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SEAWATER INTRUSION DUE TO FRESHWATER DRAFT IN COASTAL AQUIFERS

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ABSTRACT *Freshwater pumping from coastal aquifers need to be properly planned to avoid aggressive seawater intrusion into freshwater aquifers. A Galerkin finite element model with sharp interface approach is adopted to simulate the seawater-freshwater dynamics in coastal phreatic aquifers due to freshwater draft. The model considers a hypothetical aquifer to analyze the effect of freshwater pumping on seawater intrusion. The results indicated that freshwater withdrawal from the seawater intruded zone (two fluid zone) need to be carefully monitored to avoid seawater upconing which will pollute the overlying freshwater zone. The effect of freshwater withdrawal on the seawater-freshwater dynamics decreases for locations farther from the intruded zone.*

Key words Coastal phreatic aquifer; finite element; freshwater draft; numerical model; sharp interface.

INTRODUCTION

Seawater intrusion is one of the most common forms of groundwater contamination for those who live in coastal areas (Bear *et al*., 1999). According to United Nations Environment Program, about 60% of world's population lives in coastal areas. Intrusion occurs when pumping lowers the hydraulic potential in a coastal aquifer, allowing seawater to migrate inland (Fig.1). The contamination of fresh groundwater reservoirs due to seawater intrusion in coastal aquifers is of major concern because even a small proportion of seawater (about 2-3%) renders freshwater un-potable and may lead to abandonment of aquifers in some extreme cases (Pinder and Stothoff, 1988).

Sustainable and environmentally sound development of groundwater and its effective management for catering to the ever-increasing needs of this resource for inter- and intra basin user interests is becoming more challenging day by day. In coastal areas, the threat of seawater intrusion into the aquifers and possible deterioration of quality of water due to uncontrolled freshwater draft adds to the complexity of groundwater management. Over the years, several mathematical and numerical models have been developed, which serve to predict the interface or transition zone behavior due to different stresses on the coastal aquifers (Reilly and Goodman, 1985). The development of these models was largely motivated by groundwater issues; that is, assessment of fresh groundwater reserves, and prediction of seawater intrusion - the landward or upward movement of the interface in response to groundwater exploitation practices (Volker and Rushton, 1982; Custodio, 1987; Bear *et al.*, 1999; Cheng and Ouzar, 2003).

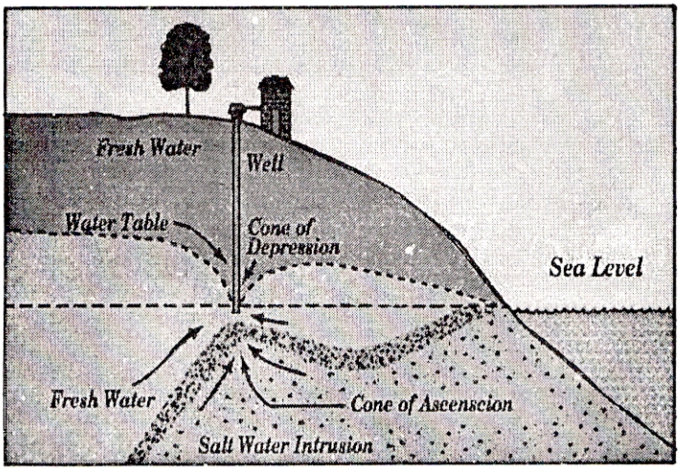

Fig.1 Seawater intrusion due to freshwater pumping in coastal areas.

Reports from coastal districts of Gujarat, Maharashtra and Andhra Pradesh highlight the origin of seawater intrusion in response to increased demands for domestic, industrial and irrigation purposes. The major factors for seawater ingress in Gujarat are low natural recharge, overexploitation of groundwater by farmers and industrial growth. In Thane district of Maharashtra, it is the intensive pumping of groundwater associated with urban and industrial development projects that has caused the problem. In coastal Andhra Pradesh, it is the lack of canal irrigation facilities which necessitated heavy dependence on groundwater resulting in seawater intrusion.

In recent decades, coastal aquifers have assumed greater importance because of increased demands placed on groundwater to meet the growing needs of water in a large urban area like Chennai city. The south Chennai aquifer that holds substantial quantity of groundwater, meets 20% of the city's water requirement. Due to constant pumping and improper management, this aquifer is facing a severe threat of being contaminated. Especially in drought years, the groundwater resource is a sole safeguarding arrangement to meet the drinking water requirement. Possible options and strategies for addressing the problems in each of the above cases include site-specific technical solutions, legislative measures, and social awareness. The inadequacy of the legislative provisions regarding water conservation and prevention of seawater intrusion is also the cause of aggressive seawater intrusion in a few cases.

The present work is primarily concerned with dynamic behavior of seawater under different freshwater pumping scenario that exist in most of the field problems. The results would be directly useful in planning the draft operations in coastal aquifers without causing seawater intrusion.

METHODOLOGY

In the present study, the Galerkin finite element model developed by Mahesha (1993), which adopts the sharp interface approach, is used with necessary modifications. The numerical model was validated earlier (Mahesha, 1995) for a specific case and the performance was found to be satisfactory. The areal model is based on the hydraulic approach and integration of flow equation over the vertical plane. The coupling between freshwater and seawater equations is formed through an additional constraint, namely that fluid pressure must be continuous across the interface. The model may be termed as quasi-two dimensional. A definition sketch of the problem is shown in Fig. 2. The aquifer is unconfined in nature with its bottom situated at a depth *D* below the mean sea level (msl). The initial equilibrium between the freshwater and seawater are maintained with a seaward freshwater flow of Q_I.

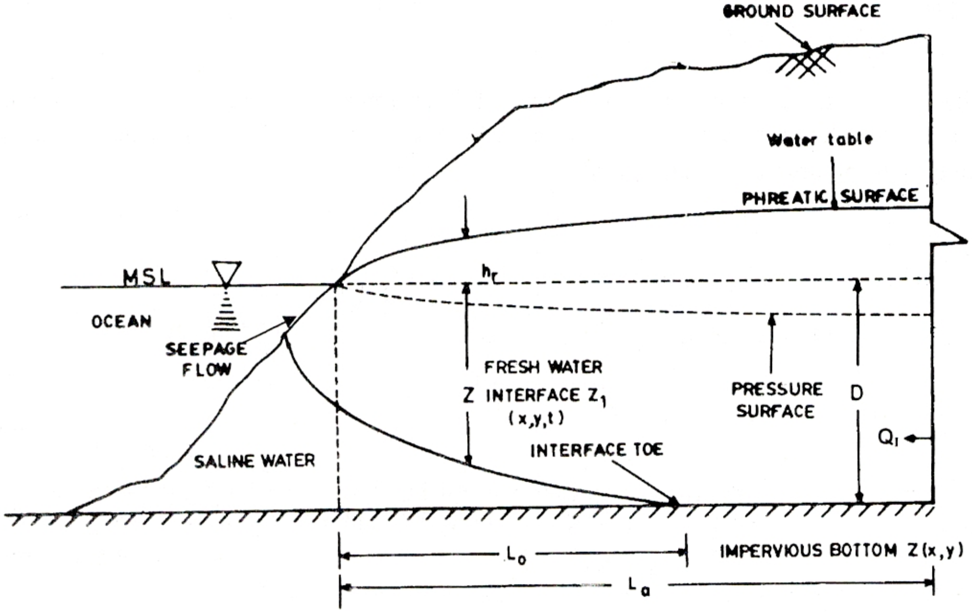

Fig. 2 Definition sketch of the problem.

Governing equations for freshwater and seawater are given by Bear (1979) as:

$$\frac{\partial}{\partial x}\left(K_f B_f \frac{\partial h_f}{\partial x}\right)+\frac{n}{\alpha}(1+\alpha)\frac{\partial h_s}{\partial t}-\left[n\left(\theta+\frac{1}{\alpha}\right)+S_f\right]\frac{\partial h_f}{\partial t}-Q_f=0 \qquad 1(a)$$

$$\frac{\partial}{\partial x}\left(K_s B_s \frac{\partial h_s}{\partial x}\right)-\left[\frac{n}{\alpha}(1+\alpha)+S_s\right]\frac{\partial h_s}{\partial t}-\left(\frac{n}{\alpha}\frac{\partial h_f}{\partial t}\right)=0 \qquad 1(b)$$

where K is the hydraulic conductivity ($K_f = K_s$); B is the zone thickness; h is the vertically averaged piezometric head; n is the porosity; α is the excess density ratio ($= \rho_s - \rho_f)/\rho_f$; ρ is the density; θ is a coefficient which equals 1 for unconfined and 0 for confined aquifer; Q_f is the volumetric flow rate; S is the storage coefficient ($S_f = S_s$); and subscripts f and s refer to freshwater and seawater, respectively. The non-dimensional X and Y coordinates are defined as $X' = X / L_o \times 100$ and $Y' = Y / D \times 100$.

The details of the solution procedure, initial and boundary conditions can be found elsewhere (Wilson and Costa, 1982; Mahesha, 1995). The output from the simulation is the pizometric head, interface elevation and the length of seawater intrusion. The advancement of the saline wedge is expressed as percentage of initial length of intrusion:

$$\%A = \left(\frac{L_t - L_o}{L_o} \right) \times 100 \tag{2}$$

where L_o is initial length of intrusion; and L_t is length of intrusion at a particular time level. The freshwater draft (pumping) rates considered cover a wide practical range with parameter Q' defined as:

$$Q' = \frac{Q}{\alpha K D^2} = 0.001 \quad \text{to} \quad 0.25 \tag{3}$$

where Q is rate of freshwater pumping in m^3/d.

RESULTS AND DISCUSSION

For the present study, a hypothetical aquifer with the following properties is considered: $D = 110$ m; $Q_l = 7$ m^2/d; $K = 40$ m/d; $\rho_f = 1000$ kg/m^3; $\rho_s = 1025$ kg/m^3; $n = 0.41$; and $S = 0.041$. Length of intrusion L_o equals 884 m, as per the steady state equation given below (Vappicha and Nagaraja, 1976):

$$L_0((x)) = ((1+\alpha)) \left[\frac{\alpha K D^2}{2Q_l} - 0.26 \frac{Q_l}{\alpha K} \right] \tag{4}$$

The freshwater draft are introduced at two locations i.e. one within the intruded zone ($0.5L_o$) and the other outside the intruded zone ($1.5L_o$) and the corresponding seawater-freshwater interface responses are monitored.

Freshwater Draft at $0.5L_o$

Table 1 shows seawater advancement due to freshwater draft at $0.5L_o$. Here no significant advancement of seawater was observed. However, variation of water table profile and interface profiles could be observed in the vertical plane as evident from Figs. 3 to 6, which show profiles of steady interface and water table for various rates of draft at $0.5L_o$ from seacoast. Initial freshwater head at the well location is 1.95 m. Due to freshwater draft, the water table drops down to a maximum of $Y' = -39.6$.

For all the pumping rates, the equilibrium is established fairly early. The effect of freshwater draft could be observed as cone of depression and for lower draft rates ($Q' = 0.001$ to 0.005), the final freshwater head at the well is above msl while for higher rates ($Q' = 0.01$ to 0.25) it is below msl. All the values shown in Table 1 indicate the final steady state condition.

Table 1 Seawater intrusion advancement due to freshwater draft at $0.5L_o$.

Initial freshwater head = 1.95 meters; Initial length of intrusion = 884 meters.

Pumping Rate, Q'	Final length of Intrusion (m)	Seawater Advancement A%	Time		Final Freshwater Head, h_f(m)
			Days	Tt/nL_o^2	
0.001	884.03	0.00	0.2	0.002839	1.88
0.002	884.03	0.00	0.3	0.004258	1.78
0.003	884.03	0.00	0.2	0.002839	1.74
0.004	884.03	0.00	0.2	0.002839	1.67
0.005	884.03	0.00	0.2	0.002839	1.61
0.01	884.03	0.00	2.9	0.04115	-0.81
0.05	884.03	0.00	0.4	0.005677	-3.06
0.10	884.03	0.00	0.4	0.005677	-8.26
0.15	884.03	0.00	1.5	0.02129	-8.60
0.20	884.03	0.00	2.9	0.03956	-26.66
0.25	884.03	0.00	3.5	0.04128	-39.02

In Fig. 3, the final steady interface completely merges with the initial interface because pumping rate is too small ($Q' = 0.10$) to show any effect on the interface. Steady water table level in this case is -8.26 m below msl over a period of 0.4 days. When the draft rate is increased to 0.15, the final position of the interface still lies over the initial steady interface except at pumping location (Fig. 4). Upconing of the interface is observed in this case at the draft location but no seawater advancement was observed.

Even though there is no advancement, it is not preferable to pump water from the intruded zone ($< L_o$), because the freshwater may get contaminated with seawater in the case of a fully penetrated well.

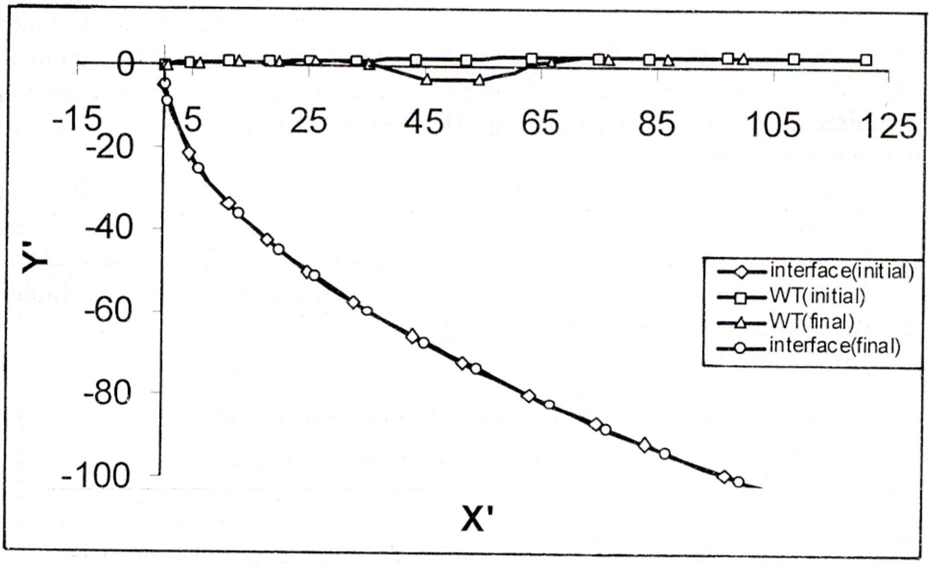

Fig. 3 Steady water table, interface profiles for f$Q' = 0.1$ at $0.5L_o$ from seacoast.

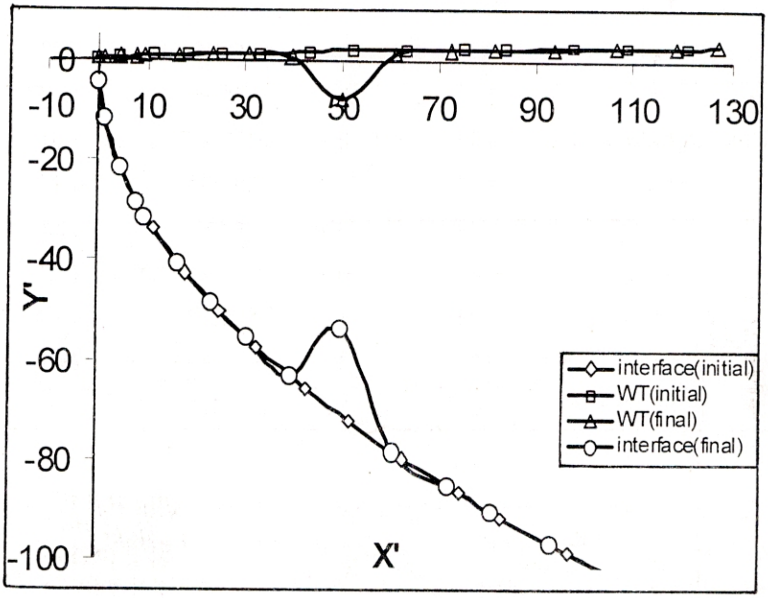

Fig. 4 Steady water table, interface profiles for $Q' = 0.15$ at $0.5L_o$ from seacoast.

Figure 5 also shows the same trend of result, but with higher drawdown value ($Y' = -22.6$) at the well. The upconing of the interface is more severe in this case compared to the previous one. The time taken to attain steady state is longer as well. Figure 6 also follows a similar trend with greater drawdown (-39.02 m below msl).

The drawdown curve and the interface profile are close to each other at the well location. At this stage, the pumping should be stopped to avoid total contamination of the aquifer due to seawater extraction. The entire period of operation is longer here than any other case.

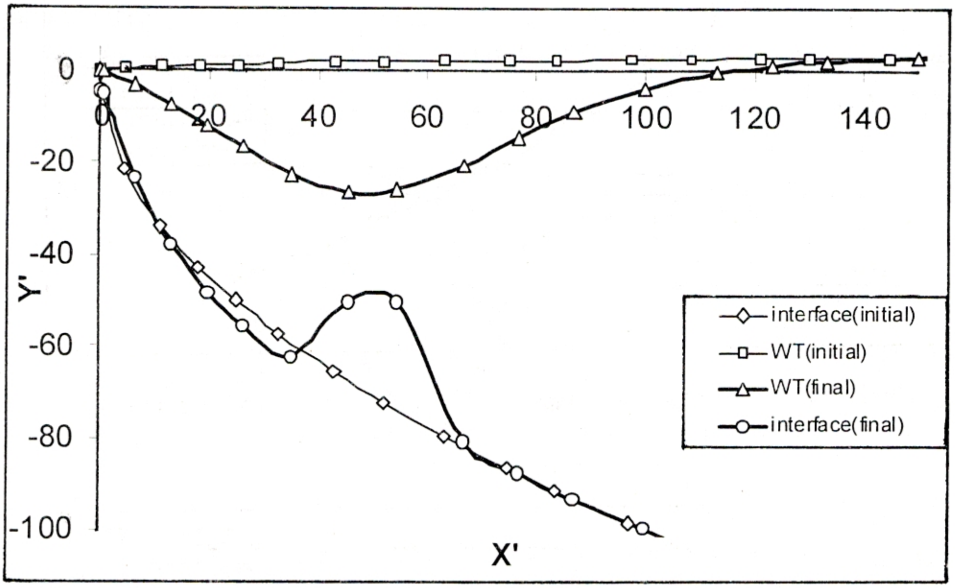

Fig. 5 Unsteady water table, interface profiles for $Q' = 0.2$ at $0.5L_o$ from seacoast.

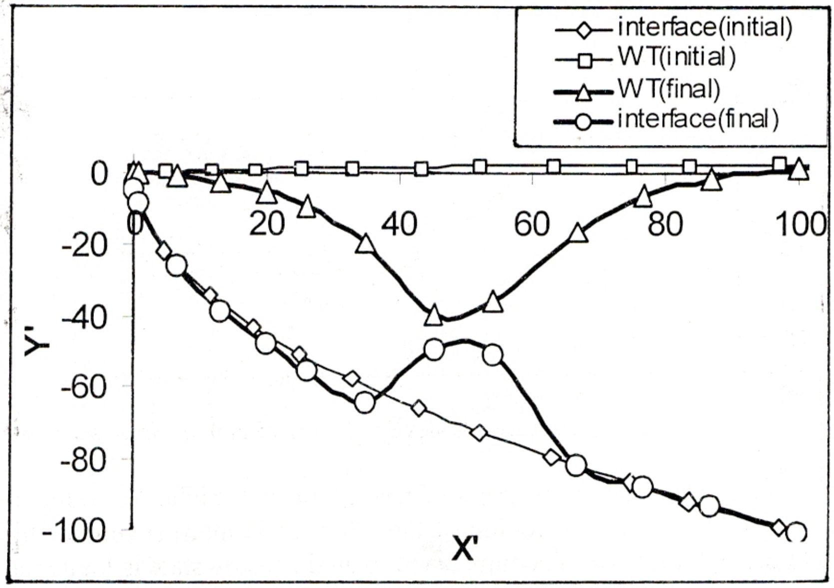

Fig. 6 Steady water table, interface profiles for Q' = 0.25 at $0.5L_o$ from seacoast.

Figure 7 shows the water table profile for various draft rates at $0.5L_o$. The increasing magnitude of cone of depression could be clearly observed with increasing rates of freshwater draft. The interface profiles for the above cases are shown in Fig. 8. A gradual increase in the upconing of steady interface profiles could be observed from the figure with the increase in draft rate. As the upconing is more and more, the cone of depression is also significant leading to possible mixing of seawater with freshwater which is not desirable.

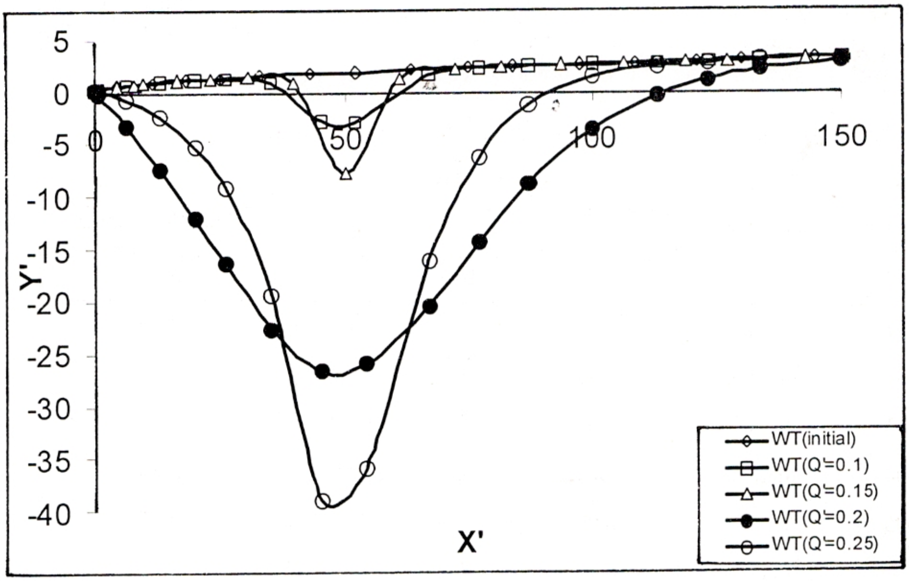

Fig. 7 Steady water table profiles for different draft rates at $0.5L_o$.

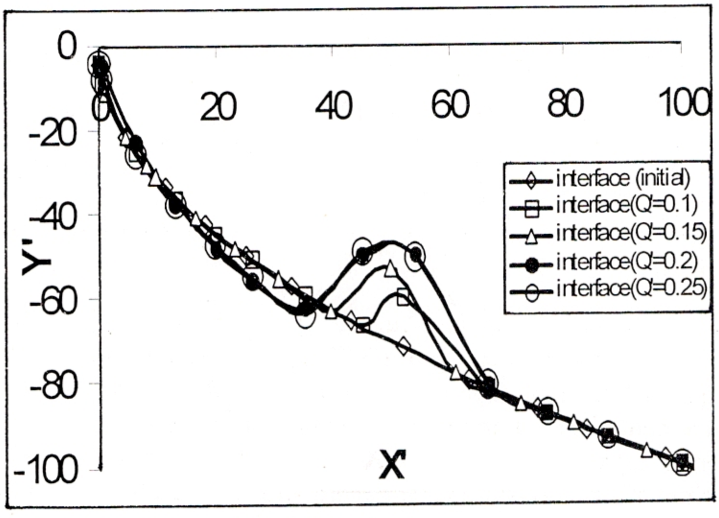

Fig. 8 Steady state interface profiles for different draft rates at $0.5L_o$.

Freshwater Draft at $1.5L_o$

The effect of freshwater draft is analyzed at a location beyond the intruded zone ($1.5L_o$). The results are listed in Table 2. Except for Q' = 0.2 and 0.25, no advancement of seawater is observed. The initial freshwater head is 3.37 m at this location. The drawdown goes on increasing until upto -6.82 m with increasing draft rate (0.001 to 0.15). Since the draft location is relatively farther from the saline wedge toe, steady state is achieved in a relatively shorter period. However, large scale pumping ($Q' > 0.2$) leads to drying up of aquifer (drawdown reaching aquifer bottom) before inducing any seawater advancement. At this stage pumping is stopped and the monitoring is continued till equilibrium.

Table 2 Seawater intrusion advancement due to freshwater draft at $1.5L_o$.

Initial freshwater head = 3.37 m; Initial length of intrusion = 884 m.

Pumping Rate, Q'	Final length of Intrusion, (m)	Seawater Advancement A%	Time		Final Freshwater Head, h_f(m)
			Days	Tt/nL_o^2	
0.001	884.03	0.00	0.25	0.000709	3.29
0.002	884.03	0.00	0.2	0.002839	3.23
0.003	884.03	0.00	0.2	0.002839	3.17
0.004	884.03	0.00	0.2	0.002839	3.10
0.005	884.03	0.00	0.3	0.004258	2.95
0.01	884.03	0.00	0.4	0.005677	2.40
0.05	884.03	0.00	0.2	0.002839	0.03
0.10	884.03	0.00	0.25	0.003548	-4.26
0.15	884.03	0.00	0.15	0.002129	-6.82
0.20	889.68	0.64	5.2	0.07305	-107.99*
0.20	944.03	6.79	83	4.740	-3.69
0.25	886.4	0.27	2.9	0.04185	-108.9*
0.25	940.51	6.39	130	1.7970	-0.42

* '-' : Aquifer is drying up.

Figure 9 shows the water table and interface profiles for $Q' = 0.2$ at $1.5L_o$ from seacoast. The initial freshwater head (Y') is 3.37 m and length of intrusion is 884 m. The aquifer dries out in a relatively shorter period of 5.2 days with negligible saltwater advancement. The pumping is stopped at this stage and the equilibrium is established after 83 days with a total advancement of saline wedge by 6.79%. Water table has been shown in dotted line when the drawdown reaches the aquifer bottom. The results show that with increasing draft, the aquifer dries out in shorter period before inducing any seawater advancement.

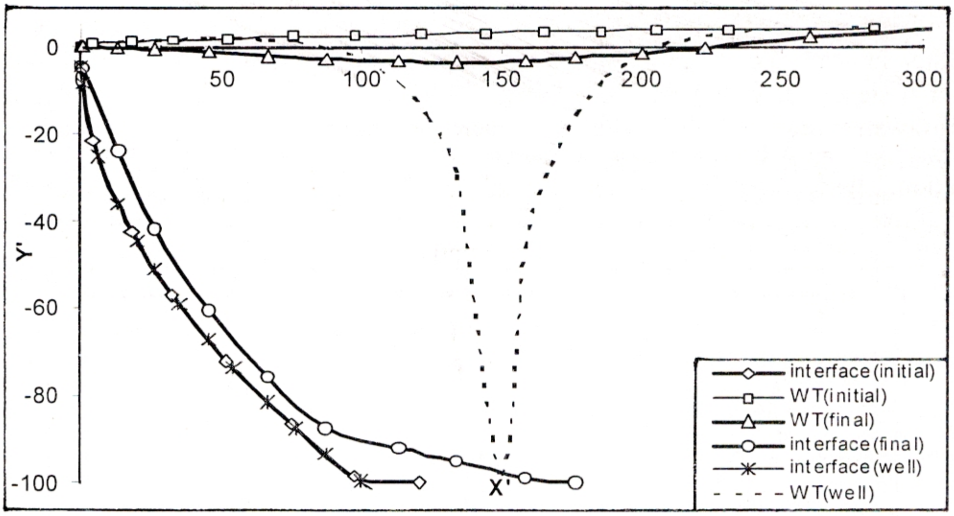

Fig. 9 Unsteady water table, interface profiles for $Q' = 0.2$ at $1.5L_o$ from sea.

The water table and interface profiles are presented in Figs. 10 and 11 for different draft rates at $1.5L_o$. The interface position remains unchanged for $Q' \leq 0.1$. For $Q' = 0.2$ and 0.25, an advancement of 6.79% and 6.39% was observed, respectively. The aquifer gets dried up for these cases and equilibrium is attained after pumping is stopped. The steady state is achieved after 83 days and 130 days with recovered water table at $Y' = -3.69$ and 0.42, respectively. From the results it is evident that the effect of freshwater draft at locations beyond $1.5L_o$ have negligible effect on the interface advancement except for $Q' = 0.25$ or higher.

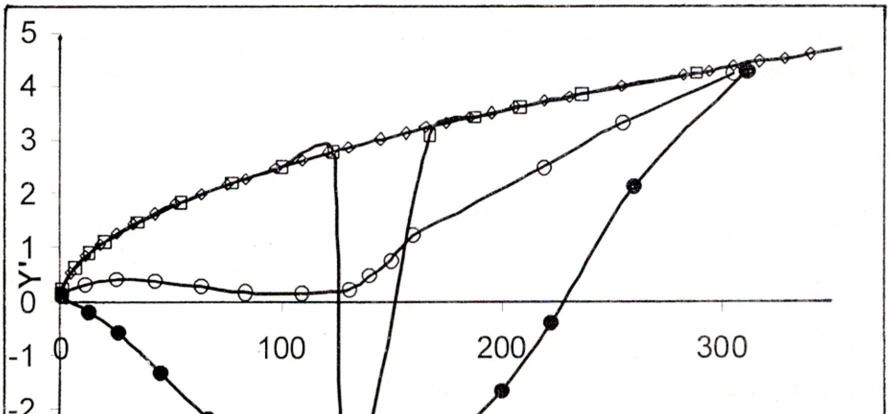

Fig. 10 Cone of depression profiles for different draft rates at $1.5L_o$.

Figures 12 and 13 show the relation between time taken to attain steady state for different draft rates at the locations. When pumping rate is increased, time taken to attain steady state also becomes longer. This may be due to the greater effect of freshwater draft as the magnitude increases. Investigations on the effect of freshwater draft at other locations are in progress to evaluate the effect of freshwater draft on the seawater-freshwater dynamics to evaluate the draft operation policy for coastal aquifers.

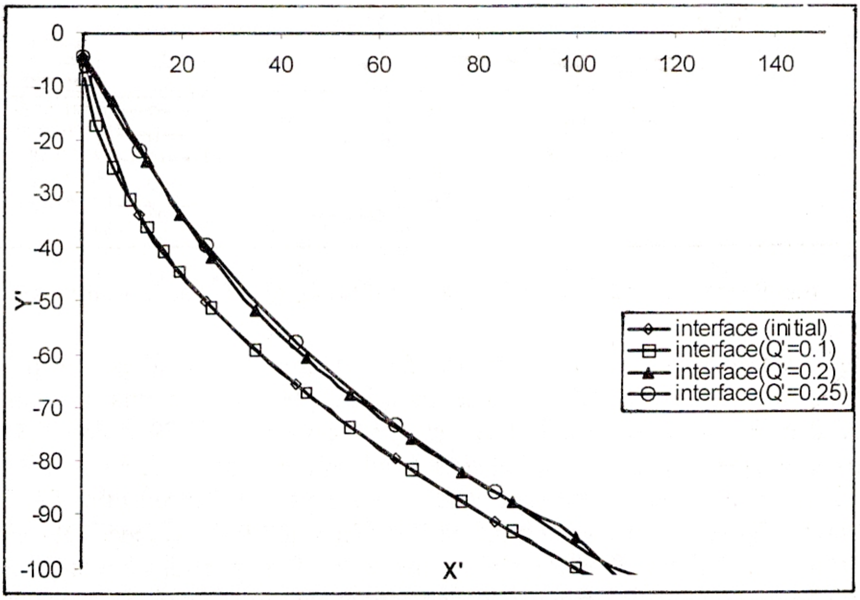

Fig. 11 Interface profiles for different draft rates at $1.5L_o$.

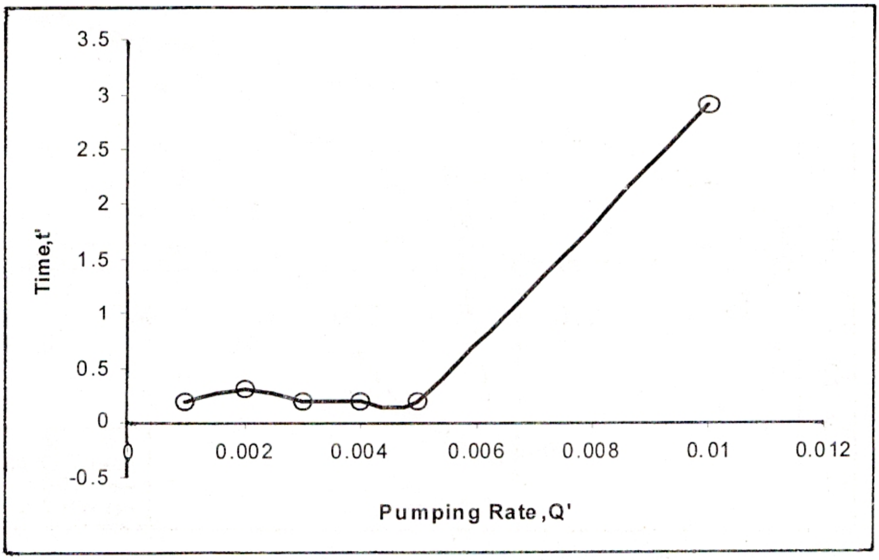

Fig. 12 Time to attain steady state for different draft rates at $0.5L_o$.

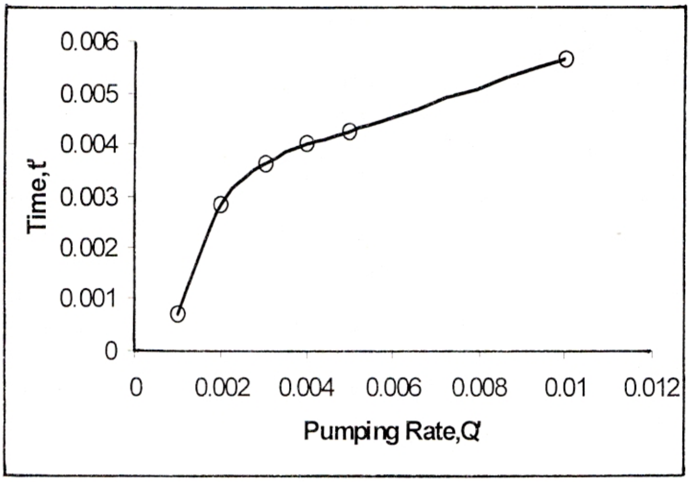

Fig. 13 Time to attain steady state for different draft rates at $1.5L_o$.

CONCLUSION

The problem of seawater intrusion in freshwater aquifers is analyzed using a quasi-two dimensional Galerkin finite element model with sharp interface approach. The model simulates seawater-freshwater dynamics in coastal aquifers under freshwater draft at specified locations. Freshwater draft in the intruded zone ($\leq L_o$) causes significant upward movement of seawater-freshwater interface (upconing) rather than horizontal movement. Hence advancement of seawater is considerably less. Care must be taken to operate the wells with draft rates $Q' \leq 0.1$ in this region. For higher rates of withdrawal, the aquifer may get fully contaminated and hence higher draft rates need to be avoided. Also, in the case of fully penetrating wells, it is likely that freshwater may get contaminated with seawater. Hence partially penetrated open wells up to a maximum depth of $Y' = -10.0$ are better suited for the region.

For the region beyond L_o, the interface response decreases for freshwater draft with increasing distance from the intruded region. For the draft rates $Q' > 0.1$, the drawdown reaches aquifer bottom before inducing the effect on the interface. This situation is not desirous due to the possibility of development of landward gradient of freshwater. Also, in most of the cases, the interface continues to advance after the stoppage of freshwater draft due to landward (towards well) gradient of freshwater. The safe region for freshwater development could be worked out considering more locations on the landward side.

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