Chapter 1. Introduction

Groundwater aquifers are being exploited indiscriminately throughout the world to meet the ever increasing water demand. It has been estimated that global groundwater mining (i.e. exploitation in excess of natural and artificial replenishment) is about 160 km^3 per year (The United Nations World Water Development Report; available at URL: http://www.unesco.org/water/wwap/wwdr). This volume of groundwater mining may appear insignificant compared to the total volume (~11 x 10^6 km^3) of fresh groundwater on the earth (Fitts, 2002). However, from the point of sustainability, the large scale mining of groundwater is of concern. This is because it has led to significant decline of piezometric levels at many places in the world resulting in increased cost of pumping the groundwater from progressively deeper layers. The alluvial aquifer systems usually have much higher porosity compared to hard rock aquifers and therefore, have higher groundwater potential. Since major agricultural zones and urban agglomerates are located in the alluvial plains, the alluvial aquifers are also the most exploited ones. In the late seventies, it was realised by water managers and planners that the easy option of exploiting the local groundwater to meet the increasing water demand will not be sustainable in the longer run. This realisation came from general observations about declining water levels, increasing cost of pumping, progressively deteriorating groundwater quality, salinity ingression in response to reduced hydrostatic pressure in the coastal aquifers, anthropogenic contamination due to application of chemical fertilisers & pesticides, and discharge of municipal and industrial effluents. It was also realised that exploitation of groundwater can not be stopped at the cost of economic development of a region but it must be judiciously and intelligently restricted. This required complete description of the regional aquifer system using both conventional geohydrological investigations and the modern geochemical and isotopic investigations that can address specific hydrological issues of a given region. The United States Geological Survey (USGS) completed (1978-1995) a nationwide programme of Regional Aquifer System Analyses (RASA) in collaboration with multidisciplinary researchers. Some of the details of this comprehensive investigation of twenty five regional aquifer systems in USA can be found at URL: http//www.usgs.org. This investigation not only generated scientific knowledge necessary for sustainable water resource development and management but also equipped the concerned agencies with an infrastructure to monitor the hydrological response to exploitation, engineered structures and global climate change. Similar large scale studies of regional aquifers systems have also been undertaken by some other developed nations (Edmunds, 2001).

In India, such a nationwide investigation of regional aquifer system is yet to be initiated but the geochemical and isotopic investigations of a regional aquifer system in Western India, presented in this thesis, offer a possible model for a nationwide replication with region specific adaptations. This study also highlights the role of modern isotopic tracers in strengthening the conventional geohydrological technique for addressing specific hydrological problems of a region.

1.1 The Research Problem

The North Gujarat - Cambay (NGC) region of Gujarat State in Western India is characterised by a unique combination of geological, hydrological, tectonic and climatic features, namely, (i) two major bounding faults, defining the Cambay Graben, and several other sympathetic faults parallel and orthogonal to these; (ii) more than 3 km thick sedimentary succession, formed by syndepositional subsidence in the Cambay Graben, acting as a reservoir for the oil and gas at deeper levels and a regional aquifer system at shallower depths; (iii) higher than average geothermal heat flow; (iv) intermittent seismicity; (v) emergence of thermal springs; and (vi) arid climate with high rate of evapotranspiration.

The surface soils in the region are loamy to sandy loam type and provide high agricultural productivity when water is available. But, the streams flowing through the region are only seasonal; therefore groundwater mining has been resorted to in some parts. This has lead to decline in piezometric levels - at more than 3 m/yr during the last couple of decades.

During the same period, it has also been noticed that fluoride concentrations in groundwater in some parts particularly, Banaskantha, Mehsana and Ahmedabad districts have progressively increased leading to endemic fluorosis. Based on the assumption that deeper ground waters have been in contact with the aquifer material for relatively longer periods, it has been argued that high groundwater fluoride of the region is due to its slow leaching from the mineral grains comprising the aquifer matrix (Patel, 1986; Ramakrishnan, 1998). Some studies have also indicated that thermal springs in the region have both high concentration of fluoride and dissolved helium. Therefore, it has also been suggested that higher concentrations of fluoride may be related to subsurface injection of thermal waters (Chandrasekharam and Antu, 1995).

It has long been recognised that helium and radon produced by radioactive decay of uranium and thorium in rocks and minerals are steadily released from grains by etching, dissolution, fracturing and alpha recoil during weathering and then subsequently released into the atmosphere by diffusion and temperature variations. Anomalously high amounts of dissolved helium and radon in groundwater from some parts of the region have been reported earlier (Datta et al, 1980). However, relationship of these dissolved gases with the tectonic framework of the region has not been studied.

There are several known thermal springs and flowing artesian wells in and around the Cambay Basin. The geothermal gradient in parts of Cambay Basin is known to be in excess of 60°C/km (Gupta, 1981; Panda, 1985; Ravi Shankar, 1988; Negi et al, 1992). Based on reports of ground waters with high temperature, anomalous helium and high fluoride, it is believed that these might be related to each other (Chandrasekharam and Antu, 1995; Minisalle et al, 2000; Gupta and Deshpande, 2003). However, detailed geographical distribution, range of variation and inter-relationship between these groundwater parameters is not known.

The average annual relative humidity at present is only ~50% in northern part of Cambay Basin; therefore water loss by evapotranspiration is expected to be very high. The Late Quaternary sedimentary record of the region, however, suggests episodes of both wetter and drier periods (Prasad and Gupta, 1999; Pandarinath et al, 1999b; Wasson et al, 1983; Juyal et al, 2003). Since, during the process of evaporation, a water mass undergoes kinetic fractionation in oxygen and hydrogen isotopes, the imprints of relatively more arid/ humid phases of the past could have been recorded in ground waters recharged during those palaeoclimatic phases. However, these possible climatic imprints on isotope composition of groundwater and modern precipitation have not been investigated.

To overcome the general scarcity of water, a community and the State driven movement for groundwater recharge is presently underway in the region. Several groundwater recharge structures have been constructed but doubts about their usefulness and efficiency persist. In recent decades, Chlorofluorocarbons (CFCs) have emerged as useful tracers of young ground waters (Busenberg and Plummer, 1992; Plummer and Busenberg, 1999). Monitoring of dissolved CFCs in the vicinity of the recharge structures provides an easy way of identifying the modern groundwater recharge and to estimate its quantity. Away from the recharge structures, the CFC concentration in groundwater can also be used to estimate the time since the water became isolated from the unsaturated zone during the past few decades. Presence of detectable CFC signal in groundwater indicates mixing of modern water with that recharged prior to 1945. Such investigations can identify the regions where modern waters have infiltrated. Though successfully employed elsewhere in world, India did not have a laboratory for analysing CFCs in groundwater. Therefore, a need for having such laboratory facility had been long felt, particularly for studying the effectiveness of groundwater recharge structures.

Based on the above considerations, it was decided to undertake a multi-parameter geohydrological investigation in the NGC region to understand the roles of (i) geohydrological; (ii) palaeoclimatic (iii) topographic and (iv) tectonic processes/ features in controlling the chemical and isotopic composition of groundwater, its interaction with aquifer matrix and movement in the regional aquifer system. In the following, some more specific information about the study area is provided followed by specific objectives and the methodology adopted to achieve these objectives.

1.2 The Study Area

1.2.1 Geography

The study area is located in the State of Gujarat in Western India between the 21.5°–24.5°N latitudes and 71.5°–74°E longitudes. The important rivers and other landmarks within the study area covering an area of approximately 90,000 km^2 are shown in Figure 1.1. The urban hubs of the Gujarat State, namely Ahmedabad, Vadodara and Mehsana, and some smaller towns such as Tharad in the NW, Ambaji in the North, Godhra in the east, Bharuch in the south and the Bhavnagar in the SW are also marked in Figure 1.1. The prominent geographic features of the study area include Nalsarovar (NS), Little Rann of Kachchh (LRK) and Gulf of Cambay (GC).

1.2.2 Geology

The rocks exposed in Aravalli foothills in the Eastern part of the study area comprise Proterozoic succession that include the Delhi Supergroup and the Aravalli Supergroup. The Delhi Supergroup includes Pre-Erinpura (Mafic) and Ambaji Granites, Sirohi and Kumbhalgarh Groups. These are intruded by the Erinpura, Post-Erinpura (Mafic) and Godhra Granites. The Aravalli Supergroup includes Champaner, Lunawada, Rakhabhdev (Ultramafic) and Jharol Groups. The geological map of the study area is shown in Figure 1.2.

A small patch of Mesozoic sedimentary rocks is exposed in the study area in the western part. These rocks comprise marine to fluvio-marine sedimentaries (Surendranagar and Wadhwan Formations) of the Uppermost Jurassic to Lower Cretaceous age. Outside the study area in north-eastern part of the Saurashtra, these occupy large area (~ 5000 km^2).

The Deccan Traps formed by the outpouring of the huge volume of basalt, marking the Cretaceous-Tertiary boundary are exposed only in a small part of the study area both on the east and west flanks of the Cambay Basin in the southern part. These outcrops rest either over Precambrian or over the Cretaceous sedimentary rocks. In the east-central part small inliers of Deccan Traps are also seen in the alluvium and soils in the vicinity of the Aravalli Foothills.

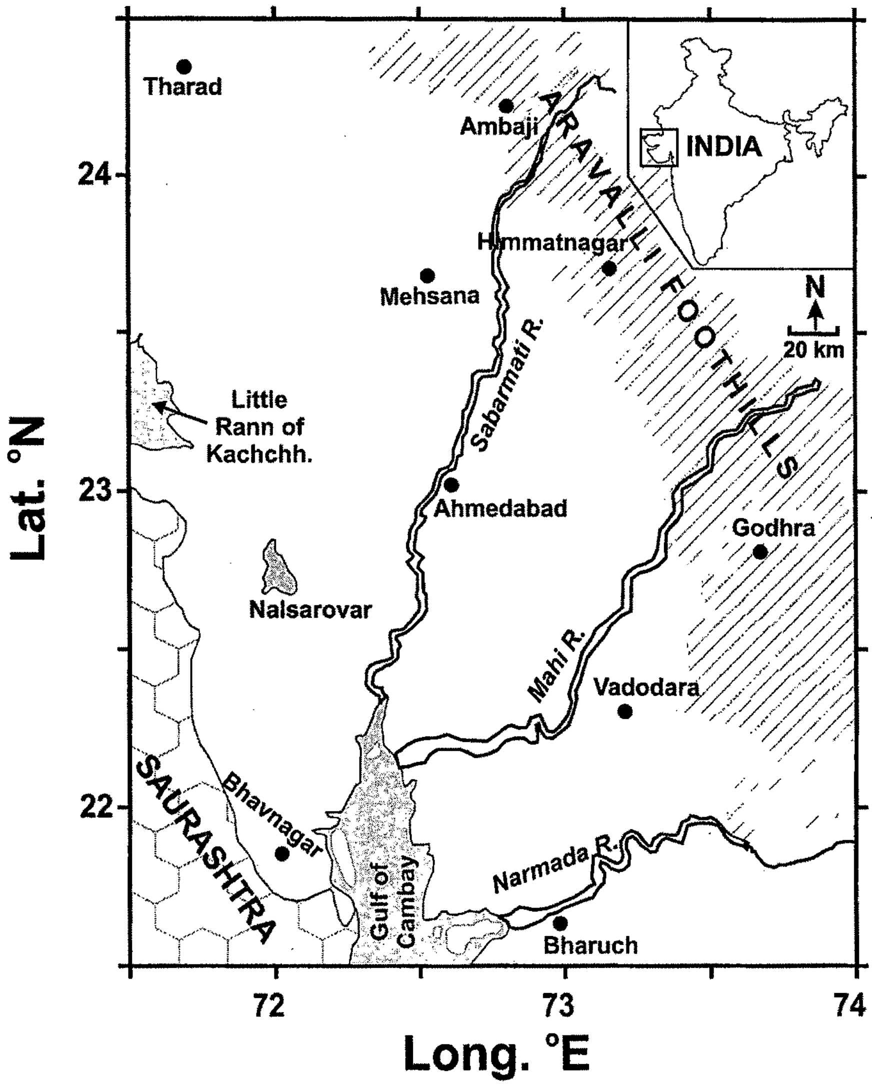

Figure 1.1 Map showing study area and the geographical locations of some important landmark features such as major rivers, towns, lakes etc. The inset map shows location of the study area.

The outcrops of Laterites are found only at a few locations within the study area, overlying the Deccan Trap in southern part, both in south Gujarat as well as Saurashtra. The Laterites are believed to have been formed by in situ decomposition of pyroclastic material or by brecciated and fractured lava flows.

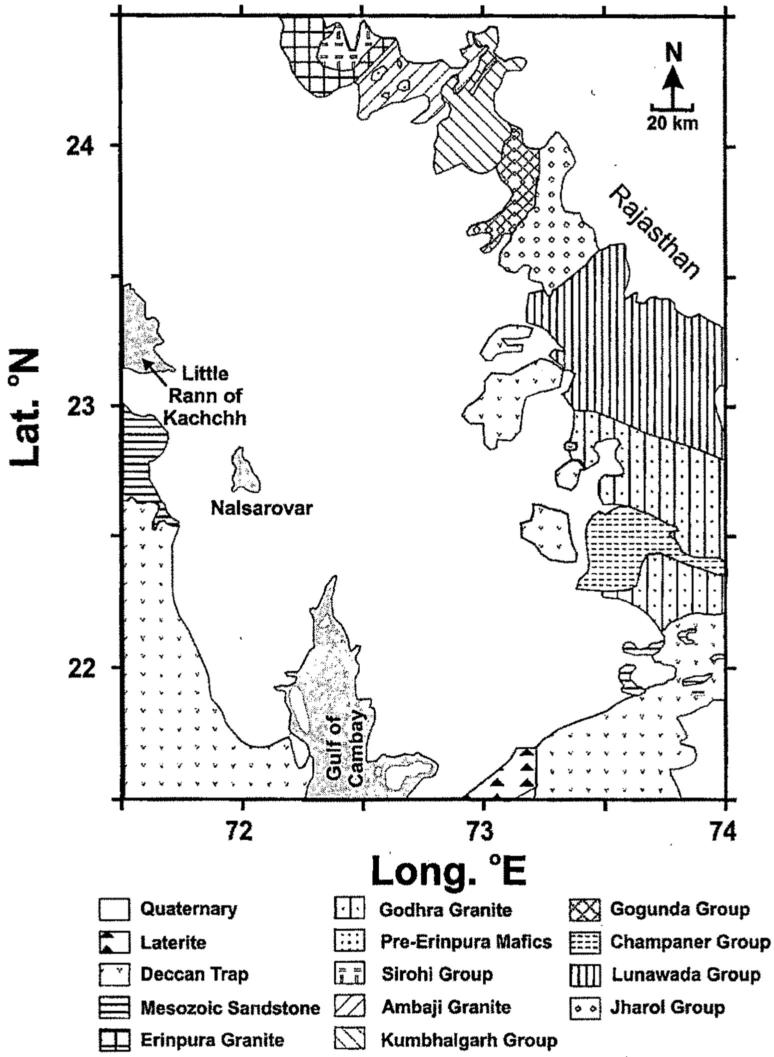

Figure 1.2 The Geological Map of the study area. A large part of the area is covered by Quaternary alluvium. Proterozoic rocks (mainly granitic) lie along the Aravalli foothills in the east and the upper Cretaceous Deccan Traps in the SW and SE corner. A small patch of Mesozic sandstone is also seen towards the west. A sub-surface lithological section along AA' is shown in Figure 1.6.

The Quaternary sediments, also referred to as Gujarat Alluvium, occupy the largest part of the study area and cover the Cambay Basin and a large area on either flanks. Regional stratigraphy based on the subsurface data shows that nearly 500 m thick Quaternary sediments comprising thick layered sequences of sediments of fluvio-marine and fluvio-aeolian origins overlie the Tertiary basement (Biswas, 1987; Merh, 1993; Merh and Chamyal, 1993; Maurya et al, 1995; Tandon et al, 1997; Prasad et al, 1998; Srivastava et al, 2001). Shallow marine sediments were also deposited in the low-lying tract between the Gulf of Cambay (GC) and the Little Rann of Kachchh (LRK) during the Late Quaternary.

A model of Late Quaternary deposition related to westward migration of a depositional front caused by marine regression and/ or tectonic uplift of the east flank was presented by Prasad et al (1997), Prasad and Gupta (1999) and Pandarinath et al (1999a). The alternating phases of humid and arid climates in this region during Quaternary period, is known to have influenced fluvial and aeolian regimes and is reflected in the mode of occurrence, extent, lithology, soil types, structure and texture of the successive horizons of the sediments. These Quaternary alluvial sediments with alternating sand and silty-clay layers constitute the regional aquifer system extending up to the low lying tract linking the Little Rann of Kachchh (LRK) – Nalsarovar (NS) – Gulf of Cambay (GC) region and having its recharge area in the foothills of Aravalli Mountains.

1.2.3 Tectonic Framework and Sedimentation

Cambay Basin of the NGC region is one of the three major marginal rift basins in the western margin platform of the Indian craton; the other two being Kachchh and Narmada basins. Earlier, Burke and Dewey (1973) identified the region of convergence of Cambay and Narmada rift basins with West Coast (WC) fault in the Gulf of Cambay (also known as Gulf of Khambhat) as a 'triple junction'. Another major tectonic structure in the south, namely the 'Kukdi-Ghod lineament zone', also converges into the triple junction (Figure 1.3). Repeated block faulting along these tectonic structures has broken the lithosphere into several blocks separated by major or minor faults running parallel as well as orthogonal to each other. The intersecting network of faults has given rise to such a tectonic configuration that movement of any lithospheric block along a particular fault is propagated along other faults. Many of these faults and fissures within these major structures seem to extend to the lower lithosphere (Ravi Shankar, 1995) and several hot springs lie along them (GSI, 2000).

Tectonic framework of the study area is shown in Figure 1.4. The Cambay basin is an intracratonic slightly asymmetrical fault bounded Graben and is defined by two major bounding faults, namely, Eastern Cambay Basin Bounding Fault (ECBBF) and the Western Cambay Basin Bounding Fault (WCBBF). This system of major bounding faults additionally comprises several successive sympathetic faults that run parallel along NNW-SSE and many orthogonal cross cutting faults (Merh, 1995). This NNW-SSE alignment of this narrow Graben (55–100 km) takes a swing in NNE-SSW direction into the Gulf of Cambay around 21.75 °N. This tectonic depression is flanked (Figure 1.3) by Kathiawar (Saurashtra) Uplift in the west and Aravalli Range in the east (Biswas, 1982;

1987). The Cambay Basin also extends along the west coast of India through the Gulf of Cambay parallel to Precambrian Dharwar trend. In the south, the Cambay Basin merges with the EW trending Narmada Graben and the Surat (Danahu) Depression where a tipple junction is formed. Though the Cambay Basin originated in the Late Mesozoic, it has mainly evolved during the Tertiary as revealed by the huge thickness of Cenozoic sediments (Merh, 1995).

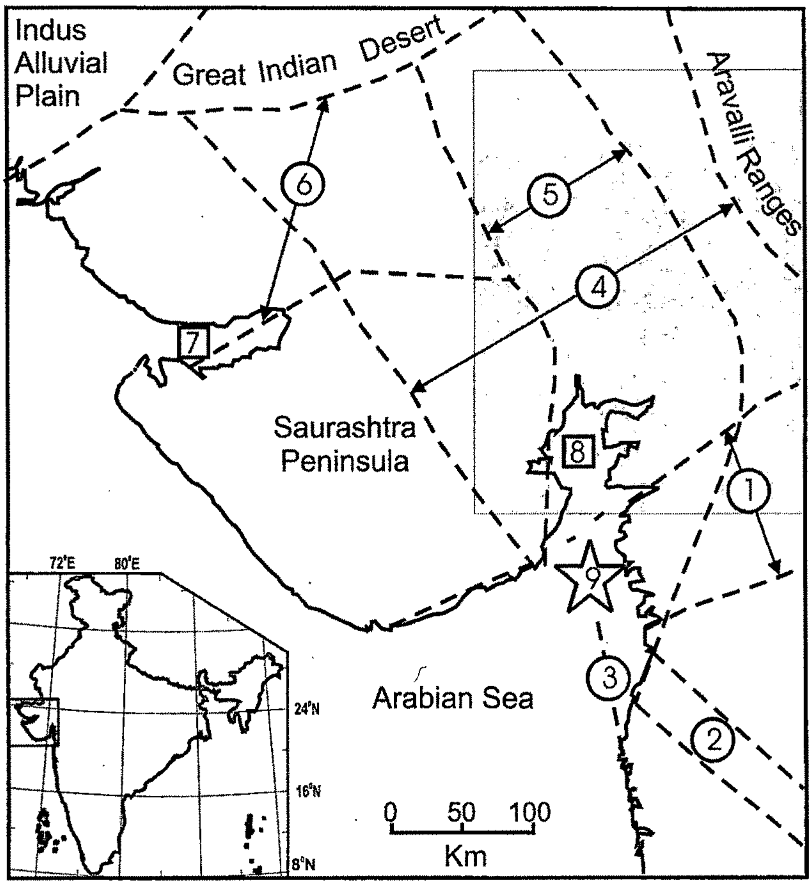

Figure 1.3 Tectonic framework of the Gujarat State in western India showing major linear tectonic structures based on Burke and Dewey (1973), Biswas (1987), Misra (1981; 2001). The various structural elements are: 1. Narmada Tapti Tectonic Zone; 2. Kukdi-Ghod Lineament Zone; 3. West Coast Fault; 4. Cambay Structure; 5. Cambay Graben; 6. Kachchh Rift; 7. Gulf of Kachchh; 8. Gulf of Khambhat; 9. Triple Junction of 1, 2 and 5. The study area is shown in grey shade.

The Cambay Graben is underlain by an uncertain thickness of pre-Deccan, terrigenous, Late Jurassic to Early Cretaceous sediments. Deccan Trap volcanics directly overlie this and are present throughout the extent of the Graben. They are thickest in the axial part of the Graben where their thickness is up to 2000 m (Kaila, 1988). The Tertiary sedimentary formations with productive oil and gas reservoirs overlie the Deccan volcanics. About 300 to 800 m thick Quaternary fluvial and alluvial sediments overlie the Tertiary sediments thus forming about 3500 to 4000 m thick Cenozoic sedimentary succession within the Cambay Graben for most of its length (Gombos et al, 1995). The thickness of the sedimentary cover, however, reduces to a few metres on both the east and the west flanks of Cambay Basin.

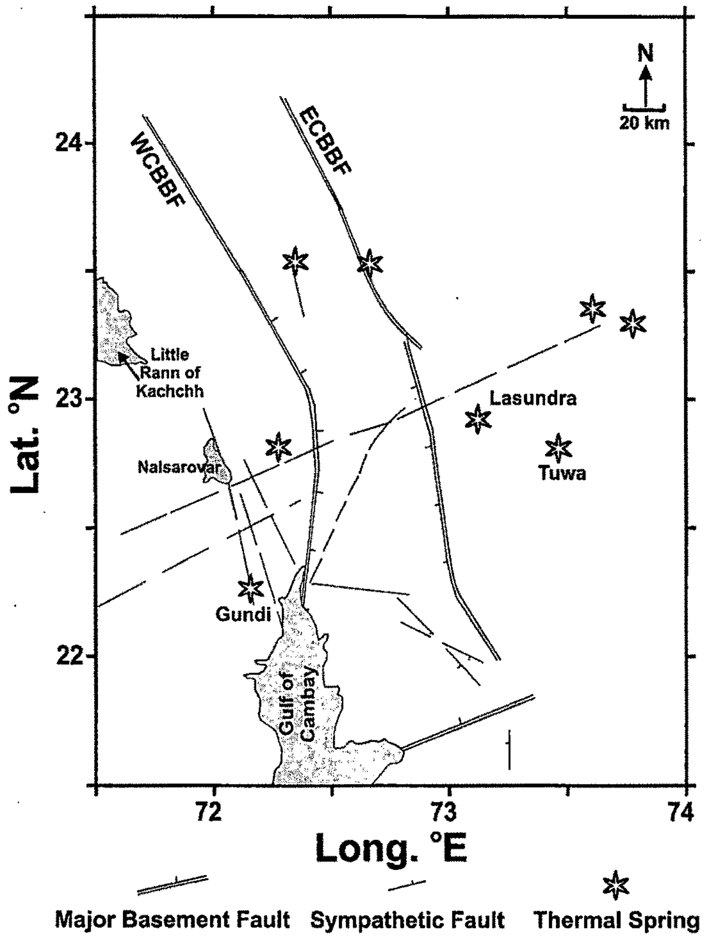

Figure 1.4 Tectonic framework of the NGC region. Two major bounding faults, namely, the ECBBF and the WCBBF define the Cambay Basin. Several sympathetic faults parallel or orthogonal to the major faults also exist. Most thermal springs are seen to be located in the vicinity of known basement faults.

The Cambay Basin seems to have subsided episodically since the formation of Graben structure in the Late Mesozoic with varying rates and finally during Quaternary the rate of subsidence slowed down. However, it can not be ruled out that the Quaternary basin experienced considerable reactivation of the pre-existing faults (Maurya et al, 1995). A variety of soft sediment deformation structures documented in the Lower Mahi River basin are slumps and slides, syn-tectonic folds, faulting, slickenside and pseudo-nodules and indicate syn-tectonic sedimentation and differential subsidence of the basin along the sympathetic step faults that developed parallel to ECBBF (Maurya et al, 1997). Based on lineament and drainage studies, Sareen et al (1993) showed that present Sabarmati River flows in NNE-SSW direction deviating from the regional slope of NE-SW. This was attributed to the neo-tectonic activity in the basin. Geomorphologic studies have indicated recent movements along many faults in this region (Srivastava et al, 2001).

1.2.4 Geothermal Regime

Cambay Basin region is characterised by higher than average heat flow and geothermal gradient which has been explained in the context of a thick high density (3.02 g cm^{-3}) igneous layer underlies the crust in this region. It has also been hypothesised that underlying the accreted igneous layer, a low velocity zone of hot mantle and/or a zone of intense interaction between lower crust and upper mantle has been identified beneath the area of triple junction (Arora and Reddy, 1991). This configuration is compatible with high geothermal regime (heat flow 55-90 mWm^{-2}; temperature gradient 36-58 $^{0}C\ km^{-1}$) in the region (Gupta 1981; Panda 1985; Ravi Shankar 1988; Negi et al, 1992). Therefore, the lithosphere beneath the triple junction and the three arms, namely the Cambay Graben, Narmada-Tapti rift zone and West Coast fault, is now much warmer, thinner, relatively ductile and less viscous compared to the margins (Pandey and Agrawal, 2000). Based on deep seismic soundings (Kaila et al, 1981; Kaila et al, 1989; Kaila and Krishna 1992) and gravity surveys (Singh and Meissner, 1995; Singh, 1998), it has been suggested that these structures reach up to the mantle (~ 40 km in depth; Kaila et al, 1989) in the Narmada-Tapti rift system and the Cambay Basin areas. This regional tectonic fabric seems to be responsible for higher geothermal regime in the Cambay Basin region.

The higher geothermal gradient in the region is also manifested in several thermal springs (Figure 1.4) and thermal artesian wells some of which are free flowing type (GSI, 2000). Existence of these thermal springs along geologically well defined structures (Section 1.2.3 above), with frequent earthquakes of moderate intensity, suggests that the associated structures may be active even presently. This was also suggested by the signatures of neotectonic movements in the Quaternary sediments and from the geomorphic studies of the region (Sridhar et al, 1994; Maurya et al, 1995; Maurya et al, 1997; Tandon et al, 1997, Srivastava et al, 2001).

1.2.5 Topography and Drainage

A surface elevation and drainage map of the study area is shown in Figure 1.5. The elevations in the study area range from >300m in the NE part to <25m near the Gulf of Cambay in the south.

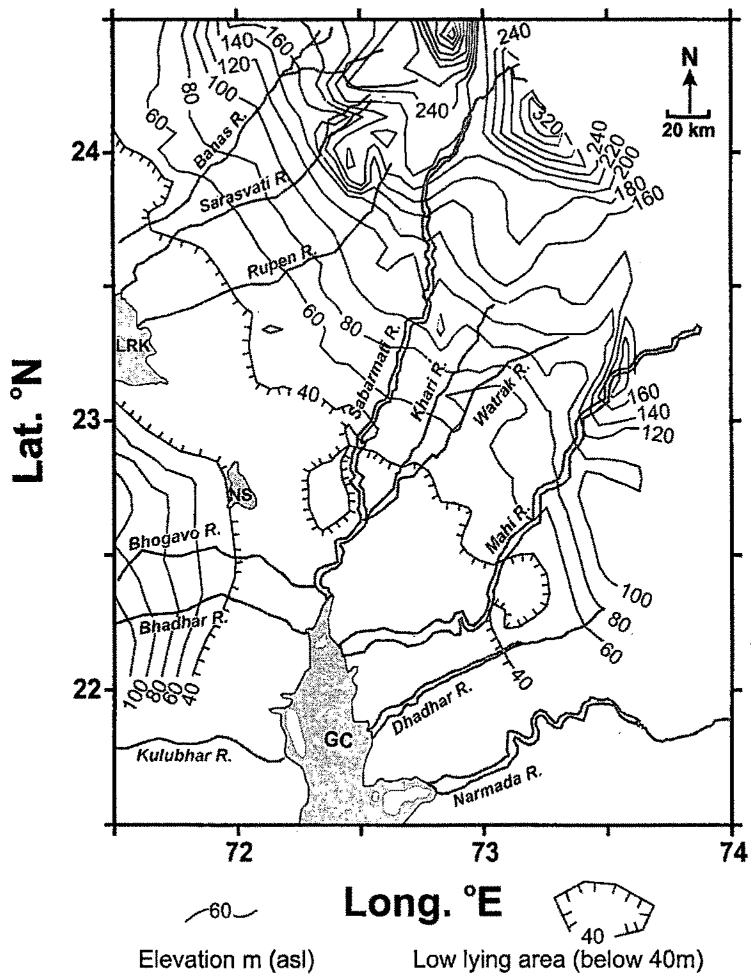

Figure 1.5 Map showing River drainage and surface elevation in the NGC region. The low lying belt linking LRK-NS-GC is less than 40 m in elevation and forms the zone of convergence for surface drainage from both the sides.

The Aravalli foothills occupy the intermediate elevation (~100-200 m) trending the NW-SE. The lowest elevations are found in the tract linking LRK-NS-GC. The elevations increase to >100m further southwest of this low lying tract. The control of surface elevation gradient on the drainage pattern is evident from Figure 1.5. It is seen that the low lying tract linking LRK-NS-GC forms the zone of convergence wherein the streams from both the sides of higher elevations converge. The rivers originating from the Aravalli hills, namely, Banas, Saraswati, Rupen and Sabarmati flow south-westward towards the LRK-NS-GC tract. The rivers (Bhogavo, Bhadar and Kulubhar) originating from Saurashtra highlands flow NE towards the LRK-NS-GC tract.

The Rupen, Saraswati and Banas rivers drain into the Ranns of Kachchh. These are seasonal rivers which carry water only during the monsoon months (June – September). The Mahi and Sabarmati are the two most important rivers that have shaped the present landform of the major part of the study area. The Mahi River originates in the Malwa region of Madhya Pradesh, flows for ~180 km in the study area before debauching into the Gulf of Cambay. The Sabarmati River originating in the south-western part of the Aravalli hills traverses a distance of ~400 km (NE to SW) across the Cambay Basin and outfalls in the Gulf of Cambay. It was suggested by Zeuner (1950) that the Sabarmati River had shifted its course gradually towards the east during the Pleistocene. Contrary to NE-SW regional slope of the alluvial plain, Sabarmati River follows N-S to NNE-SSW path attributed to neotectonic activity (Sareen et al, 1993). On the basis of sedimentological and geomorphologic studies, it was suggested (Sridhar et al, 1994) that the volume of Quaternary sedimentation in the Sabarmati basin could not be accounted for by the modern day flow of the river and a super fluvial system during Quaternary was postulated. However, it was subsequently indicated, based on sedimentological analyses, that upper fluvial sedimentary sequence is deposited by the meandering of the same river system but during a persistently wetter phase (Srivastava et al, 2001). The region between Sabarmati and Mahi is drained by a number of tributaries of Sabarmati namely, Khari, Shedhi, Majham, Andheri, Meswo and Vatrak. The Bhadar and Bhogavo are two major rivers flowing eastwards from Saurashtra draining into the Gulf of Cambay. Bhogavo, however, joins Sabarmati at its mouth before draining into the Gulf of Cambay.

1.2.6 Climate

The study area falls in the sub-tropical climate zone with the tropic of Cancer passing through the middle. The northern part of the study area comprises districts of Banaskantha and western part of Sabarkantha having arid to semi-arid climate, with less than 400 mm of average annual rainfall. In the southern part around Ahmedabad and parts of Saurashtra, the average annual rainfall is ~750 mm. Most of the rainfall is received during the southwest monsoon in the month of June to September. The average annual relative humidity is low (~50-60 %) throughout the year excepting the areas in the vicinity of the Gulf of Cambay. The area lies between the average annual isotherms of 35 °C and 45 °C indicating that, in general, aridity prevails in most part of the study area.

The area is known to have recorded palaeoclimatic fluctuations in form of various proxies in sedimentary deposits. The palaeoclimatic significance of sedimentary deposits in the Sabarmati, Mahi and Narmada basins was recognised by Zeuner (1950) and he postulated that climate in this region alternated between wet and dry during the Pleistocene. The arid excursions have also been documented in several other studies. Prasad and Gupta (1999) reported the presence of a thick gypsum layer, representing periods of extreme aridity, corresponding to estimated luminescence age ~20-30 ka, in a sediment core from Nalsarovar. Based on the crystallinity index of illite, Pandarinath et al (1999b) have also indicated aridity for this layer. Regional evidences of aridity have also been reported in the form of enhanced dune building activity which began ~20 ka in N. Gujarat (Wasson et al, 1983; Juyal et al, 2003, 2006).

1.2.7 Groundwater Hydrology

The groundwater occurrence in the study area can be grouped under three physiographic settings, namely: (i) hilly area of Aravalli foothills in the northeast and east; (ii) alluvial plains including Cambay Basin and it's both flanks; and (iii) part of the Saurashtra upland in the study area.

In the hilly region of Aravalli foothills where hard rocks are either exposed on the surface or are at a very shallow depth of few meters, groundwater is found in the secondary porosity zones resulting from weathering, joint planes, cracks and fissures. The water table in this terrain is generally at relatively shallow depths of less than 10 m. The groundwater level rises considerably in the post monsoon period due to direct infiltration of rainwater in the secondary porosity. The sediments in the foothill region are relatively coarse and this zone between Aravalli hills in the east and the alluvial plains in the west forms the principal recharge area for the confined groundwater in the Cambay Basin area. Using tritium tagging of soil moisture annual recharge to groundwater in the recharge area has earlier been estimated to ~15% of average annual precipitation (Gupta and Sharma, 1984).

A thick succession of Quaternary alluvial deposits comprising multilayered sequences of sediments of fluvio-marine and fluvio-aeolian origin forms the regional aquifer system which extends from the Aravalli foothills in the northeast and east to the Little Rann of Kachchh and Saurashtra highlands in the west (Figure 1.2). A subsurface lithological cross-section across the Cambay Basin from Nayaka to Chadotar (along the line AA' in Figure 1.2), based on drilling logs obtained from Gujarat Water Resources Development Corporation Ltd (GWRDC), is shown in Figure 1.6.

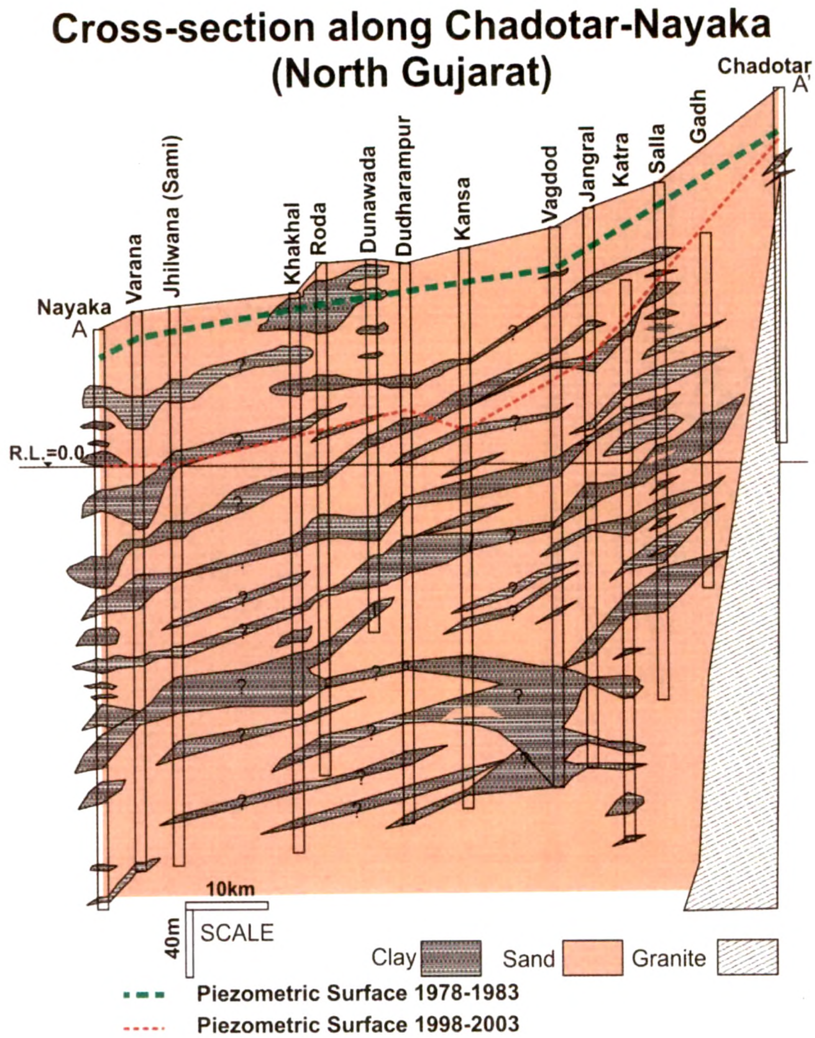

Figure 1.6 Sub-surface lithological cross-section along line AA' (in Figure 1.2) from Nayaka to Chadotar. The sandy layers forming aquifer horizons are seen to be laterally continuous and vertically interspersed with thin semi-permeable clay/silt layers that may not have lateral continuity over a large area. The uncertainty of continuity in view of large separation is indicated by (?). Tubewells tap all water bearing horizons up to their maximum depth.

As can be seen, the thickness of the alluvium rapidly increases westwards away from the Aravallis and a sand-clay/silt succession replaces the coarse sediments of the foothill. The sandy layers forming aquifer horizons are seen to be laterally continuous and vertically interspersed with thin semi-permeable clay/silt layers that may not have lateral continuity over a large area. It is also seen that various sub-aquifers are roughly inclined parallel to the ground surface; so that at different locations, a given depth below ground level (bgl) reaches approximately the same sub-aquifer within the Cambay Basin. According to Patel (1986), the deeper aquifers are under artesian condition. Towards their western extension, the deeper aquifers abut against a thrust plane little north of LRK. Along the LRK-NS-GC belt, tubewells tapping the deeper aquifers exhibit free flowing condition at ground have high water temperature and saline water. Recently, excess dissolved helium has also been recorded from groundwater of these wells (Datta et al; 1980).

The upper aquifers are under semi-confined condition. They receive recharge (i) directly by seepage from the overlying unconfined aquifer; and (ii) by lateral flow from the recharge zone of Aravalli foothills in the east. The shallow unconfined aquifer receives direct recharge from (a) rainfall infiltration, (b) nearby stream flow, and (c) by return flow from irrigation.

The groundwater development in the region can be sub-divided in three phases:

1. Pre-1935 phase - Groundwater at shallow depths (5-10 m), obtained from dug wells by bullocks and manual lifting.
2. 1935-1955 Phase - Groundwater levels declined to 10-30 m and dug-cum-bore wells became prevalent and diesel pump sets were used for lifting.
3. Post 1955 Phase - Groundwater levels began to decline rapidly and from sixties onwards the decline has been between 1-3 m per year. Deep tubewells fitted with electric motors have been used to lift groundwater from 100-250 m depth.

Deterioration in the groundwater quality almost parallels the post 1955 phase, when, with the advent of tubewells and electric motors, the groundwater extraction increased many folds. Gradually, the soil fertility was affected by irrigation from high TDS groundwater and several native crops disappeared. Presently, cash crops of cotton, *bajari* and *jowar* are grown in the region.

In recent years, the deeper groundwater from this regional aquifer system, particularly in the Cambay Basin region, is being exploited to meet agricultural, domestic and industrial water demands. Since extensive withdrawal of deeper groundwater is not made up by natural or artificial groundwater recharge, the water levels in most of the study area have declined at a rate of 3-4 m/yr (see piezometric surfaces in Figure 1.6). In some parts of the NGC region, the groundwater levels have declined to >400 m depth and the water is being pumped at progressively increasing cost.

1.3 Specific Objectives of the Study

The hydro-geological and climatic conditions (temperature, rainfall, evaporation etc) prevailing in the recharge zone govern chemical and isotopic properties (e.g. temperature, pH, dissolved ions, oxygen and hydrogen isotopic compositions and dissolved gases) of the infiltrating water. During groundwater flow in the aquifer, these properties can be modified by subsurface processes such as evaporation from the capillary zone, leaching from the aquifer matrix, venting of thermal fluids, release of gases such as helium etc.

Thus, geochemical and isotopic investigation of groundwater can provide insight into a variety of surface and sub-surface processes operating during recharge and movement in the aquifers. With this background, following specific objectives have been defined:

1. To identify the regions of groundwater recharge to the regional aquifer system of NGC region.
2. To determine direction and rate of groundwater movement within the regional aquifer system.
3. To estimate groundwater ages employing ^{14}C, ^{4}He and $^{4}He/^{222}Rn$ methods and to understand their relationship with various ionic and isotopic properties of groundwater from the recharge towards the discharge area.
4. To determine regions of anomalous helium, temperature and fluoride in groundwater and to explain the origin of observed variation in terms of tectonic framework and geothermal regime of the study area.
5. To identify the possible ionic or isotopic signatures of past climatic changes.
6. To set up a laboratory for analysing dissolved Chlorofluorocarbons (CFCs) in groundwater.

1.4 Motivation and Approach

Motivation for identification of the above as specific objectives of this study and the methodology adopted to achieve these is introduced in the following:

1.4.1 Groundwater Dating

Based on general topography, geology, the lithologs of drilled tubewells and the water level/ piezometric level data, recharge area of the regional aquifer system in the study area was identified in the foothills of the Aravalli Mountains in the NE. The low lying LRK-NS-GC region has been identified as the area of convergence both for surface- and ground-water beyond which the groundwater may be discharging into the Gulf of Cambay.

However, this inference of groundwater recharge and discharge areas, based on topographic and lithological parameters, needs to be strengthened and refined by determining the age of groundwater, its direction and rate of movement in the aquifer. The radiometric dating methods provide information on age and residence time of groundwater, exchange between shallow and deep aquifers and interaction with the aquifer matrix. Therefore, groundwater dating employing ^{14}C decay, ^{4}He accumulation and $^{4}He/^{222}Rn$ methods, was undertaken. Laboratory and field procedure for water sample collection, carbonate precipitation, storage and analyses were developed for various groundwater dating methods.

1.4.2 Groundwater Helium and Temperature Anomalies

It has long been recognised (Golubev et al, 1975; Dikum et al, 1975) that helium (^{4}He) produced by α-decay of U and Th series nuclide in rocks and minerals get liberated during convective circulation, rock dilation and fracturing. Since the Cambay region has several deep seated faults, anomalously high amounts of this liberated helium may be escaping from these faults, either directly or as component of injected deeper fluids. Before escaping to atmosphere, injected gases, including helium, are trapped by omnipresent groundwater at shallower levels. Therefore, if groundwater acquires additional ^{4}He from deep subsurface sources, its dissolved ^{4}He concentration can be in excess of atmospheric equilibration value plus that acquired from radioactivity in the host aquifer matrix.

High concentrations of dissolved helium and high temperature of groundwater in some parts, particularly around thermal springs, was reported earlier (Datta et al, 1980). However, geographic distribution and interrelationship between these two parameters and their relationship with deep seated faults in the region were not known.

Therefore, a survey of dissolved helium and temperature of groundwater in the study area was undertaken. As part of the investigations, simple standardised procedures were also developed for sample collection, storage and measurement of helium concentrations in soil-gas and groundwater samples using commercially available helium leak detector.

1.4.3 High Fluoride in Groundwater

In response to extensive groundwater mining during the past 2-3 decades it has been noticed that fluoride concentrations in groundwater in some parts particularly, Banaskantha, Mehsana and Ahmedabad districts increased progressively leading to endemic fluorosis. Evidences of dental and skeletal fluorosis in many parts of this region have been reported (Gupta and Deshpande, 1998).

Although knowledge concerning fluoride-affected parts of Gujarat is available (Vasavada, 1998; Gujarat Water Supply and Sewerage Board, unpublished data, 1997), little is understood about the origin of high groundwater fluoride in affected areas though several hypotheses exist.

None of these hypotheses were tested, except the self evident geographical coincidence of high fluoride ground waters zones in arid parts of the globe.

Therefore, a survey of dissolved fluoride in groundwater was undertaken to understand the origin of high concentration of groundwater fluoride in terms of depth of source water, age of groundwater, proximity to fluoride rich source rock and hydrothermal springs. In addition to a purely academic enquiry, understanding the origin of fluoride in regional groundwater could be useful in devising water exploitation and management strategies. Since electrical conductivity (EC) is a proxy of total ionic concentration of water, EC was also measured along with fluoride concentration, temperature, pH, Eh and chloride (at some locations) in groundwater samples from the various depth zones ranging from shallow dug wells, geothermal springs, hand-pumps, tubewells and flowing artesian wells up to 450 m depth.

1.4.4 Isotopes in Groundwater: Palaeoclimatic Imprints

The stable isotopes of oxygen and hydrogen constituting water, due to isotopic fractionation processes accompanying precipitation and groundwater recharge, record the climatic signatures. Some studies based on this premise have been reported from other parts of the world (see Clark and Fritz, 1997; Kendall and McDonnell, 1998).

With a view to identify the possible signatures of the past aridity and to identify the source of thermal spring water, oxygen and hydrogen isotope ratios ($\delta^{18}O$ and δD) in the thermal springs and groundwater samples were measured. Isotopic analyses of modern precipitation were also carried out to provide reference for interpretation of the groundwater data.

In this Chapter, after introducing the research problem, specific objectives were defined. This was followed by enunciation of the motivation and approach. In the Chapter 2, theoretical aspects related to various geochemical and isotopic investigations undertaken are described.