Saltwater Intrusion in Coastal Aquifers

ANUPMA SHARMA
National Institute of Hydrology, Roorkee

INTRODUCTION

All around the world, coastal areas have been attracting human settlements, especially in deltaic regions and around major seaports and tourist resorts. Coastal aquifers form a vital source of freshwater in these regions, and are increasingly being tapped to meet the water-supply needs. However, groundwater is vulnerable to contamination from a variety of sources. In coastal aquifers, which are in hydraulic contact with the sea, it faces an additional threat of contamination from sea water intrusion due to large-scale abstraction of groundwater. This calls for a rational groundwater development of coastal regions, which is of particular importance in the Indian context, because of the long coastline and increasing population.

SOURCES AND MECHANISMS OF SALTWATER INTRUSION

The possible sources of saline water in a coastal aquifer may be either one or a combination of the following:

- Intrusion of saltwater from the sea
- Presence of salt domes in geologic formations
- Seawater present in aquifers from past geologic times
- Salts in water concentrated by evaporation in tidal lagoons, playas or other enclosures
- Return flow from irrigation
- Leakage from sewer systems and industrial effluents etc

The mechanisms of salt water intrusion may be broadly classified into the following categories: (a) Reduction or reversal of water table gradients due to heavy pumping, which permits the heavier saline water to displace the lighter freshwater (b) Destruction of natural barriers that separate fresh and saline water e.g., construction of a coastal drainage canal, which enables tidal water to advance inland and infiltrate into the adjacent freshwater aquifer, and (c) improper subsurface disposal of waste saline water into disposal wells or landfills.

COASTAL HYDROGEOLOGY

In some areas, coastal hydrogeologic conditions may simply be represented by an individual confined, unconfined or island aquifer. In other cases, the hydrogeologic setting may be that of a multi-layer aquifer system. In either situation, the aquifer system has a sea front so that there is a direct contact between continental freshwater and marine saltwater. Besides a slight difference in viscosity between the two fluids, there exists a density change that depends mainly on salinity differences. Under natural, undisturbed conditions, a seaward hydraulic gradient exists in the aquifer with freshwater discharging into the sea. The heavier saltwater flow in from the sea and a wedge-shaped body of saltwater develops beneath the lighter freshwater, with the freshwater thickness decreasing from the wedge toe towards the sea. The freshwater/saltwater interface is stationary under steady state conditions with its shape and position determined by the freshwater head and gradient. Inland changes in recharge or discharge modify the flow within the freshwater region, inducing a corresponding movement of the interface. A reduction in freshwater flow due to overdraft, causes the interface to move inland and results in the intrusion of saltwater into the aquifer. Conversely, the interface retreats following an increase in freshwater flow. The rate of interface movement is governed by the boundary conditions and aquifer properties.

Saltwater encroachment, resulting from human action, can be either active or passive. Passive saltwater intrusion occurs when some freshwater has been diverted from the aquifer, but the hydraulic gradient in the aquifer is still towards the saltwater-freshwater interface. In this case, the interface slowly shifts landwards until it reaches an equilibrium position based on the reduced freshwater discharge from the coastal aquifer. Passive saltwater intrusion is taking place in many coastal aquifers where groundwater resources are being developed. It occurs slowly and in some areas may take hundreds of years for the boundary to move a significant distance.

The consequences of active saltwater intrusion are considerably more severe. It takes place when the natural hydraulic gradient has been reversed and freshwater actually moves away from the saltwater-freshwater interface. The interface moves much more rapidly than it does during passive saltwater intrusion.

Formation of Transition Zone

Seawater intrusion occurs mainly on account of saltwater transport by advection and hydrodynamic dispersion. In reality, due to hydrodynamic dispersion, the zone of contact between freshwater and saltwater takes the form of a transition or diffusion zone (also termed as disperse interface), across which the salt concentration and hence density of water varies from that of sea water to that of freshwater (Fig. 1).

In the transition zone the diluted saltwater, being lighter than original sea water, rises and moves seaward, causing saltwater from the sea to flow towards the transition zone. This induces a cyclic flow of saltwater from the floor of the sea to the transition zone and finally back to the sea.

In some instances, the transition zone is thin, a few meters or less, but in other situations it can attain a thickness of more than a hundred metres, especially in highly non-homogeneous formations (e.g. limestone aquifers). In non-homogeneous highly permeable materials, with small freshwater flow, the top of the transition zone can reach the water table. Moreover, the thickness of transition zone is not constant, and may expand or contract in accordance with a succession of low and high tides and wet and dry periods.

Upconing of Saline Water

An aquifer subject to saltwater intrusion may be pumped for freshwater through a partially-penetrating well, which taps only the upper freshwater portion of the aquifer. However, as a result of the pumpage, a local rise of the interface below the well takes place. This phenomenon, which occurs at the local level is termed as upconing and differs from saltwater intrusion occurring at the regional scale (Fig. 2).

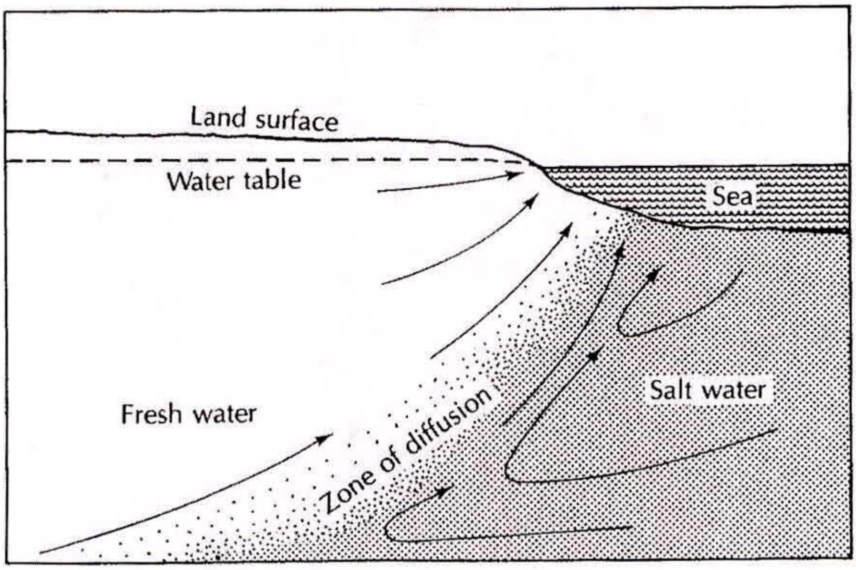

Fig. 1 Flow of freshwater and saltwater in a coastal aquifer (after Cooper et al., 1964).

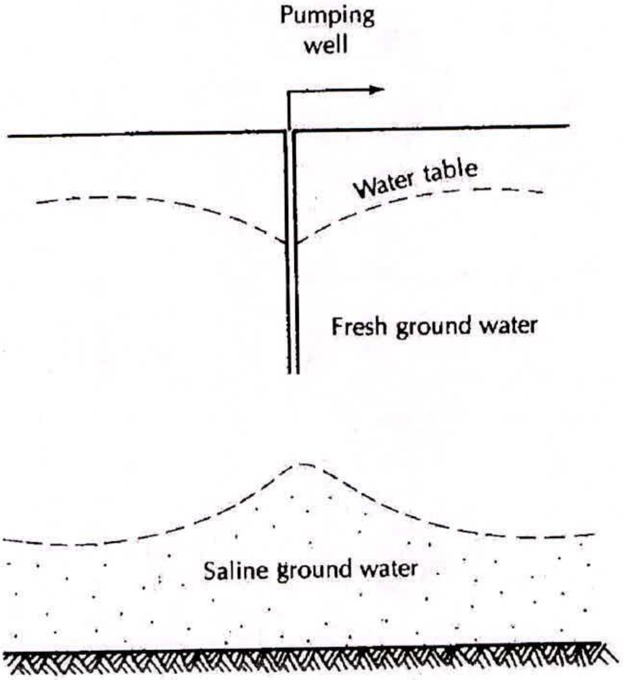

Fig. 2 Upconing of saline water caused by a well pumping from an overlying freshwater zone.

At the local level, initially, the interface is horizontal at the start of pumping. With continuous pumping, the interface gradually rises, until it eventually reaches the well. When pumping is stopped, the denser saline water tends to settle down, and returns to the former interface position. For a relatively thick aquifer, the upconing of interface as a function of time and distance from the pumping well is expressed as (Bear and Dagan, 1964):

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

where R and T are, respectively, the dimensionless distance and time parameters given by

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

and Z = rise of interface above its initial position at a radial distance r from the center of well at time t; Q = time invariant pumping rate of well; D = vertical distance between the initial position of interface and bottom of well; r = distance from well; ϕ = aquifer porosity; K_x, K_z = horizontal and vertical hydraulic conductivities, respectively; γ_f and γ_s = specific weights of freshwater and saltwater, respectively; $\Delta\gamma = \gamma_s - \gamma_f$; and t = time elapsed since start of pumping.

The maximum rise of the interface below the pumping well for a given pumping rate is

$$Z_{\max}=\frac{Q}{2\pi(\Delta\gamma/\gamma_f)K_xD} \tag{3}$$

In order to skim freshwater from above saline water, with minimal upconing, it is necessary to have a proper design and optimum operation (in terms of pumping rate and pumping sequence) of a well.

It may noted that, in reality, due to miscibility of freshwater and saltwater, the transition zone (in which the 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 that is attributed to hydrodynamic dispersion.

By neglecting the effects of hydrodynamic dispersion, it is not possible to predetermine the salinity of the pumped water at early times. The model presented by Shalabey et al. (2006) permits design of pumping wells in fresh-saline aquifers, accounting for the effects of hydrodynamic dispersion. The design may include, among others, estimation of permissible discharge and/or duration of pumping for restricting saltwater concentration in pumped water to a stipulated permissible limit, as well as the recovery rest period between two successive spells of pumpage.

MATHEMATICAL MODELLING OF SALTWATER INTRUSION

In order to plan sustainable groundwater development of coastal regions at the regional scale, it is essential to have a prior knowledge of the immediate and long term transient behaviour of a coastal aquifer in response to a given pumping policy. In such cases, mathematical modelling of the coastal aquifer system is an indispensable tool that can simulate the physical complexities, as well as the spatial and temporal variations inherent in a coastal system.

Modelling Approaches

The mathematical analysis of the saltwater intrusion problem may involve several simplifying assumptions. Depending upon whether the freshwater and saltwater are taken as miscible or immiscible fluids, there are two distinct approaches to model a coastal aquifer system (Sharma, 2006):

- *Sharp interface approach*
- *Miscible transport approach*

The sharp interface approach, which assumes that freshwater and saltwater being immiscible fluids are separated by an abrupt interface, is suitable when the width of transition zone is small relative to the thickness of the aquifer. For a thicker transition zone, the miscible transport approach is adopted, which accounts for the effects of hydrodynamic dispersion and explicitly represents the transition zone.

Sharp Interface Models

In the sharp interface approach basically two flow domains, freshwater and saltwater, are considered. The flow equation in each of the domains are coupled by the boundary conditions that specific discharge and pressure must be equal on either side of the sharp interface (Bear, 1979). The numerical solution of these equations subject to appropriate boundary conditions yields the distribution of heads in the freshwater and saltwater zones, and simulates the general position, shape and behaviour of the interface.

Many sharp interface models incorporate additional simplifications such as assuming the saltwater to be stationary. The famous Ghyben-Herzberg principle based on the sharp interface approach, relates the freshwater head above sea level (Φ_f) to the depth of the interface below sea level (ζ_s) for a system in hydrostatic equilibrium and stationary saltwater. At the interface, the pressure due to the overlying column of freshwater must be equivalent to that due to the column of saltwater, and therefore, the following relation holds:

$$\zeta_s \gamma_s = (\zeta_s + \Phi_f)\gamma_f$$

$$\text{or} \qquad \zeta_s = \delta\,\Phi_f \tag{4}$$

where $\delta = \gamma_f/(\gamma_s - \gamma_f)$. For common values of freshwater and saltwater densities (1.0 gm/cm^3 and 1.025 gm/cm^3, respectively) the value of δ is 40. This implies that the depth to the interface below sea level is forty times the freshwater head. In groundwater literature, the assumption of stationary saltwater is commonly known as the Ghyben-Herzberg approximation.

The erroneous result inherent in Eq. (4) is that the thickness of freshwater zone is represented as zero at the shore where the elevation of water table is zero. This is because the Ghyben-Herzberg principle relates the head at the water table to the position of interface. An improvement upon the Ghyben-Herzberg principle is the relation given by Hubbert (1940) which relates the freshwater and saltwater heads at a point on the interface to its elevation, as follows:

$$Z = \frac{\gamma_s}{\gamma_s - \gamma_f} h_s - \frac{\gamma_f}{\gamma_s - \gamma_f} h_f \tag{5}$$

where Z = elevation of interface.

Assuming saltwater to be stationary, the position of the interface accounting for the movement and discharge of freshwater from a coastal aquifer, under steady flow conditions is given as (Glover, 1959)

$$z^2 - \frac{2Q}{\Delta\gamma K} x - \frac{Q^2}{(\Delta\gamma)^2 K^2} = 0 \tag{6}$$

where Q = freshwater flow per unit length of shore; K = hydraulic conductivity of the medium; x = distance from the shore; z = depth from mean sea level.

Miscible Transport Models

In miscible transport models, the problem of seawater intrusion is posed as that of a variable density fluid flow accounting for both advective and dispersive transport (Kashyap and Sharma, 1994) of saltwater. These models require the simultaneous solution of the coupled groundwater flow and advective-dispersive equations accounting for dependence of density upon the salt concentration. Most of the numerical solutions to the governing equations are based on finite differences (FD), finite elements (FE) and Method of Characteristics (MOC).

MOC, originally proposed by Garder et al. (1964), minimizes the problem of numerical dispersion in the solution. It involves estimating advective component of transport by tracking a set of moving points across the flow domain and subsequently obtaining the dispersive component using a FD scheme. Over the years, a number of variant forms of MOC have been proposed that have been successfully applied to field problems. One such model developed in the vertical plane, besides providing the velocity field and spatial distributions of the concentrations at various discrete times, also gives the time-wise positions of the moving points along with their volumes (Sharma et al., 2001). This permits a detailed mass balance of seawater including quantification of the circulation. Other features of the model include simulation of the time-varying outflow face present on the seaward side of a coastal aquifer and its capability of simulating both a narrow and a wide disperse interface. The model was employed to simulate the advance and retreat of disperse interface in the Biscayne aquifer in Cutler area, Miami, Florida, in response to variations in the pumping policy, as well as to estimate the time lag between the recharge variation and the attainment of the new steady state interface position.

Other FD or FE based numerical miscible transport models that can be used for 2D or 3D transient simulations include SUTRA, SEAWAT, FEFLOW, HST3D and FEMWATER. For instance, the SEAWAT code has been used to investigate the transport of saltwater in the Krishna Delta region of Andhra Pradesh (Sharma and Kumar, 2005).

Suitability of Modelling Approaches

Each of the modelling approaches has advantages and limitations, and can be employed successfully under appropriate conditions. The sharp interface approach, in conjunction with the hydraulic approach, allows the problem to be reduced by one dimension. Thus, it can be applied areally to large physical systems. This approach does not give information concerning the nature of the transition zone; however it does represent the overall flow dynamics of the system and reproduces the general response of the interface to applied stresses. The miscible transport approach should be adopted in areas where the transition zone is wide. When concentration gradients are low, the governing equations can be solved areally on a basin-wide scale. However, when the flow is density-dependent, the vertical dimension must be included. Because of computational constraints, studies based on this approach have been generally limited to two-dimensional vertical cross-sections. While simulating the movement of a narrow concentration front, some numerical instabilities and errors may occur, especially in areas where the transition zone approaches a sharp interface. The steady state solutions of the sharp interface model and miscible transport model approach each other as the coefficient of hydrodynamic dispersion decreases. The choice of the approach used to model a particular system ultimately depends on the nature of the coastal aquifer system as well as the goals of modelling effort.

METHODS TO COMBAT SALTWATER INTRUSION

Less than 2% of seawater in freshwater can diminish the water's potability. The existing threat to freshwater coastal aquifers may be averted by development of effective management strategies that control landward advancement of seawater. Therefore, considerable attention has been focussed on methods to control saltwater intrusion. Selection of a particular method depends largely on geological conditions, water needs, and economic factors of the area (Custodio, 1987).

Modification of Pumping Pattern

The first possible method to ameliorate an existing situation is to reduce pumping especially in severely affected areas and areas near the coast. In aquifers, which receive a significant portion of recharge through induced infiltration from rivers or other surface freshwater bodies, a reduction in pumping is not fully effective in diminishing seawater intrusion because the induced freshwater recharge may also decrease at the same time. In such cases, modification in the well network, usually by spreading out the wells in inland areas, is an attractive alternative in order to maintain freshwater recharge as well as reduce excessive local drawdown near the coast.

Artificial Recharge

Raising groundwater heads by artificial recharge, is another effective technique. For unconfined aquifers, recharge can be through surface spreading, whereas, for confined aquifers, recharge wells are needed. This method requires development of a supplementary freshwater source.

Hydraulic Barriers

(a) **Pumping barrier:** Maintaining a continuous pumping trough by pumping a line of wells located parallel to the coast, creates a barrier for the intruding saltwater. Seawater flows inland from the ocean to the trough and freshwater within the aquifer flows seaward towards the trough. The pumped saline water is normally discharged into the sea. A pumping barrier is an effective method for reducing existing seawater intrusion, however, it is seldom recommended as a permanent solution. Once partial restoration of the aquifer has been achieved, other methods are usually adopted e.g. modification in pumping pattern or artificial recharge.

(b) **Injection barrier:** Here, maintaining a pressure ridge parallel to the coast by a line of recharge wells, creates an effective barrier. In this case, the injected freshwater flows both seaward and landward. In case of unconfined aquifers, with no low permeability layer between the ground surface and water table, the hydraulic recharge barrier can be created by coastal canals, trenches or infiltration fields. This is possible if the ground surface is at a large enough altitude above sea level to allow creation of sufficiently high freshwater elevation. In confined aquifers or when a low permeability layer exists close to the ground surface, injection wells are the only solution. However, clogging of wells and high operation and maintenance costs are some of the drawbacks of the well injection technique.

(c) **Pumping-Injection barrier:** In some cases, techniques that utilise a combination of injection and pumping barriers may prove to be more effective in controlling the landward movement of interface by forming a pumping trough near the sea and a pressure ridge further away. Merits of the method include lower rates of pumping and injection compared to the individual cases. Disadvantages of the method are higher cost of operation of the two systems and wastage of a sizeable quantity of freshwater.

Physical Barrier

Construction of an impermeable or semi-pervious subsurface barrier extending parallel to the coast and through the thickness of the aquifer, prevents the inflow of saltwater. Such a barrier can be built in unconsolidated materials with sheet piles, or filling up deep trenches with clay, cement, concrete or asphalt. The extent of control over intrusion relies on the location, depth and permeability of the barrier. The costs involved may be very high and only small penetrations may be attained. In highly permeable formations it may be difficult to achieve a substantial permeability reduction.

Prior to adopting any of the control/remedial measures described above, the effectiveness of a particular method for a given coastal scenario can be evaluated by carrying out appropriate simulation studies using a suitable numerical model.

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