Modelling of a Scavenger Well System

K. Saravanan, Deepak Kashyap[1] and Anupma Sharma[2]

Research Scholar, Dept. of Civil Engineering, IIT Roorkee, Roorkee
[1]Professor, Dept. of Civil Engineering, IIT Roorkee, Roorkee
[2]Scientist, National Institute of Hydrology, Roorkee

Abstract: A scavenger well system, essentially a skimming well system designed to pump fresh water from a fresh-saline aquifer, consists of two pumping wells located side by side. One of the wells taps the freshwater zone and the other taps the deeper salinewater zone. These wells pump fresh and saline waters from the same site simultaneously without mixing, through two separate discharge systems. The rise of interface (upconing) due to pumping of freshwater well is countered by the pumping of salinewater well. This leads to a reduction in the upconing of the interface. A finite-difference model is developed to study the upconing below a scavenger well system. The model accounting for both advective and dispersive components of saltwater transport is based upon numerical solutions of the coupled differential equations governing two dimensional axis symmetric flow and salt transport. Results of a few numerical experiments performed on the model are presented herein.

INTRODUCTION

The existence of fresh water overlying saline water in groundwater system is widespread in many inland aquifers as well as in most coastal aquifers. Such aquifers are usually termed as fresh-saline aquifers. The fresh water lens in the fresh-saline aquifer is an important resource for domestic, irrigation and industrial water supply in arid and semi arid region. When the fresh water is pumped from a well tapping a fresh-saline aquifer, pressure heads in the vicinity of the well are lowered, and consequently the underlying saline water rises towards the well to maintain the hydraulic equilibrium. This phenomenon is called upconing. The extent of saline water upconing affects the pumped freshwater quality. In such a scenario, the wells must be so designed that the salt concentration in the pumped water stays below an acceptable level. Such wells are termed as skimming wells. Various skimming well techniques are: conventional partially penetrating single and multi strainer wells, scavenger wells, recirculation wells and radial collector wells (Sufi et al., 1998).

The paper investigates the performance of a scavenger well system through numerical modelling. For meeting this objective, a numerical model accounting for both advective and dispersive components of saline water transport is developed. A few numerical experiments are conducted on the model, to understand the flow/transport processes involved.

DESCRIPTION OF SCAVENGER WELL

A scavenger well system consists of two pumping wells located side by side, one of which taps the freshwater zone while the other taps the salinewater zone. These wells pump fresh and saline waters from the same site simultaneously without mixing, through two separate discharge systems as shown in Fig. 1. The rise of saline water due to pumping of freshwater well is countered by the downconing of the interface caused by pumping from salinewater well. The discharges of freshwater well and salinewater well are adjusted so that underlying saline water may not intrude into the freshwater well. This is a potential technology for sustainable groundwater development in shallow fresh-saline aquifer. The main disadvantage of scavenger well is problem of disposal of pumped saline water. This may be overcome by using the pumped saline water for domestic purpose after treatment, irrigation purpose, aquaculture, etc. or disposed safely into seas.

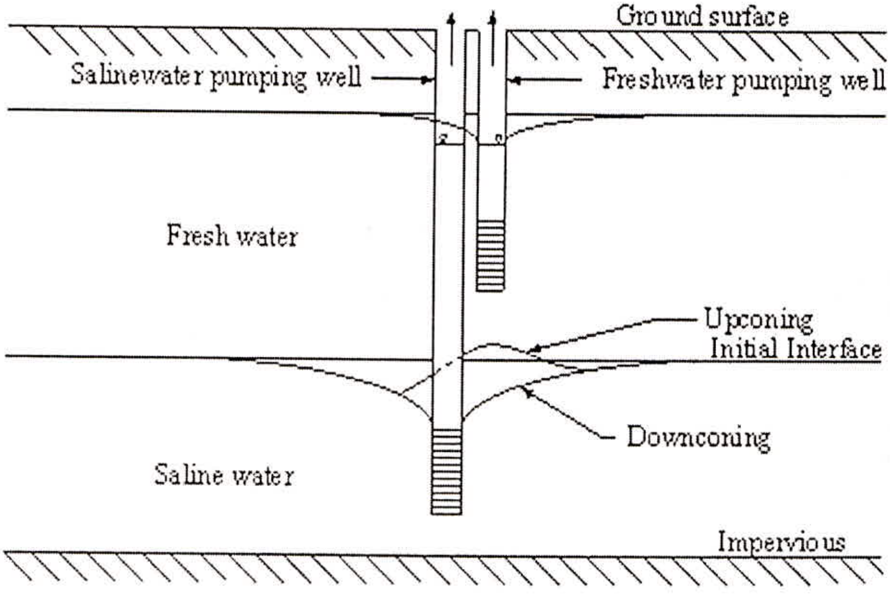

Fig. 1. Upconing under scavenger well.

LITERATURE REVIEW

There are only a limited number of reported studies on scavenger well systems. These studies are divided into two categories i.e. experimental and numerical.

Experimental Studies

Long (1965) studied feasibility of scavenger well application in Louisiana, USA. Zack (1988) carried out a scavenger well field investigation in an abandoned well at Puerto Rico. From the field data they determined the optimal fresh water recovery. They concluded that salinity of pumped fresh water depends on sum of discharge of fresh and saline water, locations of pumping screens and hydraulic conductivities. Stoner et al. (1993) reported the historical development of scavenger wells concept and salinity problem in the lower Indus plain of Pakistan. Beeson et al. (1993) conducted field experiments at four scavenger well sites in the lower Indus plain of Pakistan. The main objects of the study is to intercept canal seepage, fresh water recovery and salinity control. Sufi et al. (1998) presented a physical model of scavenger well system. They studied the influence of aquitard, fresh/saline discharge rates and screen positions to the scavenger well performance. Zack and Lara (2002) conducted field experiments on scavenger well installations in Cozumel island aquifer of Mexico. It was concluded that scavenger well installations effectively improve the pumped water quality by controlling the upward advance of saltwater by scavenger-well abstraction.

Numerical Studies

Eiji Fukumori et al. (1986) developed a numerical model based on sharp interface approach to study the flow behaviour of simultaneous pumping of two wells from both sides of the interface. Sufi et al. (1998) presented a physical model of scavenger well system. This physical model is used to calibrate a density dependent 3-D finite element numerical model VDGWTRN (Sakr, 1995). Aliewi et al. (2001) studied the scope of scavenger well application in the Pleistocene Aquifer of Gaza and Jericho Areas, Palestine using SUTRA (Voss, 1984). The model output shows that saltwater upconing is considerably reduced by scavenger well application. They concluded that the optimal ratio between salinewater and freshwater pumping in Gaza aquifer is 0.5. Later investigations revealed that SUTRA model could not adequately simulate the behaviour of fresh and saline water in the vicinity of scavenger well. Particularly, it cannot handle the temporal changes in the dispersion zone in the vicinity of well (Ali et al., 2004). Ali et al. (2004) studied the hydraulic performance of two scavenger wells in the lower Indus basin. They simulated the groundwater flow with MODFLOW (McDonald and Harbough, 1988) and the solute transport processes with MT3D (Zheng and Wang, 1999).

MODEL DEVELOPMENT

In the present work a numerical model is developed to determine the hydraulic and hydro salinity aquifer response to pumping from a scavenger well system. The axis of the saline water well is assumed to coincide with the axis of fresh water well. Further, flow and mass transport around the well system are deemed to be symmetrical about well axis and having radial and vertical components. As such, the problem is viewed in terms of cylindrical coordinates (Fig. 2).

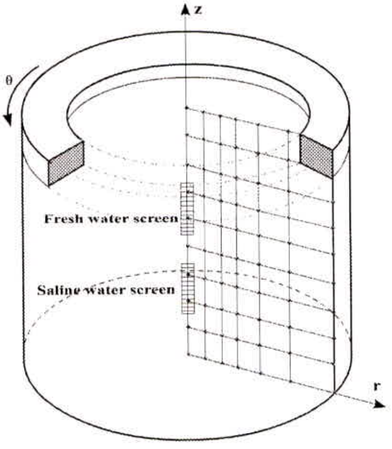

Fig. 2. Cylindrical flow domain.

Governing Equations

The partial differential equation describing unsteady state axis symmetric radial groundwater flow in cylindrical coordinates (Bear, 1979) is as follows:

$$\frac{k_r}{\mu r}\left(\frac{\partial p}{\partial r}\right)+\frac{\partial}{\partial r}\left(\frac{k_r}{\mu}\frac{\partial p}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{k_z}{\mu}\left(\frac{\partial}{\partial z}(p+z\gamma)\right)\right)=\frac{S_s}{\gamma}\frac{\partial p}{\partial t} \tag{1}$$

where p is water pressure, μ is dynamic viscosity of water, γ is specific weight of water, k_r and k_z are intrinsic permeabilities in radial and vertical directions, r is radial distance from the axis of well system, z is vertical coordinate measured from lower impervious layer and S_s is specific storage.

The Darcy velocities in r and z directions are computed as follows.

Darcy's velocity in r direction

$$q_r=-\frac{k_r}{\mu}\left(\frac{\partial p}{\partial r}\right) \tag{2}$$

Darcy's velocity in z direction

$$q_\mathrm{z}=-\frac{k_\mathrm{z}}{\mu}\left(\frac{\partial}{\partial z}(p+z\gamma)\right) \tag{3}$$

The partial differential equation describing unsteady state axis symmetric transport of dissolved solutes in cylindrical coordinates (Bear, 1979) is as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rD_\mathrm{r}\frac{\partial C}{\partial r}\right)+\frac{\partial}{\partial z}\left(D_\mathrm{z}\frac{\partial C}{\partial z}\right)-\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{rq_\mathrm{r}C}{\phi}\right)-\frac{\partial}{\partial z}\left(\frac{q_\mathrm{z}C}{\phi}\right)=\frac{\partial C}{\partial t} \tag{4}$$

where C [$= (\gamma - \gamma_\mathrm{f})/(\gamma_\mathrm{s} - \gamma_\mathrm{f})$] is normalized mass fraction of salt in solution, γ_f and γ_s are specific weights of fresh and saline water, D_r and D_z are dispersion coefficients in radial and vertical directions and ϕ is porosity of aquifer.

Values of dispersion coefficients are (Bear, 1979)

$$D_\mathrm{r} = \alpha_\mathrm{r} U \tag{5}$$

$$D_\mathrm{z} = \alpha_\mathrm{z} V \tag{6}$$

where α_r and α_z are dispersivities in radial and vertical directions, and U and V are seepage velocities in radial and vertical directions.

A simplified relation between γ and C is

$$\gamma(C)=\gamma_f\left[\ 1+C(\frac{\gamma_s}{\gamma_f}-1)\right] \tag{7}$$

The variation of μ with C is as follows (Shalabey et al., 2006)

$$\mu(C)=\mu_\mathrm{f}(1+0.02825614\,C) \tag{8}$$

where μ_f is viscosity of fresh water.

The relation between S_s and C under constant porosity is (Shalabey et al., 2006)

$$S_s(C) = S_f\left[1 + C\left(\frac{\gamma_s}{\gamma_f} - 1\right)\right] \tag{9}$$

Boundary Conditions

No flow boundary conductions are assigned along the lower and upper impervious boundaries of the aquifer and also along the blind pipes of the two wells. A constant head boundary condition is assigned at a "far-away" section. Neuman type (i.e. discharge assigned) of boundary conditions are assigned along the screens of the two wells. The necessary gradients are computed assuming the fresh water and the saline water discharges to be uniformly distributed along the two respective screens. The flow and solute transport domain boundary conditions are shown in Fig. 3, in which boundary type 1 represents a no flow boundary, type 2 represents a constant head boundary, and type 3 represents a discharge assigned boundary.

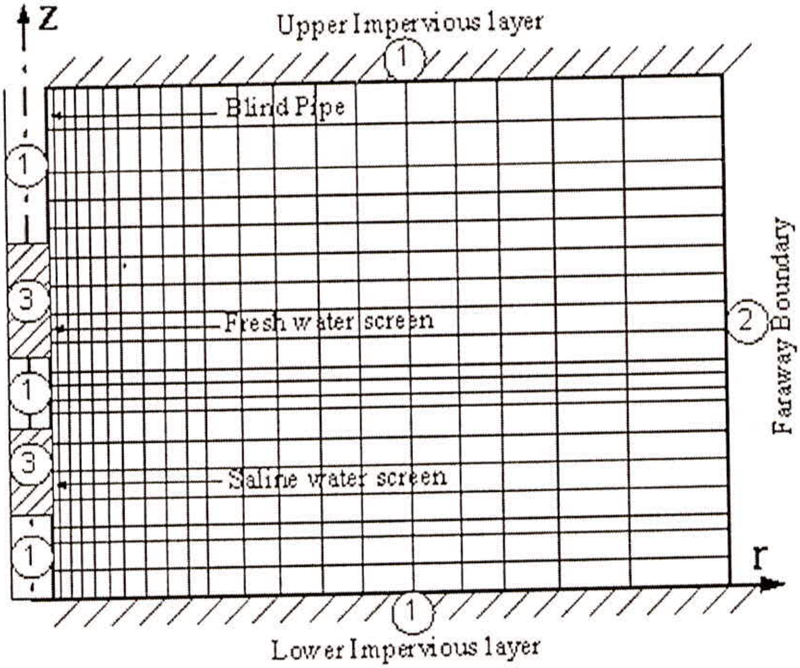

Fig. 3. Flow and solute transport domain boundary segments.

Solution of the Governing Differential Equation

The flow and mass transport equations listed above are solved numerically invoking the finite difference based Iterative Alternating Direction Implicit Explicit (IADIE) scheme (Remson et al., 1971); and assigning the boundary conditions described above. Commencing from assigned initial pressure heads and concentrations, the solution provide the pressure head and the concentration distributions at successively advancing discrete times. The interface position is located by identifying the 0.5 isochlor.

Model Validation

The numerical model has been validated using field data from Left Bank Outfall Drain stage I project (LBOD-I) of Pakistan. Beeson et al. (1993) conducted detailed field investigations and pumping tests at four scavenger well sites in the project area. The data pertaining to two scavenger well systems (namely, PSW1A and PSW3) were used to validate the model.

Numerical Experiments

Experiments were performed on the model described in the preceding section. The adopted scavenger well system is shown in Fig. 4. The freshwater pumping rate (Q_f) was kept as 15 m^3/hr. The salinewater pumping rates (Q_s) were taken as 0, 2.5, 15.0 and 30.0 m^3/hr. The model computed positions of the upconed surface at the end of 12 and 24 hours of the pumpings are shown in Figs. 5 and 6. The corresponding velocity fields are shown in Figs. 7, 8, 9 and 10.

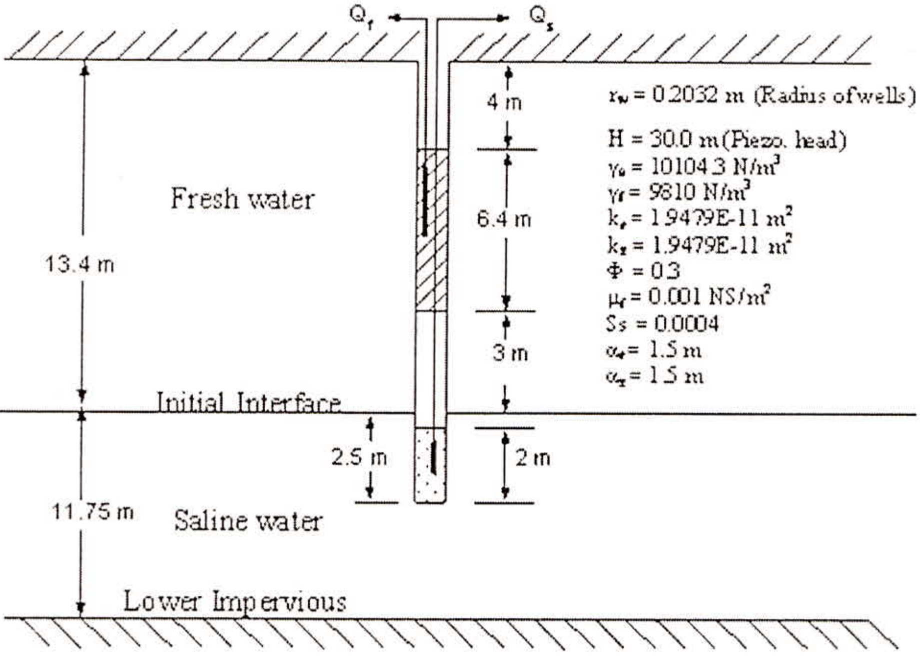

Fig. 4. Adopted scavenger well.

DISCUSSION OF THE RESULTS

The effect of scavenging of saline water on the upconing is quite apparent in Figs. 5 and 6. It can be seen that as the saline water discharge is increased, the upconing reduces. Interestingly, as Q_s is increased beyond Q_f the upconing completely vanishes and the interface gets "down-coned" near the wells.

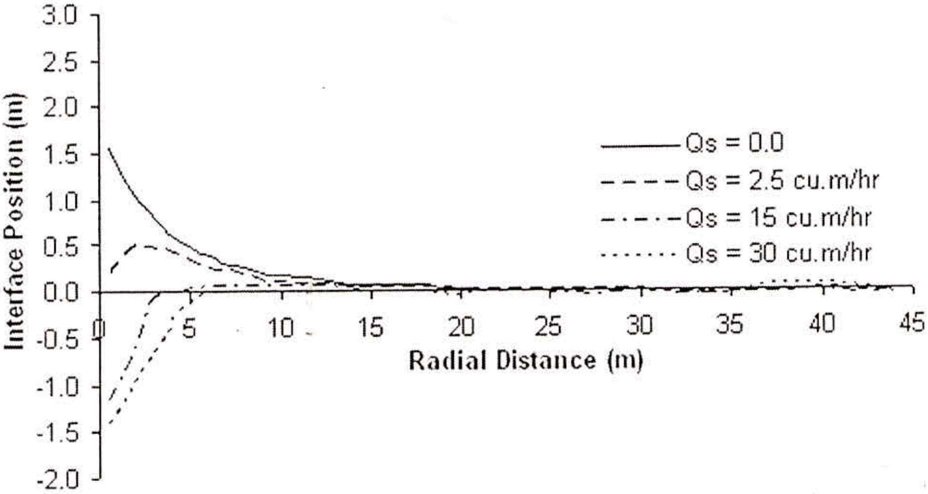

Fig. 5. Upconed interface at 12 hours.

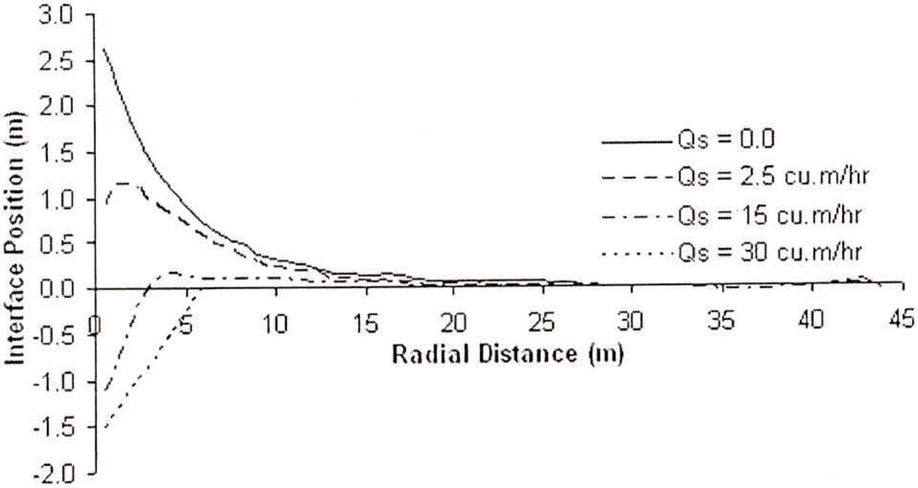

Fig. 6. Upconed interface at 24 hours.

The model computed velocity fields at 24 hours (Figs. 7, 8, 9 and 10), provide an insight into the scavenging process. It can be seen that as the saline water discharge is increased, the vertical and lateral movement of the saline water towards the freshwater screen attenuates. As the discharge is increased to 15 m^3/hr (i.e. same as the freshwater discharge), the vertically upwards movement of the saline water is completely arrested across the initial interface and there is a minor downwards movement of the fresh water towards the saline water screen (Figs. 9 and 10). This reduces salinity of the pumped saline water (Table 1). The salinity of the pumped fresh water decreases as the saline water discharge increases (Table 1).

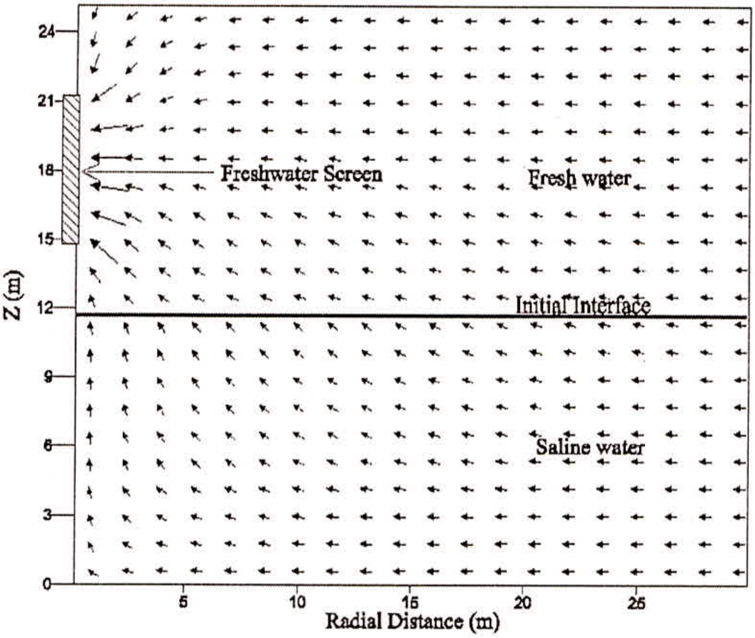

Fig. 7. Velocity distribution at the end of 24 hrs (Q_f = 15 cu. m/hr: Q_s = 0).

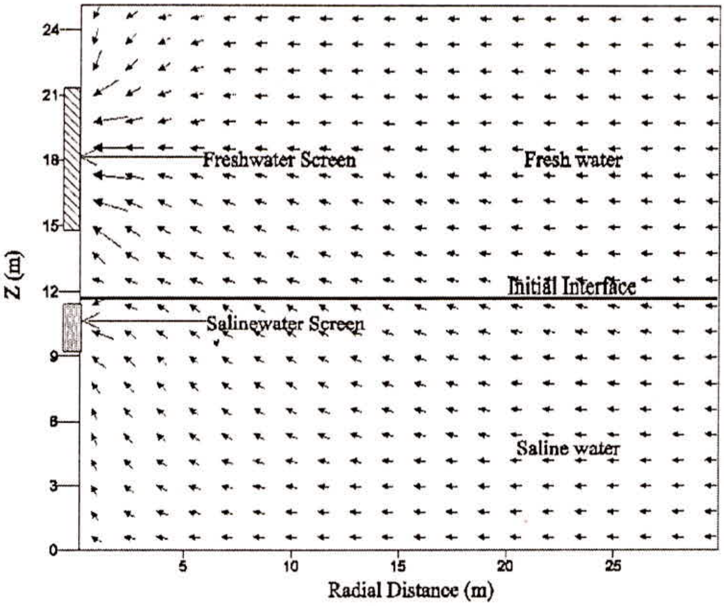

Fig. 8. Velocity distribution at the end of 24 hrs (Q_f = 15 cu. m/hr: Q_s = 2.5 cu. m/hr).

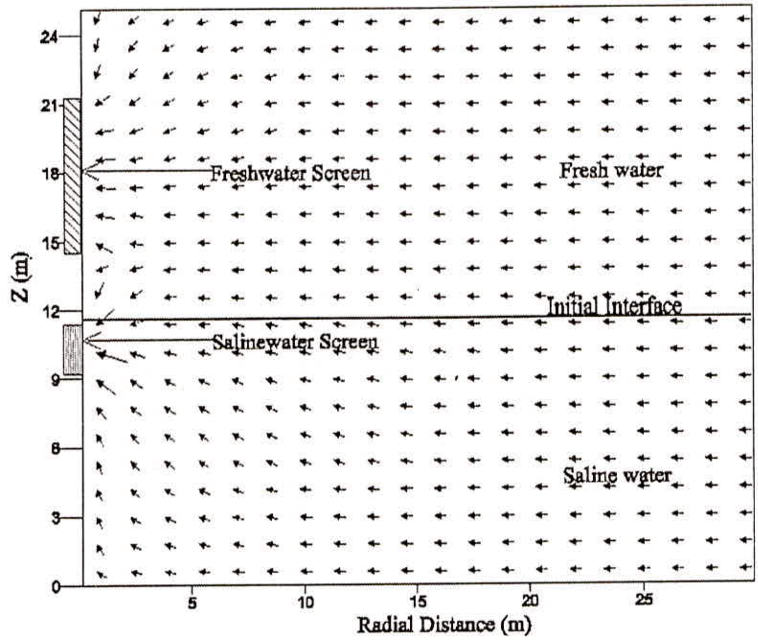

Fig. 9. Velocity distribution at the end of 24 hrs (Q_f = 15 cu. m/hr: Q_s = 15 cu. m/hr).

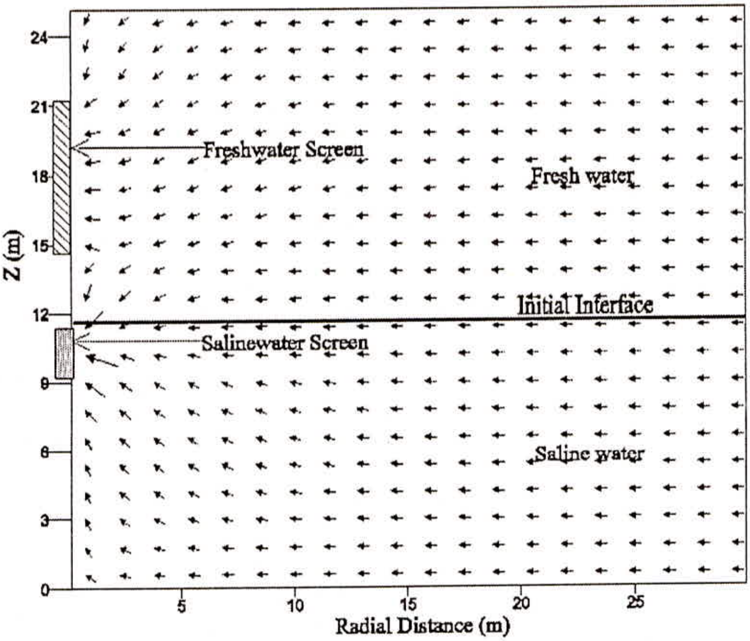

Fig. 10. Velocity distribution at the end of 24 hrs (Q_f = 15 cu. m/hr: Q_s = 30 cu. m/hr).

Table 1. Quality of pumped waters (Q_f = 15 m^3/hr)

Qs (m^3/hr)	*Salinity of pumped freshwater (mg/l)*	*Salinity of pumped salinewater (mg/l)*
0	2652	—
2.5	1615	29789
15	5	24346
30	0	21102

CONCLUSION

The vertically upward movement of the salinewater towards freshwater screen of a scavenger well system can be attenuated and even completely arrested by maintaining adequate salinewater discharge. However an excessively large salinewater pumping discharge can cause downwards flow of freshwater towards the salinewater screen leading to wastage of freshwater. Therefore it is necessary to optimize the salinewater discharge through numerical modelling.

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