Groundwater Development and Management in Coastal Zones

ANUPMA SHARMA
National Institute of Hydrology, Roorkee

INTRODUCTION

Coastal zones, accounting for approximately 70 per cent of the world's population, contain some of the most densely populated areas in the world as they generally present the best conditions for productivity. Settlements in 'coastal lowlands' are especially vulnerable to risks resulting from climate change; yet an increasingly large number of industrial hubs, trade and commerce centers are coming up in coastal lowlands and growing rapidly. The low elevation coastal zone (elevation less than 10 m above mean sea level) covers 2 per cent of the world's land area but contains 10 per cent of the world's population and 13 per cent of the world's urban population.

India has a long coastline of about 7500 km of which about 5400 km belongs to peninsular India and the remaining to the Andaman, Nicobar and Lakshadweep Islands. With less than 0.25% of the world coastline, India houses more than 63 million people living in low elevation coastal areas (land area 82,000 km^2 that constitutes about 3% of India's land area) and nearly 250 million people living within 50 km of the coastline. India's coastal zone is endowed with abundant coastal and marine ecosystems that include a wide range of mangroves, coral reefs, salt marshes, estuaries, lagoons, and unique marine and coastal flora and fauna. The coastal zone also provides sites for productive agriculture, export-processing zones, industries, harbors, airports, land ports, and tourism.

However, coastal zones are vulnerable to a variety of hydrological problems including cyclones, storm surges, flooding, seawater sprays, and seawater ingress through surface waters and through porous media. All these hydrological phenomena contribute towards salinization of fresh groundwater making the freshwater unfit for human use. In addition, anthropogenic pressures (indiscriminate groundwater abstraction, irrigation return flow, waste and waste water disposal) as well as other human activities that affect local and regional hydrological conditions (e.g. mining and land reclamation) are strong drivers for inducing seawater ingress leading to groundwater salinity. Compounding these issues are increasing risks from climate change, particularly sea-level rise.

Saltwater Intrusion

In coastal aquifers, which are in hydraulic contact with the sea, the groundwater faces an additional threat of contamination from seawater 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 develop beneath the lighter freshwater, with the freshwater thickness decreasing from the wedge toe towards the sea (Fig.ure1). 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 (Figure. 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.

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.ure 3). The next pumping spell may then commence.

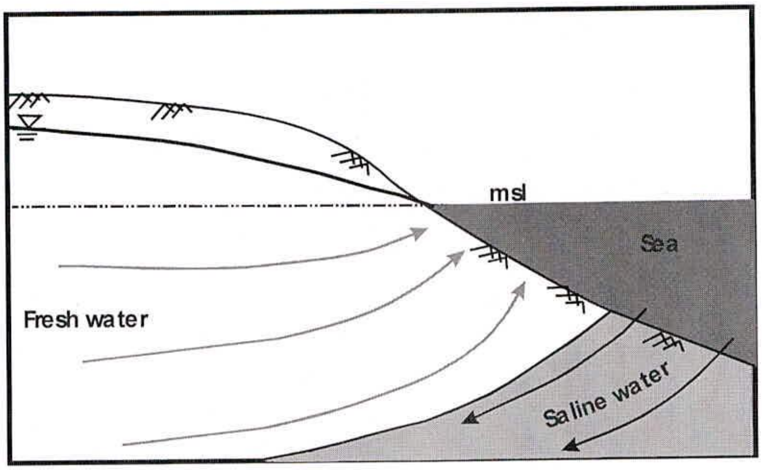

Fig. 1 Coastal aquifer system

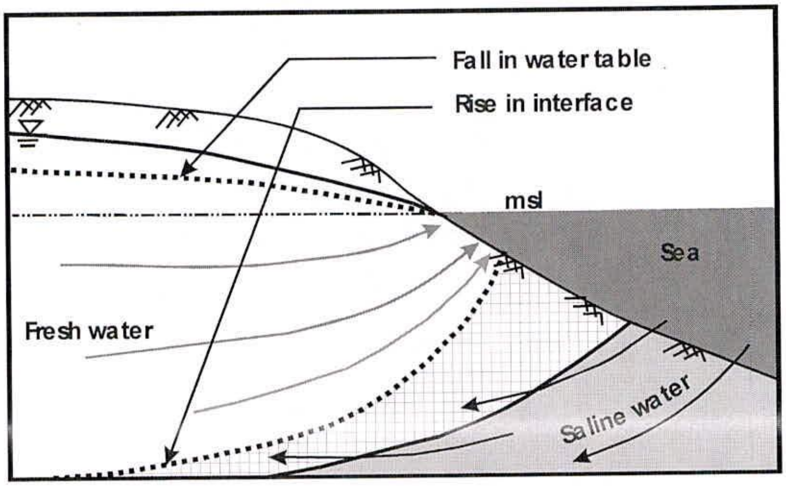

Fig. 2 Interface movement

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 (Figure. 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.

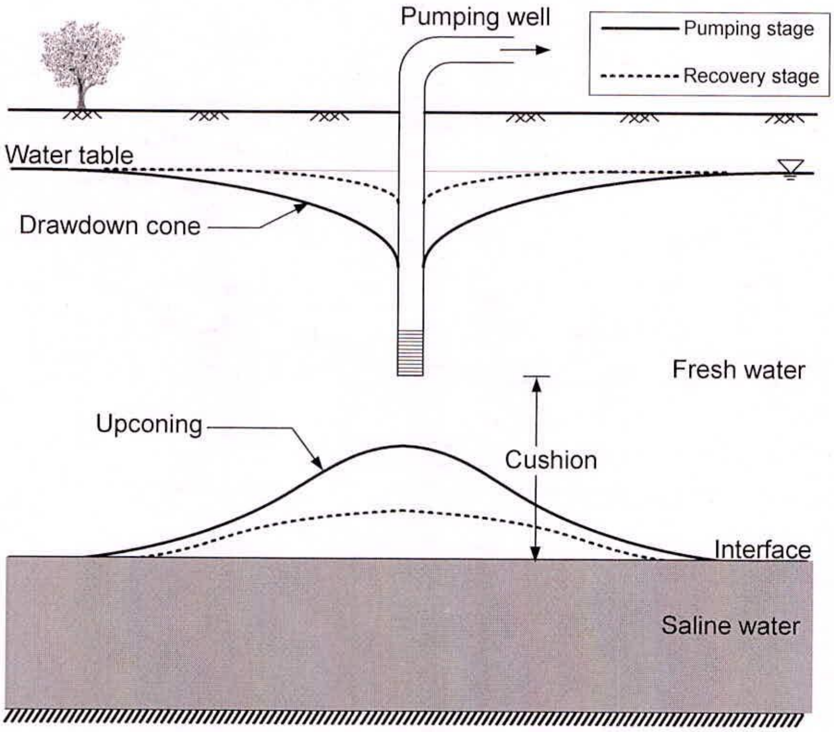

Fig. 3 Upconing and recovery

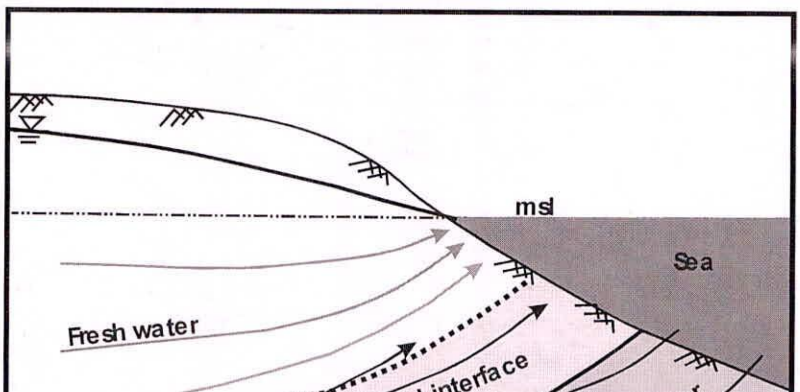

Fig. 4 Disperse interface

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.ure 5). As such, fresh groundwater may occur below saline groundwater.

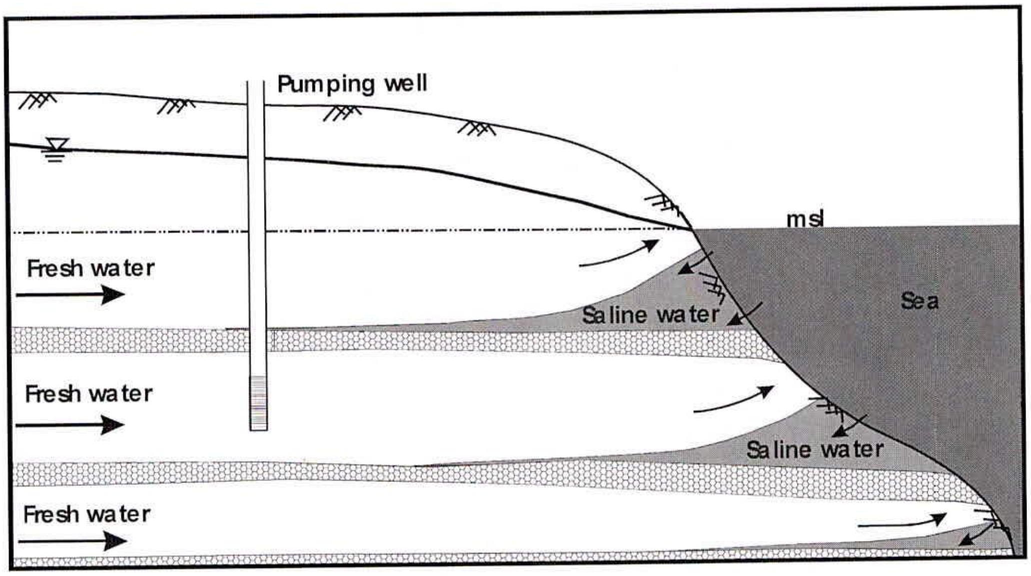

Fig. 5 Multi-Aquifer Formation

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:

i) Providing sufficient cushion between the well screen and the rest position of the interface

ii) Restricting pumping rate/ duration

iii) Providing sufficient "rest period" between two successive pumping spells

iv) 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 STRATEGIES

To preserve groundwater resources in the coastal zones, it is necessary to manage the threat of seawater ingress. Management strategies can generally be placed into following three categories with the ultimate goal of preserving groundwater resources for current and future use (Bear, 2004):

I. Scientific Monitoring, Assessment and Modeling
II. Behavioural and Institutional Approaches, and
III. Engineering Measures

I. Scientific Monitoring, Assessment and Modeling

Scientific monitoring and assessment form an essential starting point for effective management of seawater intrusion. As specific aquifer dynamics can vary greatly from location to location, these tools give decision makers an in-depth, localized understanding of their coastal freshwater resources and enable them to make sound and informed decisions. The groundwater development and management of coastal aquifer systems should form part of integrated water management, comprising surface water and groundwater, both in terms of water quantity and water quality, and taking into account the water demands.

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:

- Surface map features (roads, streams, well locations, topographic features)
- Well information (depth, location, aquifer identification)
- Historic and projected pumping information (linked to the well information)
- Groundwater quality [chemical and isotopic composition, particularly Chloride sampling data (dated, linked to well locations), and sources of groundwater pollution]
- Water level data (dated, linked to well locations and chloride concentration)
- 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
- Surface water (natural outflow, availability and quality of surface water for artificial recharge)
- Present and past artificial recharge (if any)
- Water demands, at present and estimates for the future
- Ecology (flora and fauna, and their relation to the groundwater table regime, and
- Relative sea-level rise

Observation-well networks that monitor groundwater levels and groundwater quality are indispensable for determining the effects of groundwater development on groundwater levels and groundwater storage and for monitoring the location and movement of saltwater-freshwater interface; in essence, they serve as warning or detection systems of any landward flow of subsurface saltwater. It is particularly important to emphasize the long-term commitment required for effective monitoring and assessment of saltwater intrusion. Again, elevated salt content within a well does not necessarily reflect intrusion; rather, active saltwater intrusion (characterized by a prolonged shift in the saltwater-freshwater interface) can be definitively identified only with numerous samples over a longer period of time. Such monitoring and assessment contributes to a thorough understanding of existing conditions in coastal aquifers and constitutes a necessary first step for understanding human impact on water and ecological resources, for assessing whether available water supplies will be adequate to meet future needs, and in determining both the severity of any seawater ingress and the best approach(es) in adapting to the impacts of climate change.

Scientific Assessment and Modeling

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.

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. Models can be further enhanced to incorporate the effect of water density (e.g., salinity) on groundwater flow, and they can be employed to identify conditions under which groundwater pumping and availability is optimized and seawater intrusion is limited. Specifically, these simulation-optimization models allow us to calculate favourable groundwater yields by identifying the optimal pumping rates, well locations, and human interventions (such as artificial recharge) that are most efficient. Modifying the pumping pattern or relocating the pumping locations further inland using the simulation-optimization model as a decision making tool can substantially reduce the intrusion.

II. Behavioural and Institutional Approaches

The second group of coastal aquifer management strategies fit into the category of behavioural and institutional approaches aimed towards ensuring sustained water quality and quantity over the long term.

Water supply and demand management

With regard to water supply-related policies, the natural choice might be to limit the amount of groundwater abstracted and, potentially, to relocate wells farther inland. In order to do this, water demand management in the form of water saving measures should be adopted. Various water saving measures are implemented at locations around the world that are highly prone to salinization. Other drivers like an overall water scarcity, naturally force people to adapt to such water saving practices. Possible water-saving measures are reduction of non-beneficial evaporative and leakage losses, increase of irrigation efficiency, a change to less water demanding production processes and land uses and to find alternative sources of water other than groundwater (surface water or re-use of waste water).

Salt tolerant crops

Groundwater salinity is also managed by adjusting groundwater use to poorer groundwater quality levels. In many coastal agricultural areas where only marginal quality water is available and where soil conditions are negatively affected by salinity, farmers are still able to grow crops profitably by changing to more salt-tolerant crops. Often the crop adaptation is accompanied by nutrients augmentation (in fertilizers) and soil quality improvement (e.g. adding gypsum sulphuric acid, and iron pyrite to reduce the negative effects of soil sodicity).

Usage of blended water

In cases of marginal quality groundwater, it is judicious to use this water in conjunction with better quality water. The poor quality groundwater could physically be blended with more freshwater to provide water with an acceptable salinity level for application. Alternatively, the poor quality groundwater could be applied in an alternating fashion with better quality surface water. The freshwater is used to meet the evaporative crop demand but also to flush the plot that prevents soil salinity build up significantly.

Coastal protection measures

In coastal zones that are prone to regular seawater flooding and seawater spray, various coastal protection measures consisting of e.g. levees, dikes, natural protection like dunes and mangroves, and forestation with high and dense trees can limit the susceptibility to salinization.

Institutional instruments

Farmers in salinity prone areas often rationally measure the investment costs needed for fighting salinity against the losses caused by salinity in case of non-action. On a larger scale, policymakers, agriculturists and natural resources managers need to estimate how much groundwater salinity is allowed in a certain area before complex and strongly interrelated systems of nature and society are significantly affected. Some of the consequences caused by salinity in such complex systems may be irreversible or may trigger even larger scale problems (like socio-economic problems caused by unemployment and migration of farmers that abandon their land due to severe salinity problems). The governmental and non-governmental organisations dealing with groundwater management and those dealing with soil management, agriculture and livelihood development have a responsibility to help make individuals mitigate, adapt to or compensate for, the salinity problems.

Institutional instruments that are practiced to control groundwater salinity are:

- regulatory (like well registration, licensing, groundwater abstraction rights and quota, land use restrictions, emission rules),
- economic (subsidies for individuals or groups/sectors to invest in new technologies to manage salinity, investments in governmental aquifer storage and recovery programs, environmental taxes to discourage salinity increasing practices, compensation for financial losses caused by salinity)
- advisory (enabling access to information, expertise, funding and creating awareness and training).

Policy and plan development

The technical, scientific, behavioural and institutional approaches of coastal aquifer management (ideally) come together in the development of policies and plans that deal with coastal groundwater salinity in an integrated way. Such a policy should contain an integrated and strategic vision on coastal groundwater management for a certain area and for a certain period.

III. Engineering Measures

The third group of coastal aquifer management strategies consists of various engineering measures that can be employed as a way to prevent seawater intrusion into estuaries and as control measures where groundwater withdrawals have caused water levels in aquifers to fall significantly below mean sea level. The same techniques can and must be utilized also in those cases where continuity of a controlled groundwater exploitation must be assured. These include seawater barriers, aquifer storage and recovery (ASR) systems, increased recharge, and skimming wells. The effectiveness of engineering techniques depends a lot on local conditions.

(i) Control Measures for Seawater Intrusion into Estuaries

During extended droughts, decreased river flow allows the saline water to migrate up the estuary. A rise in sea-level will also cause seawater to migrate upstream. The general methods of preventing seawater intrusion up estuaries are similar for sea-level rise, drought conditions, and storm surge. Storm surge elevates the ocean in relation to the estuary water level, causing seawater intrusion. A major difference is that storm surge and drought conditions last for a limited duration, whereas the sea-level rise is expected to last much longer.

In order to minimize seawater migration, provisions must be made for low-flow augmentation and water conservation requirements during periods of low flow. Water from rainfall is stored in large surface reservoirs and released continuously during droughts to maintain a flow that helps push back the seawater from migrating upstream. The prevention of seawater ingress can be achieved by various measures including:

- *Barriers*. Dams can be constructed that physically prevent the seawater from moving past a certain point in the estuary. Injection barriers can also be employed successfully.
- *Restrictions on pathways for seawater intrusion*. Construction of canals allows seawater to migrate into inland areas and allow a pathway for saltwater intrusion to occur; this should be minimized.
- *Alternate sources of water*. Water users may be able to obtain water from other sources that are not endangered by saltwater intrusion.
- *Restrictions on use of water*. During periods of higher sea-level or drought, stricter conservation and restrictions on export of water from the river basin may be considered for short durations.

(ii) Control Measures for Seawater Intrusion into Coastal Aquifers

Several control strategies can be used to prevent or retard seawater intrusion into aquifers. The control strategies include:

- *Seawater barriers.* One attractive solution is to design seawater barriers that prevent seawater from flowing inland, thereby protecting groundwater pumping zones. Different types of barrier designs can be considered: low permeability subsurface barriers, and, hydraulic barriers viz., injection hydraulic barriers, extraction hydraulic barriers and mixed hydraulic barriers
- *Aquifer storage and recovery (ASR).* Technique used is a particular type of artificial recharge whereby freshwater is injected into the aquifer (through a well) during high-supply seasons and then recovered (pumped to the surface) during low-supply seasons.
- *Increased recharge.* Spreading of water on the land in upland recharge areas allows more percolation (infiltration of water into the aquifer), which retards saltwater intrusion.
- *Skimming wells.* In coastal regions where freshwater is underlain by saltwater and saltwater upconing is a common problem, skimming wells are employed to restrict the salt concentration in the pumped water to an acceptable limit. Traditionally, skimming well configurations such as partially penetrating (single or multi strainer) well, radial collector well etc., have been employed to skim the freshwater. More recent configurations include the compound well systems comprising two closely spaced wells. The screens of these two wells are located at different depths with an objective of reducing the effective upconing. The commonly adopted arrangements are: scavenger and recirculation well systems. The key factors in developing a sustained skimming technology for a given coastal field are: selection of suitable skimming technique, proper design of well configuration in terms of screen positions, and operation of well in terms of permissible discharge and pumping schedules. Proper design and optimal well operation can be achieved through simulation-optimization models (Saravanan et al., 2014).

Combinations of above techniques can also be effectively employed. Combinations of an extraction and an injection hydraulic barrier, or, increased recharge with injection barrier are quite effective in preventing seawater ingress in coastal aquifers.

It is to be noted that while engineering technologies can prove effective in addressing problems of groundwater quality and quantity in a coastal aquifer system, they are generally more expensive, invasive, and site-specific than the adaptation options of scientific monitoring, assessment and modeling, and, behaviour and institutional approaches.

CONCLUSIONS

Coastal aquifers are complex environments characterized by transient water levels, variable salinity and water density distributions, and heterogeneous hydraulic properties. Climate variations, groundwater pumping and fluctuating sea-levels impose dynamic hydrologic conditions, which are inter-related with the distribution of dissolved salts through water density-salinity relationships. These processes are often important at vastly different spatial and temporal scales with wide ranging impacts on coastal hydrology and seawater ingress.

In coastal regions of India, there is still a great deal to be learned about the hydrogeologic conditions and hydrogeochemical processes that currently influence the prevalence and severity of coastal groundwater salinity. The natural occurrence of seawater intrusion depends on site conditions and, therefore, does not necessarily take place to the same extent even at sites within close proximity. At some locations, the saltwater-freshwater interface may be found at a significant distance seaward from the shoreline, while at other locations it may extend a significant distance inland.

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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