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A Review of Modeling Approaches to Simulate Saline-Upconing under Skimming Wells

Muhammad Mazhar Saeed
Centre of Ecel. in Wat. Resour. Eng., Lahore, Pakistan

M. Bruen
University College, Dublin, Ireland

M.N. Asghar
International Water Management Inst., Lahore, Pakistan

The occurrence of saline water along with fresh water in inland aquifers is due to different reasons. The extraction of fresh water from these aquifers is severely hampered by the underlying saline water. The saline water may rise in the form of a cone under the well bottom if the design and operational parameters for skimming well are not selected carefully. Physically, it is difficult to play with different design and operational scenarios due to economic and time constraints. Analytical and numerical models can help solve this problem. The paper reviews different models to simulate the saline-upconing under different pumping regimes. These models are categorized based on the assumptions of sharp interface and transition zone.

Introduction

In a fresh-saline aquifer system, the understanding of saline water movement in response to fresh water extraction by pumping wells is important in any assessment of fresh water resources (Tellam and Lloyd 1986; Tellam *et al.* 1986). The possible causes of saline water occurrence in these aquifers are; seawater intrusion (ASCE 1969), native saline groundwater (Ahmed 1979), washing of salt contents in soils (Richards 1954), saline water disposal in deep wells (ASCE 1969), dissolution of salt rocks in the formation (Wirojanagud 1984), and salts in runoff water (Sowayan and Allayla 1989). The exploitation of groundwater in these areas is severely hampered by the saline water intrusion into fresh water zones.

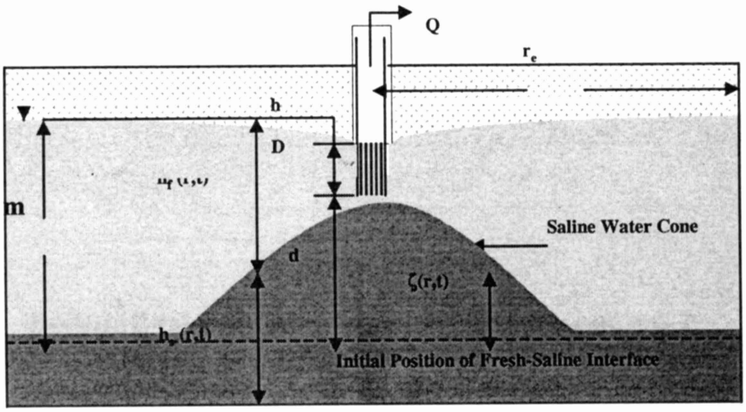

Fig. 1. Saline-upconing under skimming well in unconfined inland aquifer.

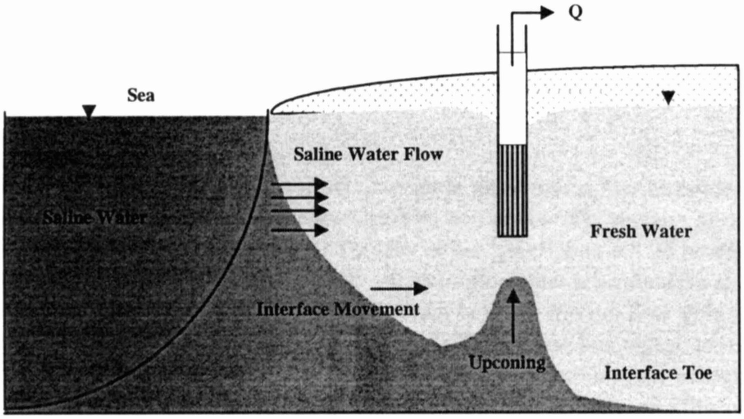

Fig. 2. Combined phenomena of saline-upconing and seawater encroachment in coastal aquifer.

In a coastal aquifer, there is a direct contact between inland fresh water and marine saline water at a sloping interface. The interface extends toward land and adopts the form of a wedge, called interface toe, resting on the aquifer floor, The fresh water thickness decreases from the interface toe toward the sea. In equilibrium, the fresh water flows from land towards the sea due to the hydraulic gradient and the interface is stationary. If the fresh water is extracted by pumping, the interface will start moving towards land to maintain hydraulic equilibrium and the movement of water will be from the sea towards land. This phenomenon is termed seawater encroachment. During seawater encroachment, the interface toe will move more rapidly than the upper portion of the interface due to greater difference in pressure caused by fresh water and saline water. In seawater encroachment, the saline water is confined to the edges of the fresh water and the interface between fresh water and saline water is tilted. Llobregat delta in Spain (Custodio 1981), Costa de Hermissillo in Mexico (Andrew 1981), Island of Ven in Sweden (Lindh and Berndtsson 1986), southwest region of Bangladesh (Nobi and Gupta 1997), western Dead Sea area (Yechieli 2000), Hernando county, Florida, USA (Guranasen *et al.* 2000) and Jericho area, Jordan Valley, Israel (Marie and Vengosh 2001) are few examples of this case.

In inland aquifers, the native deep groundwater is saline water. This saline water has marine origin, which is either trapped in the sediments during deposition or invaded the sediments during previous high level of the sea. For example Colorado, Wyoming and Utah (ASCE 1969), Mississippi River alluvial aquifer, north-eastern Louisiana in United States (Whitefield 1975) and Indus plain in Pakistan (Ahmed 1979; Sufi 1999). As a result of recharge to these aquifers, fresh water layers lay over saline water in such a way that the fresh water and saline water portions of the aquifers can be penetrated vertically by the same well.

Under natural conditions, fresh and saline waters in inland aquifers are in equilibrium. Extraction of fresh water disturbs this equilibrium and saline water may start moving up towards the well bottom in the shape of a cone. This phenomenon is termed saline-upconing (Fig. 1). A similar situation exists when fresh water near shore is extracted by a well. In this case, the upconing phenomenon accompanies an inland movement of seawater interface towards the well (Fig. 2). A typical example of this is near-coastal well fields in Sultanate of Oman (Sarvary 1995).

Physical Processes in Upconing – When water is pumped from the fresh water layer of the aquifer, the drawdown cone propagates out from the well. This causes an initially horizontal interface to move up as the system tries to maintain equilibrium along the interface. When the pumping rate is increased, a new equilibrium is established following a transition period and there is a new head distribution in each layer. Up to a certain pumping rate, equilibrium with a raised interface is possible. At a specific pumping rate, the interface is unstable. Any increase in pumping rate will move saline water into the pumping well. This pumping rate is termed the critical pumping rate and the corresponding height of the cone is termed the critical rise (Reilly and Goodman 1985). It is observed that the term critical pumping rate, and hence critical rise, is misleading as it will depend on the thickness of fresh water lens and recharge to the well. The critical pumping rate will be high if the thickness of fresh water lens is large and the recharge to the well is high. As long as the well discharge is equal to or less than the recharge, the saline water will not intrude the well. At a specific well discharge higher than the recharge, the saline water may enter into the well bottom.

In the situation when the saline water has already intruded the well, immediate reduction in well discharge will not result in a salt free water supply (personal communication; Stoner 1997). This can be viewed from the streamlines that are flowing

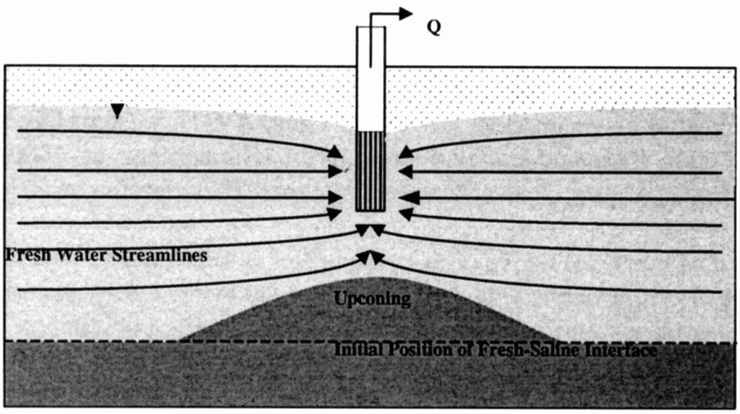

Fig. 3. Streamlines pattern during initial stage of upconing under skimming well.

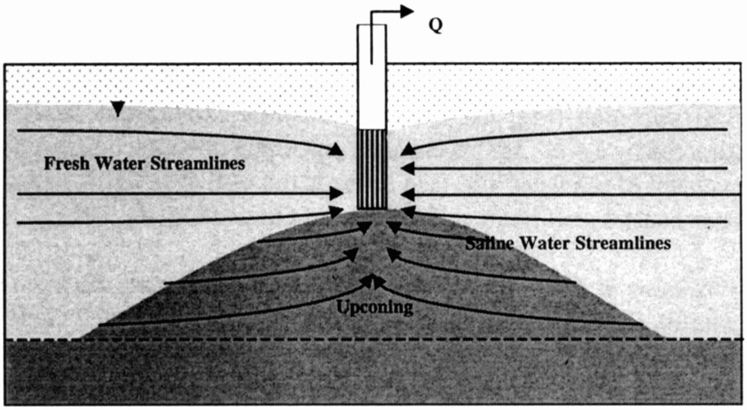

Fig. 4. Streamlines pattern during final stage of upconing under skimming well.

into a well, especially those flowing up from below. At initial stage of pumping, much of the water contribution is from the fresh water layer (Fig. 3). The saline cone is formed by the streamlines tangential to the top of the saline layer. All the streamlines below these ones will conduct saline water into the well (Fig. 4). Now, if the well discharge is reduced, the flow towards the well will continue along the same streamlines but at a reduced rate (*i.e.* start of well recovery). The streamlines, which originate from saline water layer, will vanish eventually at full recovery and saline cone will slowly subside back into the saline layer. Here it should be noted that the position of the interface, after it subsides, would be higher than the initial position. This change in position may be attributed due to mixing between two fluids during pumping. A steady-state situation in upconing may arise when the drawdown reaches a constant head recharge boundary or the aquifer is recharged naturally from rainfall or irrigation field losses.

The upconing phenomenon depends upon the pumping rate, pumping duration, initial position of the interface, well penetration with respect to interface and geo-hydrological properties of the aquifer (Reilly and Goodman 1987). Among these, the geo-hydrological properties and the initial position of interface of an aquifer cannot be changed. The manageable factors are pumping rate, pumping duration, and position and length of screen. The nature of the ultimate use of the water decides which of the above factor can be controlled without affecting the purposes of groundwater extraction.

To control the upconing under pumping wells in fresh-saline aquifers, different skimming well options are being used. A skimming well is a general term used to represent a well, in which the depth of the well is defined by taking into consideration the underlying saline water layer, and with an intention to extract relatively fresh water. The types of skimming wells include shallow tube wells (Fig. 5), skimming tube wells (Fig. 6), scavenger wells (Fig. 7), shallow dug wells and radial collector wells (Fig. 8) and. Among these, shallow tube wells and skimming tube wells are common among farming communities in the Indus basin of Pakistan due to the availability of locally manufactured materials and technical manpower, and less technicalities involved in operation and maintenance. A shallow tube well is used in thick fresh water layers (> 45 m). The shallow tube well partially penetrates in the fresh water layer and is operated by a centrifugal pump. A skimming tube well is used in relatively thin fresh water layer (45 – 25 m). In this well, two or more well points (or strainers) are jointed together and are operated by a single centrifugal pump. This technique gives more discharge, spatially distributes the pumping stress, and hence reduces the hazard of upconing. Due to the overlapping of drawdown cones at different well points, the maximum rise of saline cone may not be under any of these wells. The number of well points in skimming tube wells may vary from 2 to more than 16. In a scavenger well, two casings are placed either in single borehole or closely spaced boreholes. One casing is screened at shallow depth in fresh water while the other is screened just above the fresh-saline interface. These two wells are operated simultaneously and discharge separately. The rise of saline water in response to pumping of first shallow well is countered by the second deep well. The discharge of shallow and deep wells are adjusted in proportion to each other so that underlying saline water may not intrude the fresh water from shallow well. The discharge from the deep well is disposed into drains. The scavenger wells are expensive, difficult to operate due to discharge adjustment, and create environmental problems due to disposal of saline water.

The present paper reviews the modeling approaches to simulate the upconing phenomenon under skimming wells. Acknowledging that the present work has much similarity with modeling the lateral movement of the interface in coastal aquifers, mainly those previous studies are reviewed, which are closely related to the problem of upconing in inland fresh-saline aquifers.

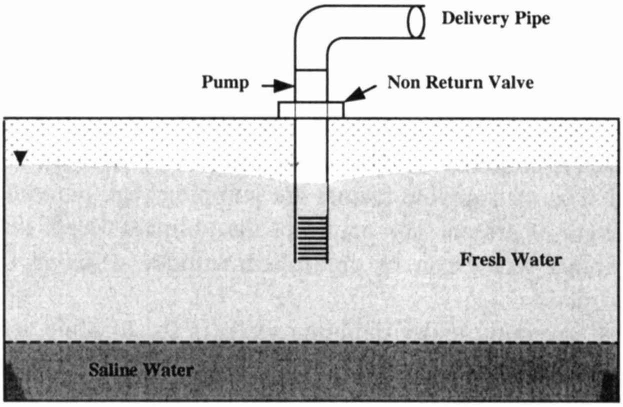

Fig. 5. Schematic presentation of shallow tubewell.

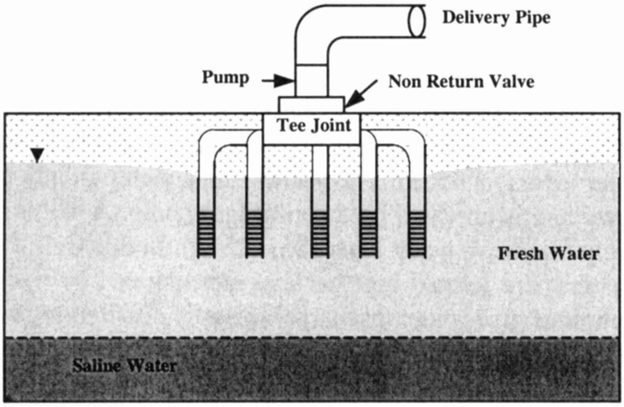

Fig. 6. Schematic presentation of skimming tubewell.

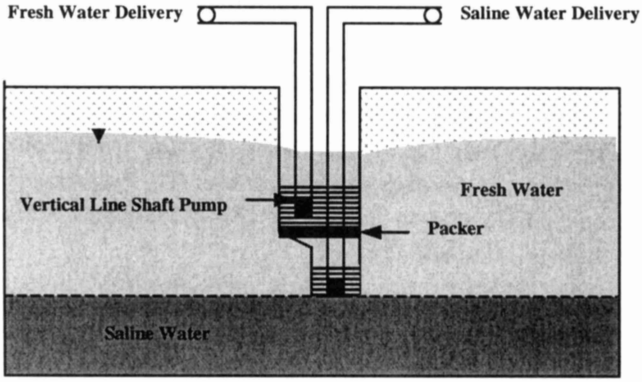

Fig. 7. Schematic presentation of scavenger well.

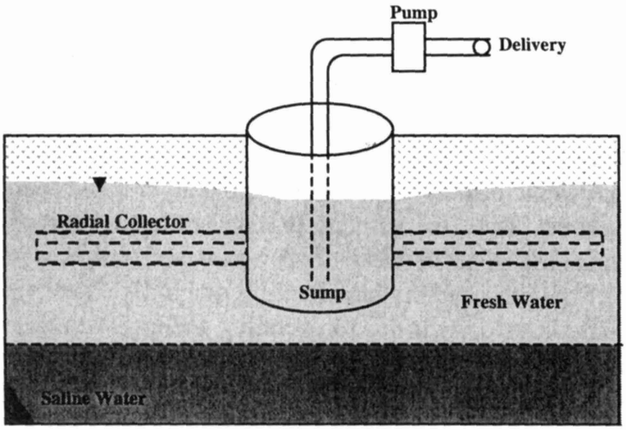

Fig. 8. Schematic presentation of radial collector well.

Representation of the Fresh-Saline Groundwater Interface

The analyses of upconing phenomenon in fresh-saline aquifers can be categorized depending upon the assumptions made regarding the surface at which the fresh water and saline water are in contact. These assumptions are discussed below.

Sharp Interface Assumption

A sharp interface assumes that there is a discrete change in concentration at the interface between fresh water and saline water. The concentrations of fresh water and saline water are uniform throughout the respective domain but changes abruptly at the interface. The concentration at the sharp interface is in between of the fresh water and saline water concentrations, but the width of sharp interface is assumed to be so small with respect to the thickness of the aquifer that it does not have any practical significance.

The sharp interface assumption was initially introduced in petroleum industry while observing the behavior of underlying water during oil extraction (Muskut and Wyckoff 1935). In case of immiscible fluids like oil and water, this assumption seems reasonable. The application of this assumption to fresh-saline water interaction thus also considers fresh water and saline water as immiscible fluids. This assumption is supported by field observations in coastal areas of Israel (Schmorak and Mercado 1969) and in an aquifer near Miami, Florida (Rushton 1980). On the other hand, researchers (Cooper 1959; Kohout 1980) have reported a wide transition zone and argued that the sharp interface assumption cannot be used in these cases. Anyhow, in case the mixing zone between two fluids is relatively small compared to the thickness of the aquifer, it is possible to assume a sharp boundary between the two fluids (Bear 1979).

Transition Zone Assumption

In reality, fresh water and saline water are miscible fluids. A mixing zone exists at the boundaries where these two fluids are in contact. This mixing zone is termed the transition zone. The concentrations in the transition zone change gradually from fresh water to saline water. The mixing process in the transition zone is mainly controlled by hydrodynamic dispersion caused by the temporal and spatial variations in local velocity patterns. Thus, the velocity that occurs in the region will govern the extent of the transition zone between fresh water and saline water (Rumer and Harleman 1963). Spatial variability in velocity is due to field heterogeneity whereas temporal variability in velocity is due to upconing and intrusion processes, and seasonal changes in aquifer recharge and discharge (and also due to tidal effects in case of coastal aquifers only). Generally, in inland fresh-saline aquifers, the spatial variability in velocity contributes more in causing hydrodynamic dispersion than temporal variability in velocity. Anyhow, temporal variation should increase dispersion to some extent as well.

The location and shape of the transition zone depend on several factors. These include the relative densities of fresh water and saline water, the rate of discharge of the pumping well, hydrogeology, and the hydrodynamic dispersion of the aquifer. Among these factors, hydrodynamic dispersion depends upon molecular diffusion and longitudinal and transverse dispersivities. Longitudinal and transverse dispersivities are directly dependent on anisotropy and heterogeneity of the porous medium (Volker and Rushton 1982).

Theoretically, the mixing between fresh water and saline water is a continuous process under natural flow conditions and the concentration of the fresh-saline aquifer must become uniform after a long period. Practically, the continuous flushing of fresh water occurs towards the sea in coastal aquifers and fresh water recharge occurs in inland aquifers from precipitation, field irrigation losses, and seepage from canals and rivers. The continuous flushing of fresh water towards sea (in case of coastal aquifers) and continuous fresh water recharge (in case of inland aquifers) counter balance the theoretically infinite increase of the transition zone width. As a result, the salinity of the transition zone gradually decreases in the upward direction.

Comments on Sharp Interface and Transition Zone Assumptions

In most of the fresh-saline aquifer studies, either the sharp interface assumption or the transition zone assumption is taken. Naturally, a transition zone of finite thickness always exists even when the assumption of a sharp interface is justified. In fact, the assumption of a sharp interface significantly reduces the mathematical difficulties. Therefore, sometimes, a sharp interface is assumed at some specific concentration level in the transition zone for ease in calculations. In some field studies, the position of the interface was assumed at levels corresponding to 50 per cent of the salinity difference between fresh water and saline water (Schmorak and Mercado 1969; Kemper *et al.* 1976). In practical situations, the use of the sharp interface assumption is erroneous due to the possible existence of a wide transition zone. For instance, when pumping starts, the transition zone moves up, and widens. Unless the pumping rate is carefully selected, saline water may enter the pumping well long before the interface (Bear 1979). For calculation purposes, we suggest assuming the position of sharp interface in the mixing zone below the salinity level at which the concentration is unacceptable with regard to the planned water use to avoid the chance of water quality deterioration.

There are some other terms, such as zone of diffusion and zone of dispersion, which are used occasionally in the literature (Brown 1925; Back *et al.* 1979) to represent the boundary between fresh water and saline water. The term 'zone of diffusion' is misleading as molecular diffusion only contributes a small part of the whole mixing process (Kohout 1980). The term 'zone of dispersion' is more descriptive as the mechanical mixing dominates in fresh-saline aquifers. Anyhow, the term transition zone is used widely in most of the literature, and we will stick to this terminology in our present work.

Simulation Models and Related Studies

The models used to simulate saline-upconing under skimming wells may be grouped into two categories on the basis of the assumption made regarding the fresh-saline interface, *i.e.* sharp interface or transition zone. But before proceeding to the discussion of the simulation models, it is appropriate to review the Ghyben-Herzberg model (Bodan-Ghyben 1889; Herzberg 1901), which was the basis of the most of initial works, especially the sharp interface models.

Ghyben-Herzberg Model

The Ghyben-Herzberg model relates the fresh water head to the depth of the interface with reference to the sea level for a fresh-saline aquifer system in static equilibrium. According to the model, the hydrostatic pressure at both sides of the interface is equal and is given as

$$\gamma_f(h_f(x) - \zeta(x)) = \gamma_s(-\zeta(x)) \tag{1}$$

or

$$\zeta(x) \equiv -\delta h_f(x) \tag{2}$$

where $h_f\,(x)$ is fresh water head (L) from mean sea level, γ_f and γ_s are specific weights of fresh water and saline water (ML^{-3}) and are approximately 1,000 kg-m^{-3} and 1,025 kg-m^{-3} respectively, $\xi\,(x)$ is depth of saline interface (L). $\delta \equiv \gamma_f/\gamma_s\text{-}\gamma_f$ and its value is approximately 40. It means that the interface is located at a depth (below mean sea level) at every place 40 times the fresh water head above the sea level. From Eq. (2), the decrease in interface depth ($\Delta\zeta$) corresponding to the decrease in fresh water head (Δh_f) is

$$\Delta\zeta = -\delta\Delta h_f \tag{3}$$

The above relationships are equally applicable to confined aquifers by replacing the water table with the piezometric surface (Bear 1979). According to the Ghyben-Herzberg model, the equilibrium between fresh water and saline water requires that the water table or piezometric surface lies above the sea level and the hydraulic gradient must be toward the sea. Without fulfilling these conditions, the seawater will advance directly to the inland.

Comments on Ghyben-Herzberg Model

The Ghyben-Herzberg model was derived empirically without considering the flow of fresh water and saline water, and the motion of the interface was ignored. Anyhow, the above relation holds true for hydrodynamic equilibrium when fresh water is flowing and saline water is stationary (Bear 1979).

The model has some limitations due to the fact that the fresh water head at the water table is assumed to be same as the fresh water head at the interface, which implies that there are no vertical head gradients. This is valid when the point of interest is away from the coast. Near the coast, where the vertical component of flow is pronounced, the model deviates significantly and underestimates the interface position from 5 to 40 per cent (Bear and Dagan 1962; Moore *et al.* 1992).

Hubbert (1940) made an improvement in the model by considering the motion of both the fresh water and saline water. According to this, if the heads are defined for each fluid, then the equation for interface position can be derived as

$$\zeta \equiv (1+\delta)h_s - \delta h_f \tag{4}$$

In case of stationary saline water, the first term on the right hand side of Eq. (4), the Hubbert model, will vanish and it will take the form of Eq. (2), the Ghyben-Herzberg model.

Sharp Interface Models

Sharp interface models assume that the transition zone between fresh water and saline water is relatively small as compared to the thickness of the aquifer and can be approximated by a sharp interface. Physically, this situation arises either due to low transmissibility of the porous medium or due to large difference in densities of two fluids (Sarma *et al.* 1987). A generalized conceptual model of a fresh-saline aquifer with a sharp interface is shown in Fig. 3. A partially penetrating well is located at a depth ($h+D$) from the static water table and the bottom of the well is situated at a distance d from the initial position of the interface. $\zeta(r,t)$ is the rise of the interface at radial distance r from the well at any time t during the upconing process. m is the undisturbed fresh water thickness, $h_f(r,t)$ and $h_s(r,t)$ are the thickness of the fresh water and saline water layers at any radial distance r and at any time t, respectively. The same notations are used in the proceeding equations.

The mathematical formulation of these models involves the solution of flow equations in the respective layers, satisfying the initial and boundary conditions. These models couple fresh water and saline water layers through the interfacial boundary condition along which the continuity of pressure and flux is also assumed. Sharp interface models are further categorized into two groups based on the assumption that the saline water is either static or flowing. These are described below.

One-Fluid Models

In one-fluid models, the presence of underlying saline water is totally ignored for ease in calculations and the flow of fresh water in the upper layer of the aquifer is considered. Generally, these models are based on the equilibrium of fresh water and saline water in terms of head and hence incorporate the Ghyben-Herzberg relationship. The flow of water in the fresh water layer of an aquifer is given as

$$\nabla(K_f \nabla h_f) \pm I = S_s \frac{\partial h_f}{\partial t} \tag{5}$$

where h_f is the fresh water head (L), K_f is the hydraulic conductivity of fresh water layer (LT^{-1}), I is the volumetric flux per unit volume of aquifer (T^{-1}) and represents the source (positive) and sink (negative), and S_s is the specific storage of the aquifer (L^{-1}). The mathematical formulation of one-fluid sharp interface models involves the solution of the flow equation in the fresh water layer under prescribed initial and boundary conditions and the coupling of the flow equation to the Ghyben-Herzberg model.

Using the Ghyben-Herzberg model, Muskut and Wyckoff (1935) described the behavior of the cone beneath a well pumping from an aquifer containing two fluids of different densities. They assumed that the raised interface would not effect the hydraulic head distribution in the fresh water layer of the aquifer. The head distribution in the aquifer is a function of the radial distance (r) from the well and the elevation (z). The fresh water head at the interface becomes

$$h_f \equiv h_f(r, \zeta) \tag{6}$$

The position of the interface was calculated by solving Eqs. (4) and (6) simultaneously. The head distribution was measured by using electric analog model.

The model was valid for less than 20 per cent rise of the cone from the initial position of the interface to the bottom of the well (Bear *et al.* 1968). An empirically correction factor of 1.33 was applied to extend the model from 20 to 50 per cent of the distance from the initial position of the interface to the well bottom (Haubold 1975). This correction factor was unchanged by the well discharge. There was also no change in the shape of the cone interface when the well screen was increased. A possible explanation is that the model was based on the assumption that the flux density was uniform at the well face. An increase in the well screen length only distributed the strength of the sink over a large interval but did not appreciably change the total head distribution in the aquifer, especially for the point on the interface directly beneath the well. Moreover, to maintain a steady-state flow towards the well, it was necessary to maintain a steady-state recharge at some distance from the well otherwise the effect of cone would extend.

The Muskut-Wyckoff model was applied to unconfined aquifers in Lower Indus Basin of Pakistan assuming that the well drawdown was very small and the topmost streamlines were effectively horizontal and hence two systems (confined and unconfined) were assumed geometrically similar (WAPDA 1965). Later on, it was investigated that in unconfined aquifers, the horizontal streamlines are present at mid point of the well screen (Bennett *et al.* 1968). So, to use the model in an unconfined situation, the mid point of the screen was considered as the upper boundary of the aquifer and then the geometry of the aquifer was adjusted accordingly.

Wang (1965) developed an analytical model for unconfined aquifers in Lower Indus Basin of Pakistan by using the Ghyben-Herzberg model. Wang's model related the well discharge to drawdown. She assumed a stable cone of saline water just under the well bottom and ignored the vertical component of the flow. The elevation of the interface beneath the well bottom was given as

$$\zeta_w = \frac{Q\delta}{2\pi mK} \ln\left(\frac{r_e}{r_w}\right)\left(\frac{D}{m}\left(1 + 7\left(\frac{r_w}{2D}\right)^{\frac{1}{2}} \mathrm{Cos}\left(\frac{\pi D}{2m}\right)\right)\right)^{-1} \qquad (7)$$

where ζ_w is the rise of the interface under the well bottom from the initial position of the interface (L), Q is the well discharge (L^3T^{-1}), r_w is the radius of the well (L) and r_e is the radius of influence (L). Wang's model does not take into account the effect of the rising interface on the well discharge and it makes no use of detailed hydraulic head distribution for locating the position of the interface. Sahni (1972) compared Wang's model with his sand tank model. The results showed that Wang's model deviated considerably from the experimental values, especially at shallow well penetration. This is due to the reason that streamlines, tangent to the cone, are more convergent at shallow well penetration and the effect of a vertical component becomes more prominent. Motz (1992) used a similar approach for semi-confined aquifers.

Bear and Dagan (1964) derived an equation for the rise of a saline interface using the methods of small perturbation. The equation for interface position under steady flow in a homogeneous and isotropic aquifer was given as

$$\zeta = \frac{Q\delta}{2\pi dK}\left(1 + \left(\frac{r}{d}\right)^2\right)^{-\frac{1}{2}} \qquad (8)$$

It was recognized that Eq. (8) does not account for the fact that the interface becomes unstable above 50 per cent rise from the initial position of the interface to the well bottom. They also compared the results of Eq. (8) with the sand tank model developed by them and concluded that Eq. (9) is valid for interface rise up to one-third the distance between the initial position of the interface and the well bottom.

McWhorter (1972) derived an equation from the Ghyben-Herzberg model for sufficiently flat slopes of the interface and static saline water. The equation for the interface height was given as

$$\frac{\zeta}{m} \equiv \left(C_1^2 + \left(\frac{QC_1}{m^2 \delta K}\right)\left(\ln\left(\frac{r_e}{r}\right) - 1\right)\right)^{\frac{1}{2}} \tag{9}$$

where $C_1 \equiv (\delta/1+\delta)$. Eq. (9) is an approximate description of the variation of the interface rise. The model implies that the vertical component of the flow is small and the velocity is not a function of the vertical coordinate. The model also does not take into account the well penetration.

All of the above discussion was confined to steady flow towards the wells. In the real situation, this condition is rarely achieved. However, solutions for steady-state conditions are useful for design purposes but their scope is limited to many field situations. For unsteady conditions in fresh-saline aquifers, the transient rise of the interface in confined homogeneous and isotropic aquifers is described as (Schmorak and Mercado 1969)

$$\zeta(r, t) = \frac{Q\delta}{2\pi K d}\left(\left(1 + \left(\frac{r}{d}\right)^2\right)^{-\frac{1}{2}} - \left(\left(1 + \frac{Kt}{2\delta n_e d}\right)^2 + \left(\frac{r}{d}\right)^2\right)^{-\frac{1}{2}}\right) \tag{10}$$

where n_e is the effective porosity (dimensionless). Eq. (10) can be applied only where the fresh water layer is considerably thick, and the rise of the cone is very small from the initial horizontal position of the interface. The above equation was used in the field studies in Israel (Schmorak and Mercado 1969) and found to be generally in agreement with the field data.

McWhorter (1972) used the Ghyben-Herzberg model and Hantush (1964) approach to derive the transient rise of the interface in unconfined aquifer as (Sarma *et al.* 1987)

$$\zeta = \frac{Q\,\delta^2}{4\pi K_f(C - \bar{\bar{\zeta}})(1+\delta)}\, W(u) \tag{11}$$

where $C = \frac{m\delta}{1+\delta}$, $u = \frac{r^2 S_y \delta}{4K_f(C - \bar{\bar{\zeta}})\, t}$ and $W(u) \int_{\frac{r^2 d}{4t}}^{\infty} {}_{t}\frac{e^{-u}}{u}\, du$

The validity of this model does not appear to have been verified by any laboratory or field experiments. The magnitude of the error resulting due to linearization of the equation is also unknown (Verma 1978).

Two-Fluid Models

Two-fluids models take into account the flow of fresh water and saline water through the aquifer. The two layers are coupled through an interface where continuity of pressure exists (Bear 1979). The fresh water layer is bounded between the top of the aquifer (in confined aquifer) or water table (in unconfined aquifer) and the interface, while the saline water layer is bounded between the interface and the bottom of the aquifer. The equation of flow in the fresh water and saline water layers are given by

$$\nabla(K_f\nabla h_f) \pm I = S_s \frac{\partial h_f}{\partial t} \tag{12}$$

$$\nabla(K_s\nabla h_s) \pm I = S_s \frac{\partial h_s}{\partial t} \tag{13}$$

where K_s is the hydraulic conductivity, h_s is the hydraulic head in the saline water layer and other terms has been explained earlier. The flow equations in both the layers are solved simultaneously satisfying the conditions along the interface, and at the external boundaries of the respective layers. The boundary conditions at the interface both for fresh water and saline water layers are given as (Bear 1979)

$$n_e \frac{\partial h_f}{\partial t} \delta - n_e \frac{\partial h_s}{\partial t} (1+\delta) + q_f(\nabla z - (1+\delta)\nabla h_s + \delta\nabla h_f) = 0 \tag{14}$$

$$n_e \frac{\partial h_f}{\partial t} \delta - n_e \frac{\partial h_s}{\partial t} (1+\delta) + q_s(\nabla z - (1+\delta)\nabla h_s + \delta\nabla h_f) \equiv 0 \tag{15}$$

where n_e is the effective porosity of the medium (dimensionless), q_f and q_s are the specific discharges in fresh and saline water layers (LT^{-1}). Eqs. (14) and (15) are non-linear partial differential equations. Analytically, it is difficult to solve exactly the non-linearity involved in the equations representing boundary conditions. The conditions at the upper and lower aquifer boundaries are introduced depending upon either they are permeable or impermeable. These will be equal to the leakage through the overlying and underlying layers for permeable boundaries and will be zero for impermeable layers. In the case of an unconfined aquifer, the upper boundary is a free surface and the drainage from the water table will be $n_e(\delta h_f/\delta_t)$.

The solutions of Eqs. (12) and (13) in three dimensions involve a lot of computational efforts and it is usual practice to integrate them over the vertical dimension, within their respective layer. The vertical integration of the flow equations implies the Dupuit approximation of vertical equipotential lines and horizontal flow within each layer. Once the values of these heads are known, interface elevation can be calculated using Eq. (4).

Comments on Sharp Interface Models

One common feature of the sharp interface models is the assumption that a well-defined interface exists and persists between the fresh water and saline water. This assumption is certainly reasonable when the fresh water and saline water layers are thick and a relatively narrow transition zone exists. In that case the salt dispersion near the interface is assumed unimportant, but when the fresh water layer is thin, the dispersion mechanism becomes more significant. Moreover, the dynamics of the interface can be described accurately with the sharp interface model when the vertical head gradient is small.

One-fluid models were the earliest attempts to determine the position of the interface and have inherited some limitation due to the incorporation of the Ghyben-Herzberg relationship. The major assumption in the Muskut-Wyckoff model that the raised interface does not affect the head distribution in the fresh water layer is not realistic. In fact, the rising interface disturbs the head distribution in fresh water layer, and hence affects the discharge of the well as a consequence. Due to the unavailability of techniques to measure the effect of a raised interface on head distribution at that time, it was common practice in modeling to assume that the raised interface had no effect on the head distribution. Later with the development of numerical techniques, due consideration was given to this aspect (Bear and Dagan 1964; Wirojanagud and Charbeneau 1985; Essaid 1990)

Two-fluid models are the advanced forms of one-fluid models in the sense that these models take into consideration of both the fresh water and saline water flows simultaneously. In inland aquifers, two fluids models have not been applied. Recently, Essaid (1990) developed a two-fluid model to be applied to coastal aquifer studies. This model can be equally well applied in inland fresh-saline aquifers. Here it should be kept in mind that the sharp interface assumption is only an approximation and can only be applied to regional studies. For observing the upconing phenomenon close to the well (local scale) due consideration should be given to the natural process of dispersion between the two fluids. For this purpose transition models are used. These models are discussed below.

Transition Zone Models

Transition zone models are based on the concept that two fluids are miscible and there is a continuous mixing between them, mainly due to hydrodynamic dispersion. The concentration of transition zone lies between that of purely fresh water and saline water. The mathematical formulation of these models involves the solution of the governing flow equations in conjunction with the solute transport equation, satisfying the initial and boundary conditions.

Transition zone models are further categorized into two groups:

(i) Disperse Interface Models: These models superimpose the theory of dispersion to the sharp interface.
(ii) Solute Transport Models: These models take into account the mixing between fresh water and saline water.

Disperse Interface Models

Disperse interface models superimpose the theory of dispersion on a sharp interface model. The models assume that a sharp interface between fresh water and saline water has been moving without any dispersion at all times $t < \tau$. At time $t \equiv \tau$, the interface has just arrived in the origin of coordinates ($\zeta \equiv 0$) and at the same time, the dispersion has become possible. At this point, the input of saline water can be viewed as a step function. For positive time ($t > \tau$), the interface keeps on moving but becomes more and more diffuse due to hydrodynamic dispersion. These models are based on the analogy of tracer displacement experiment in an infinite column and assume that upconing is a one-dimensional (upward) solute transport process.

The one-dimensional partial differential equation governing the distribution of saline water is

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial \zeta^2} - \tilde{v}\frac{\partial c}{\partial \zeta} \qquad (16)$$

where c is concentration of the fluid at any point in transition zone (ML^{-3}), $D \equiv \alpha_L \tilde{v}$ is coefficient of dispersion in the direction of flow (L^{2}T^{-1}), $\tilde{v}$ is the average pore velocity through the porous medium in the direction of flow (LT^{-1}), and α_L is the longitudinal dispersivity for saline water (L). The initial conditions are

$c = c_f$ for $t \leq 0$ and $-\infty < x < 0$

$c = c_s$ for $t \leq 0$ and $0 < x < +\infty$

and the boundary conditions;

$\frac{\partial c}{\partial x} = 0$ for $t > 0$ and $x = \pm\infty$

$c = c_f$ for $t > 0$ and $x = +\infty$

$c = c_s$ for $t > 0$ and $x = -\infty$

The solution of Eq. (16) as given by Bear and Todd (1960) is

$$C(\zeta, t) = \frac{1}{2}\mathrm{erfc}\left(\frac{\zeta - \zeta'}{2(Dt')^{\frac{1}{2}}}\right) \qquad (17)$$

where $C = \frac{(c_i - c_f)}{(c_s - c_f)}$ is relative concentration (dimensionless), c_i is concentration in the transition zone (ML^{-3}), c_f is concentration of the fresh water (ML^{-3}), c_s is concentration of saline water (ML^{-3}), ζ is distance of the any point from initial position of the interface (L), $\zeta = \zeta - \tilde{v}t$ is relative distance of the interface from initial position (L), and *erfc* is complementary error function.

In the equation above, it was assumed that the flow domain has infinite boundaries. The same approach may be applicable to the case with finite boundary as an approximation, because, in reality, the saline water is not allowed to diffuse backwards below the cone (while the infinite approach assumes that such a backward diffusion is possible).

Schmorak and Mercado (1969) used Eq. (18) to solve the inverse problems for dispersivities. They used the field data on salinity profiles. The calculated values of dispersivities were used in the prediction phase for superimposing the effect of hydrodynamic dispersion on the sharp interface upconing. The results obtained by using the above equation were in agreement with the field data. Anyhow, disperse-interface models should be used keeping in view the one-dimensional effects of hydrodynamic dispersion. Practically, the pumped water may be contaminated well before the interface actually reaches the well bottom.

Solute Transport Models

The movement of saline water into a fresh water layer during extraction from the fresh-saline aquifer can be viewed as the movement of a contaminant into the aquifer system and can be simulated using solute transport models. The three-dimensional flow through porous media is given by Eq. (5). The partial differential equation describing the three-dimensional solute transport in the groundwater is given as

$$\nabla(D\,\nabla C)-\nabla(\tilde{v}C)\pm I\,C_s=\frac{\partial C}{\partial t} \tag{18}$$

where D is hydrodynamic dispersion coefficient (L^2T^{-1}), C is the concentration (ML^{-3}), C_s is the concentration of the source or sink (ML^{-3}), I is the volumetric flux per unit volume (T^{-1}) and $\bar{v}$ is the average pore velocity (LT^{-1}).

The mathematical formulation of these models involves the simultaneous solution of the flow and solute transport equations. Hsieh (1977) solved the flow and solute transport equations using iterative Galerkin finite element method to determine the upconing under shallow wells in two-dimensional radial coordinates for confined aquifers. Chandio and Larock (1984) formulated a skimming well model for the transient conditions. They used the finite element method to solve the equation in three-dimensional form for the case of unconfined aquifer. Chandio (1983) validated the above model using field data of skimming wells from the pumping experiments conducted in the Indus basin of Pakistan. These experiments were conducted to see the hydro-salinity behavior under different well arrangements. The model was then used to simulate different scenarios. The numerical experiments indicated that the transient growth of upconing towards the skimming tube wells had been simulated correctly with model for relatively thin upper fresh water layer. Currently, a number of solute transport models are available which can be used to simulate flow of saline water under skimming wells. A good review of solute transport models are given in literature (Anderson and Woessner 1996; Bedient *et al.* 1994). Recently, Ashgar *et al.* (2002) used MODFLOW (McDonald and Harbough 1988) and MT3D (Zheng 1990) to model the interface movement under a shallow well. Data collected by Kemper *et al.* (1976) were used to calibrate and validate these models. Using various scenarios, Asghar *et al.* (2002) tried to develop operational and design guidelines for single-strainer skimming well. The practical use of these guidelines is indecisive, as the hydro-salinity distribution in the aquifer has changed significantly,

Table 1: Summary of the models used to simulate saline-upconing under skimming wells.

Reference	Aquifer Type	Aquifer Properties	Time Status	Model Type	Observations	Remarks
Sharp Inteerface Models						
Badon-Ghyben (1889) and Herzberg (1901)	Confined	Homogeneous Isotropic	Steady State	Empirical	Thickness of fresh water Depth of interface	Static saline water No vertical head gradient
Muskut-Wyckoff (1935)	Confined	Homogeneous Isotropic	Steady State	Analytical	Fresh water potential Elevation of interfac	Static saline water No effect of upconing on potential distribution Valid for only 20% cone rise
Hubbert (1940)	Confined	Homogeneous	Steady State	Analytical	Fresh water potential Saline water potential Interface location	Fresh water and saline water are flowing No vertical head gradient
Wang (1965)	Unconfined	Homogeneous and Heterogeneous	Steady State	Analytical	Drawdown Maximum discharge	Same as Muskut-Wyckoff plus: Stable cone exists at well bottom No use of hydraulic head distribution
WAPDA (1965)	Unconfined	Homogeneous Isotropic	Steady State	Analytical	Drawdown Well discharge	Same as Muskut-Wyckoff plus Well drawdown is small and topmost streamlines are horizontal
Bear-Dagan (1964)	Confined	Homogeneous Isotropic	Steady State Interface location	Analytical	Well discharge	Same as Muskut-Wyckoff plus: No consideration that cone becomes unstable at 50% rise
Bennett et al. (1968)	Unconfined	Homogeneous and Heterogeneous	Steady State	Electric Analog	Fresh water head Well discharge Interface location	Same as Muskut-Wyckoff plus: Horizontal streamlines are present at mid of well screen Mid point is considered as upper boundary of aquifer
Schmorak-Mercado (1969)	Confined	Homogeneous Anisotropic	Transient	Analytical	Well discharge Interface Position Hydro-salinity profile	Valid for thick fresh water layer Valid for only very small cone rise
Sahni (1972)	Unconfined	Homogeneous Isotropic	Steady State	Sand Tank	Fresh water head Well discharge Interface location	Same as Muskut-Wyckoff
McWhorter (1972)	Unconfined	Homogeneous Isotropic	Steady State	Analytical	Drawdown Well discharge Interface location	Valid for flat cone Small vertical component of flow No consideration of well penetration

Table 1: Continued

Reference	Aquifer Type	Aquifer Properties	Time Status	Model Type	Observations	Remarks
Sharp Inteerface Models						
McWhorter (1975)	Unconfined	Homogeneous Isotropic	Transient	Analytical	Drawdown Well discharge Interface location	Linearlization of equations No field or lab verification of model
Haubold (1975)	Confined	Homogeneous Isotropic	Steady State	Analytical	Fresh water head Saline water head Interface location	Same as Muskut-Wyckoff except: Valid for 50% cone rise
Wirojanagud (1984)	Unconfined	Homogeneous Isotropic	Steady State and Transient	Numerical	Well discharge Hydro-salinity profile	For small and large diameter wells
Motz (1994)	Semi-Confined	Homogeneous Isotropic	Steady State	Analytical	–	Same as Muskut-Wyckoff
Transition Zone Models						
Hsieh (1977)	Confined	Homogeneous Isotropic	Steady State	Numerical	-	For shallow wells Two-dimensional Finite element solution method No consideration of density of fluids
Chandio (1984)	Unconfined	Homogeneous Isotropic	Steady State Transient	Numerical	Well water quality Well discharge Hydro-salinity profile	For relatively thin fresh water layer Three-dimensional Finite element solution method No consideration of density of fluids Better well presentation
Voss (1984)	Unconfined Confined	Homogeneous Heterogeneous Isotropic Anisotropic	Steady State Transient	Numerical	–	Two-dimensional Finite element solution method Due consideration of density of fluids
Kipp (1987)	Unconfined Confined	Homogeneous Heterogeneous Isotropic Anisotropic	Steady State Transient	Numerical	–	Three-dimensional Finite element solution method Due consideration of density of fluids
Sufi (1999)	Unconfined Semi-confined	Homogeneous Isotropic	Steady State Transient	Numerical	Drawdown Well Discharge Well water quality	Three-dimensional Finite element solution method Due consideration of density of fluids Verified with sand tank model Some restriction in using results of studies

possibly due to overexploitation of groundwater in the region. The data collected by Kemper *et al.* (1976) showed a distinct demarcation between fresh water and saline water in the aquifer. Along the time, the overexploitation of groundwater extraction has disturbed this demarcation between two fluids. In the present hydrogeological conditions of the aquifer, the guidelines developed by Asghar *et al.* (2002) should be used with care. A better option is to conduct local hydrogeological investigations before using such guidelines. Moreover, the data collected by Kemper *et al.* (1976) showed aquifer response during long pumping hours (well was operated for 15 days continuously).

In solute transport model, if the density of the saline water is high, the effect of gradient due to density difference of the two fluids can be taken into account. For this purpose, the density dependent flow and solute transport models can be used in the saline water upconing (Voss 1984). The density dependent flow and solute transport equations are given as (Kipp 1987)

$$\nabla\left(\rho\frac{k}{\mu}(\nabla p+\rho g)\right)\pm I\rho_s\equiv\frac{\partial(\rho)}{\partial t} \tag{19}$$

$$\nabla(\rho D\,\nabla C)-\nabla(\rho vC)\pm I\rho_s\,C_s=\frac{\partial(\rho C)}{\partial t} \tag{20}$$

where k is the permeability of the porous media (L^2), p is the pressure of the fluid (ML^{-2}), ρ is the density of the fluid (ML^{-3}), ρ_s is the density of the fluid source/sink (ML^{-3}). All other terms have been described previously.

Sufi (1999) used density dependent model, VDGWTRN (Sakr 1995) to simulate the upconing. He compared the results obtained by numerical model with his own sand tank model and the field experiments conducted by Kemper *et al.* (1976). The design discharges used in these simulation studies were very low (less than 6 liter per second), which do not comply with the existing field situations where the wells of more than 28 liter per second are being used. This scenario restricts ones to apply these results in the field.

Comments on Transition Zone Models

Physically, the transition zone in inland aquifers is created by transverse dispersion (and by both transverse and longitudinal dispersions in the coastal aquifers). Bear and Todd (1968) totally ignored the effect of transverse dispersivity in their model. Their method is based on the assumption that flow in the saline water is uniform and vertically upward in the region of upconing, which is not true. The interface rises under the well in a form of flat bell. Nevertheless, the method has been found to be useful to the hydraulic conductivities and dispersivities by solving the inverse problem. The required data of observed heads and concentration are usually available from the pumping tests. As a matter of fact, one-dimensional solute transport model described above is still very far from reality, but the solutions obtained for them are useful approximation to other more realistic but also more complicated problems.

Realizing the importance of skimming technologies to extract relatively thin fresh water layer overlying saline water in fresh-saline aquifers, a comprehensive field study has been started in the Indus basin, Pakistan. The authors of this paper had conducted field experiment of skimming wells under different pumping regimes. The results of these studies will be presented elsewhere.

Summary

The summary of the models discussed above are summarized in Table 1.

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Addresses:
Muhammad Mazhar Saeed,
Centre of Excellence in Wat. Resour. Eng.,
University of Eng. and Tech.,
Lahore,
Pakistan.
Email: center@xcess.net.pk

M. Bruen,
Centre for Wat. Resour. Res.,
University College Dublin,
Earlsfort Terrace,
Dublin 2, Ireland.

M.N. Asghar,
Int. Water Management Inst.,
12 km Multan Road,
Chowk Thokar Niaz Baig,
Lahore, Pakistan.