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RADIAL FLOW TRACER TEST FOR INVESTIGATING COEFFICIENT OF TRANSVERSE DISPERSION IN AN AQUIFER IN THE EASTERN NIGER DELTA, NIGERIA

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ABSTRACT: Studies have shown that the flow dynamic of water in aquifer is very complex and it is difficult to observe or characterize directly the processes that occur in the porous media of the soil structure. As a result of this, carrying out studies on the characteristics of contaminants at the subsurface often relies on indirect measurements of the parameters of the system. However, the continuous use of tracers in simulation studies to model hydrological characteristics at the subsurface have provided an important tool for understanding the flow and mixing dynamics of water resource systems. Result obtain from this tracer test shows that multidimensional transport in an aquifer involves both longitudinal and transverse dispersion in addition to advection and can be achieved using a radial flow test. Transverse dispersion in an aquifer can spread dissolved contaminant faster than advection by molecular diffusion when flow velocity of groundwater is highly low. The initial concentration of dissolved contaminants at a source point can cause an upstream spreading by molecular dispersion in an aquifer. The use of tracer test can provide preliminary information for site characterization and groundwater monitoring to help in the design of environmental network to evaluate possible accidental migration of contaminants once it occurs in aquifers and plan suitable mitigation actions to safeguard our water resources.

KEYWORDS: Aquifer, advective velocity, contaminant, transverse dispersion, longitudinal dispersion.

1 BACKGROUND

In many parts of the world including the Niger Delta, groundwater has been recognized as the main source of drinking water. In the past and present, many sources of groundwater contaminants has been identified in the area resulting from activities such as leakage of petroleum products; damaged underground storage tanks and vandalized pipelines, spills of hydrocarbon by damaged well heads and leachates from dump sites. These Contaminants can be spilled accidentally or due to human activities (intentionally) into the environment at any point. The possibility of this event occurring and product infiltrating downward to encounter groundwater in aquifers has become a thing of great concern to those diverting and using water from aquifers, streams and rivers. These hydrocarbon contaminants spillage for instance occur regularly during the exploration, production, refining, transport and even storage of the products and becomes a main cause of water and soil pollution in areas of occurrence and beyond due to their ability to migrate. These affect the quality of groundwater and make it inadequate for human and irrigation uses [1]. These numerous activities occurring at points that can lead to pollution of groundwater in our immediate environment suggest that it will be very difficult in the future to maintain the present high quality of groundwater and springs unless greater care is taken to protect our groundwater sources [2]. For the control of such pollution or warning system on water bodies where data are limited, a method of estimating the travel time or dispersion is required. Therefore, the ability to simulate potential pollution buildup in water bodies' (aquifers) becomes increasingly important.

The flow dynamic of water in aquifer is very complex and it is difficult to observe, or characterize directly the processes that occur in the porous media of the soil structure. As a result of this, carrying out studies on the characteristics of contaminants at the subsurface often relies on indirect measurements of the parameters of the system [3]. However, the continuous use of tracers in simulation studies to model hydrological characteristics at the subsurface have provided an important tool for understanding the source, flow and mixing dynamics of water resource systems through their imprint on the system or their sensitivity to alteration within it [4]. Tracer techniques are multipurpose method and most reliable and efficient means to investigate and characterize the subsurface, evaluating transport velocity, porosity, dispersivity, preferential flow pathways, structural anisotropy etc.[5],[6],[7],[4],[8].

In the study of contaminant migration, the use of conservative tracers have shown to be a useful tools 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 provides an efficient method of obtaining the data necessary to calibrate and verify pollutant transport models. 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. For developing sustainable management policies for the protection of water resource and the aquatic environment therefore, a continuing need to promote their use is highly required [4]. Concern for this class of study in the Niger Delta is important because the status of oil contaminated sites in the area has been poorly studied and little is known on the flow dynamics and fate of hydrocarbon contaminants once released into the environment especially the subsurface [9].

2 MATERIAL AND METHOD

2.1 WELL DRILLING, CONSTRUCTION, COMPLETION AND TRACER INJECTION

The piezometers used for monitoring the piezometric heads in the aquifer for the radial flow test were constructed manually by rotary drilling method. Average depth to water table from the surface is 3.74m. Holes were lined with a small casing of 10cm diameter polyvinyl chloride (PVC) pipe [10], which corresponds with the size of the auger used for the drilling. A total of 20 wells (1 injection and 19 monitoring wells) were designed and installed in the study site covering a total distance of 15m. According to [11],[12] a distance of (7-20m) is sufficient to describe the range of horizontal heterogeneity in a small scale tracer test. All piezometer used were advanced to a depth of 8m down, PVC pipes screened from a depth of 3.00 to 8.00m, which is approximately the full extent of the middle and lower aquifer. 12 of the 19 piezometers used as monitoring points were installed at radial distances (1m, 2m and 3m from the injection piezometer) keeping the wells close enough apart since effective monitoring requires a dense network of sampling points [5]. The remaining 7 piezometers were installed 3m apart from the radial arrangement up to 12m from the injection well in the direction of the prevailing ground water flow. Wells were then purged to allow only water freshly withdrawn from the aquifer into the installed wells. The field design layout for this tracer test is illustrated in the cross section of the study site in (fig. 1). Cuttings obtained at interval of 0.5m from the top down to a depth of 8.0m were used for hydraulic property test (particle size distribution analysis, porosity and permeability) in the laboratory. (See Table 1 for results of PSD). According to [13], "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 selected for this study for it is chemically and biologically inert and "Environmental friendly". 20kg of NaCl was dissolved in 20litres of water and mixed with 280liters of water drawn from the same aquifer and made up to 300litres, concentration of the aqueous solution was determined in the laboratory by titration method and found to be 66.67g/l with a molarity of 1.140mol/l. Electrical conductivity and PH of the solution were measured in situ using Thermo Orion conductivity meter (model 145) APHA 2510-A and APHA 2510-B. Electrical conductivity measured was 992µS/cm. Conductivity value was also measured in all the piezometers to determine ambient conditions of the aquifer water before recharging the injection well at a steady rate of 1.15litre/minute and lasted for a period of 262 minutes (4hours 37mins). Tracer migration was carefully monitored using PVC bailer in the absence of multilevel sampling device. Water samples from the observation wells were obtained simultaneously from four wells of the same radius from the injection well at an interval of 2-5minutes after injection started before resulting to sampling at every 30 minutes interval after the breakthrough moment has been recorded for each well and tested for conductivity value. See Table 2 for conductivity values obtained.

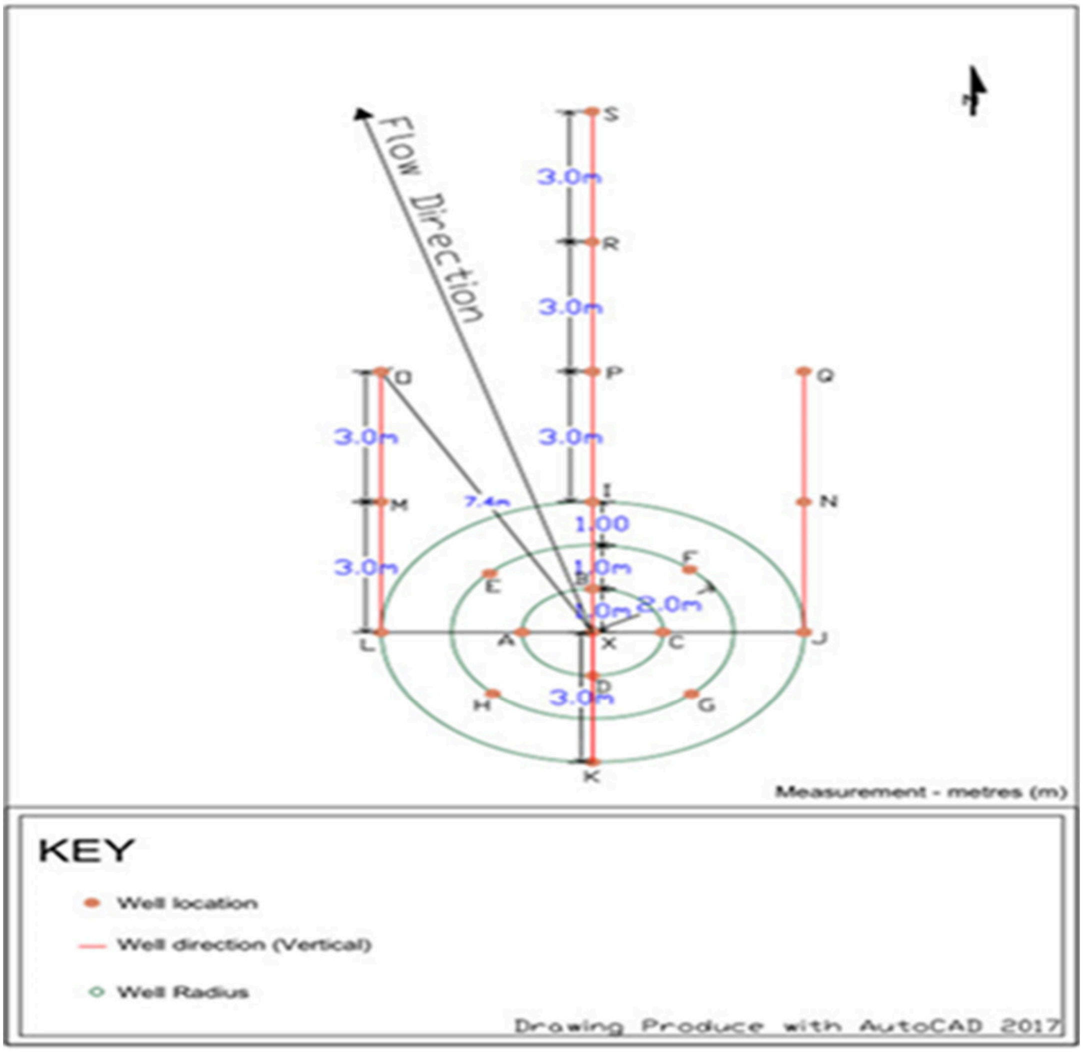

Fig. 1. Schematic Layout of tracer test field design

3 Results

Table 1. Result of PSD Laboratory Analysis for well X

	PARTICLE SIZE (ASTM P 2487-92)				
SAMPLE ID (layer)	Depth (m)	Coarse Sand (%)	Medium Sand (%)	Silt (%)	Clay (%)
A	2	0.13	11.18	61.19	27.38
B	4	0.19	13.06	68.48	18.26
C	6	0.15	12.21	83.11	4.52
D	8	0.26	22.20	74.04	3.50

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

Well number	Well dist. From injection well (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

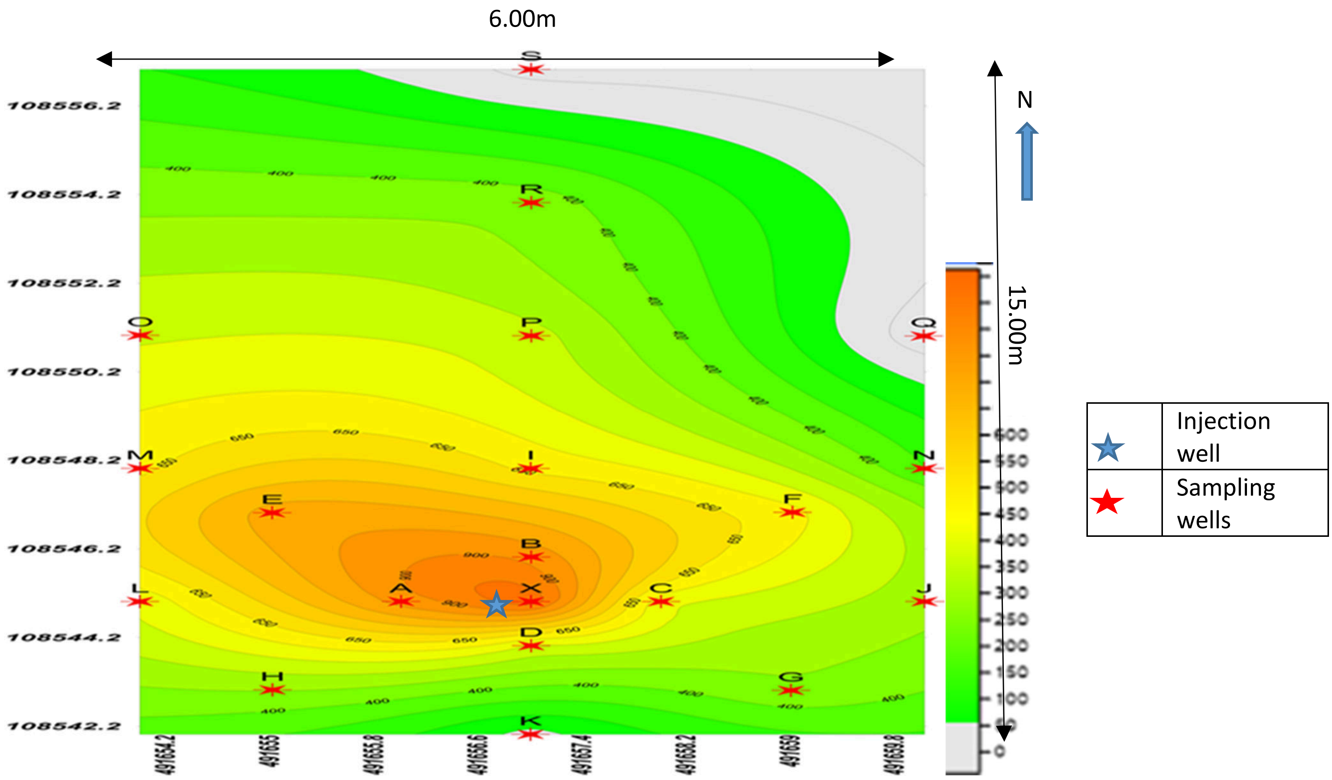

Fig. 2. Avector and concentration map illustrating the mignitude and direction of tracer within the tracer test site

3.1 BREAKTHROUGH MOMENTS, ADVECTIVE VELOCITY AND DISPERSION OF TRACER

The mean transport velocity of a tracer can be obtained by considering the tracer breakthrough curve along a streamline putting the elapsed time after tracer injection into account. 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 [14],[12].

Tracer travel-time was therefore calculated using:

$$t_c = T_{c(n+1)} - T_{cn} \quad (1)$$

Where, T_{cn} is the elapsed time to the centroid of the breakthrough curve at point n. (sampling point closer to the injection well). $T_{c(n+1)}$ is the elapsed time to the centroid of the breakthrough curve at a point farther from the injection well. t_c is the elapsed time (travel-time) to the centroid of the breakthrough curve between the two observation wells, well B to O, both in the direction of groundwater flow over a distance of 6.40m

Considering the values obtained for peak arrival time of tracer cloud in the wells as presented in table 2

Travel-time, t_c calculated = 5280 sec.

Mean velocity of tracer cloud calculated = $1.212\times10^{-3}ms^{-1}$. This velocity value obtained represents the advective velocity of the migrating tracer cloud in the longitudinal direction of flow of the aquifer water at the study site. This value ($1.212\times10^{-3}ms^{-1}$,104.73m/day) compares reasonably with the value obtained by [12] 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 ($1.403\times10^{-3}ms^{-1}$, 121m/day) and that of [11] ($1.26\times10^{-3}ms^{-1}$, 109m/day) in a shallow aquifer in Little pond, Cap Cod, Massachusetts, both using a conservative tracer (Sodium Chloride).

Longitudinal dispersion coefficient D_L is given by,

$$D_L = \frac{V^2\sigma_L^2}{2t} \quad (2)$$

Transverse dispersion coefficient D_T is given by,

$$D_T = \frac{V^2\sigma_T^2}{2t} \quad (3)$$

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 can be obtained by;

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

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. Aquifer parameter values evaluated 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

The movement of contaminants through the subsurface is rather complex and difficult to predict due to one's inability to access the environment directly. However, having a basic knowledge on groundwater flow pattern in an aquifer can be a guide in interpreting the flow dynamics of contaminants at the subsurface. Tracer tests has been used over the years and has proven to be an effective techniques that can be used to gain data from the environment, in particular on groundwater systems that are 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 in an accidental hydrocarbon spill. The tracer analysis performed in this study investigate a short time scale (4 days) in order to investigate the migrating pattern of a soluble tracer for modeling the migrating pattern of soluble components of non-aqueous phase liquids substances by dispersion process when they encounter groundwater at the subsurface, so as to provide information as a guide to immediate remediation and mitigation actions in cases of contaminant spills from hydrocarbons to help protect our water resources.

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 here is however referred to as mechanical dispersion and is related 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 taken place simultaneously is a physical process that occur at the subsurface and known as hydrodynamic dispersion. As described by [15], it an unsteady, irreversible process in which mass of tracer continuously mixes with the non-labeled portion of moving water in an aquifer. Fig. 2 shows the migration pattern of the tracer substance in the test field by both advection and dispersion. Aside the advective process, dispersion was in three dimensional domain (x, y and z) that is in the longitudinal, transverse and longitudinal transverse directions. With transverse dispersion, tracer originating from a small subdomain at a source point rises to occupy an ever growing volume of the region thereby spreading the tracer beyond the advective area. These spreading patterns introduces an upstream spreading of the initial cloud which is in the longitudinal transverse direction, caused as a result of the initial concentration at the injection point for the period of tracer injection. This upstream spreading of initial cloud brings about a decrease of peak concentration about the advective front and a spreading out of the breakthrough curve tails as a result of molecular diffusion.

When hydrocarbon products such as LNAPLs are released into this environment, due to their non-mixing characteristics, some portion can be held in pore spaces in soil while free phase 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 can dissolve in groundwater to cause a long-term groundwater plume 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 fig. 2.

5 Conclusion

The movement of contaminants through the subsurface is rather complex and difficult to predict. However, having a basic knowledge on groundwater flow pattern in an aquifer can be a guide in interpreting the flow dynamics of contaminants at the subsurface. 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. The model used in this study has however help in the understanding of the hydrogeological characteristics of the study site and how soluble contaminant can be spread in the area bringing about a reduction in contaminant concentration about the advective front, attenuation and spreading in directions 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 source of spill 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 source point.

Every water aquifer is a valuable asset and in the management of water resources, 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. Using this suitable golden surfer software for 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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