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# GEOLOGICAL CONTROLS ON SALINE WATER INTRUSION IN THE COASTAL AQUIFERS OF THE EAST COAST OF INDIA

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*Hydrogeology and the rate at which freshwater is taken from coastal aquifers controls the intrusion of saline water. The phenomenon is common in the extensive coastal sedimentary deposits and the deltas of major rivers of the east coast of West Bengal. Extensive work on saline water intrusion and hydrogeology has been carried out on the Indian coast and several other places. These have guided the theoretical and practical assumptions that were used for studying and analyzing the data collected from boreholes in the area. The east coast of India was divided into five geological regions from which three hydrogeochemical provinces were created. Methods of controlling saline water intrusion and managing groundwater exploitation in the coastal areas are suggested. The paper also suggests further studies and research work that can lead to sustainable use and management of groundwater resources in coastal areas.*

## INTRODUCTION

The geological formations of coastal areas are composed of deposits usually laid down under fluvial, lascustrine and marine environments. These deposits normally grade into one another and usually vary widely in lateral extent and thickness. In some faulted regions, bedrock outcrops along the shore with hardly any sedimentary cover. In deltaic areas of major river valleys, the coastal plains may extend hundreds of kilometers, with sedimentary strata of great thickness spanning a large interval of the geological time scale. The stratification of these deposits reveals that grain sizes may vary widely depending on the environment under which they were deposited. The coarsest materials are usually derived from the fluvial environment, while the finest materials are usually deposited beyond the neritic zone in the deep seas. Deltaic deposits occurring in the outfall regions of river systems are of particular interest because they hold some of the most productive aquifers, and can form a significant part of a coastal sedimentary basin. The total area of delta deposits has been estimated to be about 5000000 km$^2$ (Twenhofel, 1961). Some large deltas such as the Ganges-Brahmaputra, Nile and Huang Ho have areas exceeding 100000 km$^2$. These deltas were formed from materials deposited both sub-aerialy and sub-aqueously, and have grain sizes that range widely from materials coarser than gravel to clay. The grain sizes depend on several factors such as maturity of the streams and distance to source rocks, and rock types in the catchment area. Coarse deposits of gravel and pebbles are commonly found where youthful streams that flowed over rocky catchments constitute the coastal drainage. Generally, materials of the size of gravel and above are confined to the basal or lower part of the sedimentary cycle. Relatively coarse sediments are found in beaches, bars and open bays while the finer sediments are concentrated in active tributaries such as in marshes, stagnant bays and abandoned channels. Plastic clay and peat are important lithologic members in some coastal deposits (Todd, 1963). In the deposits laid sub-aqueously, grain size may change abruptly due to a sudden reduction in the velocity of stream flow near the coasts. Grain size distribution of the sediments deposited on the continental shelf is more uniform parallel to the coast. The deposits are coarsest near the shore followed by silty materials in the inner marine shelf and clay in the outer marine shelf. The sediments in the coastal areas are wedge-shaped, with thickness increasing seaward from the shore, conforming to the topography of the basement on which the deposits are laid. These deposits may acquire an initial seaward dip conforming to the slope of the continental shelf and stratification according to the variation in the texture of the materials brought in from the streams. The dip may be accentuated due to differential compaction/consolidation of the sediments. Coastal aquifers generally have a complex sequence because of a history of sea level rise and fall. Huge thicknesses of sediments that accumulated in coastal regions have formed part of outfall areas of geosynclines, which are characterized by subsiding floors. Deposits accumulated in this way may attain a thickness of several thousand meters as sedimentation keeps pace with consolidation. Porosity, specific yield and permeability of coastal sediments are similar to those of materials having similar textures in other types of deposits.

The quality of water in deltaic phreatic aquifers changes from fresh within the limits of freshwater tides to brackish in the upper reaches of estuaries and to saline in the lower reaches. The saline zone in the phreatic aquifer is likely to be wider in plains with tidal influx deep into the interior than in plains in which the tidal influx is narrow. Changes in the estuarine river courses may render groundwater in the phreatic aquifer saline in extensive areas. The absence of artesian aquifers with distant sources of recharge does contribute to the salinity of coastal aquifers (Todd, 1960). Deeper confined aquifers overlain and underlain by relatively impermeable layers outcropping in elevated areas beyond the tidal reach are likely to contain freshwater far down dip beneath the sea. Aquifers that outcrop in low altitude within the tidal reach are less likely to contain freshwater far down-dip because of lower hydraulic head resulting in less opportunity for flushing of salt as well as the possibility of the outcrop areas having been submerged by saline water in the past. Examples of freshwater layers of considerable thickness (greater than 100m) are the deltaic plain of Song Liao, Changjians and Huang ho rivers in China (Shuqin, 1985) and the Bhagirathi and Muhanadi-Brahmani rivers (Dutt, 1977). In the Gulf coastal plain of South West Louisiana, confined aquifers have been tapped by offshore wells yielding freshwater (Jones et al., 1966).

## Theory of Saline-Freshwater Interface

The boundary between salt and fresh water is termed the saline freshwater interface. Ghyben-Herzberg gave a relationship that under conditions of static equilibrium between saline and fresh water in a phreatic aquifer having hydraulic connection with the sea level, is given by:

$$\gamma_s \cdot G \cdot Z_s = \gamma_f g(Z_s+Z_w) \tag{1}$$

From which;

$$Z_s = [\gamma_f/(\gamma_s-\gamma_f)]Z_w \tag{2}$$

For: $\gamma_f = 1$ and $\gamma_s = 1.025$; $Z_s = 40Z_w$

Where :

$\gamma_s$ = density of saline water

$\gamma_f$ = density of fresh water

$Z_s$ = depth of the interface below sea level

$Z_w$ = elevation of the phreatic level above sea level

$G$ = acceleration due to gravity

## Review of Literature

Many investigations on the interrelation of two miscible fluids in porous media have been conducted both theoretically and under field conditions. Among the important theoretical works the earliest analyses were carried out independently by two scientists; Ghyben (1888) and Herzberg (1901) both assuming simple hydrostatic conditions in a homogenous unconfined coastal aquifer. The correlation they developed underestimated the depth of the saline-freshwater interface. Hubbert (1940) did a more realistic analysis for steady outflow into the sea. With Hubbert's suggested methodology, the exact position of the interface could be estimated with a fair degree of accuracy by a graphical flownet construction. But this analysis assumes a sharp interface boundary, whereas in reality, a diffused mixing zone exists. Henry (1960) presented a mathematical solution for steady-state flow considering dispersion. Pinder and Cooper (1970) provided a numerical solution for calculating the transient position of a saline waterfront in a confined aquifer. Lee and Chang (1974) carried out finite element analysis of the same. Wicks and Herman (1995) performed a modeling study to address the effect of a single, high permeable zones on mixing in a coastal aquifer. Among the fieldwork worth mentioning is Todd (1960) who carried out in situ tests in an unconfined coastal aquifer to obtain flow patterns of saline water into a freshwater aquifer. The geological profile of fresh water and saline water interrelations at Far Rockaway, Nassau county, New York, has been studied by Perlmutter and Geraghty (1963). Cooper et al. (1964) studied the basic properties of the transient zone of the Biscayne aquifer near Miami, Florida. Schmorak and Mercado (1969) investigated the upconing of underlying saline water due to well pumping. Todd and Meyer (1971) studied the effect of annual variation in pumping rate on the upconing of underlying saline water in Honolulu, Hawaii. Smart et al. (1988) studied calcite dissolution in the freshwater-saltwater interface. Wallis et al. (1992) mainly studied the reduction in the thickness of the freshwater lens due to the presence of a buried high conductivity layer in the Bahamas. Burnet et al. (2001) conducted a comparative field study on direct discharge of freshwater from coastal aquifers into the sea. Taniguchi et al. (2002) performed an extensive field study with data compilation on submarine groundwater discharge (SGD) in South America, Africa and part of Asia. Bhattacharya (2002) carried out an investigation on the cause and effects of saline water intrusion into the coastal aquifer of West Bengal. Sharma et al. (2002) developed a three-dimensional model study to investigate saltwater intrusion in coastal aquifers in regions of high permeability. Amer et al. (1988) developed a finite element model to investigate the Nubian aquifer system in Egypt.

## Geological regions of the East Coast of India

Some regions underlain by rock types of different ages, origin and mineral compositions are characterized by a general similarity in the mode of occurrence of groundwater. These regions may be grouped into a groundwater province by ignoring the subtle difference in the hydrologic and hydraulic properties of various lithologic types. Also, from a practical perspective, the methods of exploration, assessment, development and management of groundwater resources are in most cases common to the various rock types within a groundwater province. Taylor (1959) grouped the various stratigraphic units of India into eight water provinces, of which five are found on the east coast of India.

### Ganges-Brahamaputra Alluvial Province

The province, encompassing an area of about 850,000 km$^2$ comprises the vast plain of the Ganges and Brahmaputra rivers underlain by late tertiary and quaternary alluvium that has been deposited in a secondary environment. The thickness of the sediments increases from north to south, with the basement surface of hard rocks under the alluvium sloping at an average angle of 1 to 3 degrees (Krishnan, 1968).

At some places, the thickness of alluvium exceeds 100 m. This vast and thick alluvial fill constitutes the most potential and productive groundwater reservoir in India. The deltaic tract from the top down to depths of 15 to 76 m is predominantly clayey and is underlain by clay interbedded with sand and gravel.

### Precambrian Sedimentary Province

The province comprises structural basins that contain limestone, shale, sandstone, quartzite and local conglomerates, principally belonging to the Cuddapah, Kurnool and Vindhyan system of late Precambrian to early Paleozoic age. The thickness of sediments is 3000 m in the Cuddapah basin. They dip at low angles of 2 to 10 degrees. Limestone, dolomite and calcareous shale have been karstified to varying degrees as evidenced by caves (Borra and Betamcherla in Andhra Pradesh). Springs mark the landscape of limestone in the Cuddapah basin.

### Cenozoic Sedimentary Province

The province comprises some narrow coastal plains on the Coromandel coast and a belt of strong rocks in eastern India. It is underlain by a sequence of semi-consolidated conglomerates, sandstone, shale and lignite ranging in age from late Cretaceous to late Tertiary. Locally and exceptionally, sandstone horizons are so hard that they require blasting. In the Coromandel coast, the seaward–dipping strata contain several artesian aquifers down to a depth of 400 m or more. In the Neyveli area (Coromandel coast) the Cuddalore sandstone forms aquifers of friable, loosely cemented, porous and permeable well-sorted coarse sandstones that are laterally extensive and fairly uniform in thickness. Dense, plastic clay and shale form effective confining layers of the flowing well areas for which individual aquifers are different. In the Krishna-Godavari interstream area in Andhra Pradesh and Caurvery-Paleru interstream area in Tamil Nadu, wells of 150 to 300 m depth tapping artesian aquifers are free flowing, with the discharge rates of some exceeding 100 $m^3$/h. Tubewells commonly yield 50 to 200 $m^3$/h.

### Precambrian Crystalline Province

Plutonic, igneous and metamorphic rocks of Archaean and Algonkian systems, consisting chiefly of granite, quartzite, and schist extend from Kanyakumari to Calcutta. Locally, deep circulation of groundwater is indicated by striking a solution cavity at a depth of 290 m in a borehole drilled through charnockite in the Ponnani basin in Tamil Nadu. Groundwater development is largely through large diameter dug wells, which have discharges generally in the range of 20 to 200 $m^3$/day. Well drilling and blasting to obtain enhanced supplies sometimes revitalizes dug wells. In recent years borewells are being constructed in increasing numbers especially for public water supplies in the basin. The yields of these borewells are generally less than 25 $m^3$/h but exceptional yields of over 90 $m^3$/h have been recorded. Generally groundwater in this province contains less than 1000 ppm of dissolved solids, but locally it may be brackish or saline. High concentration of fluoride has been reported to occur in localized areas in this province, especially in Audhra Pradesh and Tamil Nadu.

### Cenozoic Fault Basins

The three discrete fault basins included in the province are; the Narmada, the Purna and the Tapti valleys, all of which contain extensive quaternary valley fill deposits consisting of lenses of sand and gravel intercalated with silt and clay. The fill ranges in thickness from about 50 m to 150 m. Sand and gravel lenses form aquifers that sustain tubewells of 25 to 150 $m^3$/h capacity. Groundwater in the Narmada and Tapti valleys contain 100 to 500 ppm of dissolved solids, but in parts of the Purna valley the groundwater is extensively saline.

## Hydrogeochemical Provinces of the East Coast of India

The basic similarities in chemical composition have been used to divide the groundwater in the east coast of India into broad hydrogeochemical provinces or zones. The zoning was also influenced by hydrogeologic and climatic situations that have bearing on the variations in the nature and concentration of dissolved solids in the groundwater. Such classification enables visualization of geochemical characteristics of groundwater from the regions and is useful in assessing the quality rating of groundwater for various uses. Handa (1964) divided the groundwater in sedimentary rocks in the east coast of India into three broad hydrogeochemical zones

### Bicarbonate zone

This zone includes generally the primary and partially softened waters that are characterized by a high percentage of bicarbonate ions generally exceeding 90% of the total anions present. The chloride and sulfate concentrations do not exceed 0.5 mg/l. The ratio of alkaline earths to sodium shows wide variations but is generally above 3, while the ratio of calcium to magnesium generally exceeds 2.

The electrical conductivity (EC) of groundwater does not normally exceed 750 micromhos/cm. The province covers the Terai-Bhaber belt as well as all the contiguous zones stretching along the Himalayan foothills and the adjoining alluvial tract. High rainfall (100 mm to 4000 mm), permeable strata and steep slopes favor flushing of salt from the soil profile. The groundwater in the eastern part of West Bengal and eastern part of Orissa falls in this category.

### Bicarbonate-Chloride zone

In this province, although the bicarbonate is dominant, the chloride and sodium ions become significant. The ratio of alkaline earth to sodium falls below 1. The EC shows an increase of up to 1500 micromhos/cm and the ratio of sulfate to chloride falls steeply to values as low as 0.1. This province extends through the southern part of the axial belt of the Indo-Gangetic alluvium and coastal Cenozoic provinces. The moderate rainfall (1000-2000 mm) and low terrain slope facilitate accumulation of salt in groundwater in the province.

### Chloride Zone

The dominance of chloride ions with concentrations generally exceeding 50% of the total anions, the exceedance of sodium ions over alkaline earth metal ions, and EC of over 1500 micromhos/cm are some of the characteristics of the groundwater in this province. The groundwater can be divided into two broad sub-provinces depending on the proportion (or concentration) of the sulfate present in it. The groundwater in some parts of the Coromandel coast falls in this category.

## Management of Coastal Aquifers

Saltwater intrusion into a fresh water aquifer occurs when pumping of wells lower the groundwater levels enough to cause salt water to move towards the well by reversal of hydraulic gradients or a decrease in fresh water heads. Because of the close association of freshwater with saline water in coastal regions, groundwater should be exploited in such a way that upconing of saline water, seawater intrusion and leakage of saline water from near surface sources to aquifers below are prevented. Seawater intrusion can be halted or prevented by maintenance of groundwater levels well above the sea level. This can be accomplished by reducing groundwater extractions, modifying the pumping patterns, and also by augmenting the natural replenishment by artificial recharge of local or imported water supplies. Another approach to control seawater intrusion is to form a subsurface dam by construction of a cut-off wall of sheet pile, concrete or puddled clay. An impervious zone can be created to prevent movement of groundwater in the aquifer through injection of cement grout, emulsified asphalt, bentonite, silica gel or calcium acrylate. A series of spreading grounds or injection wells or a combination of both could be utilized along the coast as dictated by the geological conditions encountered to create a groundwater mound or ridge. A line of pumping wells properly spaced along the coast can lead to formation of a pumping trough. In this case, these wells would produce a mixture of saline and freshwater resulting in waste of considerable quantities of freshwater. The pumping costs involved and the waste of usable waters are major factors to be considered in evaluating the practicability of protecting groundwater on the basis of maintaining a pumping trough. For prevention and control of seawater intrusion Todd (1960) listed several measures that include:

Reducing pumping, rearrangement of pumping patterns, or redistribution of points of extraction.

Artificial recharge to create a freshwater ridge by injection wells or water spreading.

Development of a pumping trough in the region between the exploitation area and the coast.

Construction of subsurface barriers.

In locations downstream from heavily irrigated areas, the water may be too saline for satisfactory crop production. The removal of salts from saline water is exceedingly expensive, especially if the water is to be used for irrigating crops. A possible solution is to dilute saline water with freshwater or waters of lower concentration so that the resulting water after mixing is suitable for use.

## CONCLUSION

The review of geological conditions and hydrogeochemistry of groundwater in the region, though having provided limited information, has also opened up an opportunity to carry out extensive research on saline water intrusion in aquifers of this region. There is a need to improve on existing knowledge that is based on simplified assumptions through expanded fieldwork, laboratory work, and thorough research. More information is required to show the pattern of variation of salinity concentration along and across the shoreline, and also with depth. If this information and data are available, it will be possible to use modern techniques to prepare, design or generate decision support systems that can be useful for planning, exploitation, and monitoring for sustainable management of groundwater resources in coastal regions of India.

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