Laboratory Investigation of Salt-water Intrusion Through Porous Media

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ABSTRACT

Flow rate of salt-water and fresh-water through porous media depends on the hydraulic gradient, porosity and hydraulic conductivity of the sand materials and the properties of the fluids such as density and viscosity. This study examined flow rate of salt-water and fresh-water in porous media in a modeled laboratory experiment. Porous materials were filled into the conduit of two arms glass cylindrical tube with valve (control) at the middle. Salt-water and fresh-water were made to flow through the porous materials from the different arms. The volume displacements of salt-water and fresh-water in the two arms glass cylindrical tube filled with riverbed sand of varying porosities were determined when the valve between the two arms was opened with different hydraulic heads of fluids in the tube. Salt-water displaced the fresh-water upward in the set up when hydraulic level of salt-water is greater than hydraulic level of fresh-water. Salt-water also displaced the fresh-water in the set up when the hydraulic level of salt-water is the same as the hydraulic fresh-water. But fresh-water displaced salt-water only when hydraulic level of fresh-water is greater than hydraulic level of salt-water.

KEYWORDS: Hydraulic head, Salt-water, Fresh-water, Porosity, Density, Hydraulic gradient, Hydraulic conductivity and Displacement

INTRODUCTION

Salt-water intrusion is the movement of saline water into fresh-water aquifers. Most often, it is caused by groundwater pumping from coastal well or from construction of navigation channels into fresh marshes. But salt-water intrusion can also occur as a result of natural process like a storm surge from a hurricane (Barlow, 2003). Salt-water intrusion occurs in virtually all coastal aquifers, where they are in hydraulic continuity with salt-water. This occurs because seawater has a higher density because it carries more solute than fresh-water (Todd, 1960). This difference in density causes the pressure under a column of salt-water to be greater than the pressure under a column of the same level of fresh-water. If these two columns are connected at the bottom, such as underground water seepage between sea water and fresh-water in an unconfined aquifer then the pressure difference would cause a flow of salt-water to the fresh-water until the pressure attains equilibrium.

The flow of salt-water into inland is limited to coastal areas (Delleur and Willy, 2006). Further inland, the fresh-water piezometric height or hydraulic column is higher due to the increasing altitude of the land and is able to equalize the pressure from the salt-water therefore stopping the salt-water intrusion. The high water level at inland has another effect which causes the fresh-water to flow seaward.

Pumping of fresh-water from aquifer reduces the fresh-water pressure and intensifies the effect of drawing salt-water into new areas (Delleur and Willy, 2006).

The first physical realization of salt-water intrusion were made by Badon –Ghijben (1888, 1889) and Herzberg (1901) called Ghijben – Herberg relation. The Ghyben –Herzberg ratio states that for every foot of fresh-water in an unconfined aquifer above sea level, there will be forty feet of fresh-water in the aquifer below sea level (Verrjuit Amod 1968).

The objectives of this study was to determine the effect of difference in hydraulic heads of salt-water and fresh-water on flow rate of both fluids in hydraulic continuity and to show the effect of difference in densities on hydraulic head of both fluids in porous media. An understanding of the salt-water intrusion studied under varied conditions in the laboratory may probably suggest way(s) of remediation salt-water intrusion problem.

THEORETICAL BACKGROUND

Generally, the hydraulic head or piezometric head is a specific measurement of water pressure above geodetic datum (Mulley, 2004 and Chanson, 2004). Hydraulic head can similarly be measured in a column of water using a standpipe piezometer by measuring the height of water surface in the tube relative to a common datum. The hydraulic head can be used to determine a hydraulic gradient between two or more points.

In fluid dynamics, head is a concept that relates the energy in an incompressible fluid to the height of an equivalent static column of the fluid (Bear,1972). The hydraulic head equation at a point in a ground water system (Fig. 1) can be expressed as

$$h = \psi + Z \qquad (1)$$

where

h is the hydraulic head (length) also known as the velocity head.

Ψ is the pressure head, in terms of the elevation difference of the water column relative to the piezometer bottom (length in m).

Z is the elevation at the piezometer bottom (length in m).

The pressure head can also be expressed as

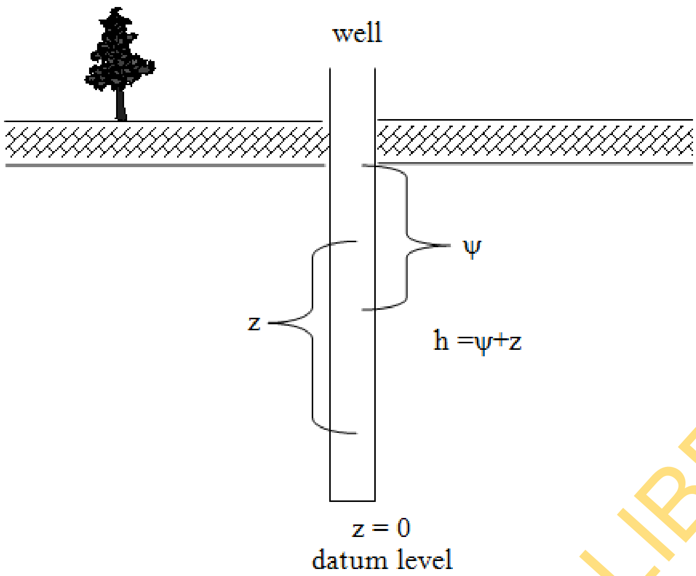

Figure 1: Illustration of hydraulic head

$$\psi = P/\rho g \qquad (2)$$

where

P = the gauge pressure (pa)

ρ = the density of water

g = the gravitational acceleration (9.81 m/s^2).

Density of salt-water is greater than that of fresh-water. Therefore, pressure under the column of salt-water is greater than pressure under the column of fresh-water. That is the reason salt-water displaces fresh-water even if their levels in the two columns are equal (from equation 2).

The hydraulic head can be expressed as the velocity head due to the bulk motion of fluid (kinetic energy).

A mass *m*, free falling from an elevation z >0.

$mgz = \frac{1}{2} mv^2$ (conservation of energy).

$v = \sqrt{2gz}$

$$\therefore \qquad h = \frac{v^2}{2g} \text{ (velocity head)} \qquad (3)$$

where v = velocity of the fluid.

As the hydraulic head increases in the piezometers, the bulk motion of the fluid will increase as shown in the equation (3) which represent the energy of the fluid. It is also known as driving force that moves ground water. Therefore, the fluid with high hydraulic head will displace the other one with low hydraulic head.

The hydraulic gradient is a vector gradient between two or more hydraulic head measurements over length of the flow path. The hydraulic head gradient can be calculated between two piezometers as:

$$i = dh/dL = (h_{sw} - h_{fw})/L$$

where

h_{sw} = hydraulic head in the column of salt-water.

h_{fw} = hydraulic head in the column of fresh-water.

L = flow path between the two piezometers (m).

As the hydraulic head decreases the flow rate decreases, which obeys Darcy's law (Jacqus W. Deller).

MATERIALS AND METHOD

Three samples A, B, and C of riverbed sand were prepared with different porosities of 0.45, 0.42 0.40 respectively. A two arms glass cylindrical tube with diameter 0.8×10^{-2}m. was placed vertically with the closed tap (valve) in between (Fig. 2). It was filled with salt-water in the (Q) arm and fresh-water in the (P) arm to equal level of 0.1m above zero level of the arms. 5ml.of the sample was poured into each arm of the glass cylindrical tube already filled with salt-water and fresh-water respectively to level 0.1m to eliminate trapped air which will obviously affect free flow of water for each case. The level of salt-water in the (Q) arm was made to be higher than that of fresh-water in the (P) arm .Volume flow of salt-water and volume flow of fresh-water in the column were obtained for every 60 seconds when the tap was opened.

Under the same condition, the level of fresh-water in the (P) arm was made to be higher than the level of salt-water in the (Q) arm. Then, volume flow of salt-water and volume flow of fresh-water were obtained for every 60 seconds. Thirdly, under the same condition, the level of fresh-water in the (P) arm was made to be equal to the level of salt-water in the (Q) arm . Volume flow of salt-water and volume flow of fresh-water were obtained for every 60 seconds

Therefore, the flow rates of salt-water and fresh-water of each sample was determined by Darcy's law i.e. volume of salt-water and fresh-water flow was divided by the time taken to flow through each sample respectively.

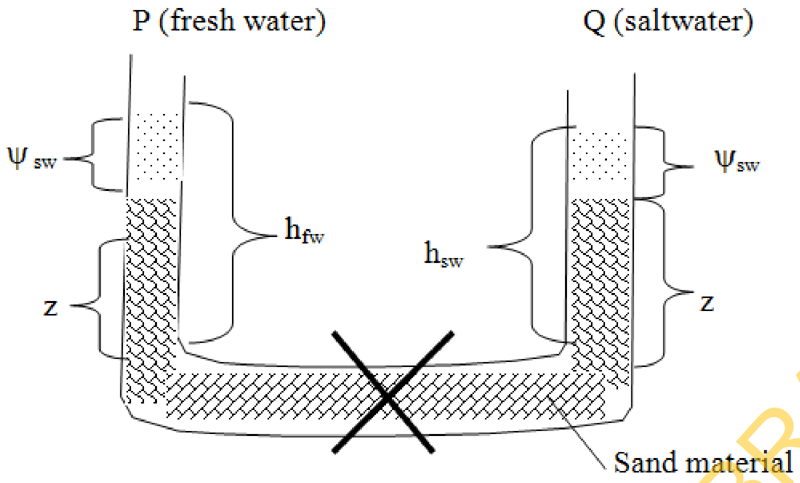

Figure 2: Experimental setup for investigation of salt-water intrusion through sand materials

RESULTS AND DISCUSSION

Tables 1 - 3 present the flow rates of salt-water (Q_s) and flow rates of fresh-water (Q_f) at different levels for samples A, B and C for every 60 seconds. In figures 3- 11, flow rates of salt-water and fresh-water displacing each other decrease with time and decay curves were obtained. The equations generated from the graphs can be used to determine flow rates of salt-water and fresh-water displacing each other at different levels in the samples for a given time as in Tables 4-6. This indicates that the flow rate of salt-water and fresh-water decrease with time in an unconfined aquifer in coastal region; when the hydraulic levels of the fluids have not change for considerable amount of time by not drawing ground water from wells near the coastal region.

The levels of salt-water and fresh-water at which there is no flow rate with time indicates the hydraulic heads where the pressure equalizes. The equations generated from graphs of flow rate against time in figures 3 to 11 can also be used to determine the hydraulic heads of salt-water and fresh-water when the flow rates will be insignificant (approximately zero) by substituting high values of time into them

CASE 1: SAMPLE A

Table 1: Flow rate of salt-water and fresh-water with difference in hydraulic head for sample A

Initial level of fresh-water is 0.3m Initial level of salt-water is 0.36m h=0.1m				Initial level fresh-water is 0.37m Initial level salt-water is 0.23m				Initial level of fresh-water is 0.34m Initial level of salt-water is 0.34m			
Difference in hydraulic head (m)	Qf (m^3/s)	Qs (m^3/s)	Time (sec)	Difference in hydraulic head	Qf (m^3/s)	Qs (m^3/s)	Time (sec)		Qf (m^3/s)	Qs (m^3/s)	Time (sec)
0.028	1.42 x 10^{-8}	1.25 x 10^{-8}	120	0.106	1.5 x 10^{-8}	1.3 x 10^{-8}	120	0.013	0.27 x 10^{-8}	0.17 x 10^{-8}	300
0.006	1.17 x 10^{-8}	1.08 x 10-8	240	0.078	1.33 x 10^{-8}	1.15 x 10-8	240	0.021	0.2 x 10^{-8}	0.15 x 10-8	600
-0.008	0.97 x 10^{-8}	0.92 x 10^{-8}	360	0.061	1.11 x 10^{-8}	1.08 x 10^{-8}	360	0.026	0.17 x 10^{-8}	0.12 x 10^{-8}	900
-0.017	0.81 x 10^{-8}	0.79 x 10^{-8}	480	0.049	0.96 x 10^{-8}	0.94 x 10^{-8}	480	0.029	0.17 x 10^{-8}	0.12 x 10^{-8}	1200

-0.02	0.67 x 10^{-8}	0.67 x 10^{-8}	600	0.039	0.85 x 10^{-8}	0.83 x 10^{-8}	600	0.031	0.12x10^{8}	0.9x10^{9}	1500

Porosity of sample A =0.45

Q_f is flow rate of fresh-water

Q_s is flow rate of salt-water

CASE 2: SAMPLE B

Table 2: Flow rate salt-water and fresh-water with difference in hydraulic head for sample B

Initial level of fresh-water is 0.27m Initial level of salt-water is 0.34m				Initial level fresh-water is 0.36m Initial level salt-water is 0.29m				Initial level of fresh-water is 0.31m Initial level of salt-water is 0.31m			
Difference in hydraulic head (m)	Qf (m^3/s)	Qs (m^3/s)	Time (sec)	Difference in hydraulic head	Qf (m^3/s)	Qs (m^3/s)	Time (sec)		Qf (m^3/s)	Qs (m^3/s)	Time (sec)
0.013	2.6 x 10^{-8}	2.2 x 10^{-8}	120	0.051	0.92 x 10^{-8}	0.67 x 10^{-8}	120	0.022	0.48 x 10^{-8}	0.42 x 10^{-8}	240
-0.011	1.75 x 10-8	1.63 x 10^{-8}	240	0.041	0.75 x 10-8	0.46 x 10^{-8}	240	0.025	0.27 x 10-8	0.25 x 10^{-8}	480
-0.018	1.28 x 10^{-8}	1.17 x 10^{-8}	360	0.036	0.56 x 10^{-8}	0.39 x 10^{-8}	360	0.027	0.20 x 10^{-8}	0.18 x 10^{-8}	720
-0.022	1.00 x 10^{-8}	0.92 x 10^{-8}	480	0.037	0.46 x 10^{-8}	0.30 x 10^{-8}	480	0.030	0.17 x 10^{-8}	0.15 x 10^{-8}	960
-0.024	0.82 x 10^{-8}	0.75 x 10^{-8}	600	0.032	0.38 x 10^{-8}	0.25 x 10^{-8}	600	0.032	0.14 x 10^{-8}	0.12 x 10^{-8}	1200

Porosity of sample B =0.42

Q_f is flow rate of fresh-water

Q_s is flow rate of salt-water

CASE 3: SAMPLE C

Table 3: Flow rate of salt-water and fresh-water with difference in hydraulic head for sample C

Initial level of fresh-water is 0.21m Initial level of salt-water is 0.36m				Initial level fresh-water is 0.35m Initial level salt-water is 0.21m				Initial level of fresh-water is 0.31m Initial level of salt-water is 0.31m			
Difference in hydraulic head (m)	Qf (m^3/s)	Qs (m^3/s)	Time (sec)	Difference in hydraulic head	Qf (m^3/s)	Qs (m^3/s)	Time (sec)	Difference in hydraulic head (m)	Qf (m^3/s)	Qs (m^3/s)	Time (sec)
0.079	1.5 x 10^{-8}	1.45 x 10^{-8}	240	0.043	2.04 x 10^{-8}	2.0 x 10^{-8}	240	0.007	0.21 x 10^{-8}	0.83 x 10^{-9}	240
0.048	1.08 x 10^{-8}	1.04 x 10^{-8}	480	0.020	1.27 x 10^{-8}	1.23 x 10^{-8}	480	0.009	0.13 x 10^{-8}	0.63 x 10^{-9}	480
0.030	0.85 x 10^{-8}	0.82 x 10^{-8}	720	0.011	0.90 x 10^{-8}	0.89 x 10^{-8}	720	0.011	0.97 x 10^{-9}	0.56 x 10^{-9}	720
0.019	0.70 x 10^{-8}	0.67 x 10^{-8}	960	0.008	0.70 x 10^{-8}	0.68 x 10^{-8}	960	0.015	0.75 x 10^{-9}	0.47 x 10^{-9}	960
0.014	0.49 x 10^{-8}	0.48 x 10^{-8}	1200	0.007	0.55 x 10^{-8}	0.55 x 10^{-8}	1200	0.021	0.52 x 10^{-9}	0.35 x 10^{-9}	1200

Porosity of sample C =0.40

Q_f is flow rate of fresh-water

Q_s is flow rate of salt-water

Table 4: Value of flow rate of salt-water and fresh-water when level of salt-water is greater than level fresh-water for samples A, B and C

Sample A Qs(m^3/s)	Qf(m^3/s)	Sample B Qs(m^3/s)	Qf(m^3/s	Sample C Qs(m^3/s)	Qf(m^3/s)	Time (sec)
1.441×10^{-8}	1.694×10^{-8}	2.915×10^{-8}	3.539×10^{-8}	1.886×10^{-8}	1.946×10^{-8}	1
1.440×10^{-8}	1.692×10^{-8}	2.909×10^{-8}	3.530×10^{-8}	1.884×10^{-8}	1.944×10^{-8}	2
1.439×10^{-8}	1.690×10^{-8}	2.902×10^{-8}	3.521×10^{-8}	1.882×10^{-8}	1.942×10^{-8}	3
1.438×10^{-8}	1.688×10^{-8}	2.895×10^{-8}	3.512×10^{-8}	1.880×10^{-8}	1.940×10^{-8}	4
1.437×10^{-8}	1.686×10^{-8}	2.888×10^{-8}	3.503×10^{-8}	1.878×10^{-8}	1.938×10^{-8}	5

Table 5: Value of flow rate of salt-water and fresh-water when level of fresh-water is greater than salt-water level for samples A, B and C

Sample A Qs(m^3/s)	Qf(m^3/s)	Sample B Qs(m^3/s)	Qf(m^3/s)	Sample C Qs(m^3/s)	Qf(m^3/s)	Time (sec)
1.409×10^{-8}	1.744×10^{-8}	0.862×10^{-8}	1.158×10^{-8}	2.806×10^{-8}	2.858×10^{-8}	1
1.408×10^{-8}	1.742×10^{-8}	0.860×10^{-8}	1.156×10^{-8}	2.802×10^{-8}	2.854×10^{-8}	2
1.407×10^{-8}	1.740×10^{-8}	0.858×10^{-8}	1.154×10^{-8}	2.798×10^{-8}	2.850×10^{-8}	3
1.406×10^{-8}	1.738×10^{-8}	0.856×10^{-8}	1.152×10^{-8}	2.794×10^{-8}	2.846×10^{-8}	4
1.405×10^{-8}	1.736×10^{-8}	0.854×10^{-8}	1.150×10^{-8}	2.790×10^{-8}	2.842×10^{-8}	5

Table 6: Values of flow rate of salt-water and fresh-water when level of salt-water is the same as level fresh-water for samples A, B and C

Sample A Qs (m^3/s)	Qf(m^3/s)	Sample B Qs(m^3/s)	Qf(m^3/s)	Sample C Qs(m^3/s)	Qf(m^3/s)	Time (sec)
0.2039×10^{-8}	0.2879×10^{-8}	0.593×10^{-8}	0.685×10^{-8}	0.0904×10^{-8}	0.286×10^{-8}	1
0.2038×10^{-8}	0.2878×10^{-8}	0.592×10^{-8}	0.684×10^{-8}	0.0903×10^{-8}	0.285×10^{-8}	2
0.2037×10^{-8}	0.2877×10^{-8}	0.591×10^{-8}	0.683×10^{-8}	0.0903×10^{-8}	0.285×10^{-8}	3
0.2036×10^{-8}	0.2876×10^{-8}	0.590×10^{-8}	0.682×10^{-8}	0.0902×10^{-8}	0.285×10^{-8}	4
0.2035×10^{-8}	0.2875×10^{-8}	0.589×10^{-8}	0.681×10^{-8}	0.0902×10^{-8}	0.284×10^{-8}	5

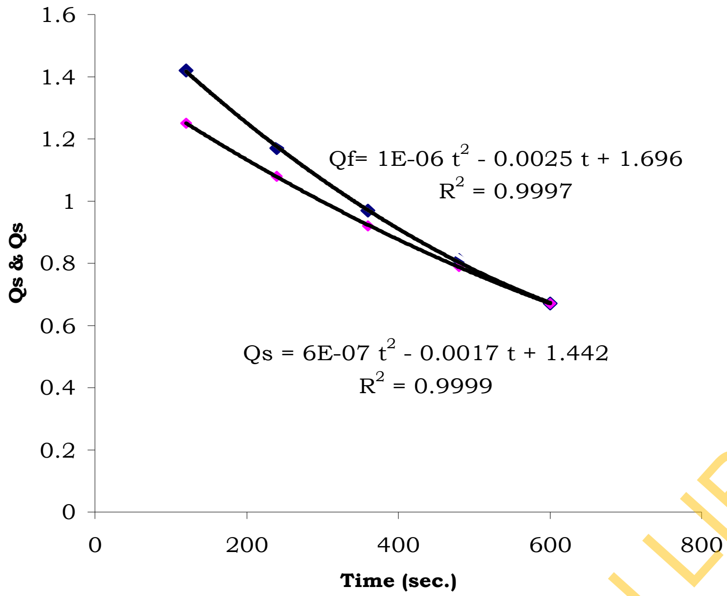

Figure 4: Graph of Qf, Qs versus Time when level of fresh-water is greater than level of salt-water for Sample A.

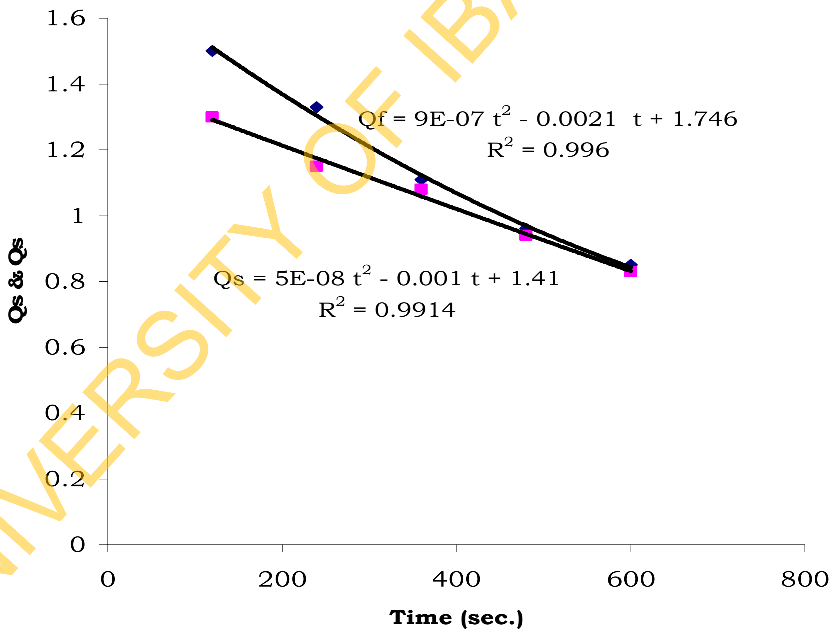

Figure 4: Graph of Qf, Qs versus Time when level of fresh-water is greater than level of salt-water for Sample A.

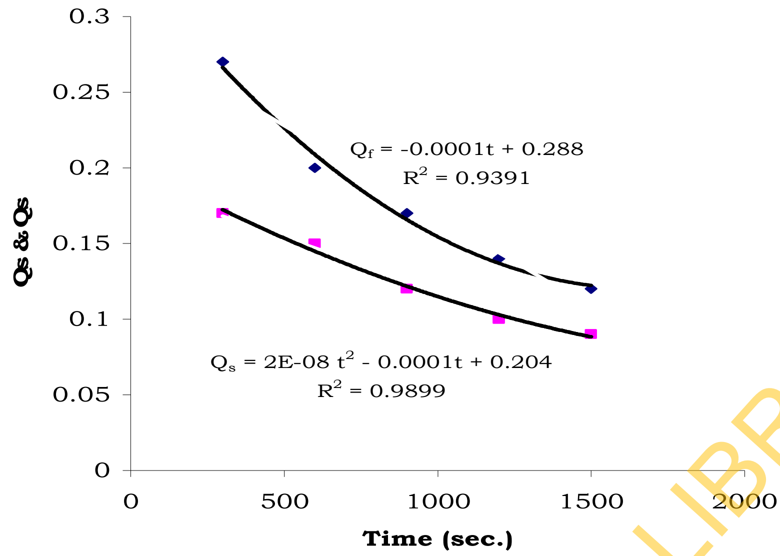

Figure 5: Graph of Q_f, Q_s versus Time when levels of salt-water and fresh-water are the same for Sample A.

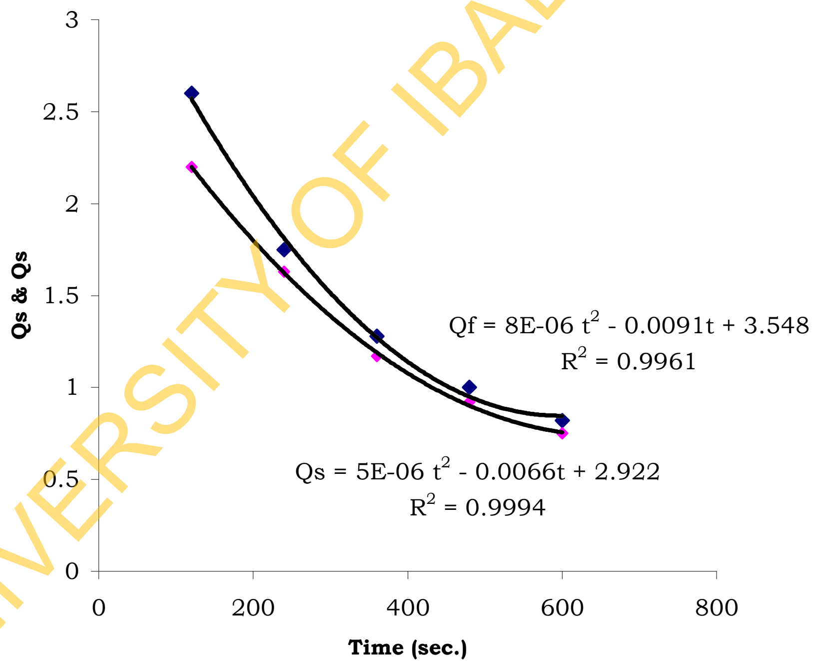

Figure 6: Graph of Q_f, Q_s versus Time when level of salt-water is greater than fresh-water level for Sample B.

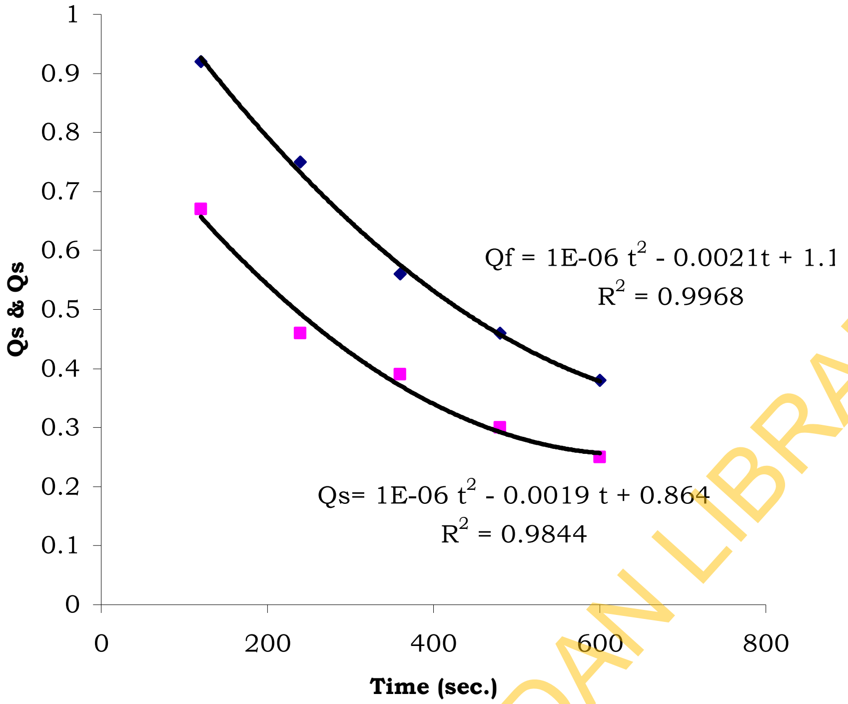

Figure 7: Graph of Q_f, Q_s versus Time when level of fresh-water is greater than level of salt-water for Sample B.

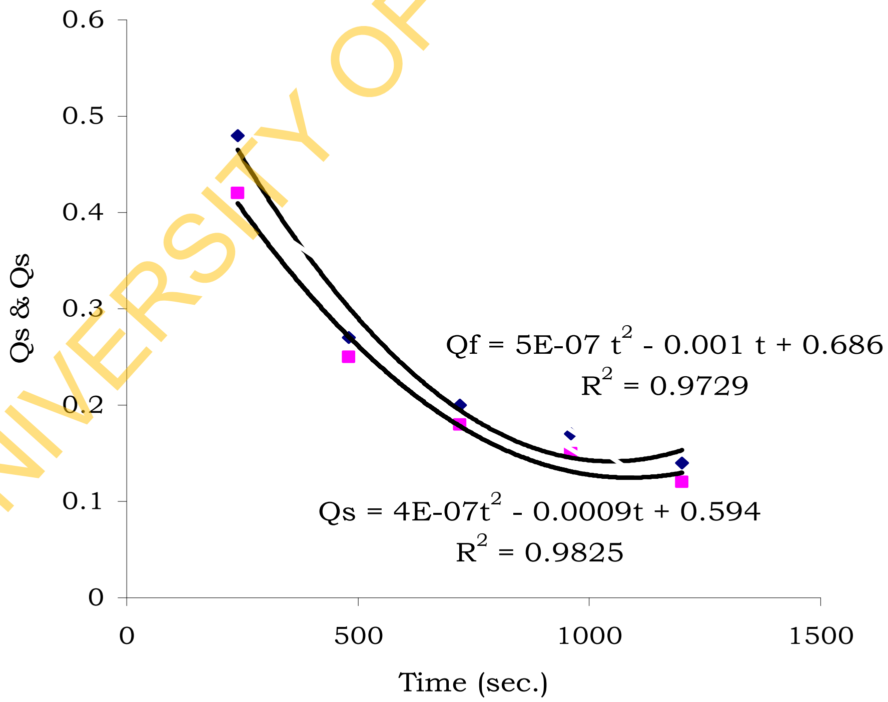

Figure 8: Graph of Qf, Qs versus Time when levels of fresh-water and salt-water are the same for Sample B.