2 Review of Literature

At present, 2.5 billion people, half of the world's population, lives within 60 km of the shoreline. It is expected that within the next 30 years, the coastal population will be doubled. With the rapid urbanization, the concentration of the urban population in large cities will increase. Coastal zones are experiencing many problems including potential impact of seawater intrusion on freshwater supplies.

2.1 Identification of Seawater Intrusion

Seawater intrusion into an aquifer depends on the characteristics of the local formations. The salinity distribution is also dependent on the flow of fresh water, the tidal range and propagation, and on freshwater head fluctuations. During the transient stages of seawater encroachment or retreat from an aquifer - often lasting several too many years - local heterogeneities may play a dominant role in advection-dominated dispersion of saline water. Thus salinity problems in a well may be the result of preferential flows through thin - sometimes poorly defined - layers and fissures, often unnoticed or unreported. Salinity problems can also be the result of upconing of saline water below a well or drain. This is dominantly affected by local conditions of the aquifer and of the well itself.

Thus seawater intrusion monitoring is not an easy task. To achieve reasonably good results there is no substitute for a good understanding of the aquifer and the flow of groundwater of variable density in the natural, heterogeneous, coastal formations under consideration.

Since seawater has a high salt content, small fractions of seawater dominate the chemical composition of common fresh groundwater with which it mixes. The clearest signal is increase of the chloride content, but other saline waters produce the same signal. There is no sure manner to identify confidently whether the cause of salinization is modern seawater or, if not, which is the actual source of salinity.

The clearest indication that seawater intrusion may be occurring is an increase, even small, of the Cl^- content, although other phenomena may lead to an increase of the Cl^- content as well. This increase has to be established against the Cl^- background. In arid and semi-arid climates and especially near the coast, and also in the coastal strip subject to seawater spray, recharge water may be brackish and even saline.

A chloride increase can also be due to soil salinity leaching, return irrigation flows, saline waters in aquitards etc., as mentioned above. The consideration of other ions may help in trying to understand the causes. SO_4^{--} behaves as conservative in non-reducing environments, if sulphate (gypsum) deposits in the soil and oxidable pyrite in the sediments are absent. When mixing of local fresh groundwater and marine water is considered SO_4^{--} has to follow the same fractional increase as Cl^-. Then the ratio Cl^-/SO_4^{--} tends towards that of the seawater (= 9.53). The large excess of Mg^{++} over Ca^{++} in seawater is also characteristic and can be used to ascertain whether or not brackish water may be of marine origin. If Cl^- increases above its background value, the ratio Na^+/Cl^- decreases and the aquifer is subjected to increasing salinity due to saline water intrusion. When Na^+/Cl^- decrease, the dominant process is saline water flushing. When groundwater salinity is high, any modification produces cation exchange, but since Na^+ dominates above all other cations, big changes in the other cations only produce slight changes in Na^+. Then the ratio Na^+/Cl^- barely modified. In that case the ratios $(Mg^{++} + Ca^{++})/Cl^-$ or Ca^{++}/Cl^- are more indicative. If Cl^- increases and the ratio $(Mg^{++} + Ca^{++})/Cl^-$ also increase there is saline water encroachment and, if the ratio $(Mg^{++} + Ca^{++})/Cl^-$ decreases, marine sediments are being leached. The results have to be checked against the flow pattern as deduced from the groundwater head pattern.

2.2 Monitoring of Seawater Intrusion

Measurements of the groundwater-table fluctuations cannot be used to determine the thickness of the freshwater zone because there is no direct relationship between the height of the groundwater-table above mean sea level and the thickness of the freshwater zone (Falkland, 1992).

Measurements of the fluctuations in the static level in observation wells do not constitute a suitable way of monitoring the amount of recharge or of outflows from the aquifer. Despite the inherent problems of water level monitoring in coastal areas, water levels have been found to be a useful indicator of the status of freshwater bodies on a seasonal basis.

Recharge and abstraction are obviously major factors having a bearing on the movement of the mixing zone. Sometimes there is a lag of as much as several months between the occurrence of rainfall of some magnitude and the lowering of the top of the mixing zone.

There is no sure method which can warn against SWI. As is the rule in hydrogeological studies, continuous monitoring with periodic assessment of data has to be carried out, with intermediate interpretations and provisions to be checked when new data are obtained. In any case a good knowledge of the aquifer dynamics is needed; otherwise wrong interpretations can easily be made.

To assess the behavior of a coastal aquifer the following methods are available:

i) Monitoring of fresh water levels in piezometers or unexploited wells penetrating the aquifer. The recommended frequency is twice a month for small aquifers and for intensively exploited confined aquifers; every two months for large water-table aquifers. It is important that the more permeable layers are monitored with boundary aquifers such as top and bottom aquifers. Water level hydrographs, relative to local mean sea level, help in looking at trends. A continuously decreasing trend in some or all aquifers is a warning of a transient stage in which salinization may occur by inflow from the sea side or by upward flow of saline water from deep aquifers or through aquitards. When there is no clear trend the hydraulic system is in steady state, but not necessarily the salinity fronts.

ii) Periodic salinity (or EC) and temperature measurements inside boreholes and wells should be made. Salinity and temperature at a given depth have to be plotted against time. A trend of salinity increase at a given depth is a warning of seawater intrusion, unless temperature changes dramatically; otherwise it may point to an upward movement of deeper saline water. Short-screened, well isolated boreholes are best suited for this method of monitoring. If they are not available, other long-screened boreholes or unused wells can be logged.

iii) Sampling for chemical analysis in pumping wells or in boreholes of sufficient depth, Short-screened boreholes and wells are preferred. A common chemical analysis should include Cl^-, Na^+, SO_4^{--}, Ca^{++}, and Mg^{++} and it is recommended that all major ions be determined from time to time and at several points. Sampling is recommended twice a year. Any excess of Ca^{++} or $(Mg^{++} + Ca^{++})/Cl^-$ is an early warning of saline water penetrating into a freshwater aquifer. The same holds for a trend in the ratio Cl^-/SO_4^{--} too.

2.3 Scenario of World Seawater Intrusion Control Scheme

Sr. No.	Country and Region	Nature of the Problem	Control Measures
1	Argentina: Mar del Plata Aquifer, Buenos Aires.	Intense and continuous exploitation causing negative heads, lateral intrusion from the ocean	Alternative supply is being considered, administrative measures to restrict extraction.
2	Australia: Eastern Coast, Queensland	Over-exploitation in excess of long term safe yield, coastal intrusion	Construction of weir on tidal inlets, diversion of runoff from catchment.
3	Cuba; Coastal aquifers	Intensive groundwater exploitation, artificial drainage and drought conditions causing strong intrusion from sea.	Pumping controlled or stopped; artificial recharge through canals, wells and closing of drainage canals.
4	France a) East Var (French Riviera).	Abstraction greater than recharge, urbanization removal of less permeable material resulting lateral intrusion from sea and through river.	Salinity control structures in the river, impervious screen at depth, and administrative measures are under consideration.
	b) Cassis near Marseille.	Intrusion through submarine fresh water spring opening into sea.	Submerged dam was constructed inside the channel at 500 m from coast restricting the entry of sea water.
5	India a) Mehsana, Gujarat and North Madras.	Declining water levels, over-exploitation causing intrusion.	Pilot studies using spreading and infiltration basin methods, injection wells.
	b) Una - Bhavnagar, Madavpur-Maliya, Maliya-Lakhpat.	Concentrated local pumping, droughts, saline water held in the clay and silty strata caused aggressive saline intrusion.	Government remedial schemes which involve check dams, tidal regulators, bandharas, recharge tanks, recharge wells and nala plugs being implemented, situation is improving.
6	Iran Dashle-Naz (North Port).	Contamination from sediments saturated with connate water during pumping with a wide zone of dispersion.	Pilot project, involving injection well barrier.

Sr. No.	Country and Region	Nature of the Problem	Control Measures
7	Israel Eastern shore of Mediterranean Sea Tel Aviv area.	Excessive withdrawal.	Limited extraction, storage of excess flood water from rivers, injection and extraction well barriers, situation under control.
8	Italy Augusta's coastal aquifers, Eastern Sicily.	Over-exploitation by industries from layered aquifers, reducing water levels drastically, and resulting intrusion.	Artificial recharge basin using Simeto river water, injection wells, alternative supplies from river Ciane, encouraging results.
9	Japan Miyako-Jima and Okinawa-Jim a Islands.	H·:aving summer pumping, proximity to sea and through faults.	Subsurface barrier with very low permeability gave satisfactory results through experiments and are being considered.
10	The Netherlands Amsterdam dune water catchment area.	Intensive withdrawals from upper and lower aquifers, lateral intrusion, upconing.	Artificial recharge from Rhine river, limited deep water extraction.
11	Spain a) Llobregat delta.	Over-exploitation of groundwater through deep wells, reduction in river infiltration, frequent droughts.	Several administrative measures including reduction in abstraction, seawater pumping wells, surface recharge from river water are being considered.
	b) Rivera d'Horta Area, Besos delta.	Sustained overdraft.	Seawater abstraction wells near the sea protecting inland wells.
	c) Rifa area, Terragona Plain.	Over-exploitation, declining water levels causing natural intrusion and from Triassic formations.	Alternate supplies, limiting abstraction are under consideration
12	United Kingdom: Chalk near Brighton.	Intrusion during summer due to intense pumping.	Controlled pumping, studies are on for the optimum development without intrusion.

Table 2.1: Scenario of World Seawater Intrusion Control Schemes

(Sources: Atkinson et al., 1986; Bruington and Seares, 1965; Coe, 1972; Custodio, 1987b; Mistry, 1989; Newport, 1977, Sheahan, 1976; Sinha, 1987; Sugio and Nakads, 1984; Williams, 1976, Mahesha 2001).

2.4 Scenario of World – Seawater Intrusion Field Studies

The aquifer fresh water balance can be improved through artificial recharge. Provided an adequate supply of water is available with acceptable quality limits. However, the feasibility of this method depends on specific aquifer characteristics. (Custodio, 1987b)

Aquifers near the estuaries and tidal canals can be protected from sea water intrusion through salinity control dams. These dams will prevent upstream sea water movement and replenish the upstream well fields by fresh water. Problems of similar nature were identified (U.S. Task Committee, 1969) in many locations of Florida. U.S.A. and were effectively controlled through salinity control dams.

Studies were carried out to analyze the behaviour of interface subjected to sudden variation of discharge at wedge toe in confined/unconfined aquifers (Bear and Dagan, 1964; Isaacs, 1985; Isaacs and Hunt 1986; Shamir and Dagan, 1971) and linear variation of surface source level and discharge in unconfined aquifers (Vappicha and Nagaraja, 1976; Mahesha, 1995; Mahesha and Nagaraja, 1995). From the parametric studies on the effect of strip recharge on sea water intrusion in unconfined aquifers (Karandikar, 1978; Mahesha, 2000), it was found that the location of the recharge strip is the predominant factor in controlling the intrusion. The economy of water spreading, however, hinges on the maintenance of high infiltration rate (Todd, 1980), which reduces exponentially with time and requires drying, cleaning or scraping operations (Bear, 1979). The cumulative effect of natural recharge (rainfall) on seawater intrusion over the years was found to be significant (Mahesha and Nagaraja, 1996) in areas receiving medium to heavy rainfall.

Fresh water recharge through injection wells is another viable alternative to form ridge counteracting incoming seawater. This method is suitable for confined, unconfined and layered aquifers. Performance analysis of a battery recharge wells in coastal confined aquifers by analytical method showed encouraging results with a retardation of about 80% of seawater (Kashef, 1976) from the initial position. The analytical solution involved simplified assumptions including superposition of uniform natural now with well flow and static sea water. Interface toe and stagnation points in a uniform seepage field were located (Hunt, 1985a, 1985b) through complex potential derived by conformal mapping and Schwarz-Christoffel transformation techniques for single/infinite number of recharge wells in confined/ unconfined coastal aquifers. Steady and transient effects of a battery of injection wells parallel to the coast proved beneficial over long periods in controlling the intrusion (Mahesha 1996'1, 1996b). Field studies regarding the effectiveness of well recharge were reported by several researchers (Bouwer et al., 1990; Bruington, 1969; Bruington and Seares, 1965; Harpaz, 1971; Kashef, 1977; Mercer et al., 1980; Montanari and Waterman, 1968; Schroeder et al., 1989; Williams, 1976) in enriching groundwater potential and preventing seawater intrusion. The method, however, has several drawbacks including clogging of wells (Bruington, 1969; Bruington and Seares, 1965; Harpaz, 1971), higher operational and maintenance costs (Bruington, 1969; Bruington and Seares, 1965) and decrease in aquifer permeability by one or more orders of magnitude due to replacement of sea water by fresh water (Goldenberg ct al., 1983)

In the extraction process, fresh water also might get extracted along with saline water which will be disposed off to sea. An example for extraction type barrier is in Oxnard aquifer basin of Ventura County, California, USA (Coe, 1972). The project was on experimental basis with a battery consisting of five wells at an extraction rate of 21000 lpm. Even with this rate, the barrier was unable to create a seaward hydraulic gradient and hence, more number of wells was suggested. However, the technique was found effective in preventing further intrusion, with relatively higher costs.

Combining injection and extraction methods suitably may be more effective (Mahesha, 1996c) in preventing intrusion by forming an extraction trough near the sea and a fresh water ridge allowing a greater development of the aquifer.

An example of this combination is the barrier in Palo Alto Area, California, U.S.A. (Sheahan, 1976). The barrier was formed by a series of injection and extraction wells with computer control over the operation activities sensing piezometric levels in a series of monitor wells. The advantage in this method is the lower rates of recharge and extraction than the individual cases (U.S. EPA, 1973), whereas disadvantages include higher cost of operation of two systems and wastage of substantial amount of freshwater (Kashef, 1977).

Inadequate supply of fresh water for recharge, wastage of substantial amount of fresh water and need for regular maintenance, have favored surface & subsurface physical barriers. In this method, saline water inflow into fresh water basin is prevented by physical impervious barriers which will permit greater developments of the basin. The extent of control over intrusion is primarily dependent on location, depth and permeability of the barrier. Suitable materials for the barrier include cement grout, sheet pile, puddled clay, bentonite, emulsified asphalt, silica gel, calcium acrylate or plastics (Knox, 1983). Figure 2.1 shows effect of construction of typical surface barrier across a stream or canal on movement of seawater wedge.

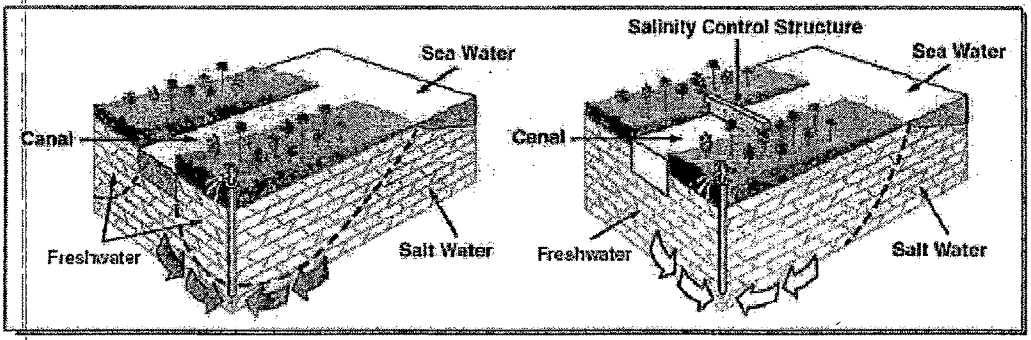

Fig 2.1: Effect of Seawater Intrusion Preventive Structure in hold back seawater intrusion

(When groundwater levels are low, water from recharge reservoir located on U/S of such structures is released to combat seawater intrusion.)

Knox (1983) studied the effectiveness of physical barriers including slurry walls, grout cutoffs and sheet piles on the motion of contaminated groundwater. The analytical and numerical solutions for the movement of contaminated groundwater under or through subsurface barriers showed the dependency on permeability of the barrier, depth to impermeable formation and the joint between barrier and underlying formation. Greater efficiencies of the impervious barrier nearer to the sea face and with increased depth of penetration were also reported (Sen, 1987), through numerical and experimental studies. Underground dams may be effective in certain situations to accumulate any spring having outlet to the sea (Custodio, 1987b). Such a work was reported in Port Miou submarine fresh water spring in the French Mediterranean coast.

The significant field studies reported include recharge well battery (Bruington and Seares, 1965), injection-extraction system (Sheahan, 1976), groundwater barrier and recharge (Williams, 1976) and physical barriers (Sugio et al., 1987).

2.5 Control of Seawater intrusion in the World

2.5.1 Studies in U. S. A.

Most of the U.S.A.'s largest sources of fresh groundwater are in close proximity to sea or to natural bodies of saline groundwater, and parts of many major streams are saline at some time. Freshwater recharge has tended to flush much saline water from permeable water-bearing materials during recent geologic time, but saline water remains at depth or in aquifers where the movement of groundwater is restricted.

In the Atlantic coast and Gulf coastal plains and in many groundwater basins on the Pacific coast, saline water occurs because of the intrusion of the seawater during recent time and also because of seawater that was trapped in the sediments during deposition or that invaded the sediments during previous high stands of the sea.

The problem of seawater intrusion is most acute in coastal regions where large groundwater supplies are developed from aquifers, which are hydraulically connected, to the sea or to tidal reaches of streams. The seriousness of the problem in these areas is usually dependent on the intensity of the urban and industrial development and consequent altering of the hydrologic or geologic environment.

The seawater intrusion into the highly permeable limestone of the Biscayne aquifer in the Miyami area of southeastern Florida provides a clear-cut example of intrusion caused by simple reversal of gradients in a non-artesian aquifer in direct contact with sea. The rate and extent of intrusion was increased because of the high permeability of the aquifer. Table 2.2 lists in abbreviated form the kinds of problems involving seawater intrusion, the kinds of study being made, the corrective measures underway or contemplated and the outlook in U.S.A.

Sr. No.	Location	Nature of Problem	Corrective measures taken	Outlook
1	Alabama Mobile – Gulf Coast	Lateral intrusion from Mobile river caused by intensive pumping.	Pumping curtailed.	Unknown.
2	California Santa Clara county	Lateral intrusion from San Francisco Bay caused by intensive pumping.	Pumping curtailed. Recharging aquifer artificially.	Managed groundwater basin.
	Los Angeles county	Lateral intrusion from ocean caused by intensive pumping.	Intrusion stopped with a freshwater pressure barrier. Pumping rates stabilized.	Continued operation of pressure barrier.
3	Connecticut New heaven and Delaware River	Lateral intrusion from tidewater in harbors caused by intensive pumping.	Pumping relocated landward.	Further pumping curtailed and greater use of alternative supplies.
4	Florida Dade and Broward counties	Infiltration of tidal water from canals constructed to drain inland areas and to lower water table.	Canal construction controlled. Canal salinity control structures were installed.	Continued management of factors affecting water supply.
	Pinellas county	Lateral intrusion from ocean into thick limestone aquifers caused by intensive pumping.	Pumping reduced.	Managed groundwater basin.

Sr. No.	Location	Nature of Problem	Corrective measures taken	Outlook
5	Georgia Savannah area	Lateral intrusion from ocean into thick limestone aquifers caused by intensive pumping.	Not known	Major Pumping curtailment.
	Brunswick	Wells encounter layers of residual seawater in thick limestone aquifer.	Seawater entering the aquifer is withdrawn at pumping centers in north Brunswick.	Pumping from selected zones only.
6	Hawaii Oahu	Lateral intrusion from ocean where pumping is too deep or excessive.	Leaky wells controlled.	Continued management of factors affecting water supply.
7	Louisiana Vermillion river	Lateral intrusion from tidal water from Vermillion river during low flow period.	Reduced pumping.	River salinity control structure.
8	New York Long Island	Lateral intrusion from ocean into producing aquifers caused by heavy pumping and reduced natural recharge.	Artificial recharge of storm runoff; reduced pumping; use of alternate supplies.	Intrusion stabilizes.
9	North Carolina	Lateral intrusion from tidal estuaries into shallow producing aquifers.	Use of alternate supply.	Studies underway.
10	South Carolina	Lateral intrusion from ocean into shallow producing aquifers.	Pumping reduced.	Major Pumping curtailment.

Table 2.2: Scenario of U.S.A. – Seawater Intrusion Control Schemes & its Outlook

2.5.2 Study of Injection Barrier to Prevent Seawater Intrusion in South California

Southern California is not unique in having seawater intrusion problems along its coastline in the groundwater basins. It is very unique in the design, construction, operation, maintenance and repairs of seawater intrusion barrier injection wells to protect its precious groundwater supplies.

Orange County, California, receives an average of only 13 to 15 inches of rainfall annually, yet sustains a population of approximately 2.5 million people. The Orange County Water District (OCWD) manages the massive groundwater basin that underlies the northwest half of the county, supplying about 75 percent of the District's total water demand. The remaining 25 percent is obtained through the Colorado River Aqueduct and the State Water Project via the Metropolitan Water District of Southern California.

By 1956, water-table lowers below sea level and seawater from the Pacific Ocean had encroached as far as 7.5km inland. The area of intrusion is primarily across a 6km front between the cities of Newport Beach and Huntington Beach known as the Talbert Gap. The mouth of an alluvial fan formed millions of years ago by the Santa Ana River, the Talbert Gap has since been buried along the coast by several hundred feet of clay.

To prevent further intrusion and to provide basin management flexibility, series of 23 multi-point injection wells 6km inland delivers fresh water into the underground aquifers to form a water mound, blocking further passage of seawater.

The first blended reclaimed water from Water Factory 21 was injected into the coastal barrier in October 1976. Several alternative sources of water were thoroughly evaluated for the seawater barrier injection program, including deep well water, imported water, reclaimed wastewater, and desalted seawater. The source of injection water finally adopted for Water Factory 21 is a blended combination of deep well water and recycled secondary effluent.

The recycled product water from Water Factory 21 meets drinking water standards through treatment using advanced processes. Recycled water was chosen for many reasons. Cost was a definite consideration, but even more important were the environmental advantages:

- Reduction of 15,000 acre-feet of wastewater discharged to the ocean annually.
- Reduction of dependency on State Water Project and Colorado River supplies.

2.5.3 Study of Injection Barrier to Prevent SWI in Los Angeles

In the late 1800's, water wells pumped by wind power were first used to tap into the ground water of the Los Angeles Basin (A). This technology provided abundant freshwater for residents of the parched coastal region, allowing for expansive growth of both population and agriculture. Increased pumping through the early 1900's caused potentiometric levels (the levels to which pressure in the aquifer would make water rise in cased wells) along the coastline to drop below sea

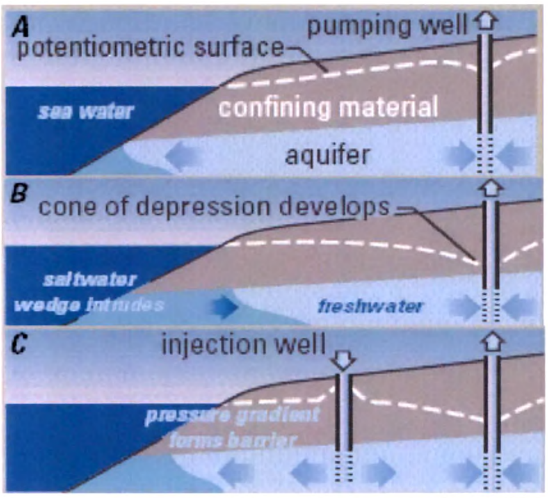

Fig 2.2: Stages of Seawater Intrusion and Control in Los Angeles Basin

level. As a result, a landward-directed pressure gradient caused seawater to begin invading coastal aquifers as early as the 1920's (B).

In the 1950's, sets of closely spaced wells were drilled to inject high quality freshwater into the ground, creating hydraulic pressure ridges or "barriers" to seawater intrusion (C). Ideally, these barriers would stem the flow of seawater into coastal aquifers. However, the barriers are not completely effective.

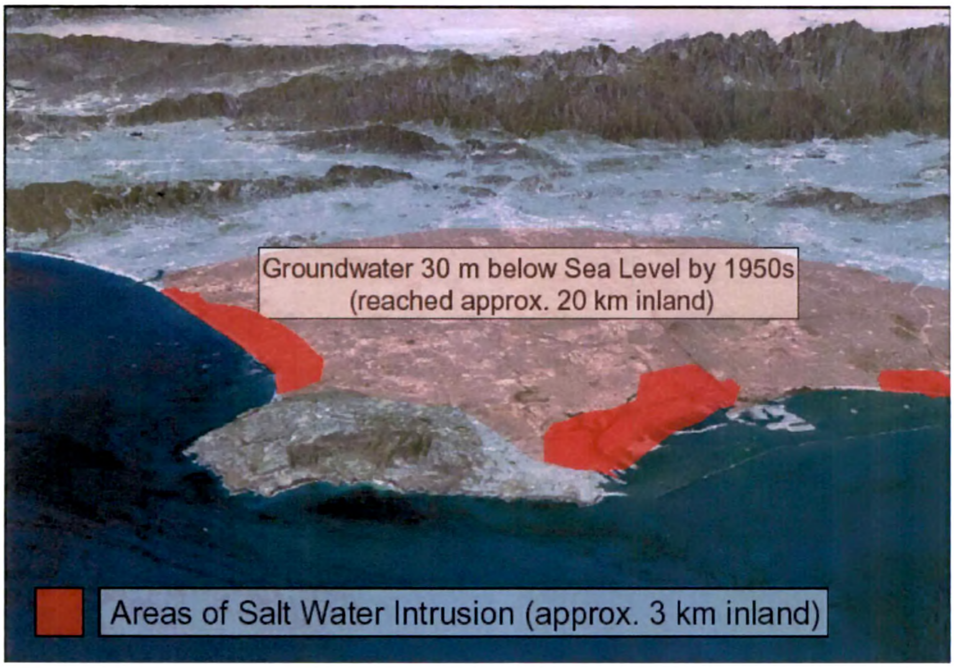

Fig 2.3: Extent of Seawater Intrusion in Los Angeles Aquifer

In the 1950's, construction began on the first of three "barriers" in an attempt to halt seawater intrusion. Each barrier consists of a series of injection wells that essentially form a subsurface wall of freshwater designed to keep seawater from penetrating further into aquifers. As the barriers are only partly effective; seawater continues to infiltrate in some areas.

Potential pathways for seawater intrusion include hydraulic connection to aquifer beds exposed at the sea floor, flow along buried ancient stream channels, and flow through crushed rock in fault zones.

One method which has been proven successful to combat this problem and is currently in use by the Department is to construct a series of injection wells along the coastline which recharge the domestic water supply with imported water and advance treated reclaimed water which has undergone micro-filtration, reverse osmosis and disinfection. This technique attempts to establish groundwater elevations greater than or equal to the original elevations within the different aquifers. The quality of water used for injection, its volume and injection costs are shown in table 2.3

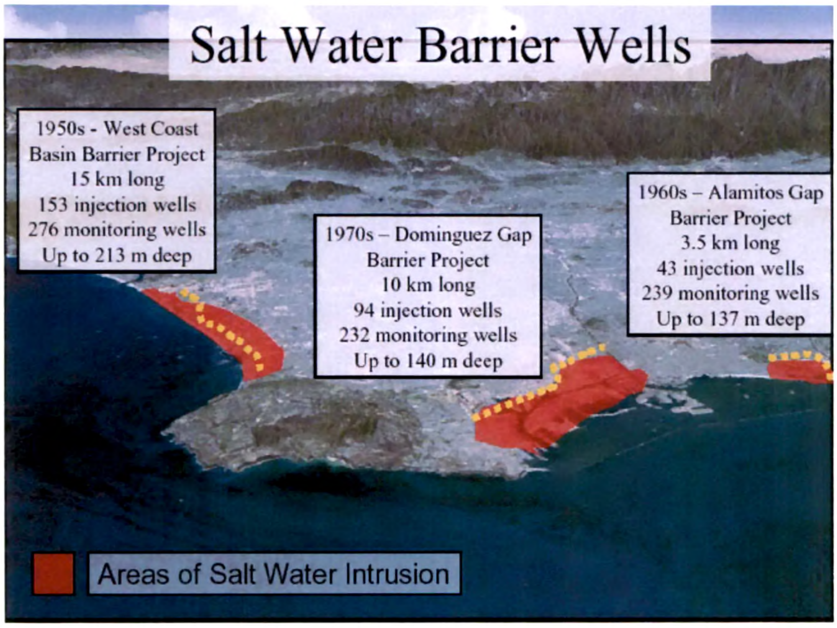

Fig 2.4: Location of Injection Barrier in Los Angeles Aquifer

Waters Used for Injection	Injection Volumes	Injection Water Costs ($ U.S.)
• Treated Drinking Water (1950s to present) • Advanced Treated Reclaimed Waste Water (started in mid 1990s)	• Injection Rates per well: 240 m^3/d – 1,100 m^3/d • Injection Volumes (5 yr avg. - total for all 3 barriers): – Drinking Water: 27 million m^3/yr – Reclaimed Water: 7 million m^3/yr	• Treated Drinking Water $0.45/$m^3$ ($570/af) • Advanced Treated Wastewater $0.35/$m^3$ ($431/af) • Total 2006/07 Barrier Water Costs: $14 Million • Total Operations Costs of Barriers: $ 3 Million af: After Functioning started

Table 2.3: Quality of Water Used For Injection, Injected Volume and Injection Costs

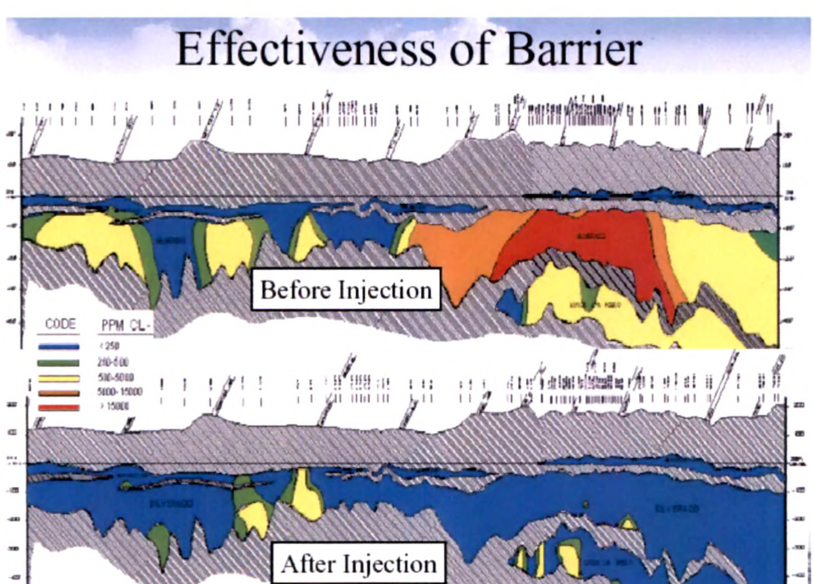

Fig 2.5: Change in Cl^- Concentration Observed after Construction of Injection Barrier

There exist three different barriers within LA County. The largest of these barriers is the West Coast Basin Barrier Project. The second largest barrier is the Dominguez Gap Barrier Project. It began operation in 1971. The Alamitos Barrier Project crosses south of the County boundary. It went into operation in 1966.

Alimitos Barrier Project (ABP)

The Alamitos Barrier Project comprise of 43 injection wells to provide a freshwater pressure ridge, and 4 extraction wells to form a trough which breaks the landward gradient of intruding seawater. It is located near the Los Angeles-Orange County line about two miles inland from the mouth of the San Gabriel River. To monitor the project performance, 175 observation wells were being constructed along the barrier alignment and placed between injection wells or spread out in the vicinity of barrier alignment. The observation wells are used to monitor water surface elevations and depth specific chloride levels.

2.5.4 Seawater Intrusion in the Biscayne Aquifer, Florida

Under predevelopment conditions, the freshwater-seawater interface in southeastern Florida extended close to the coastline, and freshwater was discharging from springs on the floor of Biscayne Bay, where the aquifer extends and is hydraulically connected to the Atlantic Ocean (Parker et al, 1955).

The position of the present-day seawater interface is a result of three principal mechanisms: (1) lateral landward movement of seawater in the surficial aquifer system from the Atlantic Ocean, (2) seepage from tidal canals containing saline water, and (3) upconing of relict seawater in response to well-field withdrawals.

During the 1940s, seawater intrusion was mitigated mostly through use of temporary sheet-pile dam control structures. Salinity control structures in Miami-Dade County were constructed by 1946 to prevent overdrainage and increase water levels in the coastal part of the surficial aquifer system, and also to allow the timely release of water during floods. Ultimately, these measures helped reverse seawater intrusion in central Miami-Dade County. The construction of surface-water control structures and improved water-management practices have considerably reduced the area of seawater contamination from its maximum extent during the 1950s and early 1960s (Fig. 2.7). During the 1970s, Tamiami Canal salinity coastal structures were replaced with a new structure located 4.5km downstream, further reducing the intrusion. During the 1980s and 1990s, chloride concentrations continued to decline as indicated in monitoring wells near the well field (Fig. 2.8) as reported by Sonenshein and Koszalka (1996).

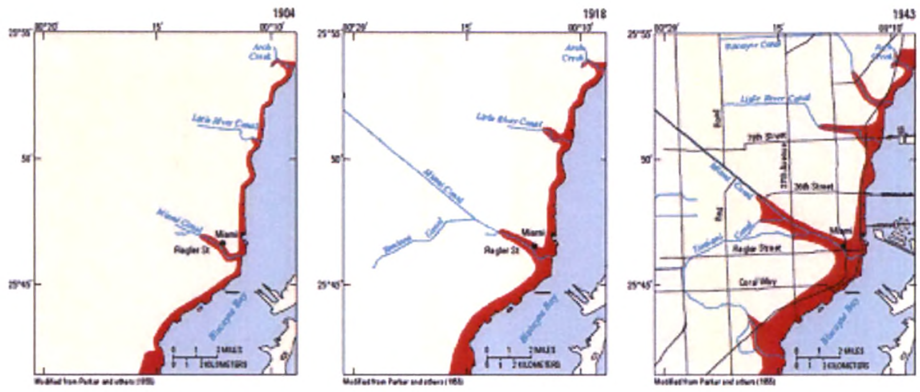

Figure 2.6: Seawater intrusion (shown in red) near the Miami Canal in Miami-Dade County, 1904-43.

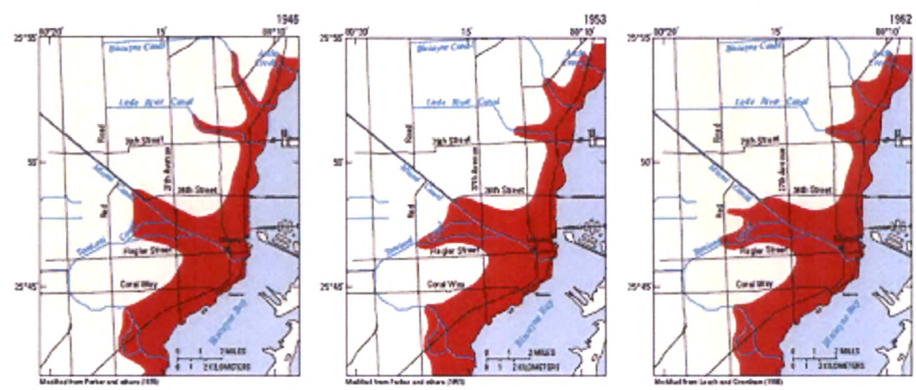

Figure 2.7: Seawater intrusion (shown in red) near the Miami Canal in Miami-Dade County, 1946-62.

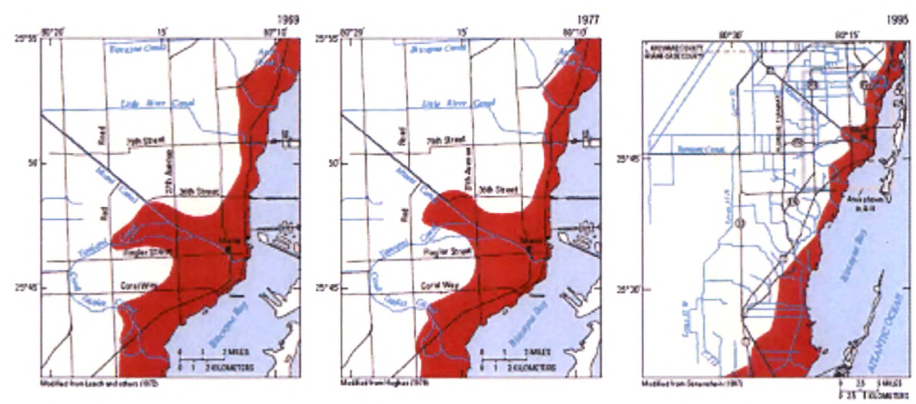

Figure 2.8: Seawater intrusion (shown in red) near the Miami Canal in Miami-Dade County, 1969-95.

2.6 Seawater Intrusion in Saurashtra, Gujarat

The major reasons for the seawater intrusion problem in Saurashtra are as follows:

i) Heavy withdrawal of the ground water to meet the increasing needs of the growing population. This has resulted from a tremendous increase in number of wells, diesel and electrical pumps etc.

ii) Cultivation of water intensive agriculture crops like Sugarcane, Wheat, Coconut, Banana, summer groundnut leading to artificial shortage of groundwater.

iii) Inefficient use and wastage of electricity owing to subsidized rates.

iv) Over-Irrigation and mismanagement of ground water. Also it has been noticed there is a high water run-off towards the sea due to inadequate water harvesting.

2.6.1 Solution of the Problem suggested by GoG

The H.L.C. (High Level Committee) formed by the GoG (Government of Gujarat) have studied the area and suggested some solutions as under. (Refer Map 4.1)

i) Management techniques
- **a.** Change in cropping pattern
- **b.** Regulation of Groundwater extraction.

ii) Recharge technique which suggest construction of
- **a.** Check Dams.
- **b.** Recharge Tanks.
- **c.** Recharge Wells.
- **d.** Recharge Reservoir.
- **e.** Spreading Channels.
- **f.** Nala Plugs.
- **g.** Afforestation.

iii) Salinity control techniques suggests construction of
- **a.** Tidal regulators and Bandharas.
- **b.** Fresh water barriers.
- **c.** Extraction Barriers.
- **d.** Static Barriers.

iv) Coastal land reclamation.

2.6.2 Management Techniques

The techniques suggested under this measure impose some control on public wells including irrigation & private wells through legislation and extension services. Excessive use of groundwater by constructing number of open wells and tube wells has to be checked so that the total withdrawal is not more than the annual recharge.

2.6.2.1 Cropping Pattern

The cropping pattern of an area depends upon mainly on soil types, prevailing climate and the irrigation facilities available.

The area between Bhavnagar to Una mainly grows the crops of Groundnut, Jowar and Bajara in Kharif and Wheat in Rabi. The area between Madhavpur to Porbandar grows the crops of Jowar, Gram, Wheat, Groundnut and Bajara etc. In low-lying area of Ghed Cotton is sown in Kharif depending upon the availability of rainfall. In Jamnagar district Bajara, Groundnut and Cotton are sown in Kharif and Wheat, Mustard, Potato, Garlic, Chilly, Lucerne etc. are sown in Rabi depending upon rainfall available. In Morbi and Maliya talukas of Rajkot district Cotton, Bajari, Jowar and Groundnut are sown in Kharif and Wheat in Rabi. Horticulture crops like Coconut, Guava, Pomegranate and Mangoes are planted in Bhavnagar to Una reach. While in Madhavpur to Maliya reach there are no horticulture plantations found.

In order to make use of the saline water for irrigation, table 2.4 to 2.6 suggests guidelines depending upon the degree of salinity and soil types. Crops like Date Palm, Ber, Bamboo, Eucalyptus, Guava, and Coconut are moderately to highly salt tolerant crops. Crops like Wheat, Bajara, Jowar, Mustard, Cotton and Castor can withstand the salinity up to some limit.

Tolerance Class	Soil Type	E.C. of Water (mmhos/ cm)	Crops
Highly tolerance	Light to medium texture	> 10,000	Field Crops like Sugarbeet, Dhaincha.
	Heavy texture	5,000 – 10,000	Orchard Crops like Date palm. Forest Crops like Babul, Shrub.
Tolerant	Light to medium texture	5,000 – 10,000	Field Crops like Sunflower, Mustard, Barley, Wheat, Bajari, Jowar, Cotton, and Castor.
	Heavy texture	3,000 – 5,000	Orchard Crops like Ber, Coconut, and Guava. Forest Crops like Eucalyptus, Saru.
Semi tolerant	Light to medium texture	3,000 – 5,000	Field Crops like Rice, Sugarcane, Maize, Sesamum, Gram, and Groundnut.
	Heavy texture	1,500 – 3,000	Vegetable Crops like Cauliflower, Onion, Potato. Orchard Crops like Mango, Pomegranate.

(Abstracted from FAO 48)

Table 2.4: Crop Selection in Respect to the Quality of Irrigation Water

In some coastal wells presence of Boron is found in irrigation water beyond the tolerant limits of the crops. For such water, crops as suggested in table 2.5 are useful.

Tolerant (more than 1 – 2 ppm of Boron)	Semi – Tolerant (1 – 2 ppm of Boron)	Sensitive (upto 1 ppm of Boron)
Date palm, Sugar beat, Lucerne, Onion, Cabbage, Carrot	Sunflower, Cotton, Tomato, Radish, Barley, Wheat, Oat, Maize, Potato	Grape, Orange, Lemon

(Abstracted from FAO 48)

Table 2.5: Tolerance of Different Crops to Boron

Field Crops		Orchard Crops	Forest Crops
Kharif	Rabi		
Bajari Jowar Cotton Castor Groundnut Math Rice	Barley Wheat Sunflower Mustard Onion Isabgul Cumin	Date palm, Ber Coconut, Guava Pomegranate	Babul Shrub Eucalyptus Saru, Subabul

(HLC Report, GoG, 1978)

Table 2.6: Cropping Pattern Suggested as Management Technique

The areas, which are badly affected and are not reclaimable economically, the crops like Babul, Saru, Subabul, and Eucalyptus etc. can be grown.

2.6.2.2 Regulation of Groundwater Extraction

The uncontrolled withdrawal of groundwater in the area without adequate provisions for recharging has resulted in over-exploitation and resultant ingress of salinity in fresh groundwater bodies.

Series of nala plugs in agriculture and wasteland were constructed in upper reaches of the catchment areas met within the problematic areas. This will help in arresting surface runoff and impounding it at intervals in nala ponds and accelerate the infiltration rate and recharge efficiency. They will also help in reducing soil erosion and silt load to downstream. In addition it is also possible that part of runoff, which is not able to percolate, can make available for irrigation of surrounding farms and thereby there is reduction in groundwater demand.

2.6.3 Recharge Techniques

2.6.3.1 Check Dams

Check dams are constructed in the beds of rivers with or without regulation device to check the monsoon flow, which otherwise passes away to the sea. The stored water contributes towards groundwater recharge and utilization by farmers for irrigation in nearby fields.

By this method recharge of groundwater can be increased in areas of increasing salinity and lowering of water-table. To increase the recharge in salinity affected areas check dams should be constructed on all streams wherever site conditions are favorable. By constructing series of check dams a good system of recharge can be developed. If such series of check is constructed on downstream side of storage (recharge) reservoir scheme then when water is released from such reservoir will fill up all the check dams and thus recharge can be increased. As the study area is in coastal belt majority of all the check dams are located on downstream side of storage reservoir scheme. Thus check dams can serves as a key element in overall planning to control the salinity ingress.

2.6.3.2 Recharge Tanks

Recharge tanks are generally constructed in low depression areas on downstream side of check dams. Recharge tanks helps in increasing the recharge rate with simultaneous improvement in quality of groundwater. The intake of recharge tank constructed without its feeding device will be restricted to its own local catchment. However generally recharge tank is connected by means of feeder channel and regulators to the existing check dams. During monsoon, floodwater from check dams can be diverted to recharge tanks through these regulators and feeder channels.

2.6.3.3 Recharge Wells

Recharge wells are like open wells with 3 to 4 meter diameter. They are back filled with rubble and with sand filter at the top. These wells will be useful to recharge pervious aquifers located at some depths below the ground level. In coastal Saurashtra belt the main geological formation is highly cavernous limestone having very high permeability. So if recharge wells are constructed at key points, they will be very much useful. The recharge wells are constructed for deeper as well as lateral recharge through Rocky strata in the riverbed. During monsoon floodwater in river will cater these wells through top filter and feeds the aquifer below riverbed.

2.6.3.4 Recharge Reservoirs

Recharge reservoirs are just a kind of medium or minor irrigation scheme with storage reservoir. It is located in upstream portion of river. Its catchment and irrigation capacity is same as that of medium or minor irrigation scheme. However its main function is to feed the check dams and other salinity control structures constructed on downstream side of it in the coastal strip so that continuous recharge and hydrostatic balance of freshwater can be maintained in the affected area.

2.6.3.5 Spreading Channels

It is an important device for the artificial recharge of the groundwater through surface water spreading along a narrow but elongated stretch. The fresh water impounded through induced recharge acts as a barrier to check the movement of seawater intrusion. Therefore if spreading channel is provided near the coastal line, they would acts as a recharge cum salinity control device, which will push back seawater intrusion by its hydrostatic head.

2.6.4 Salinity Control Techniques

2.6.4.1 Tidal Regulators & Bandhara

Tidal Regulator is a gated structure (Barrage like) constructed near the mouth of the river to prevent unplanned movement of tidal water in the river estuary on upstream and to create sweet water storage in the upstream, which is useful to create hydrostatic head of freshwater in river estuary portion and on later used for lift irrigation. The reservoir water so stored will also recharge the aquifers of the surrounding area. Moreover it also stops the tidal inundation due to high tides.

The main function of the Tidal Regulator is to prevent the tidal water ingress into the lands by sealing the mouth of the river. Generally the gates remain in closed condition round the year to prevent the entry of tidal water into the lands. Tides are entering through estuaries of the rivers twice a day. Due to flat slopes of the riverbeds near the mouth, tides are running into the land for considerable distance. It is generally observed that village wells surrounding this tidal ingress region of the estuary have been converted saline due to the constant process of tidal water ingress into the land. As a result of overdraft of sweet water from these wells, process of contamination is increasing year by year and more and more number of wells is turning saline, which are affecting agricultural land and production there from. Besides, direct infiltration of seawater also takes place through riverbeds and contaminates groundwater. It is therefore, necessary to stop tidal water ingress into the land by sealing the mouths of these rivers by construction of some structures near the mouths.

In study area (Saurashtra) structures on large rivers were constructed with gates, while structures on small rivers, local drains and creeks were constructed without gates as solid barriers (Weir like), which are called Bandhara. The height of these structures will be so kept as to keep submergence of land to the minimum and yet the project remains economically viable.

The Tidal Regulators and Bandhara were constructed with impervious cut off below the foundation. Such cut off, taken down to relatively impervious strata, will enable to prevent tidal water ingress even through foundation strata directly to contaminate groundwater. Thus, the tidal regulator & Bandhara will be designed and constructed in such a way that it would not only arrest the tides entering the estuary from surface but it would also be possible to prevent seepage of sea water into the land and polluting sweet groundwater.

The top of the gate will be kept above maximum tide level during the year, so that the waves from the sea do not splash above the gates and pollute the sweet water reservoir behind the gate. In case of Bandhara, the top is kept one meter above the highest tide level.

During floods, gates are opened and regulated as per flood forecast so as to allow the flow of the excessive flood water without creating undesirable submergence of the land in the upstream. As soon as the flood starts receding, the gates are closed to store fresh water on upstream side. The stored sweet water will improve the existing groundwater quality in wells situated in the periphery of the proposed Tidal Regulators. Population of the surrounding villages will be benefited by improved quality of water due to such structures.

The sweet water reservoir can be used for irrigation in the surrounding command areas through Lift Irrigation. This will increase recharge into the groundwater through the command area also. The lands around the reservoirs will be leached out through use of sweet water for irrigation and will make it possible to fetch higher yields from the same fields.

2.6.4.2 Static Barrier

A static Barrier consist of drilling a narrow slit up to impervious layer and filling it with clay concrete mix to make an impervious concrete barrier. This technique is economical and easy to practice in shallow aquifers. The Static Barrier is useful in the region where there is shortage of fresh water for constructing fresh water Barrier.

Above proposal to check the seawater intrusion in coastal aquifers of Saurashtra were made during the years 1978 to 1987. GOG has constructed number of such Seawater Intrusion Preventive (SIP) structure by the year 2003. They are listed in the Para 4.1. First of all after collecting the data from various Government sources, various literatures reviewed to prepare a model to study the efficacy of SIP structures.

2.7 Usefulness of Models in solving Problems of Seawater Intrusion

Coastal aquifers are important sources of water for domestic, agricultural and industrial uses. Furthermore coastal areas are frequently heavily urbanized which makes the need for domestic water more acute and, simultaneously, increases the risk of pollution from domestic and industrial effluents. Under natural conditions the hydraulic gradient is towards the sea so that there is a natural outflow of fresh groundwater. Frequently the hydraulic gradient is small. Therefore very little extraneous activity is required to disturb the natural system and cause the fresh water to become, at least, brackish. This situation poses a difficult management problem which can be addressed by means of models.

2.7.1 Physical Models

A coastal aquifer contains the interface between the fresh water, which has a relative density of approximately unity, and seawater which has a relative density in the order of 1.025. This difference in density results in the seawater lying underneath the fresh water on the landward side of the coastline. The simplest way to view the situation is to assume that the fresh and saline water are immiscible. Thus the interface is sharp. In practice the fresh and saline water are miscible. Therefore the interface is not sharp and a mixing zone exists, the thickness of which depends upon the hydrodynamics of the aquifer. If this transition zone is only a small fraction of the saturated thickness of the aquifer then the assumption of a sharp interface is reasonable and a good mathematical description of the shape of the saline wedge can be obtained. The thickness of the fresh water wedge decreases in the seaward direction and the slope of the water-table steep towards the coast. Therefore the shape of the interface is concave upwards.

If the more realistic view is taken that the fresh and saline water are miscible, then the interface cannot be sharp and the mathematical description of the problem becomes more complicated. The assumption of a sharp interface cannot be considered reasonable if the flow situation varies with time since the hydrostatic pressure distribution will vary and the assumed interface will move either landwards or seawards. This results in the sharp interface being replaced by a zone of dispersion in which the salinity of the water varies from fresh to very saline. Clearly the simplifying assumption of a sharp interface makes for a mathematically simpler but less accurate model.

2.7.1.1 The Badon Ghyben – Herzberg Equation

It has been discussed earlier in Para 1.4.3 about the Ghyben - Herzberg principle which provides an initial estimate of the inland extent of seawater intrusion in a simple unconfined aquifer of infinite depth. The seawater is 1.025 times denser than the freshwater, the seawater/fresh water interface lies a distance below mean sea level (H) for a given height of the freshwater above mean sea level (h). The interface location below mean sea level in terms of h, the freshwater head above mean sea level is $H = 40h$. At any point in time, for every meter that the freshwater-table lies above mean sea level, the depth to the seawater is 40 m below mean sea level.

This simple expression gives a remarkably good first approximation to the depth below sea level of the interface under steady state conditions when the zone of dispersion is only a small fraction of the saturated thickness of the aquifer.

This concept can be further developed to determine the extent of the penetration of the saline wedge inland. Many analyses were done, for example the determination of the shape of the interface when the seepage surface is submerged beneath the sea (Glover, 1964) and the shape of the saline upcone beneath a pumping well in a coastal aquifer (Schmorak and Mercado, 1969; Sahni, 1972).

2.7.1.2 A Sharp Interface with some Mixing

When a sharp interface is assumed, then this interface is a flowline in the same way as the water-table is a flowline. Hence it is a boundary condition for the problem. Since fresh water is flowing along the interface some mixing will occur due principally to microscopic and macroscopic dispersion. When the saline and fresh water mix in the zone of dispersion then the diluted saline water becomes less dense and will rise along a seaward path. The resulting mechanism is similar to thermal convection, the only difference being that the gradients are caused by changes in density due to changes in salinity instead of temperature (Cooper, 1964). This flow will advect some saline water towards the sea. Therefore, in order to preserve the saline mass balance, a small flow of saline water must occur in the landward direction. This flow creates a head loss, thus a reduction in pressure at the interface and a reduction in the level of the interface as predicted from the Badon Ghyben-Herzberg equation.

2.7.1.3 Field Data Required for Development of Model

Various data required for SWI or any GW models are Geological data, Hydrological data, Advection – Dispersion data, Boundary conditions and lastly successfully transferring field data to the solution grid. Field data can be transferred to the grid either aerially or on a point-by-point basis. Aerial models require vertically averaged data while profile and fully three-dimensional models require data point-by-point. Whichever type of model is being used the process is going to be difficult since all the types of data required will be sparse in comparison to the area to be modeled. Hence subjective judgments will have to be made. Some form of interpolation will be necessary. Traditionally this has been done either by hand, based on knowledge of the aquifer and hydrogeologic judgment, or by simple least squares fit. Increasingly the statistical interpolation method of kriging is being used. This technique determines the Best Linear Unbiased Estimate (BLUE) of the variable being interpolated. In essence the method optimizes the estimates of a variable which is distributed in space with measured values at a random network of points. Kriging makes the fundamental assumption that the variable under consideration is a random function in which spatial correlation decreases with increasing distance. Kriging is able to preserve the field values of the variable at the measured points unlike. This is useful when comparing the interpolated value of a variable with the likely range of values based on field knowledge.

For practical purposes it is not yet possible to simulate seawater intrusion in three dimensions on a regional basis even when the interface is assumed to be sharp because the boundary conditions consist of two non-linear partial differential equations in (h) and (H), where (h) and (H) is the piezometric heads in the fresh water and saline water zones respectively (Bear and Verruijt, 1987). Voss (1984) makes the additional point that aerial simulation is usually physically unrealistic for variable density fluid flow problems. However, regional models in two dimensions are possible by vertically averaging the equations and assuming that the interface is sharp (Wilson and Sa Da Costa, 1982). Bredehoeft and Pinder (1973) simulated seawater contamination by means of an aerial model by assuming that the chloride concentrations were sufficiently low for the density to be effectively constant. When vertical averaging is not considered an acceptable approximation, for example when the aquifer contains impermeable or semi-permeable layers which may intersect the interface, then models are made of a vertical cross-section through the aquifer. The cross-section must be aligned along a flow path. Flow paths are frequently assumed to be at right angles to the coast. Simulations of this type are called profile models.

2.7.2 SUTRA Model

SUTRA (which is named from the acronym **S**aturated **U**nsaturated **Tra**nsport) was published by the United States Geological Survey (Voss, 1984). The model is two-dimensional and can be applied either aerially or in a cross-section to make a profile model. The equations are solved by a combination of finite element and integrated finite difference methods. Although SUTRA is a two-dimensional model, a three-dimensional element is provided since the thickness of the two-dimensional region may vary over the solution domain. The coordinate system may be either Cartesian or radial which makes it possible to simulate phenomena such as saline upconing beneath a pumped well. SUTRA permits sources, sinks and boundary conditions of fluid and salinity to vary both specially and with time. The dispersion processes available within SUTRA are particularly comprehensive. They include diffusion and a velocity dependent dispersion process for anisotropic media. The standard method of modeling dispersion assumes that longitudinal and transverse dispersivities are independent of flow direction. SUTRA permits the modeling of a velocity dependent dispersion process for anisotropic media. This means that it is possible to model the variation of dispersivity when the flow direction is not along the principal axis of aquifer transmissivity.

SUTRA, in common with other models, will only provide accurate answers to well posed well defined problems which have also been well set up. Saline intrusion problems are seldom well defined.

2.7.3 MOCDENSE

MOCDENSE (Sanford and Konikow, 1985) is specifically written to model a two constituent density dependent flow in the vertical plane. It is a development of the method of characteristics model written by Konikow and Bredehoeft (1978). It uses the finite difference method to solve the flow equation and the method of characteristics to solve the advection - dispersion equation. This includes a particle tracking procedure to simulate advective transport and a two-step explicit finite difference procedure to deal with the hydrodynamic dispersion. The program checks the Courant condition and automatically adjusts the time step to ensure that the stability criteria are satisfied. Because the program involves a variation in density it solves for fluid pressure rather than for piezometric head in the flow equation. As in SUTRA the density is considered to be a function of concentration and not to be affected by temperature or pressure. This assumption is valid for saline intrusion. MOCDENSE does not seem to have been used to the same extent as SUTRA. This is probably due to the fact that it is more specialized and because the method of characteristics can be cumbersome to execute. Furthermore the computational requirements and run time become quite heavy for all but small-scale problems. However, the use of the finite difference method to solve the flow equation simplifies the discretization of the solution domain. This is a distinct advantage over SUTRA.

2.7.3.1 Choice of Suitable Model

The choice of model is decided by user preferences, the availability of software and its level of user friendliness. Whether a sharp interface model is used or whether it is decided to model the zone of dispersion will depend on the thickness of the zone of dispersion in relation to the saturated thickness of the aquifer and the availability of software. Most of the publicly available software permits the dispersive processes to be modeled for very small scale. It also depends on characteristics of the aquifer for which model is required to be prepared. In Saurashtra region the coastal aquifer system is Karstic.

2.8 Karstic Aquifers

The term "Karst" originates from the Karst plateau in the northwest of former Yugoslavia, near the Italian border, and refers to the dissolution of the carbonate rocks, limestone and dolomite. These carbonate rocks have been formed by deposition of organic carbonate material and by precipitation of dissolved carbonates. Much limestone was formed during the Cretaceous period.

Limestone and related rocks consist mainly of $CaCO_3$ and dolomitic rocks of $CaMg(CO_3)_2$. They have been formed by deposition of organic matter (shells and corals), i.e., as sedimentary rocks, which have successively been consolidated, and by precipitation of dissolved carbonates. Their primary porosity and permeability are low to moderate. Due to tectonic processes, fracturing has occurred in many cases. The water flowing through these openings dissolves, gradually and irregularly, the surrounding carbonate material thus forming wider and deeper channels and even caverns. The fractures, fissures, channels and caverns make up the so-called secondary porosity and permeability which is much larger than the primary porosity and permeability. In fact a dual-porosity system is developed. After and besides passing through the primary rock system the discharge of the natural recharge water takes place in the karst channels and openings, which are so wide and large that the flow is often non- Darcian. The water transport and storage in the primary rock system lags behind.

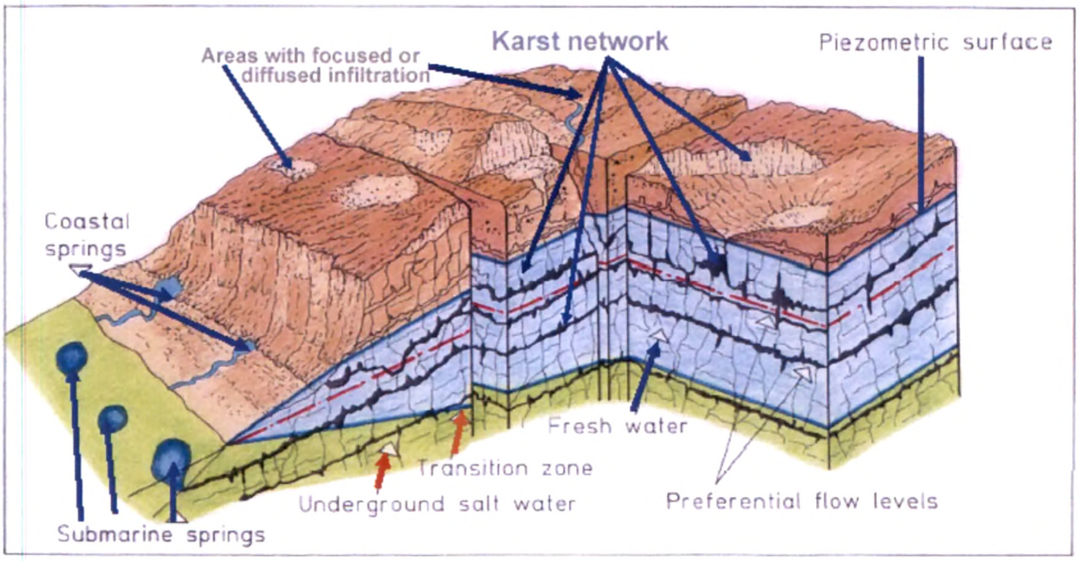

Fig 2.9: Schematic View of Karst Aquifer Network

As for any other aquifer, karst aquifers can be phreatic or (semi)-confined. In general, the secondary porosity and permeability of karstic aquifers decrease with depth. Natural recharge in phreatic karstic aquifers is great in comparison to other terrains but usually it is also quickly released. The natural recharge of phreatic karstic aquifers concentrates in terrain depressions, below which vertical channels have developed in the karstic aquifers. Such depressions, named dolines, have diameters ranging from one to several hundreds of meters. The topsoil of such dolines can be washed into vertical channels, as has occurred in many places. This leads to local lowering of the land surface on the one hand and to a decrease of the secondary aquifer porosity and permeability on the other hand.

As a consequence of this behavior of carbonate rocks, the groundwater flow system is complicated and difficult to understand and describe. For instance, the groundwater divide mostly does not coincide with the topographic divide.

2.8.1 Seawater Intrusion in Karstic Coastal Aquifers

Due to the large openings in karstic aquifers the response to impulses is generally very rapid. This does not only hold for the response to natural recharge or human activities, such as groundwater abstraction, but also for the effects of tides, storm surges and variations in atmospheric pressure. The latter effects are seawater intrusion. Depending on the system, with or without submarine springs, and more in particular the levels of outflow, as determined by the presence and the levels of natural thresholds, seawater intrusion can take place at the outlets or, more inland, at greater depths.

In general, mixing of fresh and saline water takes place rapidly, rendering the out-flowing fresh water unfit for use. Mixing of fresh and saline water in karst regions takes place under a completely different regime compared to homogeneous and isotropic porous media (Milanovic, 1981). Convective flow of fluids, non-hydrodynamic dispersion, dominates the physical mixing. Thus, the fresh-saline relationship in karstic regions only partly follows the Badon Ghijben - Herzberg principle. All together, description of this feature with mathematical formulas is complex or even impossible, unless very rough assumptions are permitted.

2.8.2 Model Concepts in Karstic Aquifers

In order to be able to take the proper measures to prevent or reduce seawater intrusion and to abstract safely a maximum fraction of the recharge, the aquifer system must first be understood. The karstic system is very capricious. Not only that; it is difficult, if not impossible, to understand. Therefore it will be necessary to resort to empirical relationships, rather than to models of the physical reality, which cannot be sufficiently known.

2.9 Summary

So for Karstic aquifers the best method is to carry out Geohydrological Water balance study. The natural rate of recharge should be estimated. The discharge of rivers and springs should be measured. Recharge and discharge should be worked out on longer time span. The aquifer properties can be found with suitable Pumping test of well in that region.

The lithological nature of karstic aquifers allows the use of some chemical parameters, the behavior of which is mainly determined by water-rock interaction processes. The chemical characteristics of saline groundwater are generally different from those of the present seawater. The most effective non-traditional and non-conservative natural tracers are the $(Mg^{++}+Ca^{++})/Cl^-$ (meq/l) ratio and some other ratios like $Cl^-/(CO_3^-+HCO_3^-)$, Na^+/Cl^- (all in meq/l).

2.10 Methodology Adopted

- **i)** Selection of sites and fixing of observation wells for individual structure as well as basin wise combined effect.
- **ii)** Monitoring groundwater fluctuations.
- **iii)** Monitoring water quality variations.
- **iv)** Effect of water quality on soil.
- **v)** Adhoc estimation of groundwater recharge due to rainfall and groundwater recharge due to seawater intrusion preventive structures using volume of storage, evaporation data and elevation – area – storage curves of reservoir.

2.11 Parameters to be Developed

- **i)** To find out coastal aquifer parameters of Saurashtra by pumping test. Volume of water stored and recharged.
- **ii)** To find out recharge rate by finding the volume of storage & volume of recharge from seawater intrusion preventive structures and from these, finding out % recharge efficiency and development of recharge rate equation for these structures.
- **iii)** To develop geochemical maps using ion ratios like like Na/Cl, $Cl/(CO_3+HCO_3)$, (Mg+Ca)/Cl to check the impact of these structures on seawater intrusion
- **iv)** Marking of zone of transition in the vicinity of the structures.