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Groundwater Modelling, An Effective Tool in the Assessment of Groundwater Contamination: A Case Study of Umunwanwa in Umuahia-South, Abia State, Nigeria

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Authors' contributions

This work was carried out in collaboration between all the authors. The geophysical study was carried out by all authors. Furthermore, AUC designed the study and led the team in carrying out the simulation of the lower aquifer, RUA led in the analytical simulation of the upper aquifer while MUI spearheaded that of the numerical analysis. KTE led in the processing of the geophysical data. The manuscript was compiled by AUC with inputs of all the authors. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

To determine the environmental suitability (impacts on groundwater) of an excavated pit located within the eastern boundary of Umunwanwa for any form of waste discharge (sewage or solid waste), modelling approach was adopted. A thorough geophysical / hydrogeological investigation carried out in the area revealed the existence of 7 layers and in the vicinity of the site an unsaturated semi-permeable zone with clay lenses. Site specific hydraulic conductivity of 9m/d was determined through grain size analysis. The groundwater flow direction of the area is from south-east to north-west and the flow system consists of two aquifers separated by a 6.1m thick confining layer. The simulation was carried out for short and long term assessment which gave rise to two sample problems.

Sample Problem 1: (Upper aquifer) which is the "Modelling of Groundwater Mound Resulting from Effluent Infiltration," where analytical and numerical models for calculating

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the groundwater mound were applied. Ten analytical simulations with recharge rates varying from 0.003125m/d to 0.75m/d were carried out. After 100days there was no significant rise in the groundwater table with recharge rates less than 0.0375m/d, while recharge rates above 0.0375m/d gave significant groundwater mound. A further numerical simulation using a recharge rate of 0.75m/d showed that the results of analytical and numerical simulations are found to be in good agreement by predicting that at the end of 50 days a 12m groundwater mound beneath the centre of excavated pit is expected.

Sample Problem 2: (Lower aquifer) is the “Modelling of Solute Transport Resulting from Effluent (Leachate) Infiltration”, where a particle tracking technique introduced uses a semi-analytical particle tracking scheme that allows an analytical expression of the particle’s flow path to be obtained within each finite-difference grid cell. Particle paths are computed by tracking particles from one cell to the next until the particle reaches a boundary, an internal sink/source, or satisfies some other termination criterion while keeping track of the time of travel for particles moving through the system. After 15 years, the contaminant plume was able to reach the well head. This has shown the effectiveness of groundwater modelling in the assessment of groundwater contamination thus revealing the unsuitability of the site for any form of waste discharge.

Keywords: Effluent infiltration; groundwater modelling; groundwater mound; contaminant plume.

1. INTRODUCTION

Groundwater pollution may be defined as the artificially induced degradation of groundwater quality.

Groundwater plays a major role in water supply to meet the ever increasing demands for domestic, agricultural and industrial usage. Many geo-environmental engineering problems and the leaching (displacement) of salts and nutrients in soils are all having direct or indirect impact on groundwater. Withdrawal of groundwater in excess of natural replenishment of groundwater resources may cause infiltration from hazardous sources such as effluent sites, leachate, salt water etc; and this infiltration may give rise to groundwater mound (Rao and Sarma, 1983; Latinopoulos, 1986).

An infiltration from a hazardous source constitutes groundwater pollution. Pollution of groundwater occurs when waste products or any foreign substance alters the biological or chemical characteristic of water and degrades the quality so that animals, plants or humans are affected. Water pollution is a major global problem which requires ongoing evaluation and revision of water resource policy at all levels (international down to individual aquifers and wells).

Numerous studies have examined the correlation between land use, sewage discharge and contamination of groundwater (Lerner and Harris, 2009).

Interactions between groundwater and surface water are complex. Consequently, groundwater pollution, sometimes referred to as groundwater contamination, is not as easily classified as surface water pollution. By its very nature, groundwater aquifers are susceptible to contamination from sources that may not directly affect surface water bodies and the distinction of point source versus non-point source may be irrelevant. A spill or ongoing releases of chemical or radionuclide contaminants into soil (located away from a surface water body) may not create point source or non-point source pollution, but can contaminate the aquifer below, defined as a toxin plume. The movement of the plume, called a plume front, may be analyzed through a groundwater model. Analysis of groundwater contamination may focus on the characteristics of the host rocks and site geology/hydrogeology and the nature of the contaminants.

Although the process of groundwater contaminant plume migration depends on numerous microbiological, physical and chemical processes; the most significant factor controlling contamination of groundwater is the source of contamination on the surface including its type, strength and location relative to the water source (Erckhardt and Stackelberg, 1995). By studying the relationship between groundwater contamination, land use and waste disposal methods, issues of sustainability can be addressed and integrated with better practices and water protection strategies.

1.1 Study Area

Umunwanwa as one of the mega communities in Umuahia-South Local Government Area of Abia State Nigeria can be located within latitude 5º29' 232N and 5º30' 653N and longitude 7º22' 503E and 7º24' 685E (Fig 1a and Fig 1b). The surface elevation of Umunwanwa is within 99m and 130m above sea level and is bounded in the east by Amuzu Obinubi and Uturu Ubakala, north by Ogbodinibe, Nsukwe and Uturu, south by Nsirimo and Abam while in the west by the Imo River.

Climate of the area falls within the tropical rainforest with two seasons, the rainy season (Mid-April to October) and the dry season (November to Mid-April). The rainy season is characterised by double maxima rainfall peaks in July and September, with a short dry season of about three weeks between the peaks known as the August break. The ending of the rainy season in October is followed by the dry Season with peak dry conditions between early December and Mid-February, with a short break of one or two rainfalls in either Late February or March thus ushering in the clearing of lands for farming season which begins in Mid-April.

The mean monthly rainfall in the rainy season in the area is about 335mm while that of the dry season is about 65mm, thus the annual average rainfall is about 2400mm with high relative humidity values over 70%.

The geology of the area indicates that it is entirely overlain by the Late Tertiary to Early Quaternary Benin Formation with a Southwest trending dip. While the western part is covered with recent alluvial deposits of Imo River. The area is being drained by Imo River and its tributaries.

The host rock of Umunwanwa groundwater is the Late Tertiary to Early Quaternary Benin Formation which comprises of shale/sand sediments with intercalation of thin clay beds (Asseez, 1976 ; Murat, 1972). Umunwanwa groundwater is particularly susceptible to groundwater pollution because the area is predominantly made of sandy soils that are generally correlated with low adsorption potentials; which allows easy leaching of foreign chemicals through the soil profile. This is evident in the predominance of gully erosions in the area.

Another concern is the historical use of septic tanks (pit latrines of hundredths of centimetres below) and the recent indiscriminate sinking of bore-holes in search of groundwater, coupled with the preference of the upper unconfined aquifer to the lower confined aquifer as a better source of drinking water because of its low iron content. There have been many studies that have correlated polluted groundwater with septic tanks (Cain et al., 1989).

During road construction in Umunwanwa in 2003, two pits were excavated for land filling, one at the western end about 600m to Imo River and the other at the eastern boundary near the cattle market. The eastern one which is about 20m in length and width about 16m was chosen for this study. The choice of this site is based on its proximity to a waste generating outfit (cattle market / abattoir) and the city. Also the tendency of using excavation pits for all forms of waste discharge by the people and inhabitants of the area is another factor. Even those who engage in sewage (septic tank) draining, end up discharging the sucked-out sewages in excavated pits. All these are done without taking into consideration the impact on the environment.

This study mainly concerns the effect on groundwater quality in Umunwanwa if the excavated pit in the eastern boundary of Umunwanwa is used for any form of waste disposal; thus investigating the relationship between the point source (sewage and solid waste disposal) and temporal variation of groundwater quality in the area.

For a proper assessment and management of groundwater resources, a thorough understanding of the complexity of its processes is quite essential. In order to predict the contaminant migration in the geological formation more accurately, numerical techniques of groundwater pollution modelling such as finite difference method is applied.

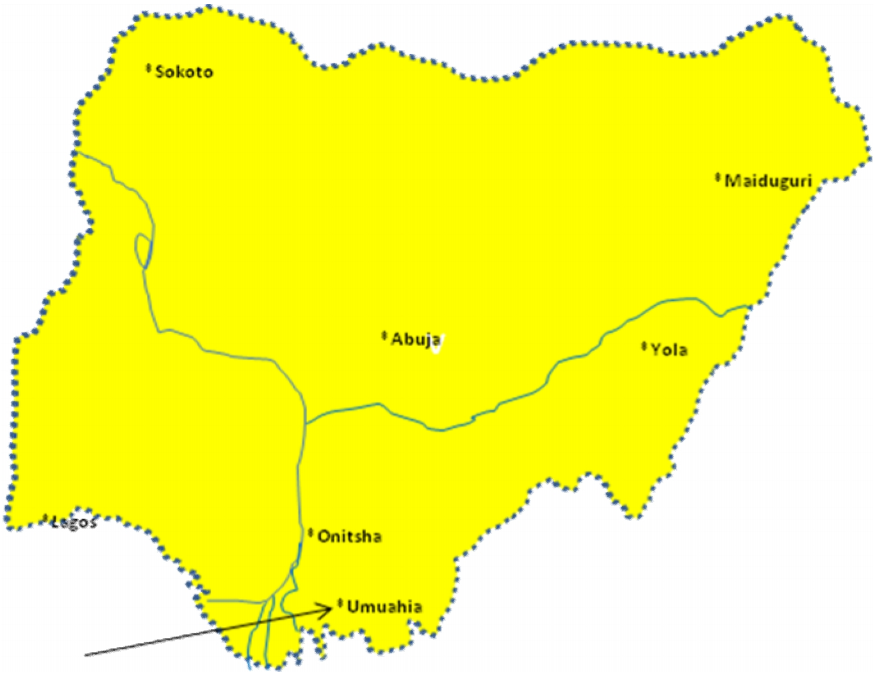

Fig. 1a. Map of Nigeria with arrow showing the study area

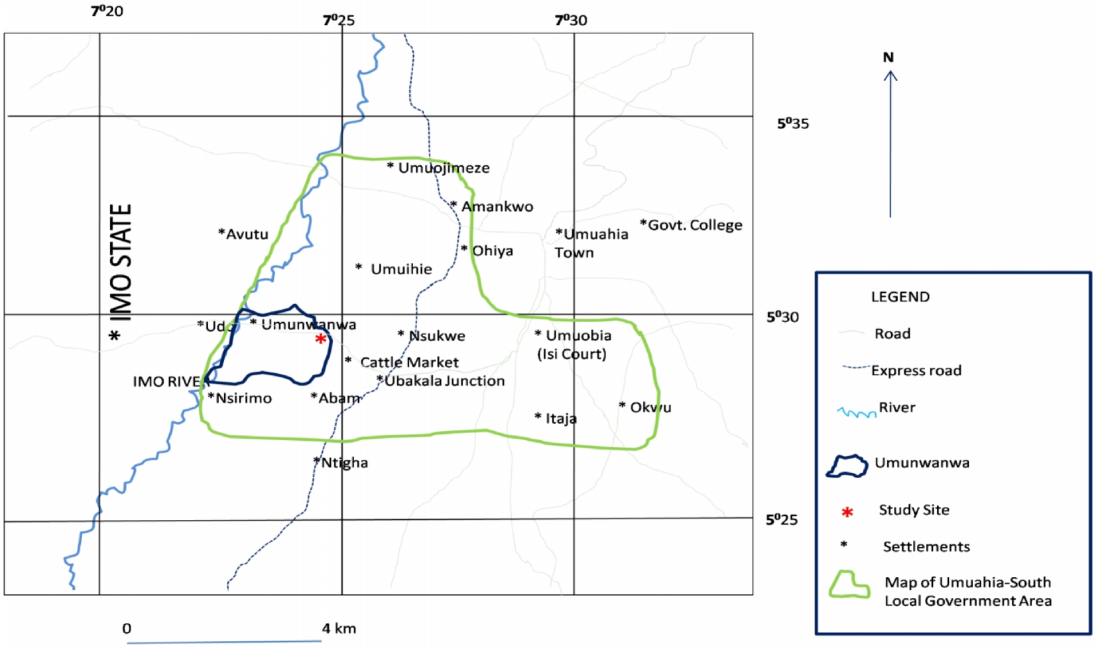

Fig. 1b. Map of Umuahia-South Area of Abia State Nigeria showing Umunwanwa

2. MATERIALS AND METHODS

2.1 Data Acquisition

The site which is an excavated pit is within latitude 5º29' 224N and 5º29' 239N and longitude 7º24' 637E and 7º24' 641E, the determination of the coordinates was made possible using GARMIN GPS 72 The descriptions and interpretations of the site-specific geophysical and hydrogeological information collected are as follows: The areal extent of the site is about 320m^2 and about 5.08m – 6.81m depth of the lateritic overburden has been excavated. The site is presently underlain with a semi-permeable silty-clay layer of thickness between 1m and 4.67m. Soil sample analysis shows that the hydraulic conductivity of the unsaturated zone is about 9m/d. The depth to the upper groundwater level in the area is about 30m. The thickness of the saturated unconfined aquifer varies from approximately 35m to 40m while the thickness of the lower aquifer is about 45m as shown in Fig. 2.

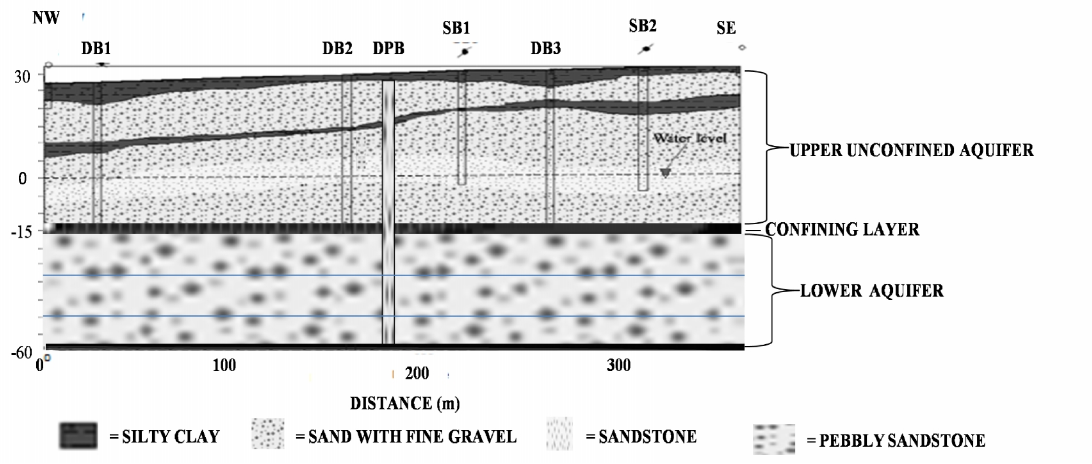

Fig. 2. Geological / Hydrogeological cross-section NW-SE, of the area showing boreholes and infiltration test ponds. DB = Deep borehole, SB = shallow borehole, DPB = Deepest borehole

Based on the depth of investigation, the area is lithostratigraphically made up of 7 layers while hydrogeologically, the area is 3 units namely upper unconfined aquifer, confining layer and lower aquifer (Fig. 3).

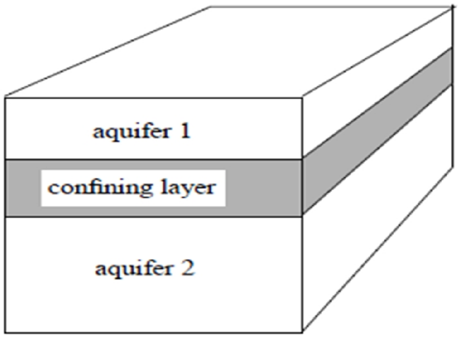

Fig. 3. The Hydrogeologic System

The hydraulic parameters calculated from estimates of pumping tests from other boreholes within the area indicate that the phreatic aquifer has an average hydraulic conductivity of 12.0 m/d and a transmissivity of 720m^2/d (Table1).

Table 1. Hydraulic parameters of the area

Location	**Resistivity values (Ωm)**	**Thickness of layers (m)**	**Field hydraulic conductivity (m/d)**	**Calculated hydraulic parameters based on surface resistivity soundings (VES)**		**Calculated hydraulic parameters based on pumping test**		**Drill log data**
				Thickness of aquiferous Zone (m)	**Transmissivity (m^2/d)**	**Screen length (m)**	**Transmissivity (m^2/d)**	
Cattle Market	3671.2 1527.7 463.2 141.7	2.00 20.10 196.00	10.80	196	2116.8	12	129.6	1.Red laterite(24m) 2.Plastic clay (2m) 3.Coarsesands20m 4.Nodular clay 7m) 5.Fine to medium sands (20m) 6.Medium to coarse sands(40m) 7.plast ic clay
Nsukwe	1354.4 853.6 470.4 150.5	2.50 16.00 172.50	-	172.50	-	15	-	1.Red Laterite(22m) 2 Medium to Coarse sands(25m) 3.Clay(4m) 4. Fine to medium sands (20m) 5.Clay (10m) 6.Coarrse to medium sands
Abam	1728.2 442.4 147.7	20.00 35.00	-	35.00	-	12	-	1.Red Laterite(20m) 2.Plastic clay (3m) 3.Coarsesands(15)m 4.Nodular clay (3m) 5.Fine to medium sands (12m) 6. Clayey fine to medium sands(45m) 7.Plastic clay

Table 1. continues ….

Umunwanwa	1884.4 848.5 481.7 270.4	3.20 31.00 224.10	13.20	224.10	2958.12	13	171.60	1.Red Laterite (22m) 2 Medium to Coarse sands (40m) 3.Clay (2m) 4.Medium to fine sands (20m) 5.Clay (2m) 6.Coarrse to medium sands (40m) 7.Plastic clay (11m) 8.Pebbly sandstone
Study Site	1845.8 889.3 473.2 276.3	30.30 14.90 45.10	12.00 (Estimated average field hydraulic conductivity)	60	720	-	-	7 layers inferred for the upper aquifer because the site is located between Abam, Cattle Market and Umunwanwa locations.

3. RESULTS AND DISCUSSION

3.1 Simulation of Sample 1 (Upper Aquifer)

A local rise of the groundwater table above its natural level resulting from a localized source such as an infiltration pond is known as groundwater mound. The shape and height of a mound depend on several factors including the recharge rate, hydraulic conductivity and thickness of the aquifer in the area.

Artificial recharge could also be a source of groundwater mounding, and this is likened to sewage discharge in pits that are permeable and porous.

Theoretical and experimental studies on the subject of artificial recharge of groundwater through surface spreading have been reported by Marino (1967, 1974), Hantush (1967), Rao and Sarma (1983) and Latinopoulos (1986). Most of these solutions are based on the assumption of a constant rate of recharge applied continuously or periodically. Common to all these solutions are the assumptions that percolation moves vertically downward until it joins the main groundwater body and that the flow of groundwater takes place in a homogeneous, isotropic, unconfined aquifer having hydraulic properties that remain constant with both time and space.

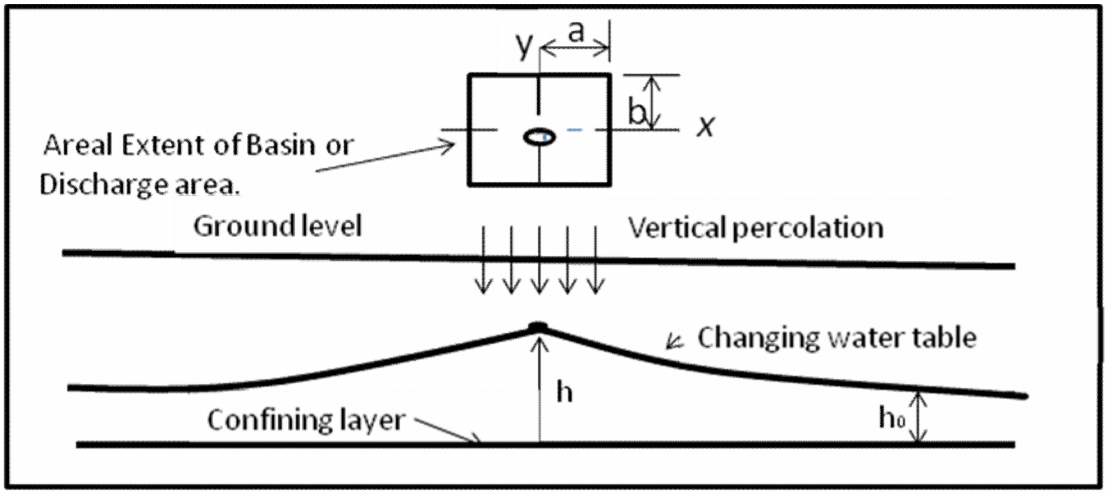

Fig. 4. Diagrammatic representation of the rise of the water table beneath the effluent discharge area

The dimensions of the mound are governed by the basin size and shape, effluent discharge (leakage) rate and aquifer characteristics.

The shape of a mound beneath a discharge (leakage) rectangular area, expressed by h-h_0, is the mound height in function of time and space, depending upon the effluent discharge (leakage) flux, the storage coefficient and transmissivity of the aquifer.

Ten simulations were carried out with recharge rates ranging from 0.003125m/d to 0.75m/d. These recharge rates were obtained by using the capacity of a normal sewage tanker which is 12,000 litres and if 20 trucks discharge liquid waste into the excavated pit daily, then an estimated 240,000 litres is expected.

This expected discharge rate which is likened to volumetric flow rate is measured in m^3/d.

So converting litres to m^3 is as follows:

1litre = $0.001m^3$, multiplying both sides by 1000, we get

1000litres = $1m^3$, and

240,000litres = 240 m^3, therefore

240,000litres per day = 240 m^3/d

In Darcy's law, Darcy flux which is also known as Darcy Velocity or, the Specific Discharge) (*q*) which is expressed as the discharge rate per unit cross-sectional area:

$$q = Q/A \tag{1}$$

Where Q = Volumetric flow rate or the discharge rate (m^3/d), Cross sectional flow area perpendicular to 1(m^2).

The areal extent of the site is about $320m^2$ and if an expected average effluent discharge rate of $240m^3/d$ is observed, this would yield an average infiltration rate (leakage rate) of 0.75 m/d. This 0.75m/d is for 20 trucks discharging into the pit on daily basis. If one truck discharges into the pit in every 12days, then the infiltration rate will be 0.003125m/d while if one truck discharges daily, it will be 0.0375m/d see (Table 2).

By using the data obtained from the geophysical and hydrogeological study with infiltration rate ranging from 0.003125m/d to 0.75m/d and an area recharge basin of 16m x 20m, the results obtained as shown in Table 2 indicates what the height of groundwater mound will be at the centre of the basin within 5 to 100days.

3.1.2 Numerical Solution

Groundwater flow simulations were made using the three dimensional finite-difference (numerical) modelling software (Groundwater Vista, GV). GV model design is generic because it can be used to create data sets for MODFLOW, MT3D, and MODPATH etc. Visual MODFLOW data sets were used in the numerical modelling which evaluated the partial differential equations for groundwater flow.

$$\left\{\left(kh\frac{d^2h}{dx^2}\right)+\left(kh\frac{d^2h}{dy^2}\right)+\left(ky\frac{d^2h}{dz^2}\right)\right\}-Q=Ss\frac{dh}{dt} \tag{2}$$

Where Kh is the horizontal hydraulic conductivity, Ky the vertical hydraulic conductivity h the hydraulic head, Ss the specific storativity, Q the source/sink term, t the time and x,y,z the space coordinates.

Table 2. Summary of the results of analytical simulations

Simulation	**Effluent discharge rate (m^3/d)**	**Infiltration or leakage rate (m/d)**	**Mound height on the 5th day (m)**	**Mound height on the 10th day (m)**	**Mound height on the 20th day (m)**	**Mound height on the 40th day (m)**	**Mound height on the 50th day (m)**	**Mound height on the 75th day(m)**	**Mound height on the 100th day (m)**
1	1	0.003125	NSR	NSR	NSR	NSR	NSR	NSR	NSR
2	2	0.006250	NSR	NSR	NSR	NSR	NSR	NSR	NSR
3	3	0.009375	NSR	NSR	NSR	NSR	NSR	NSR	NSR
4	4	0.0125	NSR	NSR	NSR	NSR	NSR	NSR	NSR
5	5	0.015625	NSR	NSR	NSR	NSR	NSR	NSR	NSR
6	6	0.01875	NSR	NSR	NSR	NSR	NSR	NSR	NSR
7	12	0.0375	NSR	NSR	NSR	NSR	NSR	1.1	1.7
8	24	0.075	NSR	NSR	NSR	1.3	1.7	3.1	5.0
9	60	0.1875	NSR	NSR	1.7	5.0	6.0	8.5	9.0
10	240	0.75	1.7	5.0	9.0	11	12	13	14

**NSR =No Significant Rise in groundwater table.*

The aquifer is considered as unconfined aquifer with a stratigraphy of 7 layers with alternating finer and coarser unconsolidated sediments. The layers are approximately horizontal, with a small inclination towards the Imo River as shown in Fig. 5.

The model domain encloses a square area of 0.2km x 0.2km centred on the effluent discharge pit (infiltration ponds). The grid is chosen to be regular with a cell size of 2m, i.e. 100 columns and 100 rows.

Model Input values of the hydraulic parameters are assigned based on the geophysical and hydrogeological investigations and the hydraulic conductivity is assumed to be constant for each layer. The hydraulic conductivity of the unsaturated zone for the soil types investigated is 9m/d for sand and 1.5 m/d for clay. The average hydraulic conductivity of the sandstone aquifer and the phreatic storage coefficient was taken from the pumping test (Table 1). The recharge rate is 0.75 m/d similar to the maximum infiltration rate of the analytical solution. Other model inputs are shown in Table 3.

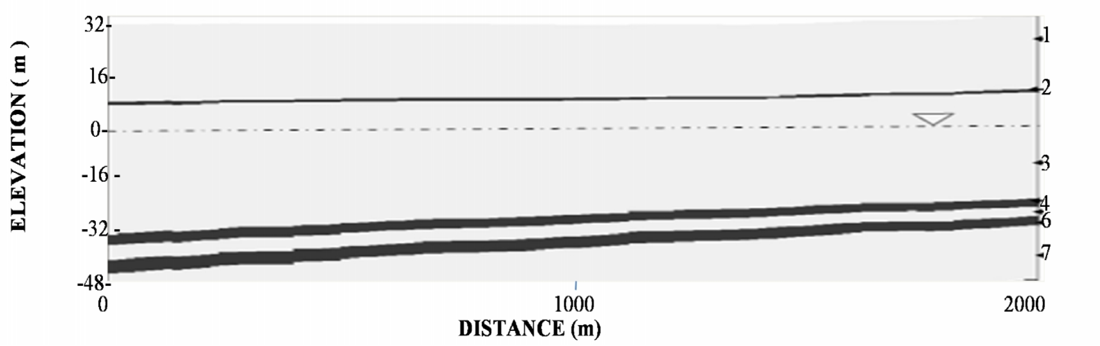

Fig. 5. Model layers: 1- Sand with fine gravel, 2-Silty Clay, 3- Sandstone, 4- Clay, 5- Sandstone, 6- Clay and 7- Sandstone

When the apparent horizontal and vertical hydraulic conductivity (Kh_A and Kv_A) differ considerably, the aquifer is said to be anisotropic with respect to hydraulic conductivity. Because sand and gravel aquifers have high porosity and permeability, they also have higher hydraulic conductivity than clay or unfractured granite aquifers (Table 3).

Table 3. Hydraulic model input parameters

Parameter	**Sandstone**	**Sand**	**Clay**
Hydraulic Conductivity (m/d) K_h, K_v	12; 1.2	9; 0.9	1.5; 0.15
Specific storage (m^{-1}) Ss	$1.\ 10^{-5}$	$1.\ 10^{-5}$	$1.\ 10^{-5}$
Specific yield Sy	0.72	0.72	0.30
Effective porosity	0.32	0.32	0.15
Total porosity	0.35	0.35	0.18

Hydraulic conductivity (*K*) values found in nature range over many orders of magnitude, vary through space and are directional e.g., vertical *K* values can be several orders of magnitude smaller than horizontal *K* values).

Due to the 3-dimensional depression of the site (excavated pit) and the basal composition (silty-clay), the aquifer (site) may be likened to a semi-confined one, where by a saturated layer with a relatively small horizontal hydraulic conductivity (the semi-confining layer) overlies a layer with a relatively high horizontal hydraulic conductivity, so the initial flow of groundwater is mainly vertical in the first layer and horizontal in the second. Therefore, the vertical conductivity was set to 10% of the horizontal hydraulic conductivity. Compare, upper limit of "Very Fine Sand, Silt" and lower limit of "Well Sorted Sand or sand and Gravel" in Table 4.

3.1.3 Results and Analysis

Five simulated observation points (wells) in the centre and at the edges of the model domain were used for the study of the resulting groundwater mound (Fig. 2). As depicted in Fig. 6, the simulation shows that after 50days, the groundwater mound beneath the centre of the infiltration area (site) is expected to rise to about 12m (DB 2), towards the edges 10.5m (SB 1) and 9.5m (DB 3) and at the edges 9m (SB 2) and 8m (DB 1).

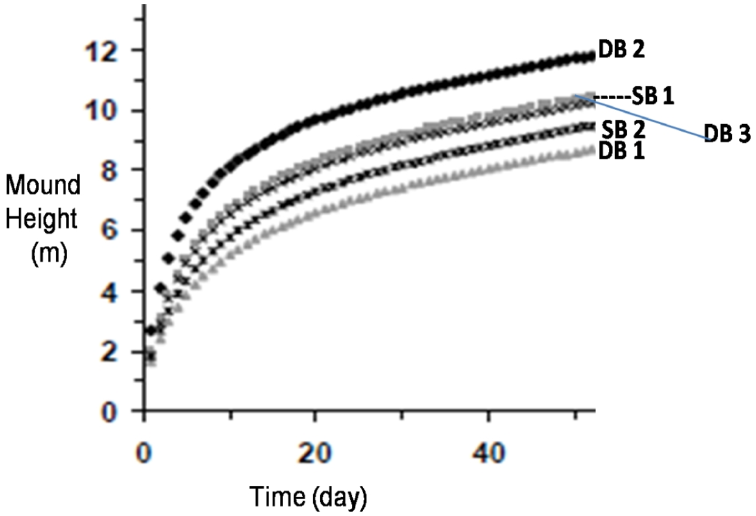

Fig. 6. Height of the groundwater mound beneath the (effluent discharge) site calculated with the numerical model

A comparison of the growth of the groundwater mound obtained in the numerical model simulation and that of the analytical solution as shown in Table 2**,** gave a very good agreement. The small differences can be explained by the assumptions that were made in case of the analytical solution, i.e. a square basin and an average groundwater table elevation to calculate the aquifer transmissivity. While in the numerical model, different ground layers are taken into account.

Table 4. Saturated Hydraulic Conductivity (*K*) values found in nature

K (cm/s)	10^2	10^1	$10^0=1$	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
K (ft/day)	10^5	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001	10^{-5}	10^{-6}	10^{-7}
Relative Permeability	Pervious				Semi-Pervious					Impervious			
Aquifer	Good						Poor			None			
Unconsolidated Sand & Gravel	Well Sorted Gravel		Well Sorted Sand or Sand & Gravel				Very Fine Sand, Silt, Loess, Loam						
Unconsolidated Clay & Organic					Peat			Layered Clay		Fat / Unweathered Clay			
Consolidated Rocks	Highly Fractured Rocks				Oil Reservoir Rocks			Fresh Sandstone		Fresh Limestone, Dolomite		Fresh Granite	

Source: Modified after Bear, 1972.

3.2 Simulation of Sample 2 (Lower Aquifer)

Recall that the entire flow system consists of two aquifers see (Fig. 3) and it is separated by a 6.1m thick confining layer as noted.

Recent study by some of the authors (Amos-Uhegbu et.al, 2012. Delineation and Hydrogeochemical Character of the Aquifer systems in Umuahia-South Area, Abia State, Nigeria. In view) reveals that the recharge to the aquifer systems of the area is through precipitation and since the average annual rainfall is about 2400mm per year.

Converting mm/yr to mm/day, we divide by the number of days that make up a year, and the exact number of days that make up a year is $365^{1/4}$ days.

Therefore, 1mm/yr = 1/365.25mm/day
= 0.00274mm/day

So, 2400mm/yr = (2400 *0.00274) mm/day
= 6.57mm/day (3)

Converting mm/day to m^3/day, we get
1mm/day = 0.000001 m^3/day
Therefore, 6.57mm/day = 6.57 *0.000001 m^3/day
=0.00000657 m^3/day (4)

Equation (3) is the average rainfall per day in Umuahia-South area and equation (4) is assumed in this context to be the recharge to the aquiferous units.

Currently, a total of 113 boreholes tapping water from the lower aquifer are located within 2km radius of the site (excavated pit).

So, if an average of 1002 litres per day discharge is observed in each of the boreholes, then the total discharge per day from the lower aquifer is

1002 litres multiplied by 113 = 113,226litres.

Recall that 1000 litres =1m^3
Therefore, 113,000 litres = 113.226m^3 per day. (5)

The design of the softwares used for the simulation (groundwater modelling) is of regional scale. So, the data generated from the study in equations (4) and (5) above are hereby multiplied by 20 for the model input.

Therefore, equation (4) now becomes
0.00000657 m^3/day * 20
= 0.00013 m^3/day
=$1.3 * 10^{-4}$ m^3/day (6)
And equation (5) now becomes
113.226 m^3/day * 20
= 2264.52 m^3/day
=$22.65 * 10^2$ m^3 /day (7)

The condition of the flow system is assumed to be in steady state, recharge to the system is uniformly distributed over the water table at a rate of 0.00013m^3 per day.

Discharge occurs along the western side to the Imo River in the upper aquifer, and also to the well (DPB) in the lower aquifer at 2265m^3/ day.

The flow system is simulated using a finite-difference grid containing 17 rows, 17 columns, and 4 layers (Fig. 7 and Fig. 8). The well (DPB) is located in row 9, column 9 and discretized model layer 3.

Grid Dimensions: 17 rows; 17 columns; 4 layers

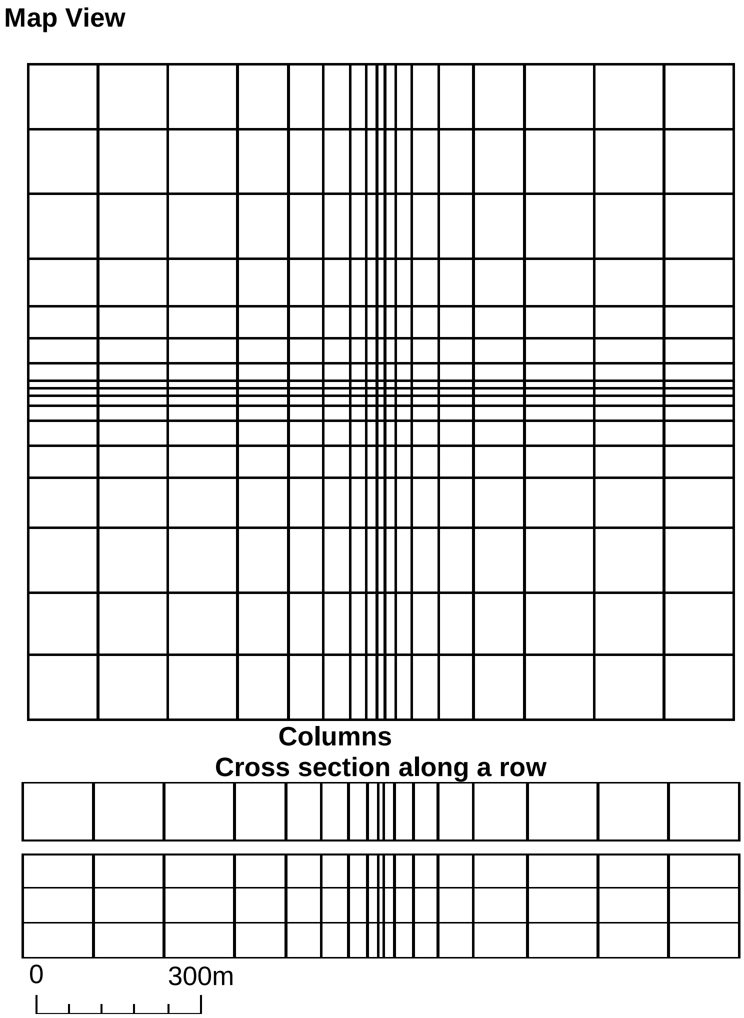

Fig. 7. Finite-difference grid of the flow system 2

Horizontal grid spacing varies from 12m by 12m squares at the well to 120m by 120m squares away from the well.

The upper unconfined aquifer is simulated as layer1 (aquifer1), while a quasi-three-dimensional representation is used for the confining layer. The lower aquifer is represented by three 15m thick layers, and the well (DPB) taps water from layer 3 (aquifer2) Fig. 8.

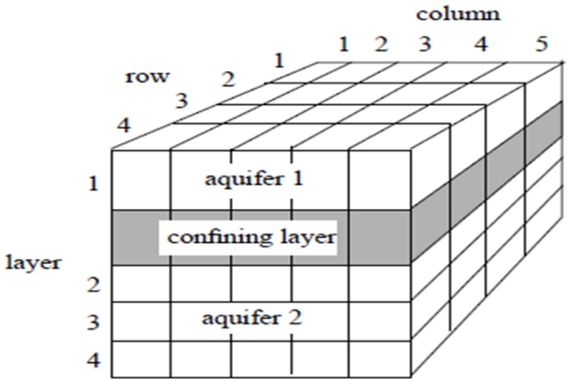

Fig 8. The Discretized Model System

The partial differential equation describing conservation of mass in a steady-state, 3-dimensional ground-water flow system was evaluated by MODPATH after initial simulation by MODFLOW.

$$\left\{\frac{d}{dx}(nv)_x + \frac{d}{dy}(nv)_y + \frac{d}{dz}(nv)_z\right\} = Q \tag{8}$$

where v_x , v_y and v_x are the principal components of the average linear ground-water velocity vector, n is porosity, and Q is the volume rate of water created or consumed by internal sources and sinks per unit volume of aquifer.

Equation (8) expresses conservation of mass for an infinitesimally small volume of aquifer. The finite difference approximation of this equation can be thought of as a mass balance equation for a finite-sized cell of aquifer that accounts for water flowing into and out of the cell, and for water generated or consumed within the cell (Fig. 9).

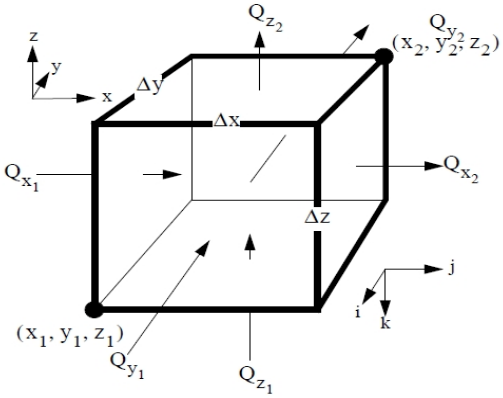

Fig. 9. Finite-difference cell showing definitions of x-y-z, i-j-k and the six faces x_1,x_2, y_1, y_2 , z_1 and z_2

Output from steady-state MODFLOW simulations was used in MODPATH to compute paths for imaginary particles of water moving through the simulated ground-water system and also track the time of travel for particles.

By carefully defining the starting locations of particles, it is possible to perform a wide range of analyses, such as delineating capture and recharge areas that contribute water to aquifers or to major discharge features, such as wells. This is done by recording the initial and final locations, and the tracking time of particles in an endpoint file. Endpoint analyses can be carried out either in forward or backtracking mode.

In this analysis, an automatic particle generation option is utilized to place a 2x2 array of particles on the top face of every cell in layer 1 (a total of 1156 particles), the following information is obtained.

- Minimum Travel Time = 1.02565W-02
- Maximum Travel Time = 0.94330W+05
- Average Travel Time = 0.48972W+04
- 78.5% of the Particles Had Travel Times Less Than the Average Travel Time
- 0 Particles Remain Active
- 1156 Particles Stopped at Internal Sinks/Sources or Boundaries
- 0 Particles Stopped in an Automatic Termination Zone
- 0 Particles Were Stranded in Inactive Cells
- 0 Particles Were Not Released
- 1156 Particles Accounted for Out of a Total of 1156

In this case, all 1156 particles terminated normally at internal sinks (the well in layer 3) or boundaries (the top faces of cells that contain rivers). When the results from the MODPATH run was plotted using MODPATH-PLOT, the plot shows that the capture area mapped out by backward tracking coincides with that produced by forward tracking (Fig 10). Then, final locations of particles are plotted. The rings of particles reflect the regular pattern of the two-dimensional arrays of particles placed on each of the well cell faces.

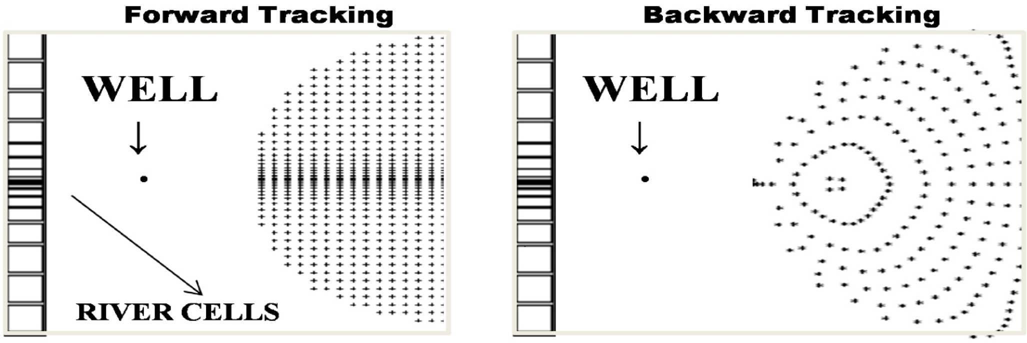

Fig. 10. Capture area for well in layer 3 delineated by tracking 1156 particles forward and 200 particles backward from the water table

A further pathlines analysis in cross-section was done along row 9 that is perpendicular to the river and passes through the cell containing the well. Twenty uniformly spaced particles are placed at the water table and tracked forward to their points of discharge (Fig 11). In this case, the pathlines show a clear picture of vertical flow in the system because the cross section was taken along a line of symmetry in the flow system where flow is truly two-dimensional in vertical cross section.

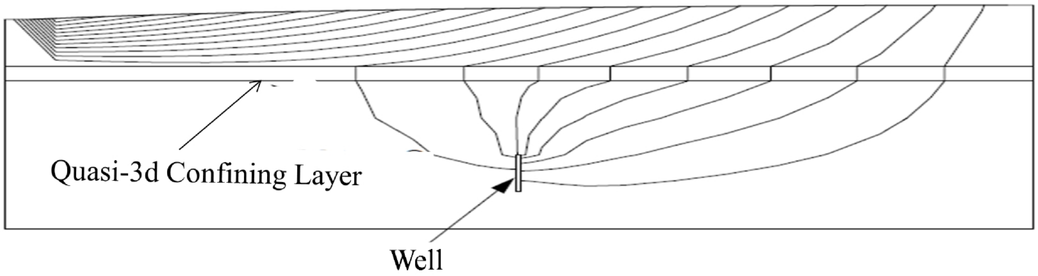

Fig. 11. Pathlines tracked forward from the water table along row 14

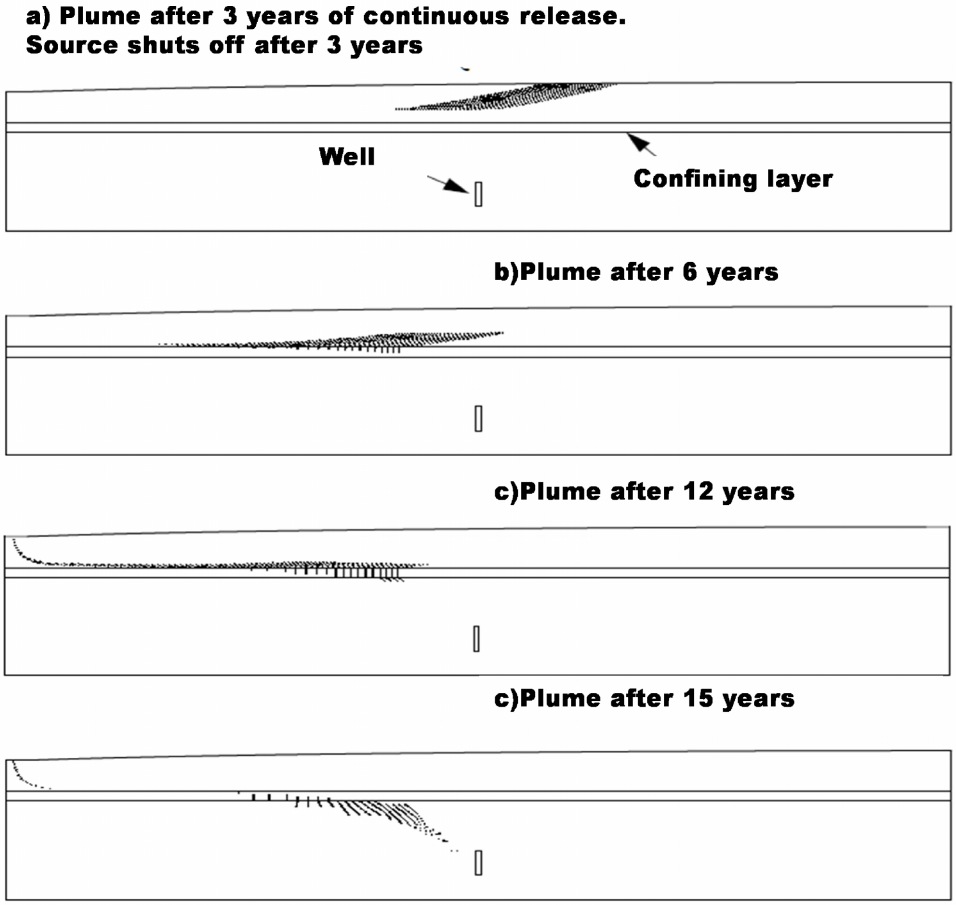

Fig. 12. Time series plots showing dissipation of a plume formed by 3 years of continuous release of particles at the water table

In addition to endpoint and pathline analyses, a time series analysis was performed. This simulation run was carried out in order to record and display the location of particles at specific points in time.

A line of particles is released along a portion of the water table in row 9 (columns 3 and 4). The particles are released every 0.5 years for a period of 3years. The 3-year plume of particles is then followed through the system. The particles are placed within the same line-of symmetry cross section used in run 3. The plume is viewed by looking at cross section plots along row 9 for a number of points in time. A series of four plots were generated with MODPATHPLOT.

Each plot shows the locations of particles at a specific point in time: 3, 6, 12 and 15 years. These points in time correspond to time steps 1, 2, 4 and 5. A composite of these four plots is shown in Fig. 12.

These plots give a visual representation of the plume as it moves vertically and laterally through the system. Note how the plume eventually splits into two parts, with one part discharging to the well and the other to the river.

4. CONCLUSION

With the advent of digital computers, numerical modelling has now turned to be one of the most reliable and interesting applications in groundwater flow and solute transport. The numerical method applied in this study is the Finite Difference Method, which has proved its efficacy in the calculation of groundwater flow rate and direction, and its usefulness in particle tracking within the aquifer domain.

The modelling studies have been carried out for an excavated pit with the aim of determining its suitability for any form of waste discharge.

It is established from this survey that the suitability of this site for sewage disposal is dependent on the volume and composition of the sewage, because in the flow model it was observed that a significant growth in groundwater mound would be expected within days if daily discharge of 6,000litres($6m^3/d$) is exceeded. The survey of the upper aquifer was limited to 100days, the fact that $6m^3/d$ sewage discharge did not reveal any significant rise in the water table within 100days, does not mean that beyond 100days a significant rise may not be detected.

Also, since our sewage discharges are not treated, the site is unsuitable for such waste discharge.

Furthermore, the simulation carried out for the lower aquifer indicated that if the site is used for waste dump, the unconfined nature of the upper aquifer will give rise to a significant increase in contaminant plume (leachate) which will also reach the lower confined aquifer in about 15 years.

We hereby conclude that the site is unsuitable for any form of waste dump and that Finite Difference Method is a reliable method in modelling of groundwater pollution.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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