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INVESTIGATION OF VARIATION OF DIFFUSION COEFFICIENT IN SALTWATER INTRUSION IN POROUS MEDIA

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Contaminant transport in coastal aquifers such as saltwater intrusion can be modelled in the laboratory. This work investigated the behaviour of contaminant plumes (salt water) with different densities and the effect of drawing down of freshwater in an unconfined aquifer in a coastal region. Experiments were performed using a two arm glass cylindrical tube filled with sand material to serve as the porous medium. One side of the arm was filled with saltwater while the other side was filled with freshwater. Saltwater solutions of different densities were used to study the effect of variation in density on the mass flux. The results confirmed that saltwater intrusion takes place when piezometric height of freshwater in an unconfined aquifer is less than the piezometric level of saltwater. The volume flow rate decreases as the density of the saltwater samples increases.

INTRODUCTION

The management of saltwater intrusion into coastal aquifers is one of the most challenging environmental problems faced by water resource planners worldwide. The intrusion of saltwater into groundwater aquifers is normally prevented by the groundwater flux discharging toward the ocean. However, over exploitation of coastal aquifers has lowered groundwater levels and reduced freshwater intrusion in several metropolitan areas. (US Geological Survey (USGS), 2000).

Catastrophic events such as tsunamis and hurricane can inject saltwater into local aquifers and contaminate large volumes of freshwater reservoirs. (Goswami and Clement, 2007).

Contaminant transport in coastal aquifers is inherently complex. At the seaward boundary, there will be a saltwater diffusion zone between the out-flowing freshwater and the seawater (saltwater). The seaward boundary condition is also complicated because of the presence of tidal fluctuation of sea level, which will induce an oscillation of the water table as well as the freshwater. Saltwater interfaces will affect the groundwater flow pattern and hence will also affect the pattern of saltwater migration near the coastline (Volker et al., 2006).

The study of coastal aquifers i.e. aquifers that have a hydraulic connection with a saline water body, forms a somewhat separate discipline in ground water science. This type of aquifer is typically characterized by variations of groundwater salinity in space and time, which warrants special treatment of groundwater flow and water resources management problems. Saltwater intrusion i.e. the displacement of fresh ground water by groundwater with a higher salinity has become an accepted scientific term in the research field. (Post and Abarca, 2009).

A series of laboratory experiments was conducted in a two arms glass cylindrical tube with a valve at the midpoint separating the two arms. The two arms glass cylindrical tube was filled with porous materials through which saltwater solutions with different concentrations were allowed to flow through one arm and the other arm freshwater to investigate the effects of variation of saltwater density on the diffusion coefficient of saltwater and freshwater that have hydraulic connection. The difference in density between the saltwater and freshwater introduces a pressure differential between the saltwater column and the freshwater column when both columns are at the same height. If these two columns are connected at the bottom by opening the valve the pressure difference causes a flow of saltwater column to the freshwater column until the pressure equalizes. (Todd 1960 and Delleur 1999)

The results of the research work would be useful in guiding field monitoring and remediation of saltwater intrusion.

THEORETICAL BACKGROUND

Generally, the driving forces of the volume flux and mass flux of matter through a porous material are hydraulic gradient and concentration gradient respectively (Delleur, 1999). According to Darcy's law, volume flux of liquid is directly proportional to the hydraulic gradient (Wolfgang et al., 2009 ; Olowofela and Adegoke, 2005).

$$V = \frac{-k}{\mu}\rho g \nabla \left(h - Z\right) \tag{1}$$

where k is the intrinsic permeability of the porous medium and μ is the dynamic viscosity of the fluid.

According to first Fick's law of diffusion, the amount of mass of saltwater passing through a unit area per unit time is called rate of mass flux in $kgm^{-2}s^{-1}$. The rate of mass flux is directly proportional to the gradient of concentration (Nag, 2008).

$$J_x = D\frac{dc}{dx} \tag{2}$$

where D is the diffusion coefficient The rate of mass flux of saltwater in kgm^2s^{-1} is given by $J_x = m/At$, where m is the mass of the saltwater displaced in kg, A is the unit area of porous medium in m^2 , and t is the unit time in seconds.

According to one dimensional second Fick's law of diffusion and continuity, we can obtain one dimensional diffusion equation:

$$\frac{dc}{dt}(x,t) = D\ \frac{d^2c}{dx}(x,t) \tag{3}$$

where c is the concentration of saltwater in porous medium, D is diffusion coefficient, t is the time of diffusion, and x is the distance (length) of diffusion.

The diffusion equation described how the concentration at position x changes as a function of time. The equation says that the rate of change of the concentration of saltwater solution at the position x is the diffusion coefficient multiplied by the rate of the gradient of the concentration with respect to position x. This second derivative with respect to position x is called one dimensional Laplacian and is a measure of how sharply the concentration changes with position (Cussler, 1984). Position$x$ of the concentration is changing with time as shown in the experimental set up in Figure 1.

The relation between x^2 and time t is determined from first Fick's law in which the dimensions of the diffusion equation are m = M, $A = L^2$, t = T which gives the dimension of mass flux J_x as M/L^2T and concentration gradient as M/L^4. By substitution $D=x^2/t$

By plotting x^2 versus time t in seconds, we obtain a straight line, whose slope is the diffusion coefficient (Cussler, 1997).

Using the equations cited above, the mass flux is derived and expressed as

$$J_x = K^{-1}\ \frac{DC_o}{\nabla(h-Z)} \tag{4}$$

where K^{-1} is the hydraulic resistivity, and C_o is concentration.

MATERIALS AND METHOD

Experiments were conducted in a two arms glass cylindrical tube with a closed valve in between. The arms were calibrated from 0 to 37 cm on each side and 0 to 20 cm on the horizontal length between the two arms M and N. The cylindrical tube is uniform with diameter 0.8×10^{-2} m. A conceptual diagram of the experimental setup is shown in Figure 1.

Three saltwater solutions of different densities were prepared and specific gravity bottle was used to determine the density of each solution. The saltwater solutions were labelled samples A,

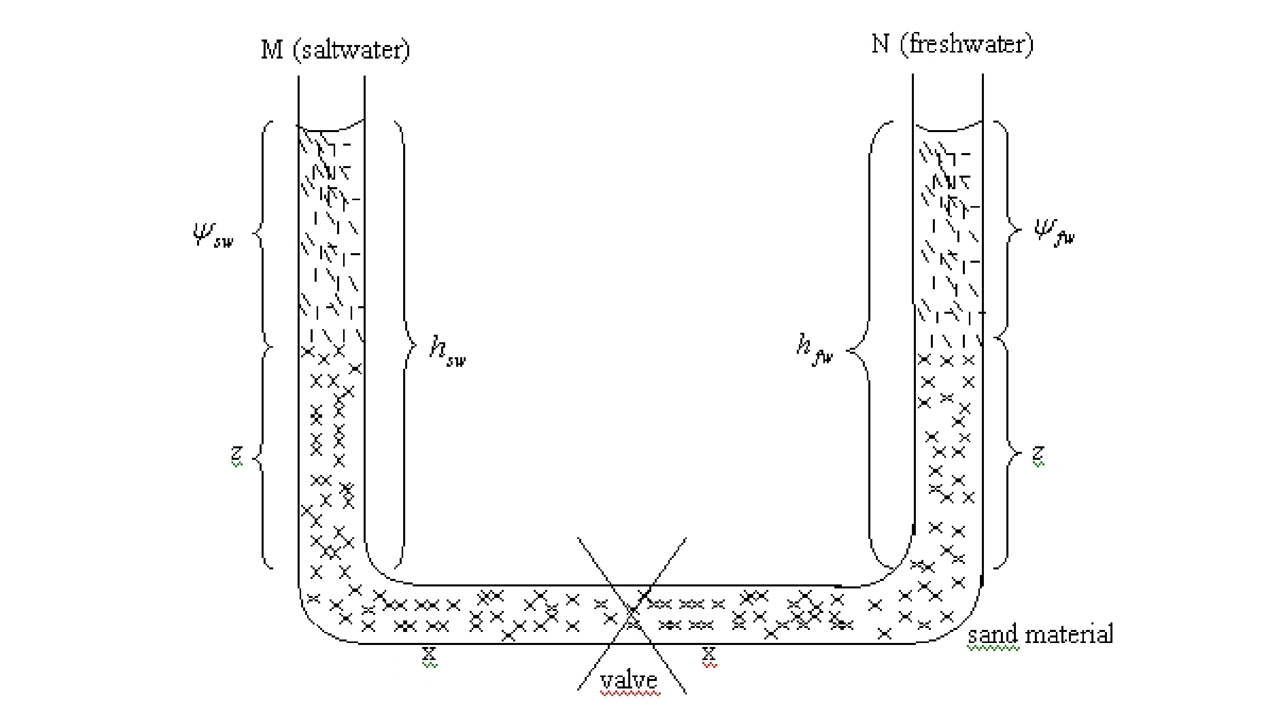

Figure 1.Experimental set up for investigation of saltwater intrusion through sand material. ψ_{sw} is the pressure head of saltwater, ψ_{fw} is pressure head of freshwater, h_{sw} is hydraulic head of saltwater, h_{fw} is hydraulic head of freshwater,z is the elevation of piezometer bottom, and$x$ is the diffusion length of saltwater and freshwater

B and C with densities 1070 kg/m^3, 1200 kg/m^3 and 1210 kg/m^3 respectively.

Riverbed sand was prepared with porosity 0.42 to serve as a porous material. It was filled with saltwater of density 1070 kg/m^3 in the M arm and freshwater in the N arm to equal level of 0.1 m above zero level. 5 ml of the riverbed sand with porosity 0.42 was poured into each arm of the tube already filled with saltwater and freshwater respectively. The sand was poured into the water in order to eliminate air trapping which would otherwise occur and affect free flow of water for each case. The level of saltwater in the M arm was made to be higher than that of freshwater in the N arm by 17cm. The hydraulic levels, volume flux, mass flux and the horizontal distance in cm were obtained at every 60 seconds when the valve was opened.

Under the same condition, the level of freshwater in the N arm was made to be higher than the level of saltwater in the M arm by 17cm. Then, the hydraulic levels, volume flux and the horizontal distance were obtained at every 60 seconds when the valve was opened. Under the same condition, the level of freshwater in the N arm was made to be equal to the level of saltwater in the M arm. The hydraulic levels, volume flux, mass flux and the horizontal distance were obtained at every 60 seconds when the valve was opened for both salt water and fresh water

The procedure was repeated for saltwater solutions with densities 1200kg/m^3 and 1210kg/m^3 respectively.

RESULTS AND DISCUSSION

The hydraulic levels of saltwater and freshwater, volume flux of saltwater solution and the horizontal diffuse distance of saltwater solution in the porous medium for every 60 seconds are as presented in Tables 1 –9. In figures 2 – 10, hydraulic levels of saltwater and freshwater were changing with time. The equation generated from the graphs showed that the hydraulic levels of saltwater and freshwater changed in the opposite directions i.e. as one increased, the other one decreased. The same hydraulic level was quickly attained when the saltwater hydraulic level was greater than freshwater hydraulic level compared to when the freshwater hydraulic level was greater than the saltwater hydraulic level. The reason is that the hydraulic head gradient and concentration gradient is higher in saltwater hydraulic column than freshwater hydraulic column. The saltwater still displaced the freshwater upward despite that they are equal in initial hydraulic levels because the concentration gradient is higher in saltwater than in freshwater.

From Fick's law of diffusion, the graph of square of diffused length (x) versus time in second, therefore, we obtain a straight line whose slope is the diffusion coefficient as shown in figures 11 – 19. The diffusion coefficient decreases with increase in density (concentration) of saltwater solution when the initial hydraulic level of saltwater is greater than initial hydraulic level of freshwater as well as when the initial hydraulic level of freshwater is greater than the initial hydraulic level of saltwater but diffusion coefficient increases with increase in density of saltwater solution when the hydraulic levels of saltwater and freshwater are equal initially.

As the density (concentration) of the samples A, B and C increases 1070kg/m^3, 1200kg/m^3 and 1210kg/m^3 respectively, the results of the experimental investigation showed that the volume of saltwater displaced and the volume of freshwater displaced with time decreased for each sample when the hydraulic level of saltwater was greater than the hydraulic level of freshwater as presented in Tables 1, 4 and 7.

Moreover, the same results were observed when the volume of saltwater displaced and the volume of freshwater displaced with time for each sample when the hydraulic level of freshwater was greater than the hydraulic level of saltwater as presented in Tables 2, 5 and 8. Therefore, the volume flow rate decreased with increase in density and this result in the decrease in diffusion coefficient for sample A to sample C as presented in Table 10.

Furthermore, the results of the experiment showed that when the hydraulic level of freshwater equal to the hydraulic level of saltwater, the volume of freshwater displaced increased with time as the density increased as presented in Tables 3, 6 and 9. Therefore, the volume flow rate increased with increase in density when the hydraulic levels of saltwater and freshwater are equalled. Consequently, the diffusion coefficient increased as the volume flow rate increased because diffusion depends on volume flow rate as presented in Table 10.

CONCLUSION

The result as presented in Table 10 shows that the diffusion coefficient is

highest in case 1 but least in case 3 for sample A , B and C respectively. Therefore, the rate of diffusion is fastest when piezometric level of saltwater is greater than piezometric level of freshwater but it is slowest when the piezometric level of freshwater is equal to the piezometric level of saltwater. Therefore, the hydraulic levels of saltwater and freshwater in an aquifer contribute to the rate of diffusion of saltwater from the ocean into the freshwater aquifer. This condition occurs when the groundwater in an unconfined aquifer is excessively pumped; the rate of seawater intrusion into the freshwater aquifer will increase because the hydrostatic pressure on the freshwater will reduce compared to the hydrostatic pressure of seawater

Case 1: Density of saltwater solution (sample A) = 1070kg/m^3, M = hydraulic level of saltwater, N = hydraulic level of freshwater.

Table 1. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial hydraulic level of saltwater is greater than initial hydraulic level of freshwater.

M (cm)	N (cm)	Vol. of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$ /A x 10^{-11} (kg/m^2s)	x (cm)	x^2 x 10^{-3} (m^2)	Time (sec)
37	20	0	0	0	0	0	0	0	0
33.40	23.60	1.81	1.81	1.94	1.81	6.4	3.6	1.3	60
31.50	25.50	2.77	2.77	2.96	2.77	4.9	5.5	3.1	120
30.20	26.80	3.42	3.42	3.66	3.42	4.0	6.8	4.6	180
29.50	27.50	3.77	3.77	4.03	3.77	3.3	7.5	5.6	240
28.90	28.10	4.07	4.07	4.36	4.07	2.9	8.1	6.6	300
28.60	28.40	4.22	4.23	4.52	4.23	2.5	8.4	7.1	360
28.40	28.60	4.32	4.33	4.62	4.33	2.2	8.6	7.4	420

Table 2. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial hydraulic level of freshwater is greater than initial hydraulic level of saltwater.

M (cm)	N (cm)	Vol. of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$ /A x 10^{-11} (kg/m^2s)	x (cm)	x^2 x 10^{-3} (m^2)	Time (sec)
20	37	0	0	0	0	0	0	0	0
22.80	34.20	1.41	1.41	1.51	1.41	5.0	2.8	0.8	60
24.50	32.50	2.26	2.26	2.42	2.26	4.0	4.5	2.01	120
25.70	31.30	2.87	2.87	3.07	2.87	3.3	5.7	3.25	180
26.40	30.60	3.22	3.22	3.45	3.22	2.9	6.4	4.10	240
26.80	30.20	3.42	3.42	3.66	3.42	2.4	6.8	4.62	300
27.00	30.00	3.52	3.52	3.77	3.52	2.1	7.0	4.90	360
27.10	29.90	3.57	3.57	3.82	3.57	1.8	7.1	5.04	420
27.15	29.85	3.60	3.60	3.85	3.60	1.6	7.15	5.11	480
27.20	29.80	3.62	3.62	3.87	3.62	1.4	7.20	5.20	540
27.24	29.76	3.64	3.64	3.90	3.64	1.3	7.24	5.24	600
27.28	29.72	3.66	3.66	3.92	3.66	1.2	7.28	5.30	660
27.31	29.69	3.68	3.68	3.94	3.68	1.1	7.31	5.34	720
27.34	29.66	3.69	3.69	3.95	3.69	1.0	7.34	5.40	780
27.36	29.64	3.70	3.70	3.96	3.70	0.94	7.36	5.42	840
27.38	29.62	3.71	3.71	3.97	3.71	0.88	7.38	5.45	900
27.39	29.61	3.72	3.72	3.98	3.72	0.82	7.39	5.46	960
27.40	29.60	3.72	3.72	3.98	3.72	0.78	7.40	5.48	1020

Table 3. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial hydraulic level of saltwater is equal to initial hydraulic levelof freshwater.

M (cm)	N (cm)	Vol. of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$ /A x 10^{-11} (kg/m^2s)	x (cm)	x^2 x 10^{-3} (m^2)	Time (sec)
30	30	0	0	0	0	0	0	0	0
29.00	31.00	0.50	0.50	0.54	0.5	1.8	1.0	0.1	60
28.80	31.20	0.60	0.60	0.64	0.6	1.1	1.2	0.14	120
28.65	31.35	0.68	0.68	0.73	0.68	0.81	1.35	0.18	180
28.55	31.45	0.73	0.73	0.78	0.73	0.65	1.45	0.2	240
28.50	31.50	0.76	0.76	0.81	0.76	0.54	1.5	0.23	300
28.45	31.55	0.78	0.78	0.84	0.78	0.46	1.55	0.24	360

Case 2: Density of Saltwater Solution (Sample B) = 1200 kg/m^3, M = hydraulic level of saltwater, N = hydraulic level of freshwater.

Table 4. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial hydraulic level of saltwater is greater than initial hydraulic level of freshwater.

M (cm)	N (cm)	Vol. of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$/A x 10^{-11} (kg/m^{2}s)	x (cm)	x^2 x 10^{-3} (m^2)	Time (sec)
37	20	0	0	0	0	0	0	0	0
33.90	23.10	1.56	1.56	1.87	1.56	6.2	3.10	0.96	60
31.90	25.10	2.57	2.57	3.08	2.57	5.1	5.10	2.60	120
30.80	26.20	3.12	3.12	3.74	3.12	4.1	6.20	3.84	180
29.90	27.10	3.57	3.57	4.28	3.57	3.6	7.10	5.04	240
29.40	27.60	3.82	3.82	4.58	3.82	3.0	7.60	5.78	300
29.10	27.90	3.97	3.97	4.76	3.97	2.6	7.90	6.24	360
28.90	28.10	4.07	4.07	4.88	4.07	2.3	8.10	6.56	420
28.70	28.30	4.18	4.18	5.02	4.18	2.1	8.30	6.89	480
28.55	28.45	4.25	4.25	5.10	4.25	1.9	8.45	7.14	540
28.45	28.55	4.30	4.30	5.16	4.30	1.7	8.55	7.31	600
28.40	28.60	4.33	4.33	5.20	4.33	1.6	8.60	7.40	660
28.37	28.63	4.34	4.34	5.21	4.34	1.5	8.63	7.45	720

Table 5. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial hydraulic level of freshwater is greater than initial hydraulic level of saltwater.

M (cm)	N (cm)	Vol. of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$/A x 10^{-11} (kg/m^{2}s)	x (cm)	x^2 x 10^{-3} (m^2)	Time (sec)
20	37	0	0	0	0	0	0	0	0
22.50	34.50	1.26	1.26	1.51	1.26	5.0	2.50	0.63	60
24.10	32.90	2.06	2.06	2.47	2.06	4.1	4.10	1.68	120
25.10	31.90	2.57	2.57	3.08	2.57	3.4	5.10	2.60	180
25.80	31.20	2.92	2.92	3.50	2.92	2.9	5.80	3.36	240
26.20	30.80	3.12	3.12	3.74	3.12	2.5	6.20	3.84	300
26.50	30.50	3.27	3.27	3.92	3.27	2.2	6.50	4.23	360
26.70	30.30	3.37	3.37	4.04	3.37	1.9	6.70	4.49	420
26.90	30.10	3.47	3.47	4.16	3.47	1.70	6.90	4.76	480
27.00	30.00	3.52	3.52	4.22	3.52	1.55	7.00	4.90	540
27.10	29.90	3.57	3.57	4.28	3.57	1.4	7.10	5.04	600
27.15	29.85	3.60	3.60	4.32	3.60	1.3	7.15	5.11	660
27.20	29.80	3.62	3.62	4.32	3.62	1.2	7.20	5.18	720
27.25	29.75	3.65	3.65	4.38	3.65	1.1	7.25	5.26	780
27.29	29.71	3.67	3.67	4.40	3.67	1.0	7.29	5.31	840
27.33	29.67	3.69	3.69	4.43	3.69	0.98	7.33	5.37	900

Table 6. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial hydraulic level of saltwater is equal to initial hydraulic level of freshwater.

M (cm)	N (cm)	Vol. of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$/A x 10^{-11} (kg/m^{2}s)	x (cm)	x^2 x 10^{-3} (m^2)	Time (sec)
30	30	0	0	0	0	0	0	0	0
29.20	30.80	0.40	0.40	0.48	0.40	1.59	0.80	0.64	60
28.90	31.10	0.55	0.55	0.66	0.55	1.09	1.10	1.21	120
28.75	31.25	0.63	0.63	0.76	0.63	0.84	1.25	1.56	180
28.60	31.40	0.70	0.70	0.84	0.70	0.70	1.40	1.96	240
28.50	31.50	0.76	0.76	0.91	0.76	0.60	1.50	2.25	300
28.40	31.60	0.81	0.81	0.92	0.81	0.51	1.60	2.56	360

Case 3: Density of Saltwater Solution (Sample C) = 1210 kg/m^3, M = hydraulic level of saltwater, N = hydraulic level of freshwater.

Table 7. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial

M (cm)	N (cm)	Vol. of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$ /A x 10^{-11} (kg/m^{2}s)	x (cm)	x^2 x 10^{-3} (m)	Time (sec)
37	20	0	0	0	0	0	0	0	0
34.70	22.30	1.16	1.16	1.41	1.16	4.7	2.3	0.53	60
33.00	24.00	2.01	2.01	2.43	2.01	4.0	4.0	1.60	120
31.90	25.10	2.57	2.57	3.11	2.57	3.4	5.1	2.60	180
31.20	25.80	2.92	2.92	3.53	2.92	2.9	5.8	3.36	240
30.90	26.10	3.07	3.07	3.72	3.07	2.5	6.1	3.72	300
30.60	26.40	3.22	3.22	3.90	3.22	2.2	6.4	4.10	360
30.40	26.60	3.32	3.32	4.02	3.32	1.9	6.6	4.40	420
30.20	26.80	3.42	3.42	4.14	3.42	1.7	6.8	4.62	480
30.00	27.00	3.52	3.52	4.26	3.52	1.6	7.0	4.90	540
29.85	27.15	3.60	3.60	4.36	3.60	1.5	7.15	5.11	600
29.70	27.30	3.67	3.67	4.44	3.67	1.3	7.30	5.33	660
29.60	27.40	3.72	3.72	4.50	3.72	1.2	7.40	5.48	720

Table 8. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial

M (cm)	N (cm)	Vol. of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$ /A x 10^{-11} (kg/m^{2}s)	x (cm)	x^2 x 10^{-3} (m^2)	Time (sec)
20	37	0	0	0	0	0	0	0	0
21.80	35.2	0.91	0.91	1.10	0.91	3.7	1.80	0.32	60
23.20	33.8	1.61	1.61	1.95	1.61	3.2	3.20	1.02	120
24.20	32.8	2.11	2.11	2.55	2.11	2.8	4.20	1.76	180
24.70	32.3	2.36	2.36	2.86	2.36	2.4	4.70	2.21	240
24.90	32.1	2.47	2.47	2.99	2.47	2.0	4.90	2.40	300
24.95	32.05	2.49	2.49	3.01	2.49	1.7	4.95	2.45	360
24.96	32.04	2.50	2.50	3.03	2.50	1.4	4.96	2.46	420
24.97	32.03	2.50	2.50	3.03	2.50	1.3	4.97	2.47	480
24.98	32.02	2.51	2.51	3.04	2.51	1.1	4.98	2.48	540
24.99	32.01	2.51	2.51	3.04	2.51	1.0	4.99	2.49	600
25.00	32.00	2.52	2.52	3.05	2.52	0.92	5.00	2.50	660

Table 9. Hydraulic levels, mass flux, volume flux and diffused length of saltwater and freshwater when initial

M (cm)	N (cm)	Volume of saltwater displ. x 10^{-6} (m^3)	Vol. of freshwater displ. x 10^{-6} (m^3)	m_s x 10^{-3} (kg)	m_f x 10^{-3} (kg)	$\dot{m}$ /A x 10^{-11} (kg/m^{2}s)	x (cm)	x^2 x 10^{-4} (m^2)	Time (sec)
30	30	0	0	0	0	0	0	0	0
00	30.60	0.30	0.30	0.36	0.30	1.2	0.6	0.36	60
28.90	31.10	0.55	0.55	0.67	0.55	1.1	1.1	1.21	120
28.60	31.40	0.70	0.70	0.85	0.70	0.94	1.4	1.96	180
28.50	31.50	0.76	0.76	0.92	0.76	0.76	1.5	2.25	240

Table 10. Values of diffusion coefficient with saltwater samples A, B and C.

Saltwater samples	Diffusion coefficient when (M) > (N) m^2/s	Diffusion coefficient when (N) > (M) m^2/s	Diffusion coefficient when M = N m^2/s
A	1.68 x 10^{-2}	1.18 x 10^{-2}	0.5 x 10^{-3}
B	1.55 x 10^{-2}	1.07 x 10^{-2}	0.6 x 10^{-3}
C	1.06 x 10^{-2}	0.59 x 10^{-2}	0.1 x 10^{-2}

Case 1: Density of saltwater solution (sample A) = 1070kg/m^3

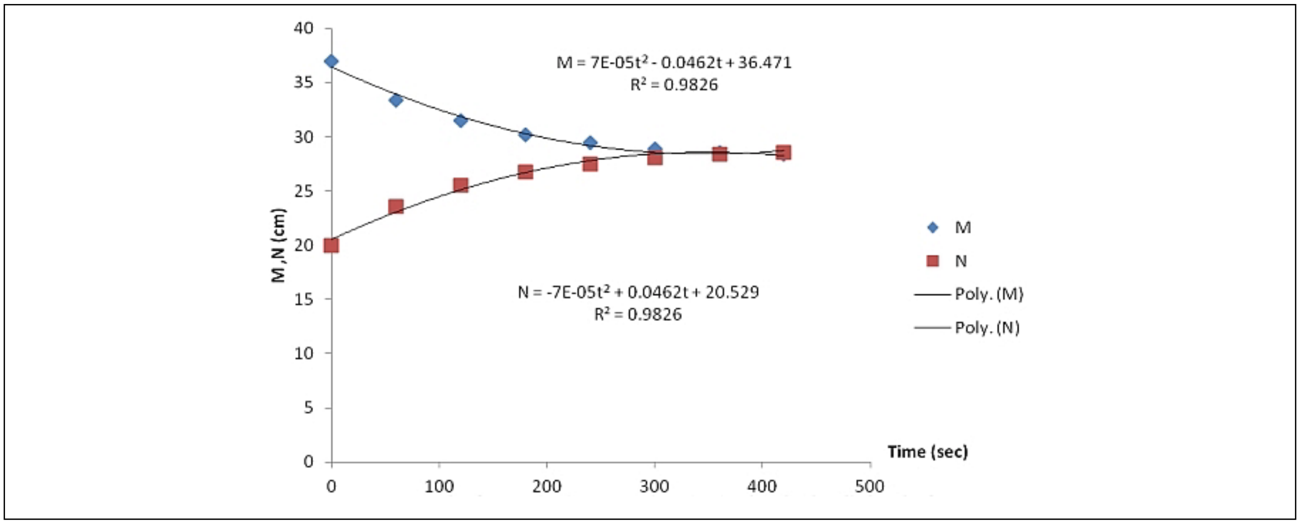

Figure 2. Graph of M,N (cm) versus time (sec) when hydraulic level of saltwater is greater than the hydraulic level of freshwater.

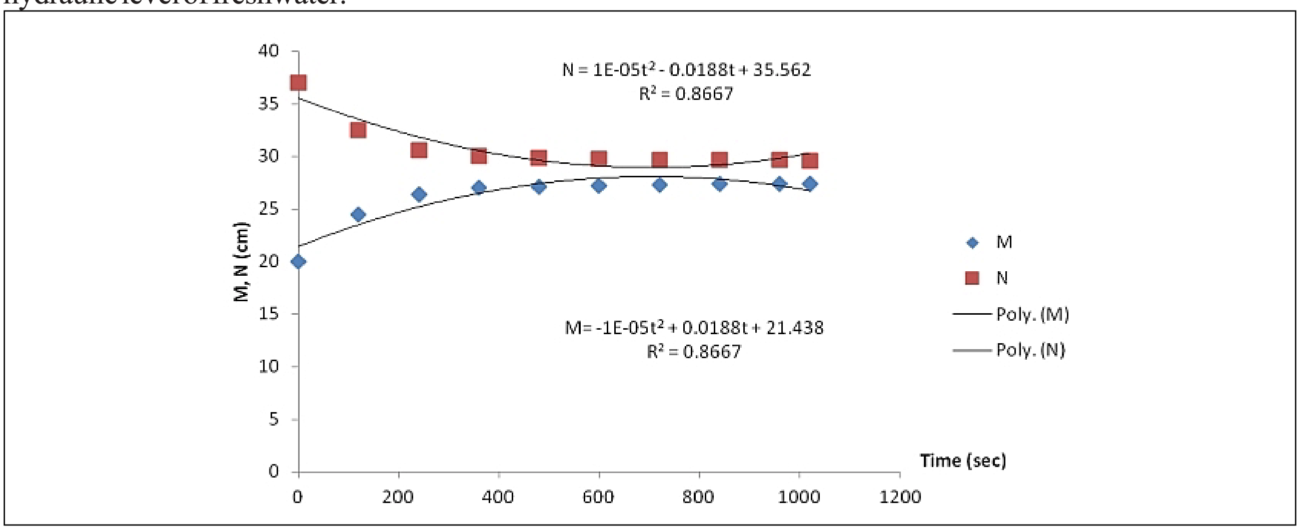

Figure 3. Graph of M,N (cm) versus time (sec) when hydraulic level of fresh water is greater than the hydraulic level of saltwater.

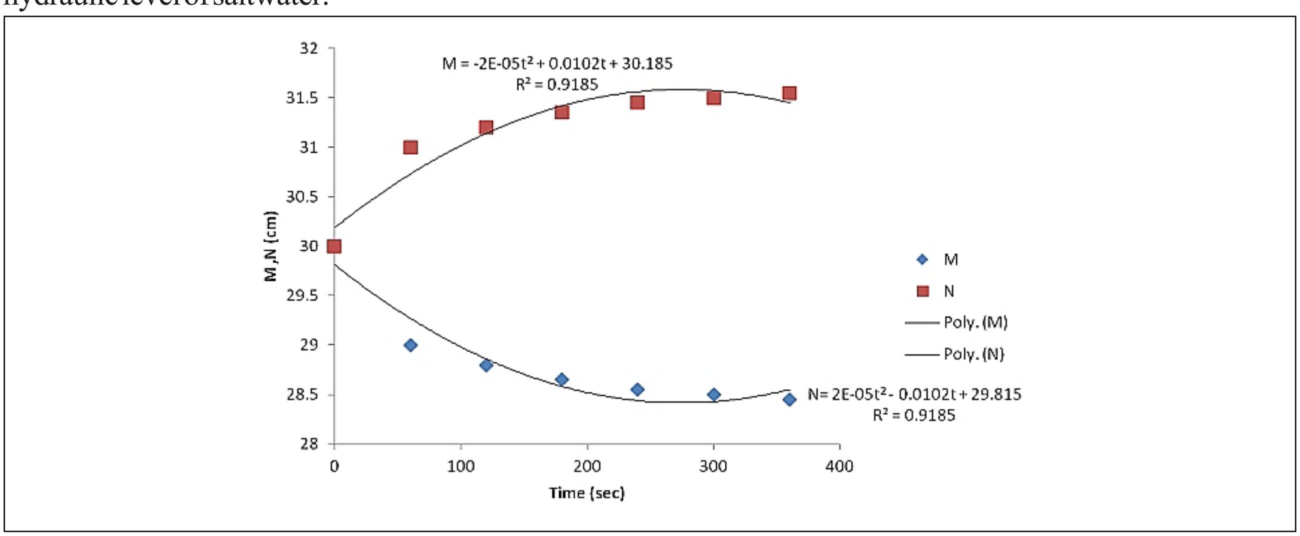

Figure 4. Graph of M,N (cm) versus time (sec) when hydraulic level of saltwater is equal to the hydraulic

Case 2: Density of saltwater solution (sample B) = 1200 kg/m^3

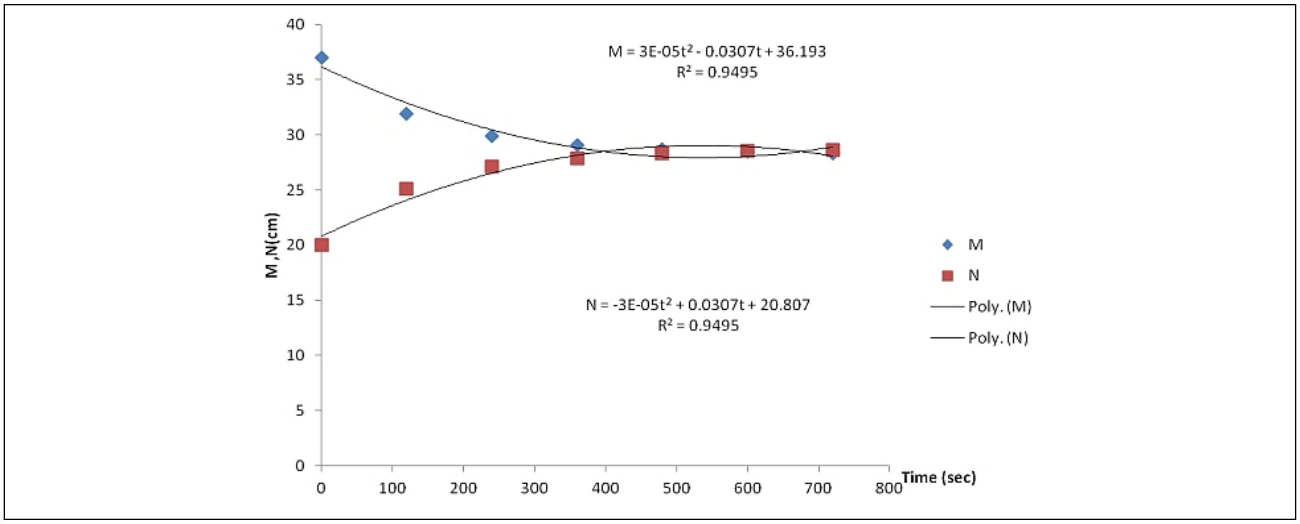

Figure 5. Graph of M,N (cm) versus time (sec) when hydraulic level of saltwater is greater than the hydraulic level of freshwater.

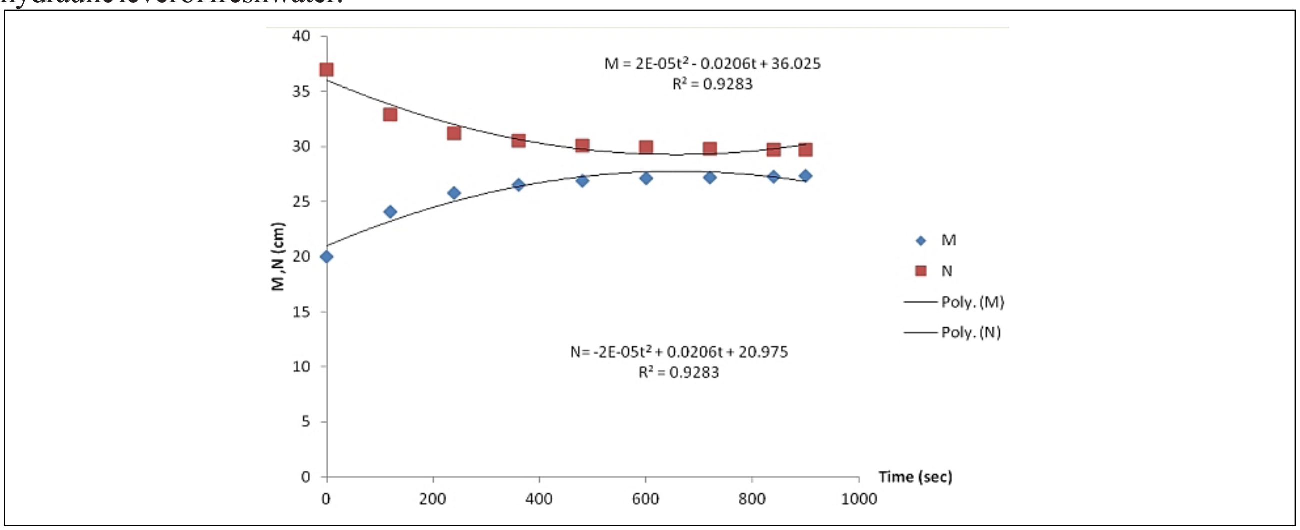

Figure 6. Graph of M,N (cm) versus time (sec) when hydraulic level of fresh water is greater than the hydraulic level of saltwater.

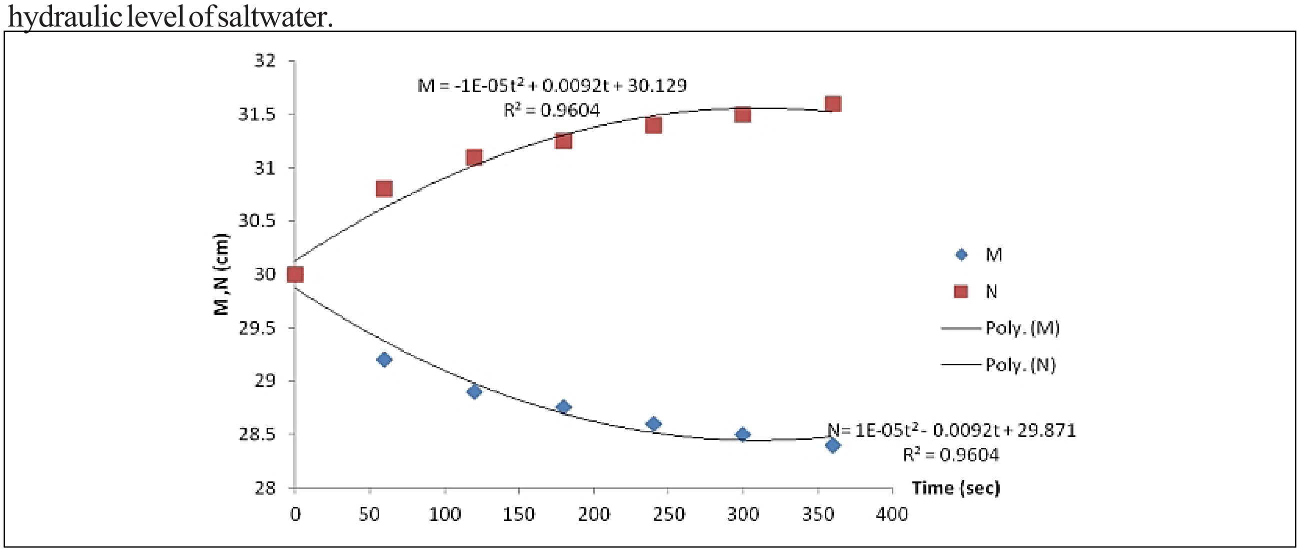

Figure 7. Graph of M,N (cm) versus time (sec) when hydraulic level of saltwater is equal to the hydraulic

Case 3: Density of saltwater solution (sample C) = 1210kg/m^3

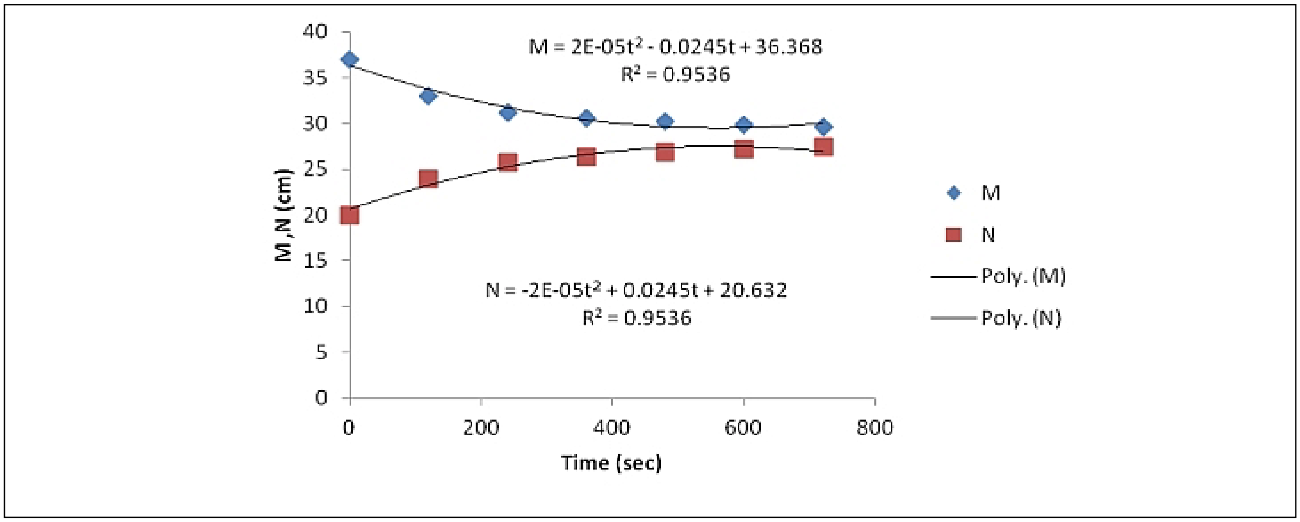

Figure 8. Graph of M,N (cm) versus time (sec) when hydraulic level of saltwater is greater than the hydraulic level of freshwater.

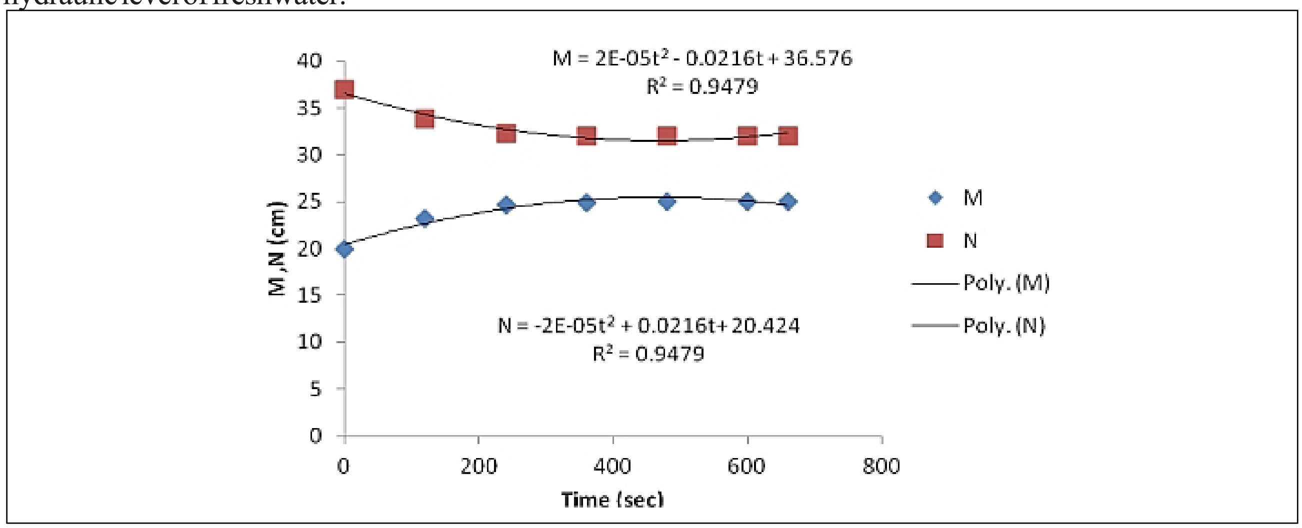

Figure 9. Graph of M,N (cm) versus time (sec) when hydraulic level of fresh water is greater than the hydraulic level of saltwater.

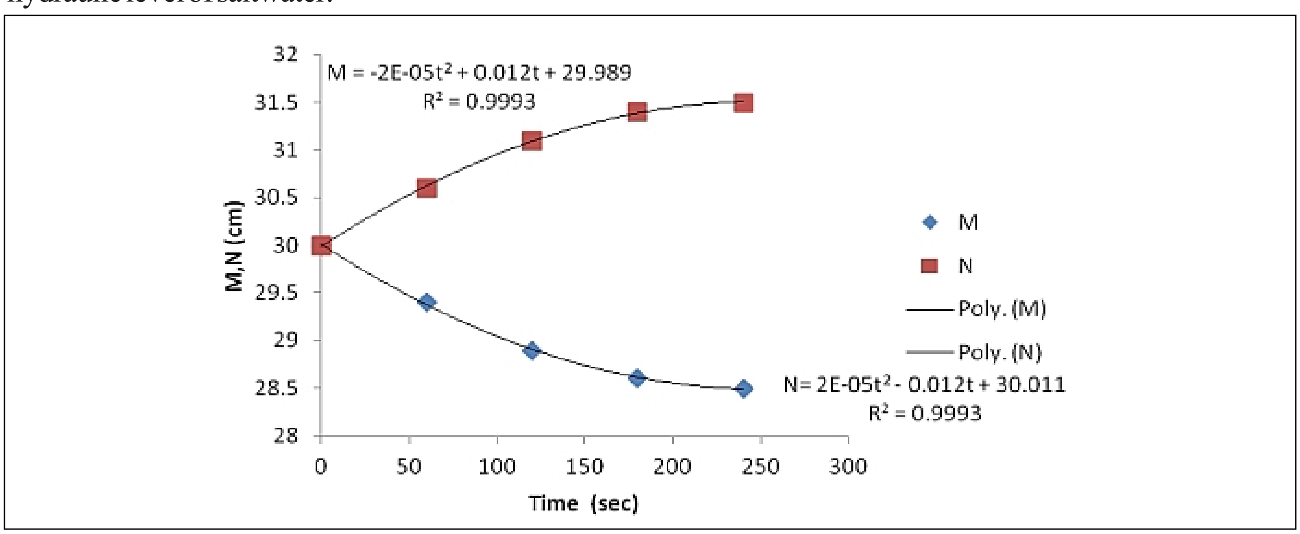

Figure 10. Graph of M,N (cm) versus time (sec) when hydraulic level of saltwater is equal to the hydraulic

Case 1: Density of saltwater solution (sample A) = 1070kg/m^3

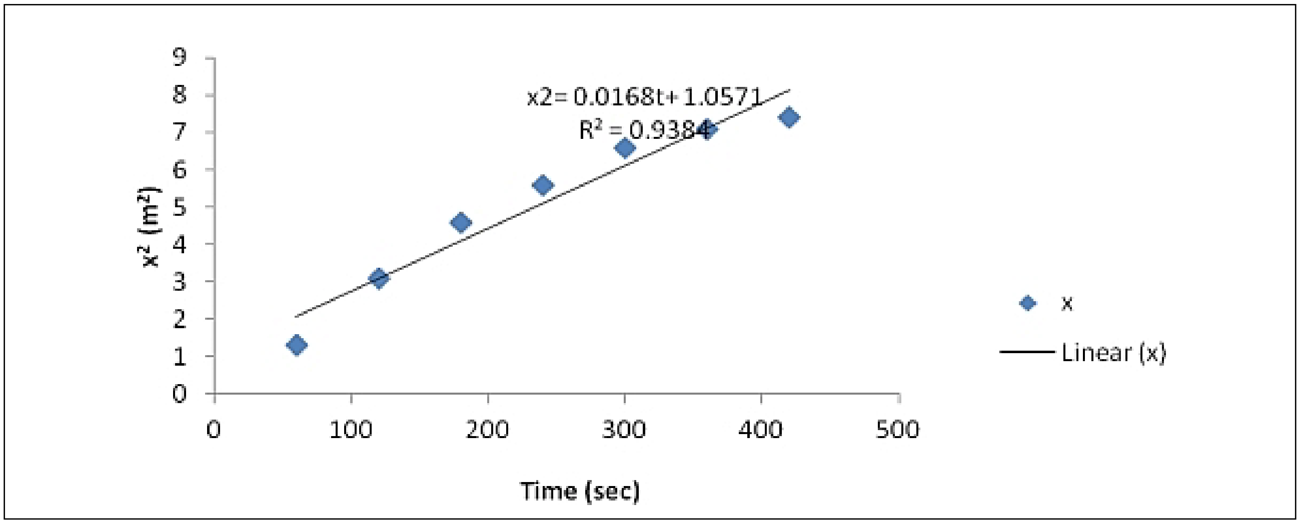

Figure 11. Graph of x^2(m^2) versus time (sec) when hydraulic level of saltwater is greater than hydraulic

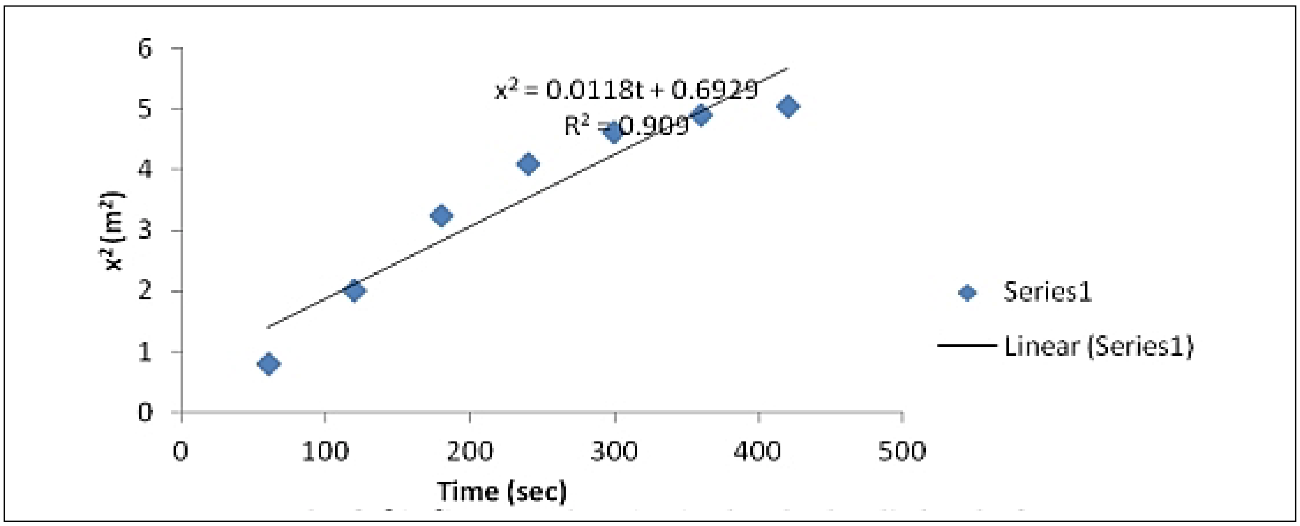

Figure 12. Graph of x^2(m^2) versus time (sec) when hydraulic level of fresh water is greater than hydraulic

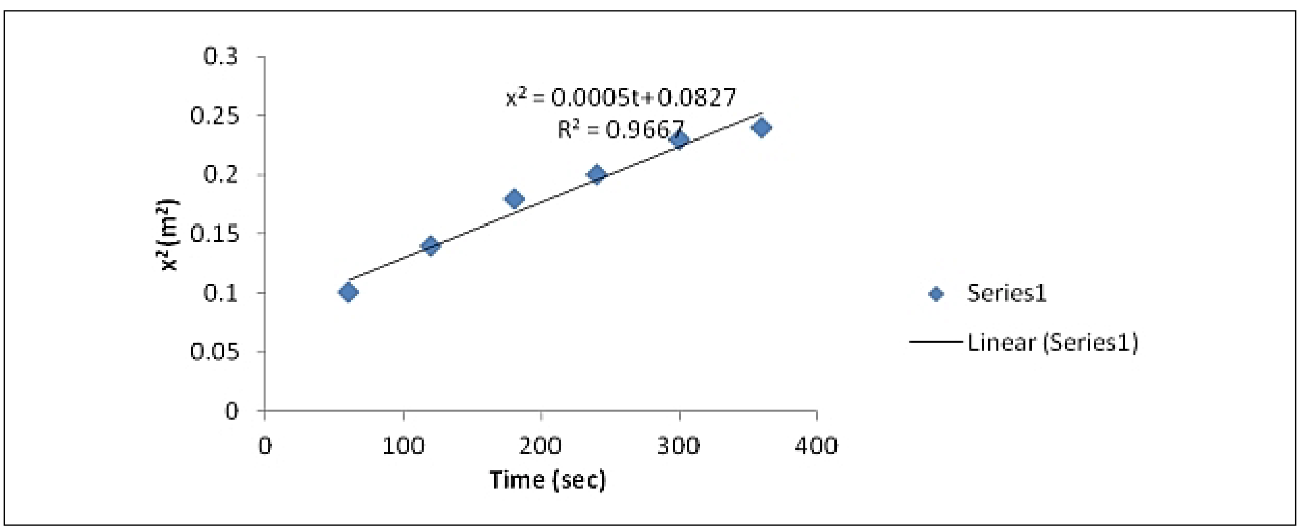

Figure 13. Graph of x^2(m^2) versus time (sec) when hydraulic level of saltwater is equal to hydraulic level of

Case 2: Density of saltwater solution (sample B) = 1200 kg/m^3

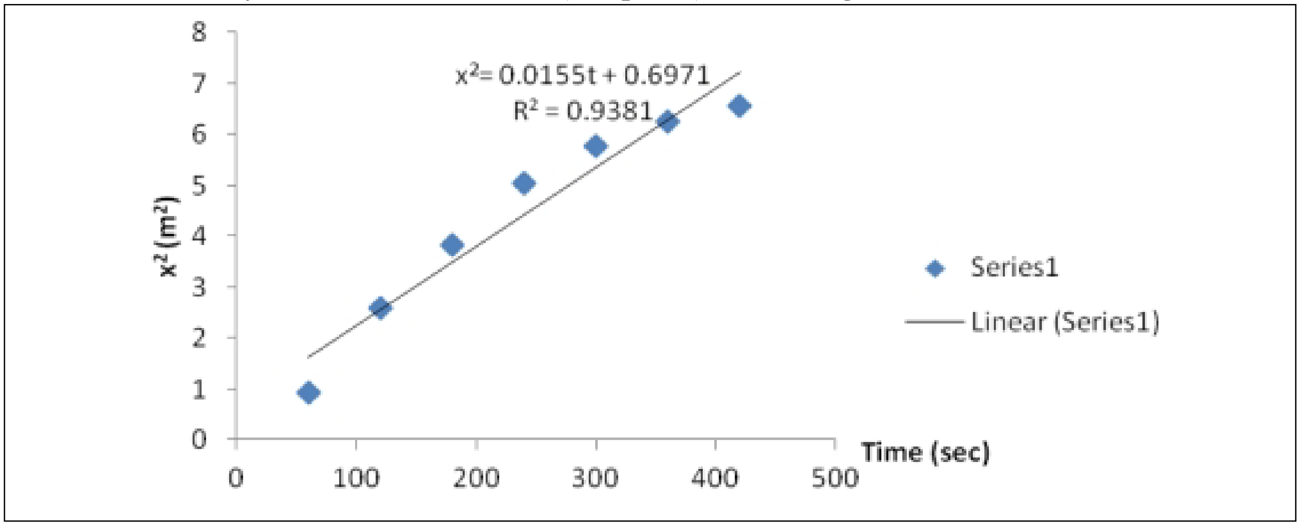

Figure 14. Graph of x^2(m^2) versus time (sec) when hydraulic level of saltwater is greater than hydraulic level of fresh water.

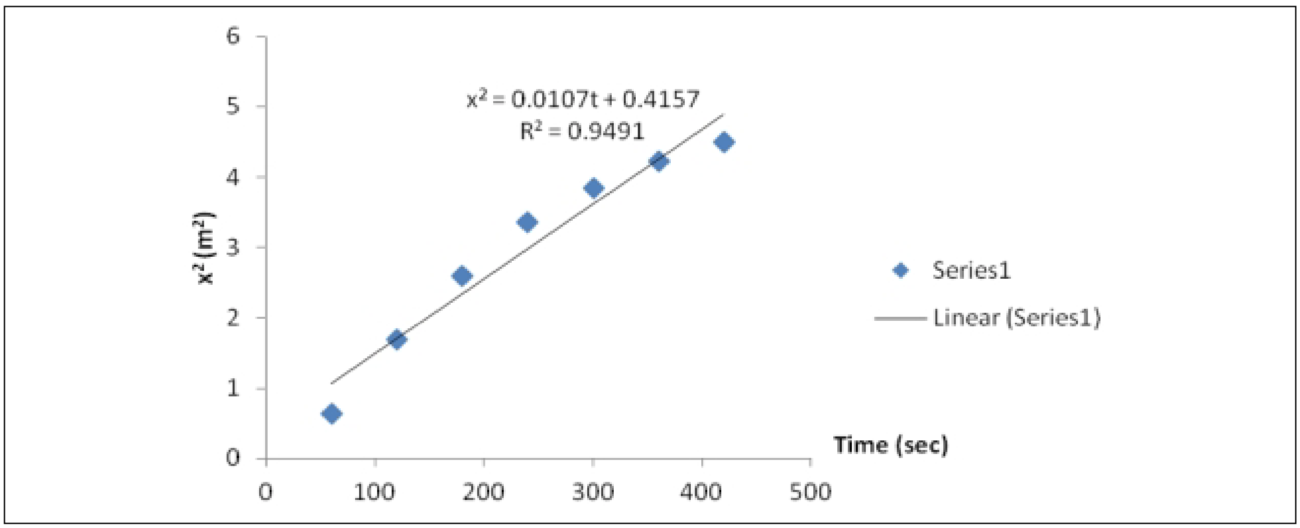

Figure 15. Graph of x^2(m^2) versus time (sec) when hydraulic level of fresh water is greater than hydraulic level of saltwater.

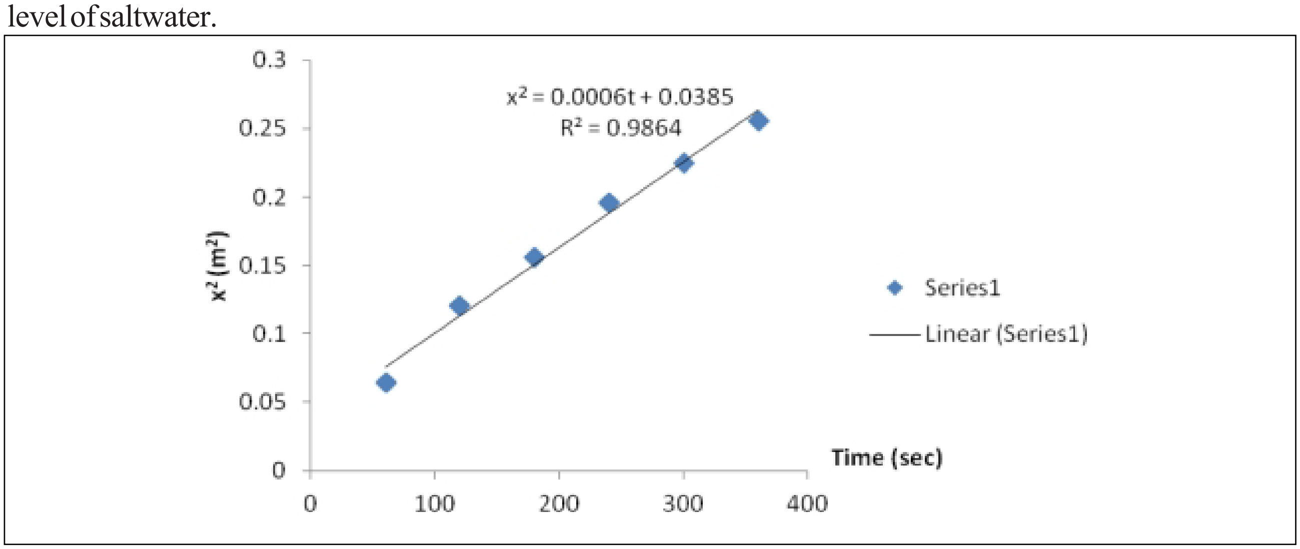

Figure 16. Graph of x^2(m^2) versus time (sec) when hydraulic level of saltwater is equal to hydraulic level of

Case 3: Density of saltwater solution (sample C) = 1210kg/m^3

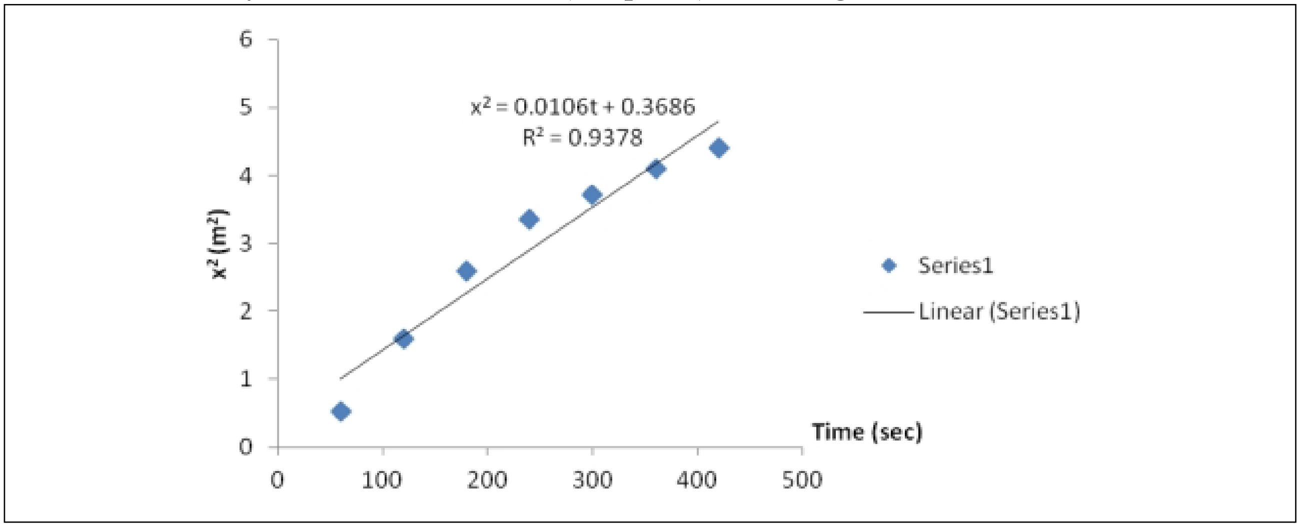

Figure 17. Graph of x^2(m^2) versus time (sec) when hydraulic level of saltwater is greater than hydraulic level of fresh water.

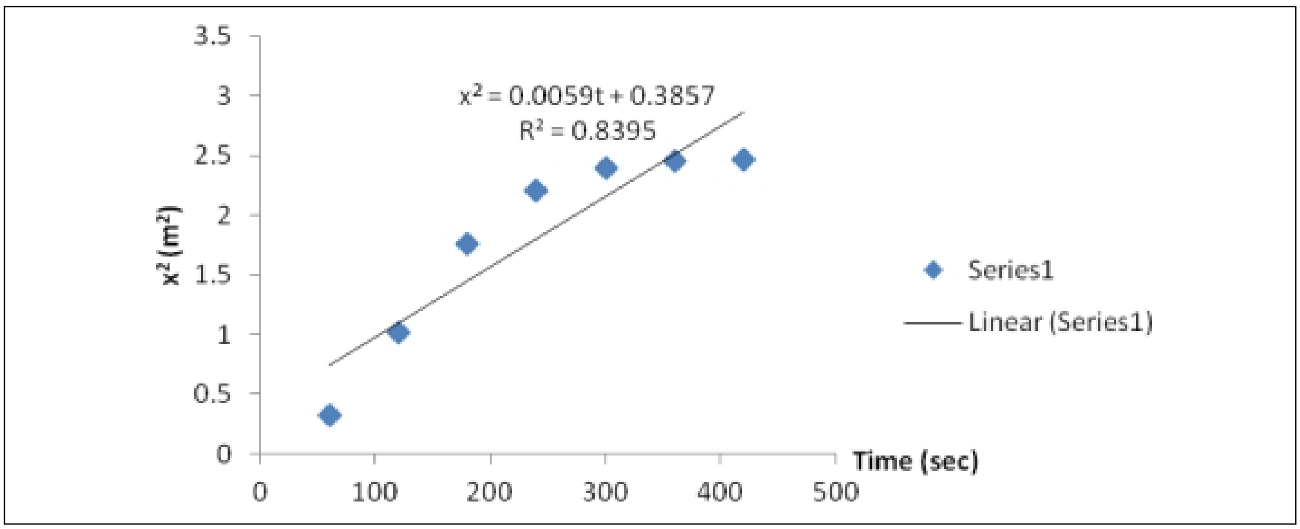

Figure 18. Graph of x^2(m^2) versus time (sec) when hydraulic level of fresh water is greater than hydraulic level of saltwater.

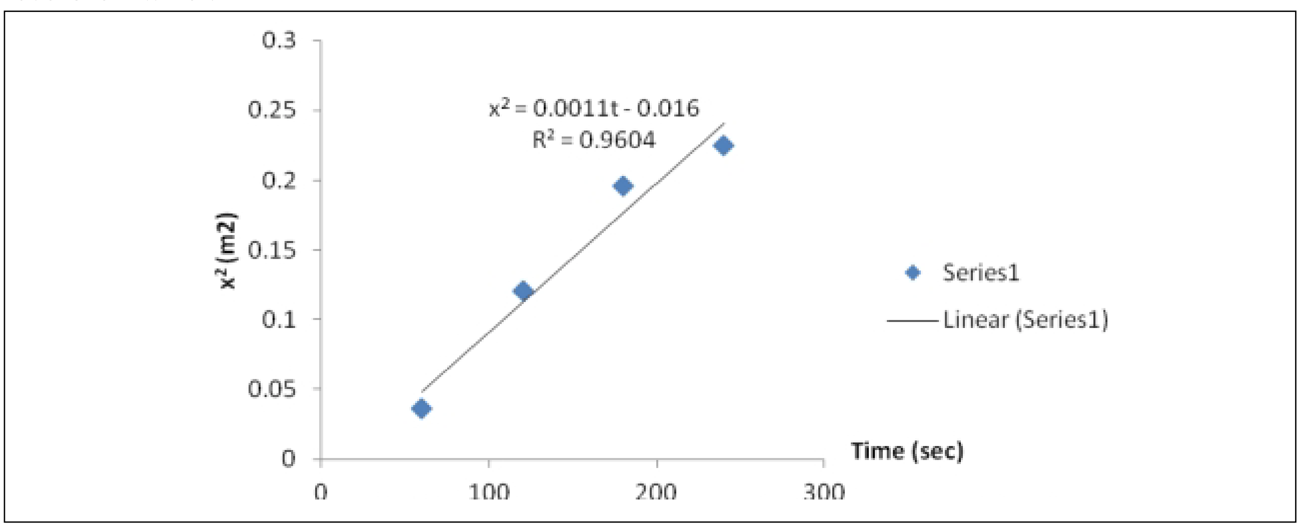

Figure 19. Graph of x^2(m^2) versus time (sec) when hydraulic level of saltwater is equal to hydraulic level of

The diffusion coefficient decreases as the density increases in samples A, B and C for cases 1 and 2 because hydraulic head has impart in the rate of diffusion but the diffusion coefficient increases as the density increases in case 3. Hence, the driving force of the mass flux in case 3 depends on the concentration gradient only.

In Table 10, rate of diffusion is much when the hydraulic level of saltwater is greater than hydraulic level of freshwater followed by when the hydraulic level of freshwater greater than the hydraulic level of saltwater and least when the hydraulic level of saltwater is equal to the hydraulic level of freshwater irrespective of the increase in density (concentration) of saltwater solution as indicated in Table 10.

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REFERENCES

Cussler, E.L., (1984, 1997). Diffusion: Mass transfer in fluid systems, Cambridge London.

Delleur, J.W. (1999). The handbook of groundwater engineering, CRC Press LL.C

Goswami, R.R and T.P Clement (2007). Laboratory-Scale investigation of saltwater intrusion dynamics. Water Resources Research, Vol. 43.

Nag, P.K. (2008). Heat and mass transfer, published by Tata McGraw-Hill publishing company limited.

Olowofela, J.A. and J.A. Adegoke (2005): Determination of Transition Length in Flow Through Porous Sand Material. Pacific Journal of Science and Technology. 10(2):716-720.

Post, V. And E Abarca (2009). Preface: Saltwater and freshwater interaction in coastal aquifers. Hydrogeology Journal Vol.18:1-4.

Todd, David K. 1960 : "Saltwater intrusion of coastal aquifers in the United States". Subterranean water (IAHS Pul.)(52):pp452-461.

U.S. Geological Survey (USGS) 2000. Groundwater resources for the future Atlantic Coastal Zone

Volker, R.E., Zhang Qi and D.A Lockington (2006). Experimental investigation of contaminant transport in coastal groundwater. Water Resources Research, Vol. 40.

Wolfgang K., (2009). Density flow in groundwater, Institute of Environmental Engineering, ETH Zurich.

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