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Abstract

In many regions coastal aquifers are major source of supply of water to various sectors. However indiscriminate pumping from these aquifers leads to seawater intrusion which is difficult to contain. A numerical model is developed to study two-dimensional steady state seawater intrusion problem involving hydrodynamic dispersion in a synthetic multi-layered confined coastal aquifer. The intrusion model is used to investigate efficacy of seawater control measures involving freshwater recharge wells and combined system of freshwater recharge and saltwater discharge wells. The study found that depth of recharge well, its location from the seashore and well head are important parameters that can control the ingress of the diffused interface. As the recharge wells are located closer to the sea shore, push back effect on the 0.5 isochlor is more pronounced. However, increase in depth of the recharge and discharge well has limited effect. The model study found that a combined recharge-discharge wells system is more effective in controlling seawater intrusion compared to the recharge wells approach.

Introduction

Growing requirement of water in various sectors in the coastal regions is met by withdrawing large quantities of ground water from the aquifers. Indiscriminate excessive withdrawals from the coastal aquifers often lead to the problem of seawater intrusion turning large quantities of fresh water to brackish. The problem may be appreciated from the fact that mixing of seawater even in very small quantities (2 to 3 %) makes freshwater impotable and may lead to the abandonment of the aquifer in some extreme cases. This results in deterioration of ground water quality for domestic, commercial, industrial and agricultural uses. The situation becomes critical when the economy of a coastal region is totally dependent upon the available under ground supplies of freshwater. For these reasons a scientific investigation for sustainable utilization of these aquifers is needed.

In order to assess the contamination and plan the remedial measures, it is necessary to determine the extent to which the ingress of seawater occurs. The resulting salt concentration distribution in the coastal aquifer is also subject to the imposed conditions. A flexible mathematical model capable of predicting saltwater concentration in the aquifer over a wide range of field conditions constitutes an important tool in the groundwater management program of coastal aquifers. In this context the chosen problem examines the influence of freshwater recharge and saline water discharge wells on the movement of diffused sea-fresh water interface for a multilayered confined coastal aquifer.

Many intrusion models are based on Ghyben-Herzberg relationship assuming freshwater and seawater are immiscible and a well defined interface. Since the two fluids are miscible, a sharp interface concept is not realistic especially when thickness of dispersion zone is considerable (Bear, 1979). Presently a synthetic rectangular confined aquifer is considered involving a set of realistic boundary conditions. The simulated steady state solutions are compared with (Henry, 1964), (Pinder and Cooper, 1970) and (Lee and Cheng, 1974) to assess the correctness of the developed algorithm. This is further modified to examine the influence of multilayer coastal aquifer and the spread of diffused interface. The study involves the role of a battery of recharge wells along the seacoast to control seawater intrusion. Further the advantage of coupled freshwater recharge and saline water discharge wells to check the growth of coastal aquifer pollution is also analyzed by adequate modeling of the multilayer coastal aquifer system.

Development of a Numerical Model

Governing Equations

The equations describing steady flow and solute transport in an isotropic porous medium can be written as:

Darcy's Equation:

$$q_i = \frac{-k_{ij}}{\mu} \left[\frac{\partial p}{\partial x_j} + \rho.g.e_j \right] \qquad \ldots(1)$$

Flow Equation:

$$\frac{\partial}{\partial x_i}(\rho q_i) = 0 \qquad \ldots(2)$$

Solute Transport Equation:

$$\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C_i}{\partial x_j}\right) - V_i\frac{\partial C}{\partial x_i} = 0 \qquad \ldots(3)$$

The constitutive equation relating fluid density to concentration is:

$$\boldsymbol{\rho} = \boldsymbol{\rho}_f(1+\boldsymbol{\varepsilon}C) \qquad \ldots(4)$$

where, V_i are the components of the seepage velocity (LT^{-1}), k_{ij} is the intrinsic permeability of the porous medium (L^2), μ is the dynamic viscosity of the fluid ($ML^{-1}T^{-1}$), ρ is the fluid density (ML^{-3}), ρ_f is the fluid density of fresh water (ML^{-3}), p is the fluid pressure ($ML^{-1}T^{-2}$), e_j are the components of the gravitational unit vector (LT^{-2}), D_{ij} is the dispersion coefficient($L^2\,T^{-1}$), C is the concentration of the pollutant (ML^{-3}), g is the acceleration due to gravity vector (LT^{-2}) and $\varepsilon = \frac{\rho_s - \rho_f}{\rho_f}$

On substituting the following

$$h = \frac{p}{\rho_f g} + z \quad ; \qquad \frac{\rho}{\rho_f} - 1 = \rho_r = \varepsilon C \qquad \ldots(5)$$

(where z is the elevation above datum (L) and h is the aquifer head L)

in equation (1) it changes to

$$q_i = -K_{ij}\left[\frac{\partial h}{\partial x_j} + \varepsilon C \;\; e_j\right] \qquad \ldots(6)$$

where, K_{ij} is the hydraluc conductivity tensor (L/T).
Introducing the non-dimensional variables,

$$x' = \frac{x}{d} \;; \qquad z' = \frac{z}{d} \;; \qquad h' = \frac{h}{d} \;; \qquad C' = \frac{C}{C^*} \;;$$

$$K'_{L\,zz} = \frac{K_{zz}}{K_{L\,xx}} \;; \qquad K'_{L\,xx} = \frac{K_{xx}}{K_{L\,xx}} \;; \qquad V'_x = \frac{V_x}{V} \;; \qquad \text{where}$$

$$V'_z = \frac{V_z}{V} \;; \quad \boldsymbol{\alpha}'_T = \frac{\boldsymbol{\alpha}_T}{\boldsymbol{\alpha}_L} \;; \quad \boldsymbol{\alpha}'_L = \frac{\boldsymbol{\alpha}_L}{\boldsymbol{\alpha}_L} = 1 \;\; and \;\; d_L = \frac{d}{\boldsymbol{\alpha}_L}$$

where K_{xx}, K_{zz} - components of hydraulic conductivity tensor in the upper aquifer and

K_{Lxx}, K_{Lzz} - components of hydraulic conductivity tensor in the lower aquifer

Substituting the above in equation (2) and (3) and **dropping the primes** on all the terms in further analysis the dimensional less form of these equations can be gives as

$$K_{L\,xx}\frac{\partial^2 h}{\partial x^2} + K_{L\,zz}\frac{\partial^2 h}{\partial z^2} = -K_{L\,zz}\,\varepsilon\frac{\partial C}{\partial z} \qquad \ldots(7)$$

The average linear velocity (i.e. V_x and V_z) in non-dimensional form for two dimensional (x-z) coordinate system can be written as;

$$V_x = -\frac{A}{\theta}K_{L\,xx}\left(\frac{\partial h}{\partial x}\right) \qquad \ldots(8)$$

$$V_z = -\frac{A}{\theta}K_{L\,zz}\left(\frac{\partial h}{\partial z} + \varepsilon C\right) \qquad \ldots(9)$$

where $V_i = \frac{K_{L\,ii}}{A}, \frac{1}{A}$ is piezometric head gradient and θ is the porosity.

The transport equation can be given as

$$D_{xx}\frac{\partial^2 C}{\partial x^2} + D_{zz}\frac{\partial^2 C}{\partial z^2} + D_{xz}\frac{\partial^2 C}{\partial x \partial z} + D_{zx}\frac{\partial^2 C}{\partial z \partial x} - \left(V_x\frac{\partial C}{\partial x} + V_z\frac{\partial C}{\partial z}\right)d_L = 0 \qquad \ldots(10)$$

where d is the depth of confined coastal aquifer, C^* is seawater concentration, α_L and α_T are longitudinal and transverse dispersivity of medium respectively, V is the average linear velocity,

K_{Lxx} and K_{Lzz} are non-dimensional hydraulic conductivities along x and z direction respectively, and, D_{ij} is the dispersion tensor, whose terms in non-dimensional form are defined in two-dimensional co-ordinate (x-z) system as:

$$D_{xx} = \frac{V_x^2}{|V|} + \alpha_T \frac{V_z^2}{|V|}$$

$$D_{zz} = \frac{V_z^2}{|V|} + \alpha_T \frac{V_x^2}{|V|}$$

$$D_{xz} = D_{zx} = (1-\alpha_T)\frac{V_x V_z}{|V|} \quad \ldots(11)$$

Thus the equations (7), (8), (9) and (10) are Governing Equations in non-dimensional form. The advantage of writing equations in this form is that the solutions are directly obtained in terms of solute (chloride) concentration.

Solution Domain, Initial and Boundary Conditions

Solution Domain

The rectangular two-dimensional vertical cross-section of length L and depth d of confined coastal aquifer is divided into three layers, where the low hydraulic conductivity layer is sandwiched between two highly permeable layers. The L / d ratio for domain is 2:1. The low hydraulic conductivity layer extends between z = 0.25d to 0.5d, in which flow can be considered to be vertical as shown in **Figure-1.**

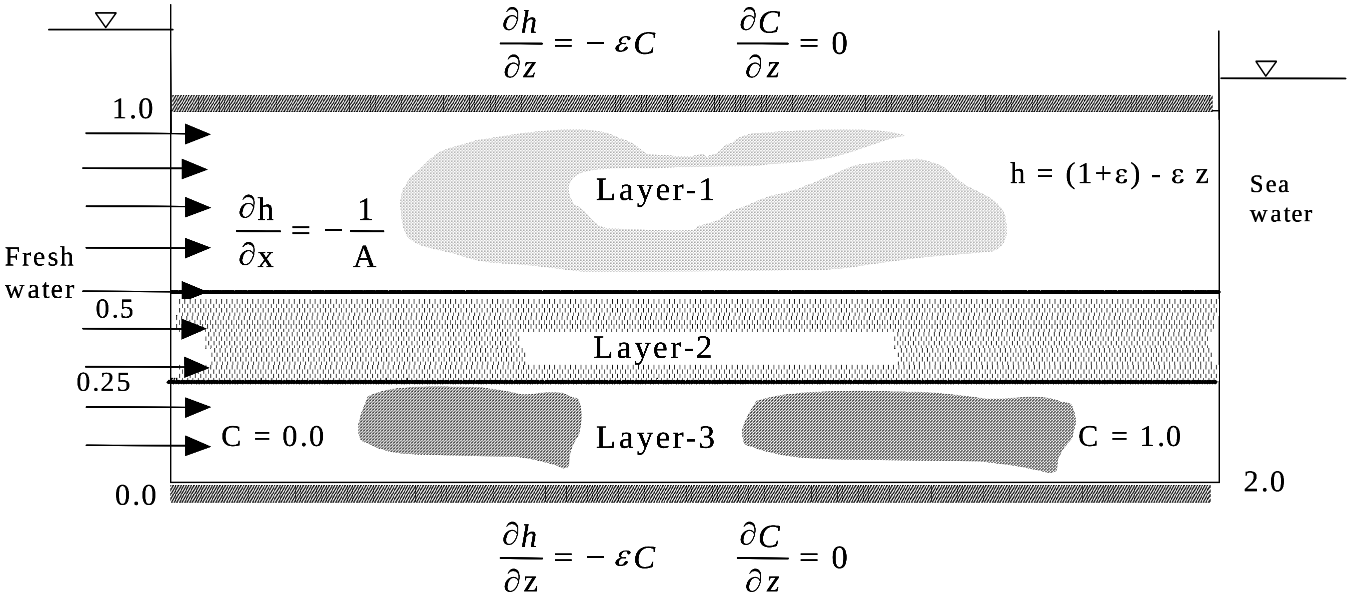

Figure 1 Definition sketch and boundary conditions

Initial Conditions

1) C = 0.0 on the upstream boundary where freshwater is flowing into the aquifer.

2) C = 1.0 on seaward boundary.

3) Initially the aquifer is assumed to contain freshwater (i.e. C = 0.0) everywhere in the aquifer.

Boundary Conditions

Boundary conditions are shown in **Figure-1** and imposed boundary conditions of seawater control measures are shown in **Figure-2.** Mathematically these can be given as

Coordinates	**For h**	**For C**
Landward side (0,z)	$\frac{\partial h}{\partial x}(0,z) = -\frac{1}{A}$	C (0,z) = 0.0
Seaward side (2,z)	h (L, z) = [(1+ϵ) – ϵz]	C (L, z) = 1.0
Bottom Boundary (x,0)	$\frac{\partial h}{\partial z}(x,0) = -\varepsilon C$	$\frac{\partial C}{\partial z}(x,0) = 0.0$
Upper Boundary (x,1)	$\frac{\partial h}{\partial z}(x,d) = -\varepsilon C$	$\frac{\partial C}{\partial z}(x,d) = 0.0$

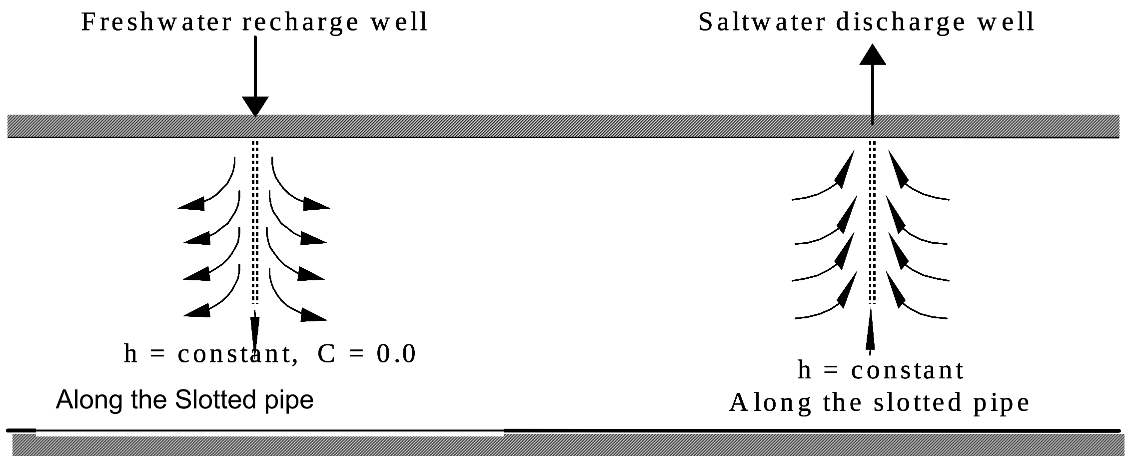

Figure 2. Boundary conditions for control measures

Finite Element Formulation

The solution to the flow and solute transport equations with appropriate boundary conditions is obtained by the finite element method using Galerkin's approach. Triangular elements are used with linear interpolation functions, which define the variation of hydraulic head and salt concentration within an element in terms of their nodal values. Presently the entire flow region is divided in 256 elements and 153 nodes.

In case of linear triangular element the field variables h and C are given as:

$$h(x,z) = N_i h_i + N_j h_j + N_k h_k$$
$$C(x,z) = N_i C_i + N_j C_j + N_k C_k \qquad ...(12)$$

where N_i, N_j and N_k are the interpolation functions for the three nodes of an element.

Applying Galerkin's approach and Green's Theorem, equation (7) becomes,

$$\int_A K_{L\,xx} \frac{\partial\{N\}}{\partial x} \frac{\partial[N]}{\partial x} \{h\} \; dA + K_{L\,zz} \int_A \frac{\partial\{N\}}{\partial z} \frac{\partial[N]}{\partial z} \{h\} \; dA$$

$$= \boldsymbol{\varepsilon}.K_{L\,zz} \int_A \{N\} \frac{\partial[N]}{\partial z} \{C\} dA + \int_S \{N\} \left(K_{L\,xx} \frac{\partial h}{\partial x} n_x + K_{L\,zz} \frac{\partial h}{\partial z} n_z \right) ds \quad ...(13)$$

After simplifying, the above equation in matrix form can be written as

$$[K_3]\{h\} = \boldsymbol{\varepsilon}.K_{L\,zz}[R]\{C\} + \{Bh_3\} \quad ....(14)$$

Applying Galerkin's approach and Green's Theorem, equation (8) becomes,

$$\int_A \left(D_{xx} \frac{\partial\{N\}}{\partial x} . \frac{\partial[N]}{\partial x} .\{C\} + D_{zz} \frac{\partial\{N\}}{\partial z} . \frac{\partial[N]}{\partial z} .\{C\} + D_{xz} \frac{\partial\{N\}}{\partial x} . \frac{\partial[N]}{\partial z} .\{C\} \right.$$

$$\left. + D_{zx} \frac{\partial\{N\}}{\partial z} . \frac{\partial[N]}{\partial x} .\{C\} + d_L \{N\} V_x \frac{\partial[N]}{\partial x} \{C\} + d_L \{N\} V_z \frac{\partial[N]}{\partial z} \{C\} \right) dA$$

$$= \int_S (D_{xx} \frac{\partial C}{\partial x} n_x + D_{zz} \frac{\partial C}{\partial z} n_z + D_{xz} \frac{\partial C}{\partial x} n_x + D_{zx} \frac{\partial C}{\partial x} n_z) \{N\} \; ds \quad ...(15)$$

After simplifying the above equation can be written in matrix form as,

$$[\mathrm{K}_4] \; \{\mathrm{C}\} = \{\mathrm{Bc}\} \quad ...(16)$$

Discretising equation (10) and applying Galerkin's approach, we get

$$\int_A \{N\} \left[V_x + \frac{A}{\boldsymbol{\theta}} K_{L\,xx} \frac{\partial h}{\partial x} \right] dA = 0 \quad ...(17)$$

The above equation can be written in matrix form as,

$$[\mathrm{M}]\{\mathrm{V_x}\} = \{\mathrm{F_1}\} \quad ...(18)$$

Similarly discretising equation (11) and applying Galerkin's approach, we get

$$\int_A \{N\}\left[V_z + \frac{A}{\boldsymbol{\theta}} K_{L\,zz}\left(\frac{\partial h}{\partial z} + \boldsymbol{\varepsilon}\, C\right)\right] \; dA \;=\; 0 \qquad \ldots(19)$$

The above equation can be written in matrix form as,

$$[\mathrm{M}]\{\mathrm{V_z}\} = \{\mathrm{E_1}\} \qquad \ldots(20)$$

where $[K_3]$, $[K_4]$ and [M] are coefficient matrices and, [R] {C}, $\{Bh_3\}$, {Bc}, $\{F_1\}$, $\{E_1\}$ are column vectors containing boundary conditions.

Results and Discussion

Equation (14) is solved for nodal values of head, assuming initial salt concentration (C = 0.0) distribution in the aquifer. The velocity vector distribution can be obtained by equation (18) and (20) utilizing the head values obtained earlier. Following this the equation (16) is solved for nodal concentration values using the velocity vectors and dispersion coefficients defined by equation (9). The concentration values obtained are substituted in the equation (14) and this iterative cycle is repeated until a predetermined level of accuracy (specified tolerance limit = 0.01) is attained. Gaussian elimination method is used to solve the equations simultaneously. Solution to the seawater intrusion problem is obtained by Head Concentration (h-c) formulation with velocity dependent dispersion process. The dispersion coefficients are considered velocity dependent. In further discussion, seawater wedge is chosen to be represented by an ($C/C^* = 0.5$) isochlor, which is an approach adopted by (Pandit and Anand, 1984) and (Das and Datta, 1999) among others. For the present model Peclet and Courant numbers are kept under 2 for numerical stability.

First, for the homogenous isotropic single layer confined aquifer the results are compared with some known solutions. **Figure-3** illustrates the comparison of positions of 0.5 isochlor obtained by the present model with the solution of (Henry, 1964), (Lee and Cheng, 1974) and (Pinder and Cooper, 1970). The present results match nicely with the existing solutions. However, the position of 0.5 isochlor is shifted towards landward side as compared to the existing solutions though the shape of the interface is S type and similar to the known shapes. This can be attributed to indicate that intrusion at the bottom of aquifer is more and relatively less at the top. The shift of seawater wedge towards landward side may be because of the velocity dependent dispersion effects, whereas in the previous models the dispersion coefficient is considered a fixed value independent of the velocity.

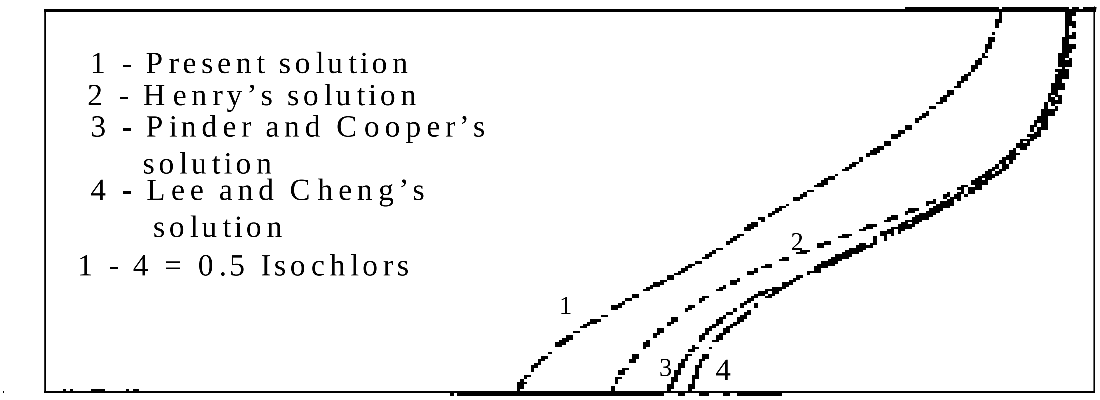

Figure 3 . Comparison of positions of different 0.5 isochlors

Efficacy of Seawater Intrusion Control Measures

To examine the spread of 0.5 isochlor interface in the multilayer coastal aquifer, the same region is divided in three layers, where the low hydraulic conductivity layer is sand witched between two highly permeable aquifer zones. **Figure-1** shows the definition sketch and boundary conditions for this case. The h-c model developed presently is used to investigate the efficacy of the following control measures for the retardation of seawater intrusion in the multi-layered confined coastal aquifer.

1) Battery of closely spaced freshwater recharge wells parallel to the coast. For this following specific cases are examined.

1-a Recharge wells at varying locations from the seashore with constant head and constant depth

1-b Recharge wells at specific location from the seashore with varying depth and constant head

1-c Recharge wells at specific location from the seashore with constant depth and varied head.

2) Combination of battery of freshwater recharge wells and saline water discharge wells.

Battery of Closely Spaced Freshwater Recharge Wells Parallel to the Coast

The simulation of recharge wells is based on the head distribution along the proposed alignment of the well in the aquifer at a specific section upto a proposed depth of the well strainer. The well is simulated by applying constant head condition at the nodes corresponding to the penetration of the well in the aquifers. It is shown in **Figure-2** for both the types of wells. To function as recharge well, the head imposed on the well is kept marginally higher than the head along the column in the aquifer where the well is installed. The recharge well causes increase of aquifer head in the flow domain. Therefore h_r = 1.050 corresponds to a definite increase of head in comparison to the recharge head conditions in the system. The build up head (cone of impression) at the recharge well is as shown in **Figure-4**.

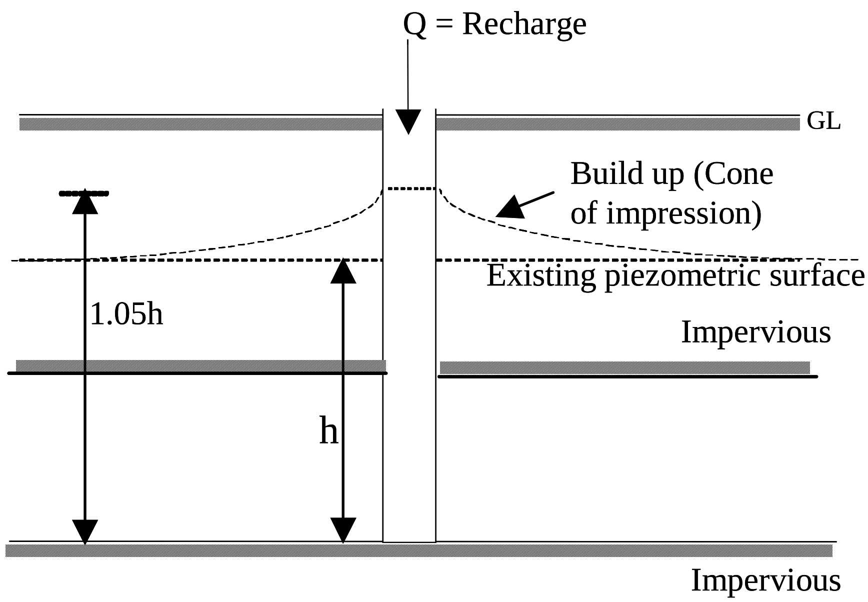

Figure 4 . Schematic diagram showing cone of impression for the recharge well

The battery has a specific number of wells equally spaced and located along a line normal to the direction of the natural groundwater flow and parallel to the shoreline. Closely spaced wells imply the flow to be two-dimensional and can be considered equivalent to a line source. The salt concentration distribution is obtained for the set of field parameters, A = 200, θ = 0.4, α_T = 0.1, K_{Lx1} = 1.0, K_{Lx2} = 0.001, K_{Lx3} = 1.0, K_{Lz1} = 1.0, K_{Lz2} = 1.0, K_{Lz3} = 1.0 and d_L = 2.0 for the presently considered synthetic confined aquifer. This simulation is utilised to study the effect of battery of freshwater recharge wells on retardation of seawater intrusion with the imposed boundary conditions as shown in **Figure-2**.

Recharge wells at varying locations from the seashore with constant head and constant depth

This case is illustrated in **Figure-5-a** and **Figure-5-b** for the data as shown in **Table-1.**

Table-1 Parametric data considered to study the effect of location of recharge well system for constant depth and head.

A = 200, K_{Lx1} = 1.0, K_{Lx2} = 0.001, K_{Lx3} = 1.0, K_{Lz1} = 1.0, K_{Lz2} = 1.0, K_{Lz3} = 1.0 α_T = 0.1 d_L = 2.0, θ = 0.4		
Depth = d_1 / d	Location = x / L	Recharge head (h_r)
0.375 and 0.75	0.250	1.050
	0.375	
	0.50	
	0.625	
	0.6875	
	0.750	
	0.8125	
	0.875	
	0.9375	

The battery of freshwater recharge wells is placed at several locations parallel to the coast at a distance from freshwater face (x/L) from 0.25 to 0.9375. The recharge well head is simulated by applying the head for a depth of well = 0.375d or 0.75d equal to 1.050 times the head computed in absence of recharge well. The influence of various locations of freshwater recharge wells for constant recharge head for two different depths on the retardation of the (0.5 isochlor) diffused interface is shown in **Figure-5-a** and **5-b.**

The seawater wedge continues to retreat back seawards, as the recharge well gets closer to the seaward side. This recession is particularly more rapid in layer-1 [refer **Figure-5-a**] for the depth of the recharge well = 0.375d, compared to layer-3. For the well locations greater than x/L =

0.875 from the freshwater face in the first layer the interface is nearly vertical whereas it slants steeply in the layer-3. This may be because of the fact that depth of penetration of recharge well lies in layer-1 and therefore pushback effect is minimum at the aquifer bottom. Due to vertical flow across the aquitard from the bottom layer (as the pumping is done from the top layer) where intrusion effect is more pronounced, the interface spreads in the low hydraulic conductivity second layer as compared to the top layer. As expected this rate of recession is rapid and uniform [refer **Figure-5-b**] in all the layers as the well penetrates upto top of layer-3. As the freshwater is recharged, there is a fall of the depth to the interface from the aquifer top causing a push back effect in the dynamic equilibrium for the steady state flow conditions in the aquifer domain. The presence of lower conductivity layer-2 causes substantiate reduction to the flow of freshwater from recharge wells to layer-3, consequently reducing the rate of retardation of seawater wedge in layer-3. Due to decreased recharge water velocity in layer 2 there is landward bulge in the interface in this layer.

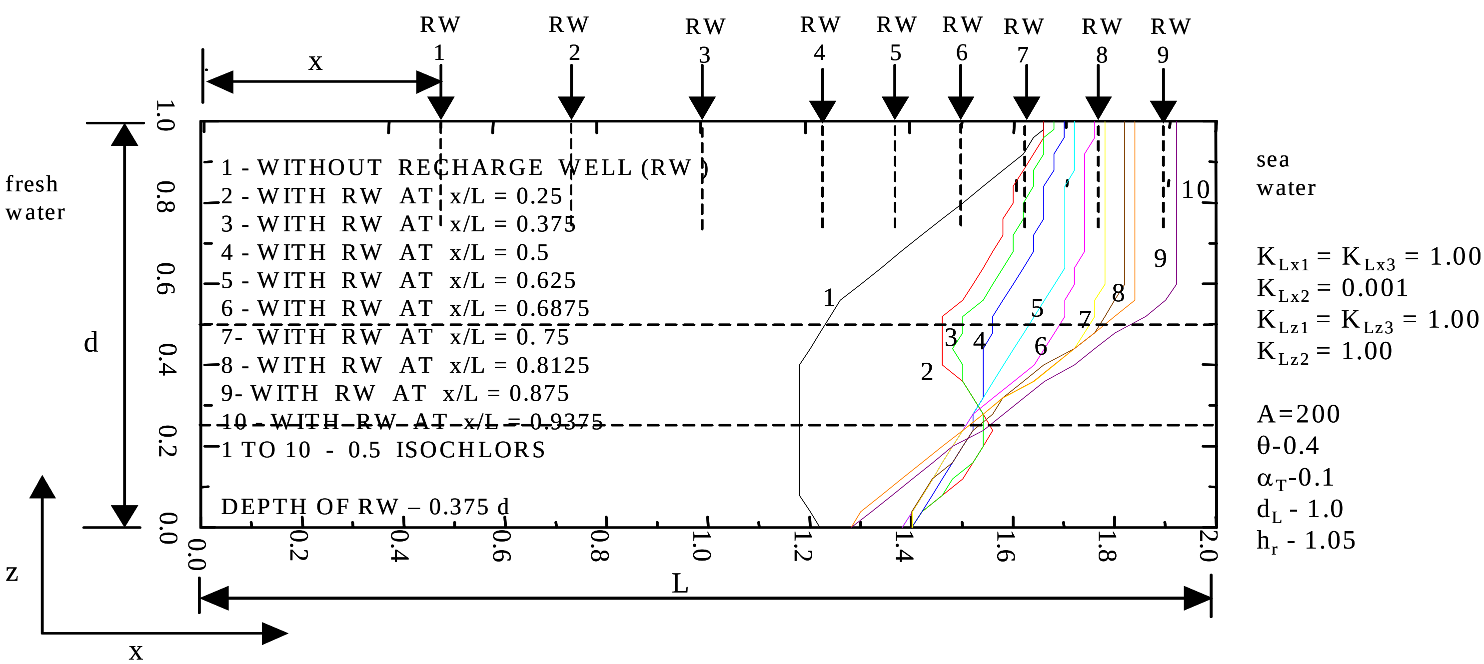

Figure 5 - a . Efficacy of battery of recharge wells at various locations on seawater intrusion control

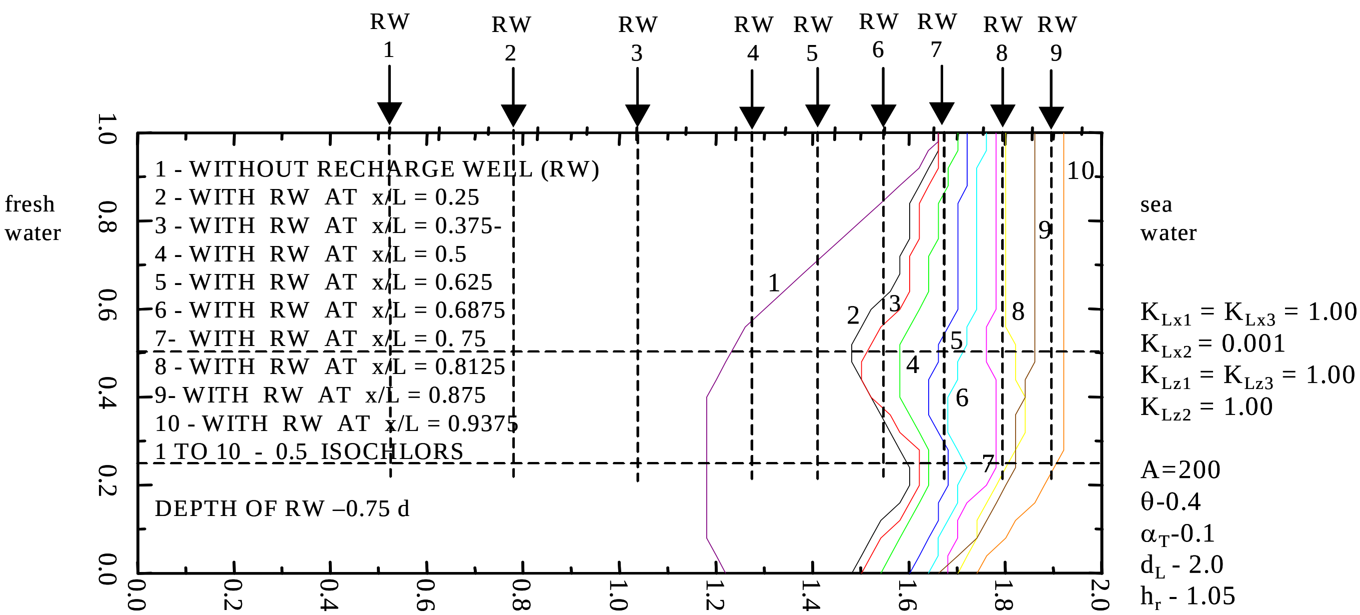

Figure 5 - b . Efficacy of battery of recharge wells at various locations on seawater intrusion control

Thus it is observed that the seaward location of recharge wells penetrating in both the aquifer layers is more effective in controlling intrusion than the landward location for a constant recharge head at the well. However from practical consideration it can be stated that after x/L = 0.5, seaward push of the interface is much less significant. Therefore this can be taken as a desirable distance from the seashore for locating the recharge wells.

Recharge wells at specific locations from the seashore with varying depth and constant head

This is illustrated in **Figure 6 a-d** for the data in **Table-2** The influence of depth of freshwater recharge well on seawater intrusion when wells are shifted from x/L = 0.25 to 0.875 is illustrated in **Figure-6 a-d.** Here it is observed that for a specific location, when depth of penetration is increased the seawater retreats back to seaward side. When well penetrates in the region of layer-1 (i.e. depth = 0.25 and 0.375) the 0.5 isochlor recedes back seaward in all the layers, but

Table-2 Parametric data considered to study the effect of recharge well at specific location with varying depth and constant head

A = 200 , K_{Lx1} = 1.0, K_{Lx2} = 0.001, K_{Lx3} = 1.0, K_{Lz1} = 1.0, K_{Lz2} = 1.0, K_{Lz3} = 1.0 α_T = 0.1 d_L = 2.0 θ = 0.4, h_r = 1.50							
Well location = x / L	Depth of well = d_1/d	Well location = x / L	Depth of well = d_1/d	Well location = x / L	Depth of well = d_1/d	Well location = x / L	Depth of well = d_1/d
	0.25		0.25		0.25		0.25
0.25	0.375	0.5	0.375	0.75	0.375	0.875	0.375
	0.75		0.75		0.75		0.75

the effect is more pronounced in layer-1. This may be because of the presence of layer-2, which obstructs the recharging of layer-3 compared to layer-1. Whereas when well penetrates upto layer-3 (i.e. depth = 0.75d) the 0.5 isochlor shifts towards seaward side by same the amount in all the three layers, as all the aquifer layers are recharged by freshwater.

It is thus inferred that the depth of the well at a specific location has definite influence in the retardation of seawater intrusion. Particularly it is more for higher depths with seaward location of freshwater recharge wells. It may be noted here that from the practical point of view, a small backward push seaward is equivalent to clearing a large aquifer area from contamination.

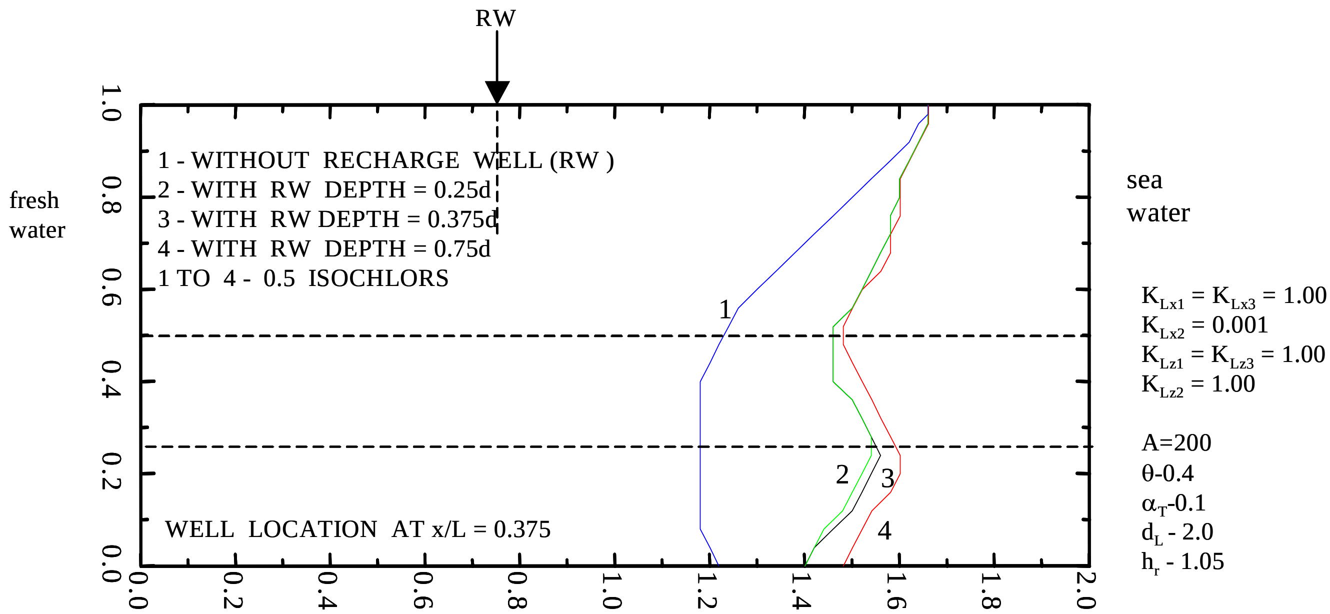

Figure 6-a . Effect of depth of recharge well on intrusion control

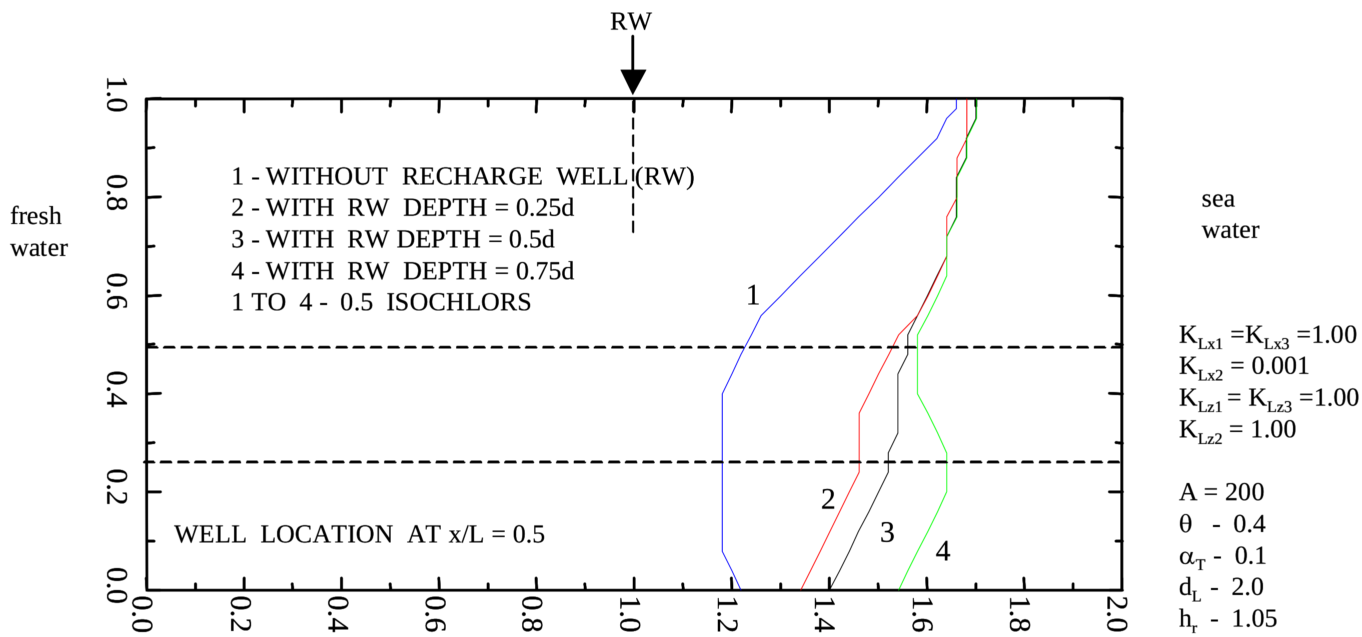

Figure 6-b . Effect of depth of recharge well on intrusion control

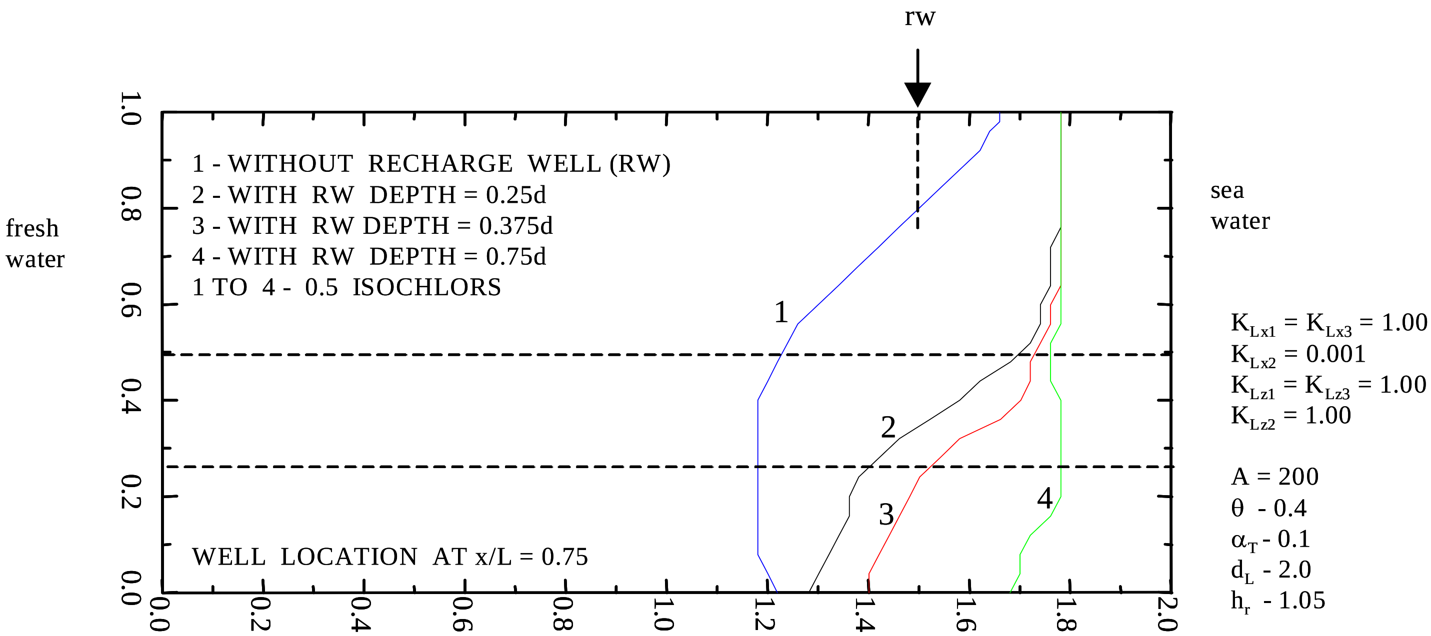

Figure 6-c . Effect of depth of recharge well on intrusion control

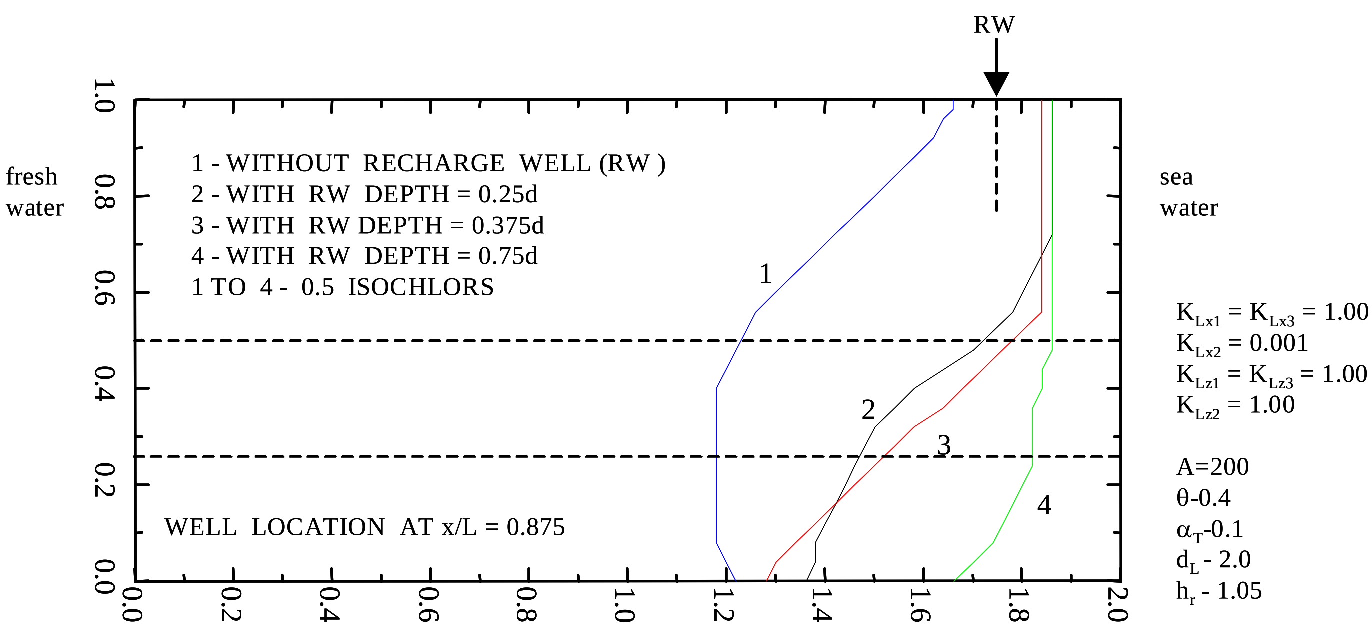

Figure 6-d . Effect of depth of recharge well on intrusion control

Recharge wells at specific locations from the seashore with constant depth and varied head

From the practical consideration increasing recharge head is equivalent to increasing the freshwater recharge rate in the coastal aquifers. The recharge water can normally be the treated municipal wastewater, which is available on a regular basis.

Data in **Table – 3** is used to illustrate the effect of recharge wells at specific location with constant depth and varied head.

Table – 3 Parametric data considered to study the effect of recharge wells at specific location with constant depth and varied head.

A = 200, K_{Lx1} = 1.0, K_{Lx2} = 0.001, K_{Lx3} = 1.0, K_{Lz1} = 1.0, K_{Lz2} = 1.0, K_{Lz3} = 1.0 α_T = 0.1, d_L = 2.0, θ = 0.4, **Depth of well = 0.375 d and 0.75d**							
Well location = x / L	Varied recharge head (hr)	Well location = x / L	Varied recharge head (hr)	Well location = x / L	Varied recharge head (hr)	Well location = x / L	Varied recharge head (hr)
0.25	1.025	0.5	1.025	0.75	1.025	0.875	1.025
	1.050		1.050		1.050		1.050
	1.075		1.075		1.075		1.075
	1.100		1.100		1.100		1.100
	1.500		1.500		1.500		1.500

Figure-7 a-d illustrates the effect of varied recharge head for different specific locations, x/L = 0.25 to 0.875 for depth of well = 0.375d. From these Figures it can be observed that retardation effect of 0.5 isochlor in all layers is nearly the same for x/L = 0.25 to 0.5 for a varied recharge head, h_r = 1.025 to 1.50 and for depth of well = 0.375d. For x / L **=** 0.75 and higher, 0.5 isochlor recedes back more in layer-1 and intrudes more in layer-3, particularly at the bottom of it. This is because the freshwater is recharged in layer-1 and percolates less in layer-3.

A better trend of 0.5 isochlor is observed in **Figure-7 e-h** when the depth of well is increased to 0.75d and the recharge head is varied from 1.025 to 1.50. For this case as freshwater is recharged to all the three layers for all locations of recharge wells, it is observed that with higher heads and seaward locations of recharge wells, seawater intrusion is controlled more effectively.

From the above Figures it can be concluded that as the well head increases the seawater intrusion is retarded since increase in head also implies increase in the well recharge.

It can therefore be concluded that freshwater recharge wells with higher depth, higher recharge head and seaward location has pronouncing effect on seawater intrusion control.

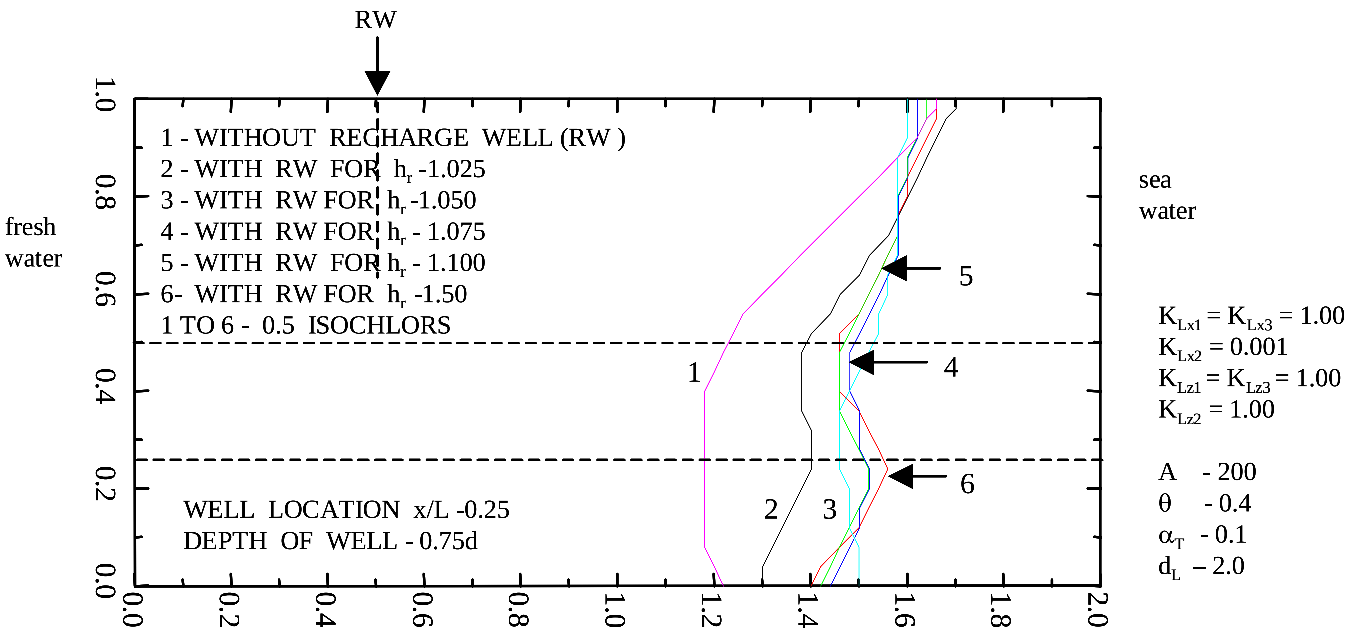

Figure 7- a . Effect of varied recharge head on seawater intrusion control

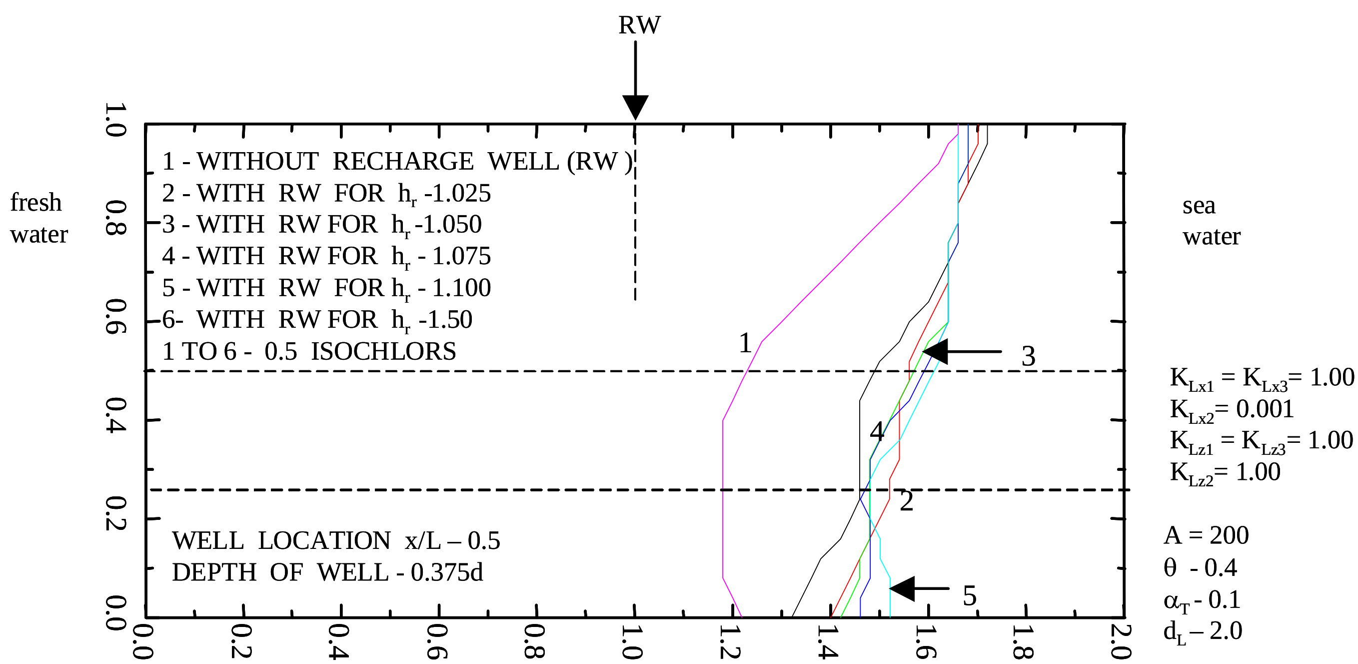

Figure 7- b . Effect of varied recharge head on seawater intrusion control

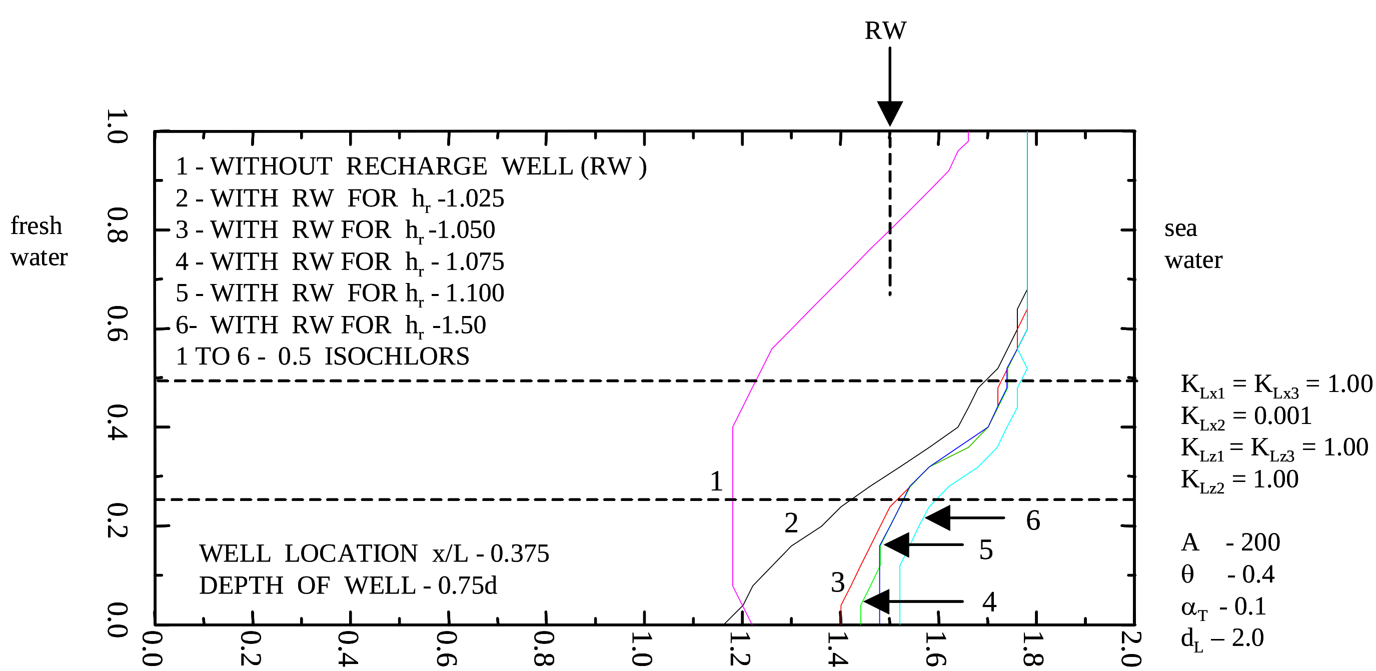

Figure 7- c . Effect of varied recharge head on seawater intrusion control

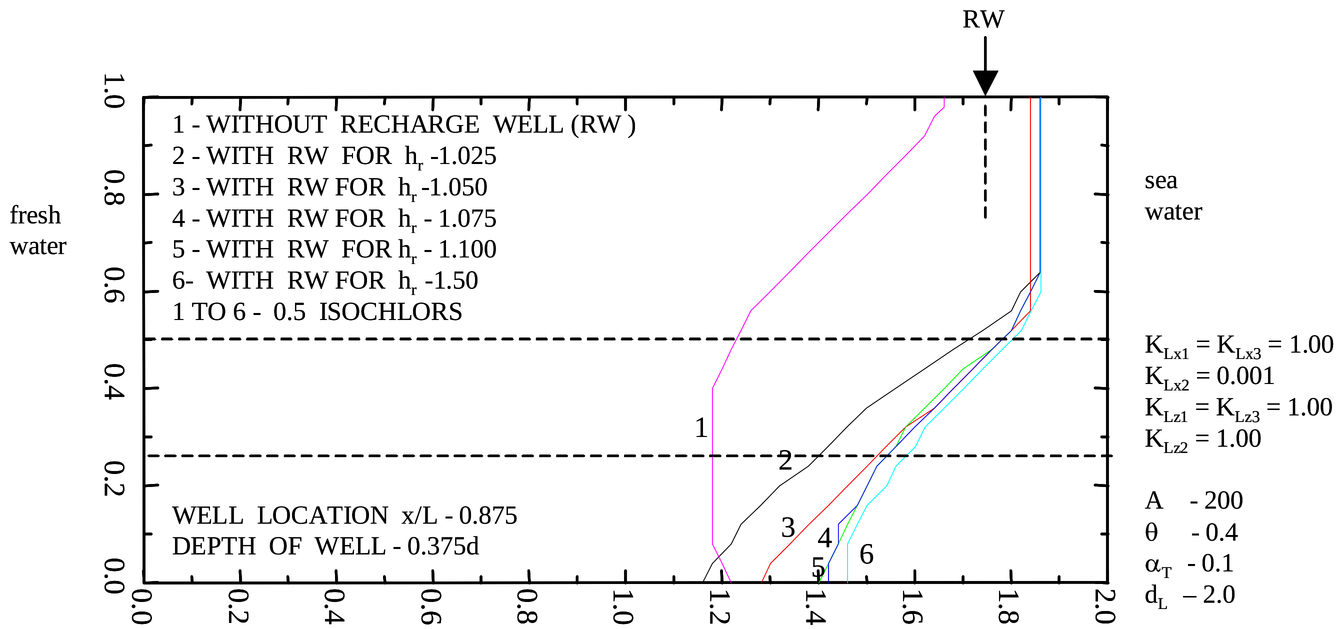

Figure 7- d . Effect of varied recharge head on seawater intrusion control

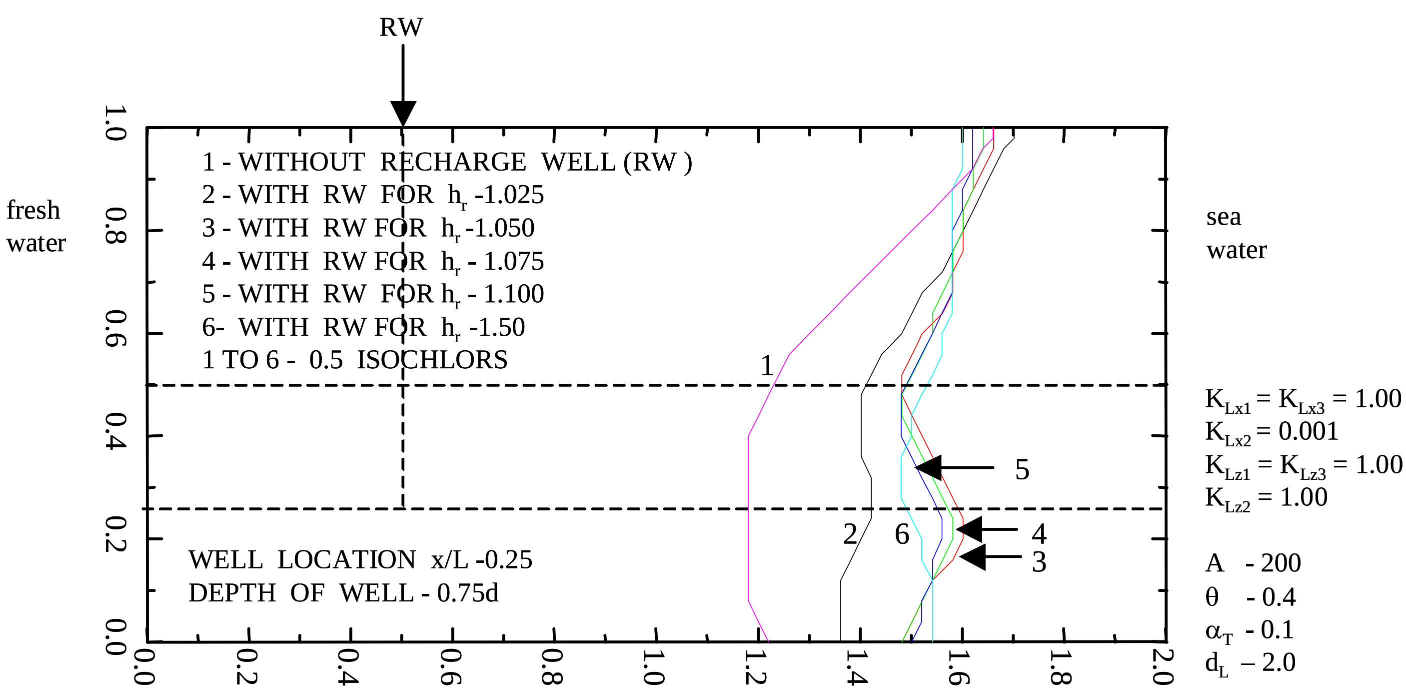

Figure 7- e . Effect of varied recharge head on seawater intrusion control

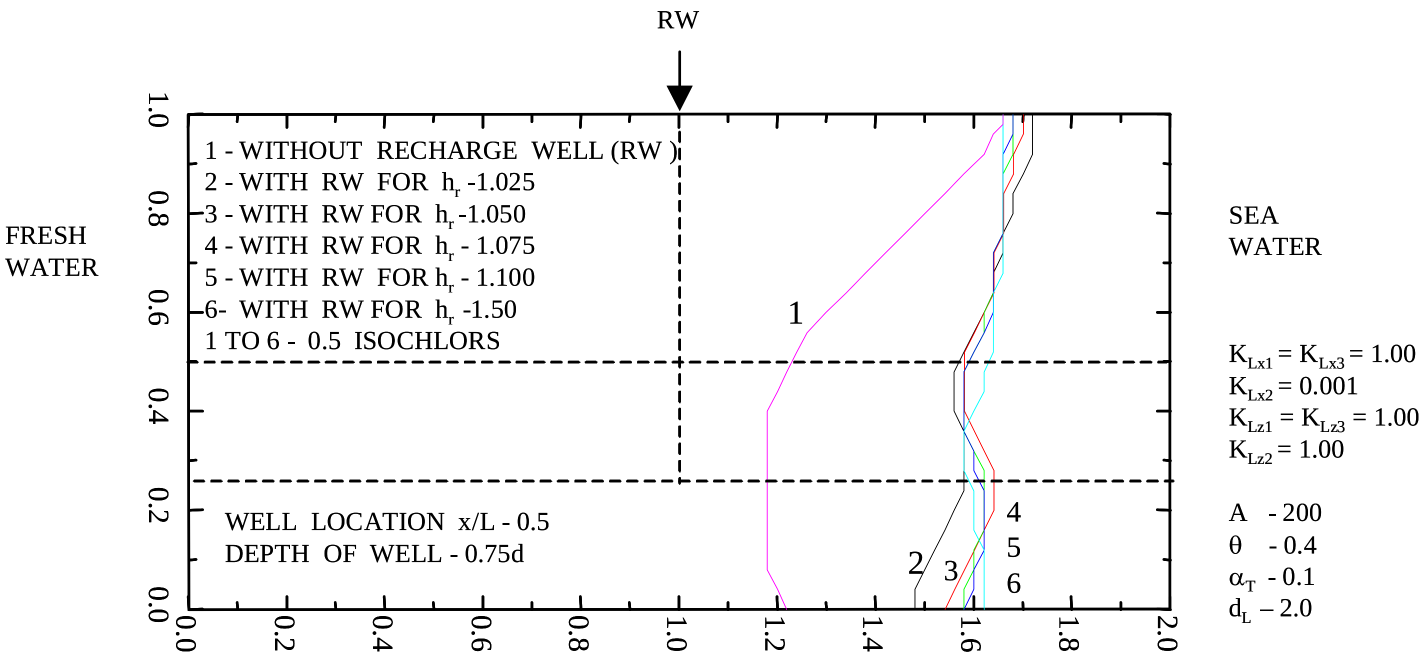

Figure 7- f . Effect of varied recharge head on seawater intrusion control

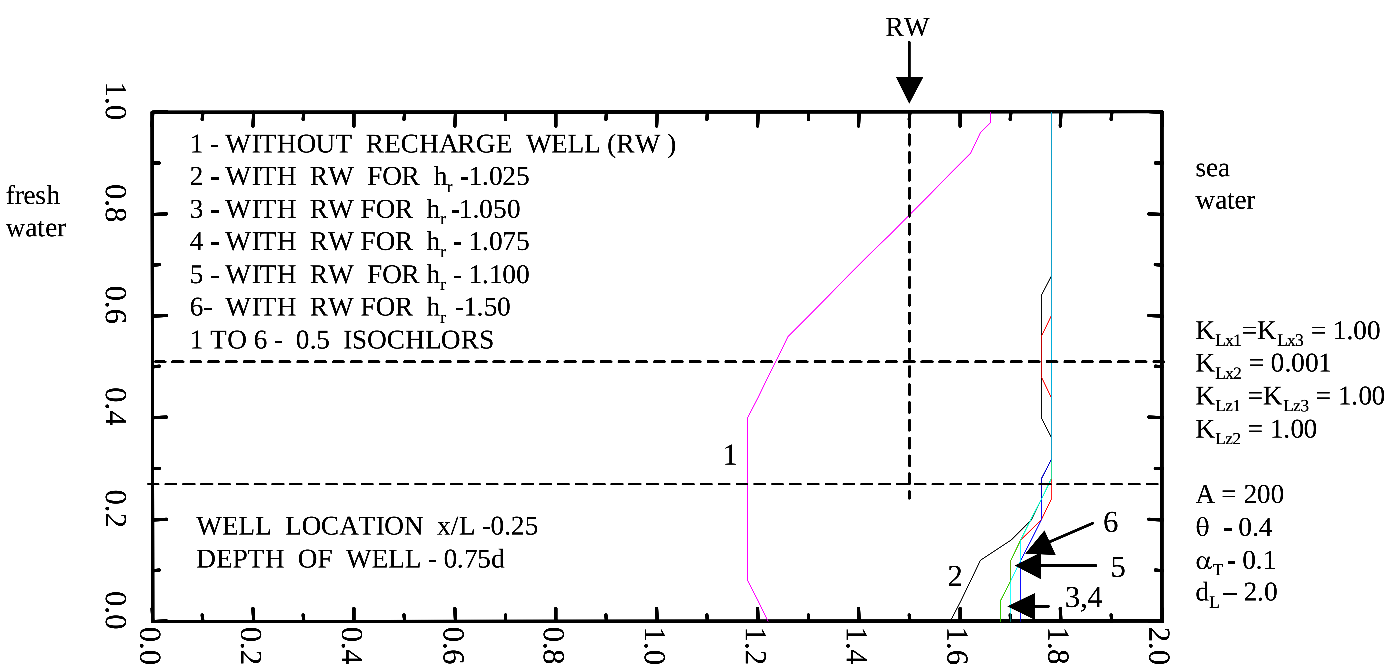

Figure 7- g . Effect of varied recharge head on seawater intrusion control

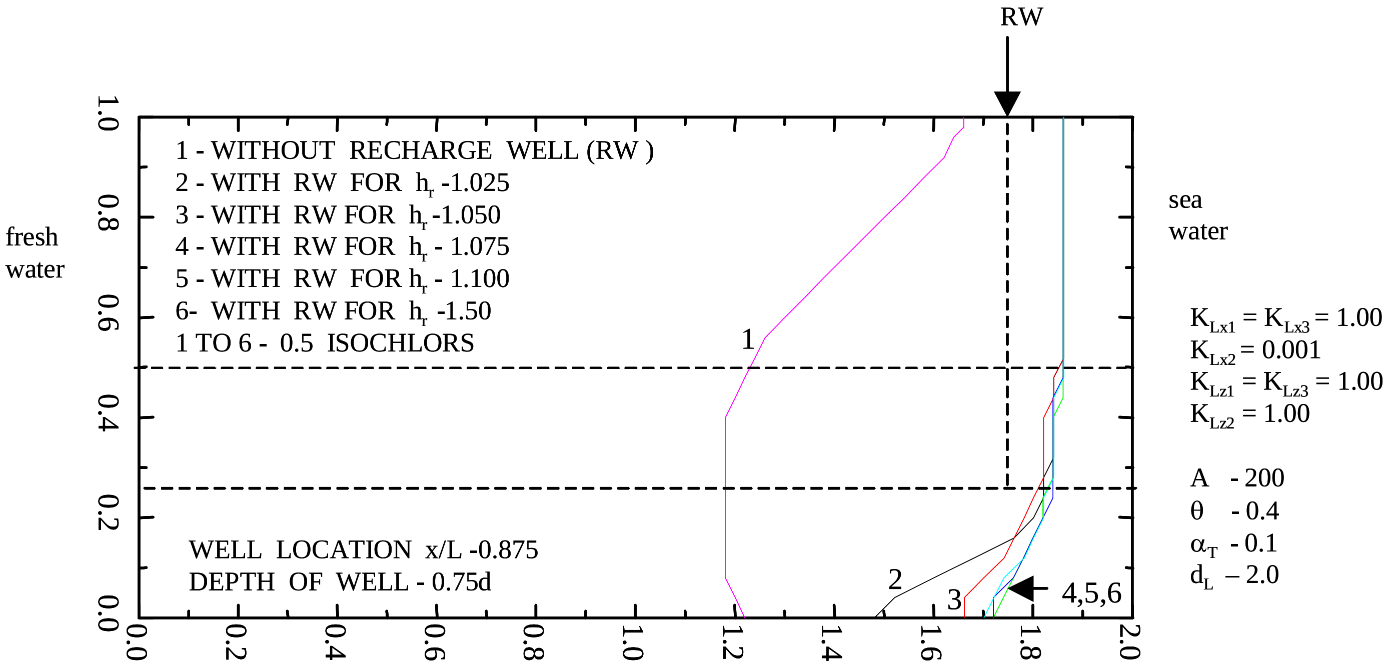

Figure 7- h . Effect of varied recharge head on seawater intrusion control

However, this practice may have limitations from practical point of view since a continuous increase of recharge head requires additional freshwater supply and increased pumping power with large diameter well. Therefore this option may have financial constraint as also the availability of freshwater supply in some cases.

Effect of Combined System of Wells on Seawater Intrusion

The recharge well causes increase of aquifer head in the flow domain. Therefore h_r = 1.050 corresponds to a definite increase of head in comparison to the recharge head conditions in the system. Whereas, discharge head causes decrease of aquifer head in the flow domain. Therefore h_d = 1.0 or 0.8 corresponds to a definite lowering of head in comparison to the recharge head conditions in the system. The cone of depression at the discharge well is as shown in the **Figure-8**.

For this analysis a series of saline water discharge and freshwater recharge wells were considered at varies locations of the coastal aquifer. The study is being conducted to ascertain the best combined system of locations of recharge and discharge wells. Knowing the best locations for both types of wells, it should be possible to verify the influence of varied recharge and discharge heads, and depth of wells.

From the analysis of movement of 0.5 isochlor it can be inferred that best combined system of wells is freshwater recharge well at x/L = 0.75 and saltwater discharge well at x/L = 0.9375. For this location seawater recedes back towards shoreline without extraction of freshwater by discharge wells, which is recharged by recharge wells.

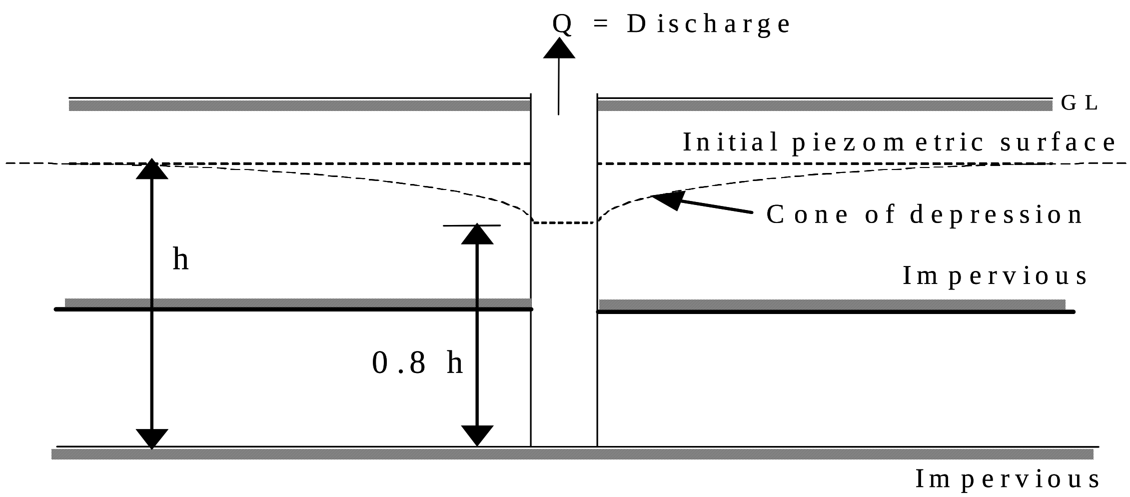

Figure 8. Schematic diagram showing cone of depression for the discharge well

Combined system of wells at specific locations with varied recharge head and constant discharge head

For the locations of freshwater recharge and saline water discharge wells at x/L = 0.75 and x/L = 0.9375 respectively with depth equal to 0.375d, the 0.5 isochlor recedes back considerably towards seaside, when recharge head h_r is varied from 1.025 to 2.0 for the data given in **Table - 4** and as depicted in **Figure-9-a**.

Table – 4 Parametric data considered to study effect of specific locations of combined system of wells with varied recharge head and constant discharge head.

A = 200, K_{Lx1} = 1.0, K_{Lx2} = 0.001, K_{Lx3} = 1.0, K_{Lz1} = 1.0, K_{Lz2} = 1.0, K_{Lz3} = 1.0 α_T = 0.1, d_L = 2.0 θ = 0.4, **h_d = 1.00**			
Depth of well	**Well location = x / L**		**Varied recharge head**
(d_1 / d)	Recharge well	Discharge well	**(h_r)**
0.375 and 0.75	0.75	0.9375	1.025
			1.050
			1.075
			1.100
			1.50
			2.00

This recession is more in layer-1. The ratio of the constant discharge head h_d is maintained equal to 1.0. The recharge well causes increase of aquifer head in the flow domain. Therefore h_d=1.0 corresponds to a definite lowering of head in comparison to the recharge head conditions in the system.

Figure-9-b shows the higher recession of saltwater wedge in all layers for increase in depth of wells to 0.75d for other data being same. Thus it can be concluded, that the recharge head at the recharge well in a combined system of wells has a considerable influence in the retardation of seawater intrusion.

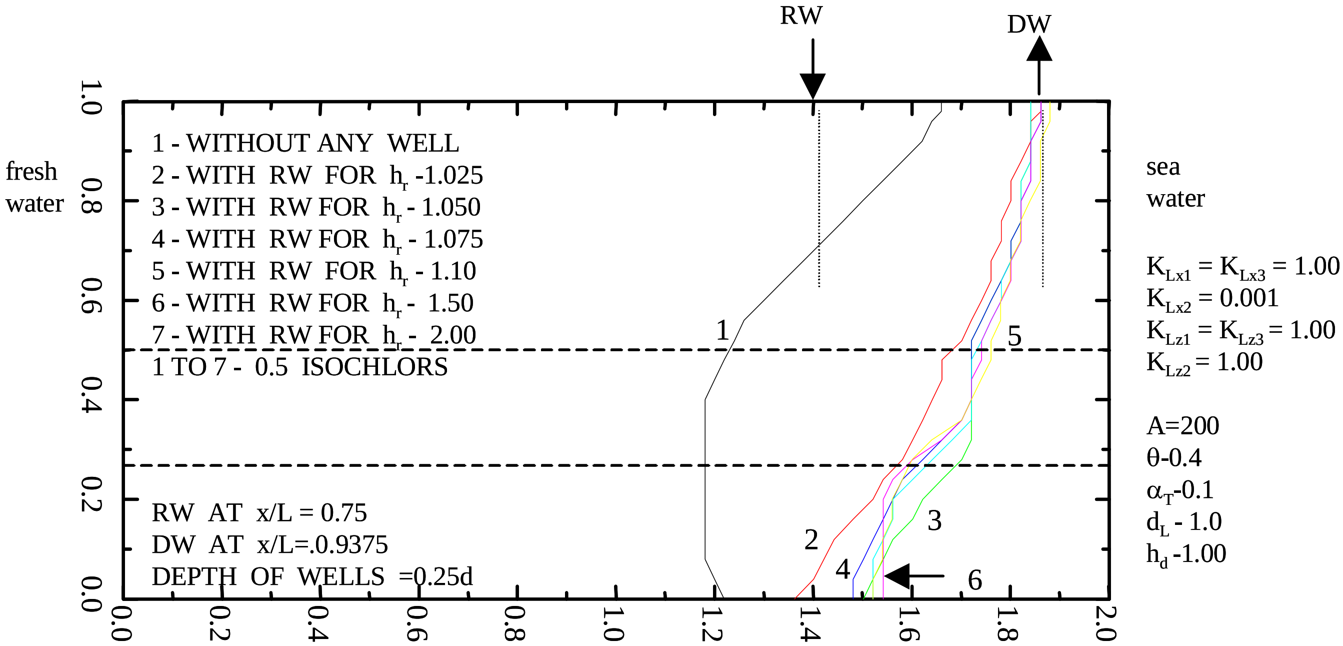

Figure 9-a . Effect of varied recharge head and constant discharge head on seawater intrusion control

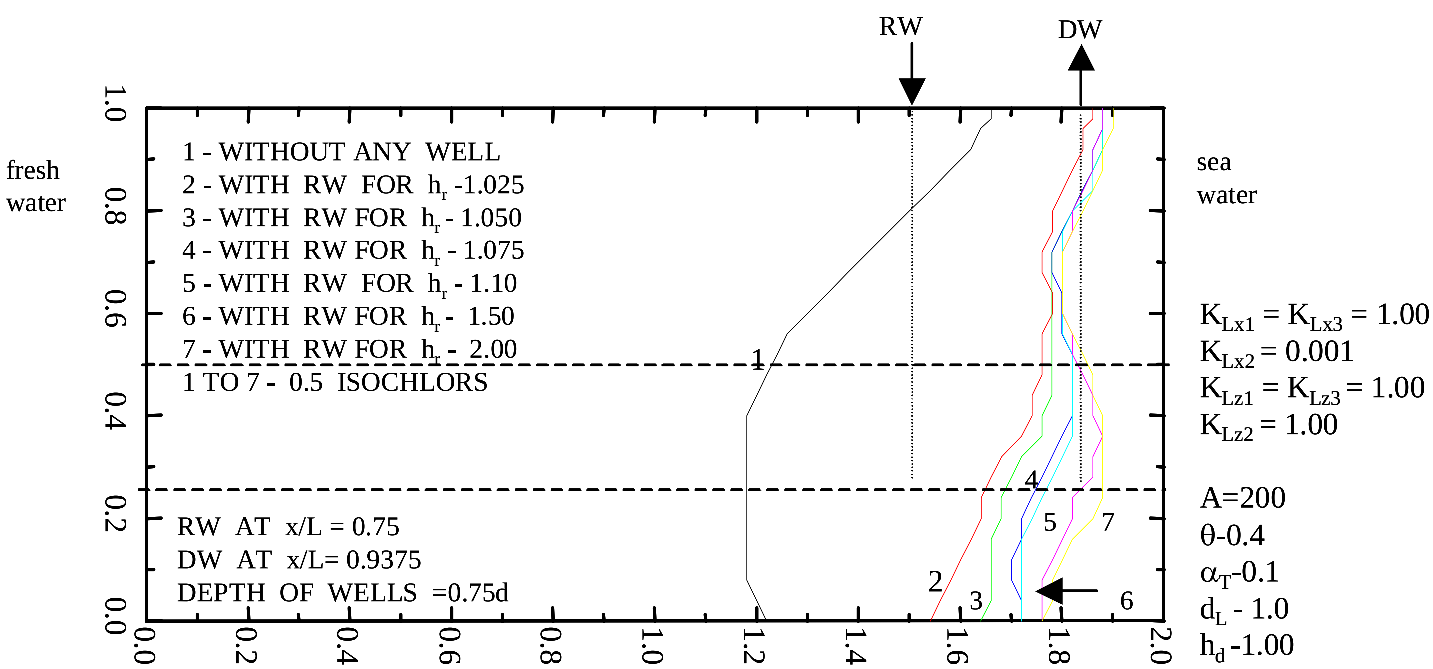

Figure 9-b . Effect of varied recharge head and constant discharge head on seawater intrusion control

Combined system of wells at specific locations with varied discharge head and constant recharge head

For the locations of freshwater recharge and saltwater discharge wells (depth = 0.375d) at x/L = 0.75 and x/L = 0.9375 respectively, the seawater wedge obtained for varied discharge head with constant recharge head equal to 1.050, is shown in **Figure-10-a.** The data used in the intrusion model for obtaining these graphs is given in **Table-5**.

Table – 5 Parametric data considered to study effect of specific locations of combined system of wells with varied discharge head and constant recharge head.

A = 200, K_{Lx1} = 1.0, K_{Lx2} = 0.001, K_{Lx3} = 1.0, K_{Lz1} = 1.0, K_{Lz2} = 1.0, K_{Lz3} = 1.0 α_T = 0.1, d_L = 2.0 θ = 0.4, h_r = 1.050			
Depth of well	**Well location = x / L**		**Varied discharge head**
(d_1 / d)	Recharge well	Discharge well	**(h_d)**
0.375 and 0.75	0.75	0.9375	1.0
			0.8
			0.6
			0.4

The seawater wedge retreats backward more in layer -1 for the decrease in discharge head from 1.00 to 0.8. The wedge continues to recede further seawards for the decrease in discharge head from 0.8 to 0.6 as depicted in the Figure 10-a.

Figure 10-b shows the higher recession of saltwater wedge in all the layers for increase in depth of wells to 0.75d for other data being the same. Thus discharge of sea water has favourable influence on the retardation of seawater intrusion.

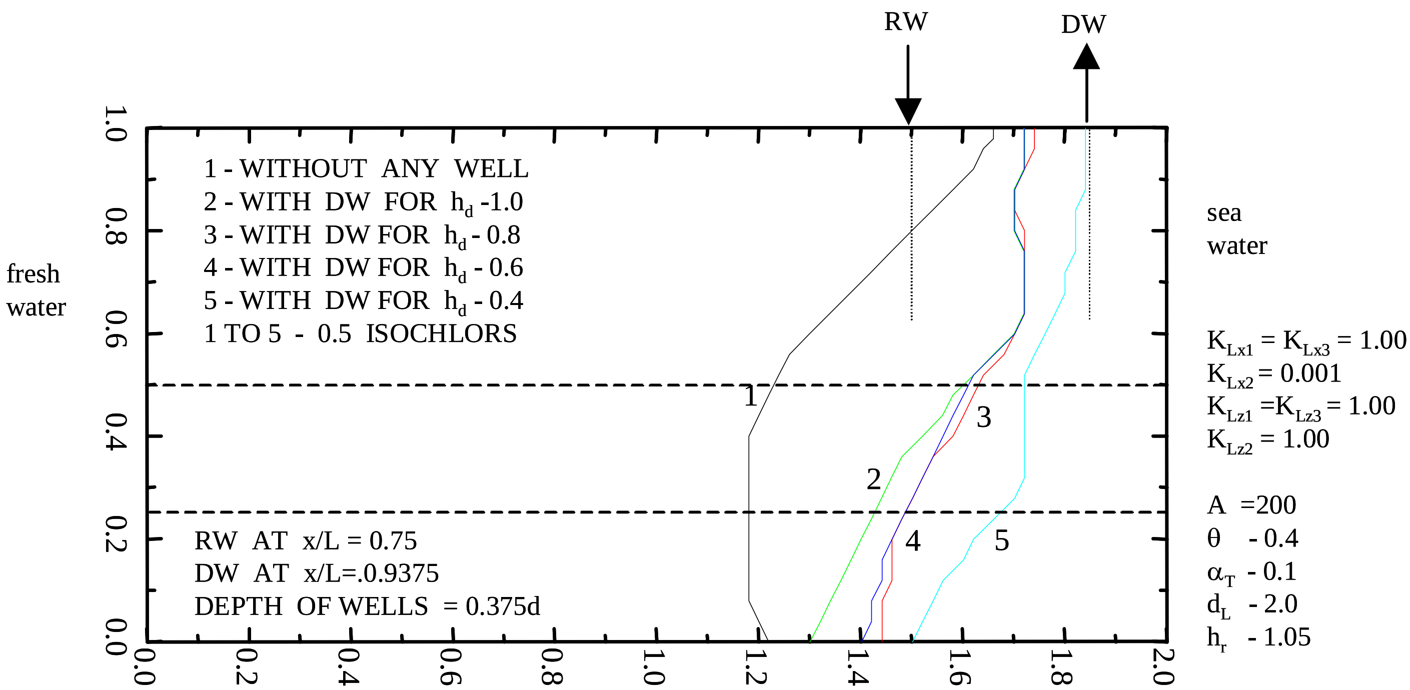

Figure 10-a . Effect of varied discharge head and constant recharge head on seawater intrusion control

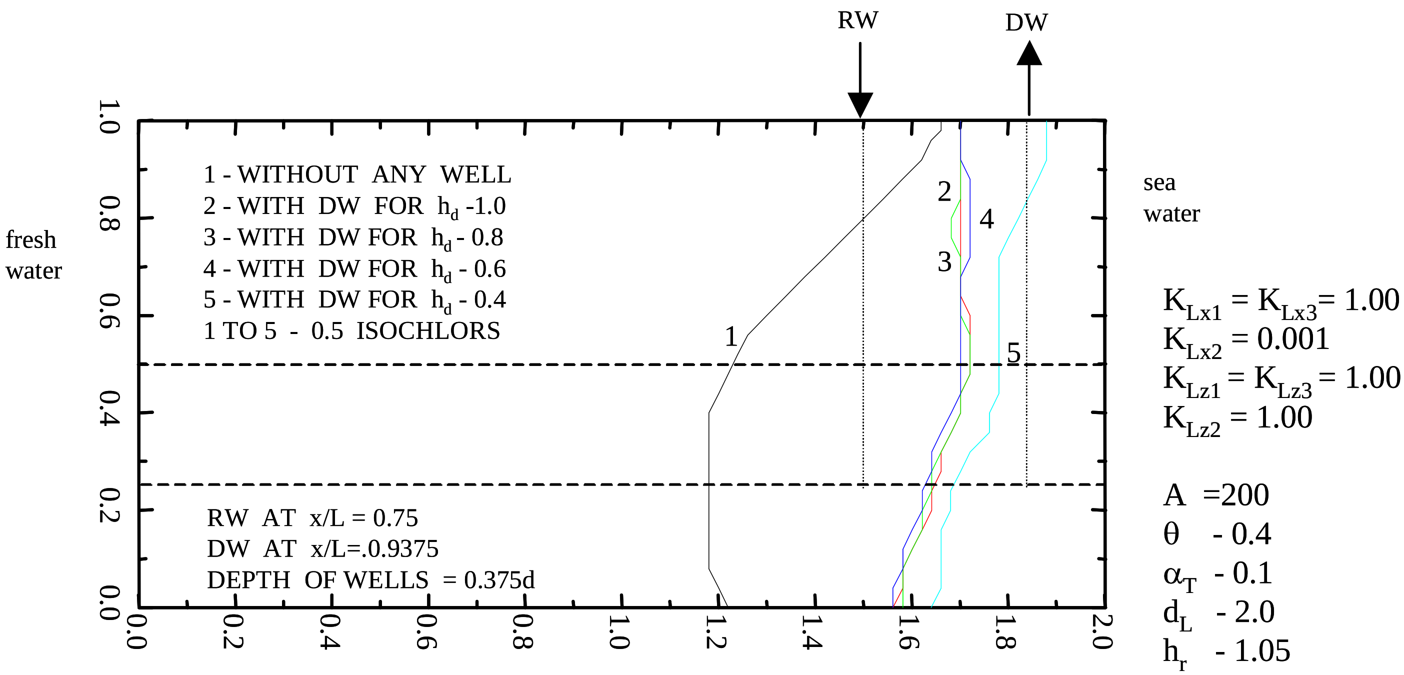

Figure 10-b . Effect of varied discharge head and constant recharge head on seawater intrusion control

Conclusions

Seawater intrusion problem with velocity dependent dispersion case was formulated and solutions were obtained by Galerkin's finite element method using triangular elements for multi-layered confined coastal aquifer. Concentration distribution in the confined coastal aquifer was determined for various conditions of the field parameters within the practical range. The efficacy of certain seawater intrusion control measures was evaluated.

The study found that the seaward location of recharge wells was more effective than landward location from the toe of interface (0.5 isochlor) to control seawater intrusion. These wells had a constant depth of penetration in the aquifer and constant recharge head. When the depth of recharge well was also increased from .375d to .75d, it had additional influence in the retardation of seawater intrusion provided the well was located towards seaward side. In another numerical experiment recharge well head was raised from 1.05h to 1.5h signifying larger recharging rates of water. For this case as expected, more retardation of seawater intrusion was obtained. However, from a practical point of view since the cost increases substantially requiring higher capacity pump and larger diameter well with increase of recharge head, it is suggested that h_r = 1.05 is quite effective presently. The middle layer aquitard layer plays the role of additional landward push of intruded zone in the third layer due to upward vertical flow from the bottom layer. Since initially the head across the aquitard layer had small difference in the system, no vertical flow was possible. However, due to pumping from upper layer, head in the bottom aquifer became higher compared to the upper layer causing upward vertical flow.

The model results showed that the combined system of freshwater recharge wells with saltwater discharge wells is more effective in controlling seawater intrusion than the recharge well alone. It was shown that increase in recharge head and constant discharge heads applied in a combined system of wells produced more retardation of seawater intrusion, compared to similar increase in recharge well alone. When the depth of well penetration is in layer-1 (top), the retardation of 0.5 isochlor is higher in layer-1 as compared to layer-3. However an increase in depth of well to intrude the third layer does not show corresponding containment effects, which is only marginal. These conclusions can be applied to the regional coastal aquifers for sustainable groundwater yield from the coastal aquifers without sea water intrusion.

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Nomenclature

A	-	Inverse of piezometric head gradient
C	-	Chloride Concentration of intruded seawater
d	-	Depth of aquifer
d_L	-	Ratio of aquifer depth to longitudinal dispersivity of the aquifer
D	-	Hydrodynamic dispersion coefficient
D_{xx}, D_{zz}, D_{zx}	-	Components of dispersion tensor
e_j	-	Component of gravitational unit vector
h	-	Equivalent freshwater head
k	-	Coefficient of permeability (Intrinsic permeability)
K	-	Hydraulic conductivity
K_{xx}, K_{zz}	-	Components of hydraulic conductivity tensor in the upper aquifer
K_{Lxx}, K_{Lzz}	-	Components of hydraulic conductivity tensor in the lower aquifer
n_x, n_z	-	Direction cosines
p	-	Hydrostatic pressure
q_x, q_z	-	Darcy velocity in x and z directions respectively
V_x, V_z	-	Seepage velocity in x and z directions respectively
ρ	-	Density of mixed fluid
ρ_f	-	Freshwater density
ρ_s	-	Seawater density
ε	-	Density different ratio
μ	-	Dynamic viscosity of fluid
θ	-	Porosity
α_L	-	Longitudinal dispersivity
α_T	-	Transverse dispersivity
Δ	-	Area of a triangular element
N_i, N_j, N_k	-	Interpolation functions