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Slug Tests for Determination of Hydraulic Conductivity of Contaminated Wells

S. A. Ola[1], O. G. Fadugba[2] & M. A. Uduebor[2]

[1] Formerly Department of Civil and Environmental Engineering, The Federal University of Technology, Akure, Nigeria. Now Afe Babalola University Ado Ekiti Nigeria.

[2] Department of Civil and Environmental Engineering, The Federal University of Technology, Akure Nigeria

Correspondence: Olaolu G. Fadugba, Department of Civil and Environmental Engineering, The Federal University of Technology, Akure P.M.B 704, Akure. Tel: 234-806-001-6983. Email: ogfadugba@futa.edu.ng

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Abstract

This paper reviews three models for analyzing slug test data to determine hydraulic conductivity of hydrocarbon contaminated wells in the study area. 50 grams/litre potassium permanganate ($KMnO_4$) was used as permeating fluid for the remediation of the site. Data of the slug-in test from five (5) observation wells varying in diameter from 0.82-1.93m in the study area in Baruwa, Lagos Nigeria were analyzed with three models used in the study, namely; Hvorslev, Ferris –Knowles and Earth Manual models. Analysis of the data showed that all three analytical methods produced similar range of magnitude of the order of 10^{-4}cm/sec values of hydraulic conductivity.

Keywords: Slug-in, Hvorslev, Ferris –Knowles and Earth Manual model.

1. Introduction

Aquifers are inherently heterogeneous. Knowledge of the spatial distribution of aquifer hydrologic properties is essential in predicting the migration of contaminants in the subsurface. Slug and pumping tests are used to determine in-situ properties of water-bearing formations and define the overall hydrogeologic regime. Such tests can determine transmissivity (T), hydraulic conductivity (K), Storativity (S), yield, connection between saturated zones, identification of boundary conditions, and the cone of influence of a pumping well in an extraction system. The hydraulic properties that can be determined are particular to the specific test method, instrumentation, knowledge of the ground water system, and conformance of site hydraulic conditions to the assumptions of the test method (ASTM 4043-96(2004). Slug tests are generally conducted to determine the horizontal K of a ground water zone. A slug test involves the abrupt removal, addition, or displacement of a known volume of water and the subsequent monitoring of changes in water level as equilibrium conditions return. The measurements are recorded and analyzed by one or more methods. The rate of water level change is a function of the K of the formation and the geometry of the well or screened interval. Slug tests generally are conducted in formations that exhibit low K. They may not be appropriate in fractured rock or formations with T greater than 250 m^2 /day (2,690 ft^2 /day) (Kruseman & de Ridder, 1990).

Slug tests are often classified as either rising-head or falling-head tests depending on the direction of water-level recovery in the control well.

- A *rising-head test* is initiated by rapidly lowering the water level in the control well and then taking measurements of the rising water level in the well. Baildown test and slug-out test are alternate terms for rising-head test.
- A *falling-head test* is conducted by rapidly raising the water level in the control well and subsequently measuring the falling water level.Slug-in test is another term for falling-head test.

The slug test method involves causing a sudden change in head in a control well and measuring the water level response within that control well. Head change may be induced by suddenly injecting or removing a known quantity or “slug” of water into the well, rapid removal of a mechanical “slug” from below the water level, increasing or decreasing the air pressure in the well casing, or emplacement of a mechanical slug into the water column. The water-level response in the well is a function of the mass of water in the well and the transmissivity and coefficient of storage of the aquifer. One method of analysis of the data from this field practice is described in Test Method ASTM D 4104.

Hydraulic properties determined by slug tests are representative only of the material in the immediate vicinity of the well. However, by performing a series of slug test at discrete vertical intervals and tests in closely spaced wells, important information can be obtained about the vertical and horizontal variations of hydraulic properties for the site (Butler, 1998). The volume of water removed or displaced should be large enough to insure that buildup or drawdown can be measured adequately, but it should not result in significant changes in saturated zone thickness (Dawson & Istok, 1991). It should be large enough to change water level by 10 to 50 centimeters (Kruseman & de Ridder, 1990). Field procedures for slug tests are also described in ASTM D 4044-96(2002).

Each slug test method was developed in response to a particular subsurface condition, but on the whole, each method is related in some way to some extent to the other methods. One method was developed to accommodate certain features that previous methods either overlooked or ignored. The following methods will be reviewed

Slug Test Method	Date Published
Hvorslev model	1951
Ferris-Knowles model	1963
Earth Manual	1974

2. Methodology

2.1 Description of the Study Area

The case study site is Baruwa community in Alimosho Local government area of Lagos state (Latitude 6[degrees] 35' N, Longitude 3[degrees] 16' E) (Figure 1a). The height above the sea level is about 42 meters (141 feet). The neighboring towns near the community to the East are Kadara and Akinogun while Fatode and Oduwale are to the south. It has an abundant rainfall of over 2,000 millimeter per year. "BARUWA" is a Lagos suburb Community in Alimosho Local Government Area of Lagos State; South Western Nigeria (Figure 1a). The community is located between the famous Iyana Ipaja and Ikotun. The petroleum hydrocarbon contaminated site is approximately 940m x 740m in size, within which a pilot scheme area of 100m x 100m was earmarked for study (Figure 1b).

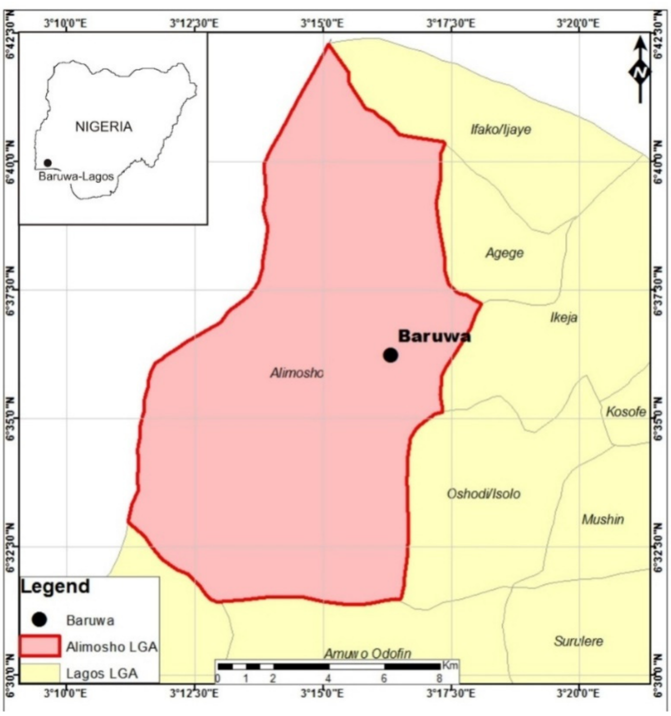

Figure 1a. Map of Lagos Indicating the Location of Baruwa

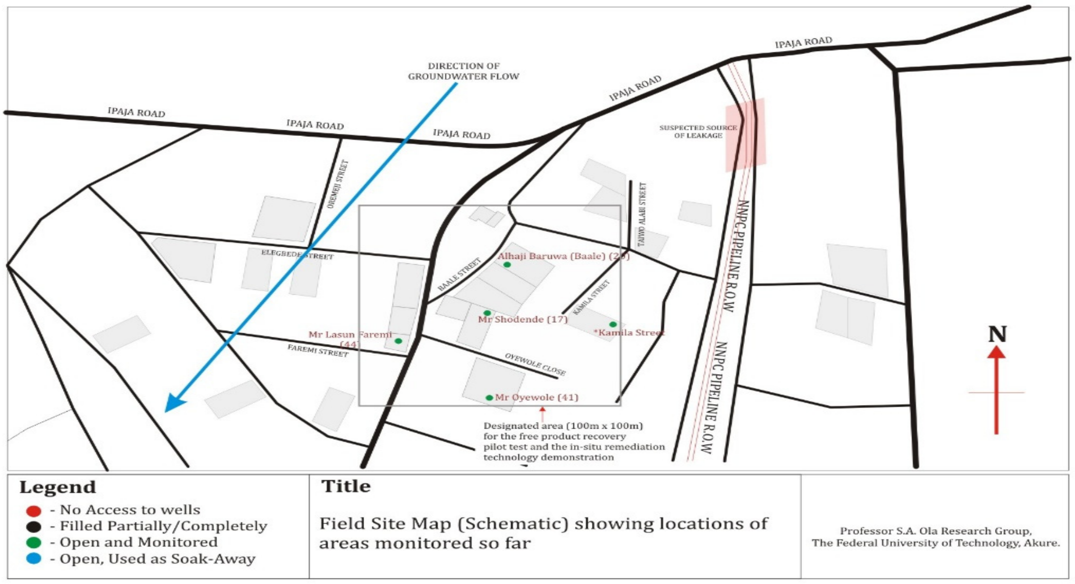

Figure 1b. The Petroleum Hydrocarbon Contaminated Site (Baruwa Lagos)

2.2 Field Tests

2.2.1. Desktop Study

A review of the site contaminant history was conducted; this included potential LNAPL sources at the site and the affected receptors. Historical groundwater levels and quality were obtained from previous studies within the area (Adekunte, 2008; Balogun, 2009) as part of the local geohydrological review.

2.2.2. Site Survey (Walkover and Visual inspection)

This was conducted to verify the validity of the information collected during the desktop study. Emphasis was placed on fixing the exact positions of the wells (utilizing a GPS tracker), linking previous aquifer test carried out on the existing wells within the area.

2.2.3 Hydrological (Water Table)

A water table characterization exercise was conducted utilizing the number of wells that were still available for testing within the area and their characteristic depths to liquid and to bottom.

2.2.4 Slug Test

Slug (Injection) tests were carried out on some selected wells within the area to determine the permeability of the water bearing aquifer. Initial water levels were recorded and monitored for level changes with the aid of an interface meter. Table 1 gives the details of the each well utilized in carrying out the test showing their location, well diameter, Water Table and Depth to bottom.

Table 1. Characteristics of Selected Wells for Slug Testing

S/N	Location	Well Identification	Easting (^{O})	Northing (^{O})	Well Diameter (M)	Water Table (M)	Depth To Bottom (M)
1	Alhaji Baruwa	20	3.271758	6.60373	1.755	24.334	25.119
2	Lasun Faremi	44	3.271125	6.60373	1.11	23.351	23.824
3	Mr Shodende	17	3.271685	6.602399	0.82	24.521	25.139
4	Pa Oyewole	41	3.271653	6.601669	1.93	24.450	25.169
5	Kamila	35a	3.272457	6.602338	1.65	24.437	25.25

Utilizing this data, the corresponding volume of fluid required to raise the water table up to a height of 0.61m (2 feet) was calculated. This was chosen as the height at which when stabilized, continuous readings till equilibrium is attained would be recorded. Table 2 shows the volume of fluid required for each well. Table 2 also shows the mass of potassium-permanganate ($KMnO_4$) that was injected into each well using a concentration of 50g/l for the remediation of the site.

Table 2. Calculation Table for the Determination of the Volume of Fluid Required for the Test

S/N	Location	Well Identific-ation	Diameter (m)	Volume for 1ft (m^3)	Volume (Litre)	Mass of $KMnO_4$ at 50g/l (g)	Mass of $KMnO_4$ at 50g/l (kg)
1	Alhaji Baruwa	20	1.755	0.7373	737.3	36,865	36.865
2	Lasun Fareni	44	1.111	0.2955	295,5	14,775	14.775
3	Mr Shodende	17	0.820	0.1610	161.0	8,080	8.08
4	Pa Oyewole	41	1.93	0.8917	891.7	44,585	44.585
5	Kamila	35a	1.650	0.6517	651.7	32,585	32.585

The wells were then injected at a uniform rate and the time and final level of the water within the wells taken and recorded. The time taken to return back to original levels were recorded at intervals (1 min, 2 mins, 4 mins, 9 mins, 16 mins, 25 mins … 1440 mins) till equilibrium was achieved. Curves obtained from readings were plotted on a graph sheet using Microsoft ® Excel software.

2.3 Field Monitoring of Water Levels

Solinst Interface meter (Water level/Interface Probe) was used in measuring the water movement in the wells. The device provides a quick and easy water-level measurements The device employs a sensor that is lowered into a well on the end of a marked cable. When the sensor contacts water, a circuit is completed, activating a light and audio signal. (Figure 2a and 2b).

Plate 2a. Interface Meter

Plate 2b. Utilizing the Interface Meter on one of the wells

3. Methods of Data Analysis

Three models were used to determine the hydraulic conductivity value of soils and well systems. These models are:

3.1 Hvorslev Model (1951)

Hvorslev (1951) pioneered the development of in-situ field tests, particularly the slug test. This method has been described by Fetter (1988) and this involves determining the ratio "H/H(0)", where "H(0)" or "H_0" is the distance the level declines upon removal of a slug of water, and "H" is the height of the water level below the static water level at some time, "t", after the slug is removed. The ratio is plotted versus time on semilogrithmic graph paper. The general form of the Hvorslev equation is given in the equation below:

$$k = \frac{r^2 Ln(\frac{L}{R})}{2LT_0} \tag{1}$$

Where:
k = hydraulic conductivity
r- Radius of well casing
R- Radius of well screen
L- Length of well screen
T_0- time required for the water level to rise to 37% of the initial change, obtained from the graph of H/H (0)

3.2 Ferris-knowles Model (1963)

Ferris-knowles (1963) made the assumptions in their method that the well was fully penetrating in an aquifer under confined conditions, radially infinite, homogenous and isotropic. In contrast to Hvorslev (1951), their method allows for aquifer storage but ignores wellbore storage. The cooper, et al. model has essentially replaced the Ferris and Knowles model.

The method involves the following relationship:

$$K = \frac{Q}{4\times \pi\times L\times S} \tag{2}$$

Where:
K= hydraulic conductivity, Q= volume of the slug, L= length of screen
S= slope of the graph, $\pi = Pie = 3.142$

Summers et al. (1983) used the Ferris-Knowles method in their study and plotted measured depth to water versus 1/t. toward late times in the test, the plot should produce a straight line as the levels approach zero (0). If this fails to occur then the method will not function on the particular data set. If a straight line occurs then the slope of the line is equal to s/ (1/t) and the equation can be solved for K. While the method gave what appeared to be reasonable results, they were often inconsistent with the results produced by other methods and substantial time was required to conduct the test.

3.3 Earth Manual (1974)

$$k = \frac{Q}{5.5rH} \tag{3}$$

Where:
k = hydraulic conductivity, Q = injection rate, r = radius of the well casing
H = calculated water –level rise caused by the slug

4. Results and Discussion

4.1 Hvorslev Method

Using the Hvorslev model, i. e., equation 2 for Observation Well 20 (W20)

$$k = \frac{r^2 Ln(\frac{L}{R})}{2LT_0} \tag{4}$$

Table 3 shows the data obtained for the slug test for Hvorslev model values for Observation Well 20 (Well 20) and Figure 2 shows Plot of h/h_0 versus Time for Observation Well (20) for the Hvorslev model

Parameters for Observation Well 20 (Well 20) using the Hvorslev model, Diameter: 1.755 m, Initial Depth to Liquid: 23.077 m, Length of Screen Le = 1.673 m, Radius of Well Casing, R = 0.8755 m, Radius of Screen, r = 0.8755 m.

Table 3. Hvorslev Model Values for Observation Well 20 (Well 20)

Elapsed Time (Min.)	**Depth to Liquid (m)**	**Change in Level, h (m)**	**h/h_0**
Static Level	23.077		
0	22.184	0.893 (h_0)	1.000000
1	22.184	0.893	1.000000
4	22.186	0.891	0.997760
9	22.189	0.888	0.994401
16	22.224	0.853	0.955207
25	22.243	0.834	0.933931
36	22.246	0.831	0.930571
49	22.266	0.811	0.908175
64	22.275	0.802	0.898096
81	22.281	0.796	0.891377
100	22.295	0.782	0.875700
121	22.314	0.763	0.854423
180	22.464	0.613	0.686450
240	22.678	0.399	0.446809
300	22.756	0.321	0.359462
360	22.879	0.198	0.221725
480	22.984	0.093	0.104143
1140	23.075	0.002	0.002240
1320	23.076	0.001	0.001120
1620	23.076	0.001	0.001120

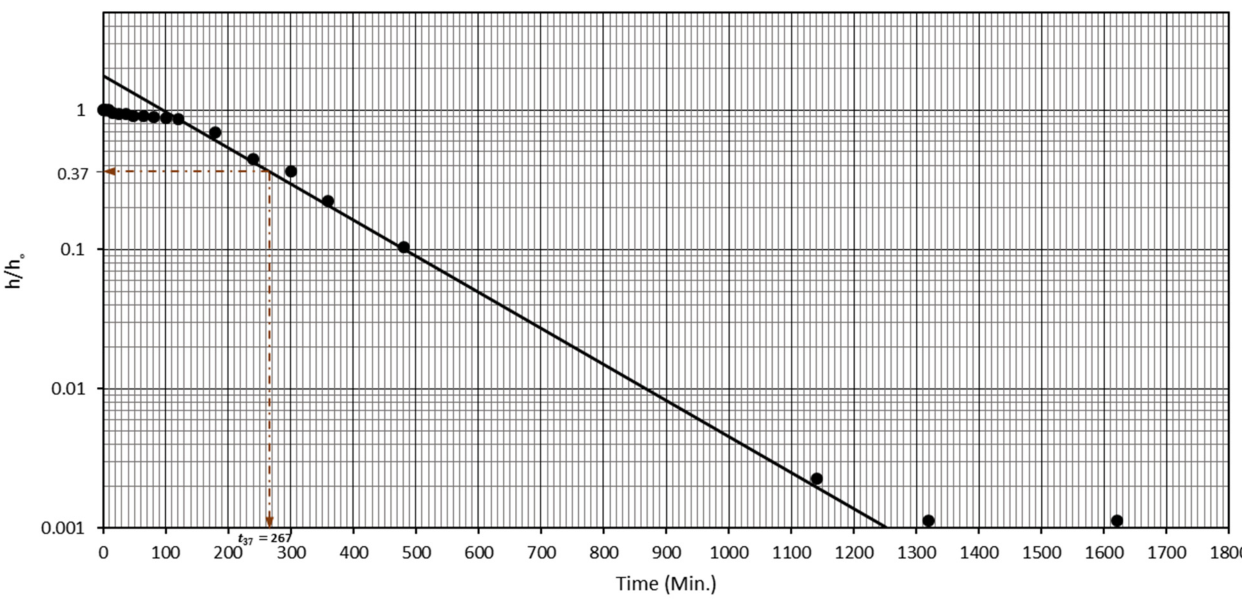

Figure 2. Plot of h/h_0 versus Time for Observation Well (20)

From the graph,
t37 =280mins,
Using the equation,

$$k = \frac{r^2 In\left(\frac{Le}{R}\right)}{2L_e t_{37}},\ k = \frac{0.8775^2 In\left(\frac{1.673}{0.8775}\right)}{2\times1.673\times280},\ k = 8.83\times\ 10^{-4}$$

4.1.1. Hvorslev Model for other Wells

Applying the Hvorslev model to other observation wells gives the following results, (W17) is $3.17 \times 10^{-4} cm/sec$, (W41) is $8.22 \times 10^{-4} cm/sec$, (W44) is $6.66 \times 10^{-4} cm/sec$, (W35a) is $5.58 \times 10^{-3} cm/sec$.

4.2 Ferris-Knowles Model

Using the Ferris-Knowles model, i.e., equation 4 for Observation Well 20 (W20), the method involves the following relationship:

$$\boldsymbol{k} = \frac{\mathrm{Q}}{4 \times \lambda \times \text{length of screen} \times \text{slope}} \quad (5)$$

Table 4 shows the data obtained for the slug test for Ferris-Knowles values for Observation Well 20 (Well 20) and Figure 3 shows Plot of H against 1/t for Observation Well (20) for Ferris-Knowles values.

Parameters for Observation Well 20 (Well 20) using the Ferris-Knowles model are as follows: Diameter; 1.755m, Initial depth to liquid; 23.077m, Length of screen Le=1.673m, Radius of well casing R=0.8755m, Injected volume, q = 750litres.

Table 4. Ferris-Knowles values for Observation Well 20 (Well 20)

Elapsed time (min)		**Depth to liquid (m)**	**Change in level**
Static level	1/t	23.077	h
0	-	22.184	0.893
1	1	22.184	0.893
4	0.25	22.186	0.891
9	0.111	22.189	0.888
16	0.0625	22.224	0.853
25	0.0400	22.243	0.834
36	0.0278	22.246	0.831
49	0.0204	22.266	0.811
64	0.01563	22.275	0.802
81	0.01234	22.281	0.796
100	0.01	22.295	0.782
121	0.0083	22.314	0.763
180	0.0056	22.464	0.613
240	0.0042	22.678	0.399
300	0.0033	22.756	0.321
360	0.00278	22.879	0.198
480	0.00208	22.984	0.093
1140	0.000877	23.075	0.002
1320	0.000758	23.076	0.001
1620	0.000617	23.076	0.001

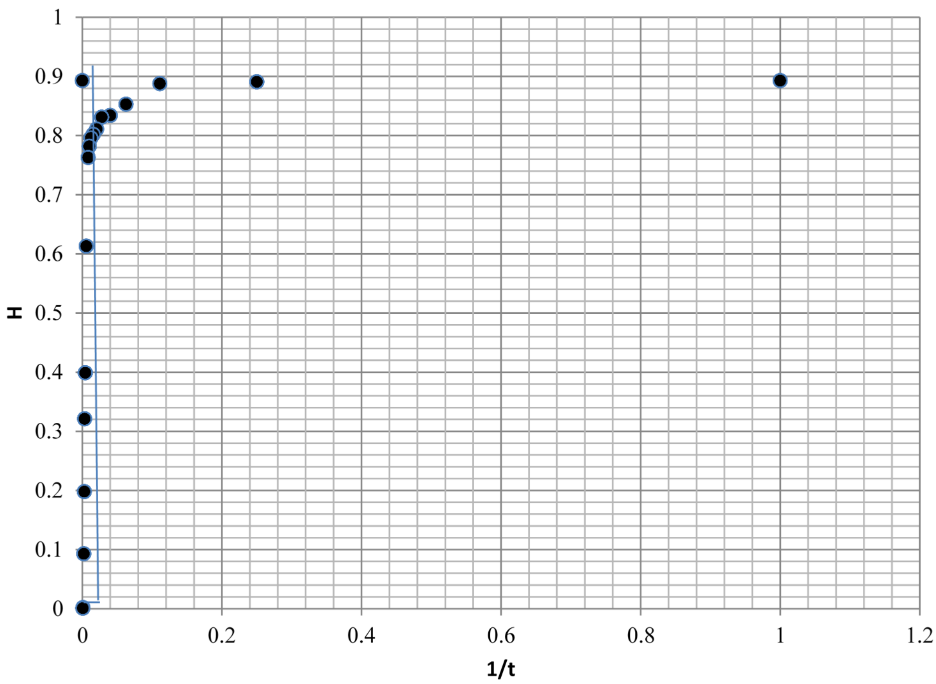

Figure 3. Plot of H against 1/t for Observation Well (20)

From the graph,
Slope = 80
Using the formula;

$$k = \frac{Q}{4 \times \lambda\lambda \times length\ of\ screen \times slope},\ \mathrm{k} = \frac{0.75}{4 \times 3.142 \times 1.673 \times 80} = 4.4587 \times 10^{-4}\mathrm{m/min},\ \mathrm{k} = 7.43 \times 10^{-4}\mathrm{cm/sec}$$

4.2.1 Ferris-Knowles Model for Other Wells

Applying the Ferris-Knowles model to other observation wells gives the following results, (W17) is 5.25$\times 10^{-4}$cm/secs, (W41) is 12.71$\times 10^{-3}$cm/secs, (W44) is 8.78$\times 10^{-4}$cm/secs, (W35a) is 35.4$\times 10^{-4}$cm/secs.

4.3 Earth Manual (1974)

$$k = \frac{Q}{5.5rH} \quad (6)$$

Table 5. Calculation for Permeability Coefficient based on Earth Manual 1974

	Mr Kamila (35a)	Alhaji Baruwa (20)	Pa Oyewole (41)	Mr Shodende (17)	Mr LasunFaremi (44)
v (l)	650	750	900	180	300
v (m^3)	0.65	0.75	0.9	0.18	0.3
t (min)	24:17	27:17	22:47	12:11	16:04
v (cm^3)	650000	750000	900000	180000	300000
t (s)	1457	1637	1367	731	964
Q (cm^3/s)	446.12	458.16	658.38	246.24	311.20
r(m)	0.825	0.8775	0.965	0.41	0.556
r(cm)	82.5	87.75	96.5	41	55.6
H(m)	23.422	23.077	23.65	23.115	23.095
H(cm)	2342.2	2307.7	2365	2311.5	2309.5
k(cm/s)	4.20E-04	4.11E-04	5.25E-04	4.72E-04	4.41E-04

Substituting the parameters in Table 5 applicable to the equation of Earth Manual in equation 3 to all the observation wells gives the following results, (W20) is $4.11\times 10^{-4}\mathrm{cm/secs}$, (W17) is $4.72\times 10^{-4}\mathrm{cm/secs}$, (W41) is $5.25\times 10^{-4}\mathrm{cm/secs}$, (W44) is $4.41\times 10^{-4}\mathrm{cm/secs}$, (W35a) is $4.20\times 10^{-4}\mathrm{cm/secs}$ (see Table 5).

Table 6. Summary of all Model results for Hydraulic conductivity K in cm/sec of Observation Wells

Model	**Observation Wells**				
	(W20)	(W17)	(W41)	(W44)	(W35a)
Model 1					
(Hvorslev model)	9.26×10^{-4}	3.17×10^{-4}	8.22×10^{-4}	6.66×10^{-4}	5.58×10^{-3}
Model 2					
(Ferris-Knowles model)	7.43×10^{-4}	3.06×10^{-4}	11.92×10^{-3}	4.64×10^{-4}	7.3×10^{-3}
Model 3					
Earth Manual	4.11×10^{-4}	4.72×10^{-4}	5.25×10^{-4}	4.41×10^{-4}	4.20×10^{-4}
K Range	$(4.11 – 9.26)\times10^{-4}$	$(3.06 – 4.72)\times10^{-4}$	$(5.25 – 119.2)\times10^{-4}$	$(4.41 – 6.66)\times10^{-4}$	$(73 – 5.58)\times10^{-4}$

Table 6 shows the various models used in determining hydraulic conductivity and the values obtained in each of the Observation wells within the study area. Hvorslev, Ferris-Knowles model and Earth manual gave the same range of order of magnitude for all the observation wells under study.

5. Conclusion

Based on the study carried out on the models of determining hydraulic conductivity, three study models were used in the analysis of the data obtained from the slug test conducted on the five wells within the pilot scheme area of the contaminated site, the model includes, Hvorslev, Ferris –Knowles and Earth Manual model.

Permeability values for all the five studied wells within the pilot area are within the range of magnitude of 10^{-4} cm/sec which is characterized by Silt, Clay/Silt admixtures or fine Sand/Silt/Clay mixtures. This is also supported by stratigraphic study with the soil profile of the observation wells with the study area showing the water bearing aquifer to be within Clayey Sand and Sandy Clay.

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