PRINT ISSN 1119-8362
Electronic ISSN 2659-1499

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 28 (10B Supplementary) 3361-3368 October, 2024

Single Well *In-Situ* Permeability Assessment to Deduce Hydraulic Conductivity of Aquifer at Gio, Gokana Local Government Area, Rivers State, Nigeria

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ABSTRACT: The impact of oil spill incidences in the Niger Delta States of Nigeria is real. Mitigation efforts are hindered by data gaps. One of such disparities is occasioned by inappropriate methods used in determining the hydraulic conductivity of the aquifer underlying a spill site. Hence, this study demonstrates the application of single well *in situ* permeability test to determine the hydraulic conductivity of an aquifer at a site in Gio, Gokana LGA of Rivers State, Nigeria. The field pumping test was conducted using standard methods. Hydraulic conductivity values were between the limits of 0.89 and 48.2 meters per day. The results agreed with the aquifer texture in Gio site that was dorminantly coarse, well sorted sand and conformed with Darcy's rule, that permeability is dependent on hydraulic gradient

DOI: https://dx.doi.org/10.4314/jasem.v28i10.51

Cite this Article as: OSSAI, F. E; SALAMI, A. S. (2024). Single Well *in-Situ* Permeability Assessment to Deduce Hydraulic Conductivity of Aquifer at Gio, Gokana Local Government Area, Rivers State, Nigeria. *J. Appl. Sci. Environ. Manage.* 28 (10B Supplementary) 3361-3368

Dates: Received: 21 August 2024; Revised: 29 September 2024; Accepted: 08 October 2024 Published: 31 October 2024

Keywords: Permeability; Hydraulic; Conductivity; *In Situ*; Penetrating

The Niger Delta region of Nigeria host over 3,000 kilometers of pipelines (PLs) criss-crossing its landmass linking more than two hundred and eighty (280) 'flow stations across the region' (FRN, 2006). Pipelines, most often laid on the surface and in shallow open-cut trenches, connect the onshore and offshore producing wells and flow stations to the major export terminals as well as refineries within and outside the region: hence right of way (RoW) used to designate pipeline routes in the industry. Petroleum industries and stakeholders in the oil business acknowledge that their operations have the potentials to impact the immediate environment. The provision of mineral oil (safety) regulations of 1963 and several petroleum acts that culminated in the environmental guidelines and standards by the Department of Petroleum Resources (DPR) was to prevent environmental degradation by petroleum related incidences (DPR, 2002). Recently (January 25, 2024 to March 8, 2024), eleven (11) oil spill incidences occurred on land with probable causes traceable to ten (10) cases of sabotage and one (1) operational failure. In one of such incidences, an estimated 56 barrels (bbls) was spilled and an associated recovery of 50 bbls was reported (SPDC Nigeria, 2024). This may suggest an introduction of about 6 bbls (more or less, 954 liters volume of crude) into the immediate unconsolidated subsurface surrounding of the spill sites, thereby presenting a hazardous situation. Free-phase hydrocarbon had been located in monitoring wells screened in the upper aquifer in some places (UNEP, 2011). The regional landform in Rivers State is low-lying and undulating

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relief, with unconsolidated aquifers that are extensive, high yielding and largely unconfined with shallow water table (≤10m below ground level) – Offodile, 2002. Irrespective of the cause (sabotage or operational failure) contamination by oil spill can be traceable to a point source - an identifiable, small-scale source. So, source loading due to initial leakages are primary contaminants. However, secondary sources of contamination of the subsurface that can be attributable to geological and hydrogeological phenomena do arise. For instance, corrective actions applied to mitigate the impact of oil spillages include the use of natural depressions, dykes or embankments, booms, trenches or pits in addition to the many artisanal refineries, thereby putting 'significant environmental pressure' on the locations where they occur (UNEP, 2011). In the recent years, security agents have also seized illegally obtained crude oil and dispensed of them by burning the tanker and its product in the nearest burrowed pit sites. The foremost pathway through which spilled crude can migrate to point of exposure (PoE) is groundwater (Sethi and Di Molfetta, 2019). Through these means unquantifiable volumes of petroleum have been introduced into the subsurface of the Niger Delta territory. Understandably, statutory requirement for spill assessment demands that it must be on site specific basis which implies identifying the source, plume size and migration, as well as the possible receptors within one (1) month of the occurrence (DPR, 2002). To be explicit, "field condition is of fundamental importance" (Musa and Gupa, 2018) and therefore assessment is best conducted on site (*in situ*). Even so, hydrogeological report involving field hydraulic conductivity measurements should state how the test was conducted because the methods of measurement and interpretations vary (Fetters, 2001). The suggestion is now well valued with the regular inclusion of *in situ* permeability test in hydrogeological surveys. Aquifer permeability test is a precursor to defining its hydraulic conductivity. This test cannot be substituted with vadose zone piston flow or infiltration test, where often, depth of measurement falls within the first one meter (1m) of the A-horizon (Musa and Gupta, 2018).

Definitely, *in situ* permeability determination, which takes into consideration the aquifer permeability at a point in the flow field (Sharp, 2007), is vital to evaluating the specific hydraulic conductivity of a site; it continues to be the best method to understanding the aquifer properties of an oil spill site. Therefore, the objective of this paper is to demonstrate the application of single well *in situ* permeability test to deduce the hydraulic conductivity of an aquifer at a site in Gio, Gokana LGA of Rivers State, Nigeria.

MATERIALS AND METHODS

Niger Delta Setting: The Niger Delta region consisting of nine (9) states of Nigeria have many streams and rivers, a number of which had their sources within the states. From observation, Ethiope River in Delta State, originated from a spring at Umuaja in Ukwani local government area of the state. These streams/rivers become estuaries to major rivers cutting through their landmass as they course into the Atlantic Ocean. Invariably, Niger Delta has many watershed and wetland areas. Characteristically, most wetland areas are below sea level towards the coastal belts. Locally, the sampling points (SPs) were set in a RoW track to avoid third party disputes. Even so, the geometry and framework of the groundwater flow system that is dependent on the knowledge of the litho-stratigraphy, is necessary in order to define the hydrogeologic system on which the study is centered (DNREC-RS, 2024). Well data from recent field works across the Niger Delta suggested that the near-surface lithology comprises of sandy clay, clayey sand or sandy silt layers. This correlated with the lithological distribution of Recent age (Fig.1) namely: the Western/Coastal, Warri-Sombreiro Deltaic, Lower Niger/Niger plain sands through the Mangrove, Beach and Barrier bars. It is instructive to note that the region is predominated by leaky unconfined aquifers. So, most often, water table rises through the aquitard to the sustained shallow groundwater levels reported all seasons regardless of the well depth. These unique features can be contributory to the finding that groundwater level in the Niger Delta ranges from 0 to 10mbgl (Offodile, 2002).

Theoretical Background: Two key concepts in groundwater hydraulics are permeability and hydraulic conductivity. The permeability 'κ' is solely a function of the medium (Poehls and Smith, 2009); that is the pore spaces and their connectivity, hence the dimensionL^2. However, Hydraulic conductivity (K) is a function of the properties of the fluid as well as the permeability 'κ' of the porous medium through which it passes. The principle of Darcy relates the volume of water (Q) flowing through a unit section (A) of aquifer to the hydraulic slope (i) typical of the section, i.e;

$$Q \propto iA. \qquad (1)$$

$$Q = KiA \qquad (2)$$

The constant of proportionality (K) resulting from the relationship is the hydraulic conductivity. It is 'the volume of fluid that flows through a unit area of porous medium for a unit hydraulic gradient normal to that area' (Sharp, 2007). Concerning water, relative permeability is equivalent to aquifers intrinsic permeability. The inference is that hydraulic conductivity (K) represents the permeability of an aquifer for sediments when dealing with water since the density is $1\text{g} / cm^3$ and viscosity is negligible. It is the basic rule governing steady-state flow in porous media (Tang *et al.*, 2017). The correlation was illustrated in the range of hydraulic conductivity and intrinsic permeability values determined for sediments (Table 1). When equated side by side and adopting the same test conditions, the values appear to have a constant factor of 10^5 in proportion between equivalent values in corresponding ranges, suggesting that: $K = \kappa. 10^5$.

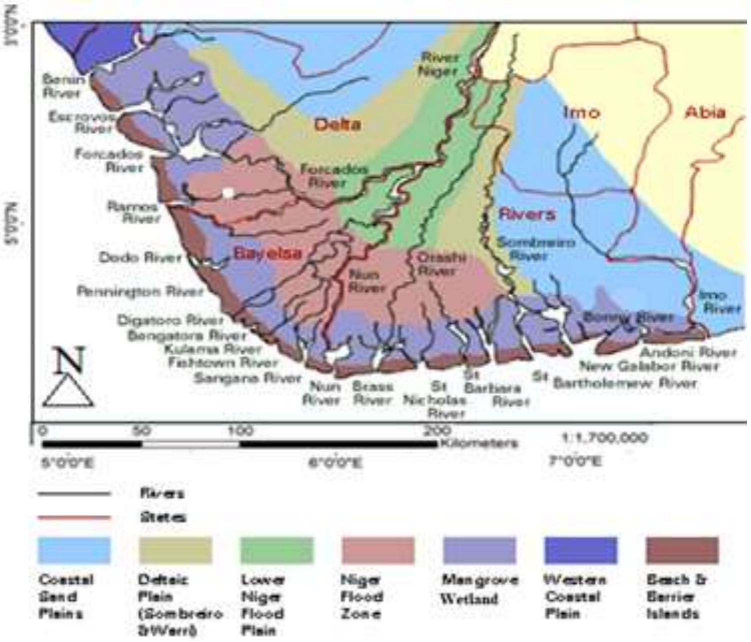


Fig 1: Near-Surface Geology in the Niger Delta Region (after Okonkwo *et al.,* 2015)

Table 1: Hydraulic conductivity and permeability ranges in Sediments (Poehls and Smith 2009)

Sediment/Rock	Hydraulic conductivity 'K' in (cm/sec)	Permeability 'k' in (cm^2)
Clay	10^{-9} to 10^{-6}	10^{-14} to 10^{-11}
Silt	10^{-7} to 10^{-3}	10^{-12} to 10^{-8}
Fine/silty sand	10^{-5} to 10^{-3}	10^{-10} to 10^{-8}
Coarse/well-sorted sand	10^{-3} to 10^{-1}	10^{-8} to 10^{-6}

Applying Darcy's theory, equation (2) is often expressed as:

$$\boldsymbol{q} = -\boldsymbol{K}(\boldsymbol{dh}/\boldsymbol{dl}) \qquad (3)$$

Where 'q' is specific discharge or discharge (Q) per unit area (A), '$\boldsymbol{dh} / \boldsymbol{dl}$' is hydraulic gradient ($\boldsymbol{i}$) that is the ratio of the limit to change in hydraulic head between two monitoring wells (MWs) to the limit of the shortest distance between the MWs in the flow field.

This would be the tangent of the angle of elevation of the higher head from the lower head. It is for this reason that the constant $\boldsymbol{K}$ usually has a negative sign indicating that when determined, flow is in the direction of decreasing head relative to datum (Fetter, 2001); not necessarily decreasing depth with respect to topography.

The earliest test applicable *in situ* was slug test, and it is one of two types - falling-head or rising-head test, (Poehls and Smith 2009). However, pumping test is now the most common investigation method used to define field hydrogeological parameters and to analyze the properties of aquifers including hydraulic conductivity (Tang *et al,* 2017). Indeed, pumping test is a direct, field method of obtaining hydraulic conductivity in a given groundwater flow regime. Generally, pumping tests are conducted *in situ* on the principles of well flow theory. It is a field experiment that involves pumping out groundwater through a well and the rate of flow into the same well or out of another well in close proximity is observed: hence single well pumping test or pumping test with observation well(s).

The choice of designing a pumping test type requires sufficient knowledge of the site specific geology and hydraulic characteristics (DNREC-RS, 2024). A three - phase approach for pumping test therefore involve: (a) inspection of the landscape, well drill logs or an existing log data, (b) design of pumping test to fit the observed local topography/geology/aquifer features and (c) a selection of appropriate data analysis method.

Site Observations: On a regional scale, Gio is on the extreme northwest horn of Gokana local government area of Rivers State (Fig. 2 inset). Four (4) MWs used in this study were located in a northwest to southeast axis beside a pipeline RoW route. There were large horizontal displacements between the drilled wells ($\geq 26m$) that summed up to 218m from BH1 to BH4 by the shortest path. The site had undergone clearing and excavation works over the years as indicated by the presence of spoil heaps and mud cakes in places. So it was easy to observe the undulation of the study area insinuated by the regional map (Fig. 2). However, at borehole points, altitude readings at the time of study returned values below sea level after correction of the GPS elevation measured on site (UNAVCO, 2019; Ossai and Salami, 2024). The topography was anisotropic, sloping gently in all directions: -10.4m relative to mean sea level (msl) at BH2,-12.9 m(msl) at BH3 and$-$11.9 m(msl), -11.8 m(msl) at BHs 1 and 4 respectively (Fig. 3). Well logs implied that the soil matrix was heterogenous in vertical and lateral extent (Fig. 3). The lithology suggested a reasonably thick unconsolidated sandy unit generally dipping from BHs 1 and 2 towards BHs 3 and 4. The about 10m deep borings alluded that the thick (5m) sand substratum in BHs 1, 2 and 3 thinned towards BH4 to 3m at depth. An intermediate, clayey medium overlie the sandy substratum in all wells but more elevated in BHs 2 and 4. There was a clayey cap cover at BHs 3 and 4. All borings were installed with strings of 3 inch (76.2mm) inner diameter PVC casing pipes (DNREC-RS, 2024). At the time of study the hydraulic heads in BHs 1, 2, 3 and 4 had risen to -14.28 m(msl), -12.75 m(msl), -14.83 m(msl) and -14.37 m(msl) in that order. This hints at very low groundwater hydraulic gradients (i). For instance the hydraulic gradient between MW1 and 2 in the flow system approximated to 3° (i.e.$\boldsymbol{dh} / \boldsymbol{dl} = tan^{-1}(0.0588)$) towards MW1.

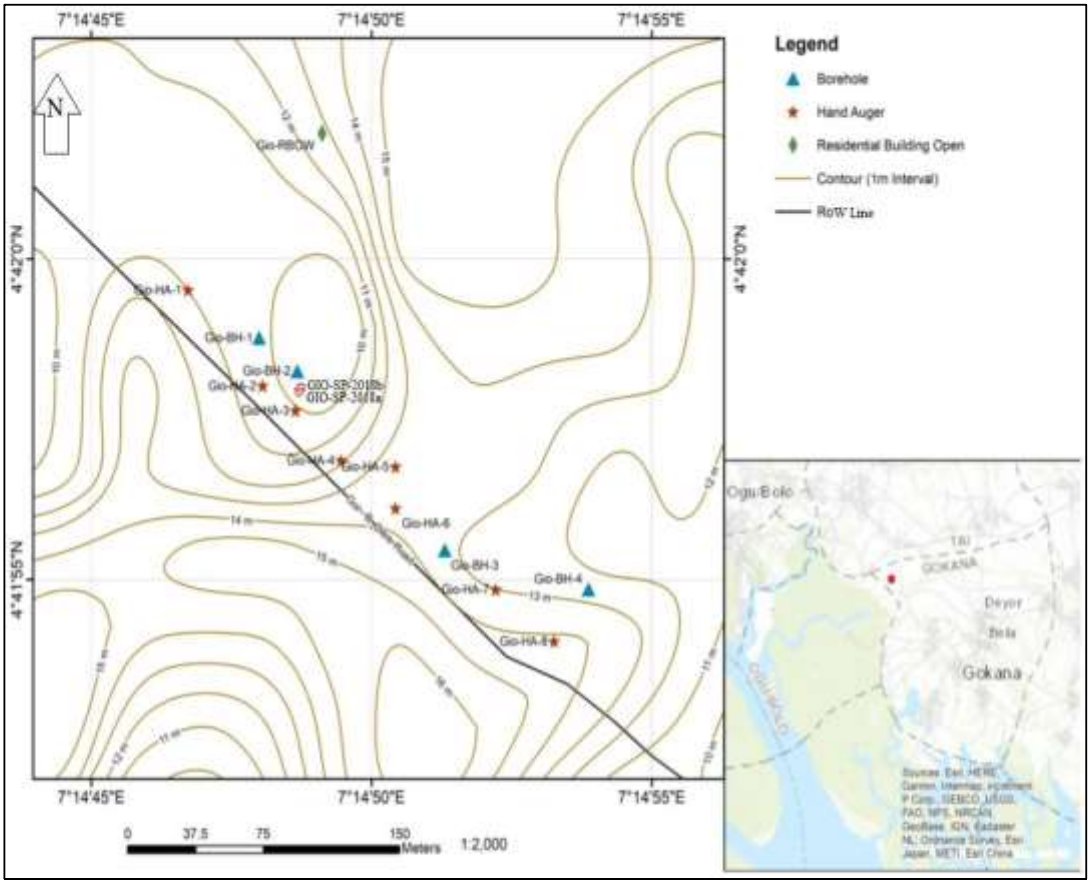
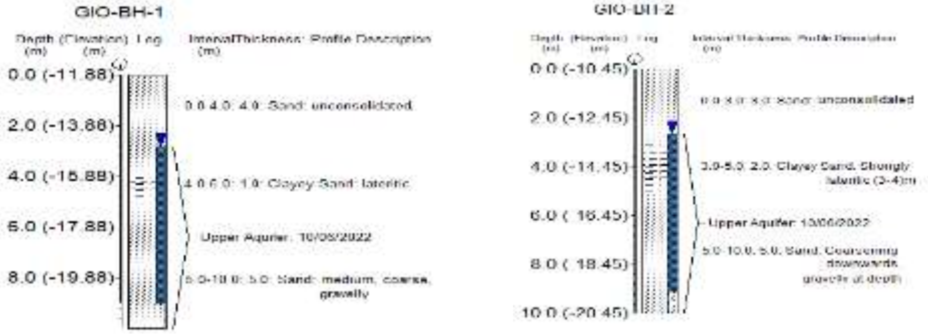


Fig 2: Topographic Map of Study Area Showing Sampled Points (Esri, 2020 Modified)

Location: N4°41'58.77" E7°14'47.99" (Gio) Location: N4°41'58.25" E7°14'48.67" (Gio)



Location: N4°41'55.46" E7°14'51.31" (Gio) Location: N4°41'54.85" E7°14'53.87" (Gio)

Fig 3: Lithology Logs of Tested Boreholes Showing Aquifer Thicknesses

In Situ Pumping Test Design/Field Measurement: The soil matrix underlying the Gio site was heterogeneous and aquifer conditions anisotropic. Also, the MWs for the study were set at large displacement ($\geq 26m$). This interval amid the prevailing sand/clay lithology does not favor the use of *in situ* falling head pumping test at the site (Chinyem and Ovwamuedo, 2023). The required draw down for falling head test would be challenging to attain if any of the MWs provided was chosen as observatory well. Water table recovery test method was therefore decided upon (Sule *et al*, 2013; Tang *et al*., 2017).Water table recovery or rising head method of *in situ* permeability test is a direct outcome of steady flow pumping test (Tang *et al*., 2017). It is a single well pumping test, implying that the same well served as the pumping and observation well. All four (4) wells were selected for this study. The accessed aquifer in all MWs was shallow, unconfined with thicknesses (h) in the range$3m \leq h \leq 7m$ (Fig. 3). The aquifer had hydraulic connectivity with the overlying aquitard. In each well the screen length (l) was in the range$3m \leq l \leq 6m$ depending on aquifer thickness. Screens were slotted in a way 'to provide maximum open area consistent with strength requirements to take advantage of the aquifer hydraulic conductivity' (NREC, 2012). The screen bottom end-cap was also perforated and the entire screened section was submerged. The bores were over pressured at depth during well installation which resulted in loss of depth in each bore. Hence actual aquifer thicknesses screened reduced considerably to the range $6m \leq h \leq 7m$ in MWs 1, 2 and 3. However, MW 4 was screened in the last 3.655m thick unconfined aquitard (Table 2). That implies that all MWs had seepage at bottom (Fig. 3) and more than 80% of aquifer screened from base of well. This pumping test was consequently conducted on the premise that all four (4) wells were fully penetrated (complete screening of aquifer) with seepage at the base (Tang *et al*, 2017). So, the pumping test analysis in this instance followed the design suggested by Tang *et al*, (2017), as illustrated in (Fig. 4).

Table 2: Properties of Monitoring Wells Installed at Gio Study Site

Monitoring Well ID	Gio-BH-01	Gio-BH-02	Gio-BH-03	Gio-BH-04
Total Depth of Bore (m)	10	10	10	10
Total Depth of Well (m)	9.55	9.55	8.06	6.875
Static Water Level (mbgl)	2.82	2.62	1.79	3.22
Screened Section (m)	3.55 – 9.55	3.55 – 9.55	2.06 – 8.06	3.875 – 6.875
Screened Section (%)	89	87	96	82
Pressure head (m)	6.73	6.93	6.27	3.655
Type of Well	**F*	**F*	**F*	**F*

*****F** *= fully penetrated (assuming screened sections approximate to*100%*)*

Regarding a fully penetrating well with seepage occurring at base, the hydraulic conductivity ‘K’ is expressed as in equation 4 (Tang *et. al*., 2017):

$$K = ((\pi r_w)/4t)\ \ln((H - h_1)/(H - h_2)) \quad 4$$

Monitoring well construction was above-ground level completed. Therefore, down-hole hydrogeological field measured parameters in each well were taken from well collar top (top of PVC stick-up). These include inner radius of PVC casing pipe (r_w), initial depth to static water level in piezometer (S_w), total depth of installed well (H_w), depth to recovering water level (S_{t_i}) with respect to measured time (t_i). All down-hole measurements are referenced to the earth surface in the absence of collar height (Fig. 3). During drilling total depth of bore H_b was also noted. In view of the tidal influence on groundwater level in near-coastal Niger Delta, each test was appropriately timed. Initial static water level measurement was taken with an electronic water level indicator (interface meter), before commencement of pumping test. One liter (1*l*) volume poly vinyl chloride (PVC) disposable bailers attached to marine ropes were deployed to conduct the pumping test. Field assistants worked diligently to achieve reasonable drawdown in the shortest possible time. Discharged water from the pumping well was released and directed down-hill at sufficient distance away from the pumping well so as to preserve the integrity of the test, since the aquifer was shallow.

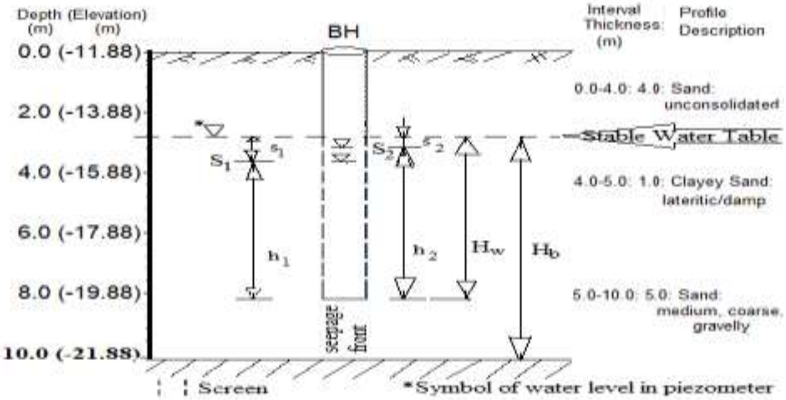


Fig 4: Fully Penetrating Single Well Pumping Test Design (After Tang *et al*, 2017)

As soon as pumping was stopped in each MW, well recovery rate measurement commenced using the water level probe (interface meter) and a stop watch. In all four test wells, the first five readings were monitored at one minute intervals with time lag increasing to two or three minutes until static water level was attained. Groundwater level fluctuation due to tidal influence was not out of place. Therefore to further enhance reliability of the survey, each test was aimed to conclude within “the o’clock” duration (1443-1454hrs; 1503-1516hrs; etc.) when groundwater level stability could reasonably be substantiated.

Field Data Analysis: Data analysis began with evaluating the parameters needed for the hydraulic conductivity solution (equ. 4) from the measured field records. In the tests conducted ‘r_w’ remains a constant alongside ‘π’ while other parameters were variables within and across MWs. The solution was simplified as:

Hydraulic Conductivity $K = \left(\frac{A}{B}\right)\ln C$ (5)

Regarding the first measurement, When

$$A = \pi r_w \quad (6)$$

$$B = 4t_1 \quad (7)$$

$$\ln C = \ln{(\mathrm{H}_b - h_1)}/(\mathrm{H}_b - h_2) \quad (8)$$

Where: pressure head

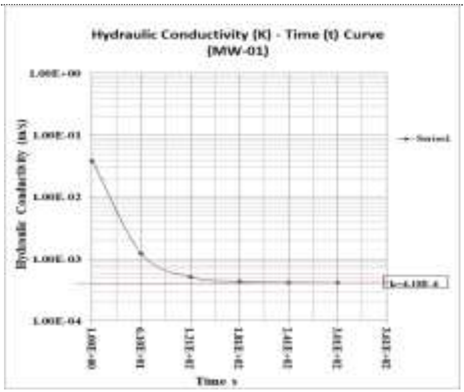
$$h_i = \mathrm{H}_w - S_{t_i} \quad (9)$$

A chart was created using Microsoft excel sheet, reflecting the input boundary conditions in equations 6, 7, 8 and 9 to deduce K (equ. 5).

The table of K_i-values in each ‘MW’ was plotted against respective t_i-values in a semi-log graph also generated from the excel program to obtain corresponding *K-t* scatter plot, along with smooth lines that would be curve-matched to fit into an exponential curve. A constant value of hydraulic conductivity was then determined and read off from the *K-t* curve. It is noteworthy that all parameters substituted directly in the applicable equations were measured in the field relative to the specific aquifer boundary condition.

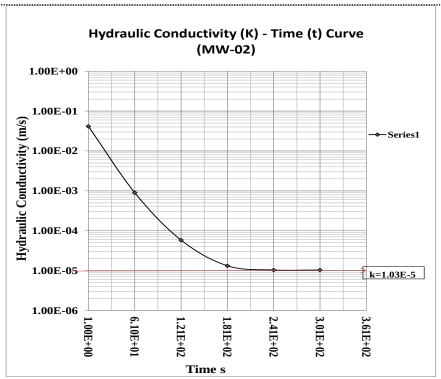
RESULTS AND DISCUSSIONS

The outcome of field data analysis of the *in situ* tests conducted in the site at Gio are presented as typical exponential curves (Fig. 5). The steep descent signifies the initial fast flow of groundwater into the cone of depression wherein sits the piezometer after pumping had stopped. As the well recovery approaches equillibrum, the flow rate reduces considerably and flattens out to a constant value. The point where the curve remains fairly constant irrespective of the time is indicated by an arrow-headed horizontal line and the value on the hydraulic conductivity axis is read off as representative of the flow system at that sample point. The data series in the result of analyses are less than the actual field data. At steady groundwater flow, presuure head becomes constant marking the end of test. That was the situation with MWs1, 2 and 3. However, the test duration at MW4 exceeded the "o'clock" by about two to five minutes; triggering a rise of about 20% in the water level earlier gauged in the piezometer. So the last two data points affected by the episode were discarded from analysis. For clarity or comparisons, the results are also presented in $\mathrm{cm/s}$ and $\mathrm{m/day}$. Therefore the final outcome of the test is reported in Table 3. The hydraulic conductivity results in the study area was in the range of $1.03 \text{ x } 10^{-3}\ \mathrm{cm/s}$ in $\mathrm{MW2}$ to $5.58 \text{ x } 10^{-2}\ \mathrm{cm/s}$ in MW 3. When compared with table 1, hydraulic conductivity $(\mathrm{cm/s})$ result implies that the aquifer texture in Gio site was coarse and well sorted sand. However, the varied hydraulic gradients have impacted the results, as MWs 1 and 3 set in low elevation areas returned higher hydraulic conductivity than MWs 2 and 4 that were located on more elevated regions.



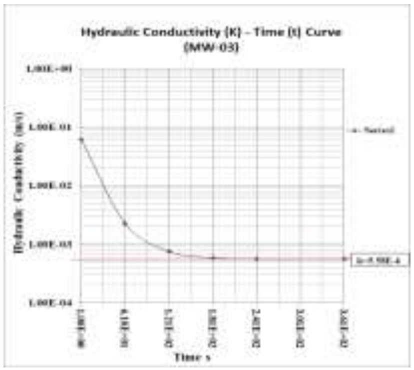
Data Points for Hydraulic Conductivity (K_i) – Time (t_i) Plot in Gio MW-1

t_i	K_i
1.00E+00	-3.92E-02
6.10E+01	-1.24E-03
1.21E+02	-1.04E-03
1.81E+02	-1.03E-03
2.41E+02	-8.58E-04
3.01E+02	-6.18E-04
4.21E+02	#NUM!
5.41E+02	#NUM!
6.61E+02	#NUM!



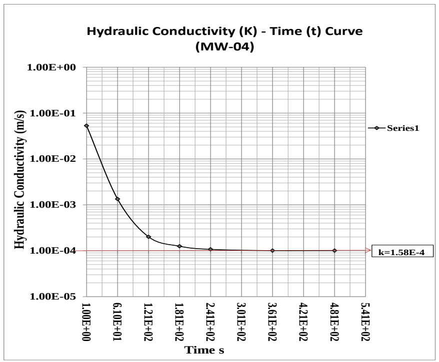
Data Points for Hydraulic Conductivity (K) – Time (t) Plot in Gio MW-2

ti	K
1.00E+00	4.15E-02
6.10E+01	8.99E-04
1.21E+02	5.82E-04
1.81E+02	5.32E-04
2.41E+02	1.04E-05
3.01E+02	1.21E-05
4.21E+02	#NUM!
5.41E+02	#NUM!
6.61E+02	#NUM!
7.81E+02	#NUM!



Data Points for Hydraulic Conductivity (K) – Time (t) Plot in Gio MW-3

ti	K
1.00E+00	6.11E-02
6.10E+01	2.26E-03
1.21E+02	1.54E-03
1.81E+02	1.14E-03
2.41E+02	8.58E-04
3.61E+02	5.73E-04
4.81E+02	#NUM!
6.01E+02	#NUM!



Data Points for Hydraulic Conductivity (K) – Time (t) Plot in Gio MW-4

t_i	K
1.00E+00	5.30E-02
6.10E+01	1.34E-03
1.21E+02	1.31E-03
1.81E+02	1.03E-03
2.41E+02	7.72E-04
3.61E+02	5.73E-04
4.81E+02	1.00E-04
6.61E+02	2.40E-04
8.41E+02	8.02E-05

Fig 5: *K– t* Exponential Curves for *In Situ* Hydraulic Conductivity Test in MWs at Gio

Table 3: Hydraulic Conductivity *in situ* Test Result at Gio Study Site

Monitoring Well ID	Gio-BH-01	Gio-BH-02	Gio-BH-03	Gio-BH-04
Hydraulic Conductivity - K (cm/s)	4.18×10^{-2}	1.03×10^{-3}	5.58×10^{-2}	1.58×10^{-2}
Hydraulic Conductivity - K (m/s)	4.18×10^{-4}	1.03×10^{-5}	5.58×10^{-4}	1.58×10^{-4}
Hydraulic Conductivity – K (m/day)	36.11	0.89	48.2	13.65

Conclusion: The study inferred that groundwater level stability was guaranteed when *in situ* permeability testing was conducted within an hour (the o'clock) duration. Hydraulic conductivity (K) values correlated with the dorminantly coarse and well sorted sandy aquifer texture in Gio site and complied with Darcy's rule. The single well *in situ* permeability assessment technique was dependent on site specific boundary conditions, in line with global best practice, economically viable and a useful tool in groundwater investigation of oil spill sites in the Niger Delta region.

Declaration of Conflict of Interest: The authors declare no conflict of interest**.**

Data Availability Statement: Data are available upon request from the first and corresponding author.

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