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Compound Wells for Skimming Freshwater from Fresh Saline Aquifers

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23.1 Introduction

Groundwater development provides assured water supply for agricultural, municipal, and industrial activities. The agricultural groundwater development not only augments the canal water supply, but also facilitates timely irrigation at critical times. However, several aquifers worldwide contain fresh usable groundwater only in a not-so-thick layer toward the top. This freshwater layer is underlain by a relatively thick layer of unusable saline water. Such *Fresh–Saline* aquifers (termed henceforth as F–S aquifers) occurring invariably in coastal regions are quite common in inland aquifers also. In coastal regions, groundwater salinity is mostly of marine origin such as salinity originating from marine transgressions, seawater intrusion, incidental flooding by seawater, and groundwater enriched in salts by seawater sprays. In inland areas and parts of coastal areas, groundwater salinity is of terrestrial origin that can be attributed to natural or anthropogenic factors. Natural factors include groundwater enrichment in salts by evaporation at or near land surface or by dissolution of naturally occurring soluble minerals underground while anthropogenic factors include groundwater enrichment in salts by irrigation and subsurface waste disposal.

In India, F–S aquifers are frequently encountered in the fertile alluvial Indo-Gangetic Plains of North India, and deltaic formations on the east coast of India and Saurashtra coast of Gujarat. Globally the problem exists in several parts of the world, namely, basins of West and Central Asia, lowlands of South America and Europe, parts of North America, Northwestern Pacific margin, and eastern Australia. Most of the affected parts fall in the category of fertile agricultural areas, along the coast and in deltas.

The design challenge posed by the F–S aquifers is to arrive at such a well configuration that permits *skimming* of freshwater without drawing the saltwater into the pumped discharge. Such wells termed *skimming wells* have traditionally been partially penetrating wells tapping only the upper portion of the freshwater layer. The partially penetrating skimming wells, in spite of being simple to install and design, are not suitable if the freshwater thickness is less than 30 m (Asghar et al., 2002). Two other well systems (scavenger well, recirculation well) that seem to work well even when the freshwater layer is thin have been in vogue lately. These compound wells essentially reduce the rise of underlying saltwater toward the pumping well by way of additional innovative pumping/recharge.

Recognizing that hydraulically, the compound wells are essentially an extension of the partially penetrating well, the present chapter commences with a section on the partially penetrating well and goes on to build up the theory of the two compound wells.

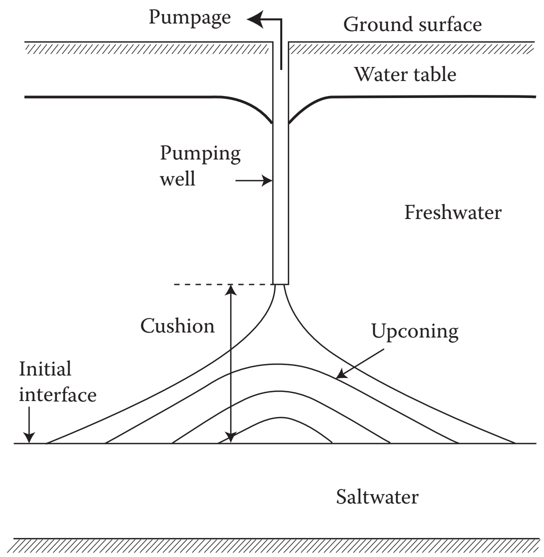

FIGURE 23.1
Saltwater upconing below a pumping well.

23.2 Traditional Development of Fresh–Saline Aquifers: Partially Penetrating Wells

Traditionally, groundwater is developed in F–S aquifers through partially penetrating wells tapping only the freshwater layer and leaving out adequate cushion between the screen-bottom and the static interface between the freshwater and saltwater (Figure 23.1). The cushion is necessary because the interface tends to rise (upcone) as a consequence of pumping. With prolonged pumping, the upconed interface may reach the screen and the well may start yielding groundwater of enhanced salinity. When the pumping stops, the upconed heavier saltwater starts falling and over time may reach its initial (static) position.

The phenomenon of upconing is mainly attributed to advective transport of saltwater. However, apart from the upconing, there is some upward movement of saltwater due to dispersion also, which leads to formation of a dispersed interface instead of a sharp interface between freshwater and saltwater. The dispersed interface, in which the fluid concentration varies from that of freshwater to that of saltwater, enlarges during the upconing process and this significantly affects the salinity of pumped water. Schmorak and Mercado (1969) observed that wells become contaminated with saltwater long before undiluted saltwater reaches them, a phenomenon ascribed to the miscible nature of freshwater and saltwater.

23.2.1 Simulation

The design of wells in freshwater aquifers is mostly focused on the discharge and drawdown only. However, the design of partially penetrating wells in F–S aquifers requires due attention to the upward movement of the interface during pumping and the downward movement in the recovery stage. Various strategies for quantification of this saltwater movement are discussed in the following paragraphs.

23.2.1.1 Sharp Interface Approach

Saltwater upconing below a partially penetrating well may be analyzed using the sharp interface method, which assumes freshwater and saltwater to be immiscible fluids. This method is applicable when the thickness of the dispersed interface is relatively small compared to the thickness of the aquifer. A dispersed interface is considered thin if it is less than one-third the thickness of the freshwater zone (Reilly and Goodman, 1985). Critical rise of a sharp interface is the rise to a location above which only an unstable cone can exist (Muskat, 1937).

Bear and Dagan (1964) presented the following analytical solution of the upconing in an anisotropic aquifer of infinite thickness.

$$\zeta(r,t) = \frac{Q}{2\pi(\Delta\gamma/\gamma_f)K_r D}\left[\frac{1}{(1+R^2)^{1/2}} - \frac{1}{[(1+T)^2+R^2]^{1/2}}\right] \tag{23.1}$$

Here

$$R = \frac{r}{D}\left(\frac{K_z}{K_r}\right)^{1/2} \quad \text{and} \quad T = \left(\frac{\Delta\gamma}{\gamma_f}\right)\frac{tK_z}{2\phi D} \qquad (23.2)$$

where $\zeta(r,t)$ = rise of interface above its position at a radial distance r from the center of well at time t; Q = time invariant discharge; γ_s, γ_f = saltwater and freshwater specific weights; $\Delta\gamma = \gamma_s - \gamma_f$; K_r, K_z = hydraulic conductivities in r and z directions, respectively; D = vertical distance between the initial position of interface and bottom of well; and ϕ = aquifer porosity. The major assumptions in this solution are that water is abstracted from a point sink, the aquifer is of infinite thickness, and upconing at the well center is small, that is, $\zeta(0,t) \le 0.25D$.

Dagan and Bear (1968) presented another analytical solution for an aquifer of finite thickness. The solution, based on the assumptions of a point sink and small upconing [$\zeta(0,t) \le 0.33D$], is as follows:

$$\zeta(r,t) = \frac{\gamma_f Q}{2\pi\,\Delta\gamma (K_r K_z)^{1/2}} \int_0^\infty \frac{\cosh[\ \ (A-D)]}{\sinh(\ \ A)} \times \left\{1 - \exp\left(\frac{-\lambda K_z \Delta\gamma t}{\phi[\gamma_f \coth(\lambda A) + \gamma_s \coth(\ \ B)]}\right)\right\} J_0(\ \ r)\, d \qquad (23.3)$$

where A, B = initial freshwater and saltwater layer thicknesses; J_0 = Bessel's function of first kind and order zero; and λ = Fourier function.

23.2.1.2 Dispersed Interface Approach

With the advent of modern electronic computers, it is perfectly possible to simulate numerically the *total* upward saltwater movement below a pumping partially penetrating well accounting for both the advective and dispersive transport—and without making the assumptions inherent in the analytical solutions. The end-product from such a simulation may comprise the spatial distribution of salt concentration in a well's vicinity and the salt concentration in the pumped water at advancing times (Shalabey et al., 2006). The contour of 0.5 concentration may be deemed to be the average interface.

Shalabey (1991) developed a numerical model of vertical saltwater movement below a partially penetrating well. The model incorporating a finite difference-based solution of the coupled differential equations governing two-dimensional axis-symmetric flow of variable density fluid was subsequently applied to the pumping and recovery tests carried out by Schmorak and Mercado (1969) on wells in the Ashqelon region in the coastal plain of Israel. The numerical solution reproduced the upconing and settlement of interface (0.5 isochlor) reasonably well uniformly at all values of ζ/D, even when the analytical solutions fail to reproduce the observed upconing (Figure 23.2). It also reproduced well the observed salt concentration in the pumped water (Figure 23.3) at advancing time. A parametric study on the model revealed that the upconing reduces as the screen length is increased. Further, it is found to decrease as the thickness of the saltwater decreases.

23.3 Design Aspects

The design of a skimming partially penetrating well has to satisfy all the general requirements of well design. The additional design variables are the cushion, duration of a pumping spell, and finally the rest period between two pumping spells. Incorporation of these design variables in design would apparently require simulation of vertical saltwater movement either by sharp interface or dispersed interface solution. The corresponding design criteria may be stated as follows.

23.3.1 Sharp Interface Approach

The design criteria with this approach could be as follows:

1. The cushion should be large enough to keep the upconed interface adequately below the screen-bottom at the end of a pumping spell of the design duration.
2. Rest period between two pumping spells must be long enough to permit the interface to fall back to its static position before the commencement of the next spell.

These criteria can be implemented by invoking the analytical solutions (Equations 23.1 and 23.3) for the sharp interface upconing described earlier. The residual upconing subsequent to the closure of pumping can be computed through superposition. This approach may lead to overestimation of upconing in case the screen length is not small enough. However, this may still provide "safe" but conservative design of the pumping discharge. The other issue as discussed earlier is that the upconing beyond the threshold level (0.33 times the cushion; Equation 23.3) may be underestimated leading to "unsafe" design of discharge. However, it may be recalled (refer Figure 23.2) that beyond 0.33D the upconed interface may become unstable and rise rather quickly. As such, it may be desirable to restrict the permissible

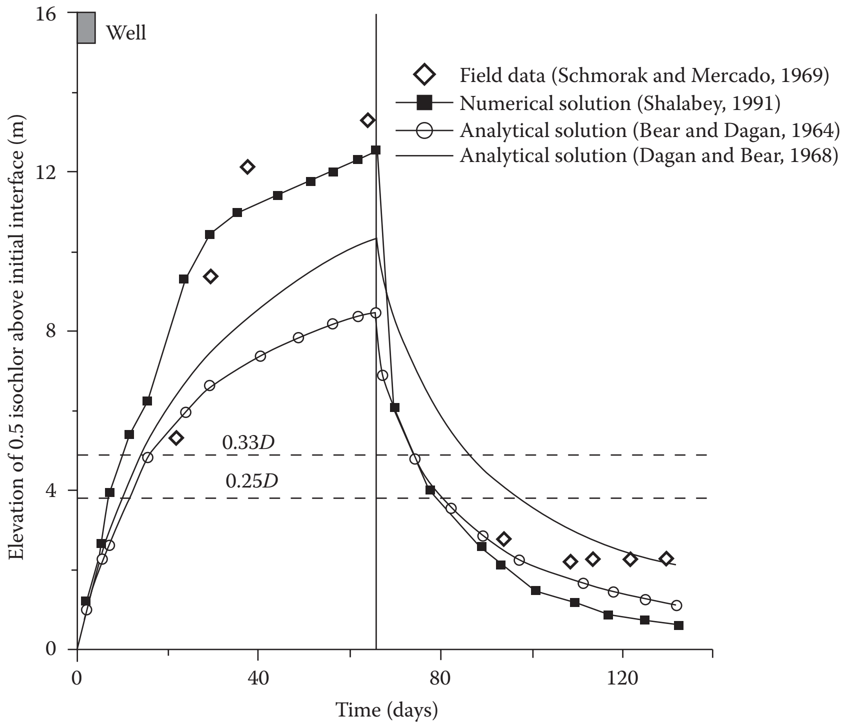

FIGURE 23.2
Upconing and settlement of dispersed interface versus time. (From Shalabey, M.E.E., Kashyap, D., and A. Sharma, *Journal of Hydrologic Engineering*, *ASCE*, 11(4), 306–318, 2006.)

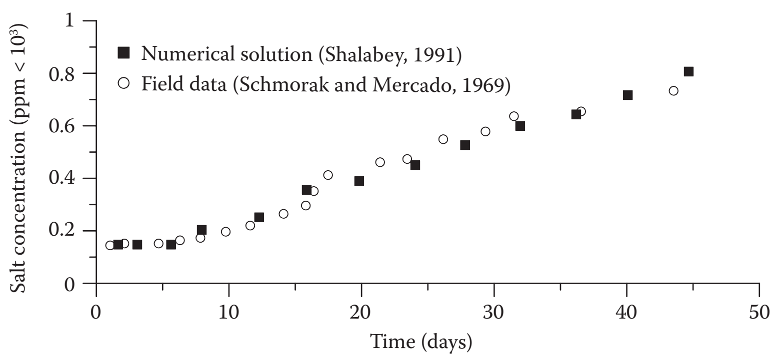

FIGURE 23.3
Illustration of increase in observed and simulated saltwater concentration in pumped water with time for given discharge in Ashqelon aquifer, Israel. (From Shalabey, M.E.E., Kashyap, D., and A. Sharma, *Journal of Hydrologic Engineering*, *ASCE*, 11(4), 306–318, 2006.)

upconing to 0.33*D*—for which the analytical solution (Equation 23.3) holds (the threshold limit for analytical solution given by Equation 23.1 is 0.25*D*). Thus, it may be concluded that the analytical solutions, in spite of rather restrictive assumptions, can be used for the designs.

23.3.2 Dispersed Interface Approach

As pointed out earlier, as a consequence of dispersion, the wells may start yielding saltwater long before the upconed interface encroaches on the screen. Thus, a more rigorous design requirement could be to ensure that salt concentration in the pumped water remains below an acceptable level. Thus, invoking a dispersion interface model, the design criteria could be as follows:

1. The cushion should be large enough to keep the salt concentration in the pumped water below the permissible value at the end of a pumping spell of the design duration.
2. Rest period between two pumping spells must be long enough to permit the 0.5 isochlor to fall back to its static position before the commencement of the next spell.

This approach, though more credible theoretically, may be more difficult to implement because it would require setting up a numerical model which always would have its own uncertainties like numerical dispersion, poorly known dispersion parameter, etc. As such, the sharp interface approach involving an easy-to-implement analytical solution may be preferable. The chances of saltwater entry into the pumping well may be small enough when the upconing is restricted to 0.33*D*. Nevertheless, the dispersed interface models are useful for the advancement of scientific knowledge and also for providing insight. For example, the desirability of restricting the upconing to 0.33*D* is derived from the dispersed interface modeling (Shalabey et al., 2006).

23.3.3 Suitability

The partially penetrating skimming wells, although simple to design and install, are effective in limiting saltwater upconing if the freshwater layer is not thin, that is, the freshwater thickness is more than 30 m. In case of thin freshwater lenses, two other well systems, namely the scavenger well and recirculation well can be usefully employed by incorporating additional innovative pumping/recharge mechanisms in the partially penetrating skimming wells. Details are as provided in the following sections.

23.4 Scavenger Well System

The scavenger well system consists of two wells, namely, production well and scavenger well, located side by side—usually located in a single bore hole. The production well taps the freshwater zone while the scavenger well taps the saline water zone. These wells pump fresh and saline waters from the same site simultaneously without mixing, through two separate discharge systems as shown in Figure 23.4.

The concept of the scavenger was developed independently by different workers in different parts of the world in the 1960s. C.E. Jacob in 1965 took out a patent on the "Doublet Well" (Wickersham, 1977), designed to recover the upper fluid, while recirculating the lower fluid and keeping the interface as a flow line, a concept essentially the same as the scavenger well. Long (1965) studied feasibility of scavenger well application in Louisiana, USA. Zack and Candelario in 1984 reported the effectiveness of scavenger wells in coastal areas of Puerto Rico, where many wells were abandoned because they were inadvertently screened in the saltwater part of the aquifer. By installing scavenger wells in these abandoned wells, freshwater could be extracted from the thin freshwater lenses occurring at the surface of the water table. The scavenger wells were tested further in the lower Indus basin and have shown their usefulness in skimming of freshwater (Stoner and Bakiewicz, 1992). More than 400 scavenger wells have been installed in the lower Indus basin to tackle water logging and soil salinity problems. More recently, Alam and Olsthoorn (2014) have numerically shown that scavenging is the only long-term option to solve the longstanding problem of sustainable groundwater extraction and overcome the salinization problem in F–S aquifers of the Indus Basin, Pakistan. The efficacy of scavenger wells has also been investigated for stopping saltwater intrusion in Louisiana (Tsai, 2011).

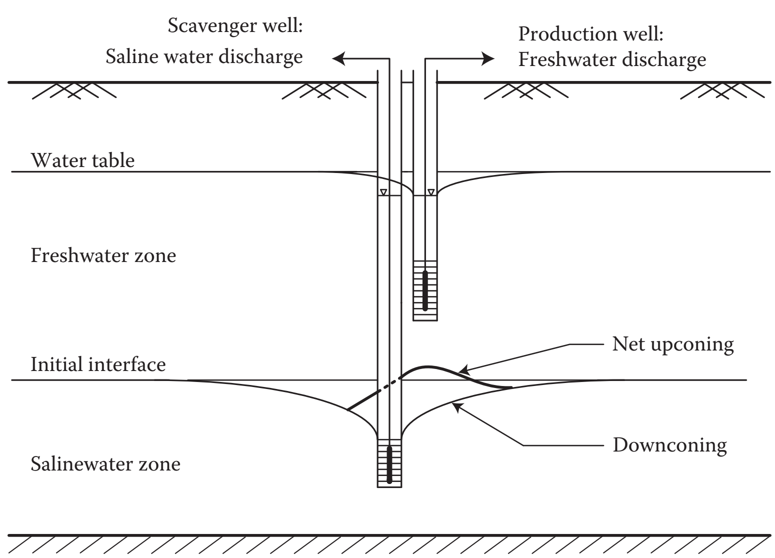

FIGURE 23.4
Saltwater upconing below a scavenger well system.

Basically, in a scavenger well system, the rise of saline water due to upconing caused by pumping from production well (Q_1) is countered by the downconing of the interface caused by pumping from a scavenger well (Q_2). The pumping rates from the two wells are adjusted in such a way that the underlying saline water does not intrude into the production well. While an under-pumping from the scavenger well may cause salinization of the production well, an over-pumping, apart from increasing the costs of pumping and the problem of saline water disposal, also creates downward gradient in the freshwater zone leading to wastage of freshwater.

23.4.1 Simulation of Scavenger Well System

The scavenging well system may be mathematically viewed as a well with two screens—first through which the production discharge is implemented, and the other through which the scavenging discharge occurs. As such, the system may be simulated invoking either the sharp interface approach, or the dispersed interface approach discussed earlier. Field and Critchley (1993) presented a solution for the upconing invoking Bear and Dagan's (1964) analytical solution for a partially penetrating well, and the principle of superposition.

$$\zeta_{net}(r,t) = \frac{Q_1}{2\pi(\Delta\gamma_1/\gamma_f)K_r D_1}\left[\frac{1}{(1+R_1'^2)^{1/2}} - \frac{1}{[(1+T_1')^2+R_1'^2]^{1/2}}\right] - \frac{Q_2}{2\pi(\Delta\gamma_2/\gamma_s)K_r D_2}\left[\frac{1}{(1+R_2'^2)^{1/2}} - \frac{1}{[(1+T_2')^2+R_2'^2]^{1/2}}\right] \quad (23.4)$$

Here, $\zeta_{net}(r, t)$ = net interface position at a radial distance r from the center of the pumping well at a time t since the beginning of pumpage. The subscripts 1 and 2 stand for production and scavenger well screens, respectively, and R' and T' are dimensionless distance and time parameters defined as follows.

$$R_1' = \frac{r}{D_1}\left(\frac{K_z}{K_r}\right)^{1/2} \quad R_2' = \frac{r}{D_2}\left(\frac{K_z}{K_r}\right)^{1/2}$$
$$T_1' = \left(\frac{\Delta\gamma_1}{\gamma_f}\right)\frac{tK_z}{2\phi D_1} \quad T_2' = \left(\frac{\Delta\gamma_2}{\gamma_s}\right)\frac{tK_z}{2\phi D_2} \quad (23.5)$$

where $Q_{1,2}$ = time invariant discharge rates, K_r, K_z = radial and vertical hydraulic conductivities, D_1 = distance between the interface and the bottom of the production well screen, D_2 = distance between the interface and the top of the scavenger well screen, γ_f, γ_s = specific weights of fresh and saline waters, $\Delta\gamma_1 = (\gamma_s - \gamma_f)$, $\Delta\gamma_2 = (\gamma_f - \gamma_s)$, and ϕ = aquifer porosity.

The analytical solution (Equation 23.4) is based on several assumptions discussed earlier. In case the assumptions are severely violated, the more rigorous approach accounting for dispersive transport of saltwater may be adopted for design of a scavenger well system (e.g., Saravanan et al., 2014). Such models based on the numerical solution of partial differential equations describing unsteady state two-dimensional axis-symmetric groundwater flow and transport in cylindrical coordinates can be used for studying the response of compound wells and arrive at the time variation of production well salinity and interface position.

23.4.2 An Insight into Scavenging Well Mechanics

Saravanan (2011) and Saravanan et al. (2014) conducted a detailed simulation study of the scavenging well system using the dispersed interface approach—revealing the mechanics of the system. The typical velocity fields are shown in Figure 23.5a and b. Figure 23.5a shows the velocity field with no scavenging discharge, that is, a partially penetrating well. For this kind of well operation, the vertical and lateral movement of the saline water is toward the production well that leads to upconing of saltwater. However, on introducing scavenging discharge, the vertical and lateral movement of the saline water toward the production well attenuates. In fact, as Q_2/Q_1 increases and scavenger discharge becomes equal to production well discharge (i.e., $Q_2/Q_1 = 1.0$) the vertically upward movement of the saline water is completely arrested across the initial interface and there is a minor downward movement of the freshwater toward the scavenger well (Figure 23.5b). These figures also reveal the necessity of optimal design of a scavenger well system to minimize both the freshwater wastage and excessive saltwater pumpage, which in turn leads to the problem of saline water disposal.

Figure 23.6 illustrates how the upconing attenuates as the scavenging Q_2/Q_1 is enhanced. For $Q_2/Q_1 \geq 0.6$, the upconing becomes insignificant. The time variation of the interface position below the well during pumping and recovery phases is shown in Figure 23.7. Figure 23.8 shows the variation in pumped water salinity at advancing times. The impact of introducing scavenging discharge in the form of significant reduction in the production well salinity is very much visible in this figure. It also reveals that as the scavenging discharge increases, the production well salinity decreases. The pumped water becomes practically salt-free as the scavenging discharge gets equal to the production well discharge.

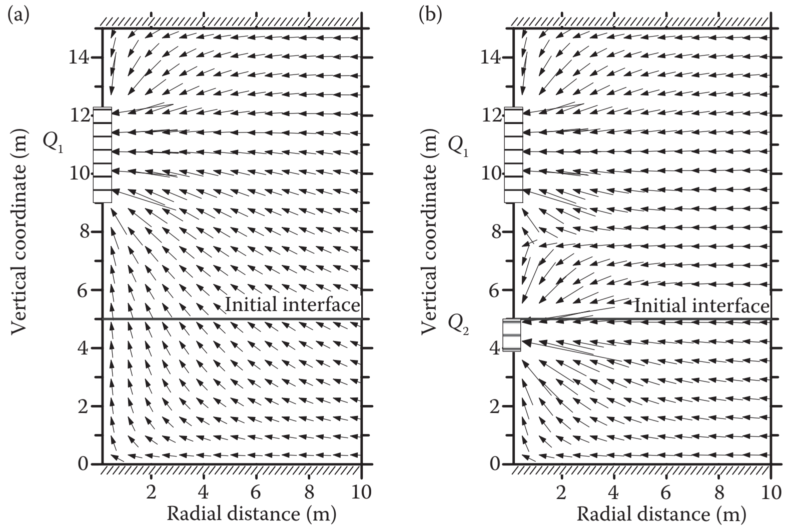

FIGURE 23.5
Velocity fields at the end of 24 hours for scavenger well system for $k_z/k_r = 0.3$ (a) $Q_2/Q_1 = 0.0$ and (b) $Q_2/Q_1 = 1.0$.

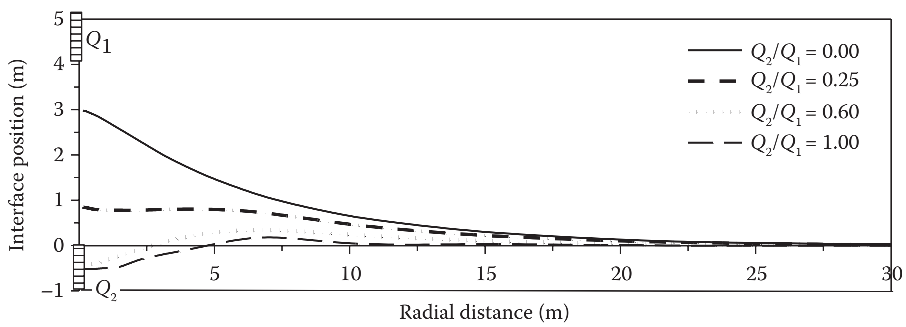

FIGURE 23.6
Impact of scavenger well on upconing: Interface position at the end of 24 hours.

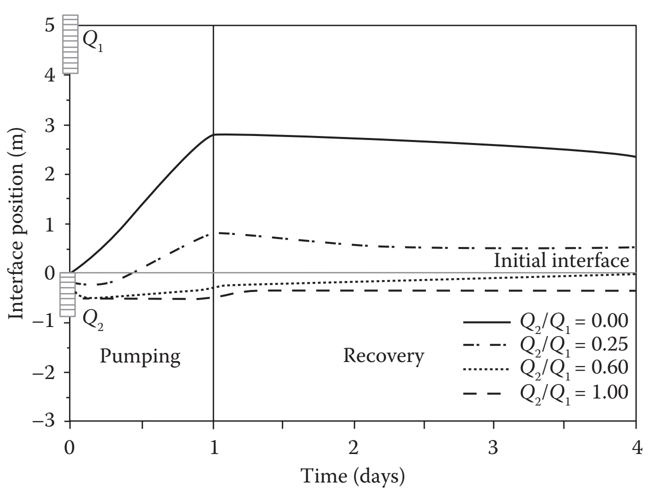

FIGURE 23.7
Scavenger well system: Time series of interface position during pumping and recovery ($r = r_w$).

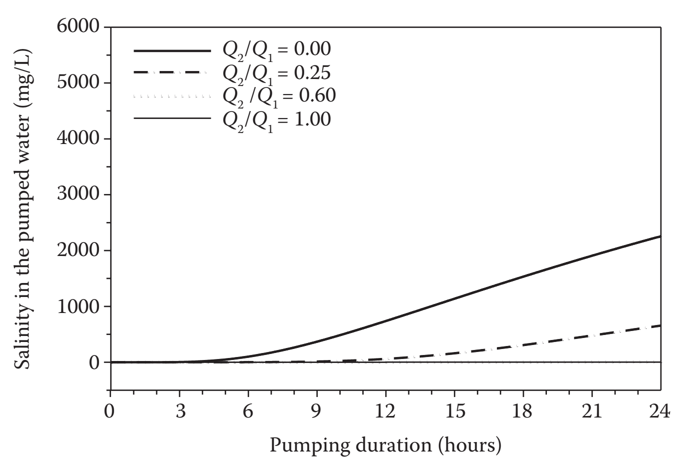

FIGURE 23.8
Scavenger well system: Time series of production well salinity.

23.4.3 Sensitivity Analysis

The simulation study on scavenging well mechanics also determines the sensitivity of the system performance with respect to Q_2/Q_1, k_z/k_r ratios, and thickness of freshwater zone. Figure 23.9 shows three isochlors (0.1, 0.2, and 0.3) at the end of 24 hours. Taking salinity in the saline layer (C_s) to be 30,000 mg/L, these isochlors represent variation of absolute salinity from 3000 to 9000 mg/L. It may be seen that at $Q_2/Q_1 = 0$, these isochlors terminate into the production well screen leading to some salinity in the production well. However, as Q_2/Q_1 increases the isochlors are downturned away from the production well.

The production and scavenger well salinities for various levels of the scavenging discharge at different k_z/k_r values at the end of 24 hours are presented in Table 23.1. The table shows that the production well salinity decreases as the scavenging discharge increases or vertical anisotropy decreases. This decrease is apparently on account of the reduced drawdown and hence reduced upconing as the scavenging discharge increases or vertical anisotropy decreases. Similarly, scavenger well salinity also slightly decreases as the scavenging discharge increases or vertical anisotropy decreases. This response is due to increase in the downward flow of freshwater toward the scavenger well and reduction in upconing as the scavenging discharge increases or vertical anisotropy decreases (refer to Figures 23.5 and 23.6).

23.4.4 Design Aspects

Saravanan et al. (2014) employed a numerical model to establish the optimum parameters for scavenger well design. It was established that optimal scavenger requirement (expressed as a percentage of the production discharge) varies from 30% to 140% with the permissible production well salinity as 2000 mg/L. The scavenging requirement reduces substantially as the permissible salinity level is increased to 3000 mg/L. At this level, the optimal scavenging requirement varies from 0.1% to 90% of the production discharge. In general, the optimal scavenging requirement is quite sensitive to production discharge, vertical anisotropy, and radial intrinsic permeability. It increases as the production discharge increases or vertical anisotropy increases or radial intrinsic permeability decreases.

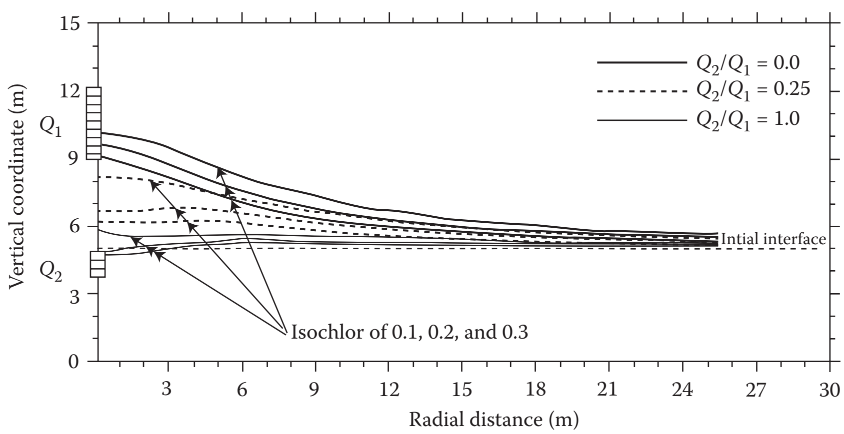

FIGURE 23.9
Scavenger well system: Dispersed interface isochlors (0.1, 0.2, and 0.3).

TABLE 23.1

Production and Scavenger Well Salinities for Varying Discharge Ratio and Vertical Anisotropy

	Production Well Salinity (C_1) in mg/L				Scavenger Well Salinity (C_2) in mg/L				Q_2/Q_1[a] Required for
	Q_2/Q_1				Q_2/Q_1				
k_z/k_r	0	0.25	0.6	1.0	0	0.25	0.6	1.00	$C_1 = C^*$
1.0	5666.53	2628.75	154.89	3.22	–	28,436.1	23,962.0	20,656.2	0.33
0.6	4242.05	1770.45	67.52	2.69	–	27,716.2	23,411.7	20,560.3	0.22
0.3	2286.67	664.42	7.22	1.99	–	26,343.1	22,402.2	20,406.1	0.04

[a] Required discharge ratio with permissible production well salinity (C*) = 2000 mg/L.

For low/moderate production discharge, the production well screen is optimally located quite close to the upper boundary of the saturated domain. However, for high production discharge, the production well screen needs to be lowered to accommodate the drawdown. In the numerical experiments performed by Saravanan et al. (2014), the production well screen was found to be optimally located at a depth varying from 12% to 26% of the initial freshwater thickness for both the permissible salinity levels (2000 mg/L and 3000 mg/L). The scavenger well screen was optimally located near the initial interface position irrespective of the magnitude of the production discharge.

23.5 Recirculation Well System

A recirculation well system comprises two closely spaced wells, a production well and a recirculation (recharge) well as shown in Figure 23.10. The screens of both the wells are located in the freshwater zone with an objective of reducing the effective upconing. The freshwater is pumped through the production well, and a portion of it is injected back into the aquifer through the recirculation well.

In 1963, Smith and Pirson applied this technique to reduce the mixing of saline water with oil. MacDonald and Kitanidis (1993) examined flow in an unconfined aquifer near a recirculation well, with emphasis on understanding the behavior of the free surface. Recirculation well system has also been used to remove the volatile organic compounds from groundwater aquifers (Lesage et al., 2003). A physical model of recirculation well system was developed by Sufi et al. (1998) and was used to calibrate a density dependent 3D finite element numerical model (Sakr, 1995). Using MATLAB®-based numerical models, Alam and Olsthoorn (2014) have shown that recirculation wells can substantially delay salinization due to upconing in F–S aquifers in the Indus Basin of Pakistan.

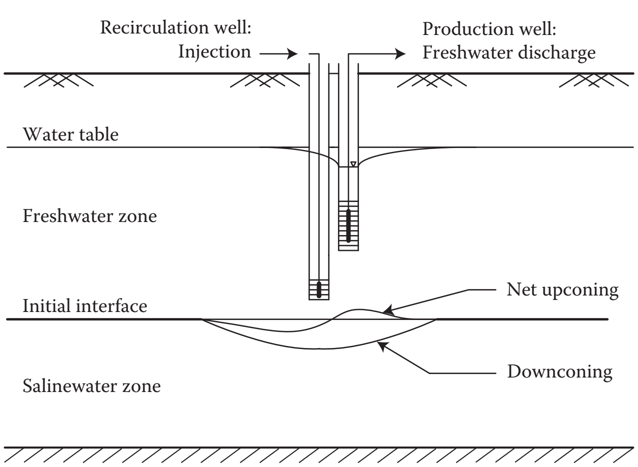

FIGURE 23.10
Saltwater upconing below a recirculation well system.

In a recirculation well system, the rise of saline water due to pumping of freshwater through a production well is countered by the downconing of the interface caused by recharging through a recirculation well. The discharge of a production well and a freshwater recharge through a recirculation well are adjusted so that the underlying saline water may not intrude into the production well. The saline water disposal problem present in the scavenger well system is overcome in the recirculation well design. Still, a flow pattern from the deeper recharge screen to the shallower production well depth may get established within the aquifer causing some intermixing of saline water with the circulating freshwater.

23.5.1 Simulation of Recirculation Well System

The recirculation well system may be mathematically viewed as a single well with two screens—first through which the production discharge is implemented, and the other through which the recharge into the aquifer takes place. The time variation of production well salinity and the position of the interface in response to the recharge from the recirculation well can be simulated using a numerical model based on the numerical solution of partial differential equations describing unsteady state two-dimensional axis-symmetric groundwater flow and transport in cylindrical coordinates (Saravanan, 2011). Such a model would facilitate realistic simulation of the recirculation well system accounting for both advective and dispersive components of saltwater movement in an F–S aquifer. Solutions based on a sharp interface approach have not been attempted.

23.5.2 Flow Mechanics of a Recirculation Well System

Saravanan et al. (2007) and Saravanan (2011) conducted a detailed simulation study of the recirculation well system using the dispersed interface approach—revealing the mechanics of the system. In a recirculation well system, the recirculation well screen can be placed (1) close to the initial interface—Configuration I or (2) close to the production well screen—Configuration II. Taking Q_1 as the production discharge and Q_2 as the recirculation well recharge, the typical velocity fields for different values of discharge ratio Q_2/Q_1 are shown in Figure 23.11a–c for both Configurations I and II. Figure 23.11a shows the velocity field for $Q_2/Q_1 = 0$ (corresponds to zero recharge) wherein the velocity is almost vertical

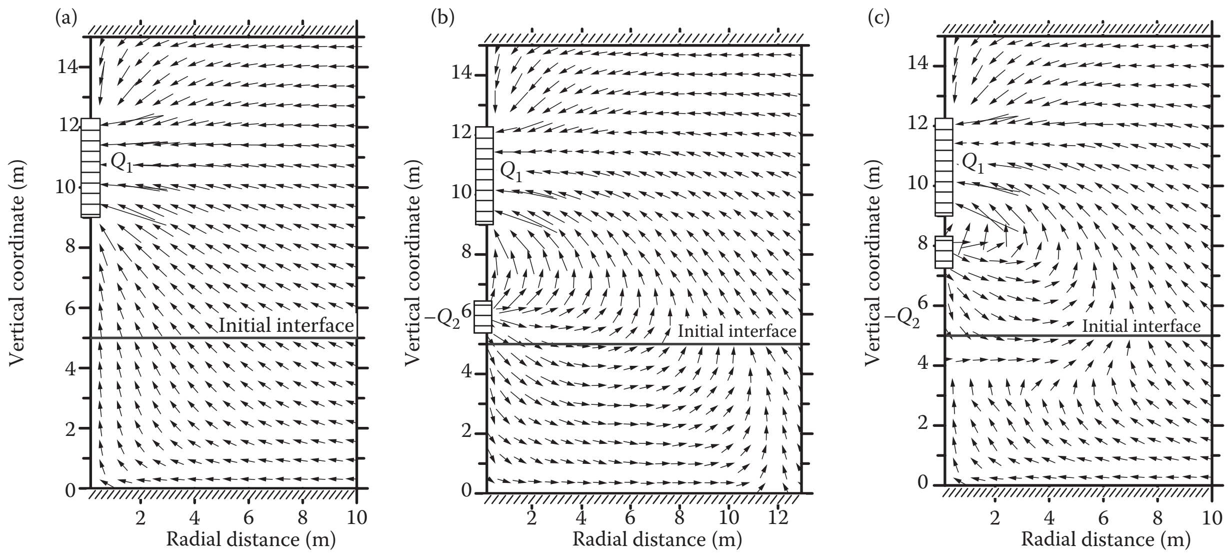

FIGURE 23.11
Velocity fields at the end of 24 hours for recirculation well system for $k_z/k_r = 0.3$ (a) $Q_2/Q_1 = 0.0$, (b) Configuration I: $Q_2/Q_1 = 0.5$, and (c) Configuration II: $Q_2/Q_1 = 0.5$.

just above and below the production well screen and almost horizontal across it. The vertical velocity below the production well is transporting the saline water toward the production well by advection. However, on introducing recharge, the vertical and lateral movement of the saline water toward the production well is cut down and instead a recirculating flow regime is created between the production and recirculation well. This prevents the advective transport of saline water toward the production well. The recirculating flow regime increases as the ratio Q_2/Q_1 increases. The regime of recirculating flow extends vertically below the initial interface in case the recirculation well is placed just above it (Figure 23.11b). In case the recirculation well is placed close to the production well (Figure 23.11c), a major portion of the recharge may be recaptured by the production well.

Figure 23.12a and b shows the model computed interface (i.e., 0.5 isochlor) at the end of 24 hours of recharging for the two positions of the recirculation well. The time variation of the interface position just below the recirculation well system during pumping and recovery phases is shown in Figure 23.13a and b for the two positions of the recirculation well. It may be seen that as the recirculation recharge (Q_2/Q_1) increases, the upconing reduces in both cases. The reduction is maximum in the vicinity of the well (when the interface position becomes even negative, i.e., *downconing*) and diminishes away from the well. It may further be seen that the reduction of the upconing on account of the recirculation is more pronounced in Configuration I (Figure 23.12a). This implies that as the recirculation screen is lowered and placed just above the initial interface position, the recirculation get more efficient.

The variation of production well salinity (C_1) at advancing times is shown in Figure 23.14a and b for the two positions of the recirculation well. The figures reveal that as the ratio Q_2/Q_1 increases the production well salinity reduces. The reduction is quite significant as the ratio Q_2/Q_1 increases beyond 0.4 for both positions of the recirculation well. A comparison of corresponding C1 time series presented in Figure 23.14a and b reveals that generally attenuation of C_1 is more pronounced for Configuration II of the recirculation well. However, if the production well salinity increases beyond 2500 mg/L, then the salinity of recharging water (which is a portion of production discharge) also increases, resulting in ineffective control of upconing through Configuration II. In such a case, Configuration II yields slightly higher C_1. It is thus inferred that while Configuration I is more efficient in controlling the upconing, Configuration II generally controls the production well salinity (C_1) more efficiently.

23.5.3 Sensitivity Analysis

The simulation study discussed above determines the sensitivity of the system performance with respect to Q_2/Q_1, k_z/k_r ratios, and thickness of freshwater zone for both configurations I and II. Figure 23.15a and b shows three isochlors (0.1, 0.2, and 0.3) at the end of 24 hours. Taking $C_s = 30{,}000$ mg/L, these isochlors represent variation of absolute salinity from 3000 to 9000 mg/L. It may

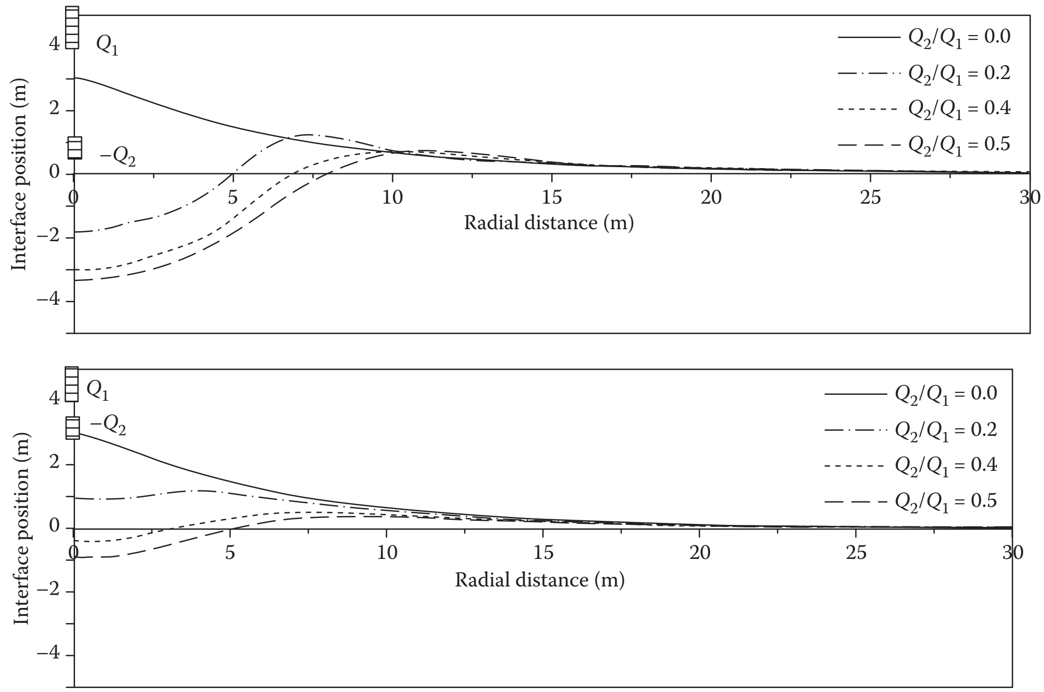

FIGURE 23.12
Impact of recirculation well system on upconing for $k_z/k_r = 0.3$: Interface position at the end of 24 hours (a) Configuration I and (b) Configuration II.

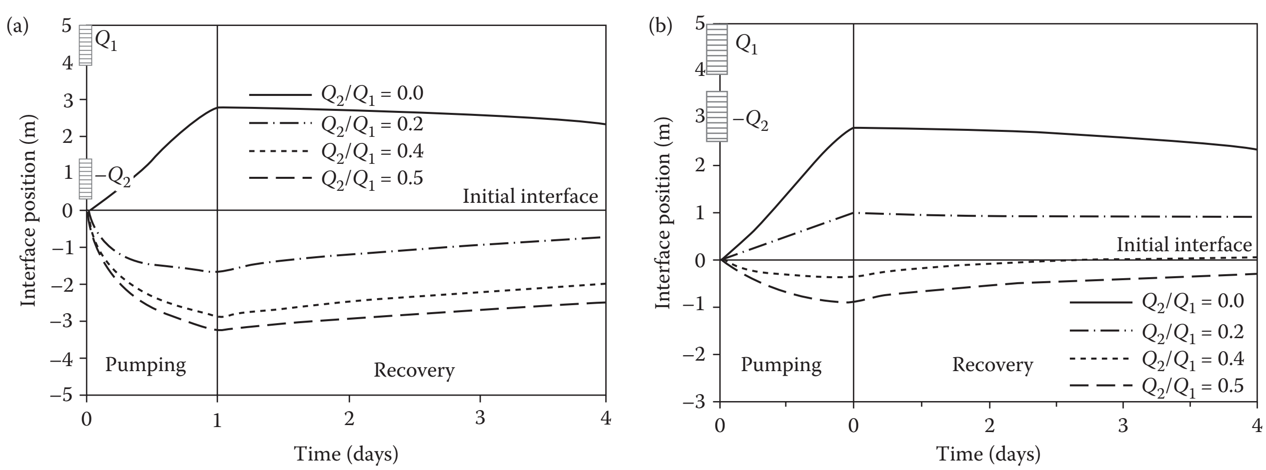

FIGURE 23.13
Recirculation well system: Time series of interface position during pumping and recovery ($r = r_w$) for $k_z/k_r = 0.3$ (a) Configuration I and (b) Configuration II.

be seen that at $Q_2/Q_1 = 0$, these isochlors terminate into the production well screen leading to some salinity in the production well. However, as Q_2/Q_1 increases, the isochlors are downturned.

The salinity levels in the pumped water for various Q_2/Q_1 and k_z/k_r ratios are presented in Table 23.2. Further, assuming the permissible salinity in pumped water to be 2000 mg/L, the necessary recirculation recharge rates are also interpolated and presented in the table. This salinity level is suitable for irrigating salt-sensitive crops (Ayers and Westcot, 1985). It may be seen that the placement of the recirculation screen in Configuration II leads to a lower requirement of recirculation recharge.

The scavenging discharge/recirculating recharge effectively reduces the vertically upward velocity component near the interface and hence reduces the resultant upconing. Irrespective of well configuration and discharge/recharge ratio (Q_2/Q_1), increase in k_z/k_r increases the upconing and consequently leads to more salinity in the production well. The upconing and production well

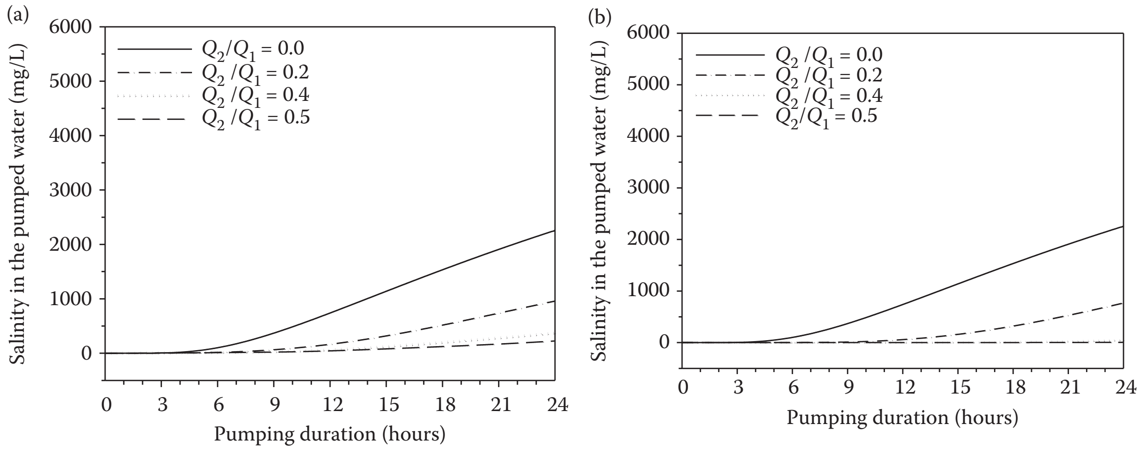

FIGURE 23.14
Recirculation well system: Time series of production well salinity for $k_z/k_r = 0.3$ (a) Configuration I and (b) Configuration II.

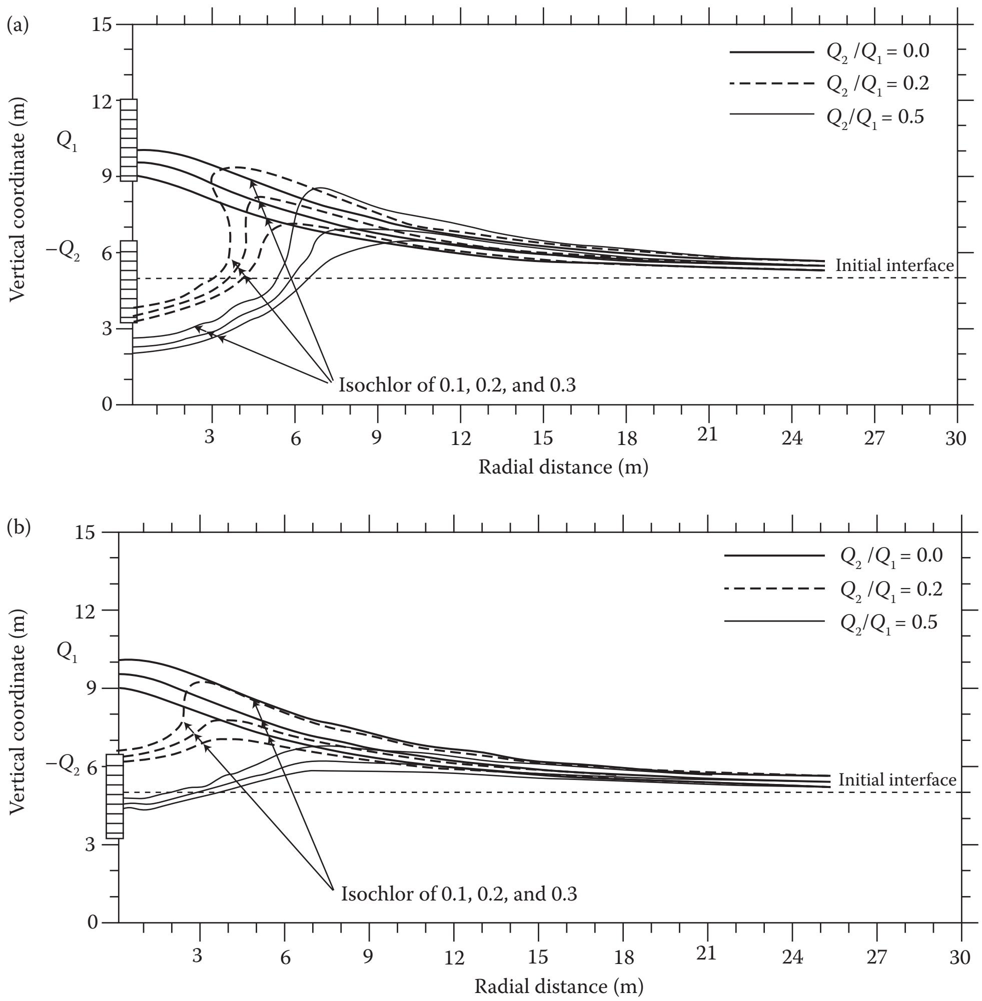

FIGURE 23.15
Recirculation well system: Dispersed interface isochlors (0.1, 0.2, and 0.3) for $k_z/k_r = 0.3$ (a) Configuration I and (b) Configuration II.

TABLE 23.2

Production Well Salinity for Varying Recharge Ratio and Vertical Anisotropy

Recirculation Well Position	k_z/k_r	Production Well Salinity (C_1) in mg/L — Q_2/Q_1 0	0.2	0.4	0.5	Q_2/Q_1[a] Required for $C_1 = C^*$
Close to the initial interface (Configuration I)	1.0	5666.53	4107.85	2698.5	2122.2	0.52
	0.6	4242.05	2620.27	1435.32	1026.78	0.30
	0.3	2286.67	968.07	369.01	227.4	0.04
Close to the production well (Configuration II)	1.0	5666.53	4377.96	2138.33	1113.27	0.41
	0.6	4242.05	2677.1	738.91	256.68	0.27
	0.3	2286.67	774.42	45.27	5.31	0.04

[a] Required recharge ratio with permissible production well salinity (C^*) = 2000 mg/L.

salinity are more sensitive to the ratio Q_2/Q_1. As Q_2/Q_1 increases, the upconing reduces and even completely vanishes at large Q_2/Q_1. However, in a scavenger well system, an excessively large Q_2/Q_1 can cause downconing, which is due to flow of freshwater toward the scavenger well. Similarly, in a recirculation well system excessively large Q_2/Q_1 may cause downconing, which is due to significant mixing of freshwater with saline water. The excessively large Q_2/Q_1 causes wastage of freshwater and increases the overall pumping cost.

23.5.4 Design Aspects

Placing the recirculation well screen close to the initial position of the interface is effective in controlling the upconing. However, this screen position leads to widening of the dispersed interface causing enhanced production well salinity. On the other hand, placement of the recirculation well screen close to the production well, though not so effective in controlling the upconing, restricts the dispersed interface more effectively and hence reduces the production well salinity more significantly.

Numerical experiments have shown that the vertically upward movement of the saline water toward the production well screen is attenuated with the production well salinity reduced by 60% by a recirculation recharge equaling 40% of the production discharge while placing the recirculation well screen close to the production well. However, when the recirculation well screen is placed close to the interface, a recirculation recharge equaling 50% of the production well discharge is found to show similar attenuation/reduction.

23.6 Conclusion

Freshwater is underlain by saline water in many aquifers worldwide. In case of thin freshwater lenses, the compound wells can prove to be more effective than the traditional partially penetrating skimming well in controlling the saltwater upconing and pumping water of permissible salinity. Depending on the existing field conditions at a given site, the compound wells may be developed as a scavenger well or a recirculation well system. However, excessive scavenging discharge/recirculation recharge could easily be counterproductive. This calls for a credible simulation of the flow/transport mechanisms that attenuate the upconing, and evolving optimal designs.

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