Groundwater Development and Management in Coastal Zones

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. The contamination increases as the groundwater development enhances. The seawater intrusion occurs in two modes viz., direct and indirect. Direct seawater intrusion implies a direct transport of seawater from sea to a hydraulically connected aquifer. Indirect intrusion implies transport of seawater first into a surface water body (river, canal) terminating into sea, followed by intrusion of a part of this transported water from the surface water body into a hydraulically connected aquifer. The extent of intrusion (direct as well as indirect) depends upon climatic conditions, the hydrogeology of area, and the pattern of groundwater development. Indiscriminate development can lead to almost irreversible damage to the groundwater quality. 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.

COASTAL HYDROGEOLOGIC CONDITIONS

A coastal aquifer displays hydrogeologic conditions that are far more complex than the conditions prevalent in inland aquifers. These conditions could be classified as follows.

Regional Conditions

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 flows 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 (Fig.1). 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 (Fig. 2). 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. It is apparent that if the interface encroaches upon the screen of a well, the well fails since it starts yielding saltwater.

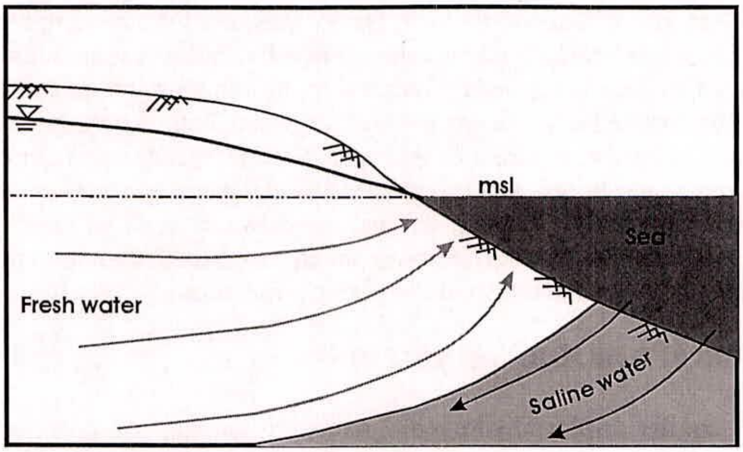

Fig. 1 Coastal aquifer system

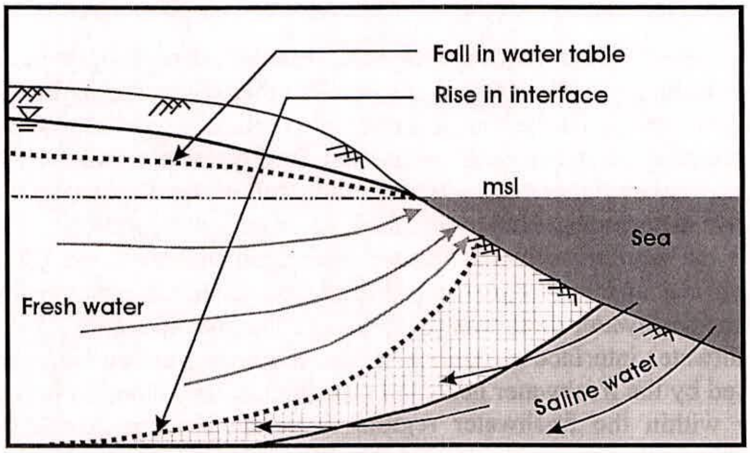

Fig. 2 Interface movement

Localized Conditions

However, merely keeping the well screen above interface cannot ensure the success of a well. This is because of a localized rise (termed as upconing) of the interface below the well as the pumping commences (Fig. 3). The upconed interface may reach a steady state below the well screen provided the pumping discharge does not exceed certain threshold. The interface rises and encroaches upon the well screen as the threshold is exceeded. Thus, the pumping duration has to be restricted if design discharge exceeds the threshold. As the pumping is discontinued, the upconed interface starts settling down and may reach back its original pre-pumping position after a while (Fig. 3). The next pumping spell may then commence.

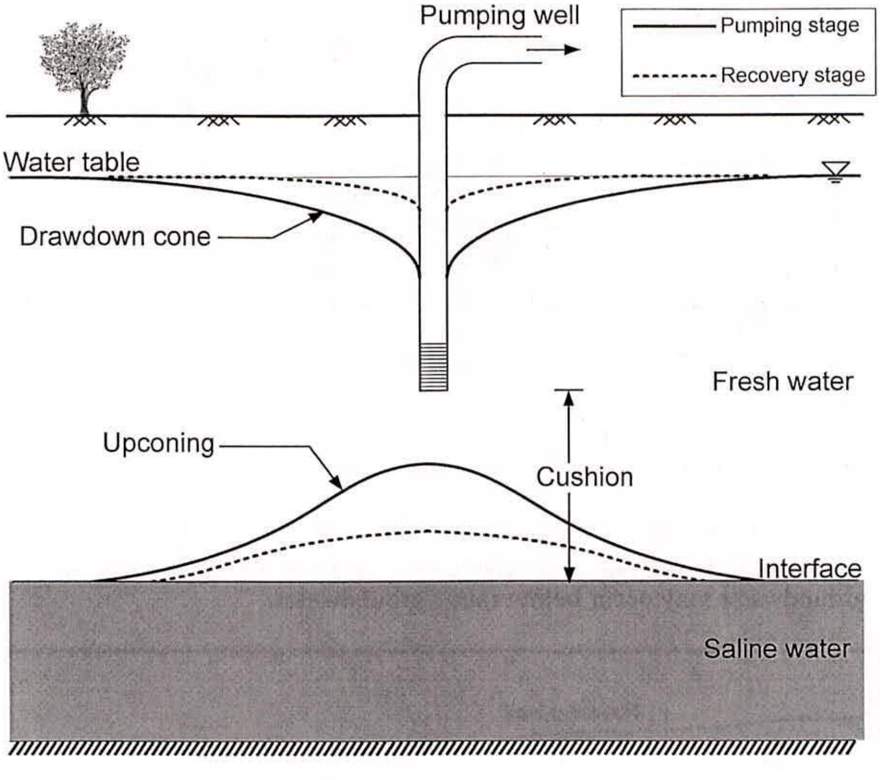

Fig. 3 Upconing and recovery

Formation of Transition Zone

Intrusion of saltwater occurs mainly by its transport due to the physical processes of advection and hydrodynamic dispersion. In coastal aquifers, due to hydrodynamic dispersion, the zone of contact between freshwater and saltwater takes the form of a transition or diffusion zone (henceforth also referred to as the disperse interface) across which the salt concentration and, hence, density of water varies from that of freshwater to that of seawater (Fig. 4). In this zone, the diluted seawater, being lighter than the original seawater, rises and moves seaward, causing saltwater from the sea to flow towards the transition zone. This induces a cyclic flow of saltwater from the sea bed 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.

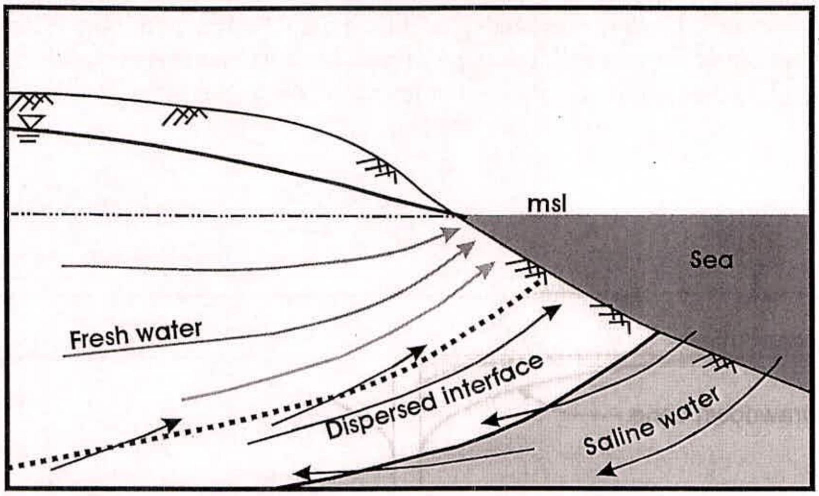

Fig. 4 Disperse interface

Multi-Aquifer Formation

The salinity of groundwater generally increases with depth. However, in a multi- aquifer system each aquifer may have its fresh water zone and the underlying saline zone (Fig. 5). As such, fresh groundwater may occur below saline groundwater.

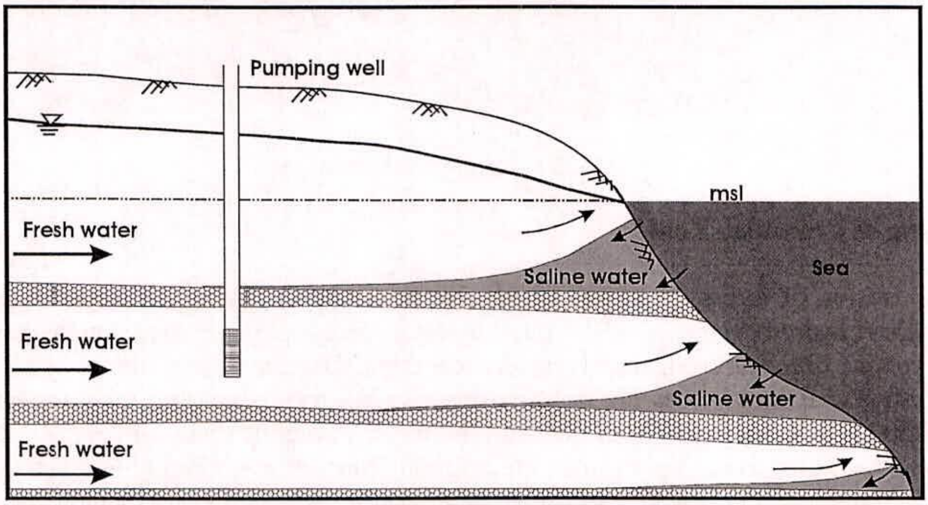

Fig. 5 Multi-Aquifer Formation

MANAGEMENT ISSUES

Planning and management issues in respect of sustainable groundwater development in coastal aquifers can be enumerated as follows.

Regional Groundwater Development

This involves a judicious planning of groundwater development ensuring that the freshwater-saltwater interface is sufficiently below the well screens in the area. This require adequate outflow to sea, which may be implemented by restricting the groundwater development or enhancing the recharge, or both.

GEC Norms

The current practice of estimating groundwater resource in India is usually based upon GEC-97 norms evolved by a committee set up by GOI in 1996. It would be interesting to evaluate these norms in respect of their suitability for coastal aquifers. These norms primarily emphasize on the vertical components (rainfall recharge, recharge from irrigation, pumpage etc.) of the water balance and the horizontal flows are severely under-emphasized.

The suggested procedure essentially involves estimating the recharge (say R) on a lumped basis and subsequently declaring a fraction say (α.R) as the groundwater resource. (α being chosen arbitrarily). The implication of this declaration is that the balance [(i.e., $(1 - \alpha)$R] goes as evapotranspiration and the subsurface outflows. Thus, the outflow to sea is lumped up with the other "loss" evapotranspiration, and decided empirically. The enormity of this arbitrary practice (if applied to coastal aquifers) immediately becomes apparent, when one realizes that it is this arbitrarily assigned outflow (to sea) that determines the position of the freshwater-saltwater interface.

Design of Wells

The wells in the area must be designed to restrict the upconing to the available cushion between the well screen and the regional interface (The cushion is determined by regional ground water development). The upconing may be controlled by one or more of the following measures:

1. Providing sufficient cushion between the well screen and the rest position of the interface
2. Restricting pumping rate/ duration
3. Providing sufficient "rest period" between two successive pumping spells
4. Localized lowering of the interface by pumping saltwater (Scavenging well) or by recharging a part of the pumped freshwater (Recirculation well).

Mathematical Modeling

The groundwater development that provides the necessary cushion between the well screens and the interface can be arrived at by invoking models of regional seawater intrusion. Similarly the well design to restrict the upconing for the available cushion may be accomplished by analytical/numerical models of upconing.

COASTAL AQUIFER PLANNING AND MANAGEMENT

Data Collection and Analysis

The first step in comprehensive coastal aquifer planning and management is to collect sufficient data to adequately define and understand the coastal aquifer system, its pumping stresses, and its associated saltwater problems. Existing data on aquifer heads and chloride concentrations in coastal wells should be reviewed.

Integrated Database

Given the complexity of analysis required for coastal aquifer studies, one of the most important parts of the overall planning approach is adequate database development and application. Data must be organized in such a way that it can be analyzed spatially, in three dimensions, as well as temporally. The long-term nature of interface movement requires that data from as far back as possible be collected. The only way to make the data available for analysis and modelling is to develop an integrated database/geographic information system (GIS).

Data elements and map coverages in the GIS database needed for coastal aquifer management include:

- Well information (depth, location, aquifer identification)
- Historic and projected pumping information (linked to the well information)
- Chloride sampling data (dated, linked to well locations)
- Water level data (dated, linked to well locations and chloride concentration)
- Surface map features (roads, streams, well locations, topographic features)
- Aquifer properties: hydrogeologic parameters such as transmissivity or hydraulic conductivity data, specific yield, storativity, aquifer/aquitard thickness
- Recharge estimates
- Maps of estimated present interface locations and depths

Development of Conceptual Model

Once available data and information have been collected and reviewed, a conceptual model of the mechanism of intrusion must be formed as a working hypothesis for further study. Intrusion generally can be categorized into one or more of several types of intrusion: horizontal and upward movement of the interface, downward leakage of brackish or salt water from surface water, or salt water upconing beneath a well field.

Computer Modelling

Although much insight can be gained from the process of collecting and analyzing the data, only through modelling of the mechanism of salt water intrusion can the plausibility of the conceptual model be tested, and a deeper understanding of the mechanism of intrusion be gained. Modelling lies at the heart of the planning and management process. Three dimensional, sharp interface salt water intrusion models, or coupled flow and transport models are both effective tools to analyze the long-term sustainability of coastal wells in a regional context.

Models can help answer important questions about the long-term viability of coastal well fields, and can help formulate plans for alternative sources or assess the need for treatment of brackish water.

Identify Solutions

Once the management objectives have been identified, potential means to mitigating intrusion can be investigated. Examples of potential solutions for sustaining groundwater quality in coastal areas include:

- Demand Management: lowering the demand for water to reduce pumping stress on the aquifer
- Non-potable water reuse: to reduce demand by replacing potable water with treated wastewater for irritation.
- Injection Barriers: create a hydraulic barrier by injecting water to form a narrow zone in which the freshwater gradient is towards the sea. This prevents intrusion of seawater into unaffected portions of the aquifer system.
- Extraction Barriers: create a hydraulic barrier by extracting saline water near the interface to lower heads and protect wells further inland. This solution is not used often.
- Tapping alternative aquifers: tapping aquifers located either below or above the impacted aquifer to provide alternative sources in some cases and relieve pumping stress on the impacted aquifer.
- Well Relocation: relocating wells to areas of higher fresh water head or areas less susceptible to intrusion. Relocation can also be used to reduce the intensity of pumping in an area and making the head gradients less steep.
- Modified Pumping Rates: in situations where the well is subject to periodic increases in salinity due to upconing, a modified pumping schedule can help in alleviating the problem.

CONCLUSION

The planning of groundwater development and management in coastal zones is far more complex than the traditional planning in inland aquifers. The complexity arises because there exists a layer of marine saltwater beneath the fresh continental water, and the interface between the two is acutely sensitive to the pumping/ recharge pattern. This leads to a variety of regional and local issues. The regional issues relate to the position of the freshwater-saltwater interface at a macro scale, while the local issues address the problems of well design and well operation. Mathematical models of varying complexity can be employed to plan the groundwater development at both the levels and manage the groundwater availability and quality in coastal zones.

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