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Radial Flow Tracer Test to Investigate Coefficient of Transverse Dispersion in an Aquifer in the Eastern Niger Delta, Nigeria

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ABSTRACT

The complex nature of flow dynamic of water at the subsurface makes it difficult to characterize directly the processes taking place in a porous medium. As a result, carrying out studies on the characteristics of contaminants at the subsurface often relies on indirect measurements of the parameters of the system. To overcome these difficulties and provide information on the subsurface, the continuous use of tracers in simulation studies to model hydrological characteristics at the subsurface has provided an important tool for understanding the flow and mixing dynamics of water resource systems. Results obtained from this radial flow tracer test shows coefficient of longitudinal and transverse dispersion of 2.104×10^{-3} m^2s^{-1} and 1.54×10^{-3} m^2s^{-1} respectively, longitudinal and transverse dispersivity of 1.73m and 1.27m respectively. Multidimensional transport in an aquifer involves both longitudinal and transverse dispersion in addition to advection process. Transverse dispersion in an aquifer spreads dissolved contaminant by molecular diffusion when flow velocity of groundwater is highly low. Initial concentration of dissolved contaminants at the point of release can produce an upstream spreading in a longitudinal transverse direction by molecular dispersion which is a diffusion-like process in an aquifer. Results obtained from tracer test can be used to characterize a site and for groundwater monitoring. Having basic knowledge of some physical processes taking place at the subsurface such as that produced from tracer test can also help in the design of environmental network to evaluate possible accidental migration of contaminants once it occur in aquifers and plan suitable mitigation actions to safeguard our water resource.

Keywords: Aquifer, advective velocity, contaminant, transverse dispersion, longitudinal dispersion, Niger Delta

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1. INTRODUCTION

In many parts of the world including the Niger Delta, groundwater is known to be the major source of drinking water. In the past and present, many sources of groundwater contaminants has been identified in the Niger Delta resulting from activities such as leakage of petroleum products; damaged underground storage tanks, vandalized pipelines, spills of hydrocarbon by damaged well heads or corrosion of pipelines that are described as very old without regular maintenance, which has been described as a common event in Nigeria. These Contaminants are spilled accidentally or due to human activities into the environment at points. The occurrence of these events and product infiltrating the soil over a period of time to encounter groundwater in aquifers and become a main cause of water and soil pollution in areas of occurrence and beyond due to their ability to migrate and spread has become a thing of great concern to users of water from aquifers. This is because they can affect the quality of groundwater and makes it inadequate for human and irrigation uses (Kamaruddin et al., 2011a). It will be difficult to maintain the current quality of groundwater in the area in the nearest future due to the occurrence of these activities polluting the environment. For a proper design of water monitoring program therefore, knowledge of the travel time or dispersion is required.

The flow dynamic of water in aquifers has been described as a complex process, and it is difficult to observe or characterize directly the processes that occur in the porous media. As a result, carrying out studies on the characteristics of contaminants at the subsurface often relies on indirect measurements of the parameters of the system (Alaziaza et al., 2016). However, the continuous use of tracers in simulation studies to model hydrological characteristics at the subsurface have proven to be a useful tool for understanding the source and characteristics of contaminants at the subsurface. Groundwater tracer test involve the use of existing or introducing a substance with a different chemistry into the subsurface to obtained information about groundwater flow rate, directions and even transport properties (Maliva, 2016). Tracer test techniques has been acknowledged as the most reliable and efficient means to investigate and characterize the subsurface; evaluate transport velocity, porosity, dispersivity, preferential flow pathways, structural anisotropy, estimate extent of discharge/recharge or total volume, estimate the hydraulic conductivity of Formation material etc. (Chambers and Barh, 1992; Field, 1999; Bloomfield and Moore, 2002; Anderson, 2005; Testoni et al., 2015). Results obtained from tracer test have also shown that it can be used in downhole fracture characterization to locate water bearing fractures and determine flow conditions in fracture bedrock wells (Brainerd and Robbins, 2004; Chlebica and Robbins, 2013)

In the study of contaminant migration, the use of conservative tracers has shown to be a useful tool for simulating the transport and dispersion of solutes in both surface/subsurface waters, because they have virtually the same physical characteristics as water and assume to imitate the characteristics of soluble pollutants. The measured tracer-response curves produced from the injection of a known quantity of soluble tracer usually produces data necessary to model pollutant transport. Therefore, our ability to understand the way tracers' mixes and disperses in a given aquifer is highly essential to understanding their application in simulation studies. In the Niger Delta, the status of oil contaminated sites have been poorly studied and little is known on the flow dynamics and fate of hydrocarbon contaminants once released into the environment especially at the subsurface. There is therefore concern for this class of study in the area to ascertain data on the subsurface flow dynamics as any observation network that will be set up for such study will be based on the anticipated behavior of the system.

2. GEOLOGIC SETTING OF THE STUDY AREA

The study area is Azumini-Isiokpo situated in the South-Eastern Niger Delta area which is underlain by the Benin Formation. The Formation is the youngest of the Niger Delta Formation and predominantly a continental deposit consisting of gravels and massive, high porous, fresh water bearing Sandstones with localized shale (Short and Stauble, 1967). The Formation which contains prolific aquifer horizons is heterogeneous and has been studied in some detail in part of Port Harcourt area by Amajor (1991) who characterized the water bearing sandy layers of its upper 300m horizon and described rapid horizontal and vertical variations in lithology and hydraulic characteristics. Azumini-Isiokpo is in Ikwerre Local Government Area South-Eastern geographical region of Rivers State with a moderate population density, situated with geographical coordinates Latitude 004º55’12” N and Longitude 006º52’44” E (Figure 1a,b). The area is low lying and exposed to periodical inundation by flooding when the rivers in the area overflow their bank (a characteristic feature of a flood plain). Four distinctive layers were identified from the 8m depth boreholes that were drilled and installed for this study with a shallow water table. Generally, aquifers in the Niger Delta occur at shallow depths but vary from point to point in different parts. It is shallower at the coastal parts as depth to water table increases as one move away from the coastal areas. Water for domestic activities in the area is achieved by direct tapping of groundwater resource from the Shallow unconfined aquifer through randomly sited rotary drilled boreholes and hand dug wells.

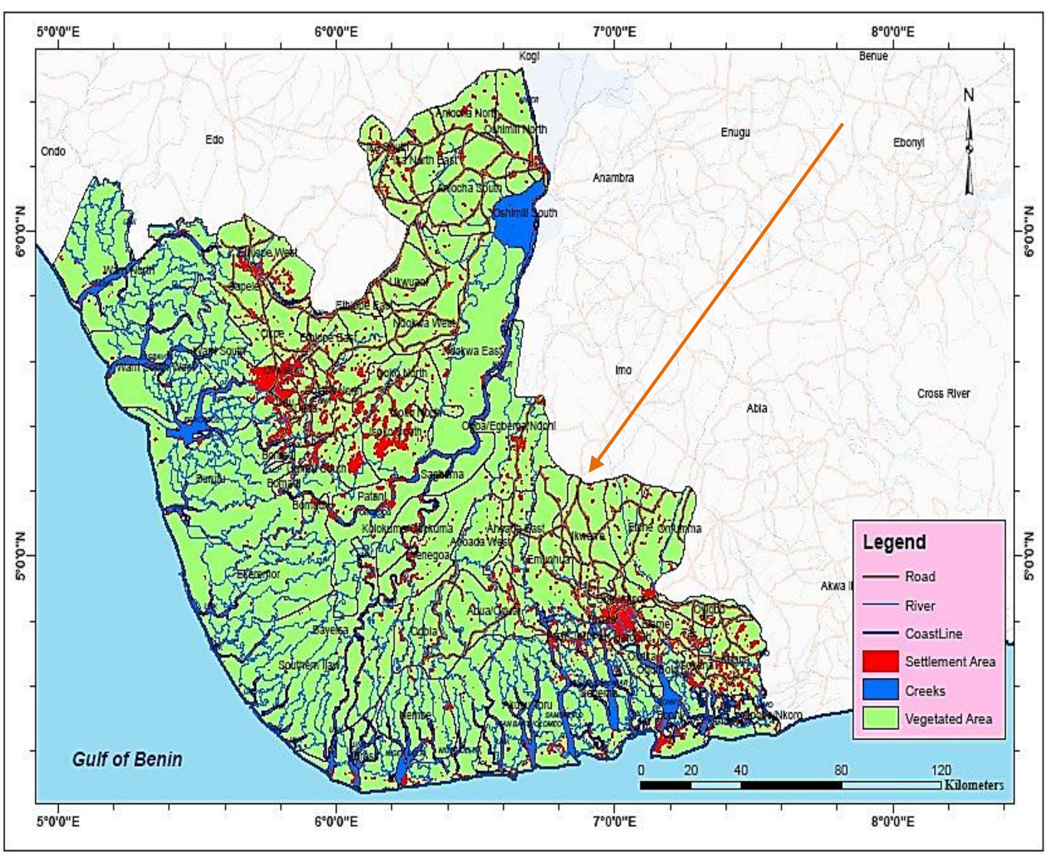

Figure 1a. Map of Niger Delta showing Ikwerre LGA

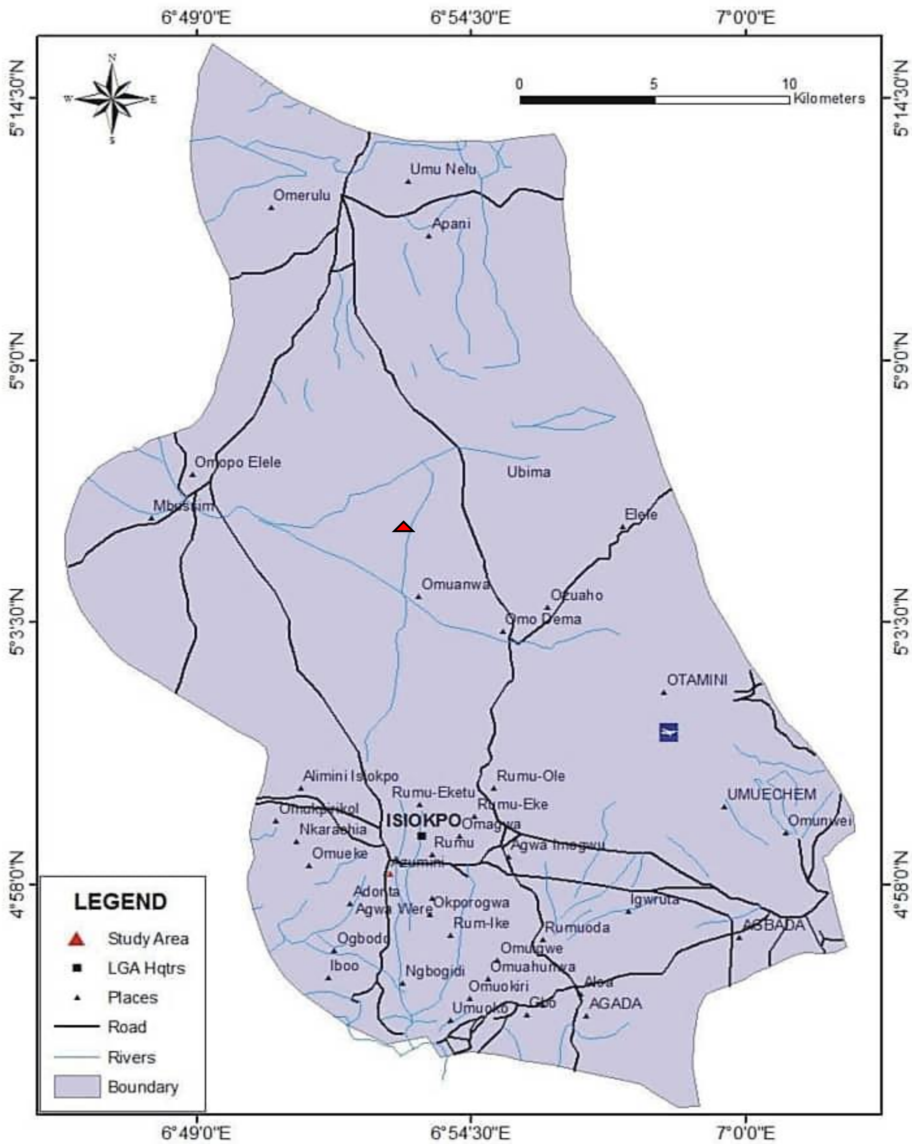

Figure 1b. Map of Ikwerre LGA showing Azumini-Isiokpo, the study site

3. MATERIALS AND METHODS

3. 1. Boreholes drilling, completion, tracer injection and sampling

The boreholes used for monitoring the piezometric heads in the aquifer for the radial flow tracer test were constructed manually by rotary drilling method. Average depth to static water level from the surface was 3.74m. Holes were lined with a casing of 10cm diameter polyvinyl chloride (PVC) pipe corresponding with the size of the auger used for the drilling. A total of 20 boreholes (1 injection and 19 monitoring boreholes) were designed and installed in the study site covering a total distance of 15m for a small scale tracer test. According to (Newton and Brain, 1995; Giadom et al., 2015) a distance of 7m-20m is sufficient to describe the range of horizontal heterogeneity in a small scale tracer test. All boreholes used were advanced to a depth of 8m, PVC pipes screened from a depth of 3m to 8m which is approximately the full extent of the middle and lower aquifer. 12 of the 19 monitoring boreholes were installed at radial distances 1m, 2m and 3m from the injection borehole, keeping a dense array of monitoring points for effective monitoring (Lee and Cherry, 1978). The remaining 7 boreholes were installed 3m apart from the radial arrangement up to 12m from the injection borehole in the direction of the prevailing ground water flow. Boreholes were developed to allow only clean water withdrawn from the aquifer into the installed boreholes. The field design layout for this tracer test is illustrated in the cross section of the study site in (Plate 1). Soil samples obtained at intervals of 0.5m from the surface to a depth of 8m were used to determine particle size distribution in the laboratory to determine the relative proportion of different grain size as they are distributed at the various layers encountered using ASTM P 2487-92 standard (Table 1). There is no ideal tracer and therefore, choice of tracer will depend upon the ultimate objective of a tracer test. Sodium chloride, a conservative tracer was used in this study for it is chemically and biologically inert. Chloride itself can be traced as a natural tracer (Sullera and Horne, 2001) 20 kg of NaCl was dissolved in 20 litres of water and mixed with 280 liters of water drawn from the same aquifer and made up to 300 litres, concentration of the aqueous solution was determined in the laboratory by titration method and found to be 66.67 g/l with a molarity of 1.140 mol/l. Electrical conductivity and pH of the solution were measured in the field using Hanna Hi 9813-6 conductivity meter. Electrical conductivity measured was 992 μS/cm. Conductivity value was also measured in all the boreholes to determine ambient conditions of the aquifer water before recharging the injection borehole at a steady rate of 1.15litre/minute and lasted for a period of 262 minutes (4 hours 37 mins). Tracer migration was carefully monitored using none reusable PVC bailers.

Plate 1. Showing Layout of tracer test field design

Water samples from the observation boreholes were obtained simultaneously from four boreholes of the same radius from the injection borehole at an interval of 2-5 minutes after injection started before resulting to sampling at every 30 minutes interval after the breakthrough moment has been recorded for each borehole and tested for conductivity value (Table 2). Sampling frequency was highest at the start to avoid missing early breakthrough (Abbagzadeh-Dehghani and Brigham)

Table 1. Showing result of PSD Laboratory Analysis for borehole X.

	PARTICLE SIZE PERCENTAGE				
Sample ID (layer)	Depth (m)	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Silt (%)
A	2	1.31	16.04	55.24	27.41
B	4	8.24	32.61	40.88	18.26
C	6	5.36	46.00	44.11	4.52
D	8	17.46	52.22	26.82	3.50

Table 2. Showing Tracer travel time and Electrical conductivity values for the radial tracer test.

Borehole number	Distance From injection Borehole (m)	Background electrical conductivity (µS/cm)	Time ($\bar{t}$) C/Co = 0.5 (Sec)	Peak arrival time (Sec)	Peak electrical conductivity (µS/cm)	Tracer tail electrical conductivity (µS/cm)
A	1	153	12000	12900	872	451
B	1	153	12000	12900	885	433
C	1	157	12600	14400	564	159
D	1	153	13500	19800	541	178
E	2	157	12480	13680	824	476
F	2	157	12780	16500	620	310
G	2	160	Not noticed	16500	441	158
H	2	158	Not noticed	18300	453	162
I	3	197	13020	15000	635	370
J	3	199	Not noticed	20400	473	203
K	3	183	Not noticed	20400	232	182
L	3	183	15000	18600	562	204
M	4	171	13980	15300	637	453
N	4	191	Not noticed	17400	351	182
O	7.4	183	15420	18180	542	327
P	6	171	16920	22800	519	173
Q	7.4	167	Not noticed	Not noticed	Not noticed	Not noticed
R	9	187	Not noticed	25920	431	245
S	12	183	Not noticed	Not noticed	Not noticed	Not noticed

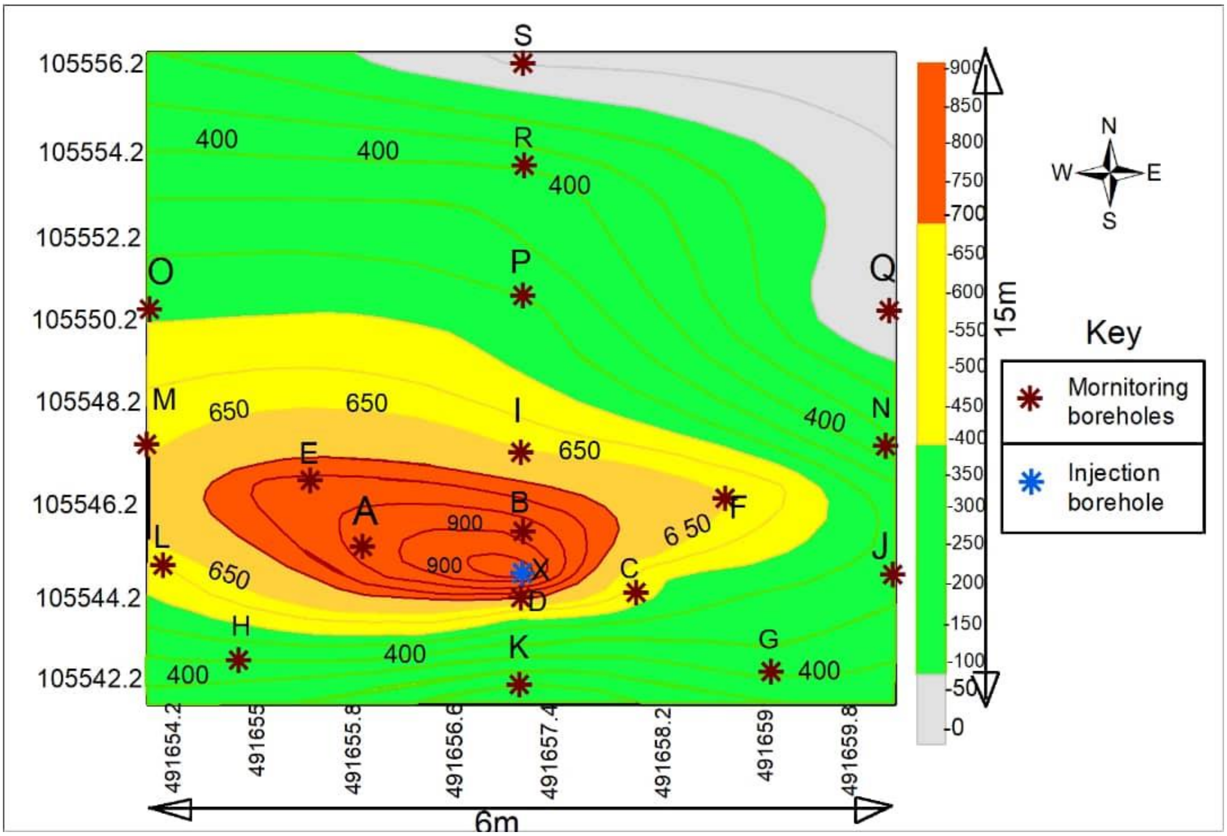

Figure 2. Showing vector and concentration map illustrating the mignitude and direction of tracer migration within the tracer test site.

3. 2. Breakthrough moments, advective velocity and dispersion or tracer

Tracer test often give ambiguous interpretations that may be due to the erroneous location of sampling points and/or the lack of the flow rate measurements through the sampler (Basirico et al., 2015). The mean transport velocity of a tracer was obtained by considering the tracer breakthrough curve along a streamline considering the elapsed time after tracer injection. This was achieved by considering the difference in elapsed time of the centroids of the tracer breakthrough curve defined upstream and downstream on the same streamline (Giadom et al., 2015).

Tracer travel-time was therefore calculated using:

$$t_c = T_{c(n+1)} - T_{cn} \ldots\ldots\ldots \qquad \ldots. (1)$$

where, t_c is the elapsed time (travel-time) to the centroid of the breakthrough curve between the two observation boreholes, borehole B to O, both in the direction of groundwater flow over a distance of 6.40m. $T_{c(n+1)}$ is the elapsed time to the centroid of the breakthrough curve at a point farther from the injection borehole. T_{cn} is the elapsed time to the centroid of the breakthrough curve at point n. (sampling point closer to the injection borehole). Considering the values obtained for peak arrival time of tracer cloud in the boreholes (Table 2)

Travel-time, t_c calculated = 5280 sec.

Mean velocity of tracer cloud calculated = 1.212×10^{-3} ms^{-1}. This velocity value represents the advection velocity of the migrating tracer cloud in the longitudinal direction of flow of the aquifer water at the study site. This value (1.212×10^{-3} ms^{-1}, 104.73 m/day) compares reasonably with the value obtained by (Giadom et al., 2015) at Ogale, Eleme from a sandy silty clay aquifer sampled at an approximate depth of 2.50m on the average in the South-Eastern part of Rivers state (1.403×10^{-3} ms^{-1}, 121 m/day) and that of (Newton and Brian, 1995) ($1.26\times10^{-3}$$ms^{-1}$, 109 m/day) in a shallow aquifer in Little pond, Cap Cod, Massachusetts, both using a conservative tracer, sodium chloride.

Longitudinal and Transverse dispersion coefficients D_L and D_T were calculated (Table 3) using;

$$D_L = \frac{V^2\sigma_L^2}{2t} \tag{2}$$

Transverse dispersion coefficient D_T

$$D_T = \frac{V^2\sigma_T^2}{2t} \tag{3}$$

where

V = average linear groundwater velocity calculated ($1.212\times10^{-3}$$ms^{-1}$)

t = peak arrival time difference of tracer between well B and O used in the determination of advective velocity

σ_L = standard deviation of breakthrough moment in the longitudinal direction (3889.90).

σ_T = standard deviation of breakthrough moment in the transverse direction (3314.99).

Longitudinal and Transverse dispersivities were also calculated using;

$$D_L = \alpha_L V \quad \text{and} \quad D_T = \alpha_T V \tag{4}$$

where α_L and α_T are longitudinal and transverse dispersivities respectively, V is the advective velocity determined for the study site aquifer.

Table 3. Showing aquifer parameter values determined for the tracer test site.

Average porosity (fraction)	Average permeability (cm/sec)	Advective velocity (ms^{-1})	Longitudinal dispersion (m^2s^{-1})	Transverse dispersion (m^2s^{-1})	Longitudinal dispersivity (m)	Transverse dispersivity (m)
0.358	2.861×10^{-3}	1.212×10^{-3}	2.104×10^{-3}	1.54×10^{-3}	1.73	1.27

4. DISCUSSION OF RESULTS

The movement of soluble contaminants through the subsurface is a complex process and difficult to predict due to one’s inability to access the environment directly. However, having a basic knowledge of groundwater flow pattern in an aquifer can be a guide in interpreting the flow dynamics of mostly soluble contaminants at the subsurface. This is achievable using tracer test. The tracer test performed in this study investigates a short time scale (4 days) in order to examine the migrating pattern of a soluble tracer, to model the migrating pattern of soluble components of hydrocarbon products by dispersion process when they encounter groundwater at the subsurface. This is to provide information as a guide to immediate remediation and mitigation actions in cases of contaminant spills from hydrocarbons to help protect our water resource.

Dispersion is another word used to describe spreading of soluble substances in a porous medium as a result of diffusion and mixing caused by velocity variations. The mixing process however is referred to as mechanical dispersion and it relates to the tortuosity of the material while the diffusion refers to molecular diffusion of particles brought about by random molecular motion of the dissolved particles in the water as a result of thermal kinetic energy of the molecules. These two processes taking place simultaneously are physical processes that occur at the subsurface known as hydrodynamic dispersion. Figure 2 shows the migration pattern of the tracer substance in the test field by both advection and dispersion. Table 3 shows value obtained for average porosity and permeability, advective velocity, coefficients of dispersion and dispersivity during the test period. Outside the advective process, dispersion was in three dimensional domains (x, y and z). These are; in the longitudinal, second dimension axis and transverse including the longitudinal transverse direction. With transverse dispersion, tracer originating from a source borehole rises to occupy other regions thereby spreading the tracer beyond the advective direction. These spreading patterns introduces an upstream spreading (backward diffusion) of the initial cloud which is in the longitudinal transverse direction as a result of the initial concentration at the injection borehole for the period of tracer injection (Jui-Sheng et al., 1996). Dispersion brings about a decrease of peak concentration about the advective front and a spreading out of the breakthrough curve tails.

When hydrocarbon products such as LNAPLs are released into the environment, due to their non-mixing characteristics, some portion can be held in pore spaces in soil while free phase products tends to float on the water at the saturated zone. The more soluble components such as Methyl tertiary butyl ether (MTBE) Ethyl tertiary butyl ether (ETBE) Tertiary methyl amyl ether (TAME) Toluene, Benzene etc. can dissolve in groundwater to cause a long-term groundwater plume and carried by advection process (Nonner, 2002) while the volatile components present can partition into soil gas. Hydrodynamic dispersion will help to distribute the dissolve components both in the longitudinal and transverse directions moving the product beyond the region that only advection would have transported the component as shown in Figure 2.

5. CONCLUSIONS

The movement of contaminants through the subsurface is rather complex and difficult to predict. However, a basic knowledge on groundwater flow pattern in an aquifer can be a guide in interpreting the flow dynamics of contaminants at the subsurface. To have a better understanding of the subsurface flow pattern, tracer test has been used over the years and has proven to be an effective technique that can be used to gain data from an environment that is not accessible directly. Using the study of tracers for modeling of contaminants migration can provide a guide on estimating where and when contaminant action can be first noticed in an environmental matrix and the extent of spreading for delineation in an accidental hydrocarbon spill. This study has however helped in the understanding of the hydrogeological characteristics of the study site and how soluble contaminant can be spread. Dispersion brings about a reduction in contaminant concentration about the advective front, attenuation and spreading in axes that are normal to groundwater flow direction in an aquifer. Longitudinal and transverse dispersion are chiefly responsible for this spreading of contaminant from their source point in an aquifer. For a continuous recharge and high quantity of hydrocarbon product at a point, multidimensional spreading is possible within the domain in the direction of x, y and z leading to an upstream spreading of the product due to the initial concentration of the product at the recharge point.

Every water aquifer is a valuable asset and in the management of water resource, the quantity and quality problems cannot be separated from each other. For its proper planning and management therefore, depth knowledge on the hydrological characteristics of groundwater is required, which is achievable using tracer test. As observed, modeling flow dynamics in an aquifer has demonstrated how preliminary information on aquifer parameters can be obtained both on site characterization and on groundwater monitoring.

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