networks at landfills. Advances in numerical modelling software such as MODFLOW (McDonald and Harbough, 1988) has simplified the study of groundwater flow, which in this paper is been

Department of Earth & Environmental Studies, Montclair State University New Jersey U.S.A

**Corresponding Author: Phone: +1973-655-3456; E-mail: nwachukwu1@mail.montclair.edu*

extended to selecting sites for groundwater quality monitoring wells. Spilling the occupational wastes of mechanics on the ground has been a common practice in the region for over 25 years (Nwachukwu et al., 2010a). There is no enforced regulation for the disposal of municipal solid waste and sewage. Solid waste is disposed of by open dumping at several locations (Ibe and Njoku, 1999), and Ibe et al., 2007). Sewage evacuated from soak-away pits present in virtually every household, is mixed with soil, and used as manure on farm lands around the southwest flank in the area.

This work models the flow regime of ground water over the entire area and the migration of particles from four contaminated sites: two mechanic villages (Orji and Nekede, marked in figure 1b), the solid waste dump, and the farmlands sewage dumps. The present study has three main objectives: to produce a 3-D groundwater flow model of the area; to select locations for water quality monitoring wells using the flow model as a guide; and to select the directions of soil sampling profiles for heavy metal analysis. In the long run, future research should provide a quantitative analysis of water quality in the newly installed monitoring wells, and continuous measurement of groundwater chemistry with respect to trace metals.

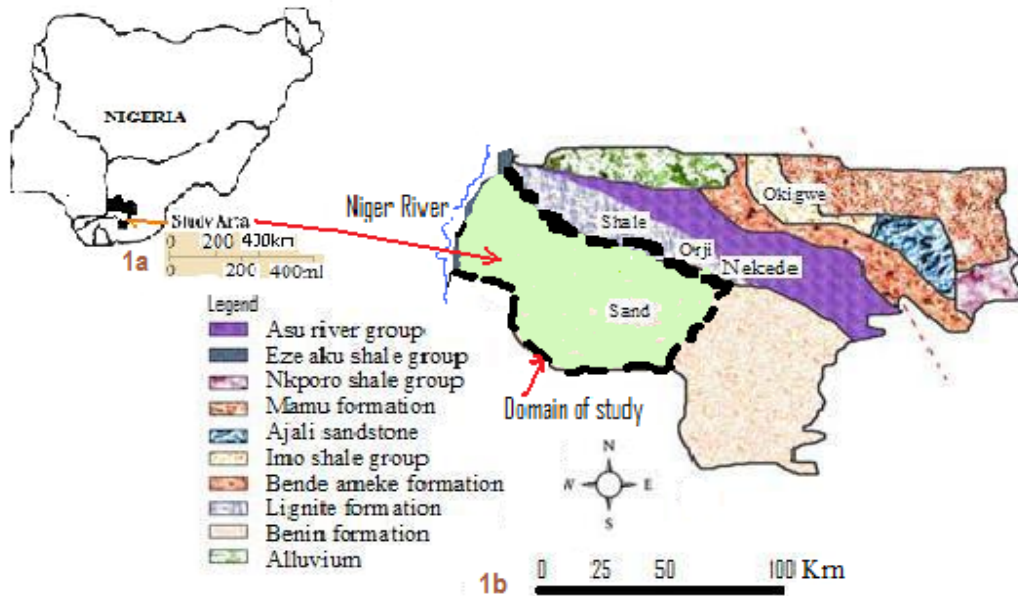


Fig. 1a and 1b: Map of Nigeria showing Imo River basin; 1b: Geologic Map of the Imo River basin adapted from [5], showing the model domain within the Benin Formation (Coastal plain sand).

The Imo River basin is a 140 km north-south trending sedimentary syncline located in the upper Niger delta within the middle of south-eastern Nigeria. The Imo River drains into the Niger River that empties into the Atlantic Ocean. The Benin Formation (BF) within the Imo River basin (Figure 1a) consists of unconsolidated yellow and white coastal plain sands with gravel beds, occasionally pebbly with grey sandy clay lenses (Nwachukwu et al., 2010a). The BF is continental in origin, and accurately represents the delta plain facies. Many aquifers with portable water occur in this region (Ophori, 2007). Near surface unconfined aquifers are the main sources of water to both public and private wells. These aquifers are especially prolific along the southern flank of the study domain occurring at depths of about 70-100 m (Uma and Egboka, 1986). The rainfall is heavy (about 2400 mm/year) and especially intense from April to October. All the most important rivers in the basin are tributaries of the Imo River: Njaba, Otamiri, Oramiriukwa, Orashi, Mba, Nwangele, Azumini Blue River, and the Aba Rivers, also is the Oguta Lake.

According to the 2007 census statistical data the Owerri municipality has a population of 3.5million people distributed over a land area of 130 km². The metropolitan area is 100 km², and the total water area is 20km². The relatively high population density (1400 person/km²) and small metro area imply high waste generation, that must be supported by adequate waste management. The lack of proper controls on waste disposal, and poor waste management in general remain major threats to water resources and public health in the area. Using relative background values, Liu et al. (2007) assessed soil pollution in seven waste dumps and came to the following conclusions: (1) domestic waste dumped on level ground pollutes to a distance of about 85m; and (2) the horizontal transport distance of pollutants can be as high as 120m if the waste leachates are directly connected to water in saturated soils; In the tropical rain forest, and coastal plain sand regions of the study area, characterized by a high rate of infiltration, high conductivity and high transmissivity values, the migration distance of chemicals and toxic heavy metals would far exceed the above values. The occupational wastes of mechanic villages, municipal solid wastes, and untreated sewage can cause high concentrations of toxic elements such as: Pb, As, Hg, manganese (Mn), copper (Cu), zinc (Zn), chromium (Cr), and cadmium (Cd), in nearby soil. In highly permeable sand or a rain forest belt media typical of the study area, water resources also easily become contaminated. Public opinion holds long-term exposure to such toxic chemicals in water and food responsible for the recent and growing prevalence of non-traditional health issues in the basin. However this explanation is still hypothetical due to a total absence of observation wells for monitoring of groundwater quality, and poor disease statistics in the area.

Previous groundwater flow assessments in the area were based on empirical methods, thus Ibe and Uzoukwu (2001), found groundwater flow to the SW in the Owerri area based mainly on topographic analysis. Nwankwo and Anyaogu (2000) described groundwater's interaction with wetland and streams based on piezometric data in part of the study area. Ibe and Njoku (1999) used the electrical resistivity method to observe groundwater flow from the abandoned solid waste dump near Obinze. Their result indicates flows in three directions: NE-SE, N-S, and E-W. Using environmental impact models, Ibe et al. (2007) also reported that pollutants could easily migrate to the water table and immediately contaminate groundwater. This result emphasizes the vulnerability of water resources in the southern parts of the Imo River basin. However none of these studies has used a standard numerical code to model or assess groundwater flow and contaminant transport at any particular contaminated site in the area. Anderson and Woessner (2002) remarked that in a steady state simulation, the shape and conditions of the boundary largely determine the flow pattern. We therefore carefully considered boundary conditions while selecting our problem domain. Barry, et al. (2009), used a groundwater flow and capture zone model to discuss well quality protection in the central Passaic River basin. They observed that the capture zone is dependent on the hydraulic characteristics of the aquifer, and the rate of pumping. We anticipate that this model will also be expanded as new investigation targets become established. At the mean time the model is intended to provide site-specific determinations of hydrologic condition at the mechanic villages of Orji and Nekede, an abandoned open municipal solid waste dump along Obinze, and a cluster of open sewage disposal sites in the southwest flank of the basin.

2. Materials and methods

The topographic base map was reproduced from a zonal atlas covering the model domain (figure 2). The greater part of the domain towards the Niger Delta is low lying, with an average elevation of 62m. We

identified nine wells for particle tracking. The nine reference wells helped to visualize lines of interaction between the two mechanic villages and nearby wells. These are data obtained predominantly during well servicing. In the absence of observation wells, groundwater elevations were determined from accessible pumping wells. In the Imo River basin, most pumping wells are private, and inaccessible to research. We used GPS to measure well site elevations, and the depth to water either directly measured from existing wells or obtained from pumping test data. The upper shale unit of the Ameke Formation (Figure 1a), to the north of the study area is a no-flow boundary. The Oramiriukwa River is not a hydraulic boundary as it is too close to the target sites. The Imo River on the east and the Niger River on the west were considered no-flow boundaries due to flow symmetry. The south boundary is a distant highway running between Aba and Portharcourt, far enough from the zone of interest, and thus was considered a no-flow boundary. All these features are present in figure 2. The groundwater flow assumed advective, despite the presence of several shallow wells of very low yields. These are predominantly private wells of very low pumping capacity, in a steady state with the isotropic and homogenous coastal plain sand. The model domain indicated in the geologic map (figure 1b) is located in the coastal plain sand or the Benin Formation (BF). The average thickness of this formation within the study area is about 800 m (Avbovbo, 1978).

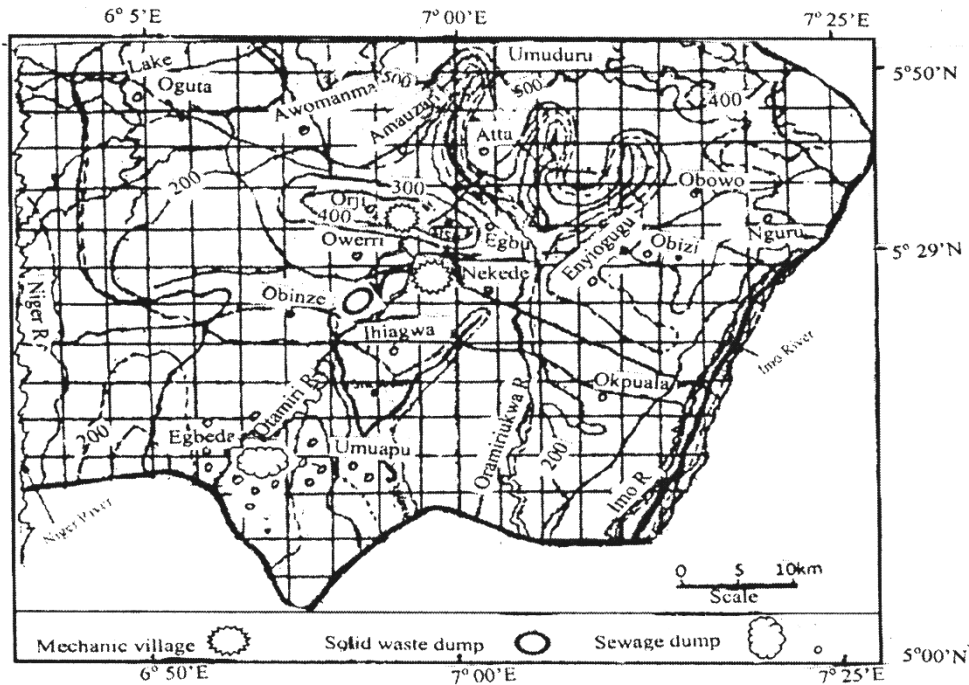


Fig. 2: Topographic Map of the Domain of study

The contaminated sites of great concerns are the abandoned solid waste dump near Obinze, the sewage dumping area, and the mechanic villages (MVs) at Orji and Nekede as identified in the model domain topographic map (Figure 2). The presence of near surface unconfined aquifer system in the area is responsible to the proliferation of shallow private/commercial wells (120-230 ft) within and around the domain of study. A typical geologic section (geo-electric) was obtained by vertical electric sounding (VES) conducted between the MVs of Orji and Nekede, approximately at the center of the conceptual domain (Figure 3). For the purposes of the model, this section approximates the near surface lithology of the study area. A lithologic explanation of the VES section is described in table 1. There are six layers; of

which the fifth layer composed predominantly of fine sand, and the sixth layer composed of silty sand and clay lenses. The fourth layer is a prospective upper horizon for the water table aquifer and all the shallow wells in the area terminate at or slightly before this depth of 84 m (Table 1). This depth represents the average base of layer-4 across the domain, and used as the working depth of the model. An interpretation of the six-layer VES curve, which also places the base of the prospective upper aquifer horizon at 84 m, is presented in Table 1. This information was useful in formulating the model layers.

Table 1: Description of VES geo-electric section of the study area

Layer	Ohm-m	Depth (m)	Lithologic description
1	830	7.0	Topsoil
2	800	32.4	Silty-sand
3	2583	58.0	Sand/gravel
4	1700	84.0	Coarse-medium sand
5	1300	120.0	Fine-medium sand
6	715	Not terminated	Silty sand

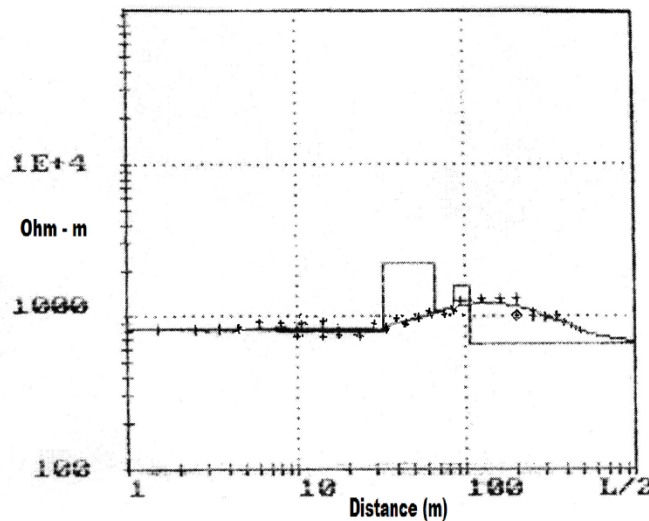


Fig. 3: VES curve, of the model area

In this study, water wells with total cased depths (TCDs) of 70 - 106 m are classified as medium wells in the area, while those with TCDs greater than 106 m are classified deep wells. The few public wells in the basin are medium or deep. They penetrate layer 5, some terminating at the base of the layer, and they produce water of better quality. However, most of the private and commercial wells in the basin are shallow (< 70 m). These wells are most at risk of pollution, so are prime targets for groundwater quality monitoring. Hydraulic conductivity in the region varies from 1.24 m/day at Amuzukwu to 26.41 m/day at Obinze near Nekede. Transmissivity varies from 41m²/day at Osuachara to 1370 m²/day at Obinze (Ekwe et al., 2006). Both Amuzukwu and Osuachara are located in less permeable geologic units, and lie outside the model domain. Thus, the numerical model can safely adopt a more limited range of hydraulic conductivities appropriate to the isotropic and homogenous subsurface layer of the coastal plain sand.

The horizontal hydraulic conductivity is 12-20 m/day depending on the layer (Table 2). The annual groundwater recharge in the area is 3.4×10^9 m³. The depth to the water table decreases southwards, while hydraulic head gradients vary between 0.09 and 0.22 (Ibe et al., 2007). Based on the average annual recharge rates, we used an average daily recharge rate of 9.315×10^6 m³ in the input model. Precipitation ranges from 18mm in December to 362mm in September, and represents the main source of recharge for both surface water and groundwater in the basin.

Table 2: Description of the layers

Model Layer	Top Elevation (m)	Bottom Elevation (m)	Lithologic Description of the layers	Horizontal Hydraulic Conductivity (m/day)	Vertical Anisotropy
1	84	60	Top soil: Lateritic,	20	6
2	60	45	Silty sand	15	3
3	45	30	Sand-Gravel* (water table)	15	3
4	30	15	Medium sand*	12	3
5	15	0	Coarse-medium sand**	12	3
-	Base	-	Medium-fine sand	-	-

** Most likely unconfined aquifer horizon, * Saturated

The assumed flow rates are -11000 in layer 1, -0.25 in layers 2 and 3, and -1300 in the two bottom layers, with the negative sign indicating water extraction. An average conductance of 8200 was assumed for all layers. The initial head value of each cell in layer 1 is the elevation of the cell digitized from the topographic base map. Within each other layer, the cells were assigned identical initial head values as follows: 60m in layer 2, 40m in layer 3, 28m in layer 4, and 10m in layer 5. All these values lie between the bottom and top elevations of their respective layers. A total of nine reference wells were used in the model and for the particle tracking and the well characteristics obtained from field measurements are as shown (Table 3).

Table 3: Reference well characteristics

Location of wells	Well #	X,Y(grid cell)	Elevation (m)	Depth to water (m)	Head (m)
Owerri	1	9,6	62	22	40
Obinze	2	7,8	62	20	42
Ihiagwa	3	9,8	62	22	40
Egbu	4	12,6	70	35	35
Okpuala	5	15,10	70	30	40
Umuapu	6	8,11	62	20	42
Obizi	7	16,6	90	40	50
Awomama	8	7,3	105	50	55
Obowo	9	16,5	90	50	40
Orji Mech. Villa		9,5	136	Area = 0.41km ²	
Nekede Mech. Villa		10,7	110	Area = 0.55km ²	

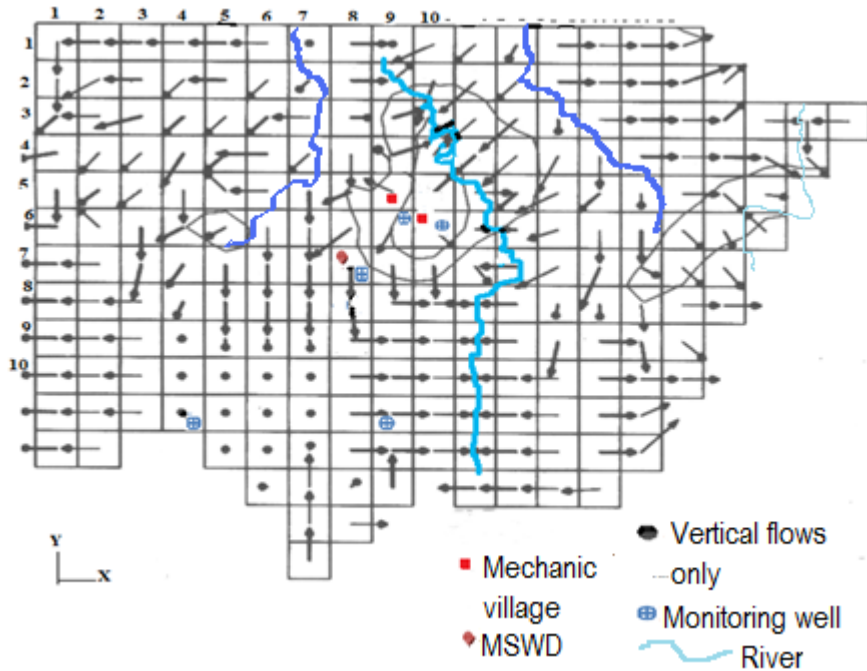
MODFLOW [4], uses a block centred finite difference scheme to describe the saturated zone. MODFLOW excels in assessing groundwater flow, but surface runoff and unsaturated flows are not included. In MODFLOW, three-dimensional steady state saturated flow in a sandy formation is governed by the following partial differential equation:

$$\frac{\partial}{\partial x} \left[K_{xx} \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[K_{yy} \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z} \left[K_{zz} \frac{\partial h}{\partial z} \right] \approx 0$$

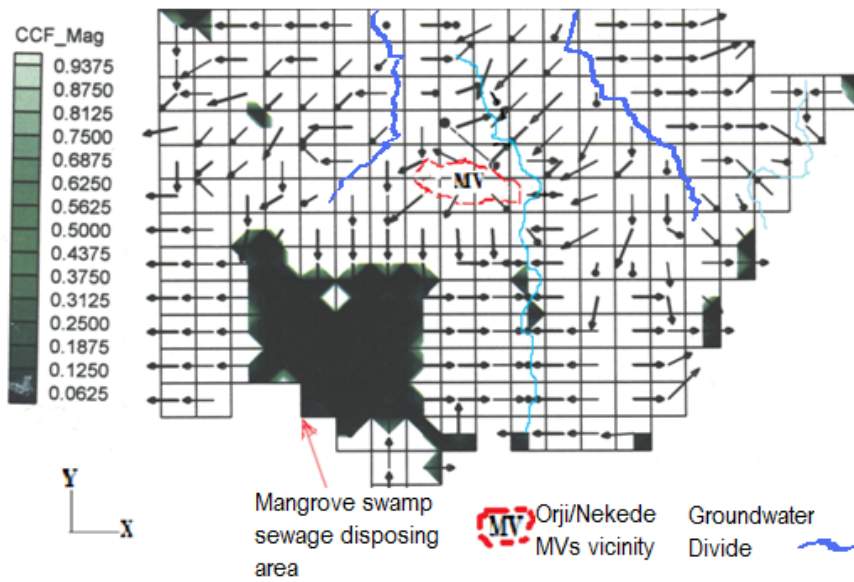
Where, K_{xx} , K_{yy} , and K_{zz} are the hydraulic conductivities along the x, y, and z axes respectively. In this case, the coordinate axes are parallel to the major axes of hydraulic conductivity. The dependent variable (h) is the piezometric head.

3. Results and discussion

The numerical model (Figure 4a and 4b) was calibrated with (Ibe et al., 2007), based on the analysis of piezometric data and the use of multiple codes (Figure 5a and 5b). The convergent flow patterns along river channels (Figure 4a) conformed to the flow pattern presented in figure 5a that was limited to river channels only. Again, the highly contaminated sewage disposal area southwest of figure 4b also conformed to the area marked as highly vulnerable (Figure 5b), and the groundwater divides in the north section of the numerical model similarly reflecting in figure 5a (Ibe et al., 2007). In the first and second layers, flow is predominantly downward with minor indications of horizontal motion to the south/southeast. The result indicates that model layers 4 and 5 are the flooded horizons, representing the prospective aquifer layers, in agreement with the VES data used in the model (Figure 3). Figures 4a and 4b shows the flow vectors observed in layer 5. There is no preferred flow direction of the water table aquifer. In the vertical sections of layer 5 (Figures 4c and 4d), the flow is predominant in the upward and downward directions. Large dots in the lower section indicate purely vertical flows. The mechanic villages of Orji and Nekede are located at $x = 9$, $y = 5$, and $x = 10$, $y = 6$ respectively (Figure 4a).



(4a)



(4b)

Fig. 4: (a and b); Groundwater flow pattern based on model layer 5, in the SW portion is the highly contaminated sewage dump mangrove swamp area of Umuapu and Egbeda

The Oramiriukwa River channel is mapped out in the model following the conspicuous convergent flows along the river channel. The model shows flows in the east and west flanks towards the Otamiri River and the Niger River respectively, and significant flow to the south. The mangrove swamp area around Umuapu (sewage disposing area) is characterized by no lateral flow but vertical flows with constant head (Figures 4a and 4b). The flow reversal below the sewage disposing area indicates higher elevation beyond the area confirming the mangrove swamp area as depressed land. The Orji and Nekede mechanic villages are shown with divergent flows, due to their high elevation (131m (430ft) and 110m (360ft) respectively, with respect to a background elevation of 60m (200ft). This high elevation difference enhances contaminant transport from the mechanic villages. Ben-Yitzhak et al. (2005) observed that geological folding influences flow direction, diverting groundwater along synclinal axes, and (Odeh et al. 2009) also confirmed that anticline structures and strike-slip faults cause groundwater flow divergence. The very high elevation of 500ft around Okwudo, Amauzari and Umuduru areas to the north of the model, is the cause of groundwater divide shown in the model within the axis of $x = 7, y = 1$ (Figure 4a and 4b). Figure 4c and 4d are front and side (west-east) vertical section of column 9 across Oji mechanic village, and column 10 across Nekede mechanic village respectively. The zones are characterized by downward and upward flows as shown by the vectors.

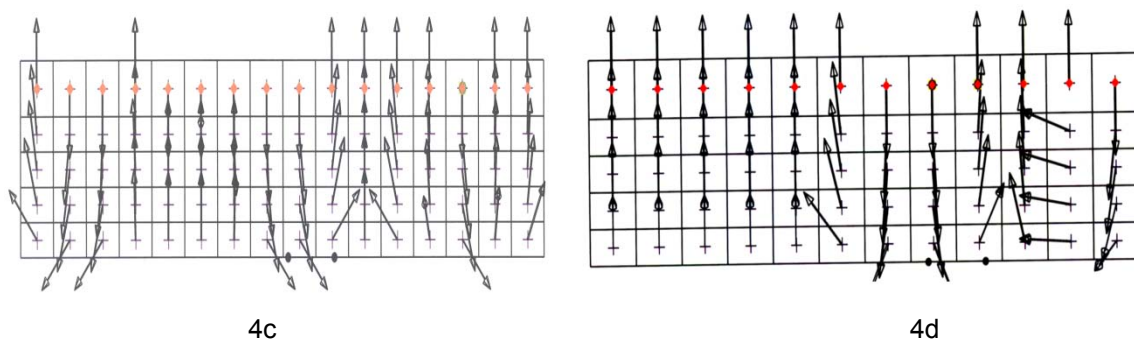


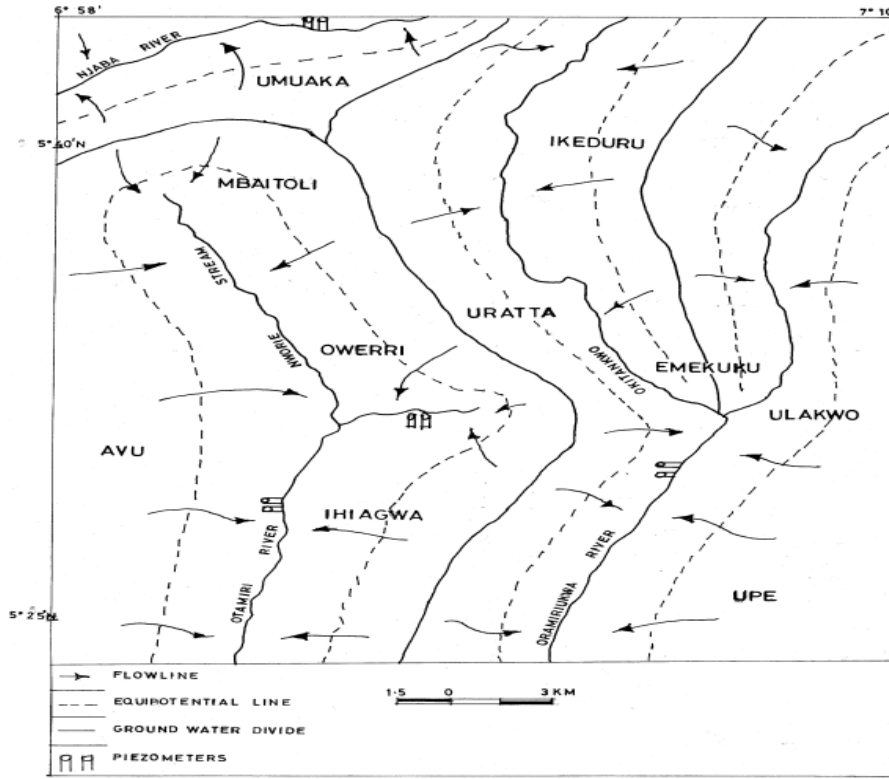
Fig. 4c: Vertical sections of the groundwater flow model 4c. Column 9 frontal view across Orji and 4d column 10 side view across Nekede

It is difficult to choose suitable locations for water quality monitoring wells near the Orji and Nekede MVs due to the divergent flow system. However, the particle tracking described in the next section, simplified the site selection process. At the abandoned municipal waste dump near Obinze ($x=8, y=7$), groundwater flows to the south towards Ihiagwa-Emeabiam (Figure 1). Generally, monitoring wells could be installed 500m away from each contaminated site in the direction of surface and groundwater flow. The exact distance chosen will depend on the proximity of domestic water wells and human residence to the contaminated sites, and on the rate of particle migration.

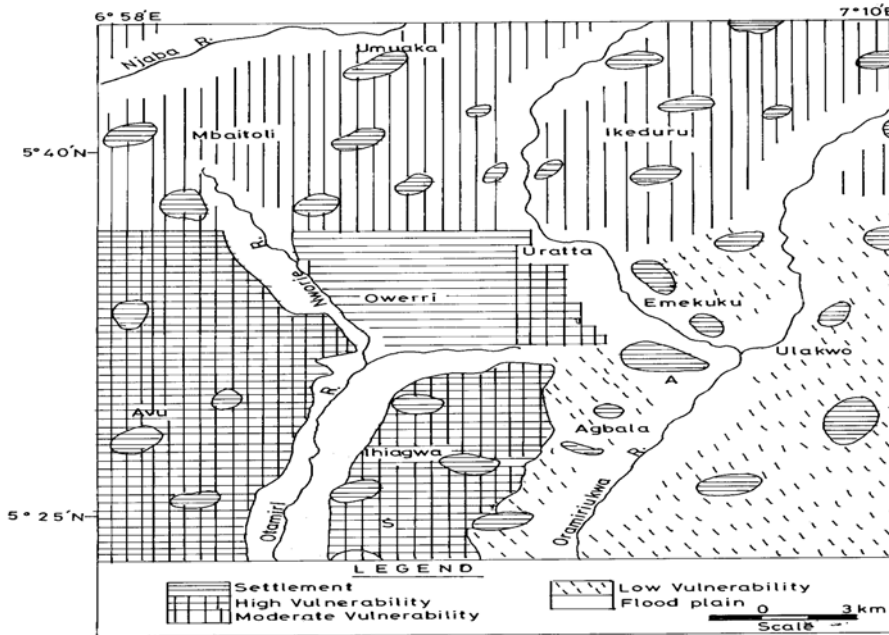
3.1 Particles tracking

In this study, the delineated capture zone refers to all areas within the model that contribute flow to one or more reference wells. Particles were tracked from their entrance to the wells and to their exit using the MODDATH module Pollock (1994) of the GMS package. This tracking method reveals local movements of water from the mechanic villages due to high elevation differentials. Considering only the contaminated mechanic villages, an extensive capture zone was observed lying to the southeast. The region is represented by the polygon in (figure 5a). Shallow wells within the capture zone have the potential to

receive and release contaminating particles from the two MVs as clearly shown by the three releasing wells (Figures 6a and 6b).



5a



5b

Fig. 5: Groundwater flow (a), and Vulnerability map of the study area (b) produced by Ibe et al.[7]

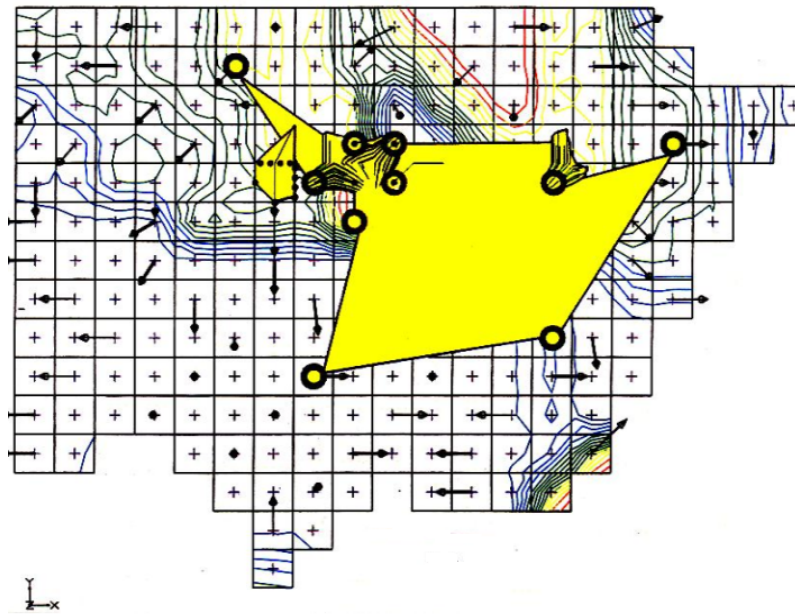


Fig. 6a: Groundwater flow model and the Particle capture zone SE of the Orji and Nekede MVs. The thin lines represent equipotential lines.

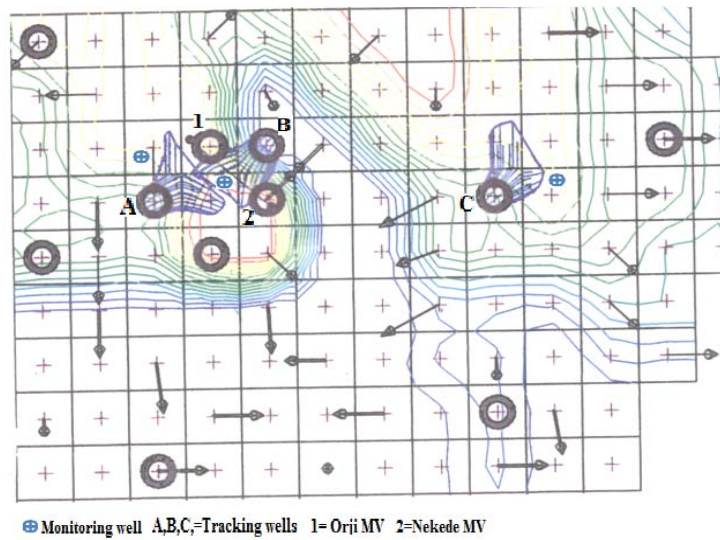


Fig. 6b: Groundwater flow and Particle tracking wells (ABC) in the vicinity of Orji MV (1), and Nekede MV (2) showing the direction of particle releases, and selected location of monitoring wells

The shallow wells nearest to the MVs in the direction of groundwater flow will first collect contaminant particles during pumping, then release particles back into the capture zone for other wells to collect. By this means, particles can migrate within the capture zone, propagating between wells, groundwater, and local streams located within the capture zone, such as the Otamiri and Oramiukwa. The 3 wells releasing particles are located at (x8, y5), (x10, y4), and (x14, y5), constituting the triangle ABC (Figure 6b). Wells A and B interact directly with the MVs, and releases particles to the capture zone, while well C receives particles from the capture zone, and could release particles outside the capture zone. Following these observations and analyses, we recommend to install eight water quality monitoring wells (WQ) as follows: WQ₁ will be located 500 m southeast of Orji MV. WQ₂ will be installed 500 m southeast of the Nekede MV, in the downstream portion of the Otamiri River. WQ₃ will be placed 1 km south of the abandoned MSW dump along Obinze, towards Ihiagwa. WQ₄ will be 1 km west of Egbeda, and WQ₅ located 1 km east of Umuapu. WQ₆ will be located 500 m northeast of well A, WQ₇ at 500 m southwest of well B, and WQ₈ 500 m northeast of well C. The distance of a monitoring well may decrease if any domestic well or human settlement is identified less than 500 m from a contaminated site.

At the open sewage disposal site, even though the model indicates zero horizontal flow, soil samples will be collected to the east of the sites within Umuapu, and to the west of the sites within Egbeda. With respect to the MVs, the horizontal distance of sampling profile will depend on the active area of a MV, but background samples will extend at least 500 m from the site against the direction of drainage. Samples will be collected to a depth of 1 m at each location. Below is a summary of the sampling directions: Mechanic villages: >>Southeast; MSW dump: >>South; and Sewage disposal site: >>west and east directions

4. Conclusions

A 3-D groundwater flow model and contaminants transport pathway was simulated in the vicinity of the three major contaminated sites in Owerri municipal. The results have simplified site selection for installation of groundwater monitoring wells near the contaminated sites for routine groundwater chemistry and pollution studies. The results also have been used to identify soil sampling profiles for quantitative analysis of heavy metal enrichment of soil within and around the contaminated sites. Significant water saturation to flooding was observed in layers 4 and 5 as indicated by the degree of horizontal and vertical flows. This result is confirmed by the saturation information obtained from VES data and well-logs. Changes in the horizontal flow directions in the area predominantly were due to topographic variations such as towards stream channels. This conforms to variable directions shown in a previous regional groundwater flow model of the Niger Delta, which includes the study area (Ophori, 2007). In the southwest portion of the model, a lower flat topography is identified from the predominance of downward flow vectors (infiltration) in the upper layers, and upward flow vectors in the lower layers. This is indicative of near surface water saturation, characteristics of swamp area, presently used for sewage dumping. Natural direction of surface drainage fairly corresponded to the direction of groundwater flow except diversions due to manmade structures.

The relatively high elevation of Orji and Nekede results in diverging flows, but particle tracking reveals a capture zone extending to the southeast of the area. Generally, the model identified preferred flow direction in each of the contaminated sites. The southward flow at the abandoned waste dump near Obinze is significant to the knowledge of groundwater regime in the area, whereas previous study by Ibe and Njoku (1999), observed flows from the abandoned solid waste dump in three directions: NE-SE, N-S,

and E-W. As a result, it was difficult to specify the preferred direction of particle migration using non numeric method. Our 3-D model clearly indicates southward flow from this site, down to 5 km before an east-west diversion occurred. In the region of Umuapu and Egbeda where sewage is mixed with soil for farm manure, standard medium public or private wells (>220ft ≤ 350ft) to deep public wells (>350ft), are recommended for drinking and domestic purposes. Shallow water wells (120ft- 220ft) common in the area are at risk wells, highly vulnerable to contamination (Nwachukwu et al., 2010b). Water quality of such wells deserves to be routinely monitored to reduce the risk of citizens being continuously exposed to water of poor quality.

Acknowledgements

We thank GEOPROBE International Consultants Limited and Federal University of Technology Owerri, for assistance. Special thanks go to the following staff of GEOPROBE: Chinedu Ohuawunwa (geophysicist), Paul Brown (geologist), Onyebuchi Nwozuzu (geologist), Maureen I. Amadi (geologist), and Kennedy Achilike (geophysicist) for assistance in the field data and base map production.

References

- Anderson, M. P., and Woessner, W. W. (2002). Applied groundwater modeling; simulation of flow and advective transport, *Acad. Press*, pg. 100-122
- Avbovbo, A. (1978). Tertiary Litho-stratigraphy of Niger Delta Bull Amer. Ass Petrol Geol. **62**, 295-305
- Barry, F., Ophori, D., Hoffman, J., Canace, R. (2009). Groundwater flow and capture zone analysis of the Central Passaic River Basin, New Jersey; *Environ Geol.* 56:1593–1603
- Ben-Itzhak, L. L., and Gvirtzman, H. (2005). Groundwater flow along and across structural folding an example from Judean Desert, *Isreal Journal of Hydrology*: vol. 312, issue; 1-4, pg. 51-69
- Ekwe, A. C., Onu, N. N., and Onuoha, K. M. (2006). Estimation of aquifer hydraulic characteristics from electric sounding data: the case of middle Imo River basin aquifers, south-eastern Nigeria. *Journal of Spatial Hydrology*; vol.6, No.2
- Hudak, P. F. (1999). A Method for Designing Up gradient Groundwater Monitoring Networks *Environmental Monitoring and Assessment* Volume 57, 149-155
- Hudak, P. F. (2001). Locating groundwater monitoring wells near cut-off walls; *Advances in Environmental Research*; Volume 5, Issue 1, Pages 23-29
- Ibe, K. M, and Uzoukwu, S. C. (2001). An Appraisal of Subsurface Geology and Groundwater Resources of Owerri and Environs Based on Electrical Resistivity Survey and Borehole Data; *Evaluation Environmental monitoring and assessment* vol. 70, n^o3, pp. 303-321
- Ibe, K. M., and Njoku, J. C. (1999). Migration of contaminants in groundwater at a landfill site; *The Electronic Journal of the International Association for Environmental Hydrology* at

<http://www.hydroweb.com>

- Ibe, K. M., Nwankwor, G. I., and Onyekuru, S. O. (2007). Assessment of Ground Water Vulnerability and its Application to the Development of Protection Strategy for the Water Supply Aquifer i Owerri, South-eastern Nigeria; *Jnl. of Env. Environ Mon and Assess* **67**: 323–360.
- Liu, C., Zhang, Y., Zhang, F., Zhang, S., Yin, M., Ye, H., Hou, H., Dong, H., Zhang, M., Jiang, J., Pei, L, (2007). Assessing pollutions of soil and plant by municipal waste dump preview by: *Environmental Geology*, Vol. 52 Issue 4, p641-651,
- McDonald, M. G, and Harbough, A. W.(1988). A modular three-dimensional finite-difference groundwater flow model, MODFLOW: U,S. Geological Survey Open-file Report 83-875
- Moline, G. R., Schreiber, M. E., Bahr, J. M. (1998). Representative Ground Water Monitoring in Fractured Porous Systems; *Journal of Environmental Engineering*, Vol. 124, pp. 530-538
- Nwankwo, G. I., and Anyaogu, C. N. (2000). Hydrologic characteristics of a small tropical riverine wetland at Ulakwo, Imo State, Nigeria *Hydrogeology Journal* 8: 646-653
- Nwachukwu, M. A, Feng, H., and Alinnor, J. (2020a). Assessment of heavy metal pollution of soil and their implication within and around mechanic villages *Int. j. Environ Sc. Tech* 7(2), 347-358
- Nwachukwu, M. A., Feng, H., Achilike, K. (2010b). Integrated study for automobile waste management and environmentally friendly mechanic villages; *African J of Environ Sc and Tech* Vol. 4 (4), pp. 234-249
- Odeh, T., Salameh, E., Schirner, M., Strauch, G. (2009). Structural control of groundwater flow regimes and groundwater chemistry along the lower reaches of the Zerka River W. Jordan, using remote sensing, GIS and field methods. *Envr. Geol.*, Springer vol. 58, pg. 1797-1810
- Ophori, D. U. (2007). A simulation of large-scale groundwater flow in the Niger Delta, Nigeria; *Environmental Geosciences* Vol. 14, No. 4, AAPG
- Pollock, D. W. (1994). User's guide for MODPATH/MODPATH PLOT, version 3: A particle tracking post processing package for MODFLOW, the U.S. Geological Survey finite-difference groundwater flow model:
- Uma, K. O., and Egboka, B.C.E.(1986). Water resources of Owerri and its environs, Imo State, Nigeria³, *J. Min. Geol* 22, 57–64