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Sea water intrusion into coastal aquifers -concepts, methods and adoptable control practices

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■ **ABSTRACT :** Seawater intrusion is one of the most wide-spread and important processes that degrades groundwater quality by raising salinity to levels exceeding acceptable drinking water and irrigation standards, and endangers future exploitation of coastal aquifers. In India, the coastal region occupies some of the most potential aquifer systems of the country. Extensive research is being carried out in many parts of the world with the objectives of understanding the mechanism of seawater intrusion and improving the methods to control it in order to protect groundwater resources in coastal aquifers. The developed numerical models are based on different concepts. The investigations on possible impacts of climate change and seawater level rise on seawater intrusion in coastal aquifers revealed the severity of the problem and the significance of the landward movement of the dispersion zone under the condition of seawater level rise due to climate change. Sea level rise caused by global warming has become a root cause, pressure from the increase in the quantity of saltwater that many will try to enter the fresh water aquifer. Future sea-level rise due to climate change is expected to occur at a rate greatly exceeding that of the recent past. For effective management of coastal aquifer system, it is necessary to thorough understand the aquifer geometry, distribution of the fresh water and saline water in the system, optimum pumping rates, movement of the fresh water saline water interface, tidal influence into the aquifer. Safe yield of the aquifer has to be evaluated and accordingly the extraction has to be restricted, remedial measures have to be done wherever sea water intrusion has taken place. This paper describes about sea water intrusion processes, extent, estimation and various control measures to combat the problem and for sustainable use of fresh water from different case studies undertaken at India, Australia, Netherlands, Brazil and United Kingdom.

■ **KEY WORDS :** Sea water intrusion, Interface, Multi electrode imaging, Sea level rise

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Groundwater is the most abundant source of fresh water, followed by lakes, rivers and wetlands represent over 90 per cent of available freshwater (Boswinkel, 2000). The concentrations of people in the coastal regions and the increased related activities have led to an increase in the abstraction of groundwater reserves. During the second half of the 20th century, groundwater withdrawals have increased and currently groundwater accounts for about one-third of the world's freshwater consumption. It is a great challenge to secure water demand, while the available water resources are nearly constant. This requires protecting available resources from pollution including saltwater intrusion and other contaminants, which deplete the current resources. The sources of groundwater salinization include infiltration of saline wastes, return flow from agriculture, evapo-transpiration and seawater intrusion. Saltwater intrusion is one of the most wide-spread and important processes that degrades groundwater quality by raising salinity to levels exceeding acceptable drinking water and irrigation standards and endangers future exploitation of coastal aquifers

A coastal aquifer is partially or totally surrounded by the sea and there is a hydraulic continuity between fresh and seawater. In these aquifers, the freshwater is supported at the base by the saltwater of marine origin penetrated inland. Due to density differences, the lighter freshwater floats on top of a denser saltwater wedge. Between the two phases is assumed that there is a limit of separation (interface), although the miscibility between fresh and salt water will not allow that this interface is definite (Henry, 1959). A sharp freshwater-saltwater interface (Fig. 1) may be considered where the aquifer thickness is significantly large with respect to the width of the transition zone (Fig. 2).The movement of saline water into a freshwater aquifer or surface reservoir is known as saltwater intrusion and if the source of this saline water is sea water, then this process is known as seawater intrusion. By excessive pumping from a coastal aquifer, the water table or piezometric surface could be lowered to the extent that the piezometric head in the fresh water body becomes less than in the adjacent seawater wedge, and the interface could start to advance inland until a new equilibrium is reached. Seawater intrusion threatens the groundwater in coastal aquifers with large-scale and slow to reverse contamination; e.g., mixing 2 per cent seawater of salinity 35000 ppm TDS with freshwater makes the mixture non-potable and 5 per cent -mixing makes it unfit for irrigation.

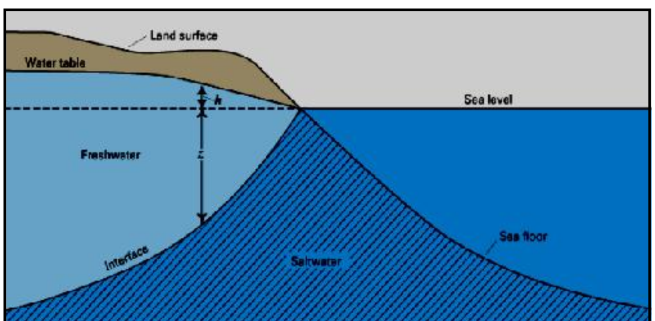

Fig. 1 : Sharp interface between fresh water and sea water (Rossi, 2011)

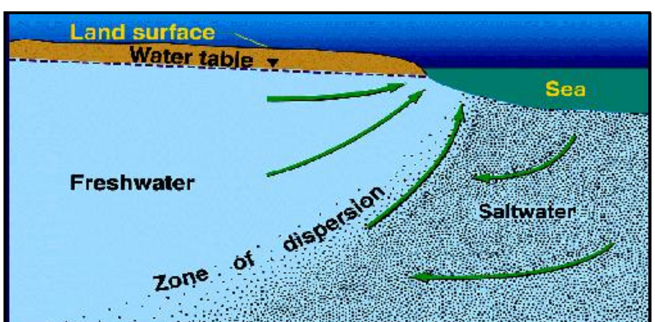

Fig. 2 : Sea water mixing- zone of dispersion (Rossi, 2011)

Seawater intrusion mechanisms :

Generally, seawater intrusion into coastal aquifers is caused by two mechanisms. Lateral encroachments from the ocean due to excessive water withdrawals from coastal aquifers, and upward movement from deeper saline zones due to up coning near coastal discharge/ pumping wells. As the interface advances, the transition zone widens.

Lateral intrusion :

In its pristine state, a uniform rate of freshwater discharge will counteract the incoming deluge of saltwater, and the position of the interface will be held in equilibrium along the coastline. This acts as natural mechanism to prevent contamination of freshwater within the aquifer. However, the development and expansion of pumping activities can easily disturb this natural balance, and induce an inward progression of the saltwater interface as shown in Fig. 3. Punthakey and Greg (2012) have concluded that as the rate of pumping increases, the interface will approach a critical 'stagnation point', after which it experiences a discontinuous jump

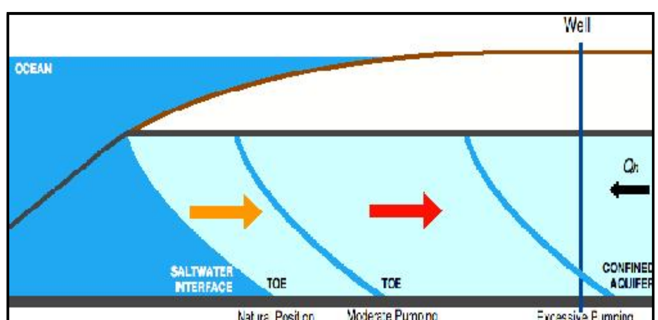

Fig. 3 : Saltwater intrusion in a coastal confined aquifer (Punthakey and Hertzler, 2012)

over and beyond the well.

Upconing :

The up coning is in response equal to rise of interface as a result of groundwater pumping shown in Fig. 4. Groundwater pumping/development can decrease the amount of fresh water flowing towards the coastal discharge areas, allowing salt water to be drawn into the fresh water zones of coastal aquifers. Therefore, the amount of fresh water stored in the aquifers is decreased (Barlow, 2003). Unless the rate of pumping is carefully controlled, seawater will eventually enter the pumped well and the wells may be abandoned.

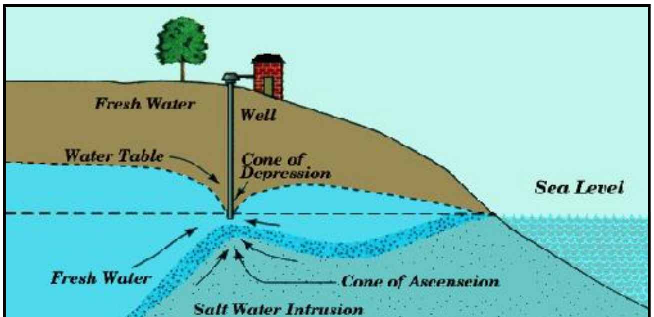

Fig. 4 : Upconing of salt water due to pumping

Model studies on sea water intrusion :

Mathematical models help to understand the relevant processes that cause saltwater intrusion in coastal aquifers. Over the years, a large number of analytical and numerical models have been used to predict the location and movement of the saltwater/ freshwater interface. The numerical models can be categorized as sharp interface models or diffusive (dispersive) interface models. Numerical solutions of steady are presented saltwater intrusion into coastal aquifer based on the assumption of sharp interface. In practice the interface is not sharp and the saltwater merges gradually with the freshwater by the process of mechanical dispersion. The width of the dispersion zone depends on the characteristics of the aquifer and the movement of water particles due to tides or the fluctuation due to recharge (Cooper, 1959).

Ghyben - Herzberg model :

The initial model on sea water intrusion was developed independently by Ghyben and Herzberg. This simple model is known as Ghyben-Herzberg model and is based on the hydrostatic equilibrium between fresh and saline water The name is due to first formulations for the physical location of the interface fresh water - salt water were established by Badon-Ghijben and A. Herzberg, thus called the Ghyben-Herzberg relation.

Rise of interface (upconing)= $z=\frac{\rho_f}{\rho_s-\rho_f}h_f$

ρ_f = freshwater density = 1.0g/cm^3; ρ_s = saltwater density = 1.025g/cm^3; z = height of saltwater column; h_f = hydraulic head above sea level

$$z = 40\,h_f$$

Depending on the values of actual densities of fresh and salt water, this ratio can vary between 33 and 50, assuming 37 as the average value. If the water table in an unconfined coastal aquifer is lowered by 1 m, the salt-water interface will rise 40 m.

Position of interface $L=\frac{1}{2}\frac{(\rho_s-\rho_f)K_b^2}{\rho_f Q^1}$

However, considering other influence parameters such as well discharge (Q), depth of fresh water- salt water interface below well bottom prior to pumping(L), hydraulic conductivity, both horizontal and vertical (K_h and K_v) porosity (n) of the aquifer and time since pumping started (t),presented an upcone equation

$$Z_t=\frac{\rho_f Q}{2\pi(\rho_s-\rho_f)K_h L}\left[1-\frac{2\rho_f nL}{2\rho_f nL+(\rho_s-\rho_f)K_v t}\right]$$

where,

Z_t = Rise of saline cone below the center of pumping well with respect time, m

L = Length of interface below the well bottom prior to pumping, m

Q = Discharge, m^3/day

K_h = Horizontal hydraulic conductivity of aquifer, m/day

K_v = Vertical hydraulic conductivity of aquifer, m/ day

n = Porosity of aquifer, per cent fraction

t = Time, days.

For t =∞, then the equation becomes $Z_t=\frac{\rho_f Q}{2\pi(\rho_s-\rho_f)K_h L}$

The critical height generally variables between 0.4 to 0.6 of L. Aquifer conditions, estimated for isotropic (K_h = K_v) and anisotropic (K_h/K_v =1.25, 2,4, 8) situations. Based on pumping drawdown of the locations, considering the critical height of upconing, maximum permissible height of upconing, an impulse response conceptual frame work of saline water upcone was developed by Movva (2006).

In recent years, different computer codes based on finite-difference (e.g. USGS SEAWAT) and finite-element (e.g. USGS SUTRA) methods have become available for simulation of density-driven problems. Some other modeling techniques that have been used to solve saltwater intrusion problems include inverse modeling (Sanz and Voss, 2006) and the Lattice Boltzman method.

Main causes of seawater intrusion :

The high population and the modern living standards demand more water, which has put the coastal aquifers under stress and causing sea water inrush and salinity upconing in the coastal aquifers. Over-abstraction is considered one of the main causes of saltwater intrusion. Some of the previous causes of saltwater intrusion are periodic (e.g. seasonal changes in natural groundwater flow), some have short term implications (tidal effects and barometric pressure) and others have long term implications (climate changes and artificial influences). The Dutch Delta lies partly below mean sea level and it is one of the first delta areas to face the impacts of climate change in combination with increased anthropogenic activities. The delta areas worldwide with similar hydro (geo) logical conditions (Fig. 5) Dutch delta area, include Mississippi, Nile, Mekong, Chinese and Indian deltas and the U.S. Atlantic coast (Barlow, 2003; Barlow and Reichard, 2010). Sea level rise caused by global warming has become a root cause, pressure from the increase in the quantity of saltwater that many will try to enter the fresh water aquifer. Global warming induces steric as well as eustatic rise in sea-level, by thermal expansion and addition of ice-melt water, respectively (IPCC, 2001).

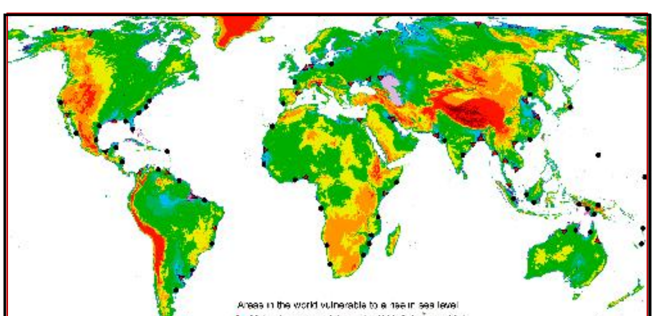

Fig. 5 : Major river deltas in the world vulnerable to sea level rise (Coleman, 1981)

Although the Intergovernmental Panel on Climate Change (IPCC, 2001) predicts that by 2100, global warming will lead to a sea-level rise of between 110 and 880 mm, more recent estimates show a global average rise of ≥1 m by the 2100 AD and it is generally understood that sea-level rise is expected to result in the inland migration of the mixing zone between fresh and saline water (FAO, 1997). One of the future challenges is climatic change and the related sea level rise. Abd Elhamid *et al.* (2015) concluded that the rise in the sea level moved the transition zone inland by about 5 per cent. However, the combination of sea level rise and over-pumping resulted in further inland movement of the transition zone (about 8%). The Nile Delta aquifer in Egypt is bounded from the north by the Mediterranean Sea has riasen by an average value of 2.5 mm/year during the last 70 years.

Measurement of sea water intrusion :

The intrusion of saltwater in coastal aquifers has been investigated by several methods including geophysical and geo-chemical methods. Late in the 1960's, efforts Rose toward drilling for chemical analysis of groundwater samples and the determination of flow patterns based on piezometric levels. Geophysical methods of investigation were introduced later and were found to provide more information faster than the drilling techniques.

Geophysical approach :

Geophysical methods measure the spatial distribution of physical properties of the earth, such as bulk conductivity of seismic velocity. Several geophysical methods can be used for hydro-geologic investigations such as electrical methods, seismic methods, ground penetrating radar and borehole methods. Being the major constitute of salt water, chloride concentration profiling is a very common method for saltwater intrusion investigations (Hem, 1989). As the concentration of chloride increases in salt water, so does conductivity. Conductivity is interdependent with temperature; therefore, profiling both of these variables becomes an important factor when determining the behaviour of the transition zone and the salt-water interface.

Multi electrode resistivity imaging survey, a combination of both profiling and sounding gives resistivity image of the profile of the area in 2D or 3D, respectively. Advantage of resistivity imaging is not only mapping the subsurface information of the area in terms of geo-electrical layers, but also generation of reliable data information of large dimension. The resistivity tomography tool has been successfully used to demarcate the saltwater–freshwater interface in different coastal settings worldwide (Choudhury *et al*., 2001 and Movva, 2006).

Geo-chemical approach :

Several geochemical criteria can be used to identify the origin of salinity in coastal aquifers. Na^+ and Cl- are dominant ions in seawater but fresh groundwater is often dominated by Ca^{2+} and HCO_3- ions. Strontium is another important ion found to be less in fresh groundwater, but more in brackish and saline water (Saxena *et al*., 2014). Cl/Br ratios (the bromide ion can be considered as a good indicator of saltwater intrusion. The concentration of bromide in fresh water is less than 0.01 mg/l, Na/Cl ratios, Ca/Mg, $Ca/(HCO_3+SO_4)$ ratios, O and H isotopes and Boron isotopes. The sea water has TDS content suggested by USGS is >35000mg/l. for fresh water TDS is less than 1000mg/l (Barlow, 2003).

Measures to control sea water intrusion :

The remediation of contaminated coastal aquifer systems is extremely difficult and expensive. In the short term, artificial recharge schemes and the installation of injection wells can counteract lateral migration of the saltwater interface. Alternatively, it may be necessary to reduce pumping rates, relocate pumping wells and reducing number of pumped wells reduced a construction that disturb a fresh water aquifer, reduced waste of fresh water near the high risk area. Hong *et al*. (2004) developed an optimal pumping model to evaluate optimal groundwater withdrawal and the optimal location of pumping wells in steady-state condition while minimizing adverse effects such as water quality in the pumping well, drawdown, saltwater intrusion and upconing. The reduction of pumping rates achieved by a number of measures including increase in public awareness of the necessity of water to save water, reduction of losses from the water transportation and distribution systems, reduction of water requirement in irrigation by changing the crop pattern and using new methods for irrigation such as drip irrigation. Extensive research has been carried out to investigate saltwater intrusion in coastal aquifers. However, only few models have been developed to study the control of saltwater intrusion. Until now there is no complete solution for this problem that can effectively control saltwater intrusion. Here it has made an effort to summarize the existing methods.

Construction of subsurface barriers (Fig. 6) is made by using sheet piling, cement grout, or chemical grout. This barrier reduces the movement of the inflow of seawater into the basin. Barsi (2001) developed two methods for optimal design of subsurface barriers to control seawater intrusion through the development of implicit and explicit simulation-optimization models with the main objective to find the optimal design of subsurface barrier to minimize the total construction cost through the selection of the width and location of the barrier. A microbial biofilm barrier for plugging permeable strata to aid the prevention of saltwater intrusion by reducing the subsurface hydraulic conductivity. Through the subsurface barriers helps to reduce the intrusion of saline water, control of saltwater intrusion using subsurface barriers could be costly in terms of construction, operation, maintenance and monitoring. It is also not efficient for deep aquifers (Abd-Elhamid *et al*., 2010).

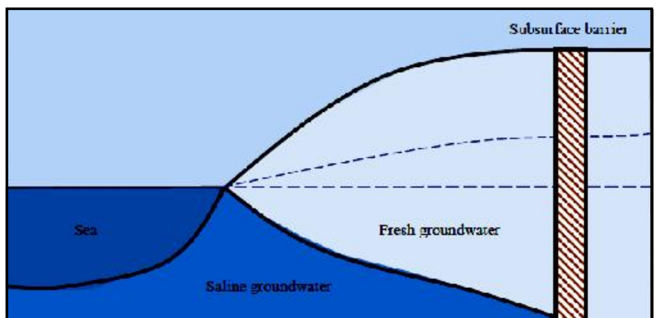

Fig. 6 : Subsurface barrier

By constructing dams and weirs the storage water feeds the aquifers with additional surface water and prevents the runoff from flowing to the sea. Infiltrated water increases the volume of groundwater storage. This method could be efficient for unconfined aquifers but it could take a long time to recharge the aquifer depending on its properties. Movva (2006) studied the natural recharge of the aquifer by using tritinium. The infiltrated water below the dam increases the aquifer storage of freshwater and pushes the saline water toward the sea. Natural recharge depends on the soil properties and requires high hydraulic conductivity. It is unsuitable for confined and deep aquifers. The cost of construction of dams and weirs and their maintenance is very high (Abd-Elhamid and Javadi, 2010). Artificial recharge is the process of recharging ground the aquifer by artificial application of water. For unconfined aquifers simple spreading of water over surface and recharge wells for confined aquifers. The potential sources of water for injection may be from different sources like surface water, pumped groundwater, treated wastewater and desalinated seawater. The source of fresh water especially in the areas that suffer from scarcity of water will be a big problem. On the other hand the cost of fresh water in cases where it is not available in these areas and transported from other places has also been another disadvantage.

In Los Angeles injection wells were used to protect the coastal aquifers from saltwater intrusion. Potable and highly treated waste water was injected into the wells. The abstraction of sea water method reduces the volume of saltwater by extracting brackish water from the aquifer and returning to the sea. The disposal of abstracted saline water was a problem. They proposed different solutions to use abstracted saline water for some purposes such as; cooling, desalting, injection into deep wells, irrigation, or disposal to the sea. Brackish water is suitable only for certain types of crops and using it in cooling may cause corrosion to the systems. The disposal of brackish water into the sea could affect the marine life in these areas, fishing and tourism activities. Another problem is that increasing abstraction of saline water could, in some cases, increase the intrusion of saltwater. Combination of injection of freshwater and extraction of saline water can reduce the volume of saltwater and increase the volume of freshwater.

Aquifer storage and recharge (ASR) system is the process of injecting water into an aquifer, where it is stored for use at a later time. It is being used throughout the world. ASR (Fig. 7) has proven to be a cost-effective way to capture and store water when it is available so it can be used during times when it is limited. A lot of water can be stored underground. This may reduce the need to construct large and expensive surface reservoirs. ASR systems are considered to be more environmentally friendly than surface reservoirs. They also offer more protection from tampering. ASR may stabilize or reverse declining water levels in an aquifer that has experienced long-term declines in water levels due to heavy pumping. The main disadvantage of this system is it can operate only at time of availability of excess water.

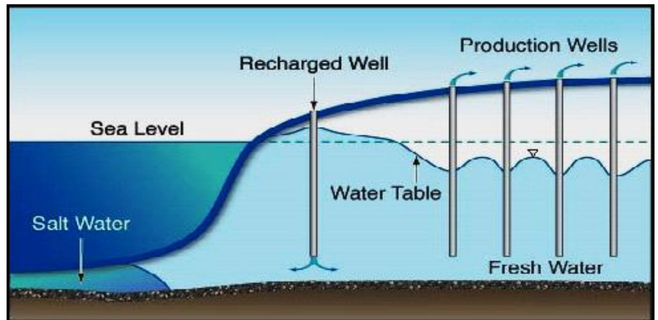

Fig. 7 : Aquifer storage and recovery system

ADR (Abstraction, Desalination and Recharge) consists of three steps; abstraction of brackish water from the saline zone, desalination of the abstracted brackish water using reverse osmosis RO treatment process, and recharge of the treated water into the aquifer proposed by Hany Farhat Abd-Elhamid and Javadi (2010). The main benefits of the ADR methodology are to return the mixing zone into the original status and to reach a dynamic balance between fresh and saline groundwater through two processes; abstraction of brackish groundwater to reduce the volume of saline water and recharge of the treated brackish water to increase the volume of fresh groundwater as shown in Fig. 8. The abstraction-recharge process continues until a state of dynamic equilibrium is reached with respect to the salinity distribution. It is generally less costly than other sources of freshwater for injection. For example, desalination of seawater has many limitations such as; high cost, pollution (mainly carbon emission), and disposal of the brine. Desalinating brackish water is an efficient alternative to seawater desalination, because the salinity of brackish water is less than one-third of that of seawater. Brackish groundwater with an amount of TDS between 1,000 and 10,000 mg/lit, can be desalinated at relatively low cost (compared with seawater which contains 35000 mg/lit of TDS). Maimone and Fitzgerald (2001) used development of new well locations and use of RO treatment for desalinating brackish water.

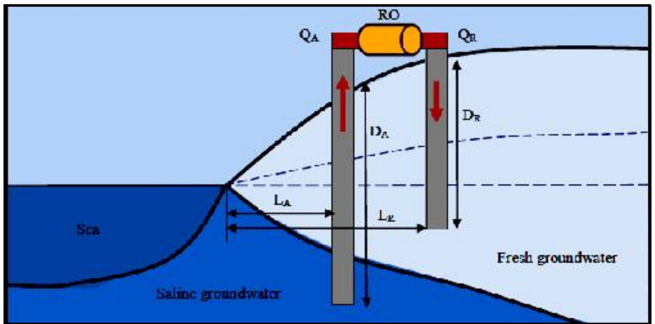

Fig. 8 : Abstraction desalination and recharge system (Hany, 2010)

Large-scale land reclamation in the study area has moved the coastline to the sea by about 1 km (Chen and Jiao, 2007). The interface between the fresh and saline groundwater may also have moved seaward by a similar amount. The fill materials became an additional aquifer and the original brackish coastal aquifer was gradually freshened. The freshening process after reclamation is schematically represented in Fig. 9. However, availability of fill material and transportation may be the main constrains of the method.

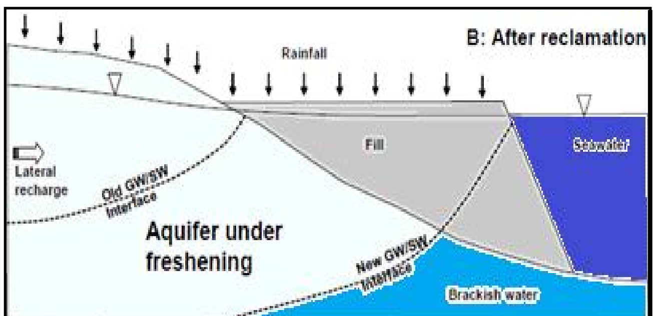

Fig. 9 : Conceptual model explaining aquifer freshening in coastal aquifers after land reclanation (Chen and Jiao, 2007)

The subsurface collector well technology popularly known as improved doruvu technology to skimming shallow depth fresh water in coastal aquifer without disturbing the hydrodynamic conditions controls sea/salt water upconig (Movva, 2006). The system consists of collector well with lateral collector lines installed at shallow depth depending on water table head above the collector lines as shown in Fig. 10, the collectors are continuously charged with fresh waters throughout their length and water flow into the well under gravity. This system is a better option to overcome problem of upconing due concentrated pumping.

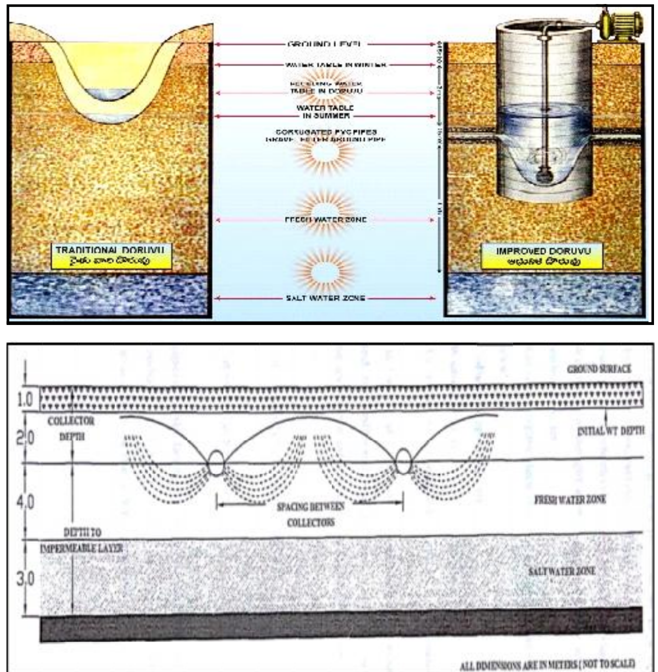

Fig. 10 : Schematic diagram of traditional doruvu and skimming well the hydraulic condition of skimming well collectors (Movva, 2006)

Saltwater intrusion in southeastern Florida has been caused by the construction of drainage canals in addition to ground-water withdrawals for water supply. Since 1946, control structures (Fig. 11) have been placed on the canals to prevent inland migration of seawater, as well as to provide flood protection and artificial recharge to the aquifer.

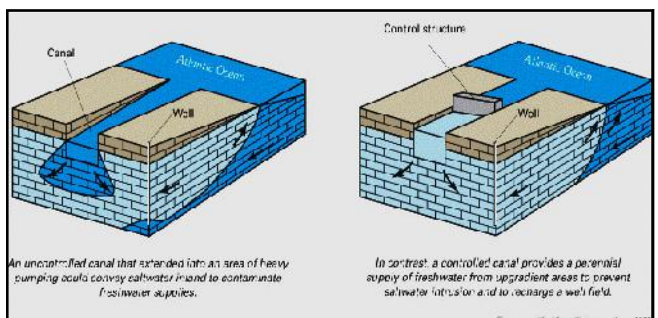

Fig. 11 : Control structures placed on the canals to prevent in land migration of seawater, as well as to provide flood protection and artificial recharge to the aquifer (Klein *et al.*, 1975)

In all of these cases, hydrologic studies and water quality monitoring are essential to help better understand the movement and interaction of fresh water and salt water in the subsurface and determine the best method to manage saltwater intrusion.Monitoring well networks allow continuous observation of the saltwater interface, after management strategies have been put in place. This provides early warnings of saltwater intrusion and tracks the effectiveness of the strategy.

Conclusion :

The concentrations of people in the coastal regions and the increased related activities like domestic, irrigation and aquaculture have led to an increase in the abstraction of groundwater reserves. The movement of ground water with in soil is generally influenced by hydro-geological properties of soil or aquifer. Mathematical models help to understand the relevant processes that cause saltwater intrusion in coastal aquifers. Over the years, a large number of analytical and numerical models have been used to predict the location and movement of the saltwater/freshwater interface. The remediation of contaminated coastal aquifer systems is extremely difficult and expensive. In the short term, artificial recharge schemes and the installation of injection wells can counteract lateral migration of the saltwater interface.

Until now there is no complete solution for this problem that can effectively control saltwater intrusion. The number of alternatives suggested in control of sea water intrusion is only through models and field results are limited. This may be due to study of effect of all these measures are costly and ineffective in unconfined aquifer systems. The large volumes of water extracted have at times lowered the regional water tables and made it difficult to control seawater intrusion. From the review it has been finally concluded that the development of effective management strategies is particularly pertinent to coastal communities faced with climate change, increasing population pressures and increased activities of agriculture and aquaculture activities. Overall, proper groundwater monitoring techniques and groundwater management, combined with groundwater conservation are needed to keep saltwater intrusion under control, and ensure fresh water supplies are sustained for future generations.

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