1 Introduction

Water is a precious natural resource vital, for sustaining all life on the earth. Water is indispensable to man, animals and plants and without water no life would be possible. It is not uniformly distributed in time and space. This explains the need for search of water on this planet. Water being a part of the hydrological cycle has capacity to change its form (i.e. its quality may deteriorate or it may be converted into another state), but it always remains as water and it reappears at another place as precipitation adding to surface runoff, ground water storage etc. The most important thing is that fresh water is constantly formed anew. Due to its multiple benefits and the problems created by its excesses, shortages and quality deterioration, water as a resource requires special attention.

On a global scale, total quantity of water available is about 1.37×10^8 M ha-m. The hydrological cycle moves enormous quantities of water about the globe. Of these global water resources about 97.2 % is salt water, mainly in oceans and only 2.8 % is available as fresh water at anytime on the planet Earth. Out of this 2.8 %, about 2.2 % is available as surface water and 0.6% as ground water. Even out of this 2.2 % of surface water, 2.15 % is fresh water in glaciers and icecaps and only of the order of 0.01 % (1.36×10^4 M ha-m.) is available in lakes and reservoirs and 0.04 % in streams, water vapour in atmosphere and as soil moisture in the top 0.6m. Out of 0.6% of stored ground water, only about 0.3% (41.1×10^4 M ha-m) can be economically extracted with the present drilling technology, the remaining being unavailable as it is situated below of depth of 800m.

Thus ground water is the largest source of fresh water on the planet excluding the polar icecaps and glaciers. The amount of ground water within 800m from the ground surface is over 30 times the amount in all fresh water lakes and reservoirs and about 3000 times the amount in stream channels at any one time. At present near one fifth of all the water used in the world is obtained from ground water resources. (Raghunath, 2007)

1.1 National Water Resources

India receives annual precipitation of about 4000 cubic km, including snowfall. Out of this, monsoon rainfall is of the order of 3000 cubic km. Rainfall in India is dependent on the south-west and north-east monsoons between June and September, on shallow cyclonic depressions and disturbances.

The groundwater is an important source of water for India. It accounts for about 80% of domestic water requirement and more than 45% of the total irrigation in the country. As per the international norms, if per-capita water availability is less than 1700 m^3 per year then the country is categorized as water stressed and if it is less than 1000 m^3 per capita per year then the country is classified as water scarce. In India per capita surface water availability in the years 1991 and 2001 were 2309 and 1902 m^3 respectively and these are projected to reduce to 1401 and 1191 m^3 by the years 2025 and 2050 respectively. Hence, there is a need for proper planning, development and management of the greatest assets of the country. Although India occupies only 3.29 Mha geographical area, which forms 2.45% of the world's land area, it supports over 15% of the world's population. The population of India as on 1 March 2001 stood at 1,027,015,247 souls. Thus, India supports about $1/6^{th}$ of world population, $1/50^{th}$ of world's land and $1/25^{th}$ of world's water resources.

The total arable land (as per Food and Agriculture Organization estimate) is 165.3 Mha, which is about 50.2% of total geographical area against the corresponding global figure of 10.2%. India possesses 4% of the total average annual runoff in the rivers of the world.

The utilizable surface water potential of the country has been estimated to be 1953 cubic km by the National Commission for Integrated Water Resources Development. But the amount of water that can be actually put to beneficial use is much less due to severe limitations imposed by physiography, topography, inter-state issues and the present state of technology to harness water resources economically. The utilizable annual surface water of the country is 690 cubic km. (about 35.5% of the total). (Rakesh Kumar et al, 2005)

Ground water is another important source of water. The annual potential natural groundwater recharge from rainfall in India is about 342.43 cubic km, which is 8.56% of total annual rainfall of the country. The annual potential groundwater recharge augmentation from canal irrigation system is about 89.46 cubic km. Thus, total replenishable groundwater resource of the country is assessed as 431.89 cubic km. After allotting 15% of this quantity for drinking, and 6 cubic km for industrial purposes, the remaining can be utilized for irrigation purposes. Thus, the available groundwater resource for irrigation is 361 cubic km, of which utilizable quantity (90%) is 325 cubic km.

Table 1.1 shows Per capita per year availability and utilizable surface water in India projected upto 2050 and Table 1.3 shows projected annual water requirement for different uses in 2010, 2025 and 2050.

Sr. No.	Year	Population (in million)	Per-capita surface water availability	Per-capita utilizable surface water
1	1951	361	5410	1911
2	1955	395	4944	1746
3	1991	846	2309	816
4	2001	1027	1902	672
5	2025 (Projected)	a) 1286 (low growth)	1519	495
		b) 1333 (high growth)	1465	
6	2050 (Projected)	a) 1346 (low growth)	1451	421
		b) 1581 (high growth)	1235	

(Rakesh Kumar et al, 2005)

Table 1.1: Per Capita per Year Availability and Utilizable Surface Water in India Projected Upto 2050.

Sr. No.		Cubic km/year
1	Total replenishable groundwater resource	432
2	Provision for domestic, industrial and other uses	71
3	Available groundwater resource for irrigation	361
4	Utilizable groundwater resource for irrigation (90% of the sr. no. 3)	325
5	Total utilizable groundwater resource (Sum of sr. no. 2 and 4)	396

(Rakesh Kumar et al, 2005)

Table 1.2: Groundwater Resources of India.

Use	Year 1997–98	Year 2010			Year 2025			Year 2050		
		Low	High	%	Low	High	%	Low	High	%
Surface water										
Irrigation	318	330	339	48	325	366	43	375	463	39
Domestic	17	23	24	3	30	36	5	48	65	6
Industries	21	26	26	4	47	47	6	57	57	5
Power	7	14	15	2	25	26	3	50	56	5
Inland navigation		7	7	1	10	10	1	15	15	1
Env. – Ecology		5	5	1	10	10	1	20	20	2
Evaporation losses	36	42	42	6	50	50	6	76	76	6
Total	**399**	**447**	**458**	**65**	**497**	**545**	**65**	**641**	**752**	**64**
Groundwater										
Irrigation	206	213	218	31	236	245	29	253	344	29
Domestic	13	19	19	2	25	26	3	42	46	4
Industries	9	11	11	1	20	20	2	24	24	2
Power	2	4	4	1	6	7	1	13	14	1
Total	**230**	**247**	**252**	**35**	**287**	**298**	**35**	**332**	**428**	**36**
Grand total	**629**	**694**	**710**	**100**	**784**	**843**	**100**	**973**	**1180**	**100**

(Rakesh Kumar et al, 2005)

Table 1.3: Annual Water Requirement for Different Uses in India Projected Upto 2050.

1.2 Water Resources of Gujarat

Gujarat state is situated on the West coast of India between 20^0 10′ and 24^0 50′ latitude and 68^0 40′ and 74^0 40′ longitude. The geographical area of the state is 1,95,984 sq km. It furnishes an interesting example of terrain characterized by geologic, physiographic and climatic diversities. It is endowed with rich potential of various natural resources of land, water, minerals, soil, vegetation, wild life, energy, marine products, etc. Its relief shows large variations but the general landscape is marked by plains of aggradational and degradational characteristics. High relief is contrasted in few pockets.

Gujarat state is agriculture based and the water resources of the state are of prime importance. India, on the whole has only 4% of the world water resources of that Gujarat is having only 2.28% surface water resources. Against the 2.28% water availability Gujarat state has 4.88% of the country's population. The state falls within the subtropical zone. However, its climate is dominantly governed by the southwest monsoon and physiographic set up producing a broad climatic range of humid to arid. The mean annual rainfall varies between 300 mm to 2500 mm with rainy days of 10 to 70. The rainfall dependability has a very broad range of 40 to 70 percent. The mean annual temperature of the state is 26^0 with mean maximum of 37^0 to 42^0 C and with mean minimum of 10^0 to 8^0 C. Thus, water resources of the state are limited.

The water situation in Gujarat state both qualitatively and quantitatively is in consonance with the prevailing scenario in the country. The dispersal differences in available water across the state and the nature of terrain of the state compound the problem further. Today, Gujarat is the most scarcity prone state in the country with almost 70% of its area prone to drought as against the national average of 19%. Population wise, 11% of the country's people are vulnerable to drought against 27% in Gujarat. Generally about 3 years in 10-year cycle are drought prone years. In the last century, severe water and food shortage due to drought have been experienced for at least 30 times in the state.

The occurrence of water resources in the state indicates considerable heterogeneity with regard to both time and space. Firstly, there is regional imbalance in the total availability of the surface water resources. The availability of water per capita is least in Saurashtra followed by Kachchh and North Gujarat. The availability of water is the maximum in south of river Narmada of Gujarat mainland. The yield of rivers also varies significantly year to year. Most of the rivers of Saurashtra, Kachchh and North Gujarat are seasonal and carry flow only during rainfall.

In terms of aquifer potential and groundwater availability there are regional variations with reference to groundwater. The availability of groundwater is ample in alluvial plains of central Gujarat against the limited scope for replenishment of groundwater. Despite these variations in the availability of water resources, the approach to the exploitation of water resources have been uniform all over the state.

Physiographically, the state comprises of three major zones, Mainland Gujarat, Saurashtra peninsula and Kachchh. (Refer Map 1.1) These zones have been characterized by their typical landforms and coastline. The present geomorphic configuration of the state is the result of the sub aerial geological processes that have given rise to a variety of erosional and depositional landforms.

i) **Mainland Gujarat**, having an average annual rainfall ranging from 500 to 2000 mm. It consists of

a. North Gujarat.
b. South Gujarat.
c. Central Gujarat.

The major water bearing formations of this region are

a. The Igneous - metamorphic rocks.
b. The Deccan traps volcanic formation.
c. The Alluvial aquifer.

ii) **Saurashtra peninsular region**, having an average annual rainfall ranging from 400 to 700 mm. It consists of

a. Northern Saurashtra.
b. Southern Saurashtra.

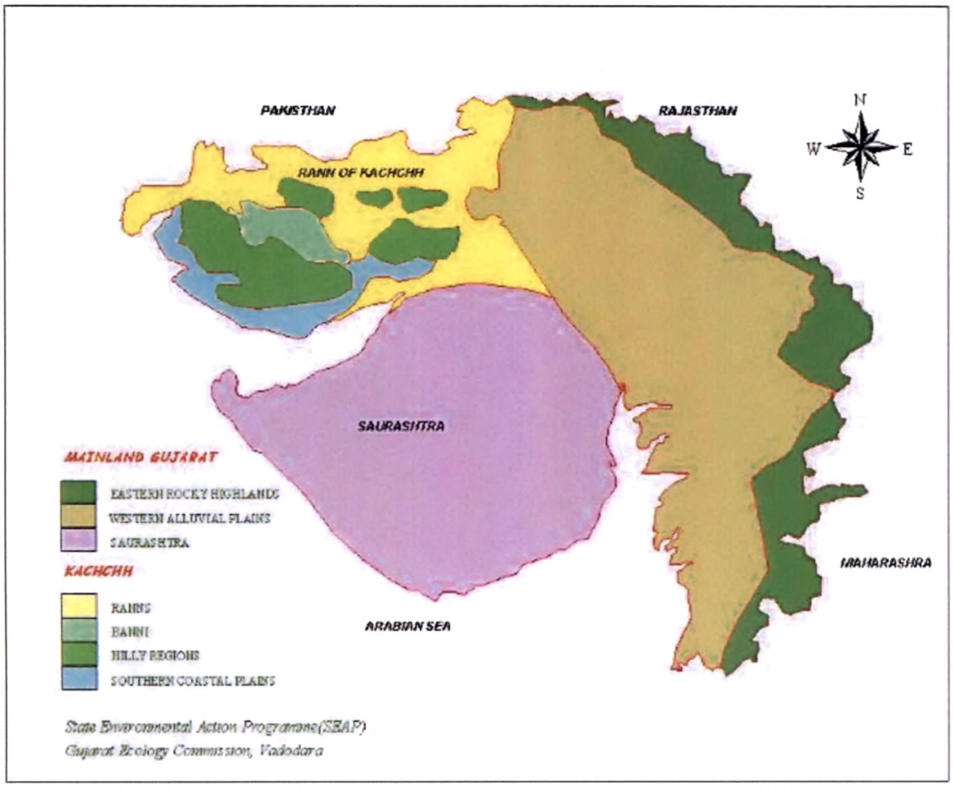
The major water bearing formations of this region are

a. The Deccan traps volcanic formation.
b. The Alluvial aquifer.
c. Dhrangadhra sandstone formation.

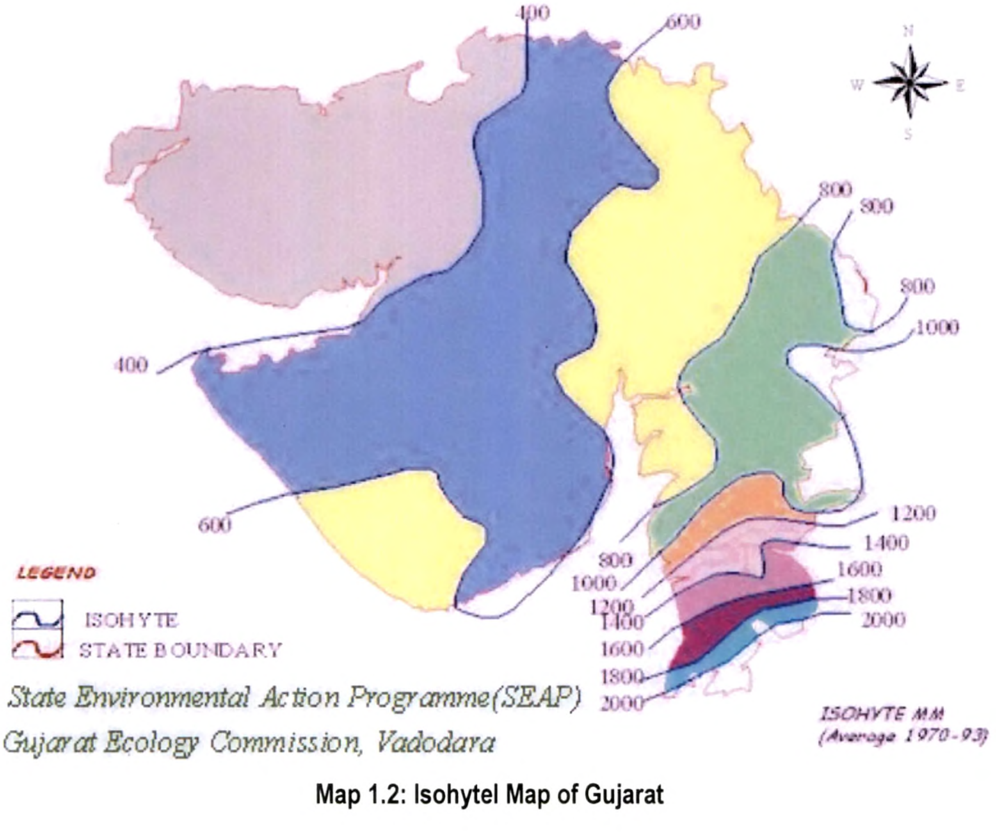
iii) **Kachchh region**, with an average annual rainfall ranging from 250 to 400 mm.

The major water bearing formations of this region are

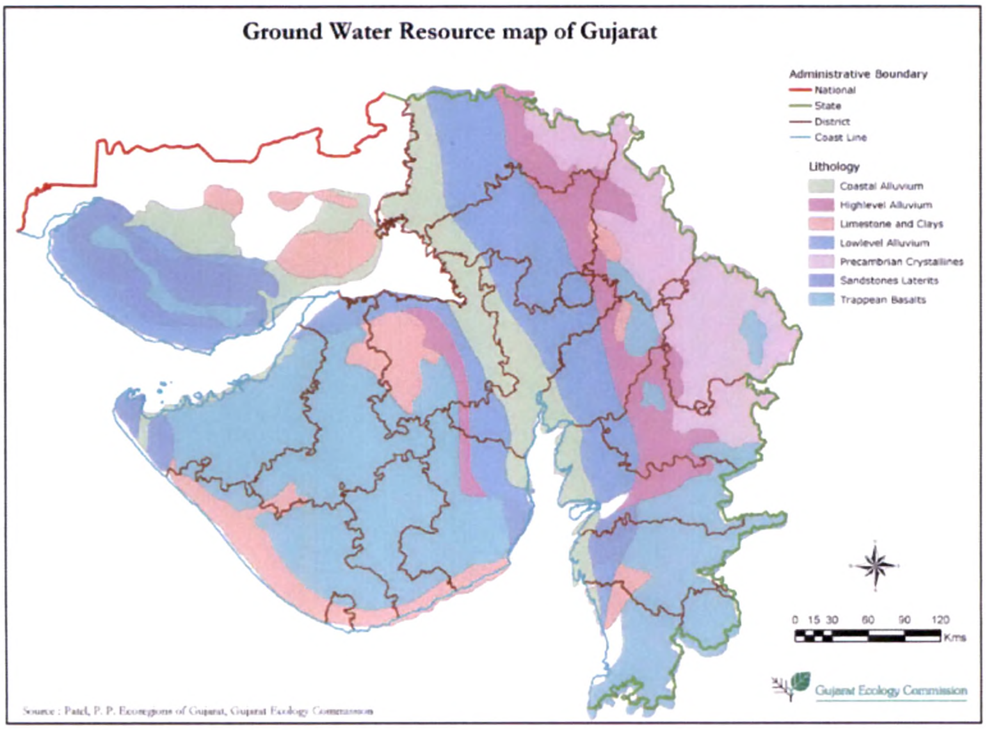
a. The alluvial aquifer.
b. Manchar sandstone aquifer.
c. Nari - Kithar – Laki – Panikot aquifer.
d. Bhuj sandstone aquifer.



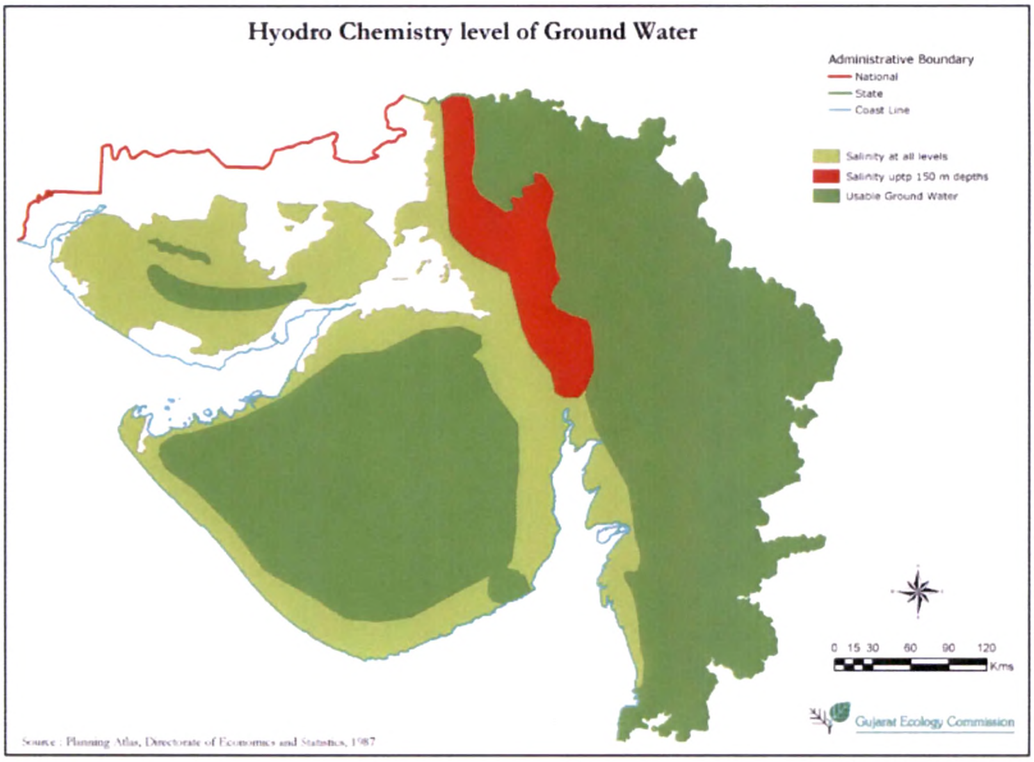
Map1.1: Physiographic Divisions of Gujarat



Map 1.2: Isohytel Map of Gujarat



Map 1.3: Groundwater Resource Map of Gujarat



Map 1.4: Hydro-Chemistry Level of Groundwater

1.2.1 Water Resources Potential and Development

Water resources in Gujarat are concentrated primarily in the southern and central part of the mainland. Saurashtra, Kachchh and North Gujarat have limited surface and groundwater resources.

There are wide variations in the annual rainfall ranging from an average of 1875 mm in southern hilly regions of Dangs to 377 mm in parts of Kachchh in western region. This is compounded by fluctuations in rainfall from year to year, with coefficient of variation ranging from 25% in Dangs to 80% in Kachchh. In many parts of the state, the rainfall occurs over a few rainy days only during monsoon in a few erratic showers. The average number of rainy days in Kachchh is 16 as against 75 in Dangs. (Refer Map 1.2).

Hydrologic regime defines the occurrence and circulation of water in a specific geoclimatic region. As regard to surface water resources south Gujarat covering 24% area of the state has 78% of total utilizable potential while the rest 76% of the state has only 22% of the water resource potential. Out of 185 river basins of Gujarat state only four basins i.e. Narmada, Mahi, Tapi and Damanganga have surplus water.

Sr. No.	Region (Geographical area in %)	No. of River Basin	Surface water available (% of total)		Groundwater available (% of total)	
			In Mm^3	In %	In Mm^3	In %
1	Gujarat Mainland (45%)	17	34272	89%	7320	65.5%
2	Saurashtra (31%)	71	3617	9.4%	3610	32.3%
3	Kachchh (24%)	97	648	1.6%	246	2.2%
	Total	**185**	**38533**	**100%**	**11176**	**100%**

(Source: NWRWS Dept, GOG)

Table 1.4: Water Potential of Gujarat State

Sr. No.	Irrigation Projects	Completed	On Going	Total Projects	Proposed Projects	Gross Total
1	Major	18	---	18	6	24
2	Medium	79	10	89	35	124
3	Minor (State)	119	24	143	98	241
	Total	**216**	**34**	**250**	**139**	**389**

(Source: NWRWS Dept, GOG)

Table 1.5: Present Status of Irrigation Projects in Gujarat State

According to available data, Gujarat state has experienced rising population on one hand from 19 million in 1951 to 50 million in 2000 and availability of water resources per capita is dwindling from 2000 Mm^3 in 1951 to 1200 Mm^3 in 1998. It has been estimated that the per capita availability will decline to 910 Mm^3 in 2010 to 800 Mm^3 in 2025.

Sr. No.	Region	Utilizable Potential In Mm^3	Irrigation Potential In ha	Ultimate Irrigation Potential (In ha)
1	South Gujarat	2302.82	218534	555735
2	Central Gujarat	3077.10	341976	656677
3	North Gujarat	2427.52	625278	512727
	Gujarat Mainland Total	7817.34	1185788	1725139
4	Saurashtra	4539.23	739460	1075342
5	Kachchh	501.60	93737	109043
	Total	**12848.28**	**2018985**	**2909524**

(Source: G.W.R.D.C. Report, 1997)

Table 1.6: Utilization of Groundwater Potential in Gujarat State

About 90% of the groundwater is used for irrigation in agriculture. The state average level of groundwater development shows a galloping increase from 31% in 1984 to 75.57% in 1997, which shows almost 143% development. About 161 out of 185 talukas of the state shows groundwater depletion. In general depletion of groundwater resources in the state has been accompanied by a rapid deterioration in the quality of groundwater. About 35,000 to 40,000 sqkm areas falling in 15 districts of the state have T.D.S. value more than 500 mgl. In Rajkot, Junagadh, Jamnagar, Bhavnagar, Amreli, Porbandar etc. districts the salinity was caused by over-exploitation of groundwater mining and as a result of that due to reversal of hydraulic gradient seawater intrusion into fresh water aquifers takes place. (Refer Map 1.4)

Sr. No.	Particulars	Irrigation Potential (lac ha)	Upto 1960		Upto June - 2000	
			Irrigation Created (lac ha)	Irrigation Utilization (lac ha)	Irrigation Created (lac ha)	Irrigation Utilization (lac ha)
A.	**Surface Water**					
1	Major & Medium Schemes	18.00	2.48	0.66	14.08	12.75
2	Sardar Sarovar Project	17.92	---	---	---	---
3	Minor Schemes	3.48	1.26	0.89	2.57	1.57
	Total (A)	**39.40**	**3.74**	**1.55**	**16.65**	**14.32**
B.	**Ground Water**					
1	Govt. Tubewells	4.00	0.30	0.22	3.00	1.91
2	Private Tubewells	25.10			17.30	16.68
	Total (B)	**29.10**	**0.30**	**0.22**	**20.30**	**18.29**
	Total (A + B)	**68.50**	**4.04**	**1.77**	**36.95**	**32.60**

(Source: NWRWS Dept, GOG)

Table 1.7: Present Irrigation Potential of Gujarat State

The prime reason of Gujarat's growing water demand is the rapid growth in irrigated agriculture. Since 1960-61, there was a quantum jump in the net irrigated area from 6% to 54%.

1.3 Water Resources of Saurashtra

The Saurashtra area forms an independent water resource region of Gujarat. Its low average rainfall and adverse topography produce low surface water potential. Similarly, its hard rock hydrogeology provides poor groundwater potential.

1.3.1 Surface Water

The water resources department of Government of Gujarat has identified a total of 71 river basins in the region. Tahal Consulting Engineers (TCE) (1996-97) computed basin-wise potential at different rainfall dependability. They have classified the 68 river basins into six basin groups and the potential has been computed as given in table 1.8.

Basin Group Name		Area km² (%)	Avg. Rainfall mm	Runoff potential at different rainfall dependability							
				75 %		60 %		50 %		Average	
				MCM	mm	MCM	mm	MCM	mm	MCM	mm
1.	Shetrunji	5571 (11)	610	219	39	377	68	539	97	705	127
2.	Bhadar	7076 (15)	775	272	39	474	67	687	97	770	109
3.	Southern Saurashtra	10234 (21)	540	380	37	755	74	1038	101	1309	128
4.	Northwest Saurashtra	7794 (16)	428	350	45	700	90	936	120	1119	144
5.	N & NE Saurashtra	13259 (27)	499	571	43	885	67	1234	93	1444	109
6.	East Saurashtra	5002 (10)	616	290	58	422	86	586	117	674	135
Saurashtra		48936	551	2082	43	3613	74	5020	103	6021	123
% of Gujarat		36	66	11	32	14	40	15	42	18	50

Table 1.8: Surface Water Potential of Saurashtra

1.3.2 Groundwater Potential and Development

The region is composed of hard rock formations and its groundwater potential is limited and it has been exploited to a greater extent.

The district wise estimation of groundwater potential and development of Saurashtra was done by GWRDC in 1984 and 1997 which is shown in table 1.9

The quality change is very much sensitive in coastal area, which is subjected to seawater intrusion. Massive efforts have been done by GoG to control seawater intrusion in this belt. However, as in this coastal belt groundwater is the only handy resource for the people to fulfill their all kinds of requirements, it has been exploited tremendously which nullifies the government efforts to control the seawater intrusion.

District	Utilizable Recharge Mm^3 / yr	Net Draft Mm^3 / yr (1991)	Development (%)	Irrigation potential created Thou. ha	Ultimate Irri. Potential Thou. Ha
1. Surendranagar	489.40	267.36	54.63	61	111
2. Junagadh	868.26	545.19	62.79	155	241
3. Rajkot	840.36	426.48	50.74	99	195
4. Jamnagar	658.23	280.58	42.62	67	157
5. Amreli	635.21	322.35	50.75	84	165
6. Bhavnagar	797.86	396.31	52.26	93	216
Total	4289.32	2238.27	52.23	559	1085
% of Gujarat	34.90	31.2	31.21	27.41	37.00

(Source: GW Estimation Committee Report – 1997)

Table 1.9: Groundwater Potential and Development of Saurashtra

1.4 Seawater Intrusion

Many coastal zones, especially low-lying deltaic areas, accommodate high-density populations. For example, about 50 % of the world population lives within 60 km of the shoreline. For ages, mankind is attracted to these areas because of the availability of an abundance of food (e.g., fisheries and agriculture) and the presence of economic activities (e.g., trade, harbours, ports and infrastructure). Due to increasing concentration of human settlements, agricultural development and economic activities, the shortage of fresh groundwater for domestic, agricultural, and industrial purposes becomes more striking in these coastal zones.

During the latter part of twentieth century there has been a widespread increase in urbanization. As many major cities in the developing world are situated on the coast, and many lie on unconsolidated aquifers, this has placed increasing importance on coastal unconsolidated aquifers for water supply. As little as 2% seawater in freshwater can render the water unpotable, and saline water has been reported to be the most common pollutant in fresh groundwater (Todd, 1980). The problem of seawater intrusion requires the application of specific management techniques.

The term seawater intrusion specifically describes the situation where modern seawater displaces, or mixes with, freshwater within an aquifer in response to a change in the hydrogeological environment. The expression is, however, frequently used to describe any case where water bodies of differing salinities occupy the same aquifer system. The most common processes responsible of salinization in coastal aquifers are: (Luis 2003)

- **i)** Present-day (active) seawater intrusion due to overpumping and upward displacement of the freshwater-saline interface.
- **ii)** In the case of confined aquifers, the natural geochemical evolution of groundwater along a particular flow-path may result in a progressive increase of salinity.
- **iii)** Changes in water chemistry due to cation exchange in coastal aquifers (Appelo and Postma, 1994).
- **iv)** Dissolution by groundwater of evaporitic minerals interbedded in the stratigraphic column.
- **v)** Upward leakage from a deeper confined aquifer into a shallow phreatic water-bearing horizon may also result in a marked increase of salinity.
- **vi)** Presence of connate, trapped brines or brackish waters mixed in different proportions with shallow groundwater.
- **vii)** Incorporation of sea salt spray into infiltrating waters in the soil layer.

Saline intrusion, in the strict sense, occurs as a result of modern seawater encroaching into a coastal aquifer. If groundwater gradients are reduced the outflow of freshwater is reduced and denser saline water may displace the fresh water within the aquifer.

1.4.1 Causes of Seawater Intrusion

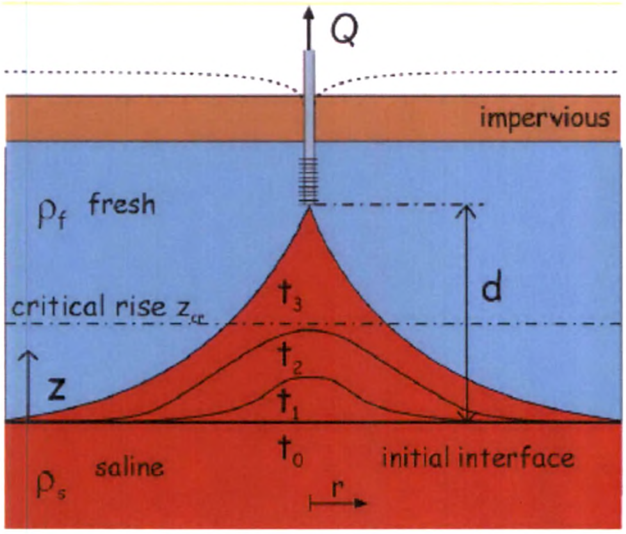


Figure 1.1: Upconing of Interface

Seawater intrusion is caused primarily by the reduction of fresh water discharge to the sea as a result of groundwater abstraction. The salt-water wedge consequently moves inland, flushing decreases, and the thickness of the wedge increases. If some fresh water flow is maintained at the coast, a new equilibrium eventually develops.

Groundwater abstraction above the interface causes upconing. Depending on aquifer characteristics, well penetration, and pumping rate, a stable situation may be attained, where salt water does not reach the well. However, when this critical state is exceeded, salt water enters the well, mixes with the fresh water, and the quality of the discharge decreases. Abstraction is not the only control on the position of the saline water/fresh water interface. A number of other factors can affect its position including:

i) Seasonal changes in natural groundwater flow

ii) Tidal effects

iii) Barometric pressure

iv) Seismic waves

v) Dispersion

vi) Climate change - global warming and associated sea level rise.

Some of these have short-term implications (tidal effects and barometric pressure) some are periodic (seasonal changes in groundwater flow) and others are long term (climate change and artificial influences).

1.4.2 Factors Affecting Coastal Aquifers

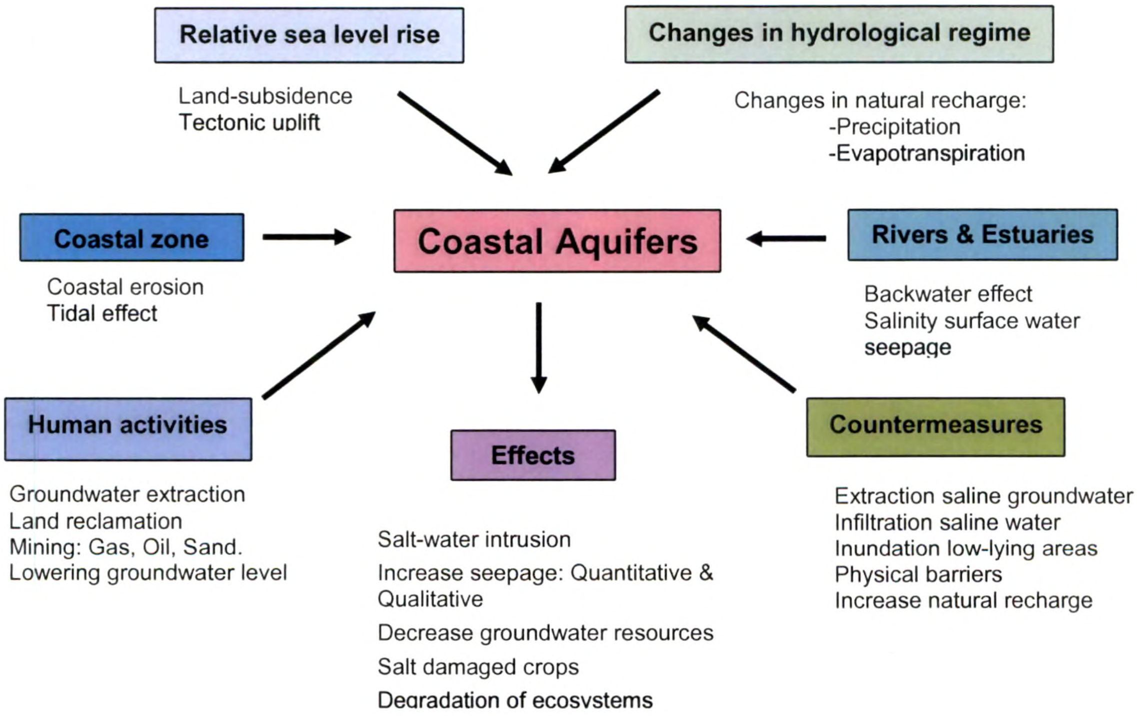


Figure 1.2: Factors Affecting Coastal Aquifers

Here it is important to define what is meant by saline water. Terms relating to the degree of salinity were suggested by the USGS (Refer Table 1.10)

TERMS DESCRIBING DEGREE OF SALINITY AS USED BY USGS	
Description	**TDS (mg/l)**
Fresh	< 1000
Slightly saline	1000 - 3000
Moderately saline	3000 - 10000
Very saline	10000 - 35000
Brine	> 35000

(Hem, 1970)

Table 1.10: Classification of Saline Water

1.4.3 Concept of Fresh – Saline Interface

A coastal aquifer contains the interface between the fresh water, which has 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 freshwater on the landward side of 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. This idealized view of the situation is shown in figure 1.3. The thickness of the freshwater wedge decreases in the seaward direction and the slope of the water table steepens towards the coast. Therefore the shape of the interface is concave upwards.

Although the differences in density appear to be small, they have a significant effect on piezometric heads and thus on the groundwater system. In many approaches, only fresh groundwater is considered in coastal aquifers, so no density differences are taken into account. In reality, however, density flow may highly affect groundwater flow in these coastal aquifers. In this chapter, a straightforward concept is applied which takes into account density flow in a simple way: the interface approximation based on the Badon Ghyben- Herzberg principle.

1.4.3.1 Badon Ghijben-Herzberg Principle

The Badon Ghyben (1889) - Herzberg (1901) principle (BGH) describes the position of an interface between fresh and saline groundwater (Figure 1.3). Following represents the Badon Ghyben-Herzberg principle:

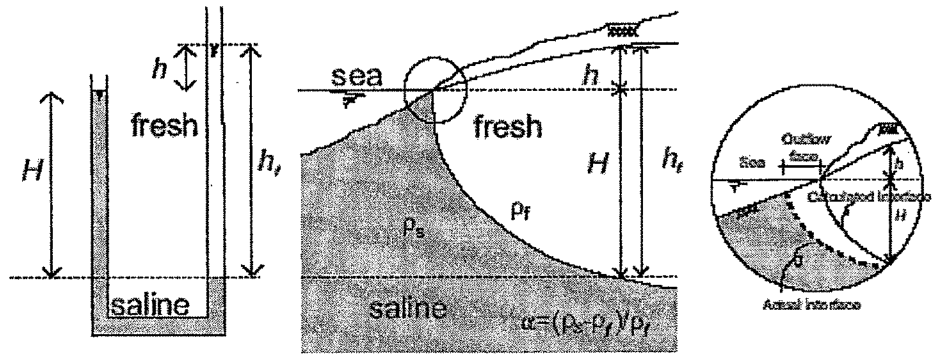


Figure 1.3: Badon Ghyben-Herzberg Principle: a Fresh-Salt Interface in an Unconfined Coastal Aquifer

pressure due to saline groundwater = pressure due to fresh groundwater

$$\rho_s Hg = \rho_f (H + h)g \Leftrightarrow \rho_f Hg + \rho_f hg$$

$$h = \frac{\rho_s - \rho_f}{\rho_f} H \Leftrightarrow h = \alpha H$$

For ρ_s=1025 kg/m^3 and ρ_f=1000 kg/m^3, the relative density difference α = 0.025. The equation is correct if there is only horizontal flow in the fresh water zone and the saline water is stagnant. The Badon Ghyben-Herzberg principle was originally formulated for the situation that the transition zone between fresh and saline groundwater is only a small percentage of the thickness of the saturated freshwater body (thus, mostly in the order of several meters). Under these circumstances, a fresh-salt interface should be applied. This situation occurs in unspoiled sand-dune areas or (coral) islands, where the freshwater lens evolves by natural groundwater recharge. In addition, the principle can only be applied in case the vertical flow component in the freshwater body is negligible. In reality, however, such systems seldom occur. Most systems are not hydrostatic and as a result, the formula leads to (small) errors, especially in the vicinity of the outflow zone. Nevertheless, though the position of the interface is not completely correct, the use of the equation still gives a rather good approximation of the real situation. As a matter of fact, the principle should only be applied under the following conditions:

- **i)** The aquifer is homogeneous,
- **ii)** Hydrodynamic dispersion is negligible,
- **iii)** Vertical flow in the aquitard, horizontal flow is negligible,
- **iv)** Horizontal flow in the aquifer, vertical flow is negligible,
- **v)** Saline groundwater is at rest: ρ_s = 0.

1.4.4 Prevention and Control of Seawater Intrusion

The prevention of seawater intrusion can be provided by following options including:

Barriers: Dams can be constructed that physically prevent the seawater from moving past a certain point in the estuary. Injection barriers have also been employed successfully.

Restrictions on pathways for seawater intrusion: Construction of canals allows seawater to migrate into inland areas and allow a pathway for seawater intrusion to occur.

Alternate sources of water: Water users may be able to obtain water from other sources that are not endangered by seawater intrusion.

Restrictions on use of water: During periods of higher sea level or drought, stricter conservation and restrictions on export of water from the river basin may be considered for short durations.

Control methods for seawater intrusion have been employed or seriously considered only in areas where withdrawals of water have caused water levels in aquifers to fall significantly below mean sea level. Because of the very slow velocity with which the seawater moves, many localities with serious overdrafts have not yet lost their aquifers as sources of water.

The greatest danger to freshwater aquifer supplies could be the migration of seawater up an estuary that recharges an aquifer. If the water levels in the aquifer were below mean sea level because of withdrawals, the seawater would recharge the aquifer.

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

Physical subsurface barriers: Subsurface physical barriers such as sheet pile, cutoff walls, clay slurry trenches under earth dams and impermeable clay walls are routinely used by engineers in the field to control the movement of water. It is also possible to inject materials that form a zone of low permeability. Figure 1.4 illustrates a cross-section of a typical physical barrier.

Kashef (1977) indicates that, although the construction methods are technically well established, the cost is usually too high because the required depths are substantial. Even in the uppermost layers where the cost may not be prohibitive, Kashef points out that the backwater effect could cause coastal lowlands to become waterlogged. The cost is highly dependent on depth of cutoff, length of wall, and specific material availability costs. Barriers require complete depth of cutoff to be effective. Impermeable walls can be almost 100 percent effective at preventing seawater intrusion. However, in actual practice, some limited penetration will occur.

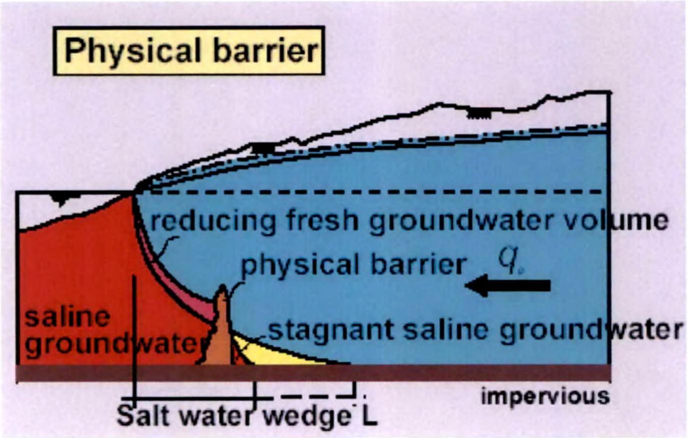


Figure 1.4: Physical Barrier

Extraction barriers: The seawater that moves inland is collected and removed. The pumping encourages further intrusion and may inadvertently withdraw freshwater. Extraction barriers have been used in various locations in order to prevent or reduce seawater intrusion. Figure 1.5 illustrates a typical extraction type barrier where the seawater intrusion is halted by the withdrawal of seawater relatively close to the shoreline.

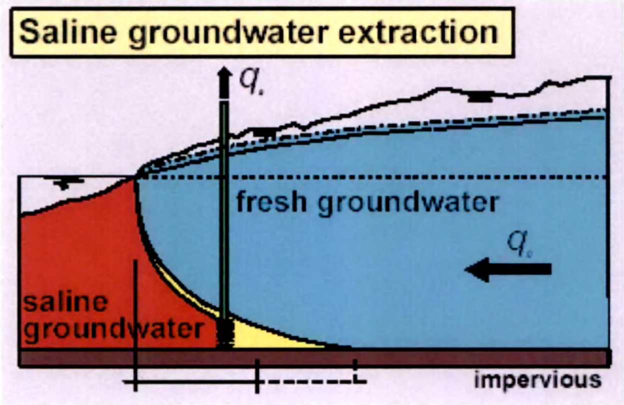


Figure 1.5: Extraction Barrier

Extraction barriers may withdraw some freshwater that would otherwise be useful and thus may not be a valuable option where water supplies are scarce. In addition, problems with seawater corrosion must be overcome.

Again, experiences by Kashef (1977), Stone (1978), and others have generally indicated that the seawater intrusion caused by pumping overdrafts can be technically controlled by extraction barriers but are usually more expensive than injection barriers. However, a major problem with the extraction barriers is that withdrawal of seawater and the inadvertent withdrawal of some freshwater cause the water levels to fall substantially throughout the basin. The increased lift and the cost of wells going dry often become costly in time. Furthermore, although a complete cutoff extraction barrier does not have to be completed all along the coast, seawater intrusion can around the barrier. The lower levels also encourage saline water from above or below to move vertically into the aquifer.

Freshwater injection barriers: Freshwater from another source is injected into the aquifer, raising water levels in the area and reversing the seawater intrusion. Figure 1.6 illustrates a typical injection barrier in operation to control the seawater intrusion. In contrast to the extraction barrier, with an injection barrier, freshwater is injected into, the aquifer through a line of wells along the coastline. The higher groundwater levels along the injection barrier prevent seawater intrusion from occurring. A proper design of well spacing and location must be performed to ensure that seawater does not intrude around the injection barrier, in between individual wells, or move vertically from above or below.

The problems with injection wells include the fact that a relatively large number of wells are required, a high maintenance cost will be necessary to prevent clogging of wells, and most important, a source of freshwater will be needed.

The Los Angeles County Flood District injection barrier construction costs were approximately $20 million from 1953 to 1973, not including the cost of purchasing the water to be injected. The operation cost depends upon the length of the barrier, the geometry and physical properties of the aquifer, differences in water levels in the aquifer relative to mean sea level, and the volumes of water injected, being recharged to the aquifer, and being withdrawn.

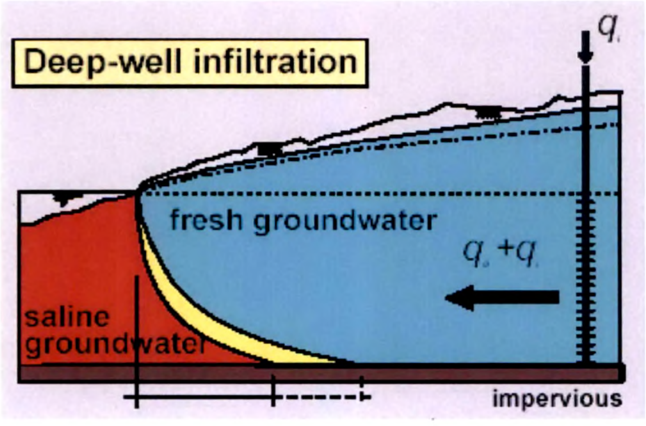


Figure 1.6: Injection Barrier

Because the injection of water raises the water levels in the vicinity of the barrier, a complete cutoff all along the coast is not required. If the cutoff barrier is maintained at 1 or 2 m above mean sea level (continuously increasing the barrier water level as sea level increases), the injection barrier will provide 100 percent effectiveness in preventing seawater intrusion along its length. In addition, the freshwater mound will tend to flow inland toward the lower water levels there. Also, freshwater from the injection barrier will flow along the coast for a limited distance, extending the effective length of barrier slightly. The effectiveness of the injection barrier will be maintained if the water levels in the vicinity of the barrier are increased as sea level increases to always maintain them at 1 m above mean sea level.

Increased recharge: Spreading of water on the land in upland recharge areas allows more percolation (infiltration of water into the aquifer), which retards seawater intrusion. In many coastal locations, sufficient amounts of freshwater are available for recharge during periods of high precipitation. If the natural plus additional recharge exceeds the groundwater withdrawals the stable seawater line would be established.

In many instances, the recharge region of the principal water supply aquifer is far away from, the coast. In these regions, it is possible to recharge the confined aquifer far from the shoreline and prevent seawater intrusion.

The problems with increased recharge can be a lack of sufficient replenishment water, lack of inexpensive land for the recharge basins shallow injection wells, and costly technical problems of maintaining an adequate inflow rate. However, as mentioned previously, many areas have excess water during wet periods, which can be utilized during dry periods.

Modified pumping patterns: Reducing withdrawals or moving the pumping locations further inland can substantially reduce the intrusion. For unconfined aquifers where no pumping exists, an intrusion of seawater as a result of sea level rise could damage agricultural crops. Either the injection barrier or increased recharge would be viable solutions if substantial crop damage were expected without control of the seawater advance.

For unconfined or confined aquifers where moderate pumping already occurs and the effect of a sea level rise is projected to be important, a phased shutdown of wells can be designed as the monitored seawater intrusion progresses.

A modification of pumping patterns will allow water levels to recover in critical areas. This will have an effect of slowing down the seawater advance. However, the seawater will intrude until it reaches a new equilibrium. Depending upon the recharge rate, the pumping rates, the net overdraft, water levels, aquifer geometry, aquifer characteristics, and the present status of seawater intrusion, the effectiveness of the modification of pumping patterns will vary. For a seawater interface currently in equilibrium, an increase in sea level rise may be counteracted by a modification of pumping patterns. However, it is possible that the intrusion will be retarded, not stopped.

Combinations of these techniques can also be employed. A combination of an extraction and an injection barrier or increased recharge with injection barrier is particularly effective combinations.

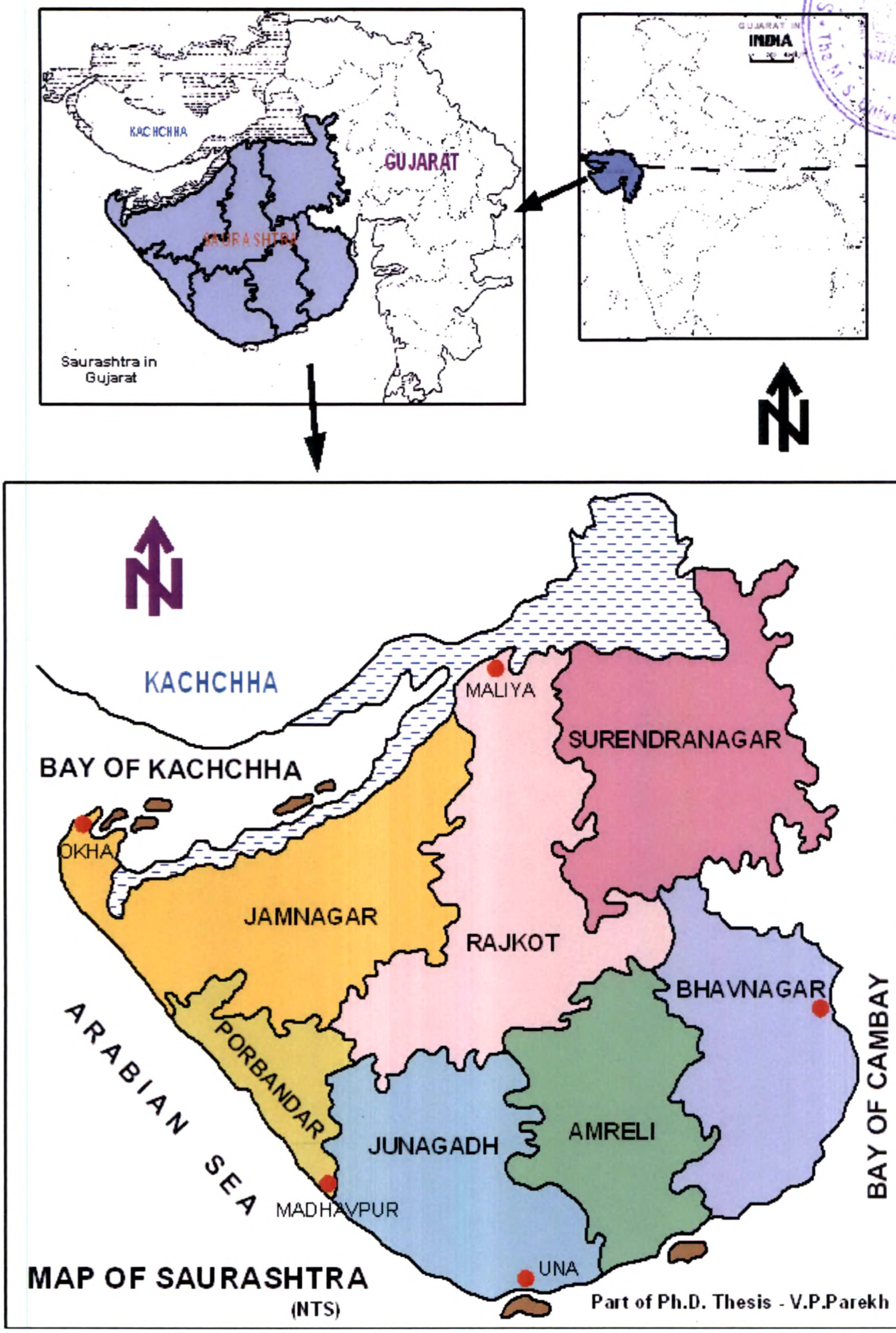
1.5 Objective of the Present Study

My study area Saurashtra is a peninsular region in the state of Gujarat, India. (Refer Map 1.5). The narrow coastal plain along the south coast of Saurashtra has long been known as a very fertile and productive tract. Groundwater is one of the most important and handy resource to the fast growing domestic, agricultural and industrial developments along the Saurashtra Coast of Gujarat state. Recurrent drought conditions, excess withdrawal of the groundwater as compared to natural and artificial recharge in past and present and an ever increasing demand of freshwater have made this resource very valuable in coastal belts of Saurashtra.

Seawater intrusion is found in public and individual water wells at many coastal areas of Saurashtra. The State Government has constructed various Seawater Intrusion Preventive (SIP) structures in the affected areas of coastal belt to check the seawater intrusion.

The rate of seawater intrusion is continuously increasing inland. Many structures have been constructed to combat seawater intrusion in coastal Saurashtra. Following are the objectives of the study.

- **i)** It is highly necessary to find out the most effective type of structures.
- **ii)** Check the efficacy of the structure.
- **iii)** It is necessary to develop performance indicators.
- **iv)** To monitor hydrogeological processes including local recharge systems, aquifer parameters in coastal Saurashtra.



Map 1.5: Index Map of Saurashtra