Hydrology Project II

Purpose Driven Study

Coastal Groundwater Dynamics and Management in the Saurashtra Region, Gujarat

A view of the spreading channel running parallel to the coast in Minsar Basin

National Institute of Hydrology, Roorkee

in collaboration with

Gujarat Water Resources Development Corporation, Ltd., Gandhinagar

Research Study Report

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Preface

Groundwater is a vital resource for communities and ecosystems in coastal zones. In many coastal regions, groundwater is the primary or sole source of drinking water supply and irrigation. Groundwater sustains the flow of coastal streams and rivers and is a source of freshwater to coastal ponds, wetlands, and other coastal ecosystems. A large number of important urban and technological centres, major industries, productive agricultural lands, and seaports are located in these coastal areas that play a vital role in India's rapid economic growth. With the economic and population growth, shortage in freshwater supply is becoming increasingly acute.

Groundwater has been tapped increasingly during the last few decades to meet the growing water-supply needs. However, coastal aquifers which have their end boundaries in contact with seawater are vulnerable to saltwater ingress and are highly sensitive to anthropogenic disturbances. The fragility of these aquifers and their sensitivity to human activities demand an in-depth understanding of the coastal groundwater dynamics and an informed, competent management to guarantee the sustainable development and management of the coastal areas.

On the western coast, Gujarat, which is one of India's most industrialized states, has a coastline about 1600 km long. About one-third of the population is engaged in agriculture, the gross area cropped amounting to about half of the total land area. More than 70% net irrigation needs of this drought-prone state are met by groundwater. The coastal zone of Gujarat can broadly be divided into three major geographical parts viz., Kachchh, Saurashtra and Mainland Gujarat. Due to excessive groundwater withdrawals and geological formations in the region, almost the entire groundwater system along the coast of Kachchh and Saurashtra has been affected by salinity ingress; the salinity has spread over 1400-3500 km^2 in the coastal zone which has an adverse impact on the soil structure, crop yields and industrial growth as well as the source of drinking water supply of the region.

To prevent further deterioration of groundwater quality, it is imperative to develop strategies for judicious utilization of groundwater resources in addition to implementing effective remedial measures wherever necessary. For this purpose, it is essential to gain a better understanding of the hydrogeology of the area and determine the source of salinity as well as the complex freshwater-saltwater interactions in the aquifer system through field and laboratory investigations. The Minsar River Basin in coastal Saurashtra has been identified for this study.

The details of extensive field investigations and field tests in Minsar River Basin conducted by the National Institute of Hydrology, Roorkee and Gujarat Water Resources Development Corporation Ltd., Gandhinagar, are available in this report. Numerical modeling exercises and stable isotope investigations carried out by the National Institute of Hydrology are also documented in this report.

The study was carried out by the National Institute of Hydrology, Roorkee, in collaboration with the Gujarat Water Resources Development Corporation Ltd., Gandhinagar, under the Purpose Driven Study component of the World Bank funded Hydrology Project, Phase-II. Central Ground Water Board has also provided support in this study.

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Executive Summary

The work under the Research and Development Project ‘Coastal Groundwater Dynamics and Management in the Saurashtra Region, Gujarat’, was carried out as per the project objectives and action plan described below.

PROJECT OBJECTIVES AND ACTION PLAN

Characterization of the various hydrologic components and their quantitative inter-relationships in the coastal aquifer system.

To characterize the hydrologic components of the study area, a comprehensive computerized database of all available and monitored data was developed. The database comprised the topographic data, litholog data, water level and water quality data from observation wells and piezometers, rainfall data and other meteorological parameters, discharge data of Minsar River at Rana Kandorana gaging site, hydraulic particulars of major reservoirs and water supply schemes in the region, data pertaining to water conservation structures, groundwater draft data, landuse information from satellite digital data, inferences drawn from pump tests, experiments, and surveys. Most of the processed information was interfaced with the ArcGIS package. The litholog data was processed in Rockworks software to mark the spatial extension and configuration of coastal aquifer system. A water balance exercise was performed to evaluate the various hydrologic components and water table contour maps were prepared. The data also contributed towards identification, understanding and estimation of water fluxes in the study area. A hydrological conceptual model of the study area was developed based on above information.

Physicochemical mechanism of mixing of freshwater-saltwater in the coastal aquifer system and identification of causes of increasing groundwater salinity and its far reaching consequences on the coastal aquifer system

Water quality contour maps were prepared. These maps were based on TDS (total dissolved solids) data monitored in the study area. TDS was computed based on EC (electrical conductivity) measurements in the field. To determine aquifer parameters, GWRDC and NIH carried out pumping tests at eleven locations. Data from pumping tests performed by GWRDC in previous years was also utilized. Gaps in the database existed with regards to data of water table, water quality, and lithologs especially close to the coastline of Minsar Basin. Attempts were made to fill out these information gaps by identifying additional monitoring wells. A total of sixteen additional piezometers were also drilled by GWRDC to monitor water level and quality at selected locations and at different depths. Additional lithologs data for deep piezometers located near the coast were obtained from CGWB.

Groundwater sampling for stable isotope analyses was carried out by NIH during the period Setember 2012 to September 2013. Water samples were collected from open wells, piezometers, hand pumps, public water supply wells, River Minsar, from the

Arabian Sea, and from various reservoir and surface water bodies in the study area. A total of 150 TDS monitoring locations were spread over four demarcated zones in the region for monitoring of groundwater salinity as well as mapping the TDS profiles in monitoring wells and piezometers. For chemical analysis, 70 locations spread over the study area were selected for chemical analysis of the parameters: pH, TDS, Na, Ca, Mg, Cl, HCO_3, K, SO_4, NO_3, B, F. Most samples collected as part of this study were from domestic or irrigation wells and piezometers installed during the study. From the isotope and chemical analysis of water samples, conclusions were drawn regarding the causative factors of salinity, saline groundwater zones at shallow and deep levels, possible zones of groundwater recharge, and hydrogeochemical processes occurring in the coastal aquifer system.

Numerical modeling of coastal aquifer system and sustainable management practices for the coastal region

The general groundwater flow regime in three-dimensions, at regional scale, was simulated for variable density flow. Model domain was taken as the Minsar River Basin, assuming that the groundwater flow does not occur across the basin boundary. Near the coast, with gentle topography, the model domain boundaries were identified using the water table contours for a normal rainfall year. On the seaward side, the sea coast was taken as the model boundary. Major topographic features of study area were digitized on GIS. Aquifer geometry was taken in accordance with the spatial extension of main aquifer unit marked out using the available litholog data. The total area of 1751 km^2 for the study extended to a maximum of 55 km from seacoast to upper reaches in Minsar Basin and 43 km along the seacoast length. Geochemical surveys and numerical modeling simulations demonstrated that the existing aquifer management practices have sufficed to control the increasing groundwater salinity. Vulnerably of coastal zone in the area was also been studied and possible remedial measures suggested.

Effect of water availability and quality on the socioeconomic growth

To evaluate the impact of the water quality and prevailing water management policies on the environment and socioeconomics of the region, a comprehensive study was undertaken that involved the integration of remote sensing techniques and socioeconomic surveys within a GIS framework. The survey was undertaken in villages located within a distance of about 15 km from the coast. The detailed socioeconomic survey was conducted through personal communication with the local farmers and general population in the region, with the help of a questionnaire prepared for interaction with the villagers.

Technology transfer to State Departments in Gujarat and Coastal States (under HP-II) in India

During the entire duration of the project, three training courses were organized by NIH Roorkee in collaboration with GWRDC, Gandhinagar at following locations:

- Anand (Gujarat) in November 2010 for State Department Officers from coastal HP-II states (total 29 participants from Gujarat, Maharashtra, Karnataka, Kerala, Tamilnadu, Andhra Pradesh, Odisha)
- Rajkot (Gujarat) in March 2013 for State Department Officers from Gujarat (total 19 participants)

- Ahmedabad (Gujarat) in March 2014 for State Department Officers from coastal HP-II states (total 21 participants from Gujarat, Karnataka, Puducherry, Andhra Pradesh)

The training courses addressed topics on coastal groundwater monitoring, development, assessment, modeling and management.

MAJOR CONCLUSIONS

The research work documented in this report, envisaging to investigate the groundwater dynamics in the coastal aquifer system of Minsar River Basin, essentially comprises the following:

- Hydrogeologic investigations
- Water quality and stable isotope investigations
- Numerical modeling of coastal aquifer system and water management aspects
- Impact of groundwater salinity on socioeconomics of the coastal river basin

Major conclusions drawn from the research work documented in this report are as follows:

Hydrogeologic investigations based on litholog study and water level data have revealed that the Miliolitic limestone forms the potential aquifer system in the coastal belt. In some areas, the limestone is more than 35 m thick. In the upland areas, the Deccan trap basalt forms the most extensive but poor aquifer due to its compactness and limited primary porosity. However, the weathered zone of the Deccan Trap, which at places is upto 30 m thick, forms a good aquifer. The water table contours in the Minsar basin, more or less follow the topography and the direction of groundwater flow is, in general, towards the sea. The region near the foothills of the steeply rising Barda Hills exhibits significant thickness of limestone and comprises a major groundwater recharge zone.

Close to the sea coast, groundwater is saline even at shallow depths. With increasing distance from the coast, the salinity in general decreases; except in the Ghed region, where the groundwater salinity is quite high (> 3000 mg/l) even at shallow depths at 12 km from the coast. Beyond a distance of 18 km from the coast, the groundwater is generally fresh (< 1000 mg/l) at shallow as well as at deeper depths. Further landward movement of salinity is curtailed by the strong seaward hydraulic gradient in the upland area. This gradient existing in both pre- and post-monsoon seasons effectively limits the freshwater-saltwater interface present in the limestone formation in the coastal zone. In the coastal belt, the groundwater salinity increases steeply with depth and at places reaches more than 10,000 mg/l. However, there are pockets of freshwater even near the coast, especially in places where a significant positive hydraulic gradient exists. During pre-monsoon, the water table gets lowered and a reverse hydraulic gradient is established near the coast leading to landward flow of seawater in some of the stretches along the sea coast. During monsoon season, the water table recovers and a positive gradient is setup which generates submarine groundwater discharge into the Arabian Sea.

Several factors contribute to groundwater salinity in the Minsar basin. Gaj beds comprising limestone, grit, sand, silt and gypseous clay of Miocene age that were formed in marine environment, have contributed to groundwater salinity both close and away from the coast in inland areas. Upconing of underlying saltwater due to groundwater pumpage for crop irrigation in the intensively cultivated region surrounding the Barda Sagar enhances the groundwater salinity for limited time periods. This increase in salinity is visible even during monsoon, when groundwater is utilized to supplement crop irrigation during a long dry spell in the monsoon period. Close to the sea coast, it is the seawater ingress in some pockets that has given rise to elevated levels of salinity. In addition, on the sea coast, high waves breaking along the seashore throw up a considerable amount of sea water in the form of spray, which gets deposited on the coastal land surface and plants and adds to soil salinity.

Chemical analyses of water samples have indicated the presence of ion exchange phenomena in the transition zone of the freshwater-saltwater interface. Stable isotope investigations have revealed that in the Ghed region (Kerly creek) the zone of transition exists at 15 m ± 3 m (approx.) altitude. For future studies, it is important to monitor this transition zone (at 12 m to 17m altitude) to understand the influence of groundwater withdrawals, climate change, land use change and other anthropogenic activities that may cause this transition zone to fluctuate.

Distributed groundwater modeling of the coastal aquifer system in Minsar river basin has been attempted in 3D at the regional-scale accounting for variable density flow. Numerical simulations for anticipated sea level rise on account of climate change do not yield any visible change in groundwater salinity near the coast; since the groundwater is already quite saline along the coastal strip. However, seawater ingress through creeks on account of higher tides needs to be investigated further.

For protection of groundwater quality, several conservation measures have been taken by the Govt. of Gujarat. The construction of bandharas at the mouth of creeks has enabled both (i) the conservation of surface water runoff from the catchment of Minsar River and Barda Sagar, and (ii) the prevention of seawater ingress through the creeks in the inland areas. The surface water irrigation schemes viz., Kerly RR/ Kerly TR and Barda Sagar, developed in the low-lying Ghed area as a byproduct of the above conservation measures, have facilitated ready access of fresh surface water for irrigation to the farmers in the Ghed area. In Ghed area, the groundwater is quite saline and the commissioning of above schemes has enhanced groundwater recharge through radial canals taking off from these schemes. As summer approaches, the water spread area of these irrigation schemes shrinks, and the fresh water turns saline due to evaporation effects. The spreading channel laid parallel to the coast between Kindri and Kerly creeks has aided groundwater recharge and has provided water for crop cultivation through lift irrigation in the coastal strip. The spreading channel, existing along the Saurashtra coast, also feeds surplus floodwater from one reservoir basin to another where rainfall is scanty. Checkdams constructed on streams and percolation tanks have also augmented the groundwater recharge.

As an outcome of the above conservation measures taken over the last two decades, relatively more freshwater is available for crop cultivation, compared to previous decades. A gradual change in cropping pattern is witnessed with more farmers opting for cash crops instead of the coarse cereals grown earlier. Major expansion in irrigation, suitable water management, implementation of drip and sprinkler irrigation, providing Kisan Credit Cards and Soil Health Cards for farmers in the past years have spearheaded the agricultural economy towards inclusive growth.

RECOMMENDATIONS

To combat the groundwater salinity, a multi-dimensional approach is required. Percolation tanks, check dams, rainwater harvesting systems, adoption of low water-intensive crop farming, renovation and deepening of ponds and run-off diversions systems to recharge aquifers are micro-steps that mitigate salinity ingress. Use of suitable technology, study of meteorological parameters, geography and geological factors, and capacity building of farming communities on efficient water management practices are other strategic interventions. Specific recommendations for the area under investigation are stated below.

1. Seaward hydraulic gradient needs to be maintained all along the coast to prevent inland migration of seawater.
2. Groundwater pumpage in the narrow coastal strip should be restricted.
3. For sustainable development of the sensitive coastal zone, long term monitoring of groundwater levels and salinity at regular intervals is essential to check any undesirable fall in the water table elevation and degradation in groundwater quality on account of groundwater overdraft in inland areas of the coastal zone.
4. Groundwater pumpage for irrigation can be further reduced by widespread adoption of efficient irrigation techniques such as sprinkler and drip irrigation technology. This technology is already in place in some areas of Minsar basin.
5. In areas with saline groundwater and no surface water resource, salt tolerant crops and / or low water-intensive crops can be cultivated.
6. The high evaporation rates result in significant loss of surface water storage. Moreover, the analysis of long term rainfall data has indicated that the region suffers from frequent drought years. The effect of evaporation intensifies especially during conditions of drought. In order to safeguard against the influence of droughts and to save water from being lost to the evaporative process, evaporation mitigation techniques need to be implemented.
7. Apart from evaporation mitigation techniques, sub-surface storages are not susceptible to loss of the critically important water resource through evaporation. Sub-surface storages also aid in building up the water table thereby keeping the groundwater salinity in check. Raising the water table through artificial recharge techniques in the inland region of the coastal belt will help in maintaining a healthy hydraulic gradient towards the sea, besides providing additional groundwater during drought years.
8. The low-lying area south of Kerly creek reservoir regularly gets flooded with river water during monsoon period and no crop cultivation is possible in this region during Kharif season. Studies can be taken up to divert the flood river water and utilize it for recharging the groundwater.
9. Large scale limestone mining near the sea coast may be restricted to protect the aquifer formation.
10. Shelterbelt plantation is already being taken up along certain stretches of the sea coast. Such shelterbelt plantations, including mangroves, along the coastline act as a bio-shield against coastal storm surges and needs to be taken up on a longer stretch of coastline. The coastal shelterbelts also act as a 'carbon sink' by absorbing emissions of the greenhouse gas carbon dioxide. Coastal shore protection structures also need to be planned to prevent coastal erosion.

CONTENTS

Chapter 1

Introduction

Marsh vegetation in Kerly creek reservoir in Ghed area

Groundnut cultivation in Kharif season

1.1 GENERAL

Coastal zones, accounting for approximately 70 per cent of the world's population, contain some of the most densely populated areas in the world as they generally present the best conditions for productivity. Settlements in 'coastal lowlands' are especially vulnerable to risks resulting from climate change; yet an increasingly large number of industrial hubs, trade and commerce centers are coming up in coastal lowlands and growing rapidly. The low elevation coastal zone (elevation less than 10 m above mean sea level) covers 2 per cent of the world's land area but contains 10 per cent of the world's population and 13 per cent of the world's urban population.

India has a long coastline of about 7500 km of which about 5400 km belongs to peninsular India and the remaining to the Andaman, Nicobar and Lakshadweep Islands. With less than 0.25% of the world coastline, India houses more than 63 million people living in low elevation coastal areas (land area 82,000 km^2 that constitutes about 3% of India's land area) and nearly 250 million people living within 50 km of the coastline. India's coastal zone is endowed with abundant coastal and marine ecosystems that include a wide range of mangroves, coral reefs, salt marshes, estuaries, lagoons, and unique marine and coastal flora and fauna. The coastal zone also provides sites for productive agriculture, export-processing zones, industries, harbors, airports, land ports, and tourism.

As population and industry migrate towards the sought-after coastal zones, increased pressure is exerted on the freshwater resources of the region. Coastal aquifers are vital strategic resources that provide and supplement the demand for freshwater. Coastal aquifers also provide base flow to creeks and rivers during dry periods, thus supporting diverse ecosystems. However, coastal zones are vulnerable to a variety of hydrological problems including cyclones, storm surges, flooding, seawater sprays, and seawater ingress through surface waters and through porous media. All these hydrological phenomena contribute towards salinization of fresh groundwater making the freshwater unfit for human use. In addition, anthropogenic pressures (indiscriminate groundwater abstraction, irrigation return flow, waste and waste water disposal) as well as other human activities that affect local and regional hydrological conditions (e.g. mining and land reclamation) are strong drivers for inducing seawater ingress leading to groundwater salinity. Compounding these issues are increasing risks from climate change.

With increasing human activity and looming risks from climate change, one of the most threatened resources along the coastal corridors of India is groundwater. Appropriate measures need to be devised to protect these resources from overexploitation and further contamination. To protect and maintain adequate supplies of freshwater to coastal settlements and sustain coastal economic activities, suitable management of these vital repositories of freshwater is a prerequisite.

Normally, surface topography and geological formations of coastal areas are different than those of upstream inland areas. By and large, the coastal regions on the western side compared to the eastern side of the lengthy Indian coastline, have steep surface topography and mixed geological formations comprising of fractured hard rock, limestone and alluvium. The climatic conditions which affect groundwater replenishment vary considerably with Saurashtra region in Gujarat on the northern side of west coast having arid to semi-arid climate and Malabar coast towards the southern side of the west coast having tropical humid climate. In arid and semi-arid coastal regions, such as the Saurashtra region in Coastal Gujarat where surface water is scarce and groundwater constitutes a significant source of water supply, degradation of water quality from saltwater intrusion can have serious repercussions on crop production and socio-economic development of the region in general. To sustain an assured water supply from these precious groundwater reservoirs, it is essential to put into place effective control and remedial measures including artificial recharge to augment groundwater resources, and minimize the impact of saltwater intrusion.

On the western coast, Gujarat, which is one of India’s most industrialized states, has a coastline about 1600 km long. About one-third of the population is engaged in agriculture, the gross area cropped amounting to about half of the total land area. More than 70% net irrigation needs of this drought-prone state are met by groundwater. The coastal zone of Gujarat can broadly be divided into three major geographical parts viz, Kachchh, Saurashtra and Mainland Gujarat.

The peninsula of Saurashtra forms a rocky tableland with fringed coastal plains. The inland area is covered with table lands of Deccan trap, while the coast line is mostly covered with sandy beaches, wetlands, marshy land etc. The area is drained by a number of south-west flowing rivers, most of which are seasonal that go dry during summer. A large portion of the area receives rainfall in the range of 600 mm to 750 mm. The major feature of the rainfall is its erratic nature and non-dependability. The coastal zone is characterized by a variety of geomorphic forms and geological features evolved under different structural controls during the Quaternary period. In the Saurashtra region facing the Arabian Sea, the coastal groundwater system comprises of mainly limestone formations and Deccan trap formations in the basement with groundwater existing under phreatic conditions.

Due to excessive groundwater withdrawals, almost the entire groundwater system along the coast of Kachchh and Saurashtra has been affected by salinization (Fig. 1.1); the salinity has spread over 1400-3500 km^2 in the coastal zone which is seriously affecting the soil structure, crop yields and industrial growth as well as the source of drinking water supply of the region.

Under the Purpose Driven Study (HP-II), detailed investigations have been carried out in the Minsar River Basin (Figs. 1.1-1.2) located in the Saurashtra region of Gujarat, to study the coastal groundwater dynamics, hydrogeology, water quality and saltwater intrusion phenomenon.

1.2 MINSAR RIVER BASIN

The Minsar River Basin extending between the latitudes 21°30’13.9” to 21°58’17” N and the longitudes 69°25’13.1” to 70°1’49.2” E, covers an area of about 1751 km^2, with a coastline about 43 km long. Porbandar, located on the sea coast with an average elevation of about 10 m above mean sea level (amsl), and Rananav, located in the coastal plains, are the major towns in this region (Fig. 1.2). In the upland portions, the

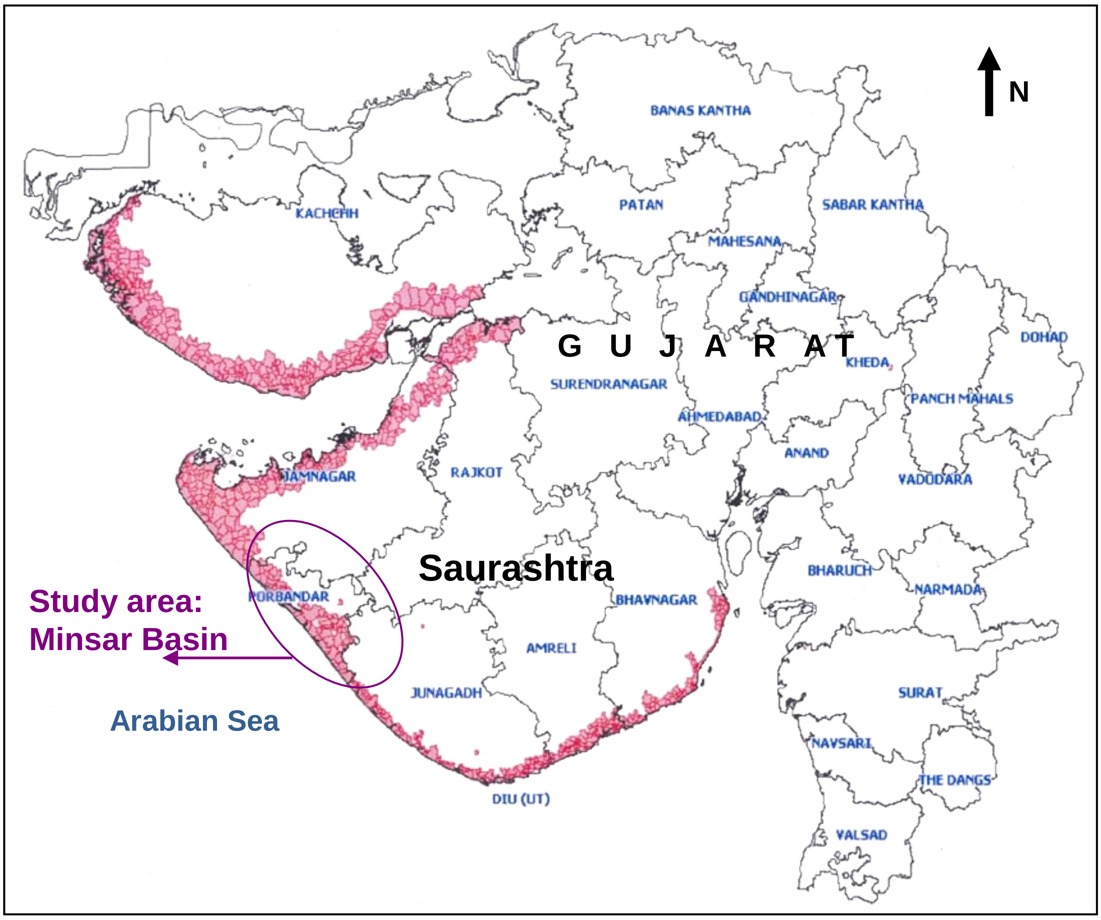


Fig. 1.1 Salinity affected (shown in red color) coastal villages in six districts of Saurashtra region in Gujarat.

hilly area shown with hatched lines has elevations above 75 m amsl. Most of the field surveys and monitoring in the present study have been carried in area with elevations less than 75 m amsl.

The River Minsar originates from the hills near village Jamvadi of Jamnagar district. It flows downhill and after covering 24 km meets the Dai river and 7.60 km from this junction meets the Bileshwari river near village Rana Khirasara. The catchment area of this river is partially hilly and partially plain. The river is ephemeral carrying water mainly during the monsoon season. In the upper catchment of the river, six reservoirs are present which store water for drinking water supply and irrigation needs. These are, namely, Fodarna, Khambala, VMinsar, DaiMinsar, Kalindri and Ishwaria.

Further downstream towards the coast, low lying flat mud land known as the Ghed area is present. In these mud flats, two schemes namely Kerly Tidal Regulator and Kerly Reservoir Scheme are located, that receive flood water from the catchment of Minsar river during monsoon. On the other end of the study area in the coast belt, another irrigation scheme, the Barda Sagar is present for meeting the irrigation demands of surrounding agricultural land. The geology of the region mainly comprises of milliolitic limestone, Gaj formations, laterites and alluvium in the coastal plains, while in the upper inland areas weathered/ hard Deccan Trap is present.

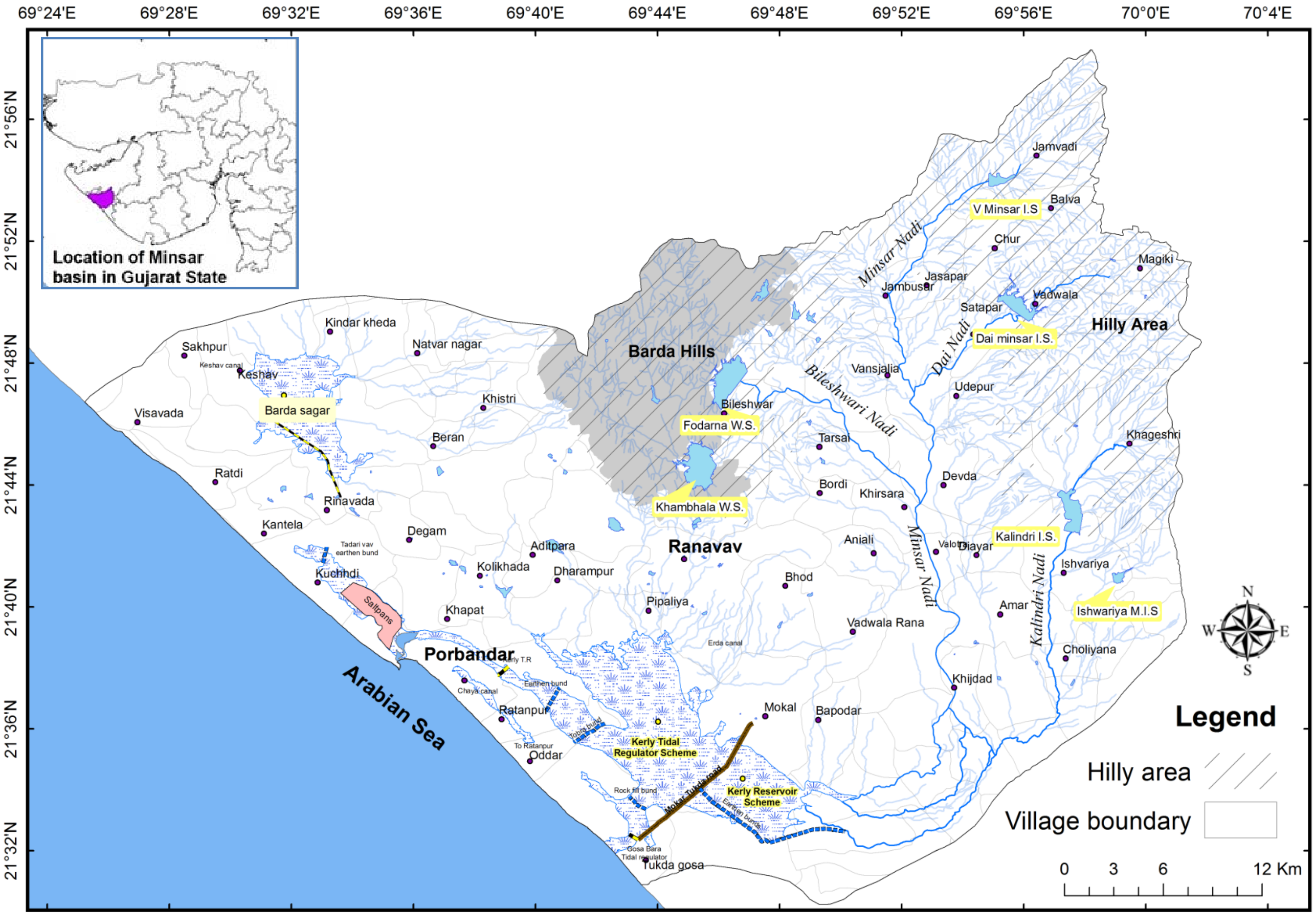


Fig.. 1.2 Study area in Minsar River Basin

1.3 PROBLEMS /ISSUES THAT PROMPTED THE PDS

The salinity problem on the Saurashtra coast first acquired serious dimensions in the 1970s. The State Government in collaboration with Physical Research Laboratory, Ahmedabad, carried out the first survey to investigate salinity in groundwater in coastal Saurashtra. The survey observed that salinity in groundwater was high due to the intrusion of seawater and vertical percolation of saline water along the creeks. A spurt in agricultural growth promoted by large groundwater withdrawals through electric engines and pumps led to lowering of groundwater levels which induced advancement of saltwater from the sea into the coastal aquifers. Reasons for groundwater overdraft also included increased usage of groundwater by the growing population and established industries. Other reasons that led to salinity ingress were (a) destruction of vegetation (i.e. mangroves and other vegetation) that resulted in saline water intrusion through surface channels/ creeks during high tides, and (b) low availability of fresh water in rivers due to construction of dams in upstream reaches of rivers.

With continued overdraft of groundwater over the years and inadequate measures to control salinity, out of a total of 954 villages located on the Saurashtra coastline, 359 villages reportedly became completely affected by salinity ingress while 177 villages were partly affected (i.e. the groundwater in these villages turns saline with TDS >2000 mg/l during summer). Thus, salinity ingress in more than 50% villages along the Saurashtra coastline adversely affected the groundwater, besides destroying the fertile land in the region (Fig. 1.1).

Various degrees of effectiveness of a variety of measures to combat problems of coastal aquifers in the region have been reported. However, long term sustainability of these measures and management of coastal groundwater resources in the context of rising demands and complex geoclimatic conditions are yet to be established. Also, field studies pertaining to the mechanism of mixing of freshwater-saltwater in limestone formations and fractured hard rock are largely lacking. In view of above, it was envisaged that a comprehensive study of coastal groundwater dynamics in Minsar River Basin would provide necessary insight into management strategies aimed at to protect, conserve and restore the coastal aquifer systems in the Saurashtra region of Gujarat.

In October 2009, under the World Bank aided Hydrology Project Phase-II, a Purpose Driven study (PDS) was initiated by National Institute of Hydrology (NIH), Roorkee, in collaboration with Gujarat Water Resources Development Corporation Ltd. (GWRDC), Gandhinagar, to investigate the coastal groundwater dynamics in Minsar River Basin in a comprehensive manner and gain necessary insight into the hydrogeology, groundwater flow, and impact of groundwater salinity on the socio-economics of the region as well as review the management strategies aimed at to protect and conserve the coastal aquifer system in the Saurashtra region of Gujarat. The study has been accomplished through in-depth field investigations and surveys, isotope and chemical analyses, and numerical simulation studies of coastal aquifer system in the region. The work carried out by NIH, Roorkee, in collaboration with GWRDC Gandhinagar and reported herein was completed in March 2014.

1.4 WORK ENVISAGED

The work envisaged in the project included the following major components:

1. Hydrogeologic investigations
2. Water quality and stable isotope investigations
3. Numerical modeling of coastal aquifer system and water management aspects
4. Impact of groundwater salinity on socioeconomics of the coastal river basin
5. Technology transfer

1.5 SCOPE OF PROJECT

The work plan for the project comprised the following activities:

- Collection of historical data
- Intensified monitoring and data collection from newly constructed piezometers
- Development of hydrological conceptual model
- Characterization of salinization process
- Water balance and resource estimate
- Numerical modeling of aquifer system
- Socio-economic surveys
- Documentation of project investigations and results
- Organization of training courses

1.6 BRIEF METHODOLOGY

To achieve the objectives stated above, comprehensive field monitoring exercises and field tests were performed by NIH Roorkee and GWRDC Gandhinagar. Isotope and chemical analyses, numerical modelling of the aquifer system and socio-economic survey was carried out by the NIH, Roorkee. For this purpose, the above work was executed as outlined below:

- Collection of meteorological, remote sensing, lithologs, groundwater and surface water data from concerned departments.
- Monitoring of surface water and groundwater levels as well as electrical conductivity (EC) to ascertain the TDS (total dissolved solids) as per the established observation network in the region.
- Chemical analyses of water samples collected from the area to establish the physic-chemical mechanism of mixing of freshwater-saltwater.
- Stable isotope analyses of water samples collected from the area in order to estimate the sources of salinity, major sources and areas of recharge.
- Conceptualization of the aquifer system.
- Analysis of data including topography, water table and water quality data (in terms of TDS, pH and relevant anions/cations), interpretation of remote sensing data for determining land use, estimation of total groundwater recharge from different sources, analysis of meteorological data etc.
- Mapping of all information on Geographical Information System (GIS).
- Numerical simulation of coastal groundwater dynamics for variable density flow.
- Socio-economic surveys

The investigations and analysis conducted during the course of the project are documented in the present report, along with the conclusions drawn and recommendations suggested on the basis of above analysis.

Chapter 2

Hydrogeology of Study Area

Limestone formation in the coastal belt

Field experiments in Odedar village

2.1 INTRODUCTION

A major portion (about 77%) of the Minsar River Basin falls in the Porbandar district which is located in the western part of Saurashtra region of Gujarat state. The climate of the area is semi-arid type with a maximum temperature of about 35^0C to 40^0 C during summers and a minimum temperature of about 8^0C to 18^0C during winters. In the Porbandar district, the minimum rainfall observed is 16 mm in Ranavav taluka (1987) and the maximum rainfall is 2452 mm in Porbandar taluka (1983).

2.2 SALIENT FEATURES OF STUDY AREA

2.2.1 Land surface altitude

To map the land surface altitude in the study area, land surface altitude data points were digitized from Survey of India (SOI) topographic maps. For this purpose, a total of nine SOI toposheets were obtained on 1:50,000 scale as follows: 41G/5, 41G/9, 41G/10, 41G/13, 41G/14, 41G/15, 41K/1, 41K/2, 41K/3. In addition, SRTM (Shuttle Radar Topographic Mission) elevation data set available at 90 m resolution downloaded from internet was utilized to develop a digital elevation model (DEM) of the study area. Figure 2.1(a) shows the DEM of the Minsar river basin, while Fig. 2.1(b) shows a 3D view of the regional topography of area under investigation.

The upland portion of the study area is hilly comprising Barda hills with altitude ranging from 55 m at the foothills to about 623 m (amsl) at the highest peak. In the present study, the area with land surface altitude above 75 m amsl has been termed as hilly area and is shown with hatched lines in most of the figures. In the coastal belt upto a distance of about 12 km from the coast, the region is characterized by low altitude especially in the Kerly creek and Barda sagar areas and relatively higher altitude in the mid-plains. The general slope of the land is towards the sea.

2.2.2 Administrative boundaries

The study area, comprising portions of Porbandar and Jamnagar districts, is divided into several administrative blocks known as talukas. Talukas with geographical area falling in the Minsar River Basin are as follows: Rananav, Porbandar, Kutiyana, Jamjhodhpur and Bhanvad. These five talukas comprise a total of 137 villages that are located in the Minsar basin as follows: Porbandar - 46 villages, Ranavav – 37, Kutiyana – 14 villages, Jamjhodhpur – 22 villages, and Bhanvad – 18 villages.

Figure 2.2 shows the layout of talukas and villages superposed over the study area. The respective boundaries of talukas and villages were digitized and geo-referenced in ArcGIS from maps provided by GWRDC.

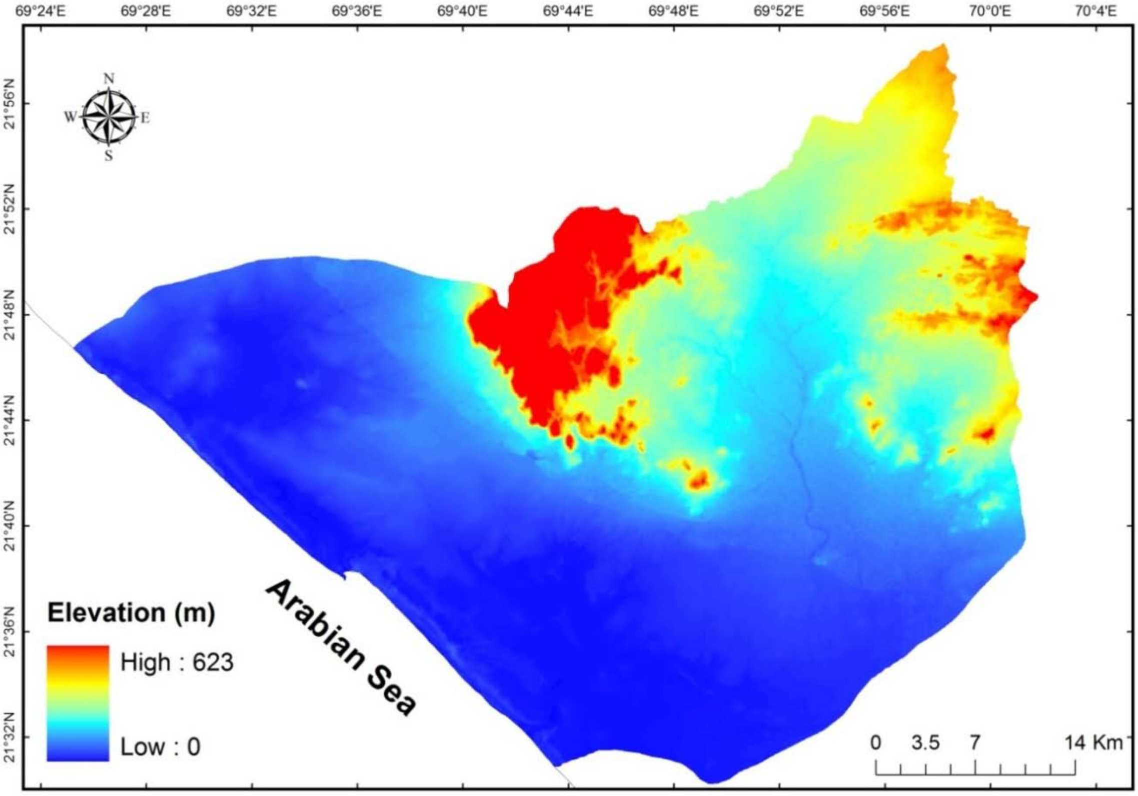


Fig. 2.1(a) DEM of Minsar river basin

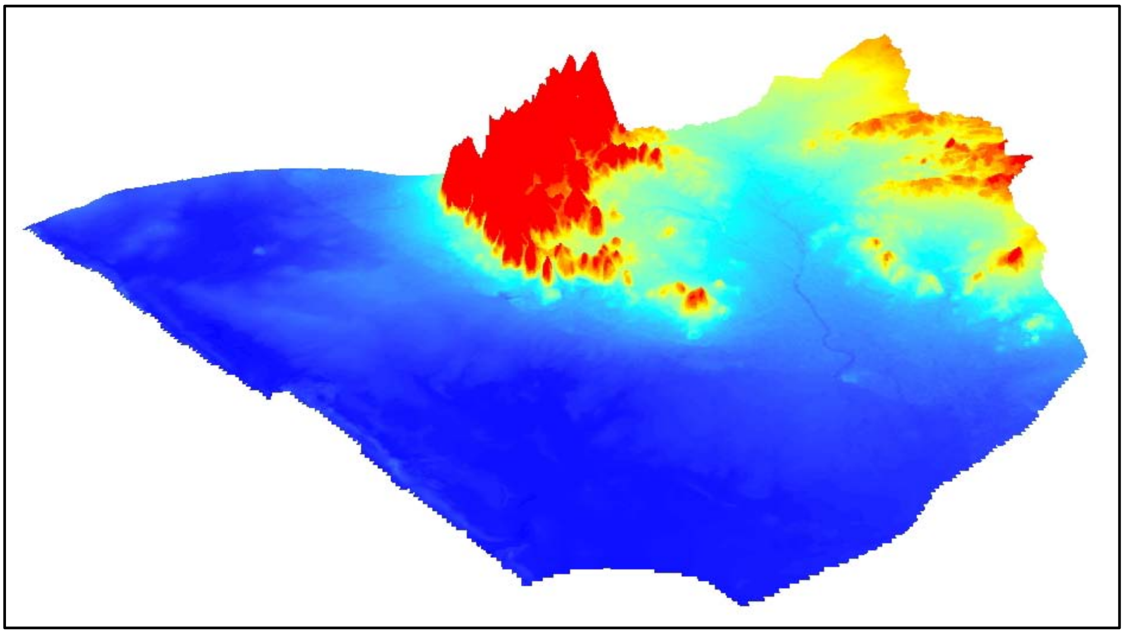


Fig. 2.1(b) 3D view of regional topography of Minsar river basin

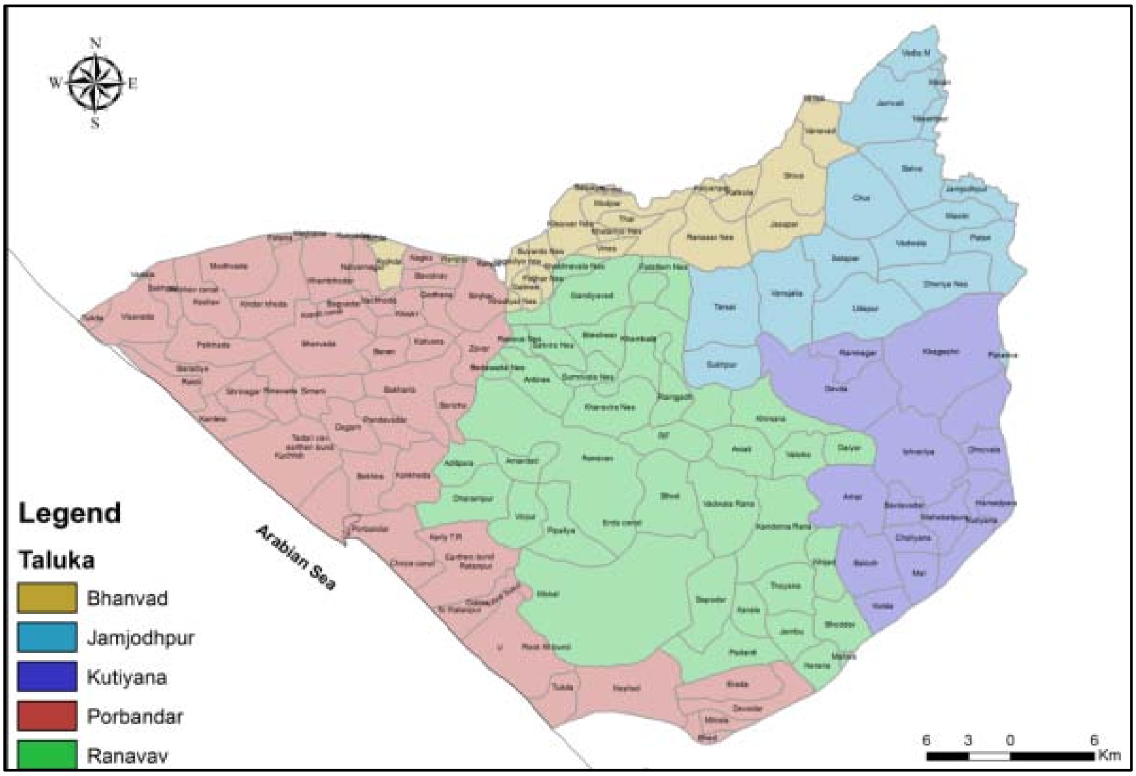


Fig. 2.2 Taluka and village boundaries in study area

2.2.3 Rainfall

The Minsar basin receives rainfall mainly from the southwest monsoon during June-September. A comprehensive collection of rainfall data [from IMD and SWDC (State Water Data Centre, Gandhinagar)] was made for the period 2001-2013 for the following rain gage stations: Porbandar, Ranavav, Kutiyana, Rana Kandorna, Tukda Gosa, Bhanvad, Jamjodhpur, Tukda Miyani, Rinawada, and Ishwariya. The weighted annual values of the rainfall for the period 2001-2013 were computed using the thiessen polygon method (Fig. 2.3). Weighted annual rainfall for the study area ranges from 263 mm in the year 2012 to 1610 mm in the year 2010 (Fig. 2.4). It may be noted here that during the period 2001-2013, the rainfall during most of the years in Porbandar has been better than the long term average for the region. Monthly distribution of rainfall recorded at above stations is shown in Annexure-I.

2.2.4 Evapotranspiration

Evapotranspiration is defined as the rate of water loss to the atmosphere due to evaporation and transpiration from plants. In Minsar Basin, during monsoon, the water table rises, with its depth below ground level varying around 1-1.5 m in some areas of the coastal belt. The high evapotranspiration rates during summers contribute to soil salinity in these areas. Table 2.1 provides the values of evapotranspiration rates during different months of a year at Porbandar (Rao et al., 1971).

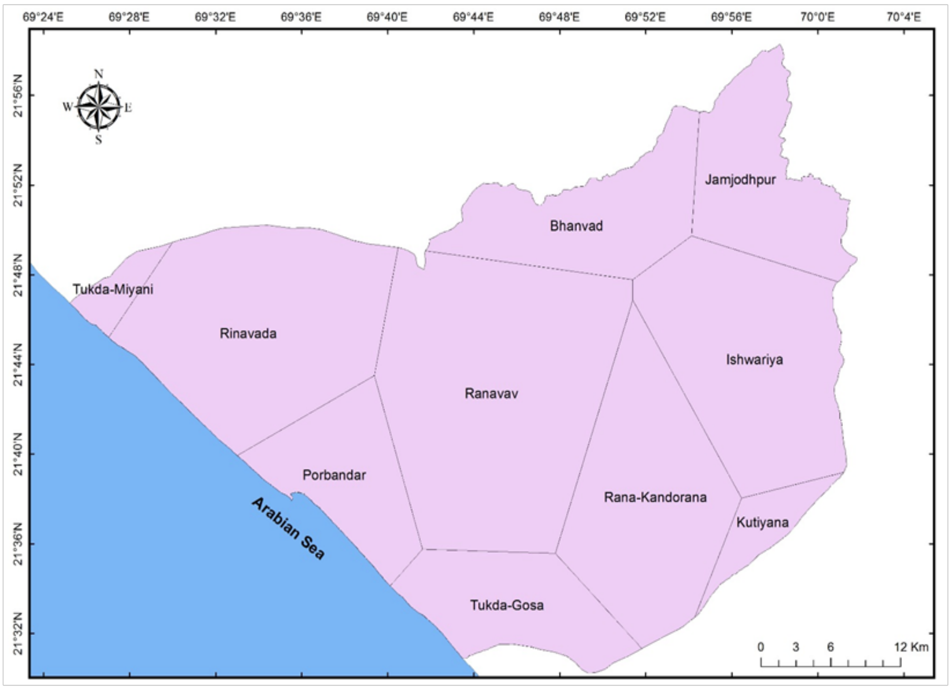


Fig. 2.3 Thiessen polygons of rain gage stations

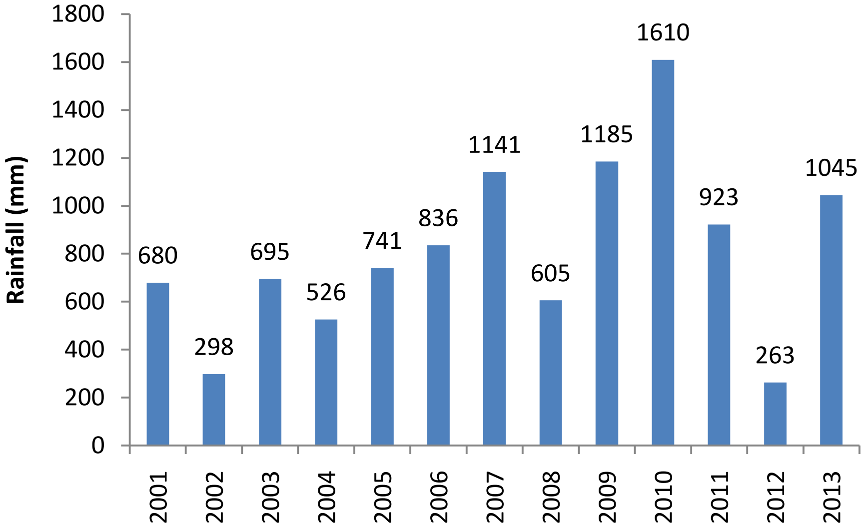


Fig. 2.4 Weighted annual rainfall (mm) for Minsar basin (2001-2013)

Table 2.1 Evapotranspiration rates (mm) at Porbandar

Station	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Porbandar	148.8	151.2	198.4	198	201.5	171	136.4	124	135	161.2	153	148.8

2.3 GEOMORPHOLOGICAL CLASSIFICATION

Based on the geomorphology, the study area can be broadly classified into the following three zones: (1) Barda Hills (2) Low lying flat mud land i.e. the Ghed area, and (iii) coastal ridges.

Barda hills and upland area: The upland area exhibiting undulating topography comprises Deccan trap formations with maximum elevation in the Barda hills reaching about 623 m amsl. The weathered zone is thick upto 30 m in some regions such as the area falling in villages Khageshwari, Devda, Ishwariya, and Daiyar.

Ghed Area: The area comprises deltaic region of Minsar river. Major portion of the area is covered by blackish brown clayey soil with thickness of the soil cover varying between 2-7 m. The geomorphology of Ghed area is such that it forms an inland basin in the shape of a saucer, due to relatively higher topographic elevations of coastal ridges all along the coast line compared to the coastal plain elevations. Since the area is devoid of any proper surface drainage, flood water flows in from the catchment of Minsar river and accumulates in Ghed area during monsoon. As such, the Ghed area remains inundated and mostly cut off from other parts of the region for several days during monsoon. The reservoir formed due to construction of bandhara (solid masonary concrete wall) on Kerly Creek, stores fresh water and prevents seawater from encroaching landwards through the creek (Fig. 2.5). This reservoir comprises two schemes, namely Kerly Tidal Regulator (Kerly TR) and Kerly Reservoir Scheme (Kerly RR) as shown in Fig. 2.5. Radial canals take off from the reservoir for irrigation water supply in nearby areas. Embankments have also been raised on the creek arm extending towards Porbandar (that joins the sea at Porbandar) to prevent encroachment of seawater through this arm during high tides into the inland area. This also facilitates availability of surface for water for lift irrigation along the coastal strip. On the other end of the study area, the region comprising Barda Sagar, located in the low lying coastal plain, falls beyond the catchment of Minsar river; however, the water table contours near the coast continue into this extended region. The contours are more or less perpendicular to the boundary drawn for the study area. The construction of a weir on Barda Sagar has led to availability of freshwater for irrigation in surrounding areas. Similarly the construction of spreading channels between Medha to Kindri creek (not shown in Fig. 2.1) and Kindri to Kerly creek have enhanced the recharge of groundwater and also have made available surface water for lift irrigation by farmers for irrigating agricultural land along this coast stretch. The geology of the region mainly comprises of milliolitic limestone, Gaj formation, laterites and alluvium in the coastal plains with channel fill deposits in the low-lying Ghed area.

Coastal Ridge: The coastal ridge is considered as the deposition feature of beach sand and miliolitic limestone along the coast. The beach sand is recent deposition along the coast extending only about 50 m inland. The topography is generally undulating with ridges occurring parallel to sea coast. These ridges are exposed at a distance of upto 1-3 km inland from the coast. The height of these ridges with reference to msl varies between 4.5 m west of Porbandar near Kantela village to about 12 m east of Porbandar at Tukda village. Near the coast at higher elevations, where the ridges make stony waste lands, heights above msl vary between 11-29 m.

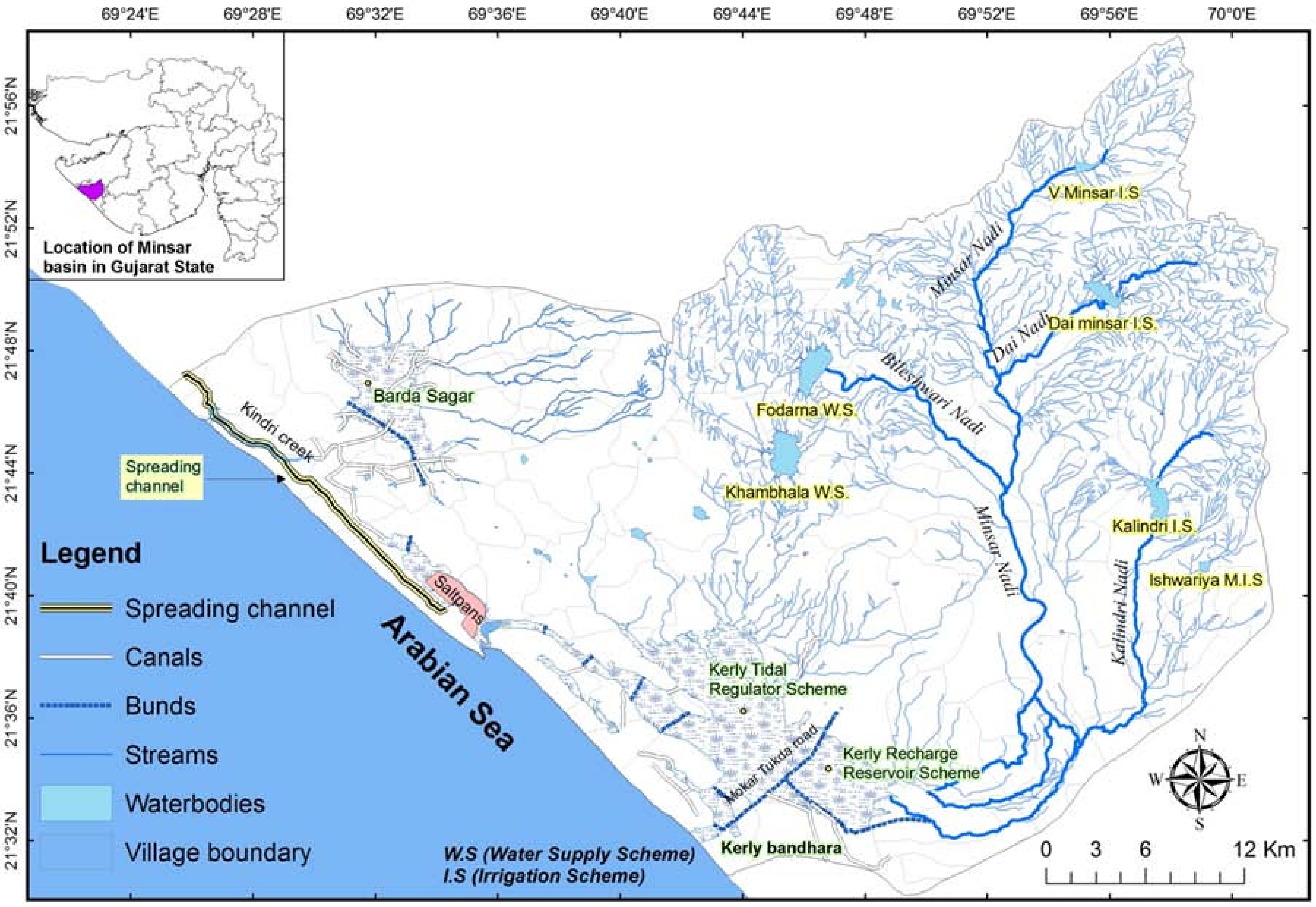


Fig. 2.5 Drainage network and water supply / irrigation schemes in Minsar river basin

2.4 LAND USE

2.4.1 Methodology adopted for interpretation of remote sensing data

Interpretation and analysis of remote sensing imagery involves the identification and/or measurement of various targets in an image in order to extract useful information about them. Targets may be environmental or artificial features which consist of points, lines, or areas. The target must be distinguishable i.e. it must contrast with other features around it in the image. Interpretation and identification of targets in remote sensing imagery may be performed using two different methods:

- Visual (manual) Interpretation
- Digital Processing and Analysis.

In Visual Interpretation, observing the differences between targets and their backgrounds involves - comparing different targets based on any, or all, of the following visual elements:

(1) tone (2) shape (3) size (4) pattern (5) texture (6) shadow, and (7) association.

Since most remote sensing data are recorded in digital format, virtually all image interpretation and analysis involves some component of digital processing. Most of the common image processing functions can be categorized as follows:

- Preprocessing i.e. formatting and correcting of data,
- Image Enhancement and Transformation i.e. digital enhancement to facilitate better visual interpretation, and/or
- Image Classification and Analysis using computer, by adopting either of the two generic approaches i.e. (a) supervised, and (b) unsupervised classification.

In the present study, a mixed approach of classification is adopted. Supervised classification followed by visual interpretation techniques are used for identification of several land-use classes. Supervised classification is based on the idea that a user can select sample pixels in an image that are representative of specific classes and then direct the image processing software to use these training sites as references for the classification of all other pixels in the image. Training sites (also known as testing sets or input classes) are selected based on the knowledge of the area. Visual interpretation techniques helped in identifying training sites for different land-use classes. For study area, training sites are identified for each landuse class in ERDAS Imagine (image processing software).

2.4.2 Analysis of remote sensing data

The satellite data was used to generate a land use map as as shown in Fig. 2.6. All the classes of land use are shown in Table 2.2. Most of the land in study area is under agriculture i.e., cropland (42%) and fallow land (13%). Hilly region of the study area is commonly known as Barda hills (wildlife sanctuary). Rocky terrain (14%) and forest (6.3%) are the two land use classes identified in this region. Near coast, large surface water bodies like Kerly creek reservoir and Barda sagar are present that together with other water bodies cover (5.8%) of the study area. Settlements in the study area include Porbandar and Ranavav towns. It covers 1.76% of the study area.

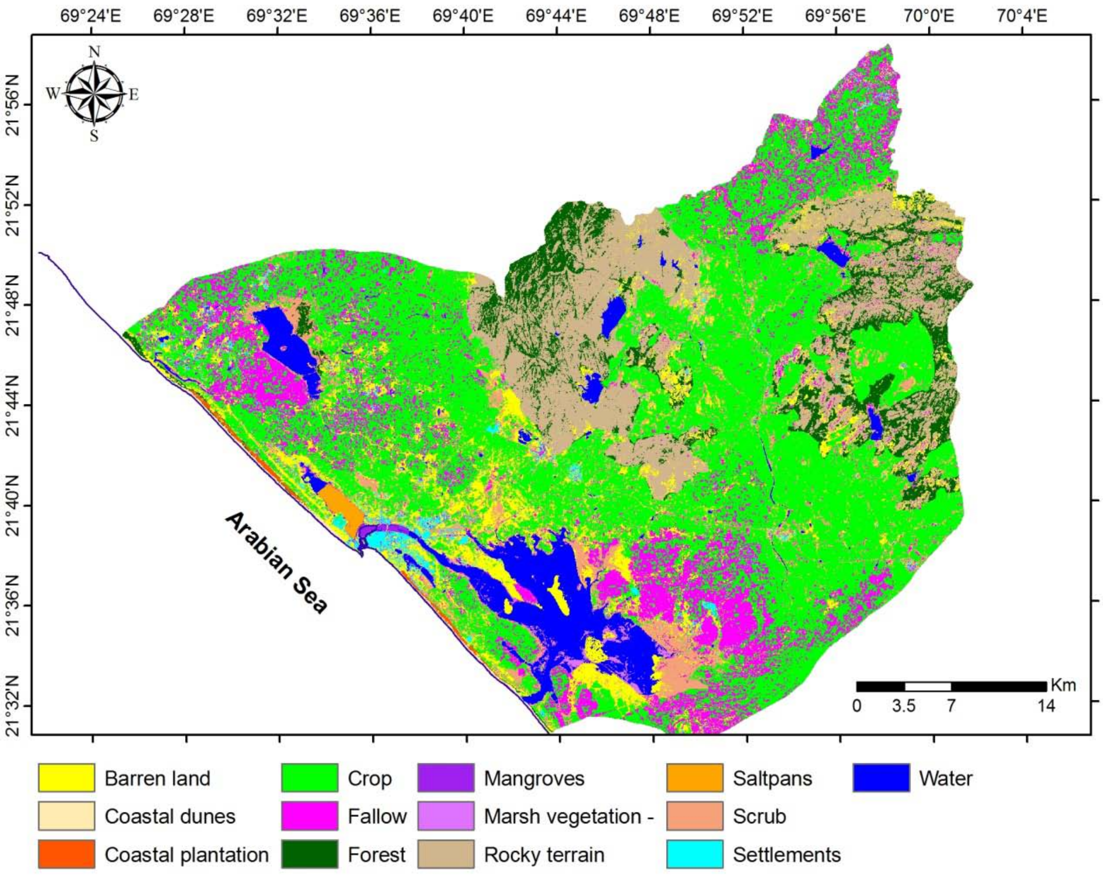


Fig. 2.6 Land use map of the study area

Table 2.2 Land use classes in the study area

Land use class	Area (km^2)	% of total geographical land
Crop land	738.2	42.15
Rocky terrain	250.1	14.28
Fallow land	230.1	13.14
Barren land	162.7	9.29
Forest	110.0	6.28
Scrub	104.5	5.97
Water	102.1	5.83
Settlements	30.8	1.76
Marsh Vegetation	6.0	0.34
Coastal Dunes	5.6	0.32
Saltpans	5.4	0.31
Coastal Plantations	4.1	0.24
Mangroves	1.8	0.11
Total	1751.3	100

Satellite data for different seasons was further utilized to generate cropped area during different seasons (Kharif, Rabi and Summer) in Minsar river basin. (Figs. 2.7-2.8)

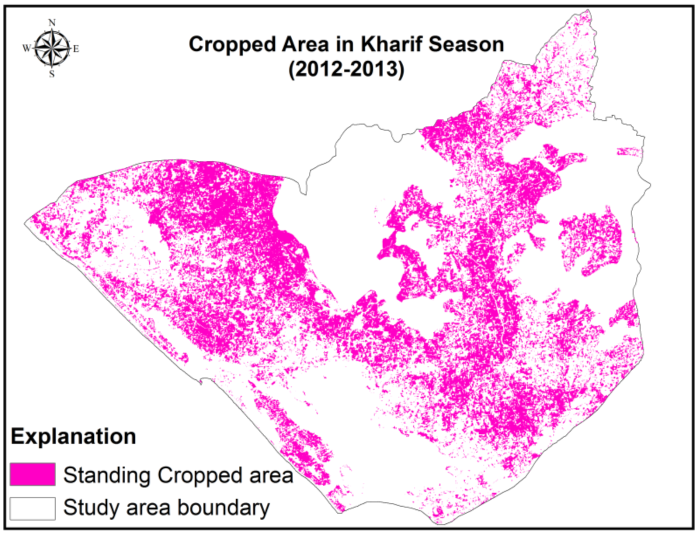


Fig. 2.7 (a) Kharif crop for hydrological year 2012-13 (low rainfall year)

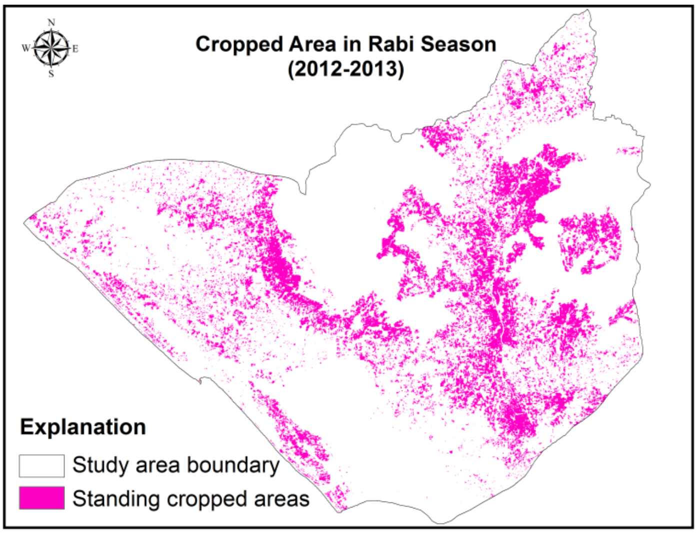


Fig. 2.7 (b) Rabi crop for hydrological year 2012-13 (low rainfall year)

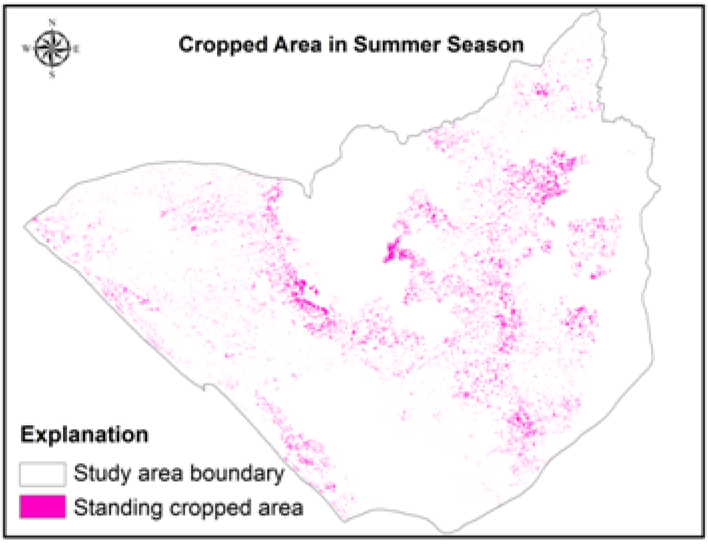


Fig. 2.7 (c) Summer crop for hydrological year 2012-13 (low rainfall year)

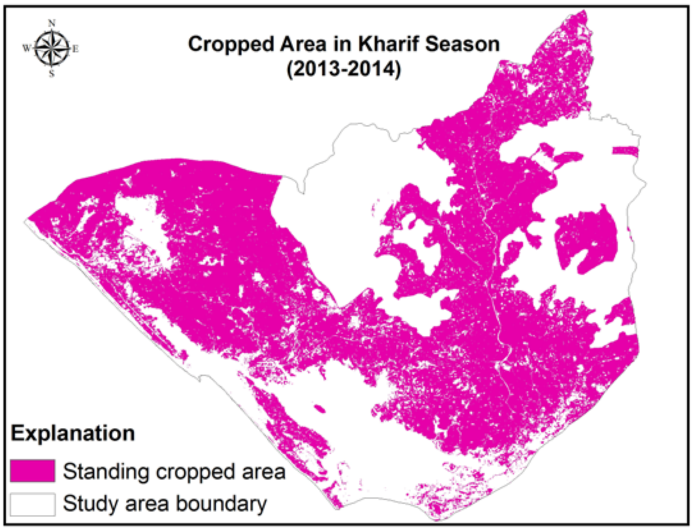


Fig. 2.8 (a) Kharif crop for hydrological year 2013-14 (above normal rainfall year)

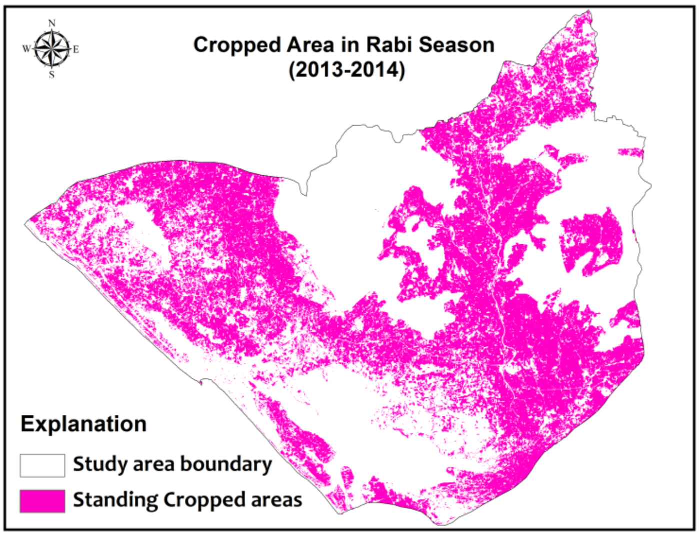


Fig. 2.8 (b) Rabi crop for hydrological year 2013-14 (above normal rainfall year)

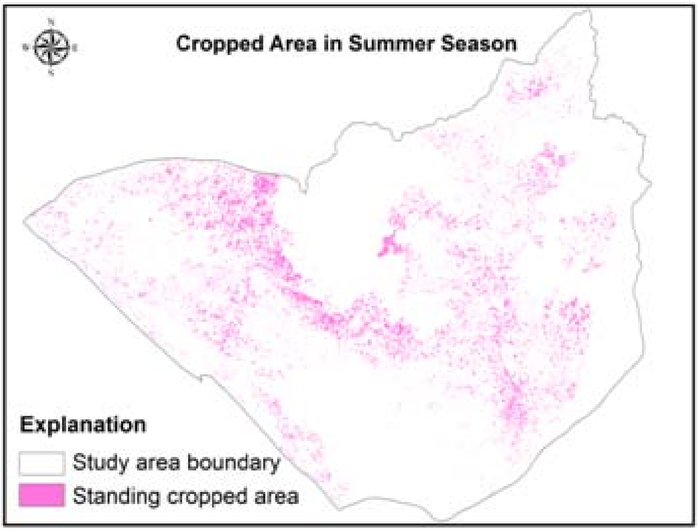


Fig. 2.8 (c) Summer crop for hydrological year 2013-14 (above normal rainfall year)

The years 2012-13 corresponds to a low rainfall year while 2013-14 corresponds to an above average rainfall year. The difference in area under cultivation during the two years is reflected by the lower cropped area for the hydrological year 2012-13 compared to 2013-14. The summer crop for 2013-14 is obtained from landsat data. The cropped area under the Kharif and Rabi seasons is shown in Fig. 2.9

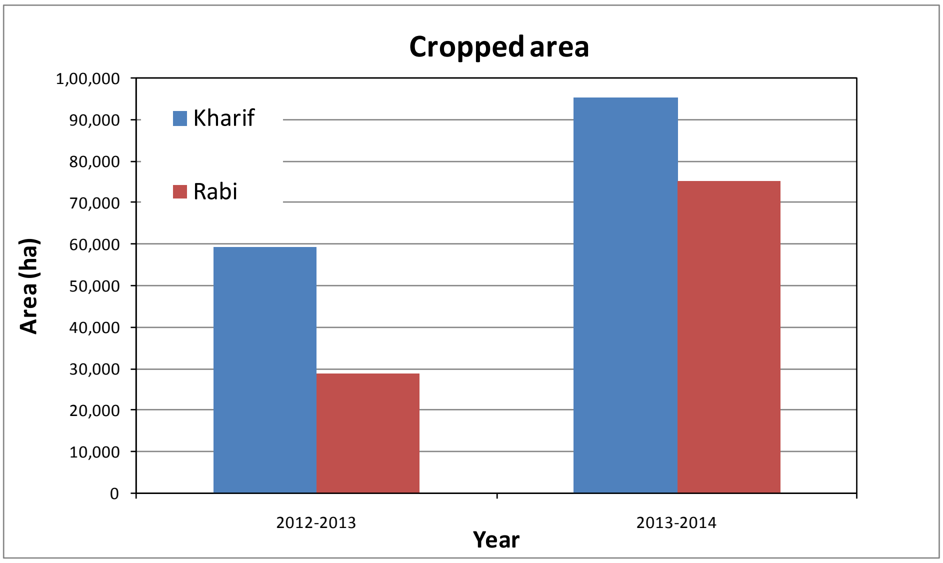


Fig. 2.9 Cropped area during the hydrological years 2012-13 and 2013-14.

2.5 DRAINAGE OF MINSAR BASIN AND SURFACE WATER SCHEMES /BODIES

Figure 2.5 shows the detailed base map of the Minsar River Basin. The Minsar River Basin was demarcated and digitized from toposheets of scale 1:50,000. Subsequently, the drainage network, coastline and existing water bodies such as creeks, reservoirs, marshy areas, percolation tanks etc., locations of tidal regulators, bandharas, embankments, checkdams etc. were digitized.

River Minsar: The river originates from the hills near village Jamvadi of Jamnagar district. It flows downhill and after covering 24 km meets the Dai river and 7.60 km from this junction meets the Bileshwari river near village Rana Khirasara. The river is ephemeral carrying water mainly during the monsoon season in months of June-October. Discharge is measured at river gauging site near village Rana Kandorna. The average discharge during July is 14.5 m^3/s, August 13.4 m^3/s, and September 22 m^3/s.

Surface water schemes: In the upper catchment of the river, six reservoirs are present which store water for drinking water supply and irrigation needs. These are, namely, Fodarna, Khambala, VMinsar, DaiMinsar, Kalindri and Ishwaria (Fig. 2.5). Out of these six schemes, two schemes viz. Fodarna and Khambala serve as water supply schemes for Porbandar city and Industries located in the region. Remaining four schemes and the two schemes in Ghed area (Kerly RR /Kerly TR and Barda Sagar) are irrigation schemes. The Barda Sagar provides benefit to the farmers of 10 villages: Rinavada, Degam, Simani, Bharvada, Kinderkheda, Modhwada, Kesahav, Palakhada, Srinagar and

Baredia. Farmers benefit by lift irrigation from radial canals emerging from the reservoir and from the reservoir itself. Similarly, Kerly RR scheme provides benefits to the farmers of 9 villages: Tukda-Gosa, Gosa, Lushala, Padardi, Earda, Bapodar, Mokar and Bokhira. Kerly TR scheme provides benefits to the farmers of 9 villages: Chaya, Ranavav, Ratanpur, Odedar, Tukda-Gosa, Virpur, Mokar, Keshod and Bokhira.

Spreading channel: These channels are constructed parallel to the coastline. Spreading channel in Minsar basin emerges from Medha creek in Tukda Miyani village and extends up to Kindri creek in Ratadi village. The channel further extends from Kindri creek to Kerly creek in village Bokhira. Its full capacity is 9.83 Mcft. Total length of spreading channel is 28.68 km. Width of channel is 6.0 m. Number of villages benefitted from spreading channel are 11 i.e., Bhavpara, Tukda Miyani, Visawada, Ratadi, Baradia, Kantela, Shrinagar, Kuchhadi, Zavar, Bokhira and Porbandar city.

Saltpans: Salt evaporation ponds, or saltpans, are shallow artificial ponds designed to extract salts from sea water or other brines. In Porbandar, near Zavar village, saltpans are present. These ponds also provide a productive resting and feeding ground for many species of water birds. The ponds are commonly separated by levees.

Availability of surface water depends upon rainfall. During normal rainfall years, fresh water get stored in dams, irrigation schemes and other water harvesting structures. It remains available for sufficient amount of time in a year so that irrigation and domestic requirements are met. During monsoon period (June to September) reservoirs are filled with fresh water to their full capacity. Figure 2.10(a) shows the water spread area of all the surface water bodies in the study area. This includes irrigation schemes, water supply schemes and tidal regulator schemes.

Water spread area of surface water bodies is related to its capacity and it changes with time in a year. During monsoon months, the reservoirs fill up so that the water spread area expands and reaches to its full extent by month of July-August. During post-monsoon, the impounded water is used for irrigation and other purposes. Some of the amount of water is also lost to atmosphere by evaporation. As a result, water spread area starts shrinking. This often starts from month of November. Estimation of this variation in water spread area can be made by processing satellite data. For monsoon year 2013 (in which rainfall is more than average) the satellite reveals that large surface water bodies like Barda Sagar and Kerly tidal regulator in the study area reach to their maximum areal extent by month of September i.e., 21 km^2 and 85 km^2, respectively. This is illustrated in Figs. 2.10 (a)-(c), in which other surface water schemes are also shown. The areal extent of Barda and Kerly shrinks to 15 km^2 and 70 km^2, respectively, by the end of February. Further shrinkage to a dry state occurs in month of April-May. These figures are subject to the rainfall received during a year. In case of a low rainfall like 2013, water appears in small patches. Large surface water bodies like Kerly tidal regulator scheme where water remains available up till the month of March in a normal rainfall year, go dry before January. Figures 2.11 (a)-(c) illustrate the water spread area in surface water bodies in a dry year in the Minsar basin.

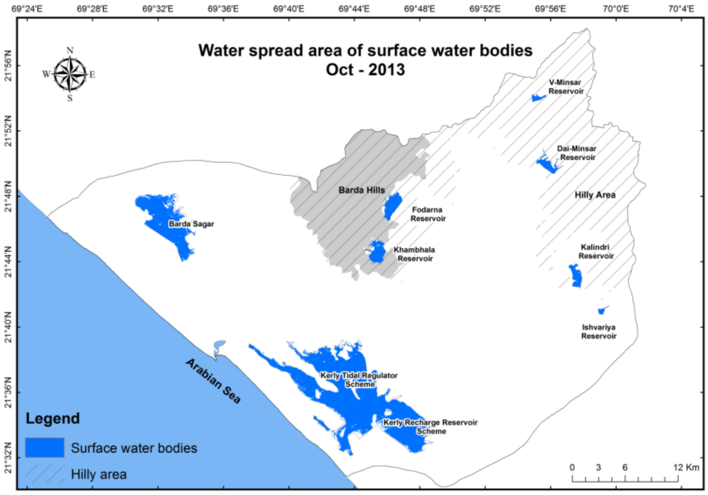


Fig. 2.10 (a) Water spread area of surface water bodies in Oct. 2013

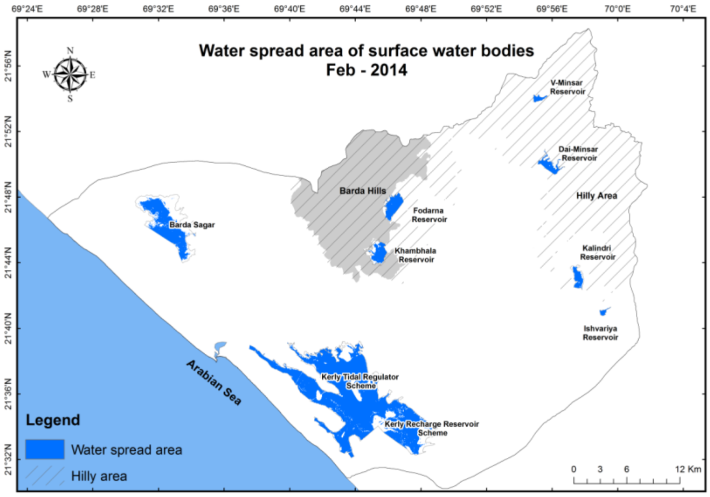


Fig. 2.10 (b) Water spread area of surface water bodies in Feb. 2014

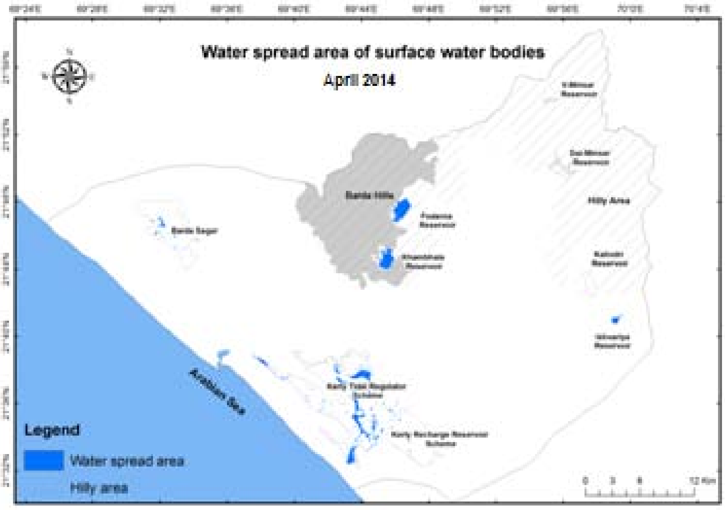


Fig. 2.10 (c) Water spread area of surface water bodies in April 2014

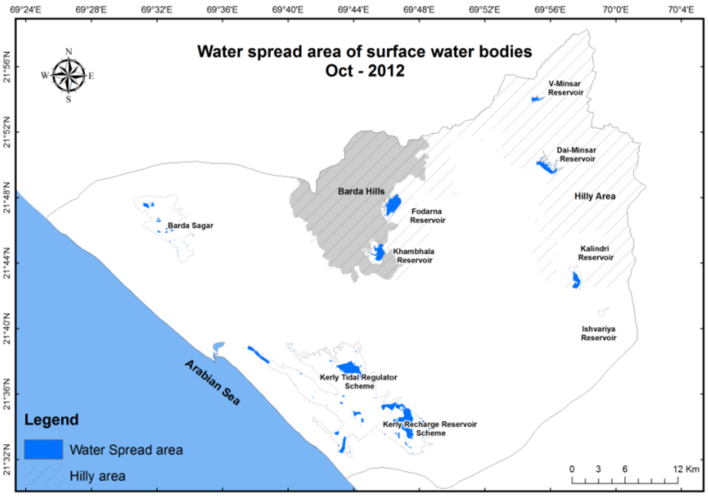


Fig. 2.11 (a) Water spread area of surface water bodies in Oct. 2012
(low rainfall year)

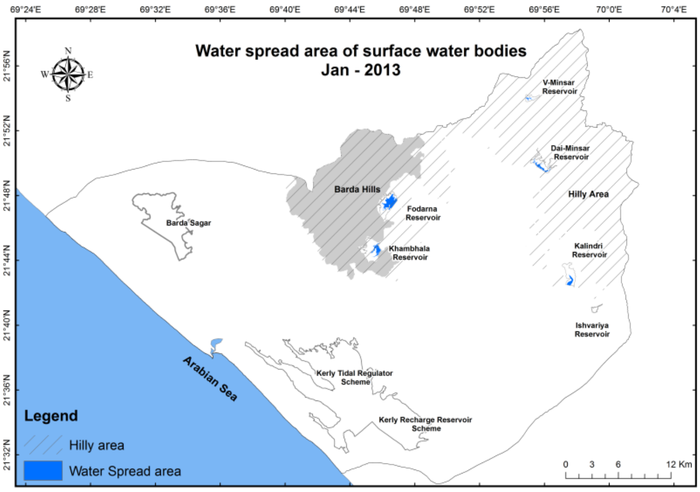


Fig. 2.11 (b) Water spread area of surface water bodies in Jan. 2013
(low rainfall year)

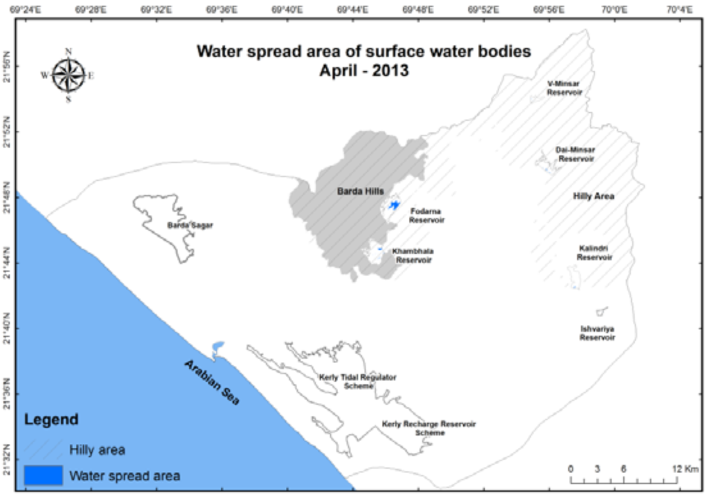


Fig. 2.11 (c) Water spread area of surface water bodies in April 2013
(low rainfall year)

Besides the reduction in water spread, the electrical conductivity (EC) of reservoir schemes in the coastal region increases, which implies that the water salinity of these schemes increases as summer approaches. This increase in EC with reduction in water spread area is shown in Fig. 2.12 for Kerly TR scheme. This is further illustrated in Figs. 2.13(a)-(b).

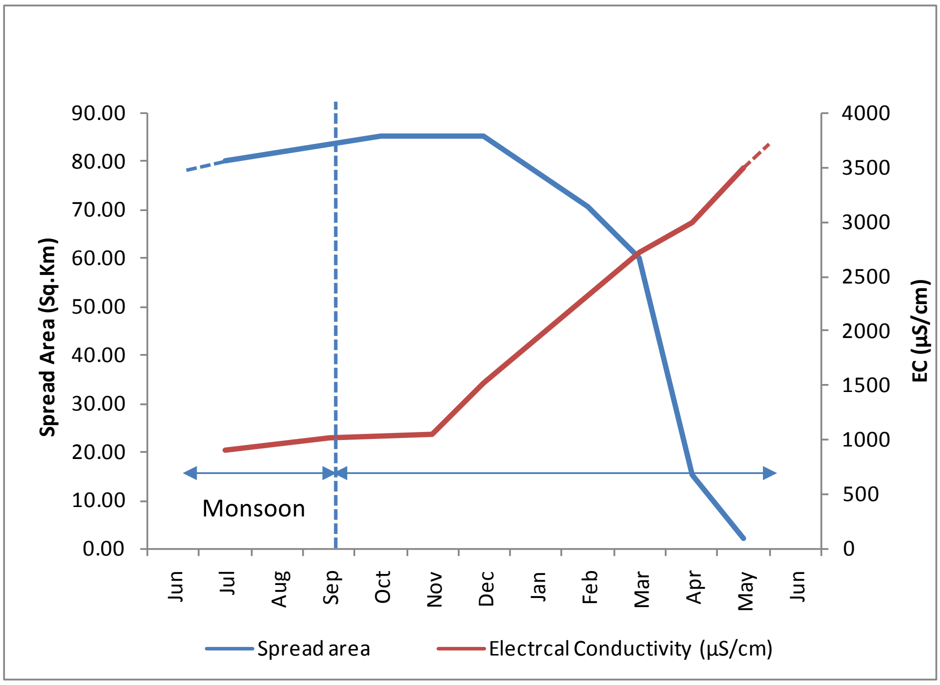


Fig. 2.12 Variation in water spread area accompanied by change in EC in Kerly tidal regulator scheme.

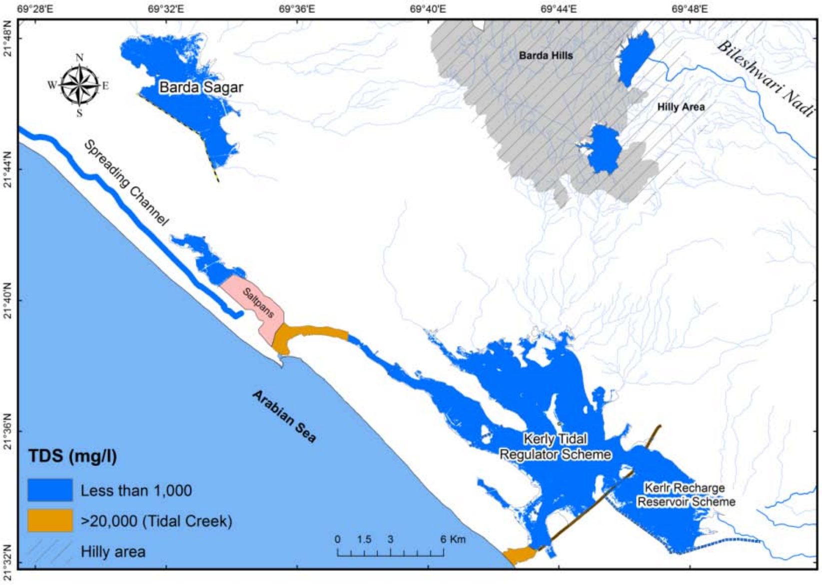


Fig. 2.13(a) TDS of surface water bodies in the coastal region in August for a normal monsoon year.

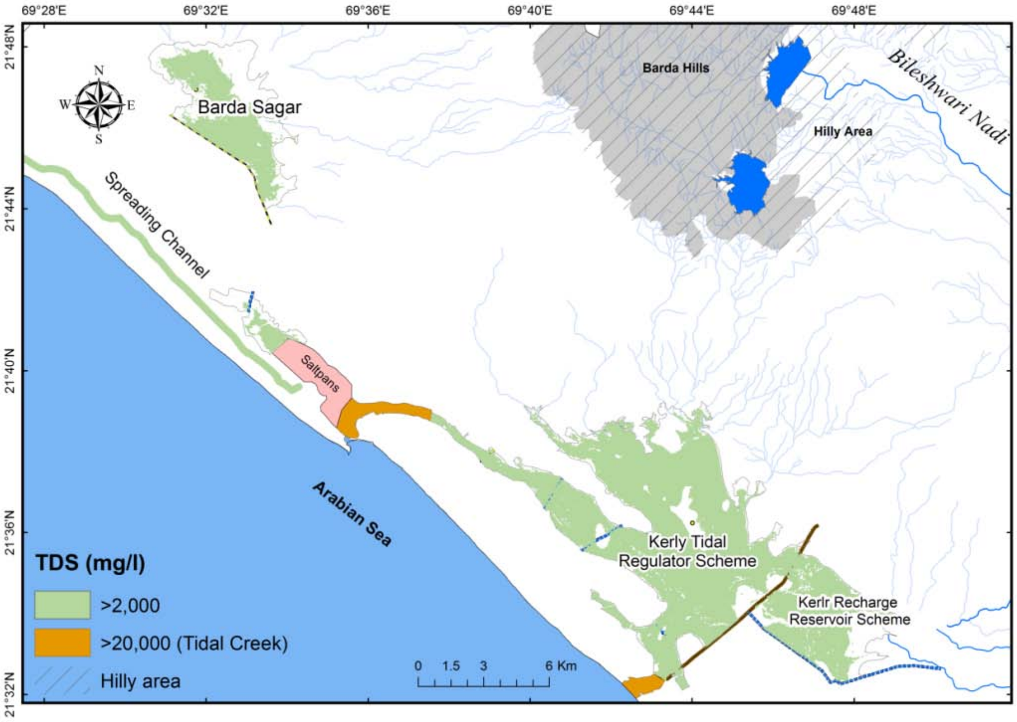


Fig. 2.13(b) TDS of surface water bodies in the coastal region in February for a normal monsoon year

The water bodies shown with TDS > 20000 mg/l, in the Figs. 2.13(a)-(b), are surface water bodies (Kerly creek) that are in direct contact with the sea, and therefore, register a very high salinity.

The surface water irrigation schemes viz., Kerly RR/ Kerly TR and Barda Sagar, developed in the low-lying Ghed area as a byproduct of the conservation measures, have facilitated ready access of fresh surface water for irrigation to the farmers in the Ghed area (Fig. 2.14).

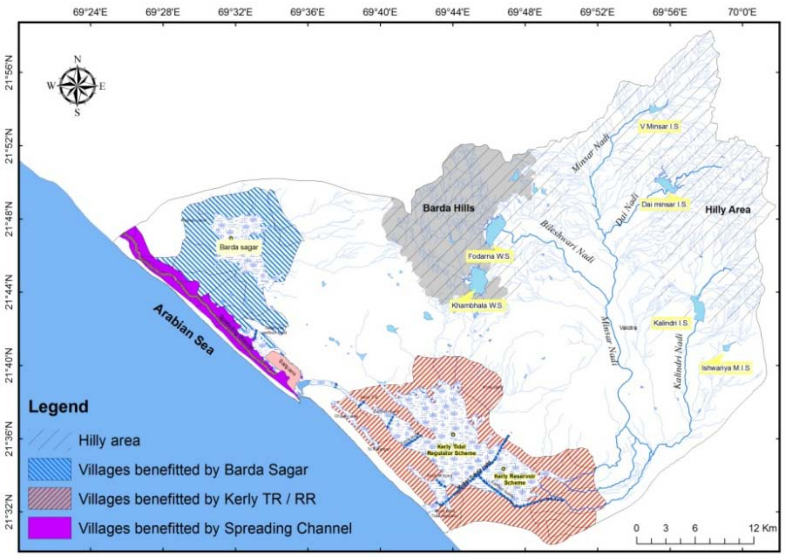


Fig. 2.14 Approx. area of benefitted villages by reservoir schemes and spreading channel

2.6 AN OVERVIEW OF GROUNDWATER SYSTEM

2.6.1 Hydrogeology and Groundwater Salinity

The geological formations range from Deccan trap lava flows of Paleocene to Cretaceous age to recent alluvial and windblown deposits. The geological formations are broadly igneous lava flows, marine deposits and alluvial deposits.

The area is covered by milliolitic limestone of Pleistocene age all along the coastal line and alluvium of recent age (locally the Ghed area). Gaj limestone and clay underlying these formations are not exposed anywhere except around Pipaliya village where these are directly overlying Deccan basalts. Exposures of Gaj formations are also seen between Porbandar and Kindri Creek along the coast. The different formations occurring in the area are discussed below (refer Fig. 2.15).

Deccan trap: Deccan traps are the oldest rocks in the area forming the main land of Saurashtra. These are exposed at a distance of 5-15 km inland from the coastline. Deccan trap in the area is represented by basalt and its type based equivalent Dolerite. These are hard Melanocratic igneous rocks with abundance of Mafic minerals and the Plagioclase Feldspar. Basalts are generally found in three forms:

- Weathered basalt
- Amygdaloidal and vesicular basalt
- Compact and massive basalt

Weathered basalt, which is generally light brown to light grey in color, is soft and friable with thickness of 5-15m followed by hard and massive trap. Weathered basalt is also found between two successive basalt flows. Usually, uppermost part of every basaltic flow is vesicular and amygdaloidal and has secondary minerals filled in the vesicles. The amygdaloidal basalts are widely spread in the region and vary in color from black and grey to reddish. The compact and massive basalts are generally greenish grey to dark grey in color and form the basement rocks in the area.

Laterite and Bauxite: The laterites are usually stratified as well as residual and found in the form of inliers of large dimensions. They consist of variegated red and white to pale colored clays representing decomposed basalt and at places they constitute Bauxite deposits. Their red color is due to high iron content. Typical laterite exposures are found around Palakhada, Tukda, and between Ratadi and Keshav.

Gaj Beds: The Gaj beds overlie the traps as well as laterites all along the coast. The Gaj formation comprises of yellow colored impure fossiliferous limestone, conglomerates and yellowish or greyish sticky clays. The alternate bands of yellow clays and limestone are dominating units.

Dwarka Beds: This formation consists of banded limestone and clay beds, partly gypsiferous with iron stains causing banding and show low angle dips towards the sea. The beds are underlain by Gaj formation and vary in thickness from 2-5 m.

Milliolitic Limestone: The milliolitic limestone comprises of calcareous, concretionary and shelly limestone varying in color from pink to white and pale. These limestones are exposed all along the coast near Porbandar and Kindri creek. The limestones are exposed in the form of stretched ridges and mounds and extend inland upto 2-10 km. Limestone exposures near Ratanpur and Odedar indicate a thickness of about 8-15 m. Limestone quarrying is carried out in some of the coastal villages. Milliolitic limestone with upper hard and compact layers are exposed near villages Tukada, Ratanpur and Gosa.

Alluvium: Broadly alluvial deposits in the region include soil, coastal sand and sand dunes, marshy lands and mud, gravel and kankar beds. The alluvium around Porbandar is locally known as ‘Ghed’. The major portion of the area is covered by blackish brown clayey soil and the thickness of the soil cover varies between 2-7 m. The mud is restricted to depressions and creeks where the water remains stagnant. Such areas exist around Odedar, Chhaya, Porbandar, and Keshav. The coastal sands and unconsolidated sandstones are restricted to the coastal strip.

The study of exploratory bore hole data indicated that Gaj limestones are underlain by laterite and basaltic formations.

In a normal monsoon year, the depth to water level has been recorded as 1.25 m to 34 m below ground level in the wells having a depth range of 4.8 to 40 m. The main geological areas of alluvium, Gaj beds, laterite and part of limestone formation mostly fall under the saline zone covering coastal Porbandar taluka, south and south eastern part of Kutiyana taluka and south eastern part of Ranavav taluka; whereas the inland areas comprising basalt and parts of limestone fall under freshwater zones. In coastal tracts, groundwater salinity varies 1000 mg/l to more than 4000 mg/l, in certain pockets, at shallow depths. The salinity increases to more than 7000 mg/l at deeper depths.

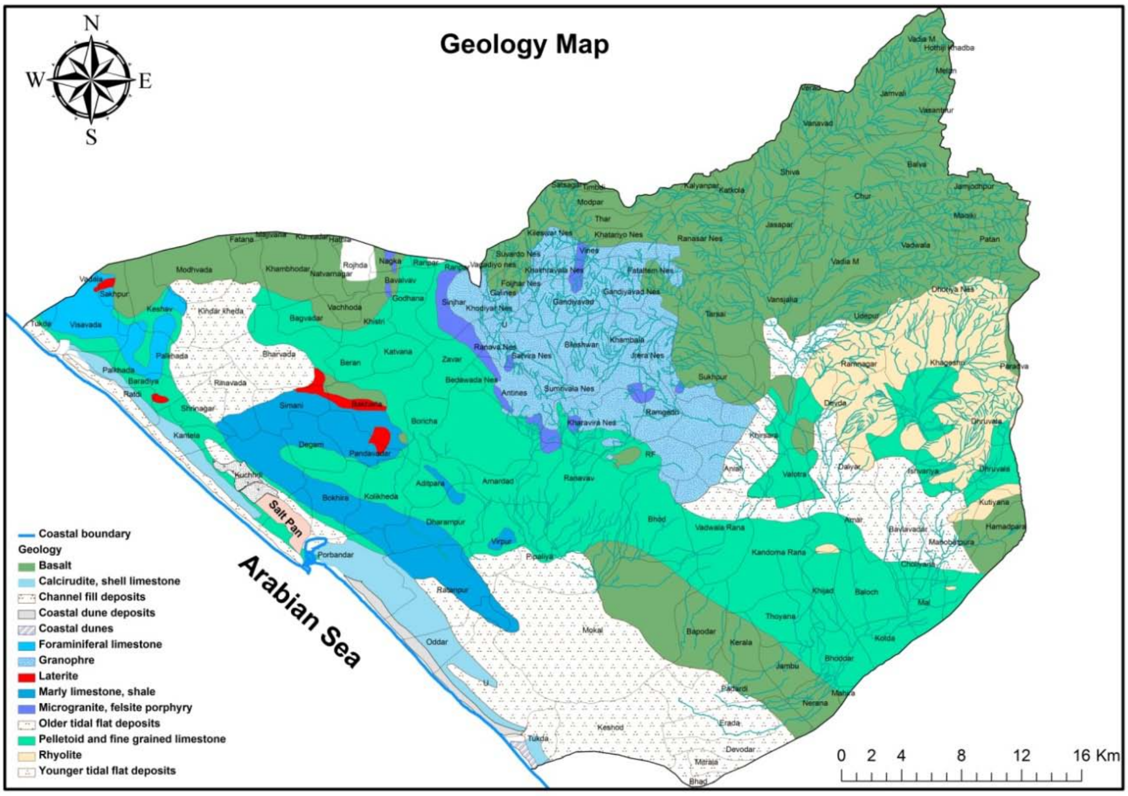


Fig.2.15 Map of surficial geology of Minsar River Basin (source: modified from GSI map)

2.6.2 Aquifer Parameters

GWRDC conducted pump tests in the area to compute the aquifer parameters. The pump test values arrived at by GWRDC are shown in the Table 2.3.

Table 2.3 Pump tests by GWRDC in Minsar Basin

S. No.	Village	Aquifer	Transmissivity (m^2/d)	Specific capacity ($m^3/min/m$)
1	Bokhira	Gaj limestone	181.44	0.1
2	Simani	Gaj limestone	77.47	0.04
3	Wadwala	Gaj limestone	78.64	0.104
4	Kinderkheda	Trap	90.7	0.277
5	Keshav	Trap	75.46	0.6
6	Tukda	Laterite	149.68	0.033
7	Palakheda	Laterite	58.16	0.041
8	Gosa	Limestone	23.2	0.112
9	Tukda (Gosa)	Limestone	149	0.182
10	Odedar, Site-1	Limestone	106	0.15
11	Odedar Site-2	Limestone	164	0.139
12	Khapat -IN4	Limestone	82.9	0.045
13	Khapat -IN7	Limestone	163	0.5
14	Kuchhadi -3N3	Limestone	166	0.142
15	Kuchhadi -3N5	Alluvial	51.2	0.242
16	Kuchhadi	Limestone	35.7	0.086
17	Kantela	Limestone	85.2	0.25
18	Rinawada	Gaj limestone	17.045	0.284
19	Ratadi	Limestone	223	0.0244
20	Baredia	Trap	113.96	0.965
21	Gorsar	Limestone	339.75	1.12

2.6.3 Groundwater Development

Major source of water for irrigation in the study area is groundwater. Near the coast, groundwater is abstracted from shallow large diameter dug wells. Discharge from the dug well ranges between 100 to 350 lpm. Surface water from reservoir schemes is utilized in cultivated lands located in nearby areas. In coastal belt the major reservoir schemes are Barda Sagar, Kerly TR and Kerly RR. However, despite the availability of surface water, farmers in these areas are dependent, to a certain extent, on dugwells and borewells for providing timely irrigation to the sown crops. Maximum wells are energized by electric supply.

Figure 2.16 shows a village-wise comparison of total number of wells with electric connection in the years 2001-02, 2005-06, 2008-09 and 2011-2012 (data supplied by Gujarat Electricity Board). It is to be noted here that in villages (e.g. Mokar, Padardi, Bhod, etc.) near the Kerly creek, groundwater is quite saline, and therefore, not many wells with electric connections are present here.

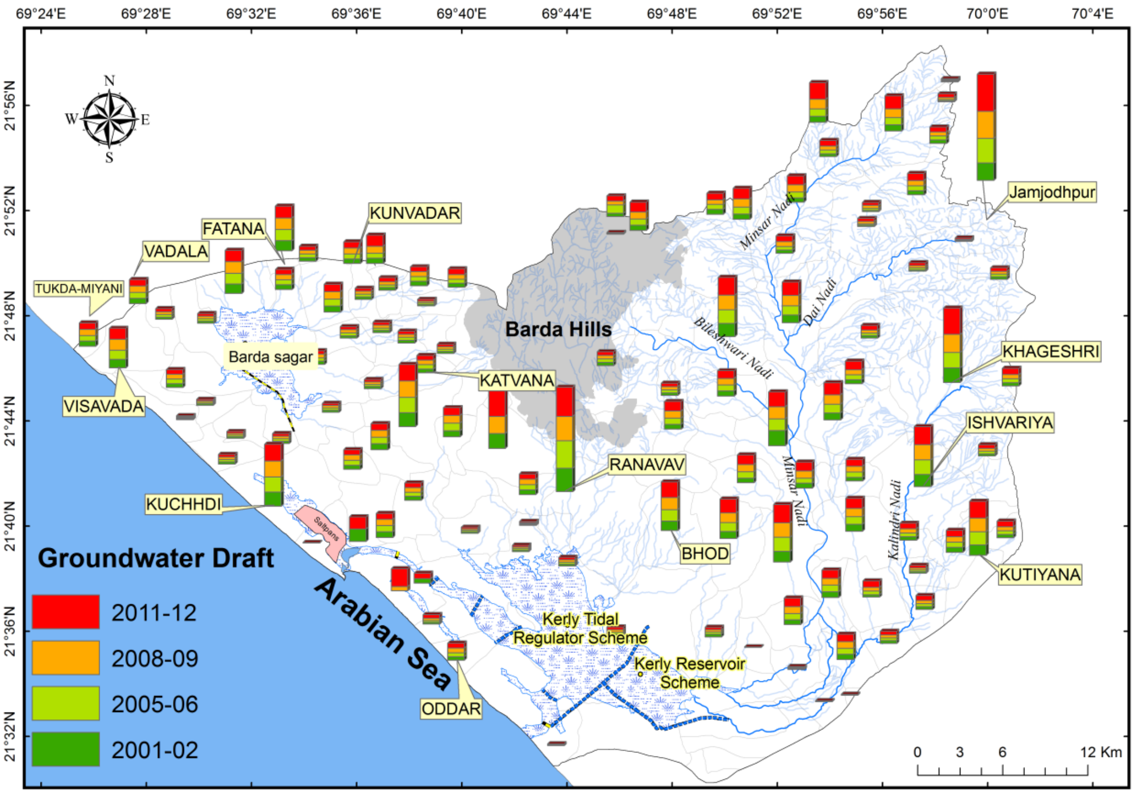


Fig. 2.16 Village-wise wells with electric connection in years 2001-02, 2005-06, 2008-09 and 2011-12

2.7 DEVELOPMENT OF DATABASE

2.7.1 Data Collection Tools and Methods

A massive data collection program was initiated by preparing a list of required data and related maps and reports to be collected from various departments. Besides obtaining SOI toposheets, satellite data IRS P6 (LISS III/ LISS IV) was procured from National Remote Sensing Centre (NRSC), Hyderabad, for the years 2010-2013 corresponding to the months January/February, March/April and October/November. Landsat imageries available on the net were also utilized.

Long term meteorological data comprising daily rainfall, maximum and minimum temperature, relative humidity, wind speed and duration of sunshine hours were obtained from India Meteorology Department (IMD), Pune, for the years 1969-2005, and also from the State Water Data Centre (SWDC), Gandhinagar for the years 2006-2013.

Data pertaining to irrigation schemes and land reclamation schemes, spreading channel, check dams, land use etc. were collected from various State Departments such as GWRDC, SIPC (Salinity Ingress Prevention Circle, Rajkot & Porbandar), CGWB

(Central Ground Water Board, Ahmedabad), GSI (Geological survey of India, Gandhinagar), CDO (Central Design Organisation, Gandinagar) etc.

Data of lithologs of dug wells, bore wells and piezometers were collected from GWRDC and CGWB. Field experiments for estimation of parameters such as infiltration rates using double ring infiltrometer, saturated hydraulic conductivity using Guelph permeameter, pump tests etc. were performed in the field keeping in view the varying geological formations.

Soil samples (both undisturbed and disturbed) and water samples of groundwater and surface water bodies for chemical and isotope analyses in the laboratory were also collected.

Details of chemical and isotope analysis are discussed in Chapter 3, while the development of fence diagram based on available lithologs is provided in Chapter 4.

2.7.2 Frequency of Data Collection

An intensive monitoring program of groundwater level and water quality was launched in Minsar River Basin (Fig. 2.17). Initially 40 wells were selected for monitoring on quarterly basis and 26 wells were demarcated for monthly monitoring. Subsequently, the observation network was modified to monitor a total of 150 locations every third month that included collection of water samples from open wells, piezometers and surface water bodies such as spreading channel, creeks, reservoirs and Arabian Sea. Rainwater samples were also collected.

Sites for installation of 16 piezometers were selected (Fig. 2.18) at strategic locations to monitor the groundwater level and water quality. The installation of these 16 piezometers by GWRDC was completed in February 2011. These piezometers which were part of the observation network were regularly monitored.

2.8 FIELD SURVEYS AND EXPERIMENTS

2.8.1 Soil survey and analysis

Disturbed and undisturbed soil samples were collected from various locations in the study area (refer Fig. 2.19). These soil samples were analyzed at NIH Soil and Water Laboratory through pressure plate apparatus. The observed retention data (moisture contents corresponding to varying pressure) for a few samples is given in Table 2.4. Based-upon the retention data, the soil moisture characteristic curves for a few soil samples are presented in Fig. 2.20.

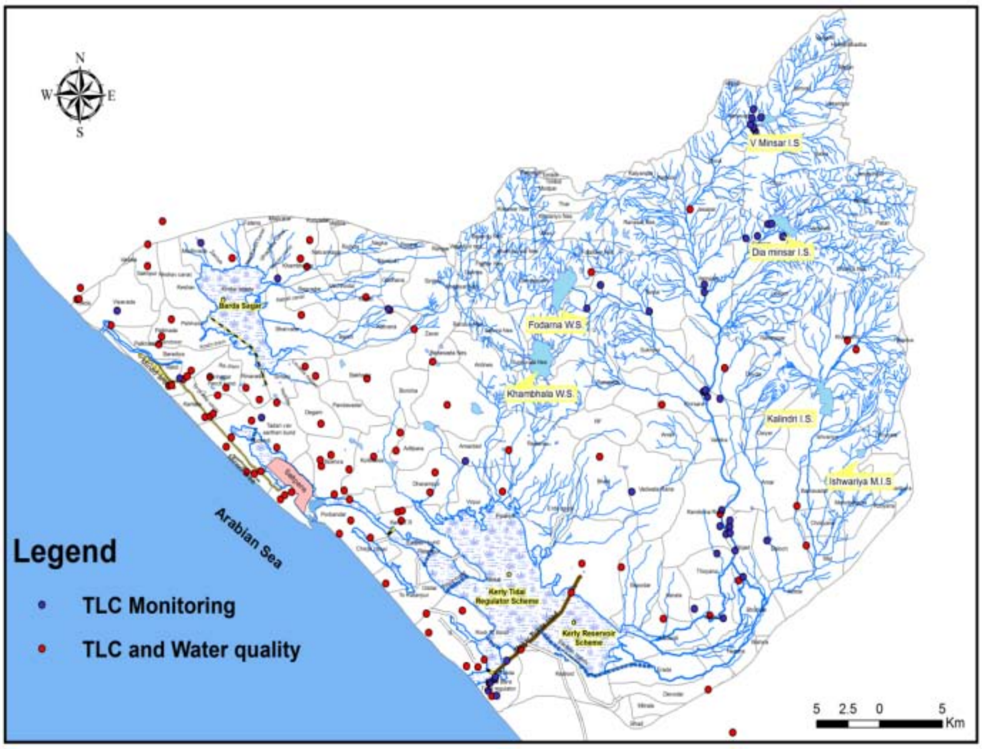


Fig. 2.17 Observation network in Minsar River Basin (the TLC meter was utilized to monitor both groundwater levels and electrical conductivity of water in surface water bodies and wells. Water samples for chemical analysis were collected from selected locations).

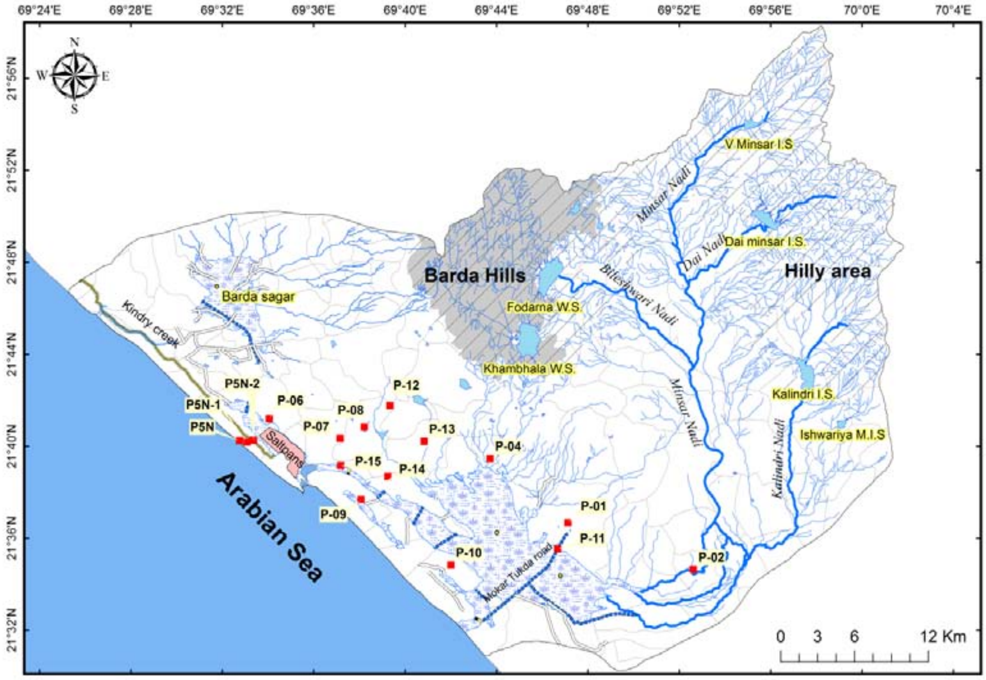


Fig. 2.18 Location map of new piezometers under the study

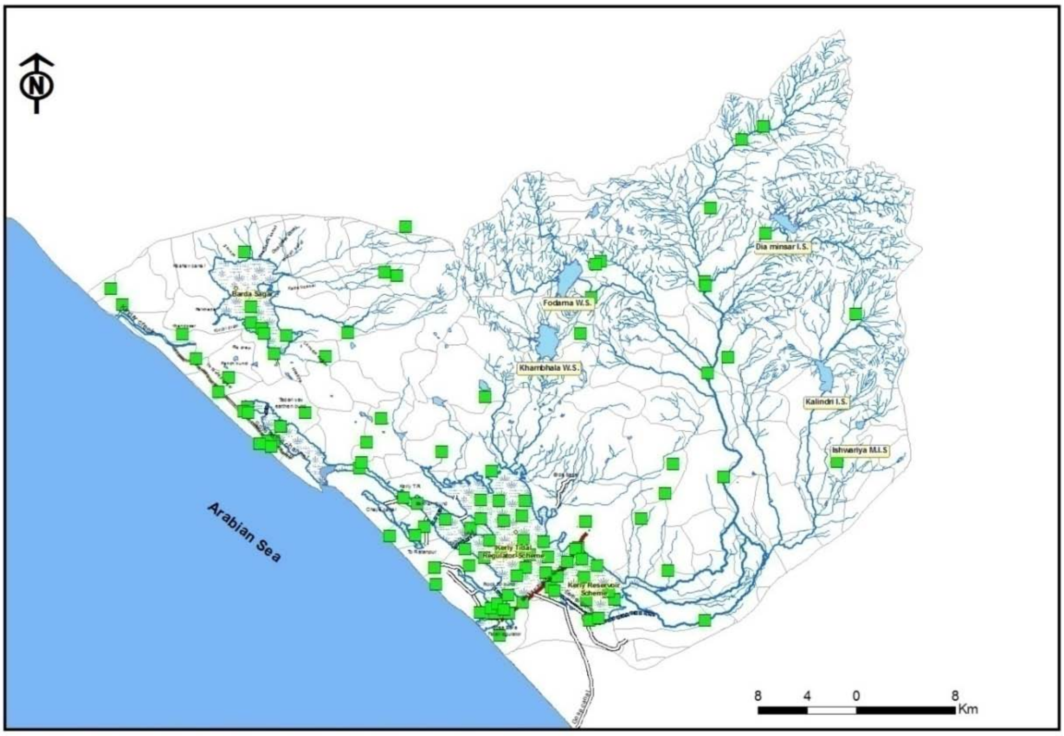


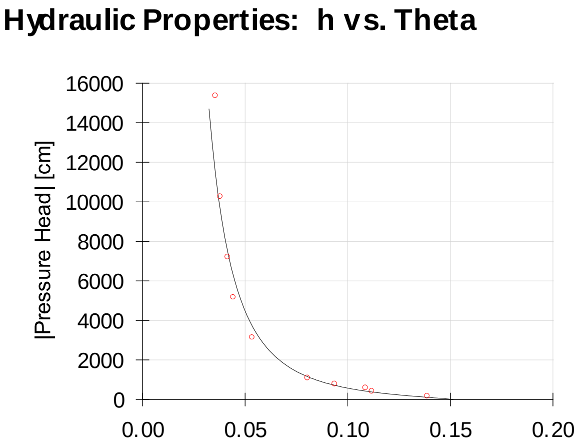
Fig. 2.19 Locations of soil sampling sites in study area

Table 2.4 Observed retention data (moisture contents corresponding to varying pressure)

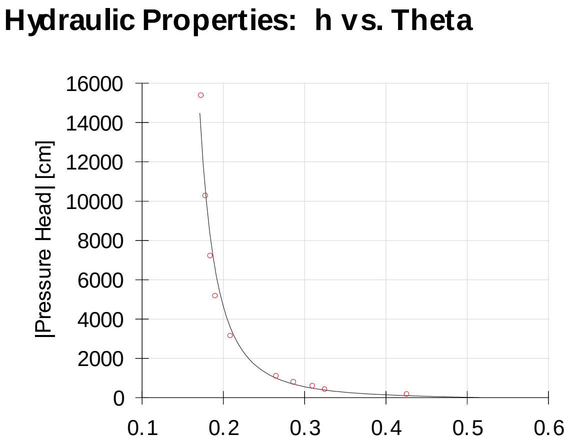
BAR→	**0.1**	**0.33*F.C.↓**	**0.50**	**0.70**	**1.00**	**3.00**	**5.00**	**7.00**	**10.00**	**15.00*W.P.↓**
H(CM)→	**101.98**	**336.53**	**509.9**	**713.86**	**1019.8**	**3059.4**	**5099**	**7138.6**	**10198**	**15297**
GJS-1Kuchhadi 0-20 cm	13.95	11.25	10.94	9.43	8.12	5.41	4.49	4.22	3.85	3.62
GJS-2A Gaytrimandir 10-20 cm	42.77	32.7	31.16	28.84	26.67	21.06	19.18	18.55	17.98	17.46
GJS-2B Gaytrimandir 40-50 cm	40.93	31.96	30.95	28.32	26.48	21.41	19.15	18.11	16.96	14.22
GJS-3A Kuchhadi 15-25 cm	31.05	25.62	22.66	21.95	20.88	17.07	15.52	15.11	13.88	13.82
GJS-3B Kuchhadi 25-35 cm	33.4	27.92	26.46	24.35	24.28	19.95	19.41	18.6	17.43	16.79
GJS-4 Kolikheda 5-15 cm	31.08	26.05	23.85	22.19	21.24	18.02	15.87	15.64	15.54	14.48
GJS-5 Dharampur 5-15 cm	35.29	27.42	24.85	22.28	20.71	17.16	15.89	15.15	14.62	13.39
GJS-6 Bileshwar 5-25 cm	23.25	19.84	15.29	14.71	13.63	11.95	11.12	10.95	10.2	9.84
GJS-7 Jasapar 5-25 cm	27.71	23.56	21.1	18.89	17.92	14.04	12.93	12.02	11.34	10.77
GJS-8A Wadwala 25-35 cm	49.98	39.2	35.75	32.95	30.28	23.13	20.06	17.98	17.17	16.12
GJS-8B Wadwala 40-50 cm	45.92	35.14	33.6	30.99	29.69	22.11	21.28	20.45	19.95	16.39
GJS-9 Pipaliya 5-15 cm	29.51	23.91	21.91	19.51	18.78	13.95	12.6	11.9	11.27	10.66
GJS-10 Khageshri 10-25 cm	32.39	23.66	21.76	21.68	19.47	17.9	15.65	15.46	13.95	12.55
GJS-11 Erda 10-25 cm	47.51	36.45	33.16	32.2	30.61	27.14	24.63	23.99	22.68	21.47
GJS-12 Odedar 10-20 cm	35.54	25.01	21.94	21.92	20.5	16.14	14.26	13.49	12.07	10.86

***Available Moisture=F.C.-W.P.**

1. **GJS-1 Kuchhadi 0-20 cm**



2. **GJS-2A Gayatri Mandir 10-20 cm**



3. **GJS-2B Gaytrimandir 40-50 cm**

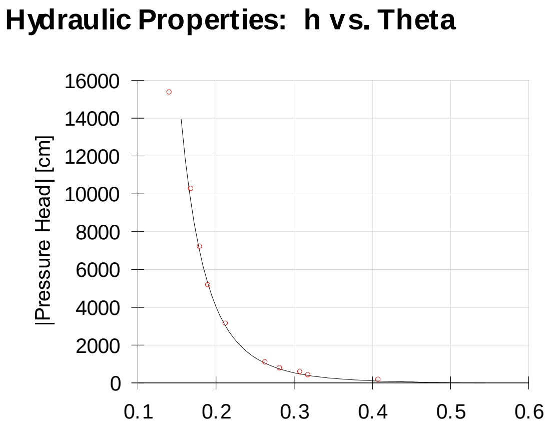


Fig. 2.20 Soil moisture characteristic curves

2.8.1.1 Soil Moisture Characteristics

To model the retention and movement of water and chemicals in the unsaturated zone, it is necessary to know the relationships between soil water pressure, water content and hydraulic conductivity. It is often convenient to represent these functions by means of relatively simple parametric expressions. The problem of characterizing the soil hydraulic properties then reduces to estimating parameters of the appropriate constitutive model.

The measurements of $\theta(h)$ from soil cores (obtained through pressure plate apparatus) can be fitted to the desired soil water retention model. Once the retention function is estimated, the hydraulic conductivity relation, K(h), can be evaluated if the saturated hydraulic conductivity, K_s, is known. In the present study, parameters of hydraulic conductivity function were derived through the van Genuchten retention parameters. For the van Genuchten model, the water retention function is given by

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) = [\,1 + (\alpha\,|h|\,)^n\,]^{-m} \qquad \text{for } h < 0$$
$$= 1 \qquad \text{for } h \geq 0 \qquad (2.1)$$

and the hydraulic conductivity function is described by

$$K = K_s\, S_e^{1/2}\, [\,1 - (1 - S_e^{1/m}\,)^m\,]^2 \qquad (2.2)$$

where, α and n are van Genuchten model parameters, $m = 1 - 1/n$.

The parameters of soil moisture retention function and hydraulic conductivity function were obtained through non-linear regression analysis (using RETC software). Table 2.5 presents the parameters of van Genuchten model for all soil samples. From the table it can be concluded that soil moisture characteristics vary widely within the study area.

Table 2.5 Parameters of van Genuchten model for soil samples

Soil Sample	α	n
GJS-1Kuchhadi 0-20 cm	.00450	1.36725
GJS-2A Gaytrimandir 10-20 cm	.01330	1.38405
GJS-2B Gaytrimandir 40-50 cm	.03409	1.20319
GJS-3A Kuchhadi 15-25 cm	.01457	1.31897
GJS-3B Kuchhadi 25-35 cm	.04335	1.22676
GJS-4 Kolikheda 5-15 cm	.00786	1.41102
GJS-5 Dharampur 5-15 cm	.00982	1.48845
GJS-6 Bileshwar 5-25 cm	.00354	2.14962
GJS-7 Jasapar 5-25 cm	.00456	1.51441
GJS-8A Wadwala 25-35 cm	.01151	1.30414
GJS-8B Wadwala 40-50 cm	.16255	1.22435
GJS-9 Pipaliya 5-15 cm	.00599	1.44153
GJS-10 Khageshri 10-25 cm	.50530	1.34604
GJS-11 Erda 10-25 cm	.31056	1.36143
GJS-12 Odedar 10-20 cm	.31197	1.32486

2.8.1.2 Soil Data Analysis

In total, 125 disturbed soil samples from 88 locations were collected. Soil texture classes identified by analysing disturbed soil samples show that most of the soil type in the area is of loam texture (51%) followed by silt loam (27%), silty clay loam (9.1%) Fig. 2.21 shows the spatial variation of soil texture classes in the study area.

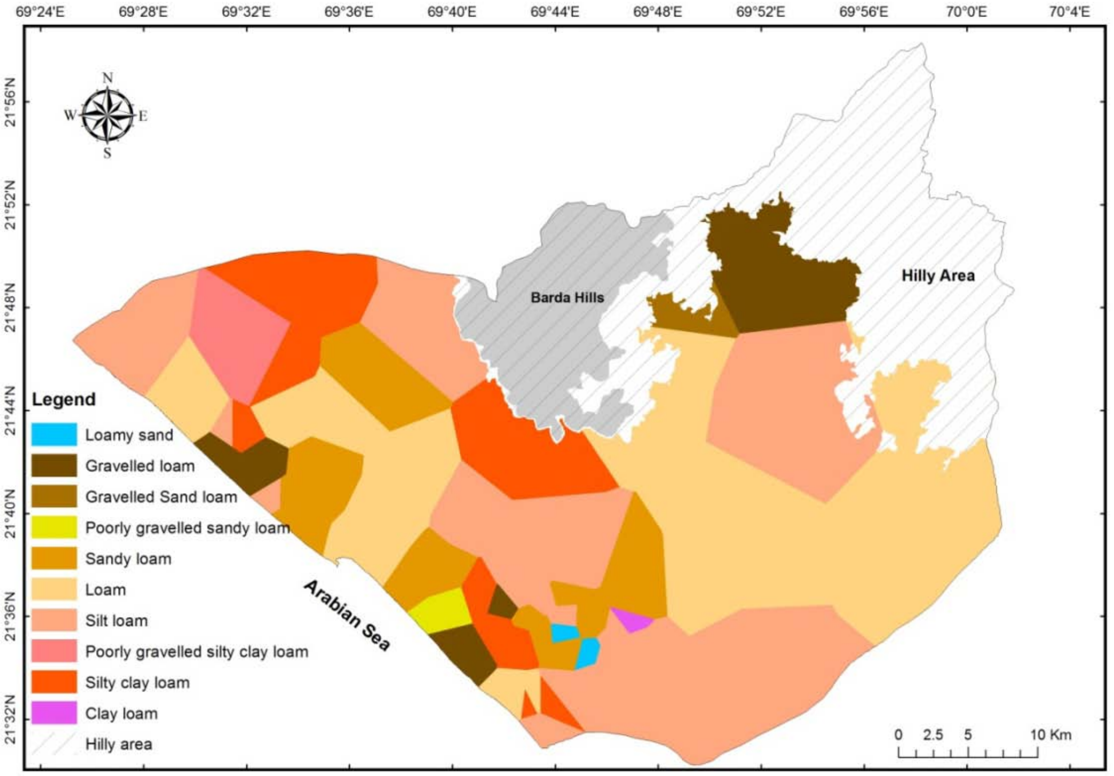


Fig. 2.21 Spatial variation of soil texture classes in Minsar basin. In the hilly region (shown as hatched) the soil sampling was not carried out.

Table 2.6 Soil texture classes in the study area

Soil Texture Class	Area (km^2)
Clay loam	2.62
Gravelled loam	90.95
Gravelled Sand loam	11.76
Loam	435.44
Loamy sand	4.55
Poorly gravelled sandy loam	9.04
Poorly gravelled silty clay loam	38.05
Sandy loam	133.84
Silt loam	434.66
Silty clay loam	140.89

2.8.2 Field saturated hydraulic conductivity

Experiments were carried out at 23 sites in the study area using Guelph permeameter to determine field saturated hydraulic conductivity. The locations of these sites and computed values of field saturated hydraulic conductivity are shown in Fig. 2.22.

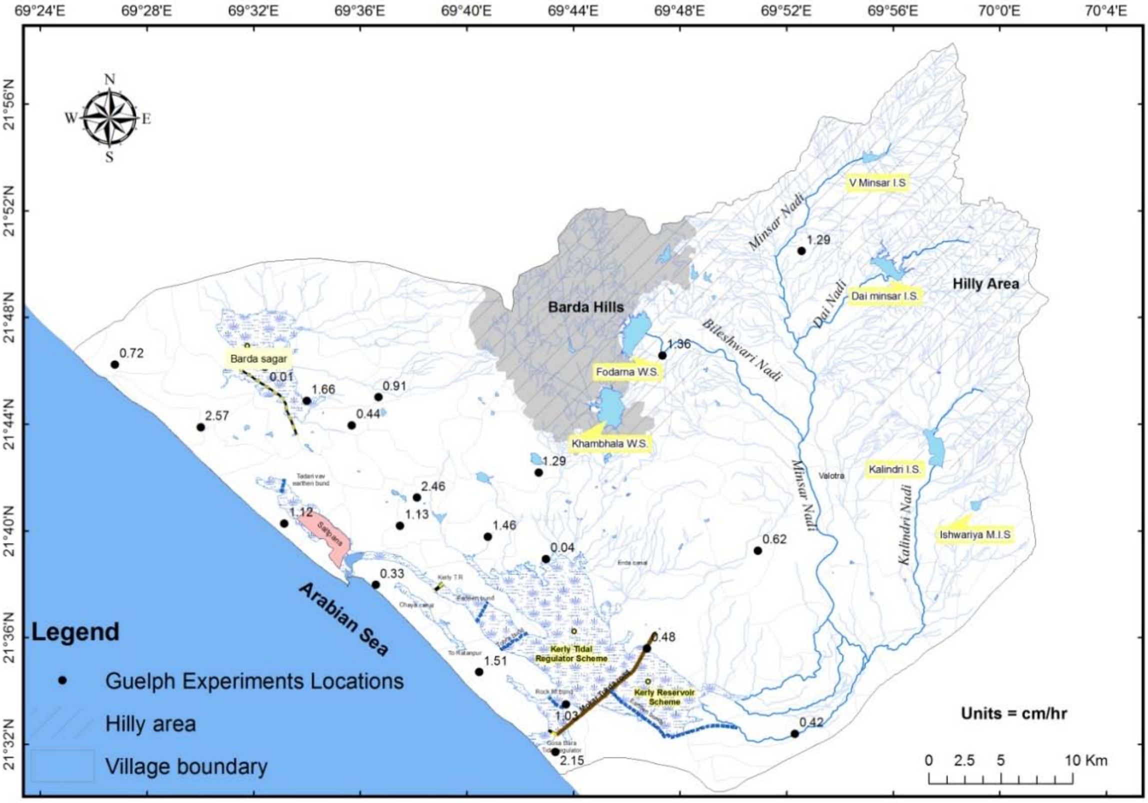


Fig. 2.22 Values of field saturated hydraulic conductivity at various sites

2.8.3 Infiltration rates

Experiments were carried out at 22 sites using double ring infiltrometer to determine infiltration rates. The locations of these sites and computed values are shown in Fig. 2.23.

2.8.4 Pumping tests

Figure 2.24 shows the locations of sites at which additional pumping tests were carried out by GWRDC and NIH. According to the pump test data analysis carried out, the transmissivity values of aquifers in the coastal belt vary from 67 m^2/d to 308 m^2/d and storativity values vary from 1.05×10^{-1} to 4.5×10^{-3}. The transmissivity values of aquifers comprising the coastal plain vary from 19 m^2/d to 181 m^2/d and storativity values vary from 6.4×10^{-1} to 1.06×10^{-4}. Aquifers in the upland areas have transmissivity values ranging from 10 m^2/d to 54 m^2/d and the storativity values ranging from 0.07 to 1.76×10^{-3}. As per communication with CGWB Ahmedabad, the transmissivity value in limestone aquifer in the region can vary upto 500 m^2/d, while for basalt terrain it can vary upto 60 m^2/d.

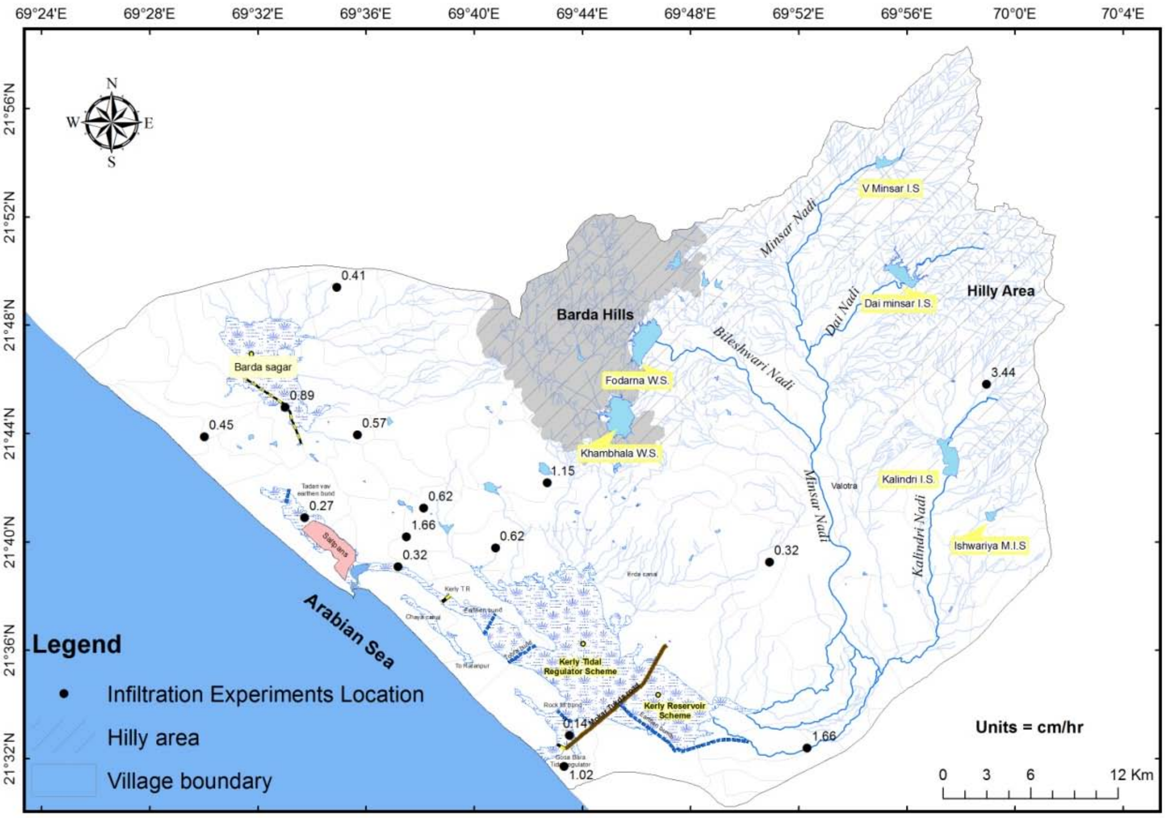


Fig. 2.23 Values of infiltration rates at various sites

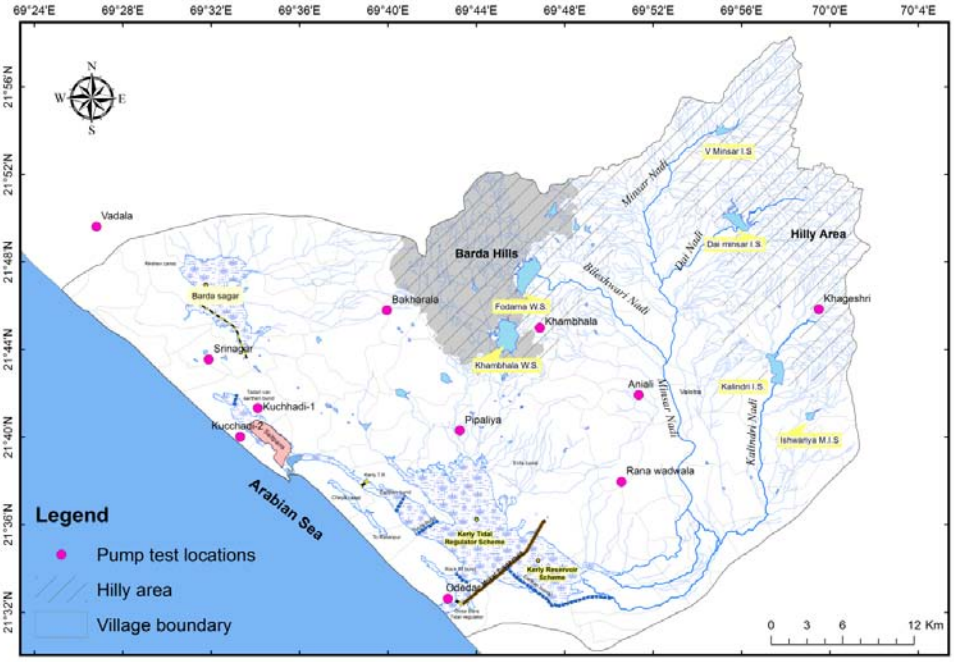


Fig. 2.24 Locations for new pump tests under the study

In addition to above field surveys, geochemical surveys and socioeconomic surveys were also carried out during the project. Details of these surveys and analyses made are described in Chapter 3 and Chapter 5, respectively

2.9 GROUNDWATER LEVELS AND GROUNDWATER MOVEMENT

The reduced level of wells and data for depth to groundwater level in respect of wells monitored biannually by GWRDC since 1985 were employed to develop historic water table contours of the region during the pre and post monsoon season. These maps indicate that groundwater in the aquifer system generally flows from upland areas to discharge areas near Arabian Sea, and, during both pre- and post-monsoon the groundwater flow direction is towards the seaward side.

Figures 2.25 – 2.32 show the pre monsoon and post monsoon water table contours drawn using the data monitored during the study period (2010-2013). In these figures (and in case of TDS contours shown in subsequent Chap. 3), the area marked as Barda hills and hilly area was not monitored. *Therefore, the contours drawn in proximity of these hilly areas show approximate values only.*

During the period 2010-2013, the year 2012 was a very low rainfall year while rainfall in the year 2010 was maximum (refer Fig. 2.4). During 2011 the rainfall received was above average for the study area. Thus, except for 2012, rainfall in all the remaining three years was above average. The impact of low rainfall is clearly visible in the coastal plain.

As noted earlier, the coastal plain is having some low-lying low permeability areas especially in the Ghed region. In these areas the water table recedes below msl in pre monsoon. The water table recovers during monsoon. However, as mentioned above, the monsoon rains were poor in 2012. During the Kharif season, more groundwater was pumped to irrigate crops compared to a normal monsoon year. The impact of low rainfall in the study area is reflected in the reduced crop area (Fig. 2.9) for the hydrological year 2012-13. Apart from reduction in the cropped area, crops normally grown in Kharif and Rabi seasons, in some areas, were replaced by fodder crops. In addition, surface water available from Kerly TR / RR schemes and Barda sagar irrigation schemes was also not available for irrigating the crops in these seasons (refer Figs. 2.11 (a)-(c)). The combined impact of low rainfall, larger groundwater draft and non-availability of surface water for irrigation resulted in excessive lowering of the water table. In post monsoon of 2012, the maximum depth to water level was recorded in the Barda Sagar region to be 31 m. During pre monsoon, the groundwater levels receded further upto 34 m in this region.

The Figs. 2.25-2.32 clearly reveal that, due to very low rainfall in the year 2012, the overall decline in water table was more severe in pre monsoon 2013 compared to pre monsoon 2012.

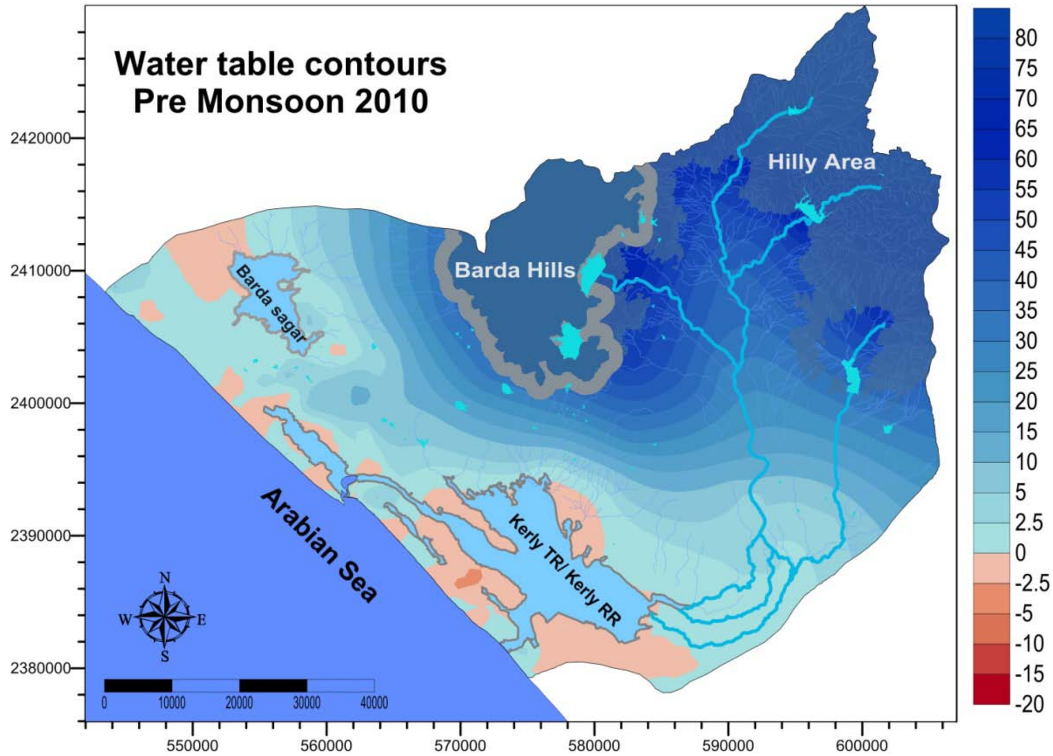


Fig. 2.25 Water table contours for pre monsoon 2010 (contours near hilly areas are approx.)

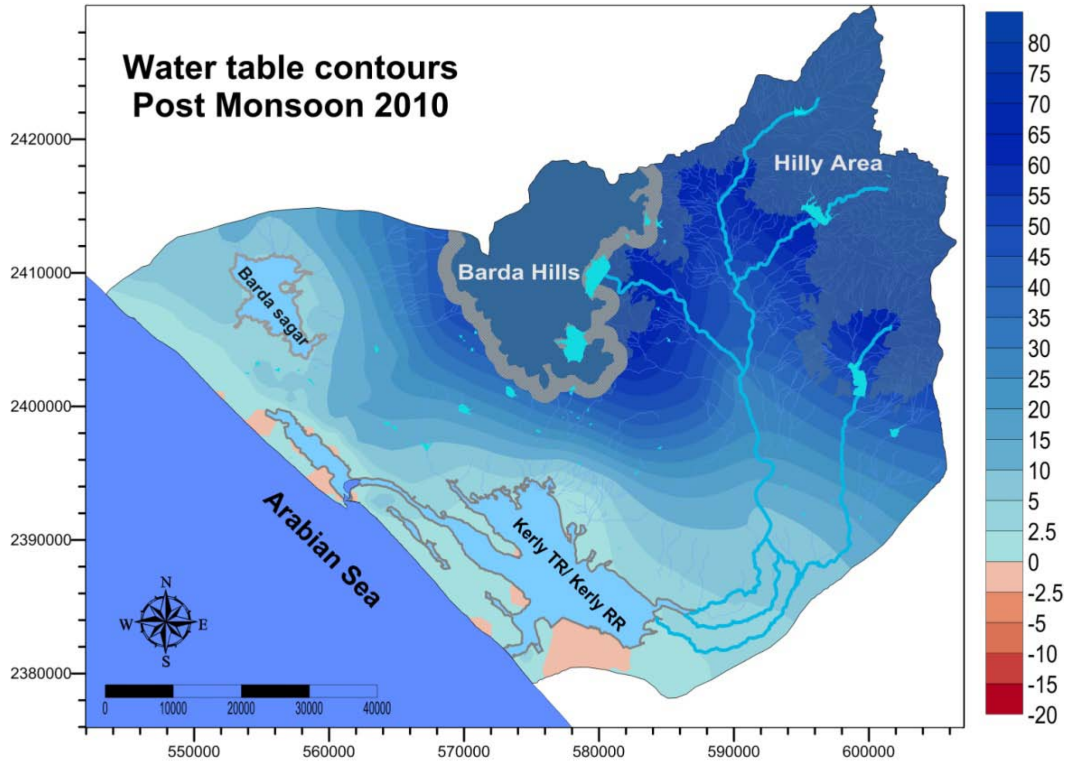


Fig. 2.26 Water table contours for post monsoon 2010

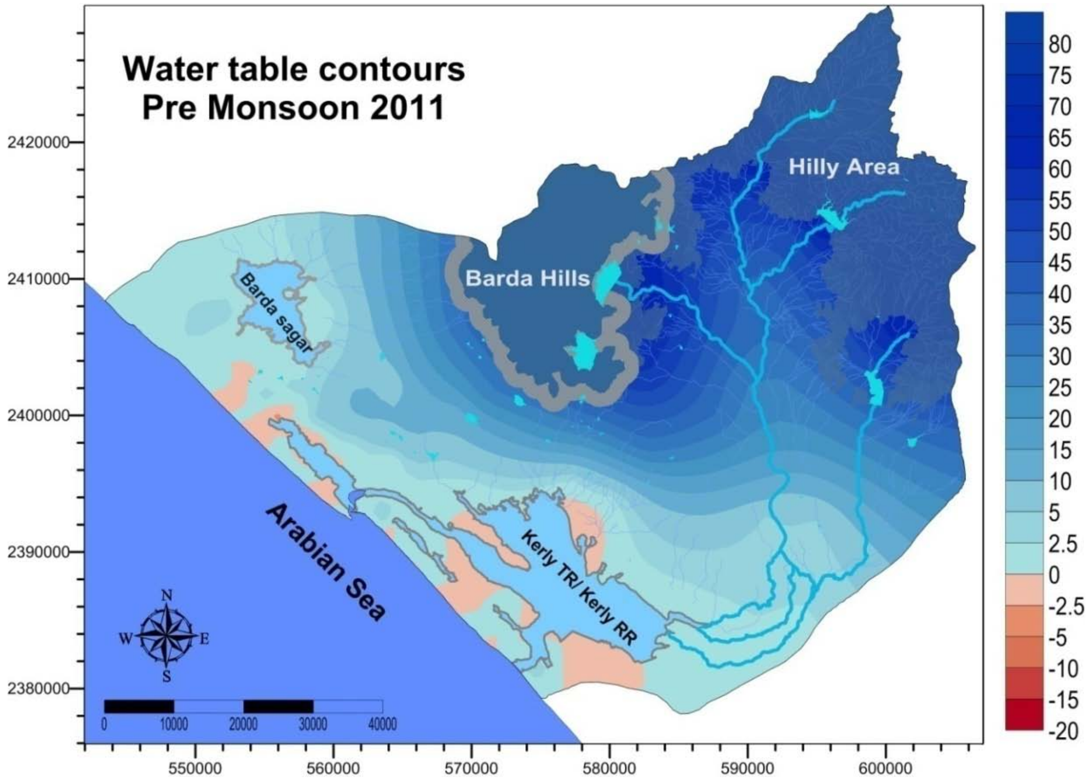


Fig. 2.27 Water table contours for pre monsoon 2011

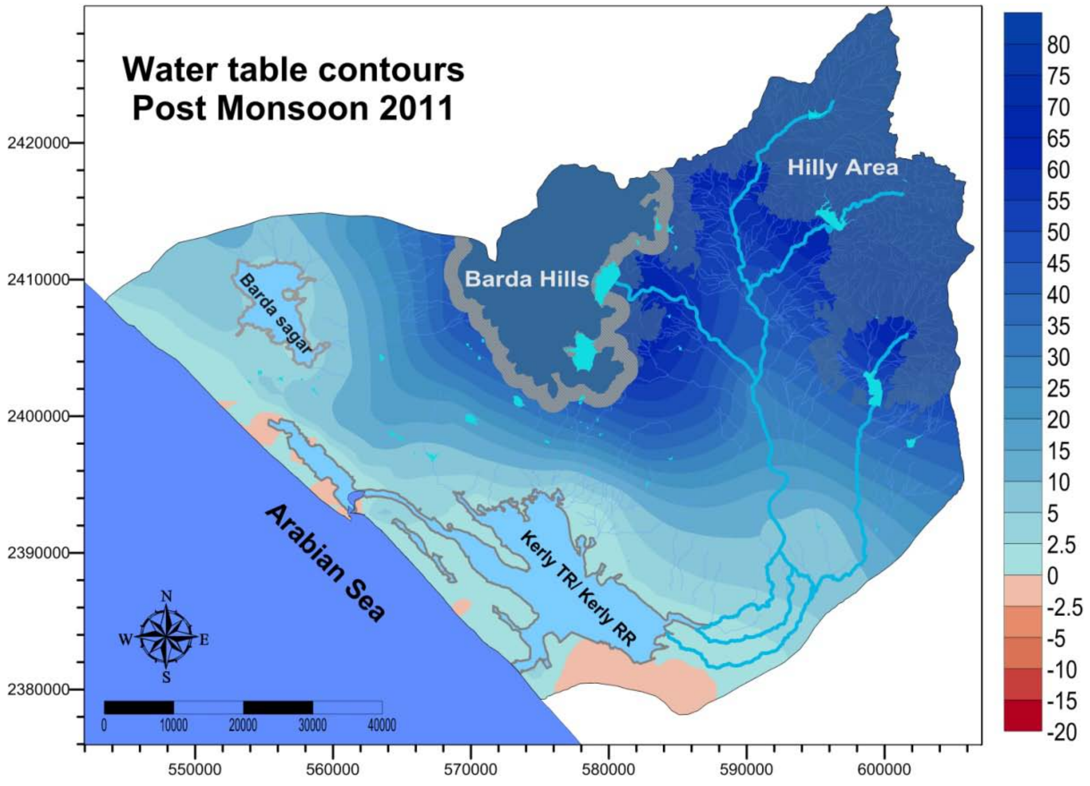


Fig. 2.28 Water table contours for post monsoon 2011

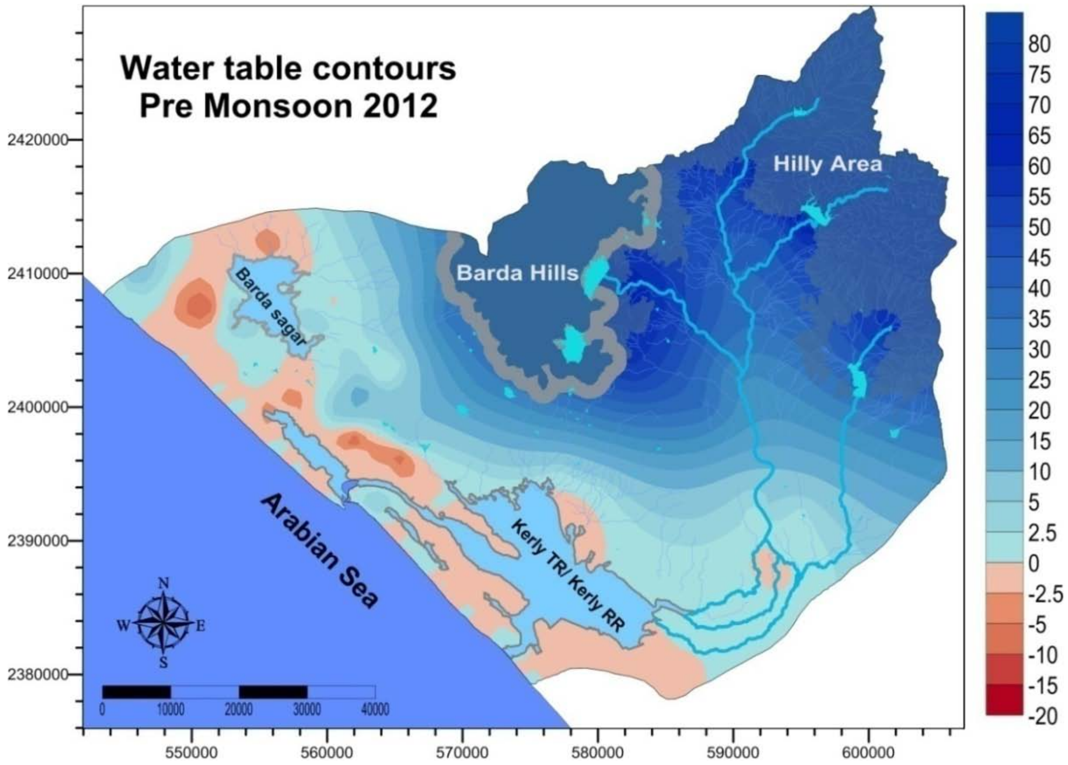


Fig. 2.29 Water table contours for pre monsoon 2012

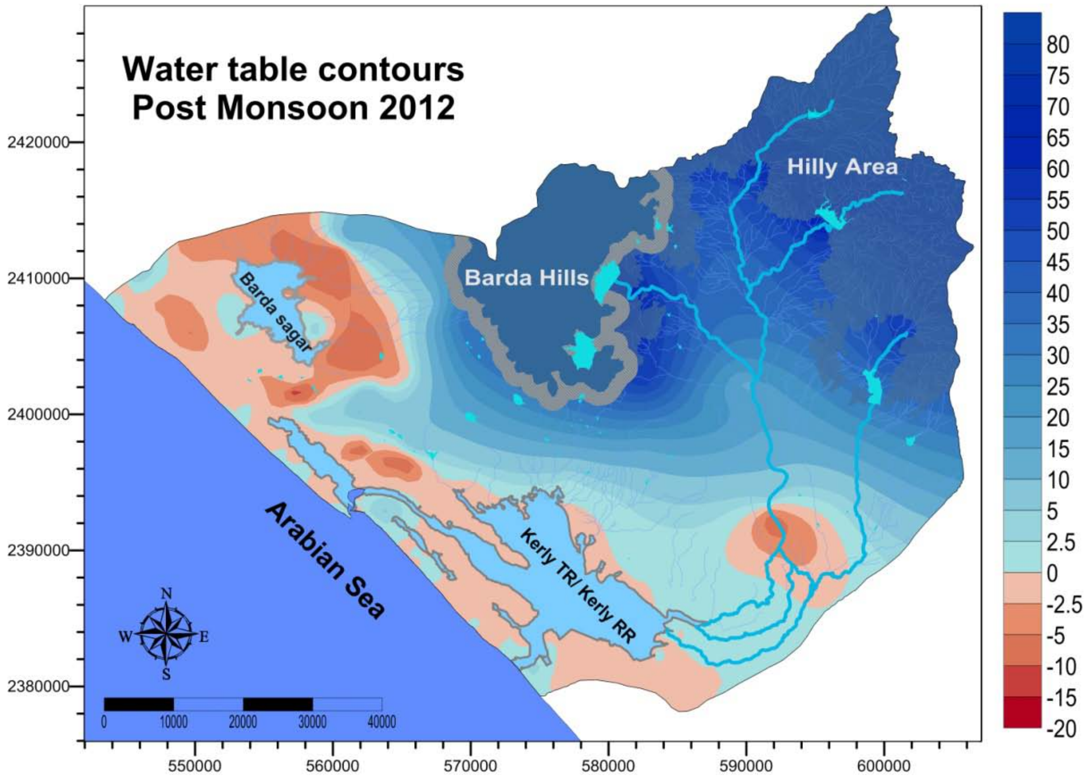


Fig. 2.30 Water table contours for post monsoon 2012

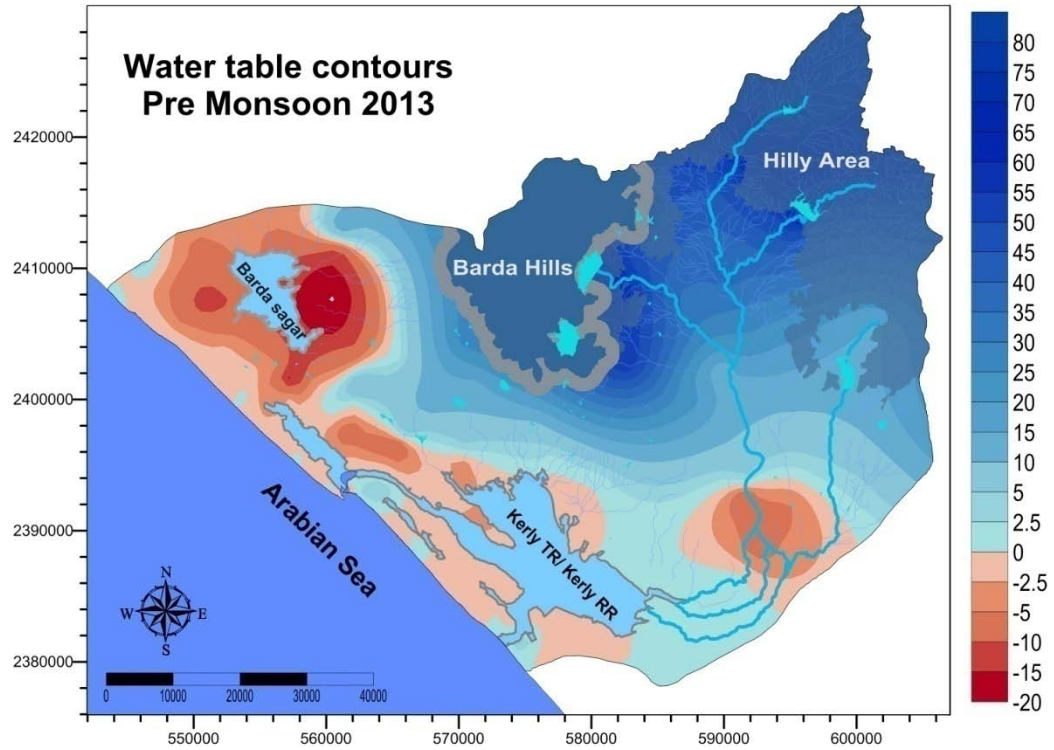


Fig. 2.31 Water table contours for pre monsoon 2013

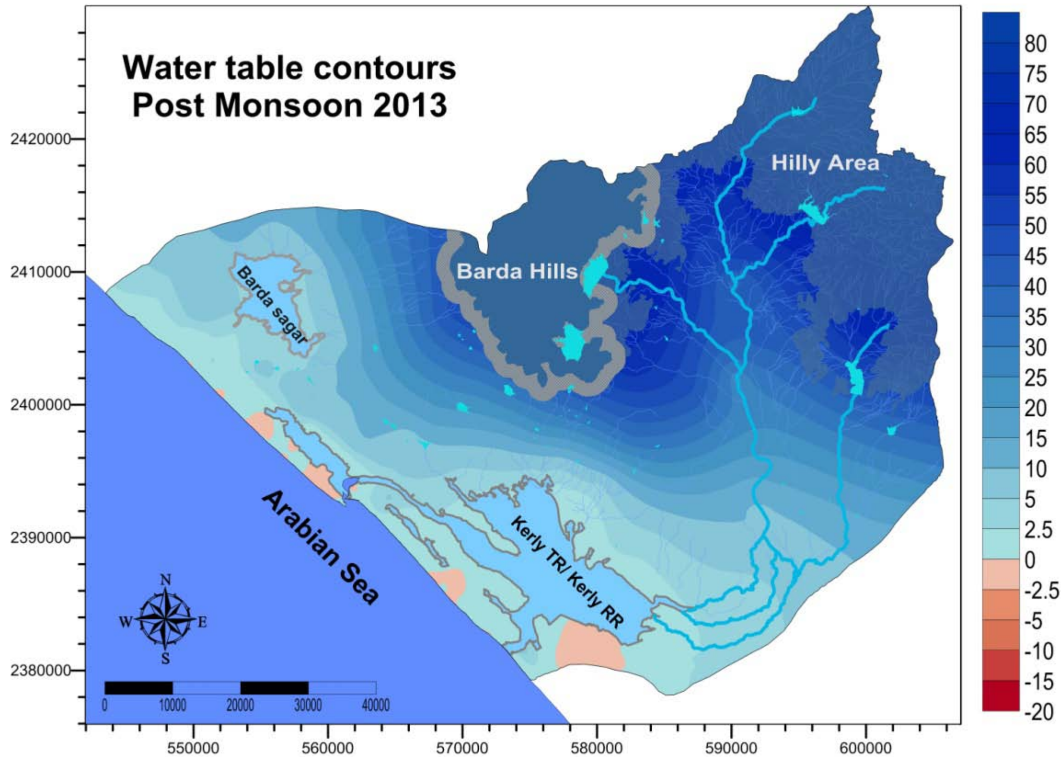
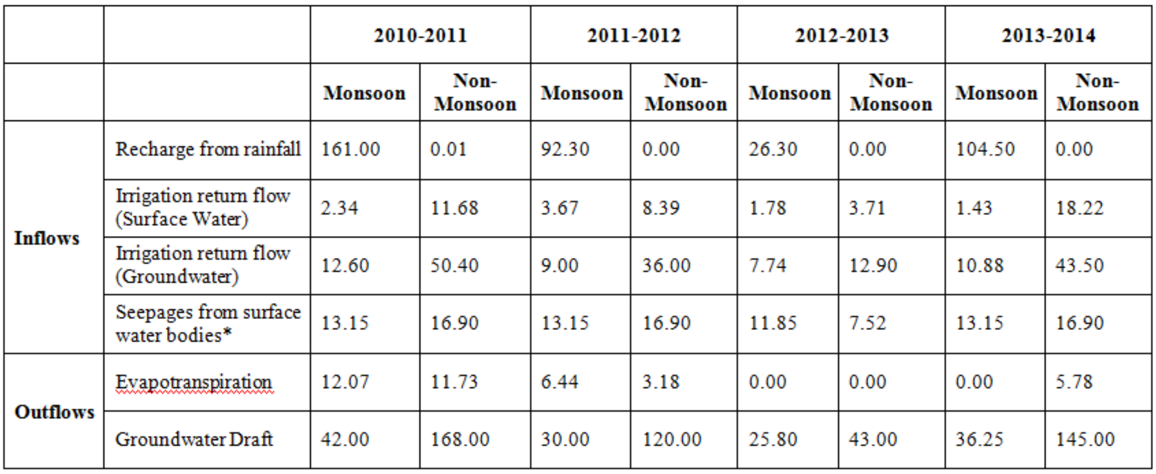


Fig. 2.32 Water table contours for post monsoon 2013

2.10 GROUNDWATER RESOURCE ESTIMATION IN MINSAR BASIN

In accordance with GEC 1997 norms, GWRDC has carried out groundwater resource estimation for the talukas falling in the districts Porbandar and Jamnagar. However, only a portion of these talukas fall in the study area under consideration. Therefore, the groundwater inflows and outflows were computed on lumped basis for the Minsar basin area. The depth of extinction for evapotranspiration was assigned as 1.2 m. Table 2.7 shows on a lumped basis the groundwater inflows and outflows computed for the Minsar basin for the years 2010-11 and 2013-14.

Table 2.7 Groundwater inflows and outflow components (mm)



		2010-2011		**2011-2012**		**2012-2013**		**2013-2014**	
		Monsoon	**Non-Monsoon**	**Monsoon**	**Non-Monsoon**	**Monsoon**	**Non-Monsoon**	**Monsoon**	**Non-Monsoon**
Inflows	Recharge from rainfall	161.00	0.01	92.30	0.00	26.30	0.00	104.50	0.00
	Irrigation return flow (Surface Water)	2.34	11.68	3.67	8.39	1.78	3.71	1.43	18.22
	Irrigation return flow (Groundwater)	12.60	50.40	9.00	36.00	7.74	12.90	10.88	43.50
	Seepages from surface water bodies*	13.15	16.90	13.15	16.90	11.85	7.52	13.15	16.90
Outflows	Evapotranspiration	12.07	11.73	6.44	3.18	0.00	0.00	0.00	5.78
	Groundwater Draft	42.00	168.00	30.00	120.00	25.80	43.00	36.25	145.00

* Surface water bodies include checkdams, percolation tanks, spreading channel, major streams and reservoirs

Chapter 3

Hydrogeochemical & Stable Isotope Investigations

Kharif season in Minsar basin

Water quality monitoring in Bakharla village

3.1 INTRODUCTION

Chemical analysis forms the basis of interpretation of quality of water in relation to source, geology, climate and use. The chemistry of water in aquifers underlying the Minsar Basin is controlled by several factors, including the chemistry of the natural recharge water and the geochemical reactions that occur within the aquifer system comprising limestone, clay and alluvial deposits underlain by Deccan trap. Intruding seawater near coast, mixing with water from surrounding and underlying deposits / existing saline zones, or mixing with water from estuarine deposits near Arabian Sea, also may alter groundwater chemistry, increase chloride concentrations, and degrade the quality of groundwater. In this study, groundwater chemistry is evaluated on the basis of major-ion data to determine native groundwater quality, the sources of high-chloride water to wells, and the geochemical reactions that occur within aquifers underlying the Minsar Basin. Most samples collected as part of this study were from domestic or irrigation well discharges and piezometers installed during the study. These samples from wells integrate, usually in unknown proportions, water that entered the well throughout the entire screened interval into a single sample, except for piezometers in which the screen has been kept short.

3.2 METHODOLOGY FOR QUALITY ANALYSIS OF GROUNDWATER

3.2.1 Frequency of Data Collection

An intensive monitoring program of groundwater level and water quality was launched in Minsar River Basin. Initially, preliminary information about the magnitude of saltwater intrusion in the area was collected by interaction with local people. Based on this information and historical field data, an observation network was established. Initially 40 wells were selected for monitoring on quarterly basis and 26 wells were demarcated for monthly monitoring. Subsequently, the study area was expanded to include the Barda sagar region and the observation network was modified to monitor a total of 150 locations every third month that included collection of water samples from open wells, piezometers and surface water bodies such as spreading channel, creeks, reservoirs and Arabian Sea. Rainwater samples were also collected. Sites for installation of 16 piezometers were selected at strategic locations to monitor the groundwater level and water quality. The installation of these 16 piezometers by GWRDC was completed in February 2011. These piezometers which were part of the observation network were regularly monitored.

3.2.2 Water Sampling

For evaluation of groundwater and surface water quality, groundwater samples and samples from surface water bodies including Arabian sea and fresh rainwater were collected. Samples were collected in 1-litre capacity Polythene bottles. Prior to sampling, these bottles were thoroughly washed with diluted HNO_3 acid and then with distilled water and also rinsed thrice with the respective groundwater to be sampled. Each sample collected was recorded and identified with a unique sample number marked on each bottle.

3.2.3 Physicochemical analysis of groundwater samples

The collected samples were analysed for the parameters stated below.

Physical parameters: Temperature, pH, EC, TDS (total dissolved solids)

Chemical Parameters: Sodium (Na^+), Potassium (K^+), Total Hardness (TH) as $CaCO_3$, Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Chlorides (Cl^-), Sulphates (SO_4^{2-}), Nitrates (NO_3^{2-}), Flourides (F^-), Alkalinity, Carbonates(CO_3^{2-}), and Bicarbonates (HCO_3^{2-}).

Portable pH and EC meters were employed to measure physical parameters, such as pH and EC, on site. Chemical parameters were analysed in the Water Quality Laboratory at NIH Roorkee. The analytical methods of APHA (1995) were used for estimating above stated physical and chemical parameters. Na^+ and K^+ were determined by Flame Atomic Absorption Method; alkalinity, CO_3^{2-}, HCO_3^{2-}, TH, Ca^{2+}, Mg^{2+}, Cl^- were analyzed by EDTA titration method; SO_4^{2-} was estimated by turbidity method; whereas F^- and NO_3^- by spectrophotometer in the laboratory.

Analytical precision for measurements of cations and anions, indicated by the ionic balance error (IBE), was computed on the basis of ions expressed in meq/l. The value of IBE was observed to be within a limit of ±10%. The precise locations i.e. longitudes and latitudes of sampling points were also determined in the field through Global Positioning System (GPS). In addition, two portable TLC (Temperature, Water Level and Conductivity) meters were utilized to monitor the salinity profiles inside individual wells. To collect high frequency data of groundwater levels, CTD divers (data loggers) were installed in three piezometers located in a profile perpendicular to the coast to monitor the impact of tides on groundwater levels. The nearest piezometer was located only 50 m from the coastline and exhibited the maximum impact of tides on the groundwater level.

3.2.4 Hydrogeochemical techniques for identification of salinization process in a coastal aquifer

3.2.4.1 Groundwater classification

There are many methods for hydrochemical classification viz., Piper (1944), Collins (1975), and Chadha (1999). These methods are used to determine the quality and other important properties of groundwater. All these classifications depend on the concentration of main cations and anions expressed in terms of unit equivalent weight of ion (epm) or meq/l. In the present study, the hydrogeochemical characteristics of the major and minor ions are analysed using piper trilinear diagram with a view to determine the groundwater types and visualize trends of groundwater chemistry.

3.2.4.2 Ion exchange

Hydrogeochemical studies are used to understand the changes in water quality due to rock-water interaction as well as other processes/ influences on the chemical composition of groundwater.

The ion exchange between groundwater and its host environment during residence or travel process can be verified, using an index of Base Exchange (Schoeller, 1965, 1967) known as chloro-alkaline indices (CAI). When Na^+ and K^+ ions in water are exchanged with Mg^{2+} or Ca^{2+} ions in weathered materials, the index value will be positive indicating base exchange, whereas low salt waters give negative value indicating chloro-alkaline disequilibrium. This is also known as cation–anion exchange reaction. During this process, the host rocks are the primary sources of dissolved solids in the water. Two chloro-alkaline indices CAI 1 and CAI 2 (Eqs. (3.1) - (3.2), with all values expressed in meq/l), are utilized to study the process of ion exchange between groundwater and its host environment during rock-water interaction.

$$\text{CAI 1} = [Cl^- - (Na^+ + K^+)]/Cl^- \qquad (3.1)$$

$$\text{CAI 2} = [Cl^- - (Na^+ + K^+)]/(SO_4^{2-} + HCO_3^- + CO_3^- + NO_3^-) \qquad (3.2)$$

3.2.4.3 Mineral Dissolution and deposition

Geochemical processes can be identified based on the combination of classic geochemical methods and geostatistical techniques. The results of the ionic ratios and scatter plots can be utilized to study dissolution of carbonate and silicate minerals and their influence on the groundwater chemistry.

3.2.4.4 Rock-water interaction

Gibbs (1970) established the mechanism controlling the chemical composition of water and ascertained a close relationship that can exist between water composition /chemistry and aquifer lithology. The mechanism controlling water chemistry and the functional sources of dissolved ions can be assessed by plotting the ratios of $Na^+ / (Na^{2+} + Ca^{2+})$ and $Cl^- /(Cl^- + HCO_3^-)$ as functions of TDS. In these diagrams, samples falling in the center of the curve are derived from rock-water interaction.

3.3 PHYSICOCHEMICAL MECHANISM OF MIXING OF FRESHWATER-SALTWATER IN THE COASTAL AQUIFER SYSTEM OF MINSAR RIVER BASIN

Geochemical processes occurring within the groundwater and reactions with aquifer minerals have significant impact on water quality. These geochemical processes are responsible for the seasonal and spatial variations in groundwater chemistry. Figure 3.1 shows the observation network comprising a total of 150 monitoring locations which include observation wells and piezometers for monitoring of TDS using the TLC meter. For water quality analysis, a representative sample of 70 locations, spread over four zones of the region viz. Zone I, Zone II, Zone III and Zone IV (as illustrated in Fig. 3.1) were selected.

3.3.1 Physical Parameters

The quality of any surface or groundwater indicates its suitability for the intended use. The physical parameters of groundwater are very important for a better understanding of the quality /geochemistry of groundwater.

3.3.1.1 Temperature

The temperature of groundwater largely depends on atmospheric temperature, terrestrial heat, exothermic and endothermic reactions in rocks, infiltration of surface water, insulation thermal conductivity of rocks, and rate of movement of groundwater. The seasonal movement of heat into and out of the upper layers of the Earth's crust causes a seasonal fluctuation in groundwater temperatures to a depth of 10 to 25 m. Groundwater temperature in the study area ranged from 20.0 to 39.7ºC. .

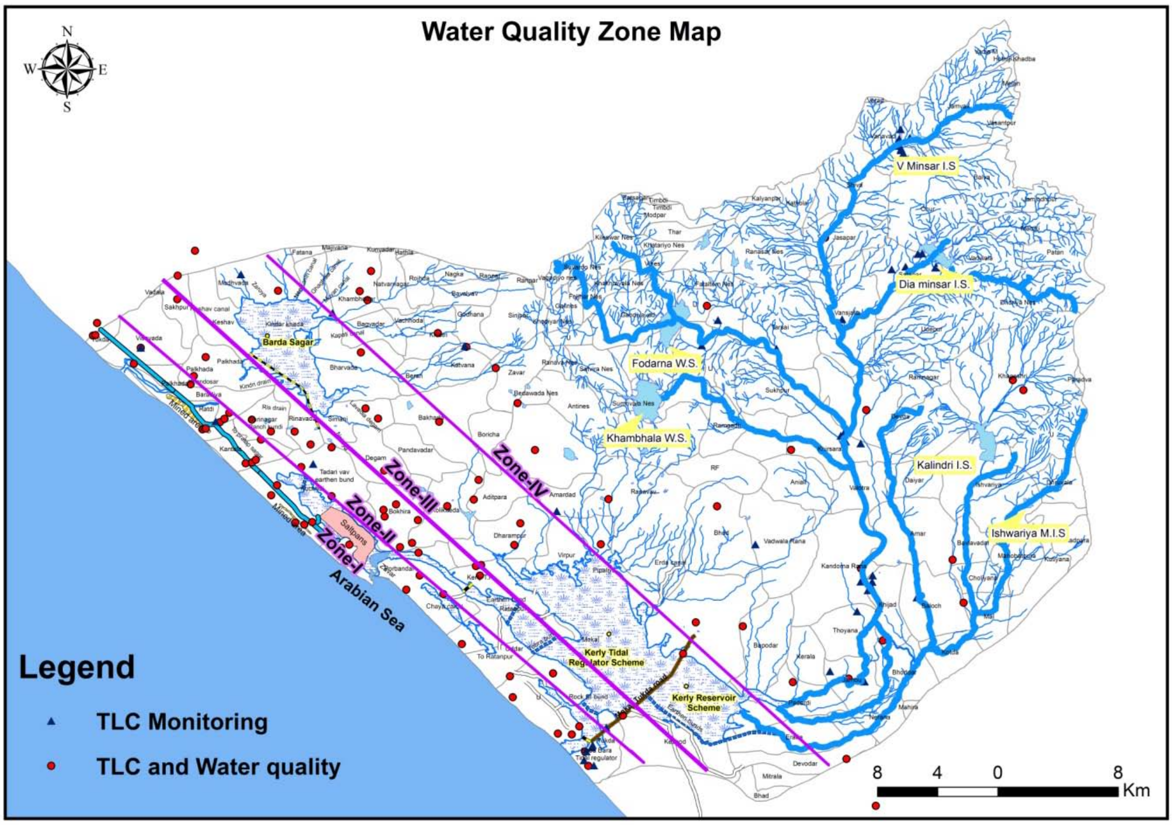


Fig. 3.1 Water quality zone map

3.3.1.2 pH

The optimum pH will vary widely according to the composition of water, but is often in the range 6.5 - 8.5. High pH causes a bitter taste; water pipes and water-use appliances become encrusted; depresses the effectiveness of the disinfection of chlorine, thereby leading to the need for additional chlorine when pH is high. Low pH water will corrode or dissolve metals and other substances. The variation in pH values is connected with the concentration of HCO_3^- and its stability in the solution. In the study area, pH of groundwater varies within a range of 6.36 – 9.64, which elaborates a trend of alkaline chemical reaction within the groundwater system. pH values in the upper range were detected in some of the coastal wells.

3.3.1.3 Electrical Conductivity and TDS

Electrical conductivity (EC) in the study area generally ranges between 315 μS/cm and 18,770 μS/cm. Conductivity in majority of the area in the coastal belt falls above the recommended WHO and BIS values, except for some locations that show low values. These high conductivity values indicate presence of high TDS concentration and enrichment due to dissolved ions, and ionic activities in the groundwater.

The EC profiles monitored using TLC meter in the observation wells and piezometers indicates that the TDS varies with depth in the region (TDS value of groundwater was computed from measured values of electrical conductivity). At increasing depths, TDS was found to increase and vice versa. Figure 3.2 show results of vertical EC loggings at some of the wells monitored in different seasons. The value of TDS is maximum during pre monsoon and minimum during post monsoon. In a few wells, the effect of upconing was quite visible in the form of higher groundwater salinity during monsoon / post monsoon. This kind of situation arises when a long dry spell occurs during monsoon and groundwater is over pumped to supplement irrigation in Kharif season. Again during post monsoon when Rabi season starts, some of the wells with underlying saline layer at shallow depths exhibit this characteristic. In Fig. 3.2 it is to be noted that rainfall was deficient in 2012, therefore, corresponding TDS profile for Nov. 2012 shows higher salinity in all the wells. Again due to low rainfall, many of the wells became dry while water column receded in others; e.g., well JND-20 (Fig. 3.2) shows low water column with high salinity in Nov. 2012.

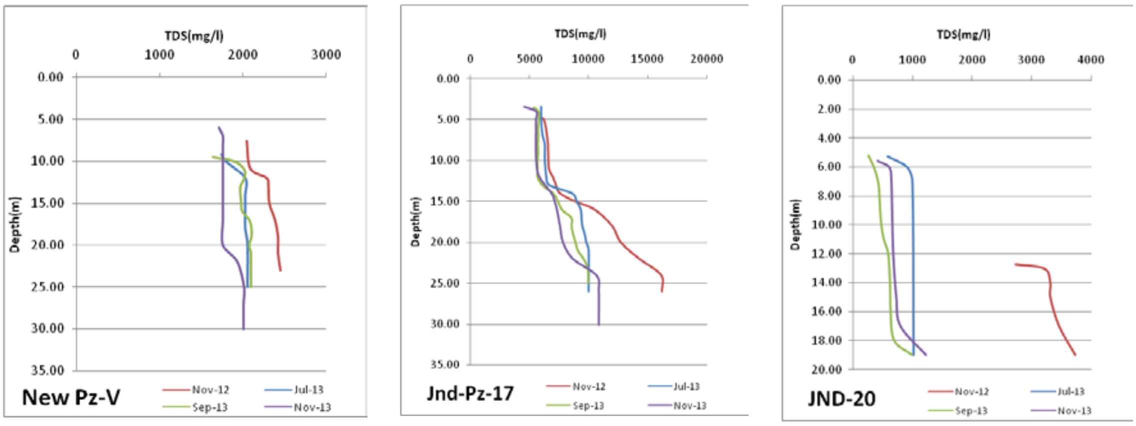


Fig. 3.2 TDS profiles in some wells during different seasons.

For Zone-I, II, III and IV as demarcated for the study area (Fig. 3.1), average value of TDS for 2013 year are 2982.17mg/l, 2755.08mg/l, 1946.92mg/l, and 1381.29mg/l in Premonsoon; 2154.05mg/l, 2023.38mg/l, 1833.71mg/l, and 853.67mg/l in monsoon and 2085.49mg/l, 2019.04mg/l, 1584.58mg/l and 770.41mg/l in Post monsoon, respectively. It is to be noted here that the average values for pre monsoon 2013 are on the higher side and reflect the impact of dry year 2012 in which rainfall was very low. For a normal rainfall year, the TDS values in pre monsoon are lesser viz. are 2399.77mg/l, 2296.80mg/l, 1767.52mg/l, and 1154.61mg/l for Zone-I, II, III and IV, respectively.

This shows that groundwater salinity decreases with increasing distance from the coast. Figures 3.3-3.5 show the TDS contours in the study area at different depths (<8 m, 8-15 m and > 15 m) for the periods: pre monsoon 2013, monsoon 2013 and post monsoon 2013. Since 2012 was a low rainfall year, during pre monsoon 2013, extensive lowering of water table was observed; and therefore, TDS could not be monitored at shallow (< 8 m) and medium (8-15 m) depths at all the locations (refer Figs. 3.3 (a)-(b)). The figures reveal that in the coastal belt salinity increases with depth. The spatial variation of TDS as illustrated in the figures, clearly shows that some freshwater zones exist even at depths > 15 m in the coastal belt. This pattern of salinity matches the groundwater flow pattern and hydraulic gradient from upland areas towards the coast. Near the Aditpara village, low permeability saline formation (leading to higher groundwater salinity) is present which slightly bifurcates the groundwater flow into two directions, and aids in the formation of freshwater pockets even at depths > 15 m near the coast. Similarly, in areas upstream / downstream of Barda Sagar, groundwater salinity responds to water level fluctuations arising from pumpage.

Near the sea coast, pockets of fresh groundwater are present due to flushing/ displacement of saline water by percolating rain water and groundwater inflows from inland areas. Groundwater circulates through porous limestone which is present at shallow depths; however, its downward movement is arrested by relatively impervious Gaj sediments and Deccan traps at deeper depths.

At the foothills of Barda (which is a major groundwater recharge zone comprising a thick limestone layer) and in upland areas, groundwater is mostly fresh and suitable for irrigation. Temporally, measured groundwater salinity, in general, decreases from its highest value in pre monsoon to monsoon and post monsoon. At some locations, salinity is slightly elevated in monsoon compared to post monsoon and vice versa due to local pumping effects during these two seasons.

Thus, spatial and depth wise analysis of water table fluctuation and groundwater salinity variation reveals that there exists a definite relationship between these two variables. As the groundwater level goes up, the amount of TDS present in water is found to decrease and vice versa. During mid monsoon period of 2013, heavy rains occurred in some areas during late monsoon resulting in retreat of interface during post monsoon. Again, groundwater pumpage for Rabi season commences during the last week of October in some areas. These areas may show slightly elevated salinity in post monsoon season on account of pumpage.

Also, in a few zones, TDS is found higher in post monsoon in terms of range but low in its mean value. This pattern of data clearly shows that there are some areas affected with saline formations. The contour maps (Figs. 3.3-3.5) can be used to identify areas / villages affected fully / partially by salinity and to find the lateral distance of salt water intrusion.

Good quality of groundwater along the coast is mostly restricted to shallow depths in Miliolitic limestone. In the inland areas of Ghed around Mokar, Jamboo, Nerana and Padardi villages, water is highly saline (> 4000 mg/l) because of existence of old unleached marine water due to low permeability geological formation. In mud areas of Chaya and Odedar near coast, the quality of water is saline (> 3000 mg/l) due to proximity of these areas to sea. The thin coastal strip from Kantela to Visawada also shows higher TDS (> 3000 mg/l).

In the villages along the coastal strip, groundwater pumpage raises the salinity levels, which deteriorates the water quality in shallow and medium depth wells. This upconing of saline water is exacerbated during low rainfall years, when the groundwater levels decline sharply. At some locations, e.g. in village Mokar, piezometer Pz-11 exhibits fluctuations in groundwater salinity for very high values (~ 6000 - 10,000 mg/l) even at shallow levels; such highly saline zones away from the coast need further investigations.

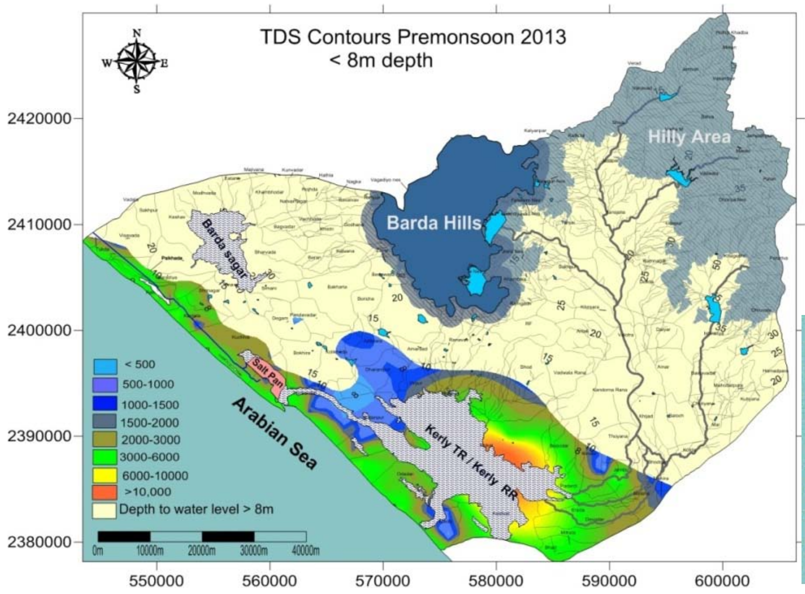


Fig. 3.3 (a)
TDS contours for pre-monsoon 2013 (depth < 8 m)

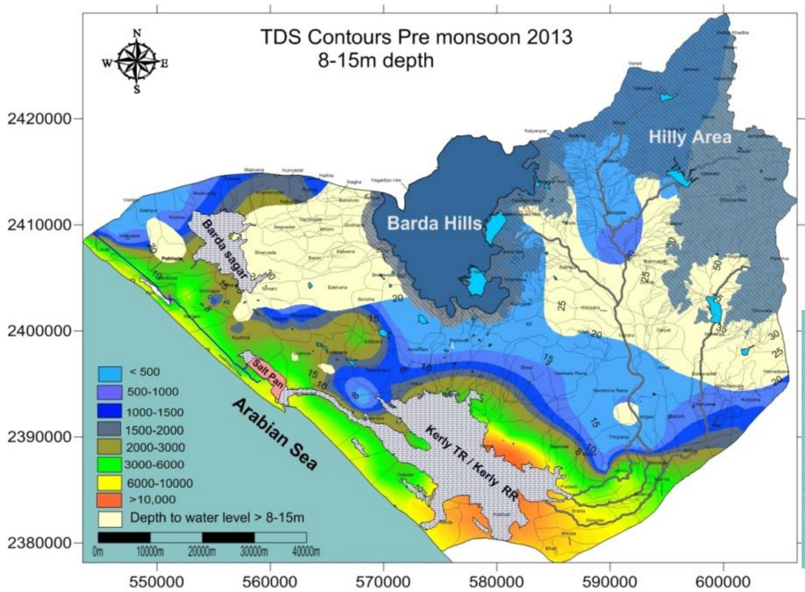


Fig. 3.3 (b)
TDS contours for pre-monsoon 2013 (depth 8-15 m)

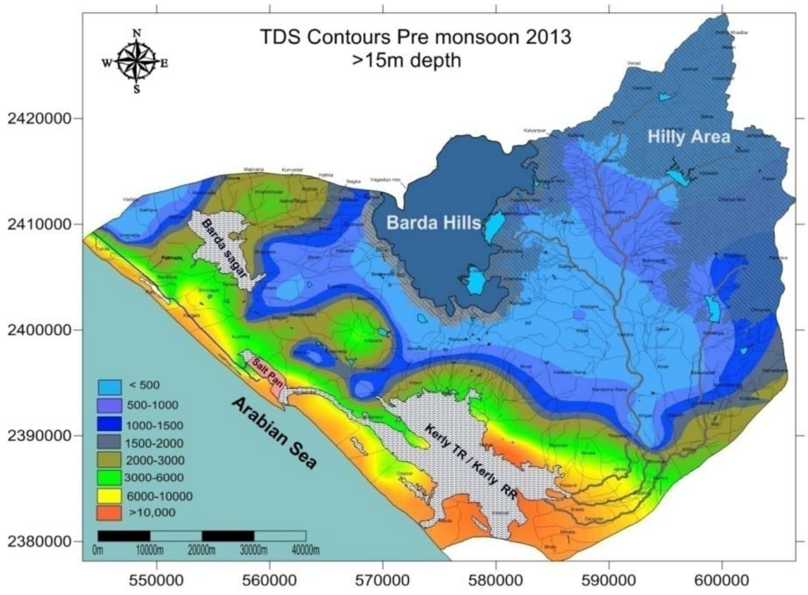


Fig. 3.3 (c)
TDS contours for pre-monsoon 2013 (depth > 15 m)

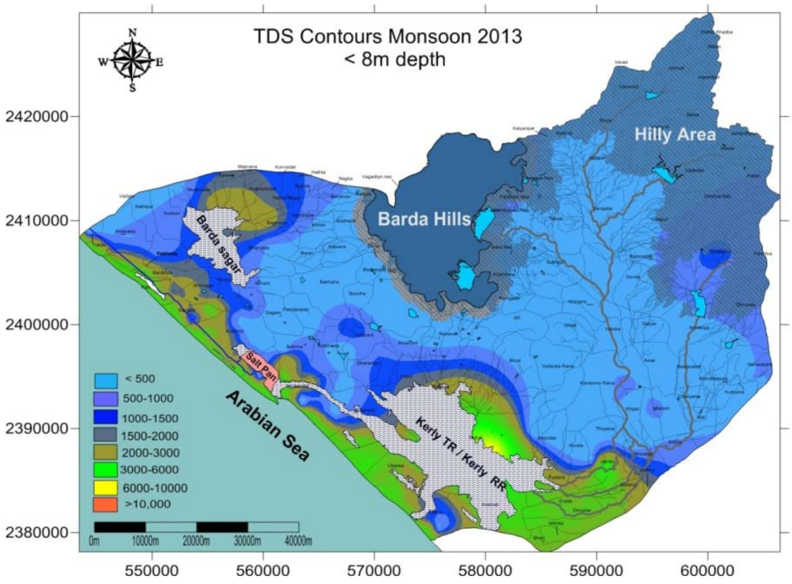


Fig. 3.4 (a)
TDS contours for monsoon 2013 (depth < 8 m)

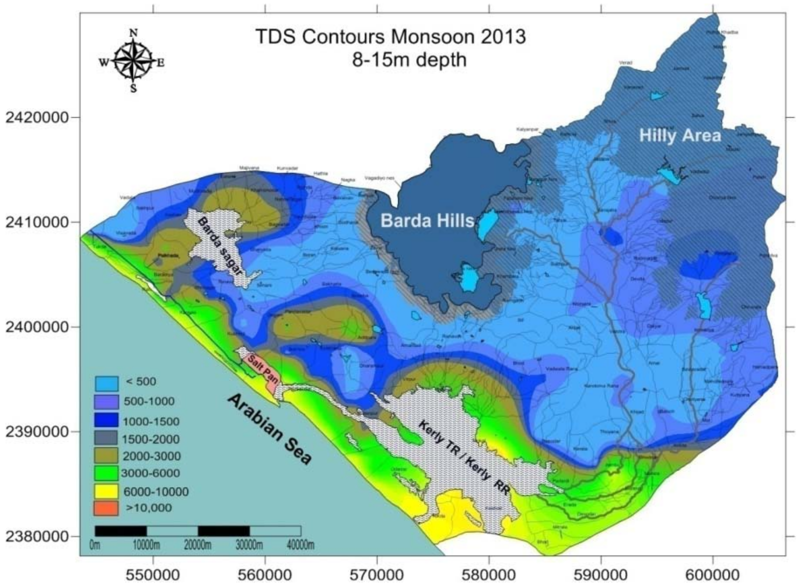


Fig. 3.4 (b)
TDS contours for monsoon 2013 (depth 8-15 m)

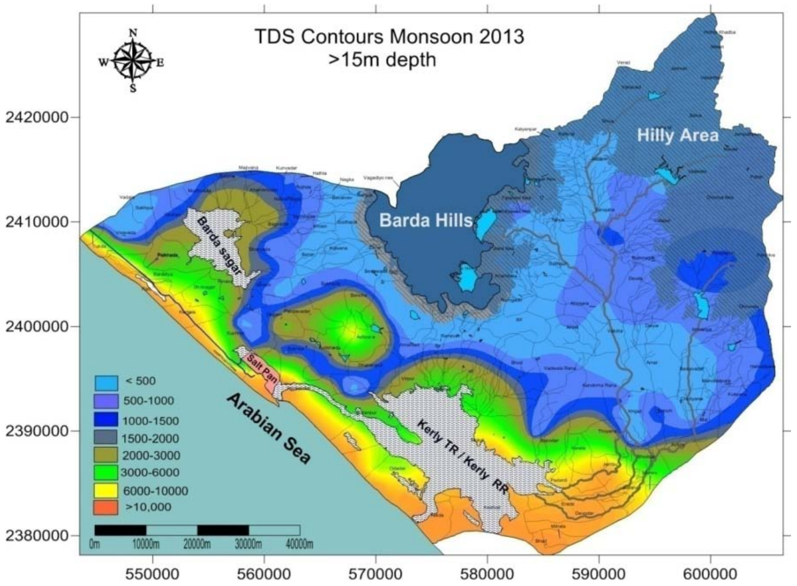
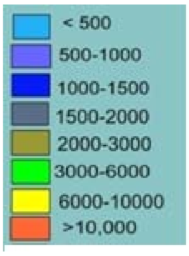


Fig. 3.4 (c)
TDS contours for monsoon 2013 (depth > 15 m)



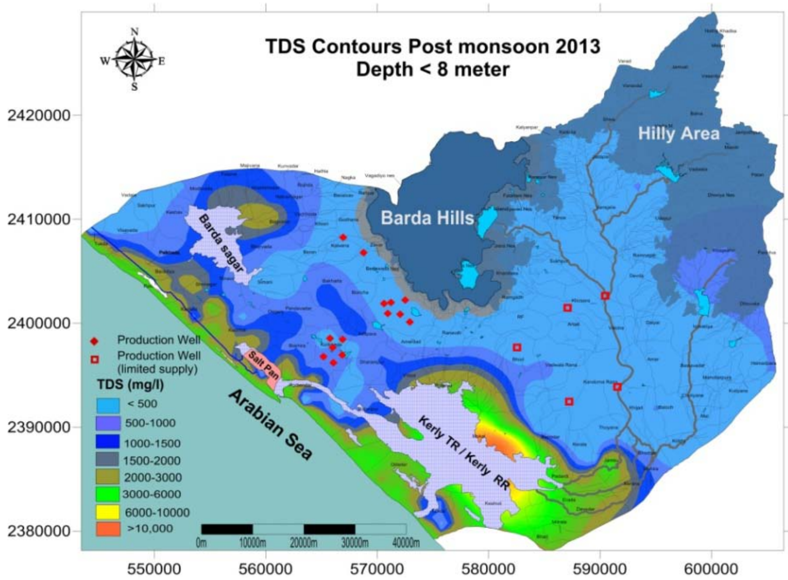


Fig. 3.5 (a)
TDS contours for post-monsoon 2013 (depth < 8 m)

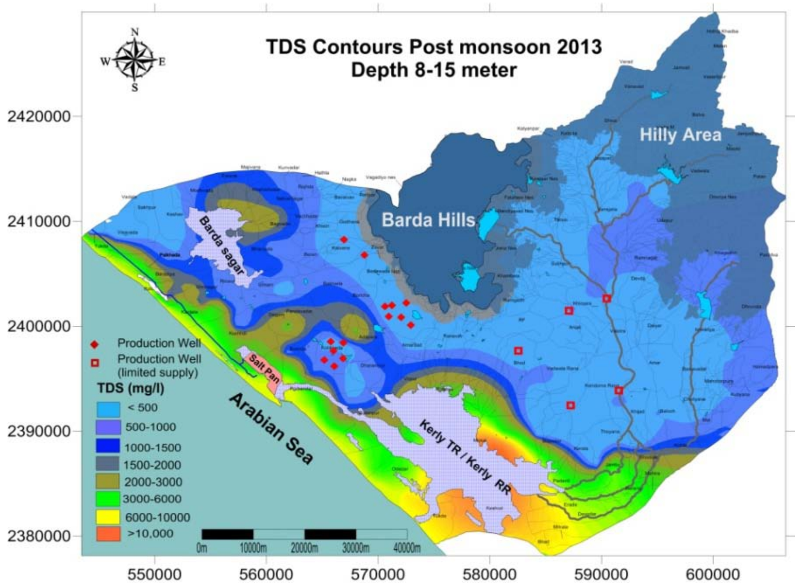


Fig. 3.5 (b)
TDS contours for post-monsoon 2013 (depth 8-15 m)

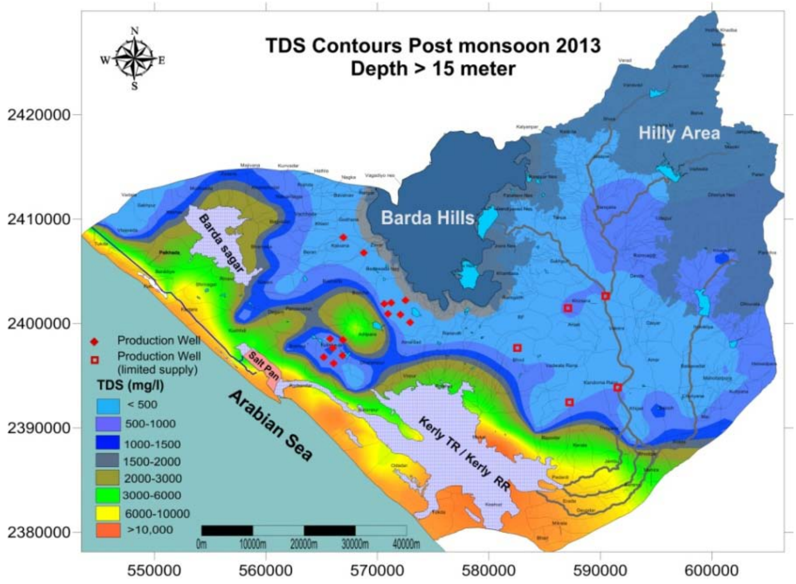
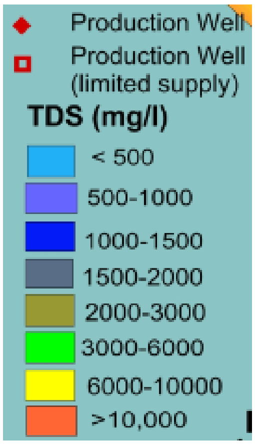


Fig. 3.5 (c)
TDS contours for post-monsoon 2013 (depth > 15 m)



3.3.2 Chemical Parameters

Alkalinity

The presence of carbonates, bicarbonates and hydroxides are the most common cause of alkalinity in water. For the study area, average value of alkalinity is 270.94mg/l, 255.25mg/l, 277.85mg/l, and 284.80mg/l in Premonsoon; 294.20mg/l, 259.25mg/l, 270.77mg/l, and 319.47mg/l in monsoon and 313.75mg/l, 245mg/l, 230.50mg/l and 331.58mg/l in Post monsoon for Zone-I, II, III and IV respectively.

Ca and Mg

Calcium and magnesium are predominantly sourced from dissolution of carbonate minerals, especially calcite (CaCO3, which can also contain significant quantities of Mg) and dolomite (Ca Mg (CO3)2), both of which are abundant in limestone terrains. Many silicate minerals are also important sources for Ca^{2+} and Mg^{2+} in ground waters. For the study area average value of Ca for year 2013 are 147.68mg/l, 183.53mg/l, 82.80mg/l, and 88.23mg/l in Premonsoon; 148.47mg/l, 207.96mg/l, 155.19mg/l, and 87.75mg/l in monsoon and 147.08mg/l, 252.18mg/l, 172.61mg/l and 77.34mg/l in Post monsoon for Zone-I, II, III & IV respectively. The average values of Mg for 2013 are 64.48mg/l, 77.26mg/l, 56.82mg/l, and 50.98mg/l in Premonsoon; 47.28mg/l, 41.42mg/l, 51.42mg/l, and 25.01mg/l in monsoon and 52.64mg/l, 37.76mg/l, 31.61mg/l and 22.72mg/l in Post monsoon for Zone-I, II, III & IV respectively. Due to abundance in most of the rocks and solubility, calcium is present almost everywhere in groundwater. High magnesium content in groundwater in coastal area indicates saline/seawater contamination.

Na and K

The most common sources of elevated sodium levels in groundwater are saltwater intrusion into wells in coastal areas, naturally occurring brackish water in the aquifer, erosion of salt deposits and sodium bearing rock minerals, irrigation and precipitation leaching through soils high in sodium, groundwater pollution by sewage effluent, infiltration of leachate from landfills or industrial sites. For the study area average value of Na for 2013 are 579.36mg/l, 407.70mg/l, 368.26mg/l, and 199.42mg/l in Premonsoon; 463.96mg/l, 409.65mg/l, 34.67mg/l, and 136.65mg/l in monsoon and 644.70mg/l, 564.85mg/l, 396.73mg/l and 186.59mg/l in Post monsoon for Zone-I, II, III & IV respectively.

HCO_3

Bicarbonate ions are considered the source of water alkalinity (carbonate alkalinity). Bicarbonate dissolved in ground waters is derived from two principal natural sources. CO2 gas in the atmosphere or in the soil dissolved in water is the principle source of bicarbonate, in addition to solution of carbonate rocks and oxidation of organic matter. For the study area average value of HCO3 for 2013 are 332.94mg/l, 317.39mg/l, 353.13mg/l, and 347.15mg/l in Premonsoon; 368.85mg/l, 314.19mg/l, 313.13mg/l, and 402.82mg/l in monsoon and 386.91mg/l, 337.21mg/l, 302.34mg/l and 404.29mg/l in Post monsoon for Zone-I, II, III & IV respectively.

Cl

Majority of the chloride ions found in groundwater are of marine origin. Sea water can enrich the chloride concentration of ground water in several ways. First, chloride ions can be introduced to ground water through mixing with salt water either as lateral intrusion from saline water bodies or as highly mineralized water upconing from deeper aquifers. Second, chloride ions can be introduced to ground water through mixing either with connate water or water that was introduced during high stands of the sea subsequent to deposition. In either case, such aquifers have not been completely flushed of salt water by fresh-water circulation. Third, chloride ions can enter ground water through fallout of marine aerosols or through rainfall that has assimilated marine aerosols. For the study area average value of Cl for 2013 are 1190.39mg/l, 1180.31mg/l, 824.73mg/l, and 439.27mg/l in premonsoon; 908.83mg/l, 788.15mg/l, 610.50mg/l, and 179.00mg/l in monsoon and 796.83mg/l, 767.24mg/l, 603.67mg/l and 172.85mg/l in Post monsoon for Zone-I, II, III & IV respectively.

SO_4

The natural source of sulfate ions (SO_4^{2-}) in groundwater is dissolution of sulfate minerals that are found in sedimentary rocks such as gypsum and anhydrite. For the study area average value of SO_4 for 2013 are 143.99mg/l, 107.73mg/l, 128.51mg/l, and 60.76mg/l in premonsoon; 124.06mg/l, 105.16mg/l, 184.38mg/l, and 37.15mg/l in monsoon and 144.67mg/l, 123.07mg/l, 170.06mg/l and 39.54mg/l in Post monsoon for Zone-I, II, III & IV respectively

NO_3 and F

The source of Nitrate ion (NO3-) in natural water is from organic sources or from agricultural activities due to the use of fertilizers. The repetitive fertilizing processes (chemical or organic), contribute efficiently in the nitrate concentrations increasing in the shallow groundwater. For the study area average value of NO3 for 2013 are 37.57mg/l, 49.21mg/l, 47.84mg/l, and 40.36mg/l in remonsoon; 10.01mg/l, 17.43mg/l, 36.45mg/l, and 12.54mg/l in monsoon and 8.99mg/l, 17.73mg/l, 13.20mg/l and 9.10mg/l in Post monsoon for Zone-I, II, III & IV respectively. Bedrock containing fluoride minerals is generally responsible for high concentration of fluoride in groundwater. For the study area average value of F for 2013 are 0.71mg/l, 0.85mg/l, 1.23mg/l, and 0.94mg/l in premonsoon; 0.34mg/l, 0.54mg/l, 0.85mg/l, and 0.85mg/l in monsoon and 0.64mg/l, 0.91mg/l, 0.93mg/l and 0.79mg/l in Post monsoon for Zone-I, II, III & IV respectively.

Variation of Groundwater Quality Parameters

The average concentration of TDS, Na, Ca, Mg, and Cl are decreasing with the distance from the sea coast. The other parameters like HCO_3, SO_4, NO_3 and F concentrations have not followed any increasing or decreasing trend from the sea coast. Calcium and magnesium are the dominant cations present in groundwater next to sodium in this region. Similarly, bicarbonate anion is also present in considerable amounts next to chloride.

3.4 HYDROGEOCHEMICAL ANALYSIS FOR IDENTIFICATION OF SALINIZATION PROCESS IN THE MINSAR RIVER BASIN

The results show that the quality of groundwater in the Minsar catchment varies from place to place, completely fresh to extremely saline, depending on its origin, the sources of recharge and the pattern of groundwater movement in the aquifer. The investigations in the area indicate that the quality of water varies with the geological formations. The results from the chemical analyses were used to identify the geochemical processes and mechanisms in the Minsar River Basin.

3.4.1 Groundwater Classification

Piper (1944) classification is applied in the present study to evaluate the groundwater type. Ionic concentrations were plotted on a Piper diagram to evaluate the geochemical characteristics of the sampled groundwater. The projection of the points in the central diamond shape reveals the heterogeneity of the groundwater chemical composition in this basin. In this coastal coastal, groundwater composition is significantly dominated by alkalies (Na^+ and K^+) over the alkaline earth (Ca^{2+} and Mg^{2+}) and strong acids (Cl^-) exceed the weak acids (HCO_3 and SO_4^{2-}). The abundance of the alkalies elements is attributed to precipitation of Ca and Mg-rich silicate minerals in the aquifer matrix. Weathering of rocks results in the release of Na and Mg from K-feldspars and plagioclase into the environment, even though potassium has low mobility and remains associated with clay minerals. On the other hand, the position of the groundwater samples in the anions triangle indicates dominance of Cl and HCO_3 in the water.

The plots in Figs. 3.6-3.7 shows that most of the samples for Zone I and II analyzed during pre monsoon and monsoon seasons fall in the field of mixed Na-Cl and Ca-Mg-Cl type with minor representations from mixed Ca-Mg-HCO3, Ca-Na-HCO3 and Ca-Cl type while for Zone III, samples fall in the field of Na-Cl and Ca-Mg-Cl type with minor representations from mixed Ca-Cl and Ca-HCO3 type. For Zone IV, samples fall in the field of mixed Ca-Mg-HCO3 and Na-HCO3 type with minor representations from Na-Cl and Ca-Na-HCO3 type during pre monsoon season while monsoon season samples fall in the field of mixed Ca-Mg-Cl, Ca-HCO3 and Ca-Na-HCO3 type which shows freshening of water due to dilution effect of rainfall.

The possibility of origin of salinity in each zone is different. In Zones I, II and III, the position of data represents mixed Na-Cl and Ca-Mg-Cl types. The Cl is the major anion and Na and Ca is the major cation in groundwater present in these zones. This facies is characterized by low concentration of HCO_3 and relatively higher concentration of Cl and Na, which are mainly distributed among the marine sediments. For Zone I, multiple factors are responsible for salinity, like influence of seawater, evaporation effects, and saline water upconing due to over pumpage; while in Zone II and III, existence of old unleached marine water due to presence of low permeable Gaj clay formation, over pumpage and evaporation are the dominant factors responsible for the salinity. Due to over pumpage, migration of saline water from underlying saline zones occur that affects the freshwater wells in the region. The depths of the wells tapping the coastal aquifers vary because the fresh water /salt water interface varies. In Zone I, villages which are affected due to influence of seawater are Kuchhadi, Kantela, Zavar, Keshod and Odedar.

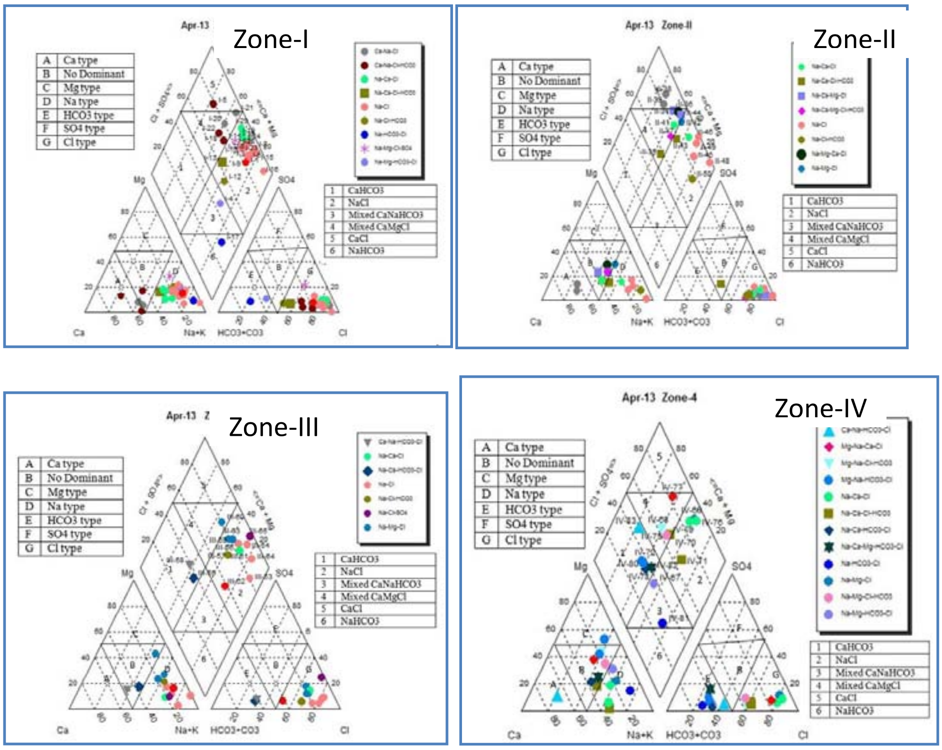


Fig. 3.6 Piper diagram of the groundwater samples from the study area for premonsoon season

In Zone IV, the position of data represents mixed Ca-Mg-HCO3 and Na-HCO3 types. HCO_3 is the major anion and Na and Ca are the major cations in the groundwater samples collected from this zone. This type of water occurs during rapid flow, which results in low ionic concentrations during high recharge. Areas near the foothills of Barda hills around Bakharla, Adityana and Simani villages represent major groundwater recharge zone.

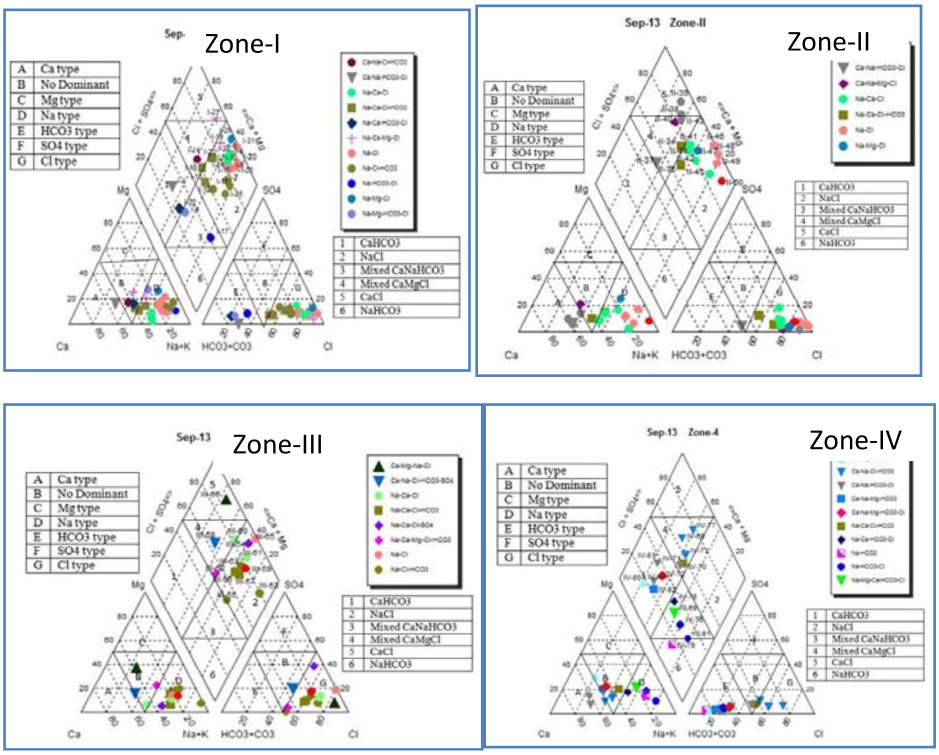


Fig. 3.7 Piper diagram of the groundwater samples from the study area for monsoon season

If groundwater simply mixes with seawater, groundwater composition should plot on a straight line connecting the background freshwater and the seawater on the diamond-shape field of the Piper diagram (Piper, 1944). However, the groundwater in the study area shows a curved path of hydrochemical evolution which starts from Ca-Na-HCO3 type via Na-HCO3 via Na-HCO3-Cl type to Na–Cl and Ca-Cl type; or from Na-Ca-HCO3 type directly to Na–Cl type.

Geochemical processes that could cause deviations from the ideal seawater-mixing line are chemical weathering, cation exchange, sorption, and pollution. The chemical weathering and cation-exchange processes are closely related to the type of rock that is in contact with the water.

3.4.2 Ion exchange

Ion exchange is a type of adsorption/desorption phenomenon. Clay minerals are the most common ion exchangers in soil and aquifer system. Cations present in the clay and groundwater are easily exchangeable than anion. pH of a solution also controls the exchange processes. Generally, fresh water in coastal terrain is dominated by the Ca^{2+} and HCO_3^- ions, as a result of dissolution of calcite and Ca^{2+} have mainly adsorbed on the surface (direct exchange), while in sea water, Na^+ and Cl^- are the dominant ions and sediment in contact with sea water will have adsorbed Na+ for large part (inverse exchange).

$2Na + (K^+) + Ca–X2 = 2Na (K^+) – X + Ca^{2+}$, and

$2Na^+ (K+) + Mg–X2 = 2Na (K^+) – X + Mg^{2+}$

Where, X represents ion exchange sites in aquifer materials.

In Zone-I, II, III and IV during post monsoon season most of the wells shows freshening as compared to pre monsoon season due to dilution of rain water while some wells shows reverse trend due to localized effect of pumping for irrigation. Pumping from coastal aquifers can cause the vertical rise of saltwater (upconing) and a reduction of the freshwater zone below pumping wells. In the present study 13%, 14%, 36% and 40% of samples shows negative value while 87% 86%, 64% and 60% of samples shows positive value of CAI-1 (refer Eq. 3.1) for Zone-I, II, III and IV respectively in pre monsoon season. However, for CA-2 (refer Eq. 3.2), 13%, 93%, 64% and 60% samples shows negative values and 87%, 7%, 36% &40% samples shows positive value Zone-I, II, III and IV respectively in pre monsoon season. For monsoon season, 53%, 21%, 45% & 33% of samples shows positive value while 47% 79%, 55% and 67% of samples shows negative value of CAI-1 for Zone-I, II, III and IV respectively. However, for CAI-2, 13%,79%,45% & 33% of sample shows positive value while 87%, 21%, 55% & 67% of samples shows negative value 1 for Zone-I, II, III and IV respectively. For post monsoon season, CAI-1 and CAI-2 shows same percentage of samples for positive and negative values and these are 37%, 57%, 36% and 20% for Zone-I, II, III and IV respectively.

3.4.3 Mineral Dissolution and Deposition

To understand the relation between different ionic species, inter-elemental correlation was made. It implies that ground-water chemistry was mainly controlled by the ions have good correlation with TDS. As a result, Na, K, Mg, Cl and SO4 have a good correlation with TDS (Table 3.1-3.3). The high correlation implies that groundwater chemistry was mainly controlled by these ions. A significant correlation of Cl observed with Na, Mg and Ca indicating most likely the source of saline water. The positive correlation of K with both Cl- and SO42-, which are all high in saline/seawater, may be interpreted in the light of seawater intrusion as well.

Table 3.1: Correlation Matrix for Pre monsoon

		pH	Cond	TDS	Na	K	Ca	Mg	Cl	HCO3	SO4	NO3
pH		1										
Cond	uS/cm	0.05	1									
TDS	mg/L	0.05	1	1								
Na	mg/L	0.0066	0.925	0.925	1							
K	mg/L	0.151	0.897	0.897	0.922	1						
Ca	mg/L	-0.379	0.598	0.598	0.575	0.36	1					
Mg	mg/L	-0.035	0.893	0.893	0.842	0.754	0.586	1				
Cl	mg/L	-0.0097	0.952	0.952	0.991	0.909	0.629	0.884	1			
HCO3	mg/L	-0.203	-0.276	-0.276	-0.252	-0.217	-0.3	-0.269	-0.3	1		
SO4	mg/L	0.08	0.935	0.935	0.82	0.798	0.532	0.881	0.846	-0.252	1	
NO3	mg/L	-0.26	0.182	0.182	0.137	0.038	0.487	0.233	0.142	-0.06	0.24	1

Table 3.2: Correlation Matrix for Monsoon

		pH	Cond	TDS	Na	K	Ca	Mg	Cl	HCO3	SO4	NO3
pH		1										
Cond	uS/cm	-0.038	1									
TDS	mg/L	-0.038	1	1								
Na	mg/L	-0.0022	0.985	0.985	1							
K	mg/L	-0.01	0.869	0.869	0.899	1						
Ca	mg/L	-0.244	0.705	0.705	0.668	0.418	1					
Mg	mg/L	-0.0094	0.955	0.955	0.947	0.857	0.608	1				
Cl	mg/L	-0.03	0.99	0.99	0.987	0.858	0.741	0.951	1			
HCO3	mg/L	-0.151	-0.219	-0.219	-0.186	-0.115	-0.259	-0.249	-0.23	1		
SO4	mg/L	0.045	0.881	0.881	0.863	0.688	0.631	0.859	0.85	-0.266	1	
NO3	mg/L	-0.026	0.118	0.118	0.079	0.023	0.193	0.218	0.114	-0.081	0.109	1

Table 3.3: Correlation Matrix for Post monsoon

		pH	Cond	TDS	Na	K	Ca	Mg	Cl	HCO3	SO4	NO3
pH		1										
Cond	uS/cm	-0.1850	1									
TDS	mg/l	-0.1840	0.9960	1								
Na	mg/l	-0.1080	0.9710	0.9670	1							
K	mg/l	0.1790	0.4410	0.4400	0.5220	1						
Ca	mg/l	-0.4970	0.3750	0.3680	0.2360	-0.1140	1					
Mg	mg/l	-0.1220	0.9130	0.9130	0.8800	0.3430	0.2100	1				
Cl	mg/l	-0.1680	0.9880	0.9850	0.9790	0.4630	0.3500	0.9120	1			
HCO3	mg/l	-0.0570	-0.3250	-0.3320	-0.2700	-0.1310	-0.2300	-0.3380	-0.3440	1		
SO4	mg/l	0.0760	0.6820	0.6800	0.6130	0.1160	0.2840	0.7810	0.6490	-0.3630	1	
NO3	mg/l	-0.4880	-0.0870	-0.0970	-0.1620	-0.1250	0.5720	-0.1920	-0.1030	0.0130	-0.1890	1

The Na-Cl relationship has often been used to identify the mechanisms to acquire salinity and saline intrusions in semi-arid/arid regions. In general, evaporation causes an increase in concentrations of all species in water. If the evaporation process is dominant, and no minerals species are precipitated, the Na-Cl ratio is unchanged. Hence the plot Na/Cl versus Cl would give a horizontal line for the present study area, which would indicate concentration by evaporation and transpiration. Figures 3.8(a)-(b) show most of the samples of Zone I, II, III and IV were affected by evaporation phenomenon and this effect was reduced during monsoon and post monsoon season. In the present study area, when Na is plotted against Cl, most of the samples lie below 1:1 trend line showing excess Cl.

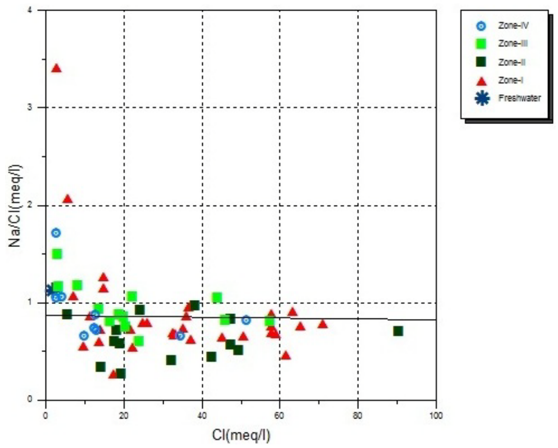


Fig. 3.8 (a) Scatter Diagram of Na/Cl Vs Cl for pre monsoon

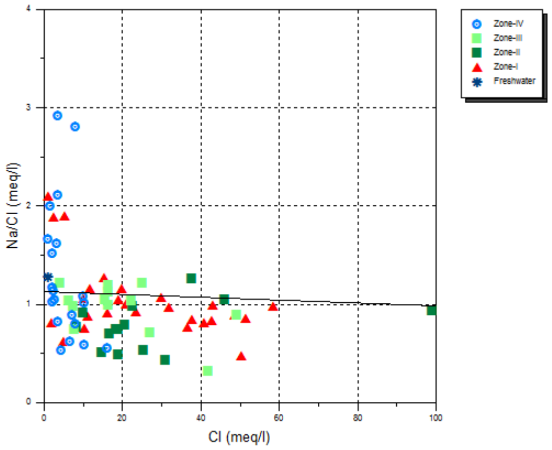


Fig. 3.8 (b) Scatter Diagram of Na/Cl Vs Cl for monsoon

The effect of salinization of the groundwater was classified using the Cl^-/HCO_3^- ratio as follows: 0.5 for unaffected groundwater, 0.5–6.6 for slightly and moderately affected, and 6.6 for strongly affected groundwater (Revelle 1941; Mtoni et.al., 2012). The bivariate diagram of Cl^-/HCO_3^- versus Cl^- (Fig. 3.9) shows that Zone I and II samples plot in strongly affected field, Zone III samples plot in slightly and moderately affected field and Zone IV samples lie in the not affected field of salinization.

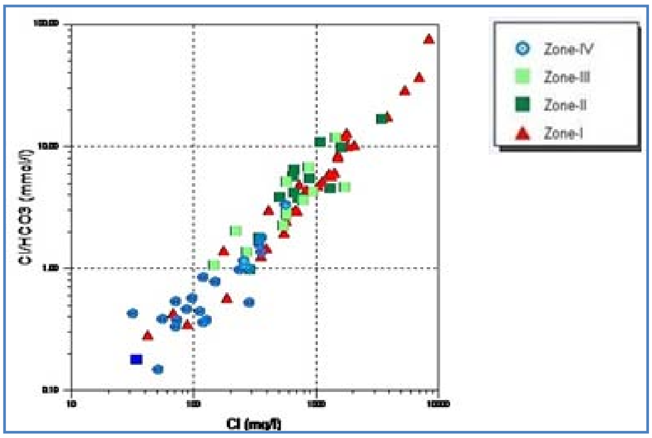


Fig. 3.9 Scatter Diagram of Cl/HCO3 Vs Cl for monsoon

The plot of Ca^{2+}+Mg^{2+}versus $SO4^{2-}$+$HCO3^{-}$ will be close to the 1:1 line if the dissolutions of calcite, dolomite and gypsum are the dominant reactions in a system. Ion exchange tends to shift the points to right due to an excess of $SO4^{2-}$+$HCO3^{-}$. If reverse ion exchange is the process, it will shift the points to the left due to a large excess of Ca^{2+}+Mg^{2+}over $SO4^{2-}$+$HCO3^{-}$ The plot of Ca^{2+}+Mg^{2+} versus $SO4^{2-}$+$HCO3^{-}$ (Fig. 3.10(a)-(b)) show that most of the groundwater samples of Zone I, II and III found above the 1:1 line except few samples which do not indicate reverse-ion exchange but extent is very less while Zone IV samples lies close to 1:1 line. Most of the points, which are placed in the Ca^{2+}+Mg^{2+} over $SO4^{2-}$+$HCO3^{-}$ side, indicate that carbonate weathering is the dominant hydrogeochemical process, while those placed below the 1:1 line are indicative of silicate weathering.

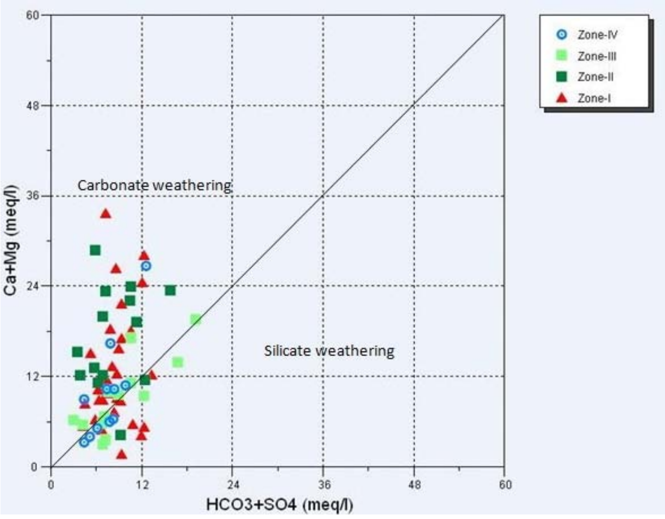


Fig. 3.10 (a) Scatter Diagram of Ca+Mg Vs HCO3+SO4 for pre monsoon

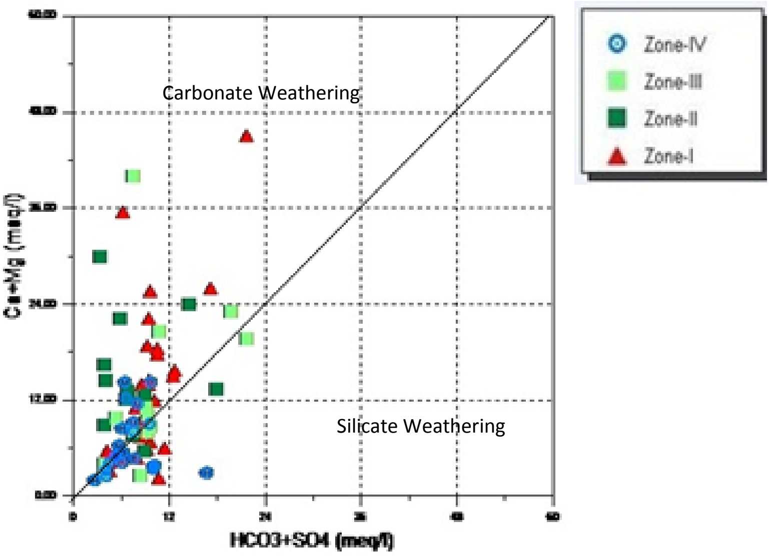


Fig. 3.10(b) Scatter Diagram of Ca+Mg Vs HCO3+SO4 for monsoon

3.4.4 Rock water Interaction

General presence of rock-water interaction was identified using TDS vs. Na/ (Na + Ca) and TDS vs. Cl (Cl+HCO_3) scatter diagrams (Figs. 3.11-3.13) as reported by Gibbs (1970).

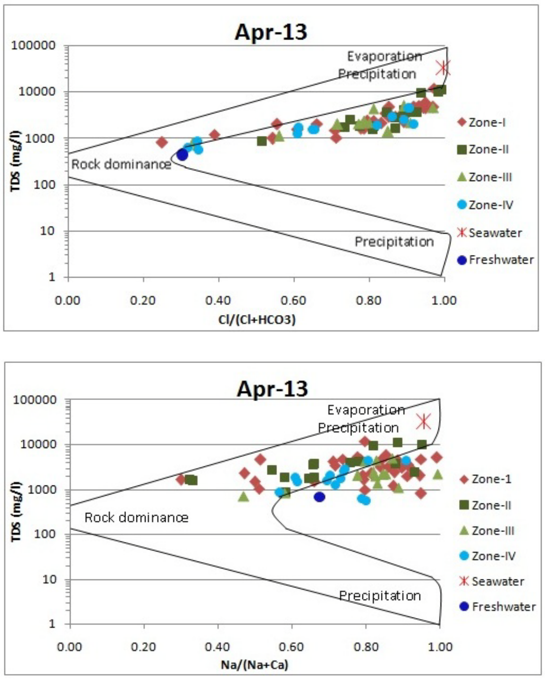


Fig. 3.11 Gibbs diagram, illustrating the mechanisms controlling the chemistry of groundwater samples in pre monsoon season

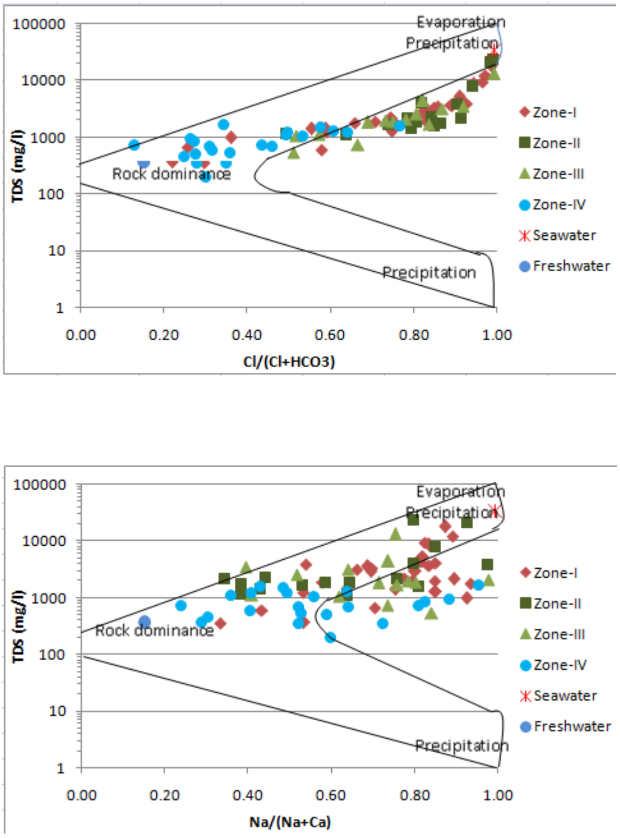


Fig. 3.12 Gibbs diagram, illustrating the mechanisms controlling the chemistry of groundwater samples in monsoon season

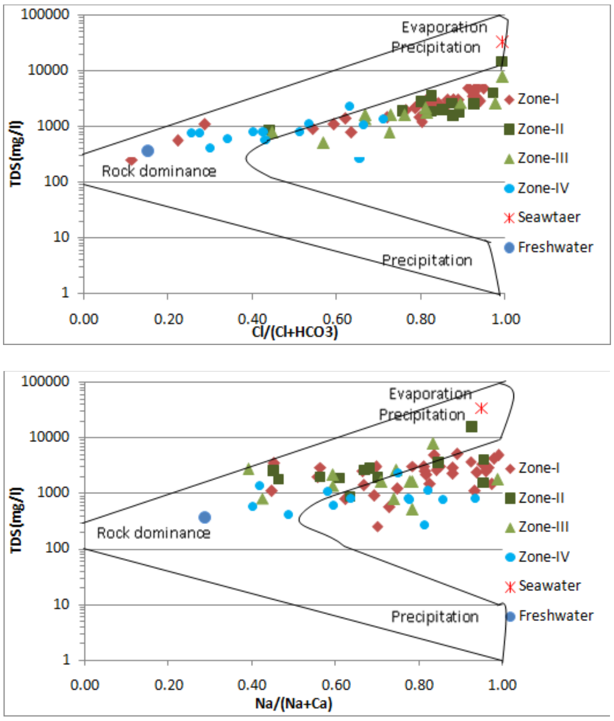


Fig. 3.13 Gibbs diagram, illustrating the mechanisms controlling the chemistry of groundwater samples in post monsoon season

3.5 ISOTOPE BASED ANALYSIS OF WATER SAMPLES

For isotopic characterization of water resources of the study area, the region is divided into three zones: (i) hilly region, (ii) coastal plain i.e. intermediate region and (iii) coastal belt (Fig.1). The groundwater in hilly region (Zone-III) receives its recharge from direct precipitation or through seepage from reservoirs or from the river channels draining the hill. The intermediate region (Zone-II) is a foot hill region and this region receives its groundwater recharge from three sources: direct precipitation, sub-surface inflow and recharge through local ponds/ reservoirs. Groundwater along the coastline (Zone-I) receives its recharge through direct precipitation, sub-surface inflow from the intermediate region, recharge through spreading channel (Zone-IB), seawater through surface creeks (Zone-IA) and recharge through surface water bodies (salt pans, local depressions etc).

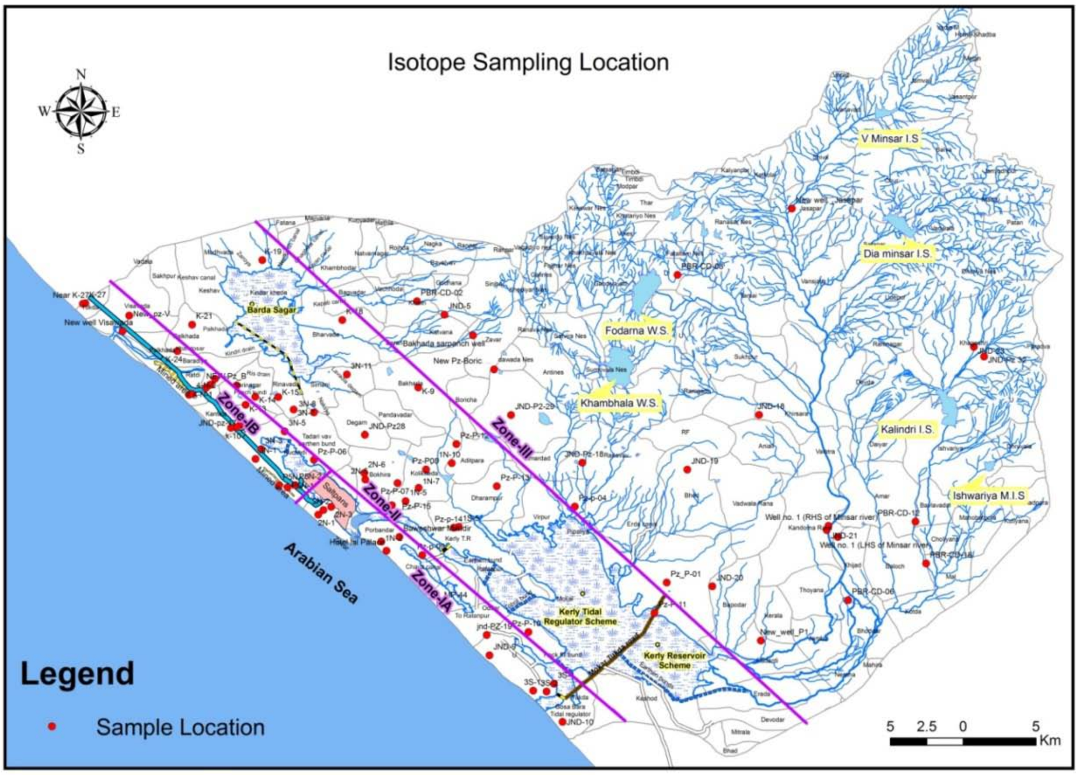
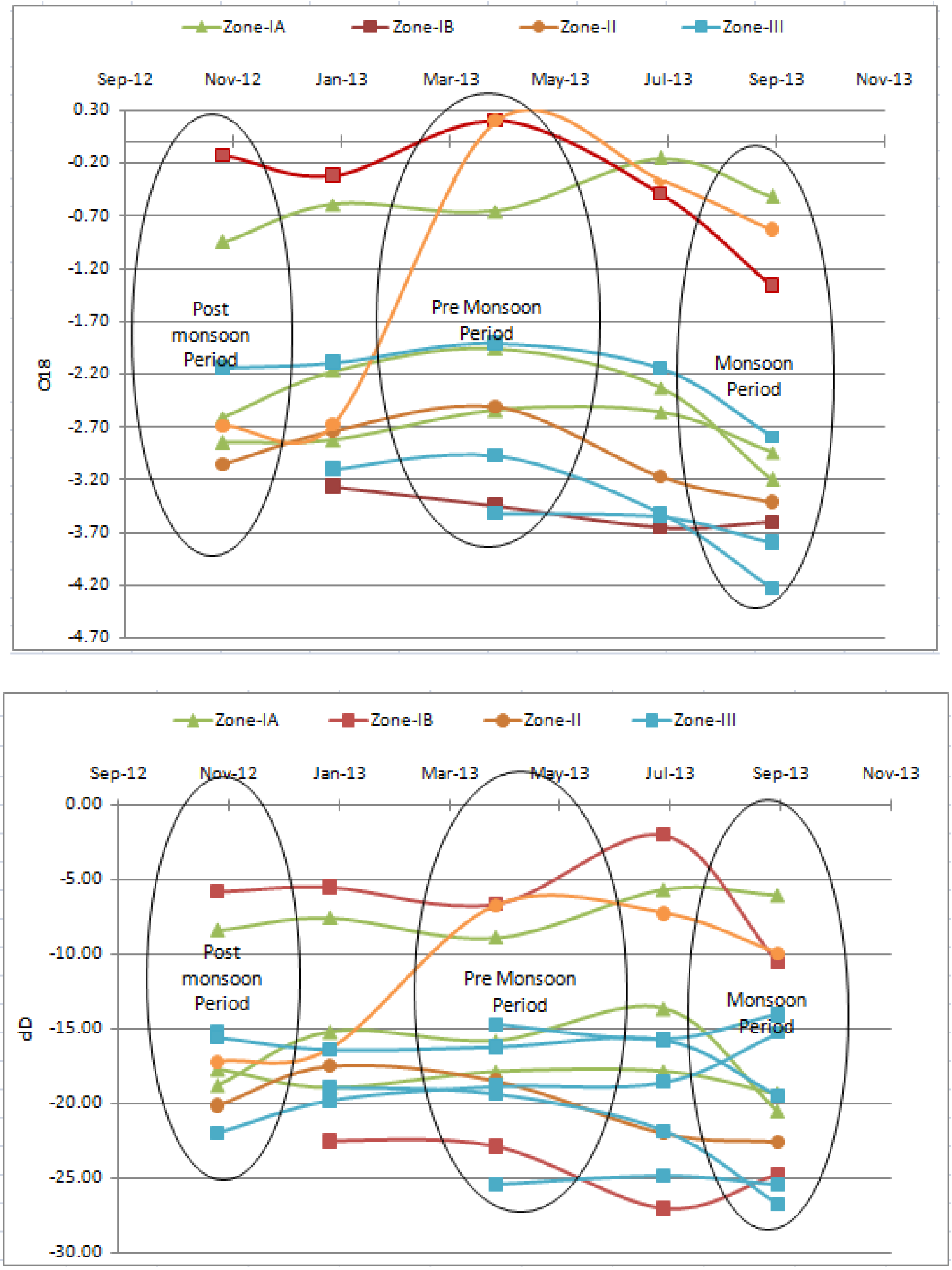


Fig. 3.14 Stable Isotope Sampling Locations in study area

During monsoon, it is expected that the groundwater in most of the region (especially, the Zone III) approaches the weighted average isotopic composition of the precipitation and after the monsoon withdrawal the isotopic composition of groundwater gets modified due to evaporation of delayed recharging groundwater component. Further, in Zones IA & IB, during the periods when water table goes deep the seawater intrusion (through direct surface connectivity or through sub-surface inflow) and recharging from salt pans becomes important in modifying the isotopic composition of the groundwater. In order to isotopically characterize these multiple recharge components and factors influencing the groundwater in various topographic regions; isotopic data of groundwater is divided and analyzed for the different topographic regions and for different seasonal periods.

The δ^{18}O and δd of groundwater samples of different zones collected at bi-monthly intervals over the period from September 2012 to September 2013 was analyzed and plotted to identify their temporal variation and spatial correlation pattern (Figs. 3.15(a)-(b)). The monthly stable isotope content showed a seasonal pattern of enriched δ^{18}O and δd values in non-monsoon period and depleted δ^{18}O and δd values in monsoon season. The most depleted value is observed for Zone-III (from higher altitude region) and these are: δ^{18}O= -4.24‰ δd= -26.77‰. This composition probably reflects the precipitation recharge in the Zone III especially from the region of high recharge efficiency (i.e., rapidly recharging component with no or very low enrichment due to evaporation during the recharge process). The most enriched value is observed for the Zone-IB (from coastal region) and these are: δ^{18}O= 0.2‰ δd= -2.01‰.



Figs. 3.15 (a)-(b) O^{18} and δ d groundwater composition during monsoon and non-monsoon period for different topographic units

Most of the wells show variation over the years (i.e. from ±0.15‰ to ±0.5‰) except for a few, such as one of the wells in Zone-II exhibited variation over the range from -3‰ to 0.25‰. Short variation indicates that isotopic composition of groundwater does not change over the year. This implies that three categories of wells are present; first, which show very small change in isotopic composition (±0.15‰); second, which show average variation i.e. ±0.5‰; and, third, that are very few in number but show very high variation i.e. ±1.5‰ over the season. One of the probable explanations for the large and small changes may be due to change in source water composition which further relates with turn-over time of groundwater i.e. formed from multiple recharge sources. The wells with minor change in isotopic composition indicates common recharge source and those with major variation indicates multiple recharge sources.

In order to examine the isotopic trend in groundwater along the riverbank of Minsar river and its tributaries and to discern the temporal variation in groundwater-river water interaction during different seasons and also to investigate the altitude effect in the groundwater (that represents average isotopic precipitation composition); samples were collected from the river bank sites of Minsar, Bileshwari, Dai, Dhangva, Dudi, Kalindri, Saran, Sorti and Vokro streams (Fig. 3.16). The observed isotopic data, plotted against the altitude of these sites, is shown in Fig. 3.17. The plotted data falls in 2 different trend lines, one with low slope (0.006‰ of δ^{18}O per km) and varies over the altitude range 15-80 m above mean sea level; isotopic range -2.8‰ to -3.1‰ and the other line with very steep slope (0.15‰ of δ^{18}O per km) and falls in the altitude below 15 m msl and the isotopic range -2.8‰ to -0.01‰. The slow enrichment in isotopic composition along the hill slope indicates converging of recharging groundwater recharged from multiple altitudes (altitude effect) along the groundwater flow path. The rapid change in isotopic composition below the elevation of 15 m cannot be explained with the same argument. Such a rapid change can only be explained if groundwater mixes with highly enriched water such as water originating from evaporating water bodies (salt pan) or seawater (since seawater has isotopic composition close to 0‰).

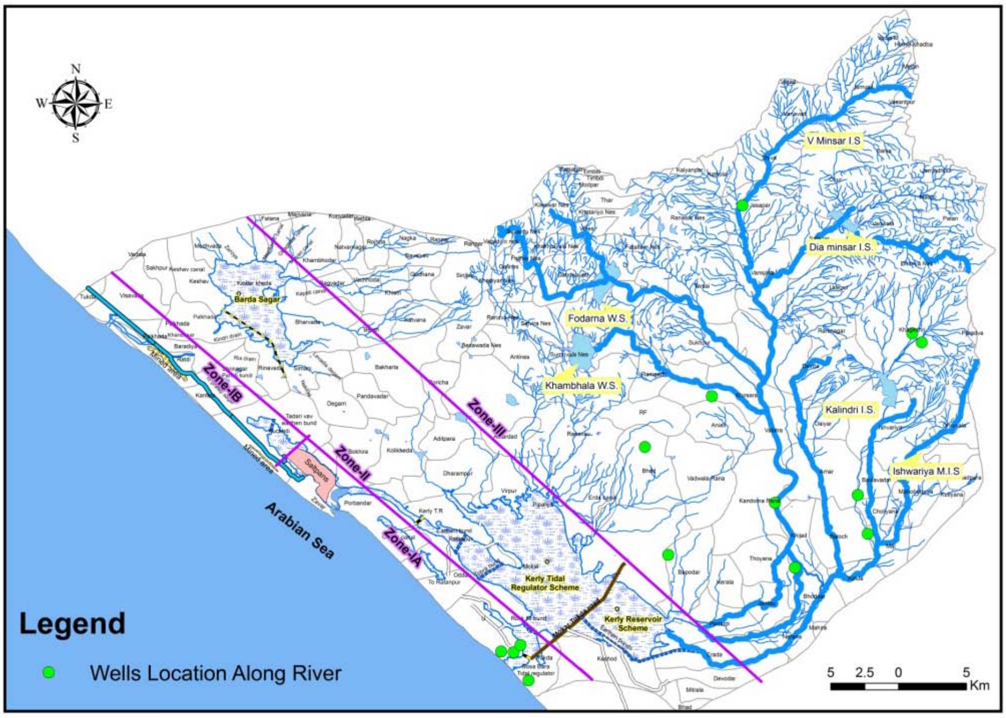


Fig.3.16 Sample location along the riverbanks

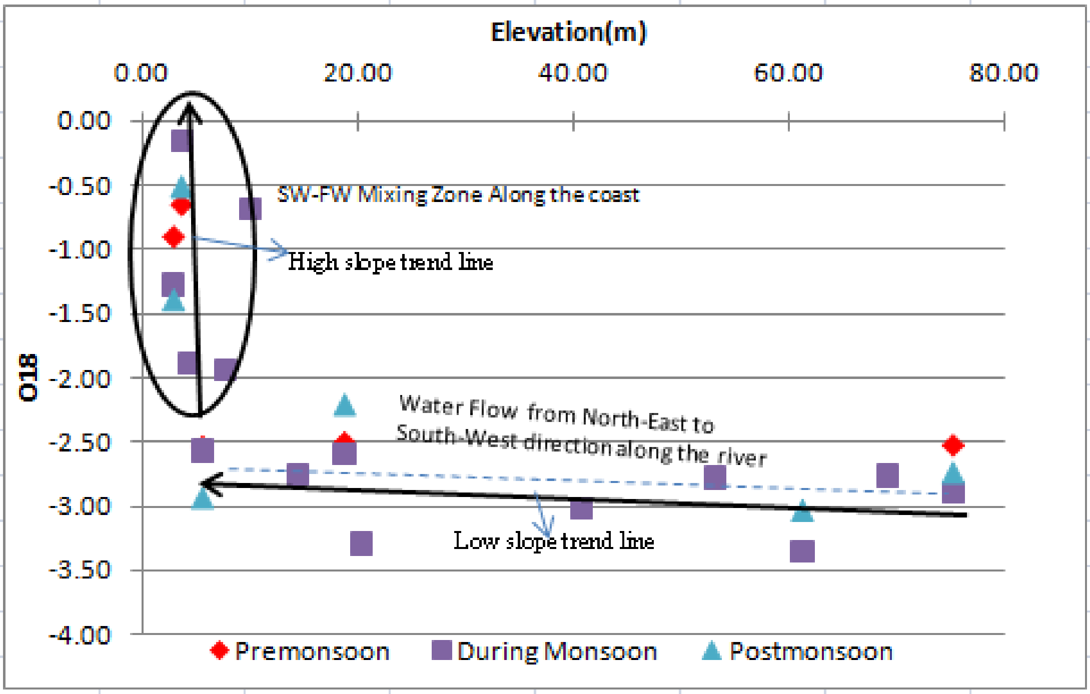


Fig.3.17 Isotopic composition of riverbank groundwater
(↓indicates isotopic depletion between pre and post monsoon season for water collected at same location)

To identify the groundwater salinity change with elevation and also to identify the source of this salinity by using isotopes, groundwater samples were collected from the river bank sites from Minsar, Bileshwari, Dai, Dhangva, Dudi, Kalindri, Saran, Sorti and Vokro streams, during pre- and post-monsoon 2013 from the elevation range 0 – 80 m above msl. The samples that were collected were spread out over a distance of 40 km from the sea coast. The objective of collecting groundwater samples is to get an overview of catchment effect of the watershed.

The variation of EC and O^{18} with elevation is shown in Fig. 3.18. The figure shows two important features:

i) The variation in EC and O^{18} is very gentle in the elevation range 15 – 80 m.
ii) Below the altitude of 15 m, both the EC and O^{18} changes very abruptly. The change over in the trend is at the elevation of 15 m.

The spatial distribution of these points in the study area shows that the points above 15 m altitude falls in the hilly terrain while below 15 m the plain region begins, and also there are several water logged regions. This indicates a direct correlation in the hydrological feature with EC and O^{18}. It is seen from this comparison that transition in recharge source take place at altitude of 15 m. Above 15 m altitude, the groundwater isotopic composition is depleted and groundwater is fresh as the source of recharge is precipitation and the recharge zone is in the hilly terrain. Below 15 m altitude, there is enrichment in O^{18} with EC. Further, in order to investigate the reason for enrichment in isotopic composition of $\delta^{18}O$ and δd, cross plot of samples along the river bank is plotted in Fig. 3.19.

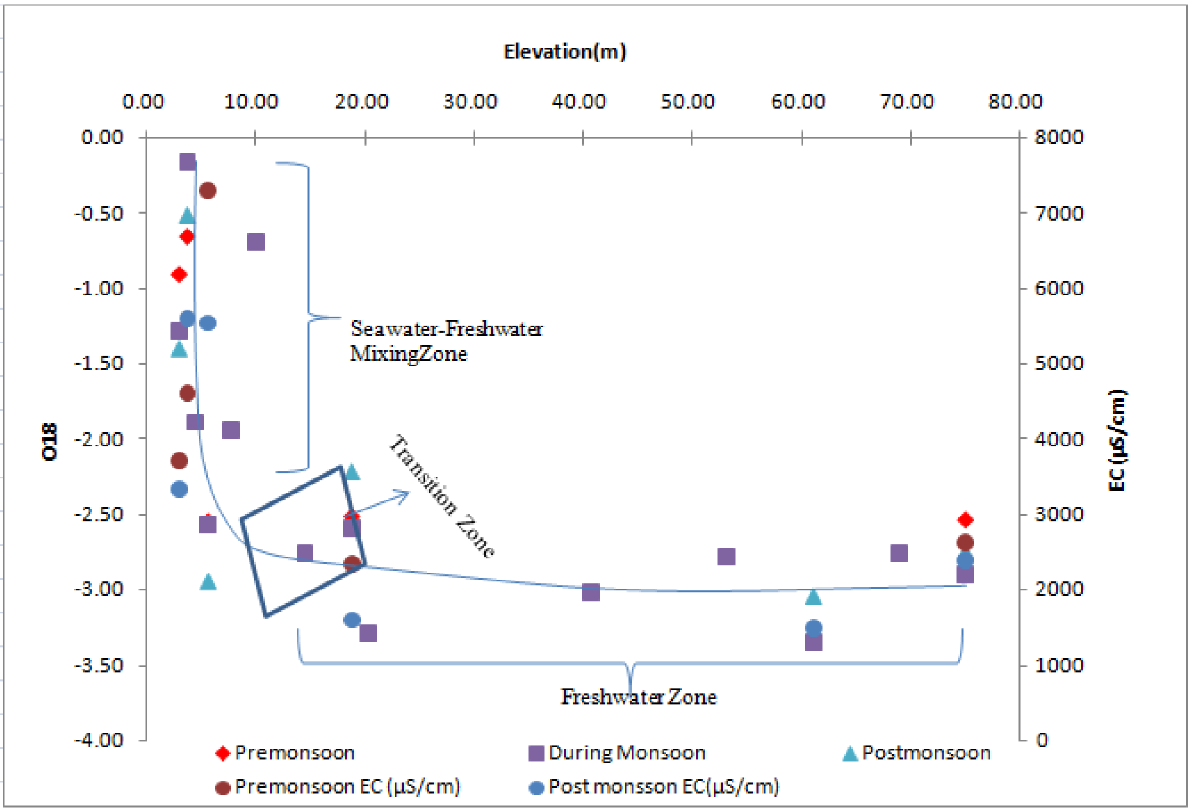


Fig.3.18 Plot for EC and O^{18} with elevation describing the GW-SW mixing zone, freshwater zone, transition zone and the effect of monsoon in diluting EC of groundwater

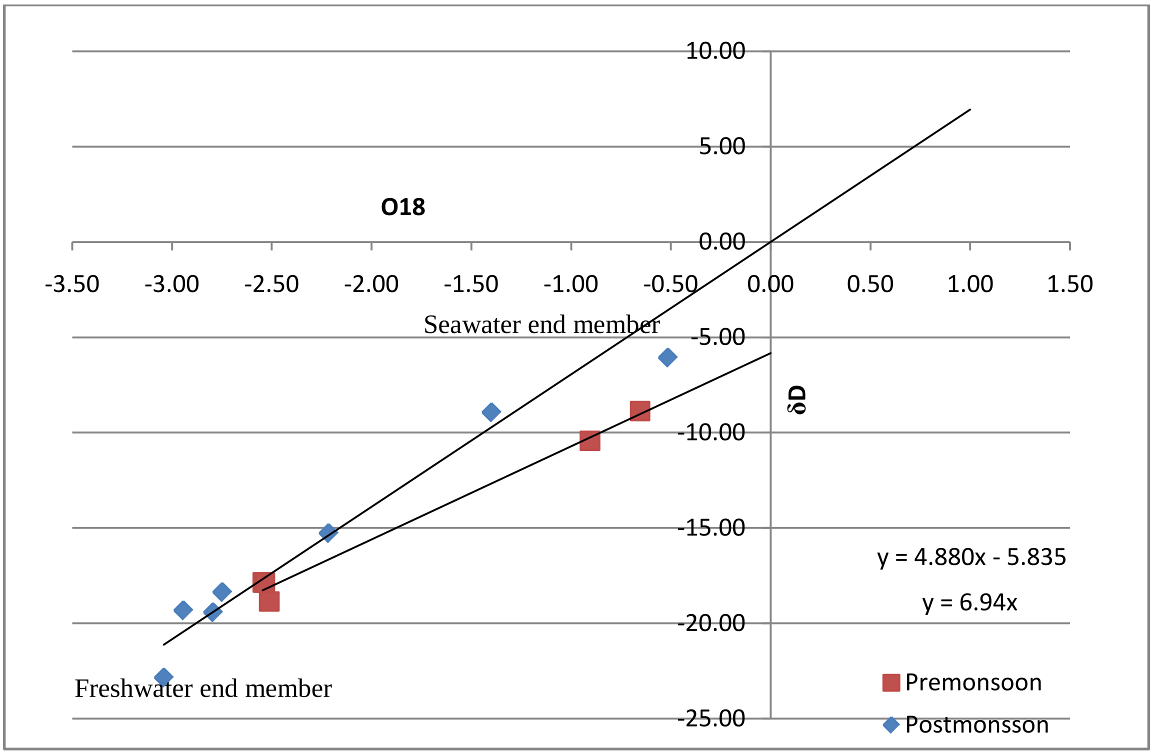


Fig.3.19 Cross plot of O18 and δd

In the plot, points fall on straight line passing through (0,0) origin (composition of seawater). Therefore, these points indicate mixing with seawater, since the fresh water isotopic composition is (-3.04‰ and -22.84‰) and has a EC value (<1500µS/cm), and with the progress of intrusion of seawater, O^{18} and δd enriches over to the sea value. The highest EC, O^{18}, and δd value observed in Fig. 3.19 is 7320 µS/cm, -0.52‰ and -6.06‰ respectively. Minor deviation from the mixing could be due to evaporation, in addition to mixing with seawater. The above interpretation is made for post-monsoon period only, as in the pre-monsoon period evaporation enrichment adds noise in the estimation of mixing percentage. From Figs. 3.18 and 3.19, it can also be seen that the difference between pre- and post-monsoon points is very marginal for O^{18} and δd values. The samples from lower altitude (Zone-IB) do not become more negative than O^{18} = -3.6‰.

From the study it is concluded that the zone of transition in the Ghed area is found at 15 m ± 3 m (approx.) altitude. For future studies, it is important to monitor this transition zone (at 12 m to 17m) to understand the influence of groundwater withdrawals, climate change, land use change and other anthropogenic activities that may cause this transition zone to fluctuate, by collecting isotopic, chemical and water level data at regular intervals for long duration. This change in spatial extent of transition zone over a time period is due to pre and post monsoon season or type of condition i.e. humid season, wet season and dry season.

It is advisable to use the groundwater resource from altitude much higher than this transition zone. Otherwise withdrawal from lower elevation can cause intrusion and expansion of saltwater-freshwater mixing / transition zone. Water bodies at the transition zone can be managed to store the freshwater precipitation runoff for its use during dry periods in place of groundwater withdrawal. This will help to shift the transition zone seawards and in expansion of the freshwater zone.

Chapter 4

Numerical Modeling Studies and Water Management Aspects

Irrigation water supply in a field near Kollikheda village

Downloading of data from data loggers

4.1 DEVELOPMENT OF CONCEPTUAL MODEL OF MINSAR BASIN AQUIFER SYSTEM

4.1.1 Interpretation of Lithologs

The oldest rock formation found in the Minsar river basin is Deccan trap basalt of Cretaceous to Eocene age. This hard rock formation is covering the upper inland region. The Supra-Trappeans comprising laterites are found to occur in some scattered patches overlain by Milliolitic limestone and Gaj clay. Rocks of Gaj formation comprising limestone, grit, sand, silt, and gypseous clay of Miocene age were formed in marine environment. In central tract, Deccan trap is overlain by lower Miocene Gaj beds comprising limestone and clay and in time overlain by Milliolitic limestone of Pleistocene to sub recent age. At places sub recent to recent alluvial deposits are found scattered at the top of Milliolitic limestone and clay.

A total of 472 lithologs of the wells drilled in the region by GWRDC and CGWB were collected from respective organizations. Out of the available 472 lithologs, 390 lithologs, ranging in depth from 15 to 152 m, were selected for further analysis. Other logs, not considered, were of shallow wells, ranging in depth from 3 to 4 m. The selected lithologs included 25 logs of piezometers provided by CGWB that were drilled to deeper depths (under the National Aquifer Mapping Program), some of them located in the coastal region. These lithologs from deeper piezometers near the coast were important in interpreting the geological formations in the coastal belt. As such, the analysed data represent lithologs of 390 locations up to the depth of about 152 m below ground level. The selected logs were plotted and interpreted with the help of ROCKWORKS software. Figure 4.1 shows the multiple logs view of the stratigraphy logs.

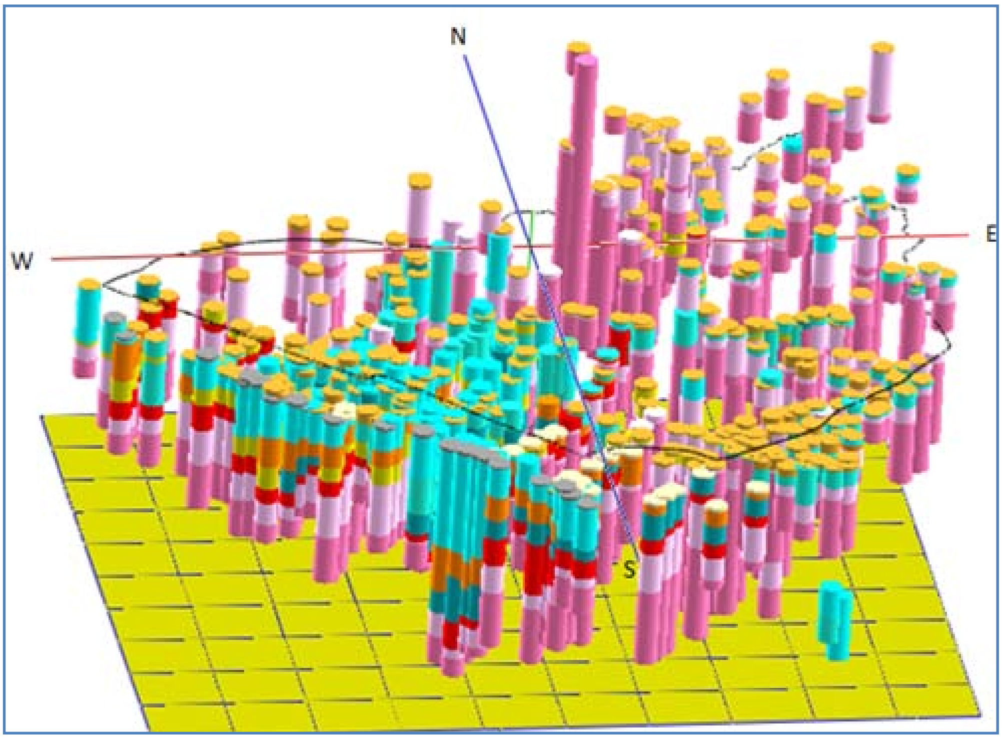


Fig. 4.1 3D multiple logs view of the stratigraphy logs

The logs indicate presence of limestone, represented by blue color, in the coastal belt. In the upland area, basalt is prominent (pink color) with weathered basalt represented by light pink color

4.1.2 Construction of Fence Diagram

In addition to the litholog data, geophysical surveys were carried out by GWRDC using the surface resistivity method in which 555 VES (Vertical Electrical Soundings) with Schlumberger configuration were conducted and 814 wells were inventoried for correlation studies along the Saurashtra coast. The investigations were conducted along 29 profiles oriented perpendicular to the coast. The profile lines were located at an interval of 5-7 km and geoelectrical soundings were taken upto a distance of 6-13 km inland. The profiles were located in different formations and also from saline water to freshwater areas. The geoelectrical cross sections along representative profiles were drawn by GWRDC using the above method. Interpretation from a total of 8 such profiles, falling in the study area, was additionally utilized for construction of fence diagram.

Based on the position and depth of the geological formations, the logs were correlated to construct the subsurface aquifer geometry of the area. The fence diagram of the area is presented in Fig. 4.2.

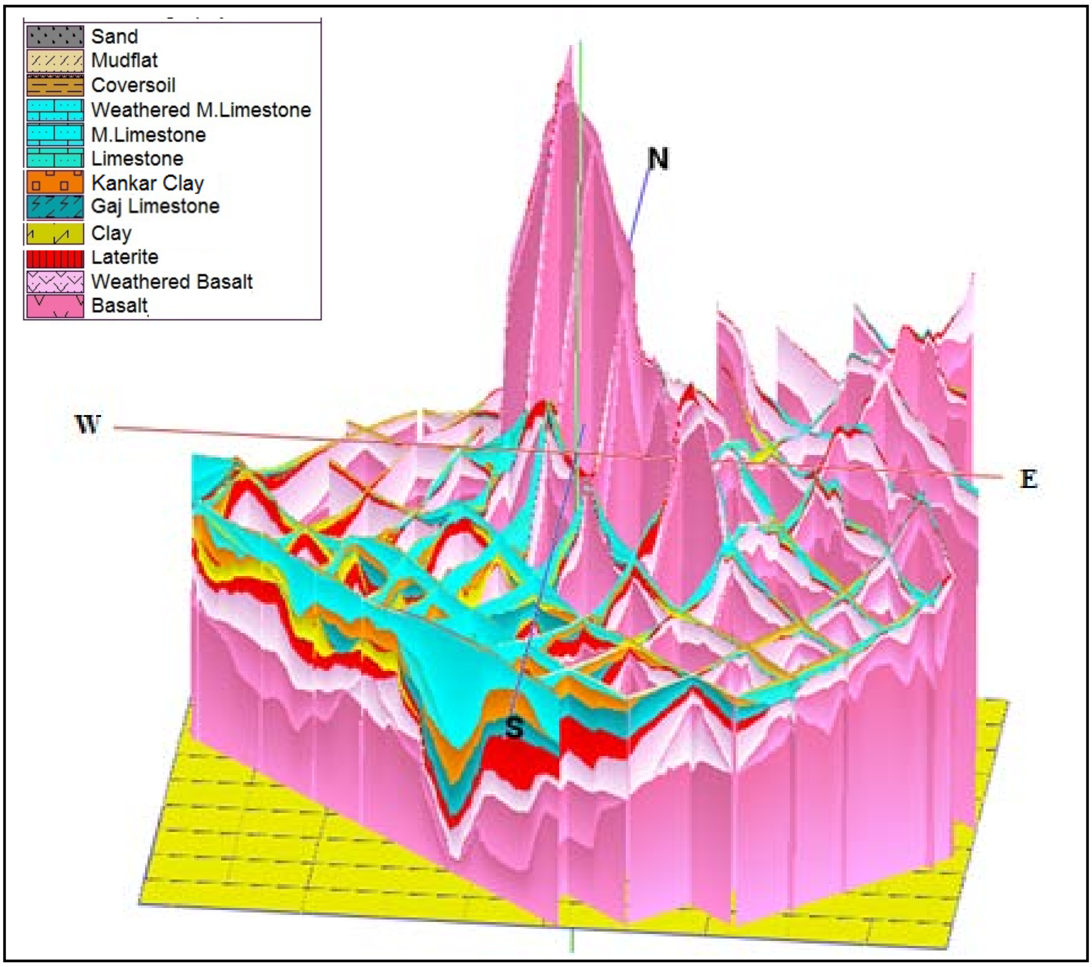


Fig. 4.2 Fence diagram of study area

The fence diagram indicates that the aquifer system in Minsar River Basin can be considered as unconfined in nature. The bottom elevation of the aquifer can be taken to be the bottom elevation of weathered basalt. The aquifer is thicker near the coast. The aquifer seem to be in contact with seawater and may be responsible for the intrusion of seawater in areas where low or negative head gradients exist. Seven cross-sections along sections AA’ to GG’ (refer Fig. 4.3) are shown in Figs. 4.4 - 4.10.

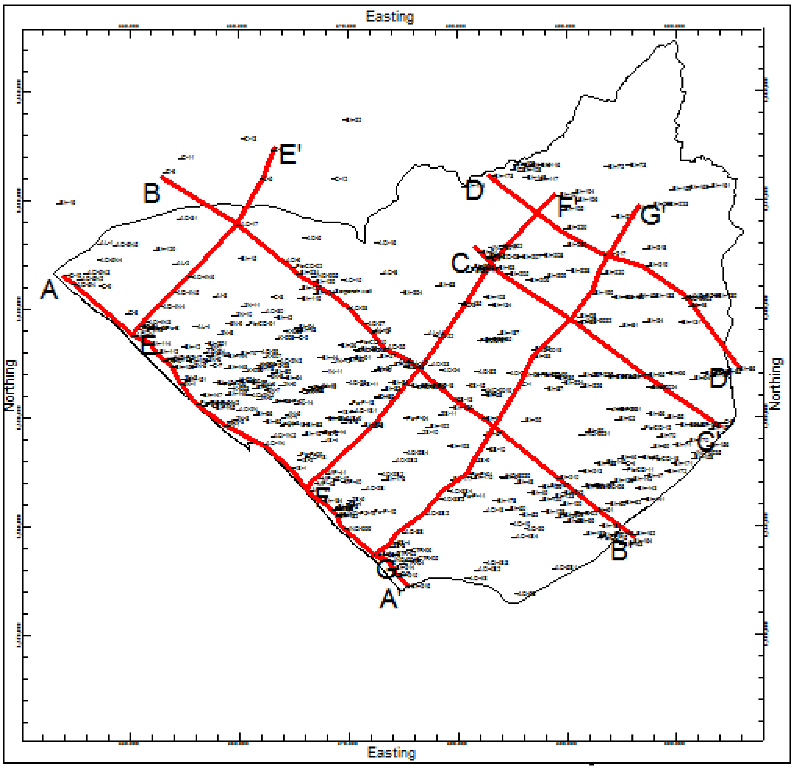


Fig. 4.3 Layout of sections AA’ to GG’.

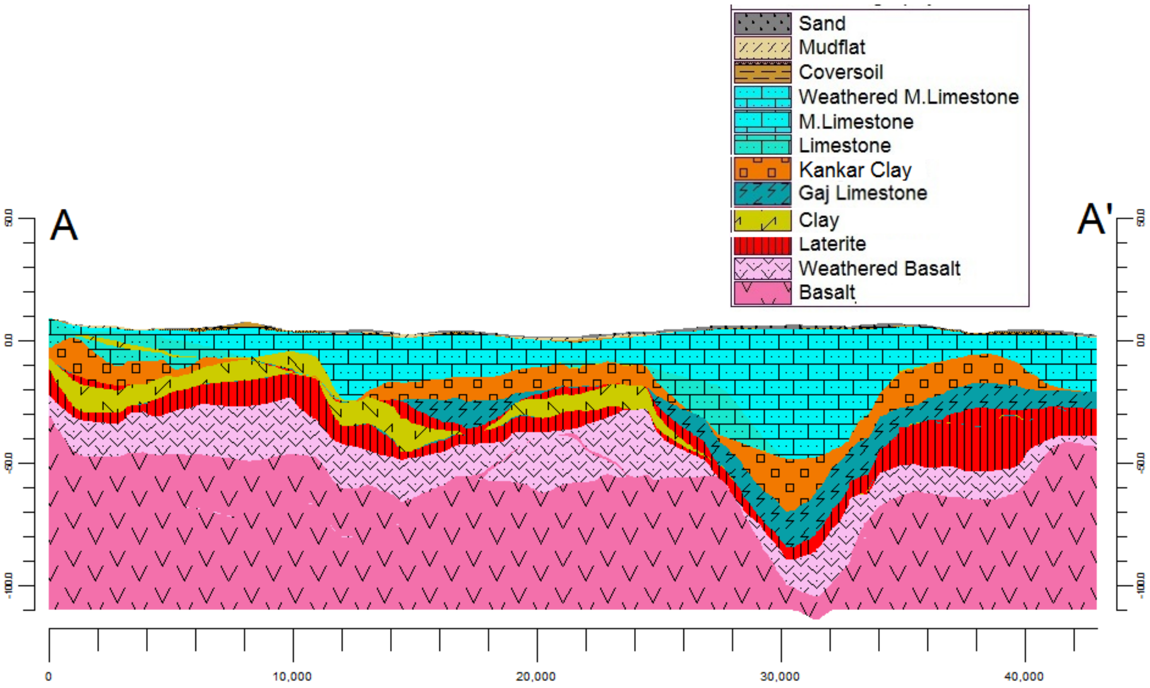


Fig. 4.4 Section along AA’

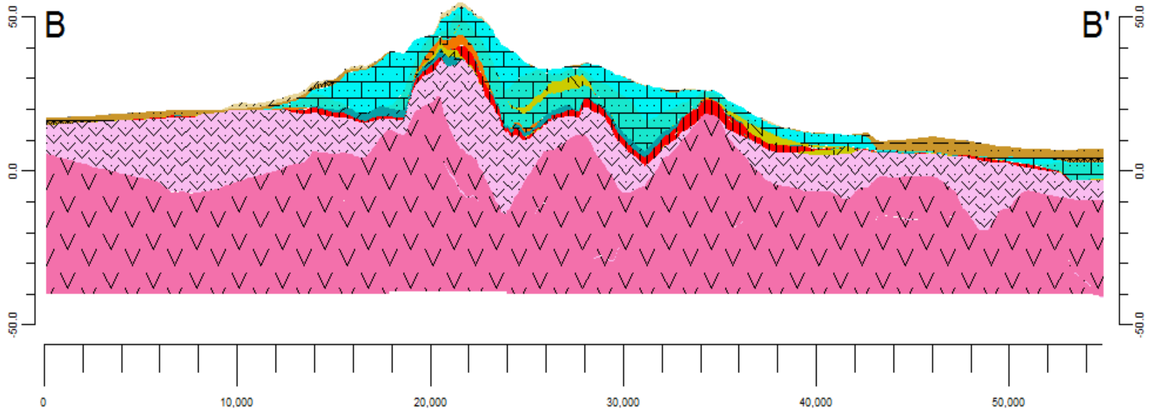


Fig. 4.5 Section along BB’

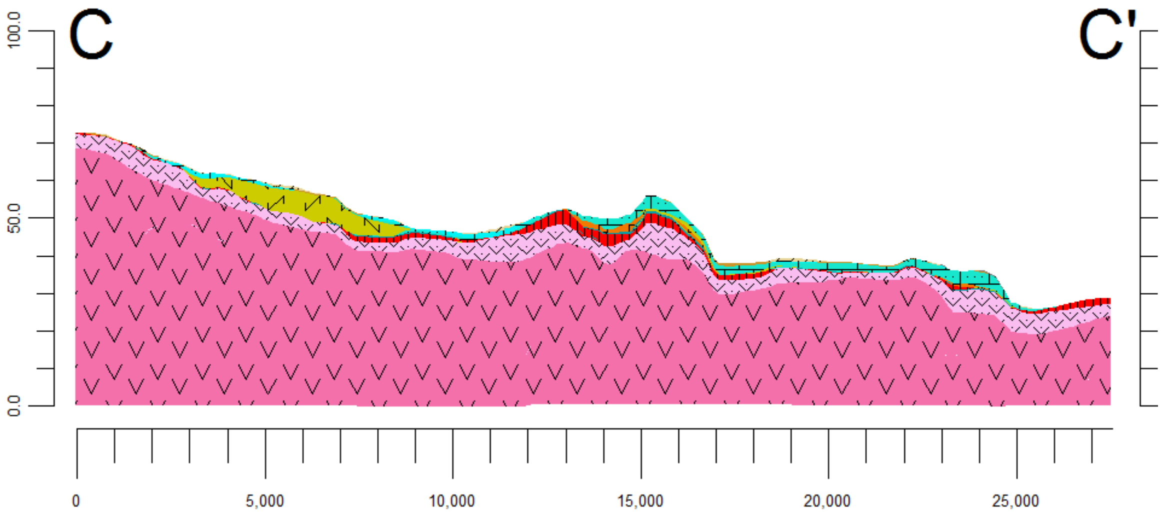


Fig. 4.6 Section along CC’

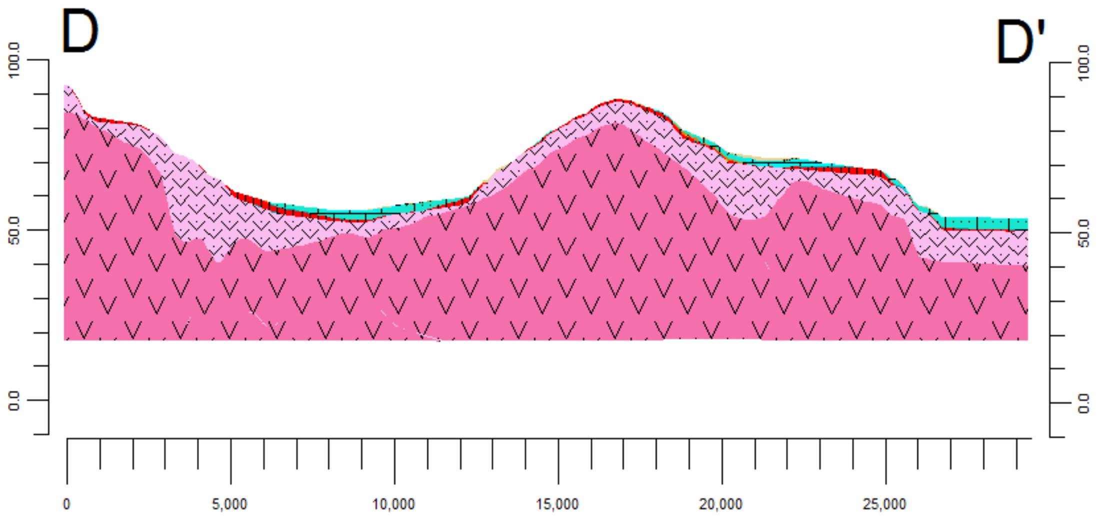


Fig. 4.7 Section along DD’

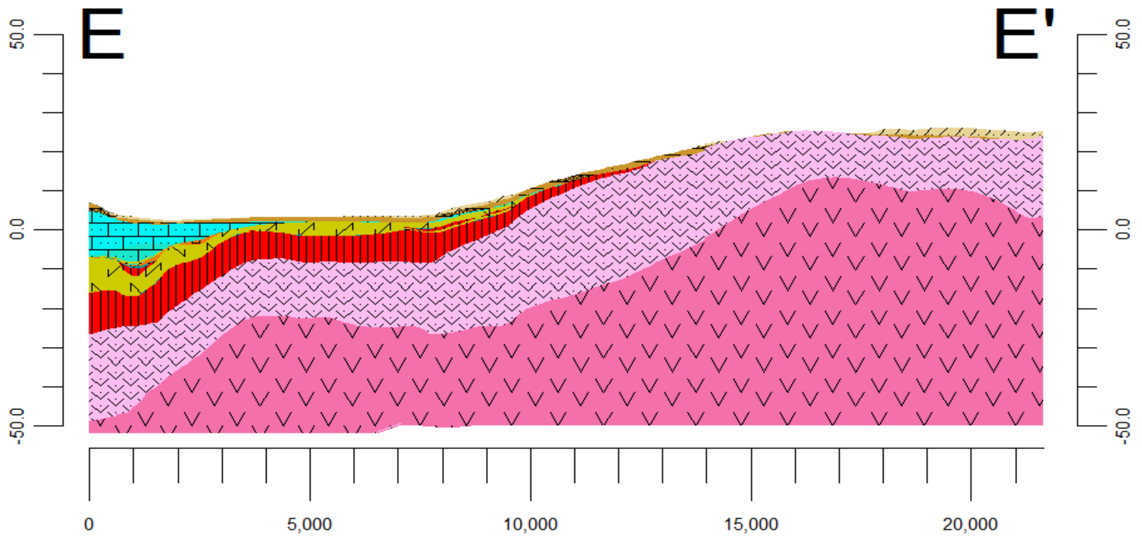


Fig. 4.8 Section along EE’

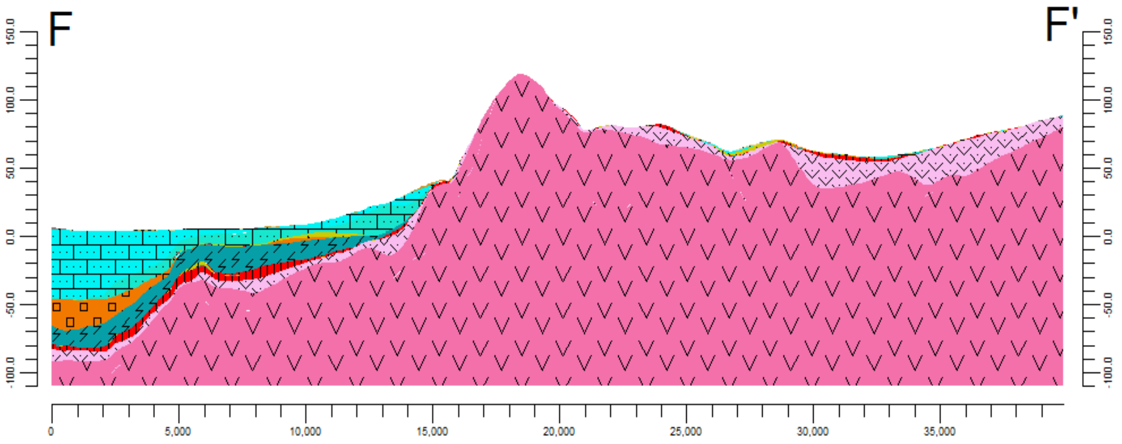


Fig. 4.9 Section along FF’

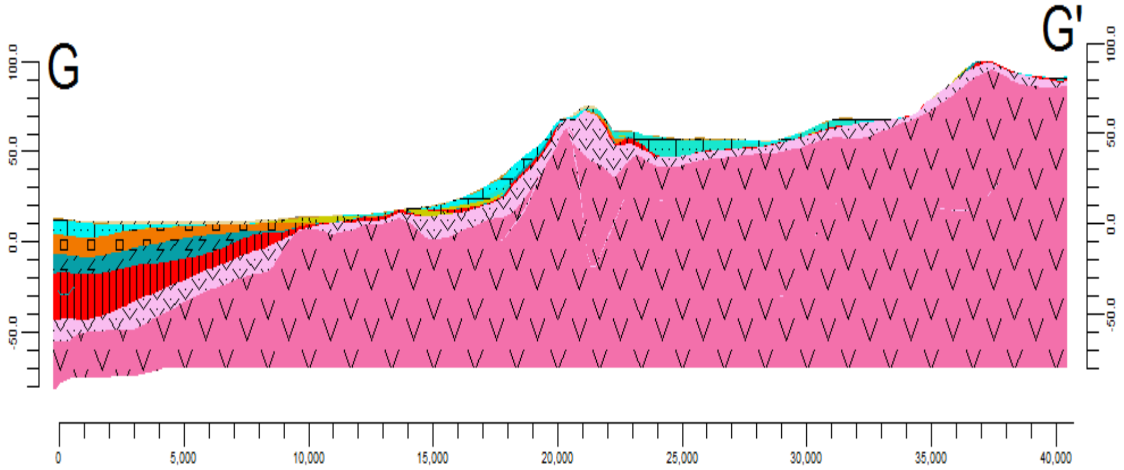


Fig. 4.10 Section along GG’

As per the recent deep piezometer litholog data, obtained from CGWB, the thickness of milliolitic limestone is about 50 m in and around Odedar and Ratanpur villages. The milliolite limestone with upper hard and compact layers are exposed near villages Tukada, Ratanpur and Gosa.

4.1.3 Groundwater Flow Paths

Figure 4.11 shows a schematic of the study area. Freshwater flows into the region mainly from upland area and recharges the aquifer. The foothills of Barda are also a major recharge zone. At the coast, where the aquifer system is exposed to the sea, saline water may migrate inland due to a lowering of the water table in some pockets. The saline water, already existing at deeper depths in Gaj formations may also get transported vertically (upconing) to shallow depths in response to pumping which sets up vertical gradients. Some of the water may get transpired from the shallow water table areas and crop lands. Submarine discharge may take place due to higher gradients of hydraulic head towards the seaward side. The possible flow paths are indicated in Fig. 4.11.

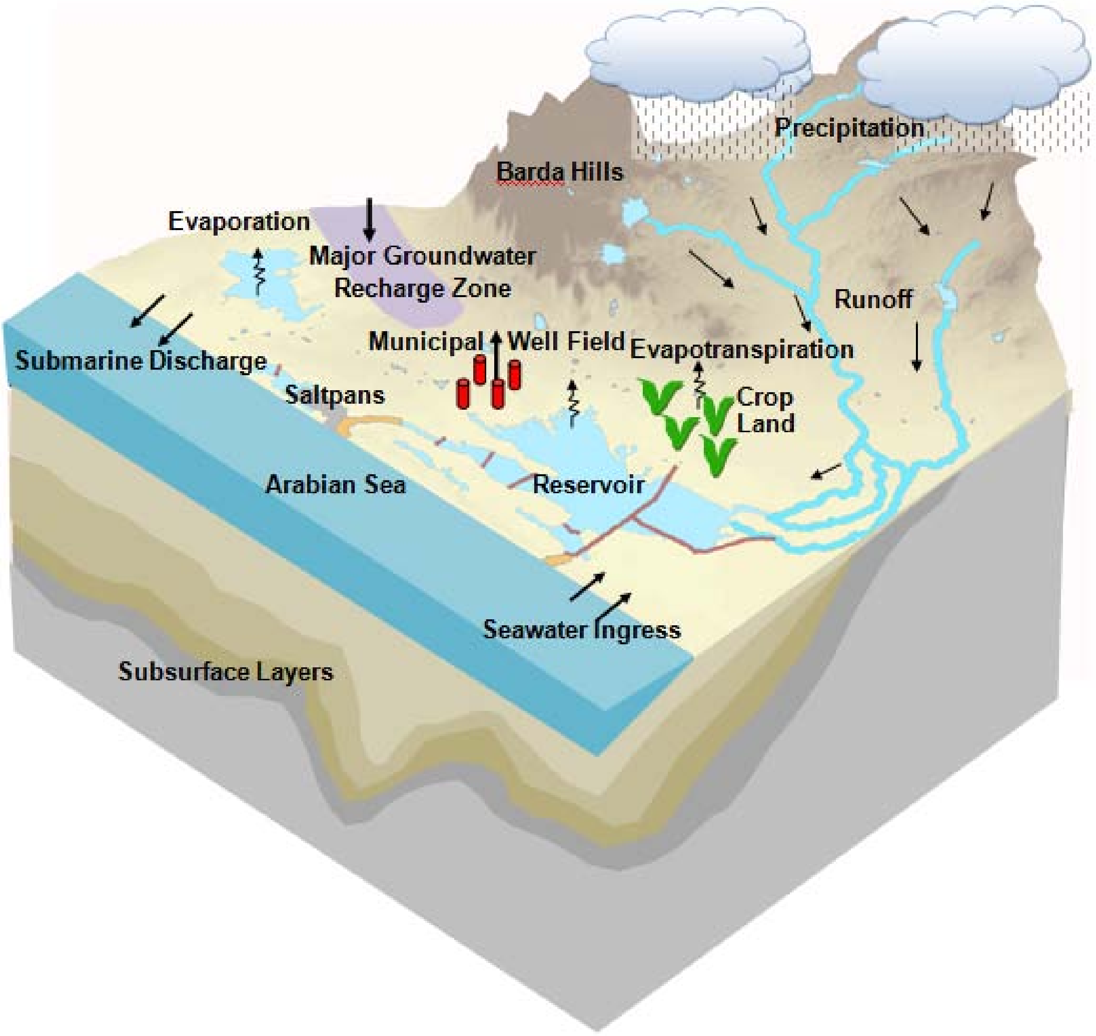


Fig. 4.11 Schematic of the coastal aquifer system of Minsar river basin showing possible groundwater flow paths and hydrological processes.

4.2 PRINCIPLES OF VARIABLE DENSITY GROUNDWATER FLOW

Numerical simulation of solute transport through a porous medium requires the solution of the governing partial differential equations of groundwater flow and solute transport. Depending on the assumptions that are valid for a particular problem, the groundwater flow equation can be expressed in several forms. For field problems in general, the flow equation is written assuming the density of groundwater to be spatially and temporally constant.

However, in order to simulate groundwater flow in a coastal aquifer that is in hydraulic connection with the sea, the assumption of constant density is not valid because seawater contains a higher concentration of dissolved salts than rainfall, which is the main source of recharge to an aquifer. Since fluid density is a function of dissolved salt, the density of fluid (i.e. mixed fluid comprising saltwater and freshwater) in a coastal aquifer is not equivalent to that of freshwater. The density difference between fresh groundwater and saltwater can significantly affect groundwater flow patterns (Kohout, 1960). Evans and Raffensperger (1992) showed that mass fluxes rather than volumetric fluxes (used in constant density fluid flow) must be used to describe the flow of groundwater if the variation in fluid density is substantial.

Thus, numerical modeling of saltwater transport through a porous medium requires the simultaneous solution of the following coupled equations:

i. Flow equation derived from the combination of conservation of total fluid mass and Darcy's Law for flow in porous media,
ii. Solute transport equation through a porous medium derived from the conservation of mass for a single-solute species,
iii. Equation of state relating fluid density to solute concentration.

The above equations are coupled through the dependence of advective and dispersive transport on the seepage velocity field, and the equation of state relating fluid density to solute concentration.

Fluid Flow: The general form of the partial differential equation governing flow of variable density groundwater can be written as follows (Bear, 1979):

$$-\nabla.(\rho q) + \rho^* q^* = \rho S_p \frac{\partial p}{\partial t} + \phi \frac{\partial \rho}{\partial c}\frac{\partial c}{\partial t} \qquad (4.1)$$

where ∇ is the gradient operator, ρ is the fluid density [ML^{-3}], q is the specific discharge vector [LT^{-1}], ρ^* is the density of water entering from a source or leaving through a sink [ML^{-3}], q^* is the volumetric flow rate per unit volume of aquifer representing sources and sinks [T^{-1}], c is the solute concentration [ML^{-3}], ϕ is porosity [dimensionless], and t is time [T].

Mass fluxes are defined as the product of fluid density and the specific discharge, or volumetric flow per unit cross-sectional area of bulk porous medium. Specific discharge is computed using Darcy's Law for variable density fluid as follows:

$$q_x = -\frac{k_x}{\mu}\frac{\partial p}{\partial x}; \quad q_y = -\frac{k_y}{\mu}\frac{\partial p}{\partial y}; \quad q_z = -\frac{k_z}{\mu}\left(\frac{\partial p}{\partial z} + \rho g\right) \tag{4.2}$$

where q_x, q_y, q_z are the individual components of specific discharge, μ is the dynamic viscosity [$ML^{-1}T^{-1}$], k_x, k_y, k_z represent intrinsic permeabilities [L^2] in the three coordinate directions, and g is the gravitational constant [LT^{-2}].

Solute Transport: The partial differential equation governing 3D transport of solute mass in groundwater can be written as follows (Zheng and Bennett, 1995):

$$\frac{\partial c}{\partial t} = \nabla.(D.\nabla c) - \nabla.(\mathrm{v}c) - \frac{q^*}{\phi}c^* + \sum_{k=1}^{N} R_k \tag{4.3}$$

where D is the hydrodynamic dispersion coefficient [L^2T^{-1}], v is the fluid velocity [LT^{-1}], c^* is the solute concentration of water entering from sources or sinks [ML^{-3}], and R_k (k = 1, …, N) is the rate of solute production or decay in reaction k of N different reactions [$ML^{-3}T^{-1}$].

Equation of state: Under isothermal conditions, fluid density is a function of fluid pore pressure and solute concentration. Therefore, the equation of the state for fluid density is:

$$\rho = f(p, c) \tag{4.4}$$

The effects of pore pressure on fluid density are included in the storage term in fluid flow equation (Eq. (5.1)). The empirical relation between the saltwater density and concentration is (Baxter and Wallace, 1916):

$$\rho = \rho_f + E\,c \tag{4.5}$$

where E is a dimensionless constant with an approximate value of 0.7143 for salt concentration ranging from zero to that of seawater, and c is salt concentration [ML^{-3}].

It is to be noted that Eq. (5.5) is applicable only for typical seawater for which the relation between fluid density and solute concentration can be expressed as a linear function.

4.2.1 Concept of Equivalent Freshwater Head

The fluid flow equation as expressed in Eq. (5.1) uses pressure as the independent variable. Alternatively, the variable density flow equation can also be written in terms of equivalent freshwater head.

Freshwater head (h_f) is defined as the elevation to which freshwater will rise in a cased well, and is expressed as:

$$h_f = \frac{p}{\rho_f g} + z \tag{4.6}$$

where ρ_f is the density of freshwater.

Following equations are used to convert head (h) at a specific density (ρ) to freshwater head (h_f) and vice-versa:

$$h_f = \frac{\rho}{\rho_f} h - \frac{\rho - \rho_f}{\rho_f} z \tag{4.7}$$

$$h = \frac{\rho_f}{\rho} h_f + \frac{\rho - \rho_f}{\rho} z \tag{4.8}$$

Thus, for a horizontally stratified aquifer, Darcy's Law in terms of equivalent freshwater head can be expressed as:

$$q_x = -K_{fx} \frac{\mu_f}{\mu}\left[\frac{\partial h_f}{\partial x}\right];\ q_y = -K_{fy} \frac{\mu_f}{\mu}\left[\frac{\partial h_f}{\partial y}\right];\ q_z = -K_{fz} \frac{\mu_f}{\mu}\left[\frac{\partial h_f}{\partial z} + \left(\frac{\rho - \rho_f}{\rho_f}\right)\right] \tag{4.9}$$

where K_f is the equivalent freshwater hydraulic conductivity (e.g. in x-direction $K_{fx} = (\kappa_x \rho_f g)/\mu_f$), and μ_f is the viscosity of freshwater.

The governing flow equation for variable density fluid in terms of equivalent freshwater head is:

$$\frac{\partial}{\partial x}\left[\rho K_{fx}\left(\frac{\partial h_f}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[\rho K_{fy}\left(\frac{\partial h_f}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left[\rho K_{fz}\left(\frac{\partial h_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f}\right)\right] + \rho^* q^* = \rho S_f \frac{\partial h_f}{\partial t} + \phi \frac{\partial \rho}{\partial c}\frac{\partial c}{\partial t} \tag{4.10}$$

where S_f is the equivalent storage term, defined as the volumetric release of freshwater from storage per unit area per unit decline in freshwater head.

4.3 MODELLING APPROACH

Numerical modeling of variable density flows is an intricate task, because the velocity field changes in accordance with the time-variant saltwater concentration, which in turn depends upon the existing groundwater heads. In order to simplify the modeling process, as well as to simulate the complexities of the Minsar Basin aquifer system, numerical modeling of the aquifer system was carried out for variable density flow using USGS SEAWAT2000 in uncoupled mode. The conceptual model of the aquifer system is discussed in Sec. 4.1.

4.4 THREE-DIMENSIONAL SIMULATION OF VARIABLE DENSITY GROUNDWATER FLOW IN MINSAR RIVER BASIN

4.4.1 About SEAWAT

The USGS SEAWAT program (Guo and Langevin, 2002) simulates three-dimensional, variable-density, transient groundwater flow in porous media. SEAWAT is based on the concept of equivalent freshwater head (refer Section 4.2.1), in a saline groundwater environment. The source code for recent SEAWAT version combines MODFLOW (2000 version) and MT3DMS (solute transport code) into a single program that solves the flow and solute transport equations in a coupled manner. MODFLOW was modified to solve the variable density flow equation by reformulating the matrix equations in terms of fluid mass rather than fluid volume and by including the appropriate density terms. Fluid density is assumed to be a function of the concentration of dissolved salts under isothermal conditions. Spatial and temporal variation of salt concentration is simulated using routines from MT3DMS program. The program uses different modules of MODFLOW for numerical simulation of various hydrologic processes. The code solves the groundwater flow equation by discretizing the study domain into a block-centered grid. The total simulation time is divided into a number of stress periods. Within each stress period, the model parameters remain constant. Each stress period in turn is divided into a series of time steps.

4.4.1.1 Using SEAWAT

In a SEAWAT application, the values of measured heads (h) in observation wells, must be converted to freshwater heads to serve as MODFLOW heads under SEAWAT. In SEAWAT2000 (recent version) the heads are converted by the code itself corresponding to field densities through Eq. (4.8) or converting the observed water levels to equivalent freshwater heads through Eq. (4.7).

4.4.2 Development of Database for SEAWAT Code

The main objective for developing the three dimensional model is to determine the regional groundwater flow patterns in Minsar Basin. In accordance with the geometry of the aquifer system, as conceptualized in Sec. 4.5, the aquifer system is unconfined in nature. The contours corresponding to the top of the aquifer and bottom of subsurface layers as discussed in Sec. 4.1 are shown in Figs. 4.12 to 4.18.

The sources of recharge to the aquifer consist of rainfall, irrigation return flows, seepages from surface water bodies like check dams, minor irrigation and percolation tanks, reservoirs and Minsar river. Location-wise details of minor irrigation and percolation tanks were not available. Therefore, recharges from these were not included in the total recharge applied to the model from the top surface layer. Transpiration losses from the root zone were considered, because a major portion of the study area remains under cultivation in Kharif and Rabi seasons. Well draft in Kharif, Rabi and summer seasons has been considered as per the crops cultivated. The similarity in trends of both the water table contours and ground surface level contours reveals that the water table for different months follows the topography.

Values of aquifer parameters obtained from pump tests, as discussed in Chapter 2, were adopted as initial aquifer parameters, for the corresponding areas where these tests were conducted by GWRDC. At other places, parameter values available in literature were adopted. Final model parameters were arrived at by calibrating the conceptual model for steady state conditions. The model validation is done to match the water balance components for a season including specific stress periods corresponding to monsoon and non-monsoon months. Taluka-wise rates of groundwater recharge and discharge were computed for the Minsar basin from GWRDC data as per GEC 97 norms.

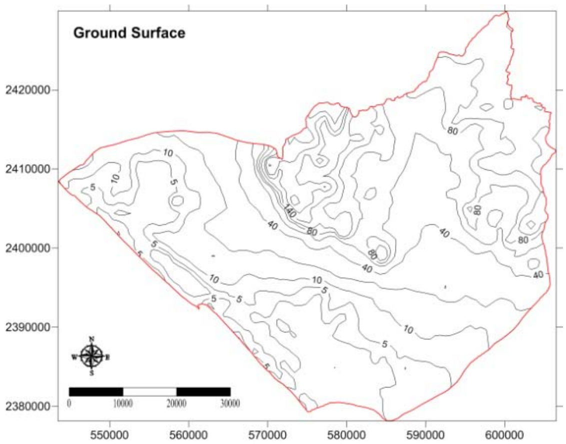


Fig. 4.12 Krigged top surface contours of aquifer

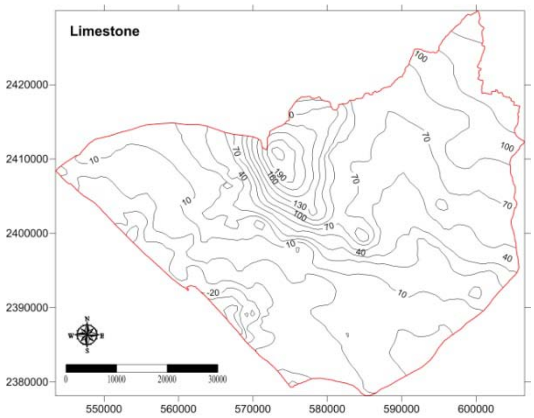
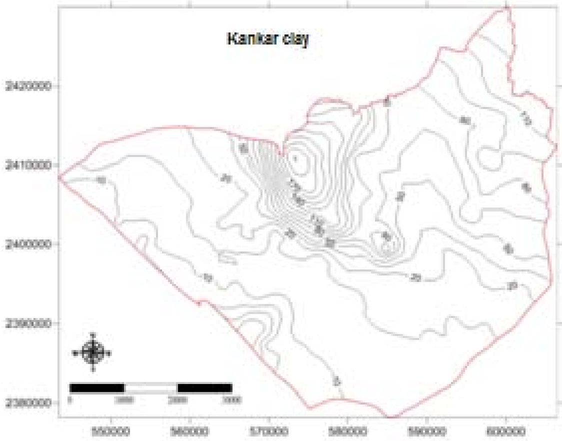


Fig. 4.13 Krigged bottom level contours of limestone layer



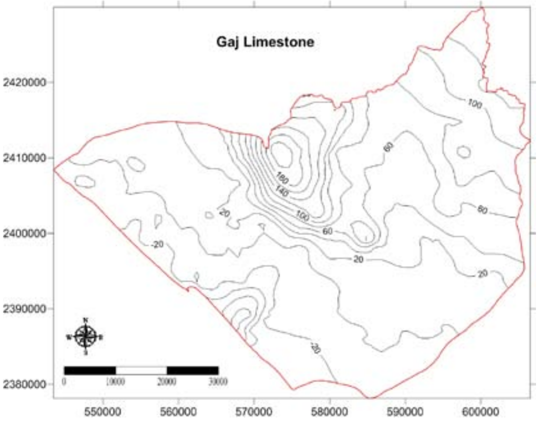


Fig. 4.14 Krigged bottom level contours of layer of kankar clay

Fig. 4.15 Krigged bottom level contours of layer of Gaj limestone

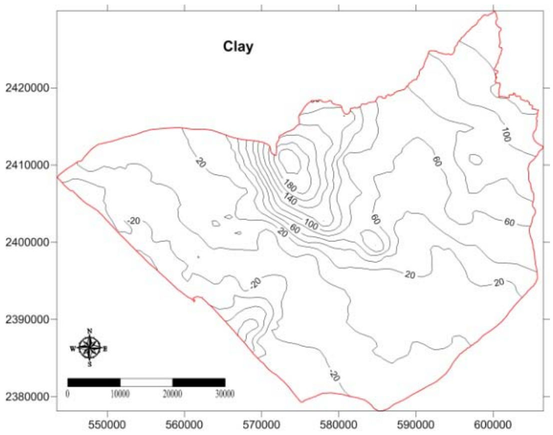


Fig. 4.16 Krigged bottom level contours of clay layer

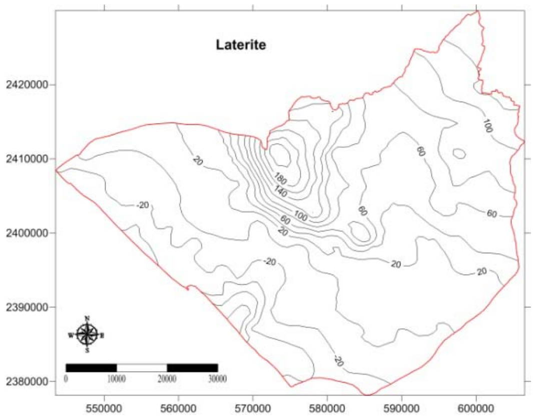


Fig. 4.17 Krigged bottom level contours of laterite layer

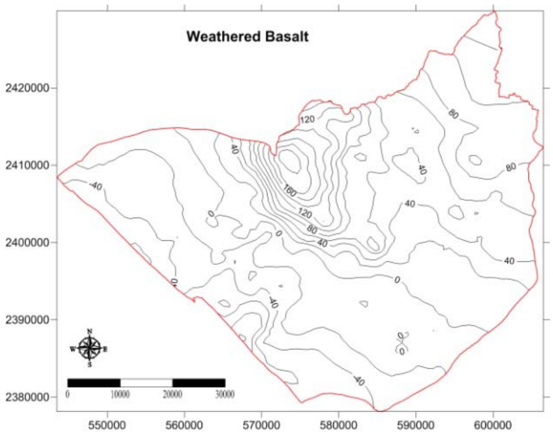


Fig. 4.18 Krigged bottom level contours of layer of weathered basalt

The major hydrological stresses in the area are: rainfall during monsoon season, seepages from surface water bodies, irrigation return flows, evapotranspiration and groundwater draft.

4.4.2.1 Spatial discretization

The model domain was vertically discretized into 7 layers. Each layer was horizontally discretized using the finite difference grid into 87,010 blocks of uniform dimension 500 m x 500 m using 113 rows and 110 columns. The discretized model domain is shown in Fig. 4.19. While carrying out discretization, one of the objectives was to sufficiently discretize the model domain while minimizing the total number of model cells.

4.4.2.2 Period of study

For calibration, the time period was taken from May 2010 to May 2011. Time period extending from June 2011 to December 2013 was chosen for validation. The stress factors for each month have been described above.

4.4.2.3 Boundary conditions

The boundary conditions used for the study area are shown in Fig. 4.19. Net freshwater recharge (which accounts for recharge from different sources and discharge due to groundwater draft) and evapotranspiration is applied to the upper boundary of the model. The depth of extinction for evapotranspiration was assigned as 1.2 m. The seaward boundary is represented by a constant head boundary with a salt concentration of 35 kg/m^3. On the landward side, no-flow boundary condition was employed, since the boundary of the study area coincides with the boundary of the river basin in upland area. In the coastal plain, the flow across the study area boundary is minimal and therefore, the boundary condition has been considered to be no-flow. The lower boundary of the model is a no-flow boundary and coincides with the bottom of the layer of weathered basalt. In addition, in the high mountain regions 75 m amsl in the study area where permeability is low, the conductivity values have been taken as small. The low conductivity values have helped in reproducing the correct trend of water table contours in the non-hilly portions of the upland area. Aquifer parameters were assigned as computed from the pumping tests in the region.

The net recharge and discharge values were assigned to the top layer in different zones. These zones correspond with the taluka boundaries in the study area. Thus, the different values of recharge and discharge in each zone correspond with those of individual talukas. River Minsar is ephemeral in nature and its discharge is measured at only one gaging site in the village Rana Kandorna. The water table contours show that the river is a gaining river; however, recharge from the river does takes place because of the checkdams constructed on the river. The recharge from these checkdams is computed separately and incorporated as groundwater recharge in the model. Therefore, the main river and its tributaries are modeled using the drain module of MODFLOW.

Once a comparable match between the computed and observed heads trends was obtained for steady state condition, sensitivity of above mentioned stresses individually were checked before finalising the model parameters and the boundary conditions.

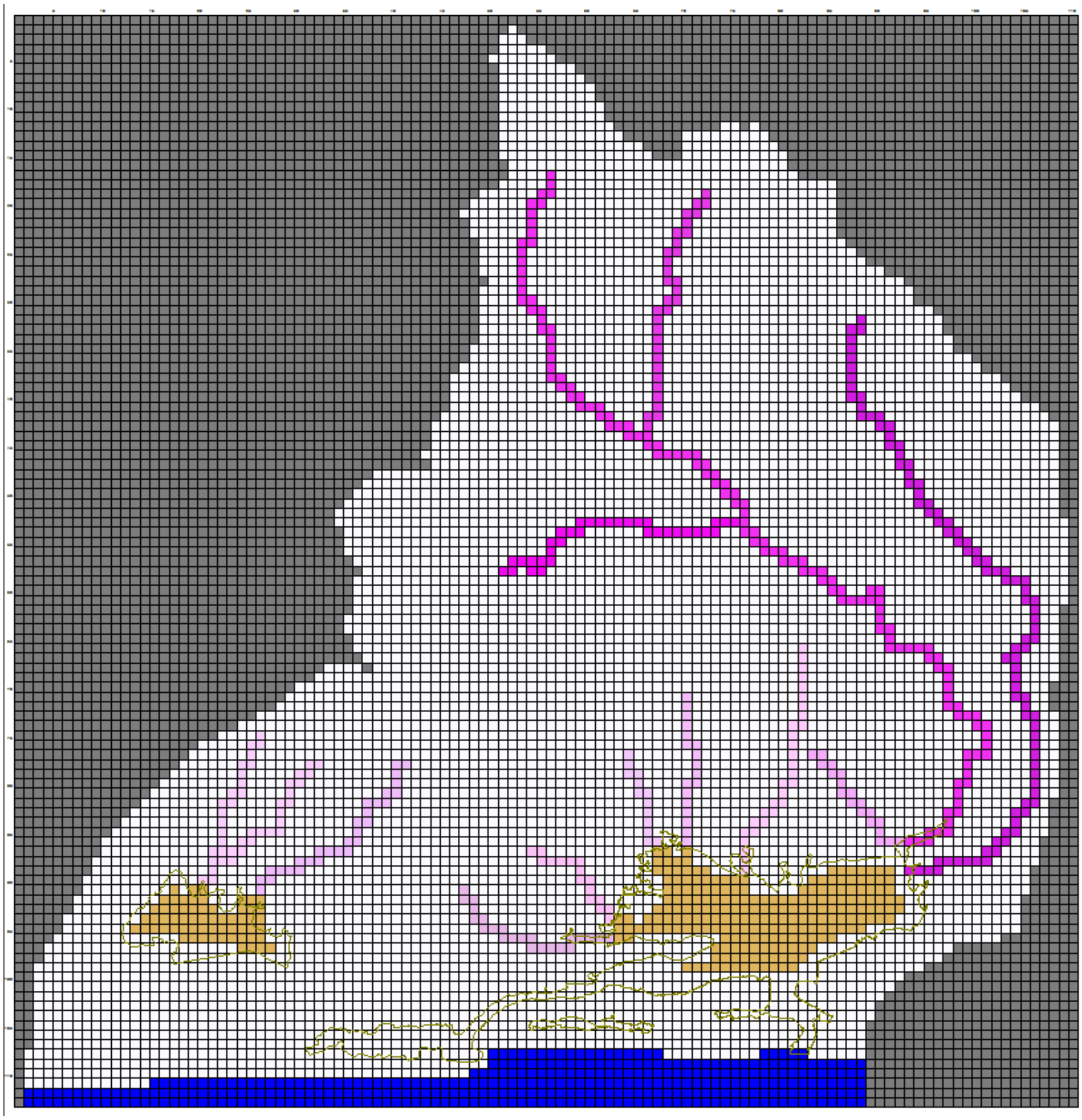


Fig. 4.19 Finite difference grid superimposed over the study area. Pink color cells depict the grid cells along major drainage streams. Blue colour cells depict the grid cells where the constant head boundary condition was applied.

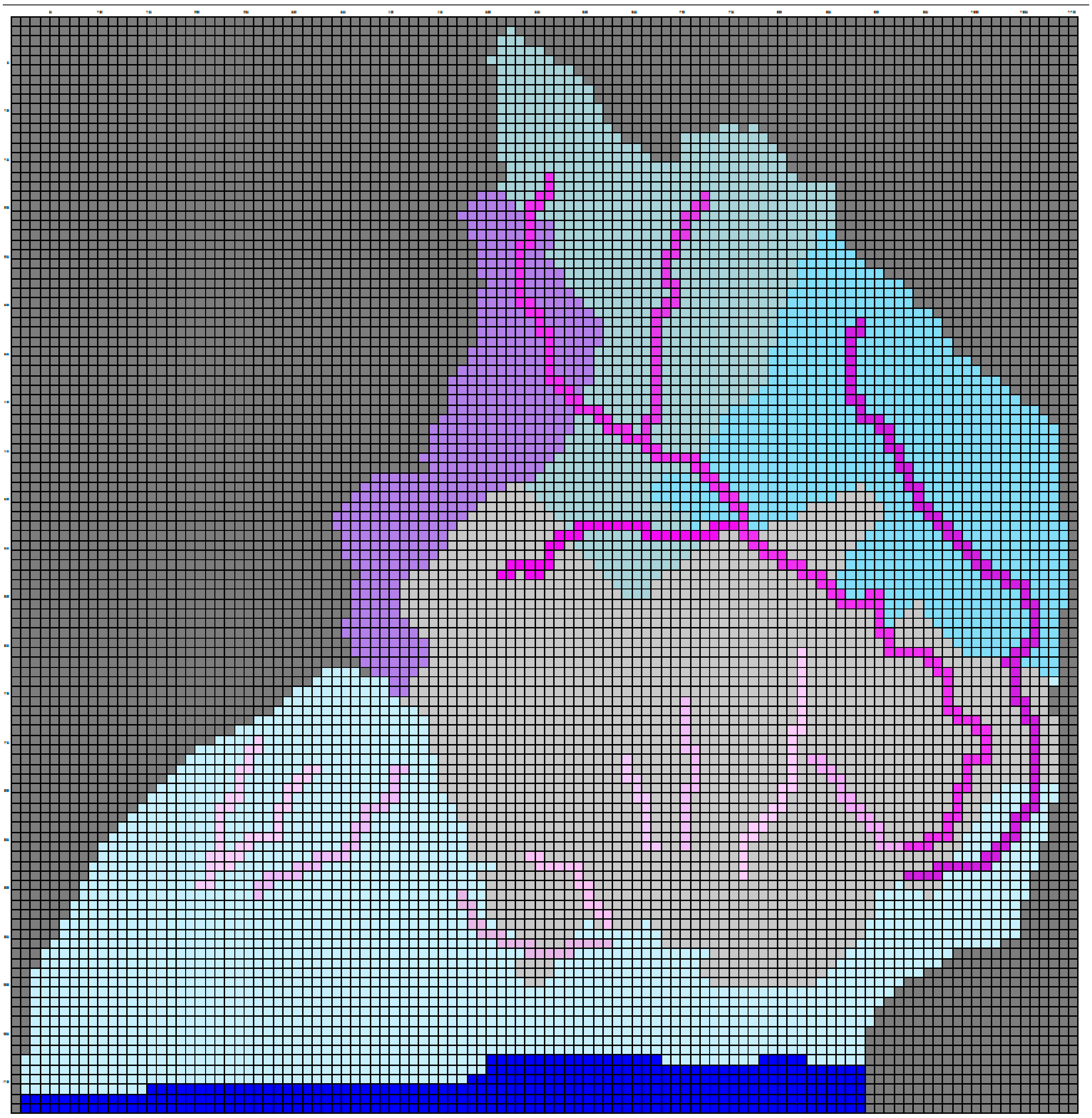


Fig. 4.20 Recharge zones assigned to the surface layer in accordance with the taluka boundaries (refer Fig. 4.2).

4.4.3 Steady State Simulations

Starting from initial model parameter values, the model is calibrated using PEST package for steady state condition, to achieve a reasonable match between observed and computed groundwater heads. Figure 4.21(a) illustrates the computed groundwater head against the observed heads, while Fig. 4.21(b) shows the generated contour map in color.

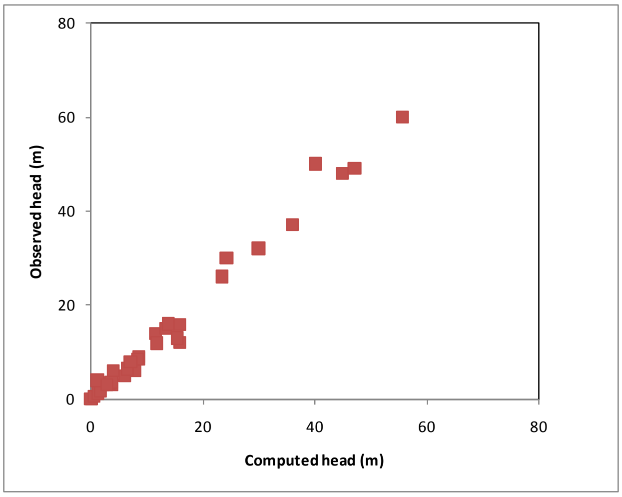


Fig. 4.21 (a) Steady state computed head vs. observed head values

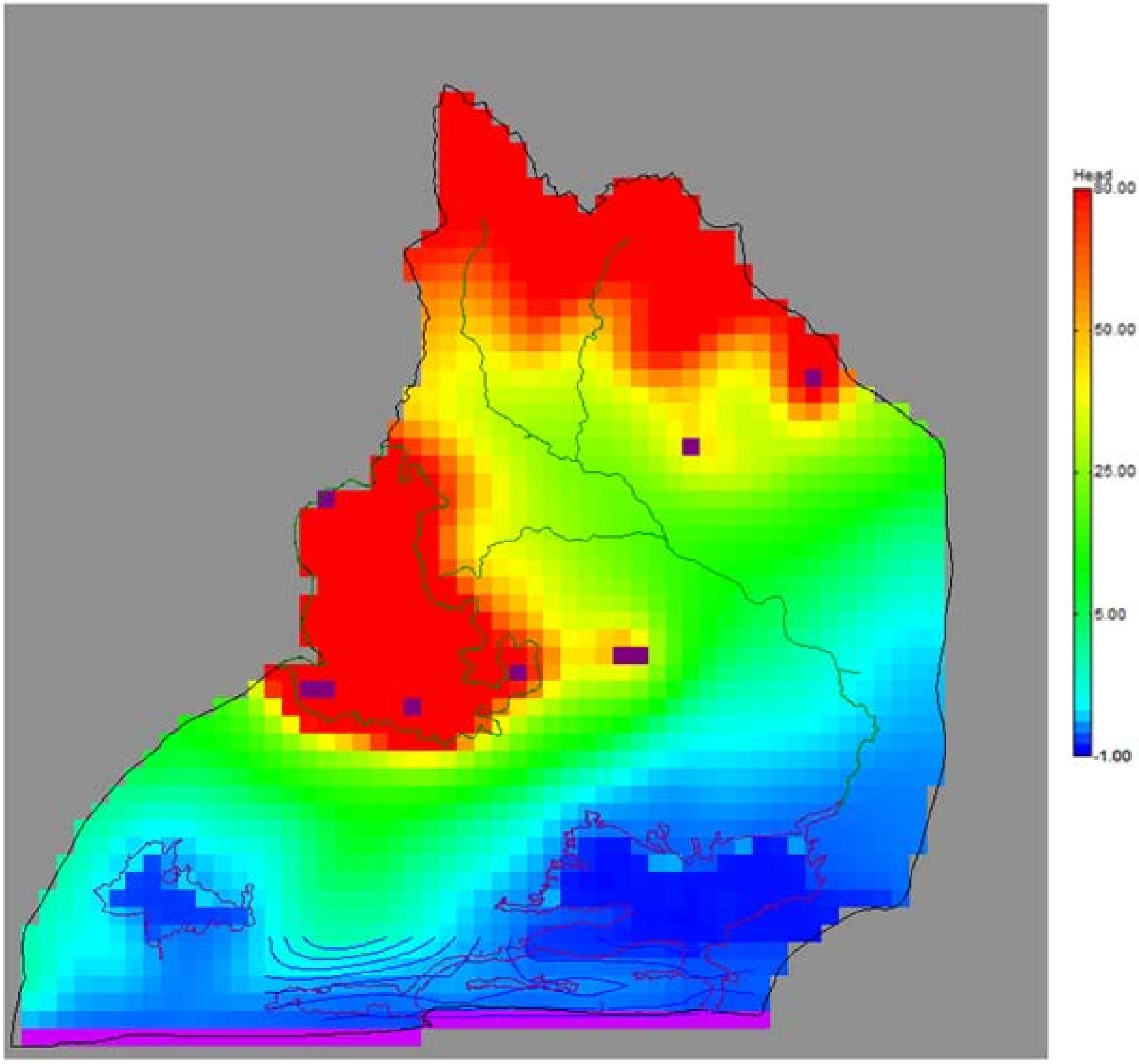


Fig. 4.21 (a) Contour map generated from steady state model

4.4.4 Transient Simulations

From the steady state runs, it is clear that the model performs well for the assigned boundary conditions. For the transient runs June to September have been considered as monsoon months and remaining months are taken as non-monsoon months. The monthly recharge data generated for the model are summarised in Tables 4.1-4.4 for the years 2010-2013, while the taluka-wise groundwater draft and max. evapotranspiration data are given in Tables 4.5-4.6.

For transient runs, initial water table condition was generated from the steady state runs described earlier. Hence, transient runs were executed for six monthly stress periods to achieve the groundwater heads corresponding to November 2010. The numerical model could compute the negative groundwater heads observed in Minsar Basin near the coast.

4.4.4.1 Estimation of recharge

Recharge to the aquifer system in the area occurs due to rainfall, return flow from irrigation, seepage from surface water bodies (checkdams, ponds, streams and reservoirs). The computed respective components of recharge in the talukas are given below.

Rainfall recharge: Monthly rainfall values were available for the years 2010 - 2013. Taking the rainfall recharge factor in the region to be 0.1, the computed monthly recharge due to rainfall is given in Tables 4.1.

Irrigation return flow: The total irrigation return flow to the area comprises return flow from surface water irrigation and groundwater irrigation. Taluka-wise values of return flow from surface water and groundwater were available from the water balance sheets provided by GWRDC.

Return flow from surface water**:** Annual values of return flow due to irrigation from surface water were available for the year 2010 - 2013 for each taluka. Monthly values for the years were obtained by taking a weighted distribution in accordance with the total water requirement of cultivated crops in a taluka during a particular month.

Return flow from groundwater**:** Annual values of groundwater draft for irrigation were available for the period 2009-2011 for each taluka. Monthly values of draft for irrigation were obtained by taking a weighted distribution in accordance with the total water requirement of cultivated crops in a taluka during a particular month and the non-availability of surface water for irrigation during that month. The data for crop water requirement were obtained in consultation with GWRDC and with local farmers by inquiring about local agricultural practice adopted for irrigating different crops. Monthly values of irrigation return flow were computed in accordance with irrigation return flow factors as defined by GEC 1997. The computed monthly distribution of return flow from groundwater for each taluka is given in Table 4.2. The annual variation in cropped area was obtained from satellite data and the draft was assigned proportionately.

Seepage from surface water bodies: Surface water bodies present in the study area are Bardasagar reclamation scheme, DiaMinsar Irrigation scheme, Kalindri Irrigation scheme, Kerly TR and Kerly RR Irrigation scheme, V-Minsar Irrigation scheme, Ishwariya Irrigation scheme and the Minsar River. The variation in water spread area of above schemes was obtained from satellite data. In addition spreading channel, checkdams, and percolation tanks are also present in the area. The seepage from these bodies was calculated as per GEC norms (Table 4.4).

Total recharge: Total monthly recharge to groundwater for the years 2010-2013 was obtained by summing all the above recharge factors.

4.4.4.2 Estimation of discharge

Discharge from the aquifer system in the area occurs due to groundwater draft, and evapotranspiration. The computed respective components of discharge in the talukas are provided in Tables 4.5-4.6.

Net recharge: Net values of monthly recharge to groundwater for the years 2010-2013 were obtained by subtracting monthly groundwater draft from monthly total recharge.

Evapotranspiration from cultivated land: The potential rate of evapotranspiration was available from IMD for Porbandar. To compute the total evapotranspiration from the cultivated crops in each taluka, major crops grown in the region were considered. Respective values of crop coefficient for each crop during various stages of crop growth were taken from Doorenbos and Pruitt (1987). The monthly values of evapotranspiration for individual crop were computed and weighted values of crop water requirement for each taluka were calculated accounting for the proportionate area during kharif and rabi seasons under each major crop.

The generated contour map for November 2010 is shown in 4.22 (a) while the color contour map with observed data is shown in Fig. 4.22 (b).

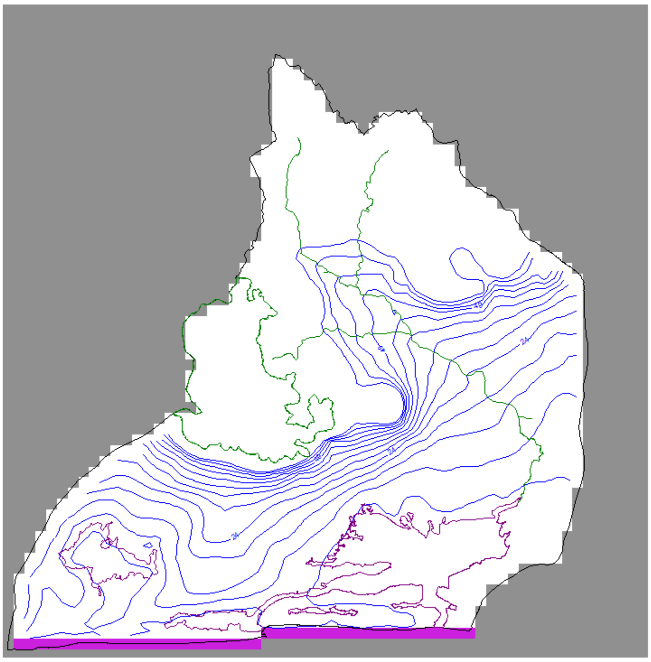


Fig. 4.22 (a) Contour map of computed heads for Nov. 2010. The simulated heads are shown for only the region (i.e. non-hilly) where heads were monitored.

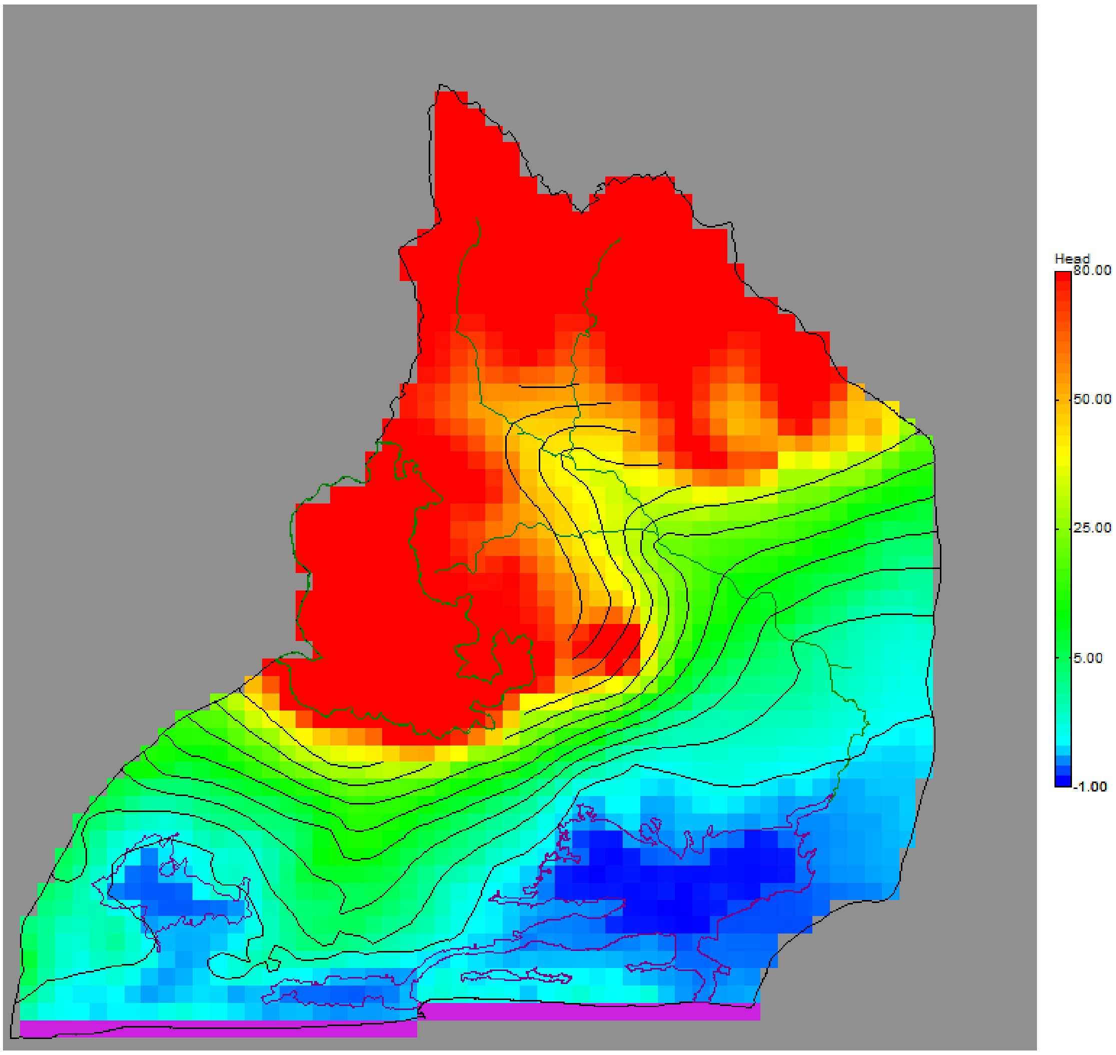


Fig. 4.22(b) Comparison of computed (color) vs observed head contours (contour lines for observed heads shown only for the portion where heads were monitored) for Nov. 2010.

These transient runs demonstrate that the model is capable of simulating future scenarios with reasonable accuracy. The model based on variable density flow was further employed to simulate the impact of rise in sea level on account of climate change. However, due to severe salinity existing near the coast, changes in the flow regime were insignificant. With further refinement in model calibration, impact of anticipated climate change in terms of rainfall events in inland areas corresponding to different climate change scenarios are planned.

Table 4.1 Rainfall recharge (mm)

TALUKA	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	2010-2011											
Porbandar	0.0	0.0	24.7	13.3	11.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Ranavav	0.0	1.8	21.5	17.8	10.5	1.2	0.0	0.0	0.0	0.0	0.0	0.0
Kutiyana	0.0	0.4	8.9	6.7	4.1	1.9	0.0	0.0	0.0	0.0	0.0	0.0
Bhanvad	0.0	1.3	5.5	3.9	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	2.5	7.4	9.2	3.2	1.0	0.0	0.0	0.0	0.0	0.0	0.0
	2011-2012											
Porbandar	0.0	7.5	5.5	5.5	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ranavav	0.0	5.4	7.2	6.3	11.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kutiyana	0.0	1.6	3.8	2.8	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bhanvad	0.0	0.3	1.6	1.5	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	1.1	3.8	3.3	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2012-2013											
Porbandar	0.0	0.0	1.5	1.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ranavav	0.0	0.2	1.4	1.2	5.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kutiyana	0.0	0.0	0.4	0.1	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bhanvad	0.0	0.0	0.2	0.2	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	0.0	0.3	0.3	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2013-2014											
Porbandar	0.0	10.8	8.7	5.5	6.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Ranavav	0.0	9.9	10.3	4.1	7.2	2.6	0.0	0.0	0.0	0.0	0.0	0.0
Kutiyana	0.0	4.9	3.7	1.5	2.6	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Bhanvad	0.0	0.7	3.7	0.9	1.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	3.1	4.8	1.7	5.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0

Table 4.2 Monthly variation of irrigation return flow arising from groundwater (mm)

TALUKA	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	2010-2011											
Porbandar	0.2	1.8	0.0	0.0	0.0	2.4	0.4	1.5	2.2	1.7	1.3	0.5
Ranavav	0.8	3.1	0.0	0.0	0.0	0.9	0.2	2.9	4.3	3.4	2.5	1.1
Kutiyana	0.3	0.4	0.0	0.0	0.0	1.4	0.2	2.7	4.1	3.2	2.4	0.5
Bhanvad	0.0	0.0	0.0	0.0	0.0	0.6	0.1	0.6	0.9	0.7	0.6	0.1
Jamjodhpur	0.3	0.1	0.0	0.0	0.0	1.4	0.0	1.4	2.1	1.6	1.2	0.2
	2011-2012											
Porbandar	0.9	0.0	0.0	0.0	0.0	3.0	0.5	1.1	1.7	1.3	1.0	0.2
Ranavav	1.8	0.0	0.0	0.0	0.0	2.8	0.7	2.0	2.9	2.3	1.7	0.8
Kutiyana	0.8	0.0	0.0	0.0	0.0	1.3	0.6	1.8	2.8	2.1	1.6	0.3
Bhanvad	0.2	0.2	0.0	0.0	0.0	0.2	0.2	0.4	0.6	0.5	0.4	0.0
Jamjodhpur	0.4	0.5	0.0	0.0	0.0	0.5	0.2	0.9	1.3	1.0	0.8	0.2
	2012-2013											
Porbandar	0.3	1.1	0.0	0.3	0.0	1.0	0.2	0.3	0.4	0.3	0.2	0.2
Ranavav	1.3	0.9	0.1	0.5	0.0	0.8	0.2	0.7	1.0	0.7	0.5	0.3
Kutiyana	0.5	0.3	0.1	0.3	0.0	0.3	0.2	0.6	0.9	0.7	0.5	0.1
Bhanvad	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.0
Jamjodhpur	0.4	0.4	0.0	0.1	0.0	0.2	0.0	0.3	0.5	0.3	0.2	0.0
	2013-2014											
Porbandar	0.3	0.0	0.0	0.0	0.0	3.6	1.5	1.9	1.6	1.2	0.9	0.1
Ranavav	0.5	2.6	0.0	0.0	0.0	0.7	1.5	3.5	3.3	2.5	1.9	0.5
Kutiyana	0.2	0.0	0.0	0.0	0.0	1.6	1.1	3.1	3.1	2.4	1.8	0.2
Bhanvad	0.1	0.0	0.0	0.0	0.0	0.6	0.3	0.7	0.6	0.5	0.4	0.0
Jamjodhpur	0.1	0.0	0.0	0.0	0.0	1.4	0.4	1.4	1.6	1.2	0.9	0.1

Table 4.3 Monthly variation of irrigation return flow arising from surface water (mm)

TALUKA	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	2010-2011											
Porbandar	0.0	0.0	0.0	0.0	0.0	1.1	0.2	0.9	1.3	1.0	0.8	0.0
Ranavav	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.2	0.1	0.0
Kutiyana	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.5	0.3	0.2	0.0
Bhanvad	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.1	0.2	0.1	0.0	0.0
Jamjodhpur	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.8	1.3	1.0	0.5	0.0
	2011-2012											
Porbandar	0.0	0.0	0.0	0.0	0.0	1.2	0.3	0.7	1.1	0.8	0.6	0.0
Ranavav	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.1	0.2	0.1	0.1	0.0
Kutiyana	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.2	0.4	0.3	0.0	0.0
Bhanvad	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.1	0.1	0.1	0.0
Jamjodhpur	0.0	0.0	0.0	0.0	0.0	0.9	0.1	0.4	0.7	0.6	0.2	0.0
	2012-2013											
Porbandar	0.0	0.0	0.0	0.3	0.0	0.5	0.3	0.4	0.5	0.4	0.3	0.0
Ranavav	0.0	0.0	0.0	0.1	0.0	0.3	0.0	0.0	0.1	0.0	0.0	0.0
Kutiyana	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Bhanvad	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.1	0.0
	2013-2014											
Porbandar	0.0	0.0	0.0	0.0	0.0	1.1	1.9	2.3	1.8	1.4	1.1	0.0
Ranavav	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.5	0.3	0.2	0.2	0.0
Kutiyana	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.6	0.6	0.5	0.3	0.0
Bhanvad	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.1	0.0	0.0
Jamjodhpur	0.0	0.0	0.0	0.0	0.0	0.2	0.3	1.1	1.2	1.0	0.5	0.0

Table 4.4 Monthly variation of seepages from surface water bodies (mm)

TALUKA	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	2010-2011											
Porbandar	0.7	0.0	0.1	0.1	0.1	1.7	1.6	1.6	1.6	1.6	1.6	0.7
Ranavav	0.9	0.0	0.3	0.3	0.3	1.2	0.9	0.9	0.9	0.9	0.9	0.9
Kutiyana	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Bhanvad	0.0	0.0	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	0.0	1.1	1.1	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0
	2011-2012											
Porbandar	0.7	0.0	0.1	0.1	0.1	1.7	1.6	1.6	1.6	1.6	1.6	0.7
Ranavav	0.9	0.0	0.3	0.3	0.3	1.2	0.9	0.9	0.9	0.9	0.9	0.9
Kutiyana	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Bhanvad	0.0	0.0	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	0.0	1.1	1.1	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0
	2012-2013											
Porbandar	0.7	0.0	0.1	0.1	0.1	1.2	1.0	1.0	1.0	1.0	1.0	0.2
Ranavav	0.9	0.0	0.3	0.3	0.3	0.6	0.2	0.2	0.2	0.2	0.2	0.2
Kutiyana	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Bhanvad	0.0	0.0	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	0.0	1.1	1.1	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0
	2013-2014											
Porbandar	0.2	0.0	0.1	0.1	0.1	1.7	1.6	1.6	1.6	1.6	1.6	0.7
Ranavav	0.2	0.0	0.3	0.3	0.3	1.2	0.9	0.9	0.9	0.9	0.9	0.9
Kutiyana	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Bhanvad	0.0	0.0	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Jamjodhpur	0.0	0.0	1.1	1.1	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0

Table 4.5 Monthly variation of total groundwater draft (mm)

TALUKA	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	2010-2011											
Porbandar	0.7	6.0	0.0	0.0	0.0	8.1	1.3	5.2	7.5	5.9	4.4	1.9
Ranavav	2.9	10.3	0.0	0.0	0.0	3.0	0.6	9.9	14.6	11.4	8.4	3.8
Kutiyana	1.2	1.5	0.0	0.0	0.0	4.9	0.6	9.2	13.7	10.7	8.0	1.7
Bhanvad	0.3	0.3	0.0	0.0	0.0	2.1	0.3	2.2	3.1	2.4	2.1	0.5
Jamjodhpur	1.0	0.4	0.0	0.0	0.0	4.9	0.0	4.7	7.1	5.6	4.1	0.9
	2011-2012											
Porbandar	3.1	0.0	0.0	0.0	0.0	10.1	1.6	3.9	5.7	4.4	3.3	0.7
Ranavav	6.2	0.0	0.0	0.0	0.0	9.5	2.3	6.6	9.9	7.7	5.7	2.7
Kutiyana	2.8	0.0	0.0	0.0	0.0	4.6	2.3	6.3	9.3	7.3	5.3	1.1
Bhanvad	0.8	0.9	0.0	0.0	0.0	0.8	0.7	1.5	2.1	1.6	1.4	0.2
Jamjodhpur	1.4	1.9	0.0	0.0	0.0	1.9	0.9	3.0	4.5	3.5	2.6	0.9
	2012-2013											
Porbandar	1.2	3.8	0.0	1.2	0.0	3.5	0.9	1.2	1.4	1.1	0.8	0.7
Ranavav	4.3	3.1	0.4	1.9	0.0	2.6	0.9	2.3	3.3	2.6	1.9	1.0
Kutiyana	1.8	1.2	0.3	1.1	0.0	1.2	0.7	2.1	3.2	2.5	1.8	0.5
Bhanvad	0.4	0.6	0.1	0.2	0.0	0.5	0.2	0.4	0.6	0.4	0.4	0.2
Jamjodhpur	1.4	1.4	0.2	0.6	0.0	0.9	0.3	1.0	1.6	1.3	0.9	0.3
	2013-2014											
Porbandar	1.1	0.0	0.0	0.0	0.0	12.2	5.1	6.5	5.3	4.2	3.1	0.4
Ranavav	1.7	8.9	0.0	0.0	0.0	2.5	5.0	11.8	11.0	8.6	6.3	1.8
Kutiyana	0.9	0.0	0.0	0.0	0.0	5.6	3.7	10.3	10.4	8.1	6.0	0.7
Bhanvad	0.4	0.0	0.0	0.0	0.0	2.0	1.3	2.6	2.2	1.8	1.5	0.1
Jamjodhpur	0.4	0.0	0.0	0.0	0.0	4.6	1.4	4.7	5.4	4.2	3.1	0.6

Table 4.6 Monthly values of max. evapotranspiration from crop lands (mm)

TALUKA	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	2010-2011											
Porbandar	7.8	27.8	19.6	26.1	33.8	18.2	5.8	13.9	35.1	27.5	20.3	4.9
Ranavav	7.6	25.7	18.3	24.4	31.3	17.0	4.6	12.8	32.3	25.3	18.7	4.7
Kutiyana	2.3	14.3	10.2	13.6	17.4	9.9	2.9	8.1	17.8	13.9	10.3	1.4
Bhanvad	0.8	7.4	5.5	7.3	8.7	5.5	1.2	2.5	6.9	5.5	4.7	0.5
Jamjodhpur	2.1	13.8	9.1	12.3	15.0	8.0	2.0	6.3	15.0	11.8	9.4	1.3
	2011-2012											
Porbandar	7.8	27.8	19.6	26.1	33.8	18.2	5.8	13.9	9.9	7.8	5.8	2.0
Ranavav	7.6	25.7	18.3	24.4	31.3	17.0	4.6	12.8	15.0	11.7	8.6	3.3
Kutiyana	2.3	14.3	10.2	13.6	17.4	9.9	2.9	8.1	8.2	6.4	4.7	0.9
Bhanvad	0.8	7.4	5.5	7.3	8.7	5.5	1.2	2.5	1.1	0.9	0.8	0.2
Jamjodhpur	2.1	13.8	9.1	12.3	15.0	8.0	2.0	6.3	6.4	5.1	4.0	1.4
	2012-2013											
Porbandar	3.2	20.6	13.9	17.5	26.0	18.1	6.4	8.2	35.5	27.9	20.8	4.9
Ranavav	5.4	19.2	13.5	17.9	23.4	13.4	4.1	10.3	30.8	24.1	17.8	4.7
Kutiyana	1.6	7.6	5.4	7.2	9.3	5.3	2.0	5.5	19.0	14.8	11.0	1.4
Bhanvad	0.4	4.1	3.0	4.0	4.8	3.1	0.5	0.8	5.5	4.4	3.7	0.5
Jamjodhpur	2.3	6.4	4.2	5.7	6.9	3.5	1.3	4.2	13.2	10.3	8.2	1.3
	2013-2014											
Porbandar	7.8	34.8	24.6	32.7	42.4	22.7	10.4	24.7	25.5	20.0	14.9	4.9
Ranavav	7.6	32.8	23.4	31.2	40.0	21.7	7.6	20.9	21.1	16.5	12.1	4.7
Kutiyana	2.3	16.0	11.4	15.2	19.5	11.1	4.6	12.8	13.5	10.6	7.8	1.4
Bhanvad	0.8	5.8	4.2	5.7	6.8	4.4	2.0	3.9	3.6	2.9	2.4	0.5
Jamjodhpur	2.1	12.7	8.4	11.3	13.8	7.3	2.8	8.7	10.4	8.2	6.5	1.3

4.5 DISCUSSION OF MODEL ASSUMPTIONS/LIMITATIONS

All numerical models contain simplifications and assumptions that may or may not hold good for the physical system under investigation. The 3D numerical model developed in the present accounts for the variable density flow arising on account of miscibility of saltwater and freshwater. The orientation of the 3D model is such that the horizontal axis is aligned with the principal direction of flow. The water level observations reveal that negative groundwater heads exist in the Ghed region. The model could simulate these negative heads to a certain extent. Based on the capability of the model to simulate fluctuations in head, the model seems to be a reasonable representation of the physical system. However, there is scope for further refinement in model calibration.

4.6 WATER RESOURCE MANAGEMENT FOR SUSTAINABLE DEVELOPMENT

4.6.1 Analysis of rainfall pattern

4.6.1.1 Rainfall dependability

To ascertain the certainty of rainfall that may occur (dependable rainfall), the probability analysis of the rainfall data for the period from 1901 to 2013 for Porbandar, 1960 to 2013 for Bhanwad and Ranawao each is carried out for different probability levels of 50%, 70%, 80% and 90%. For doing the analysis, daily rainfall data has been converted to the average monthly data. The monthly rainfall data has thereafter been analyzed for different probability levels. The analyzed rainfall results will help in the management practices during the lean season, or during various months and also during the year. Lower probability indicates, less assurance to the occurrence of rainfall, while higher probability indicates, rainfall has more chance to occur. The probability of annual rainfall at different percentage of probability is shown in Figs. 4.23, 4.24 and 4.25 for Porbandar, Bhanwad and Ranavav, respectively. The probability of monthly rainfall for different probability of exceedance is shown in Figs. 4.26, 4.27 and 4.28 for Porbandar, Bhanwad and Ranavav, respectively. Figures 4.23 to 4.28 showed that as the probability increases, the magnitude of rainfall decreases implying more assurance in the occurrence of the corresponding rainfall.

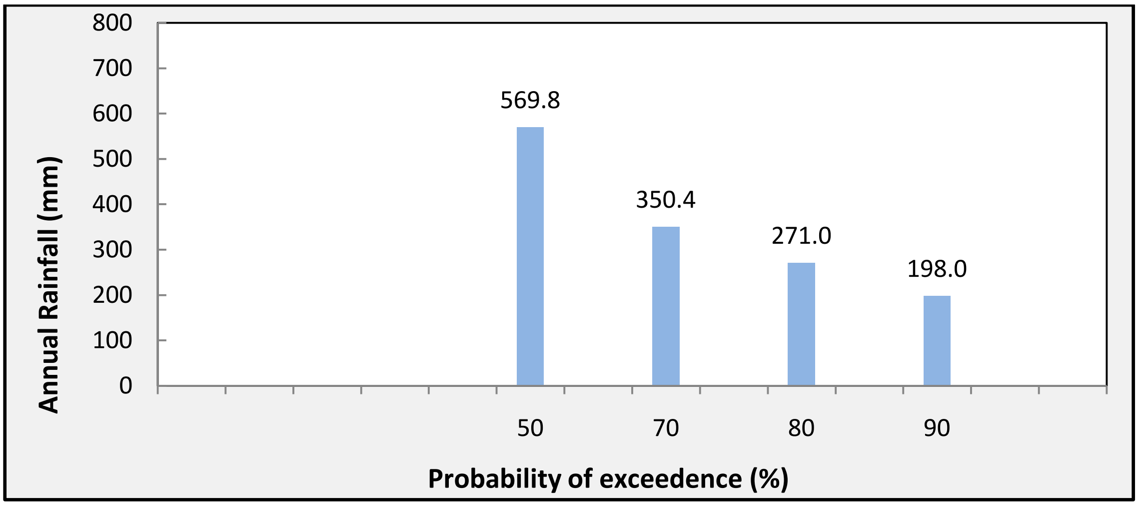


Fig. 4.23 Average annual rainfall of the Porbandar for different probability of exceedance.

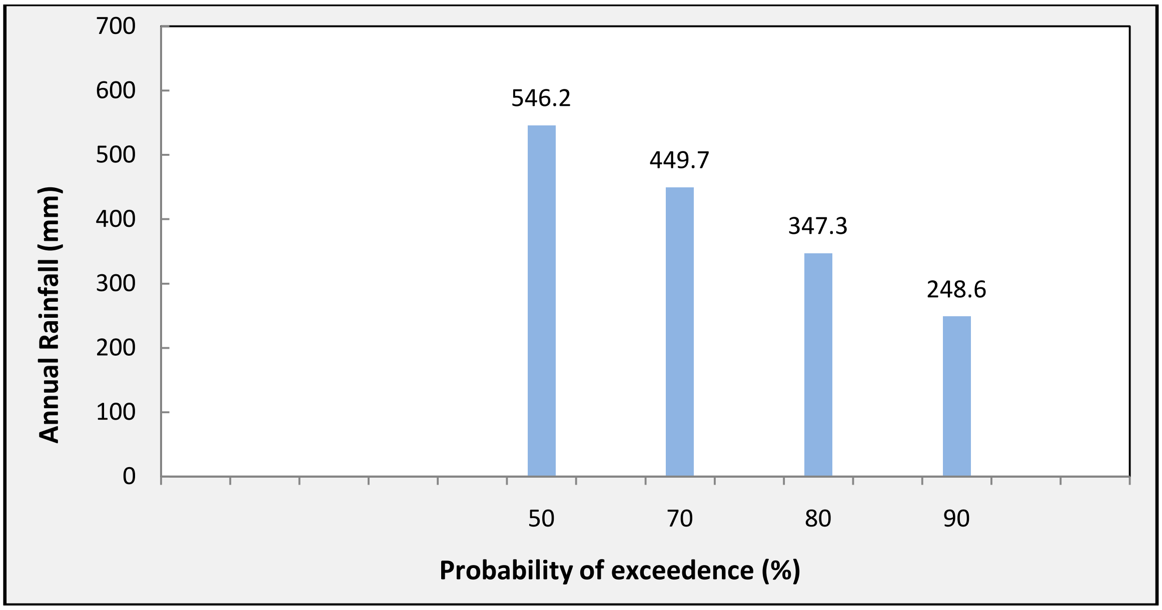


Fig. 4.24 Average annual rainfall of the Bhanwad for different probability of exceedance.

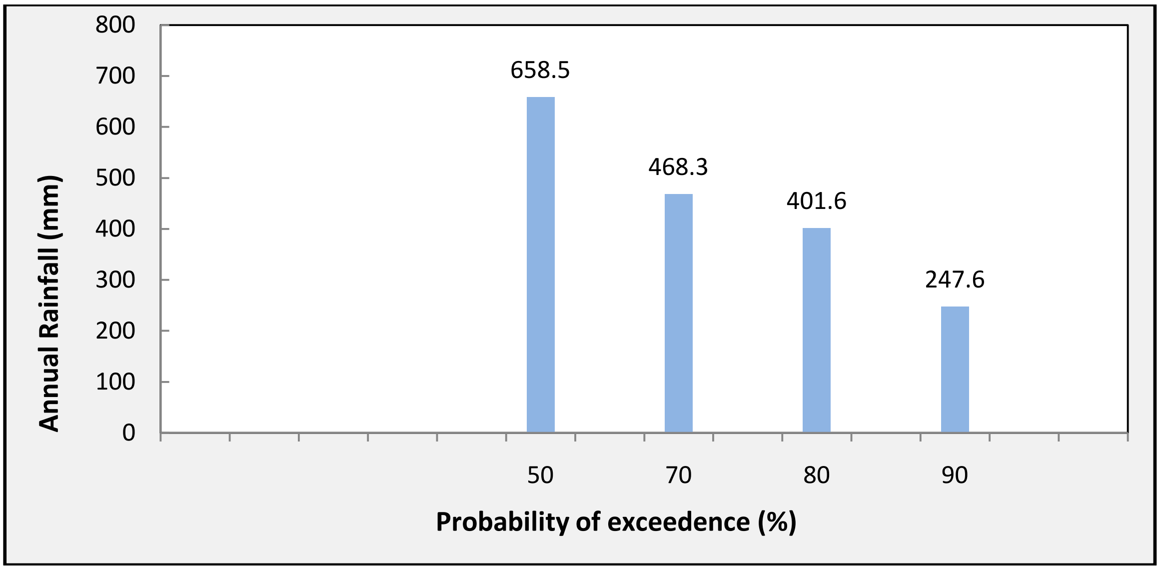


Fig. 4.25 Average annual rainfall of the Ranavav for different probability of exceedance.

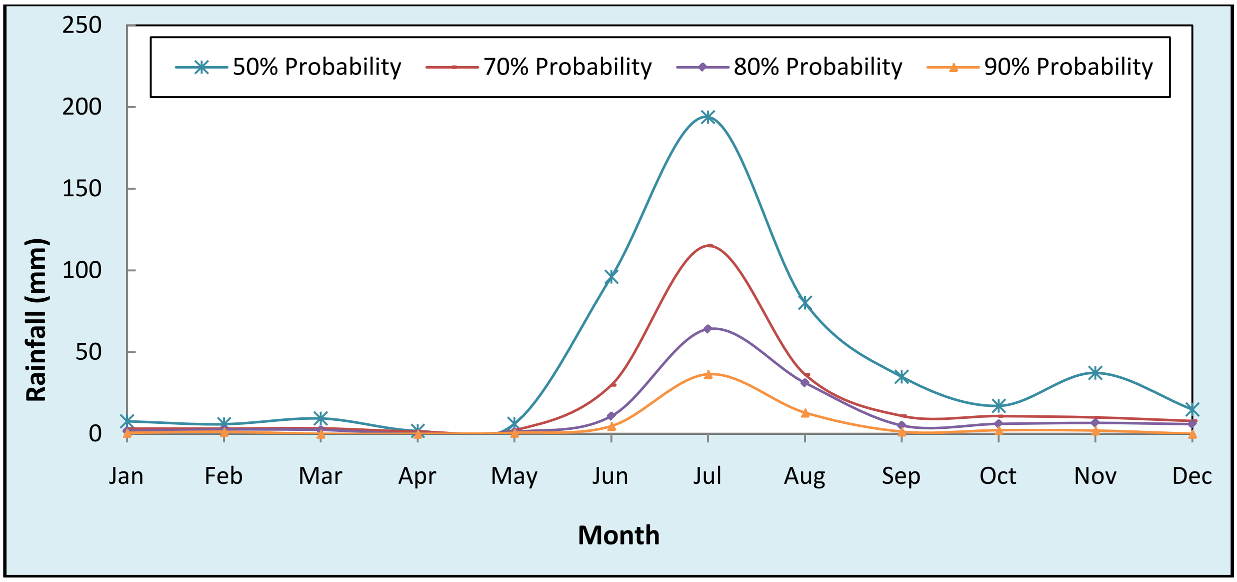


Fig. 4.26 Month-wise variation of rainfall of Porbandar for different probability of exceedance.

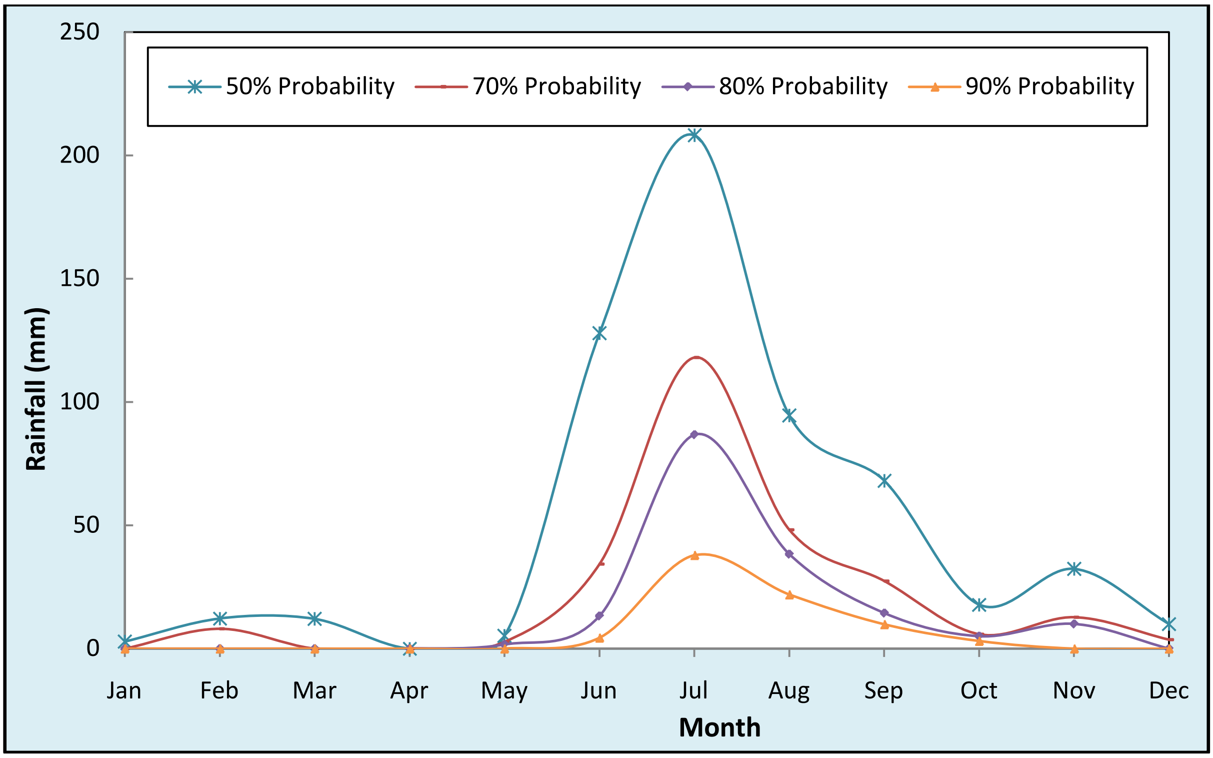


Fig. 4.27 Month-wise variation of rainfall of Bhanwad for different probability of exceedance.

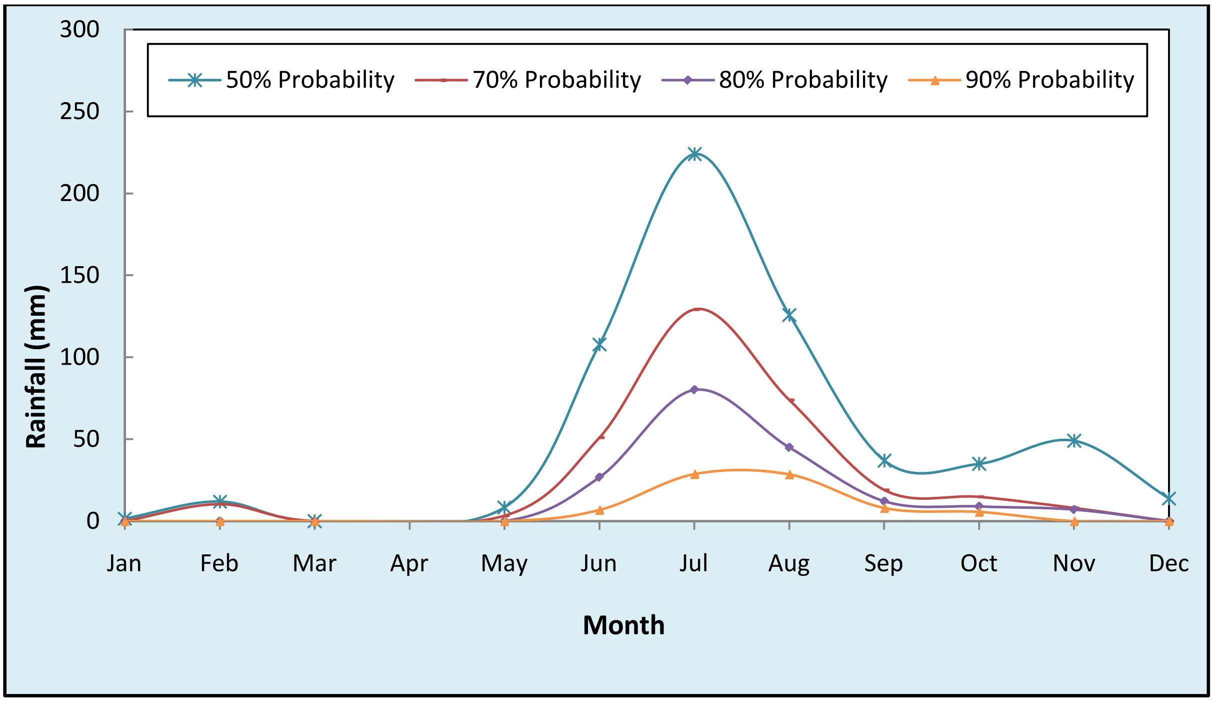


Fig. 4.28 Month-wise variation of rainfall of Rananvav for different probability of exceedance.

4.6.1.2 Variability of rainfall

The variability of rainfall is also carried out to examine how rainfall varies from one year to another for the rainfall stations namely Porbandar, Bhanwad and Ranavav. For this purpose, the year that has rainfall less than 25% of the annual average rainfall is categorized as drought year (criteria suggested by IMD). The years having annual rainfall more than the average annual rainfall are categorized as wet years and years with annual rainfall less than average annual rainfall are categorized as the dry years. Figures 4.29 to 4.31 show the annual rainfall variability from the long-term rainfall. The drought years are indicated in the red colour. For the Porbandar rainfall station, the average drought frequency is found to be one in three years (2.61) based on rainfall data series of 1901- 2013. Similarly, for the Bhanwad rainfall station, the average drought frequency is found to be one in three years (2.89) based on rainfall data series of 1960-2013; and for the Ranavav rainfall station, the average drought frequency is found to be one in three years (2.60) based on rainfall data series of 1960- 2013. At all these three stations continuous drought up to four years have been noticed. At Porbandar station, continuous drought for five years is also noticed during 1938 to 1942 as shown below in the Fig. 4.29.

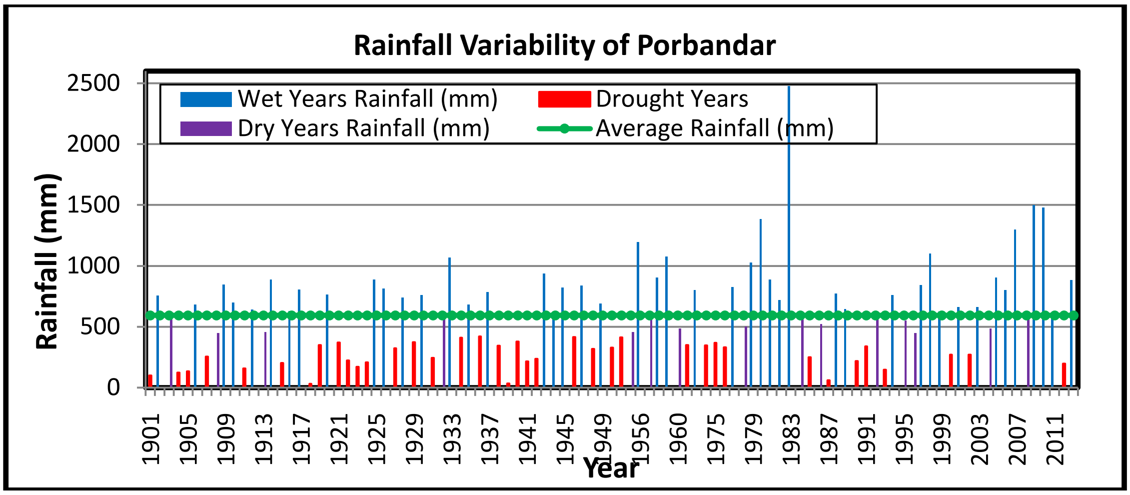


Fig. 4.29 Rainfall variability derived based on 113 years (1901- 2013) rainfall data series of the Porbandar rainfall station.

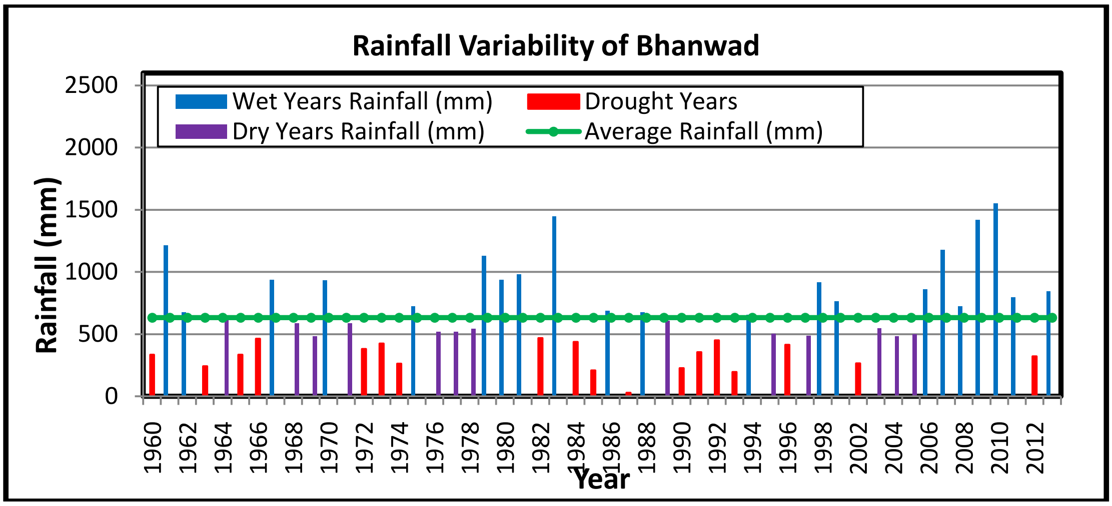


Fig. 4.30 Rainfall variability derived based on 44 years (1960- 2013) rainfall data series of the Bhanwad rainfall station.

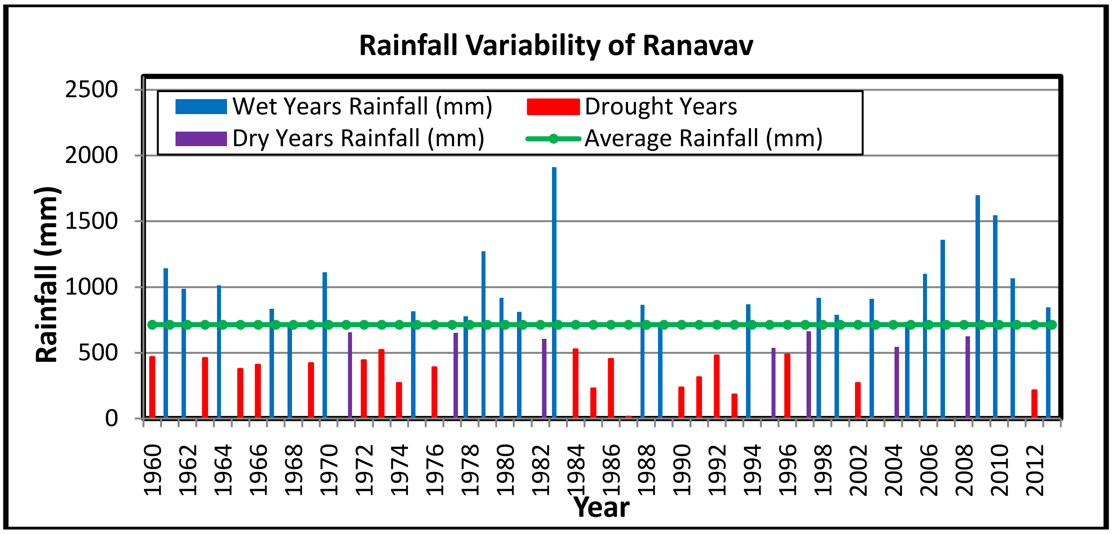


Fig. 4.31 Rainfall variability derived based on 44 years (1960- 2013) rainfall data series of the Ranavav rainfall station.

4.6.2 Groundwater suitability for irrigation

U.S. Salinity Laboratory (1954) has classified groundwater to determine the suitability of water for irrigation purposes based on electrical conductivity (EC). In the plot for suitability classification, the conductivity (horizontal axis) is classified into low (C1), medium (C2), high (C3) and very high (C4) salinity zones. These zones (C1–C4) have the value of EC 250, 250–750, 750–2,250 and > 2,250 µS/cm, respectively. The SAR (vertical axis) is subdivided into four classes, with decreasing limiting values as EC increases: low (S1), medium (S2), high (S3) and very high (S4) sodium hazard.

The analytical data plots are shown in Fig. 4.32-4.34.Most samples in the study area in pre monsoon fall into very high and high salinity water while in monsoon and post monsoon samples from very high saline water shifts towards high saline water and from high to medium salinity water.

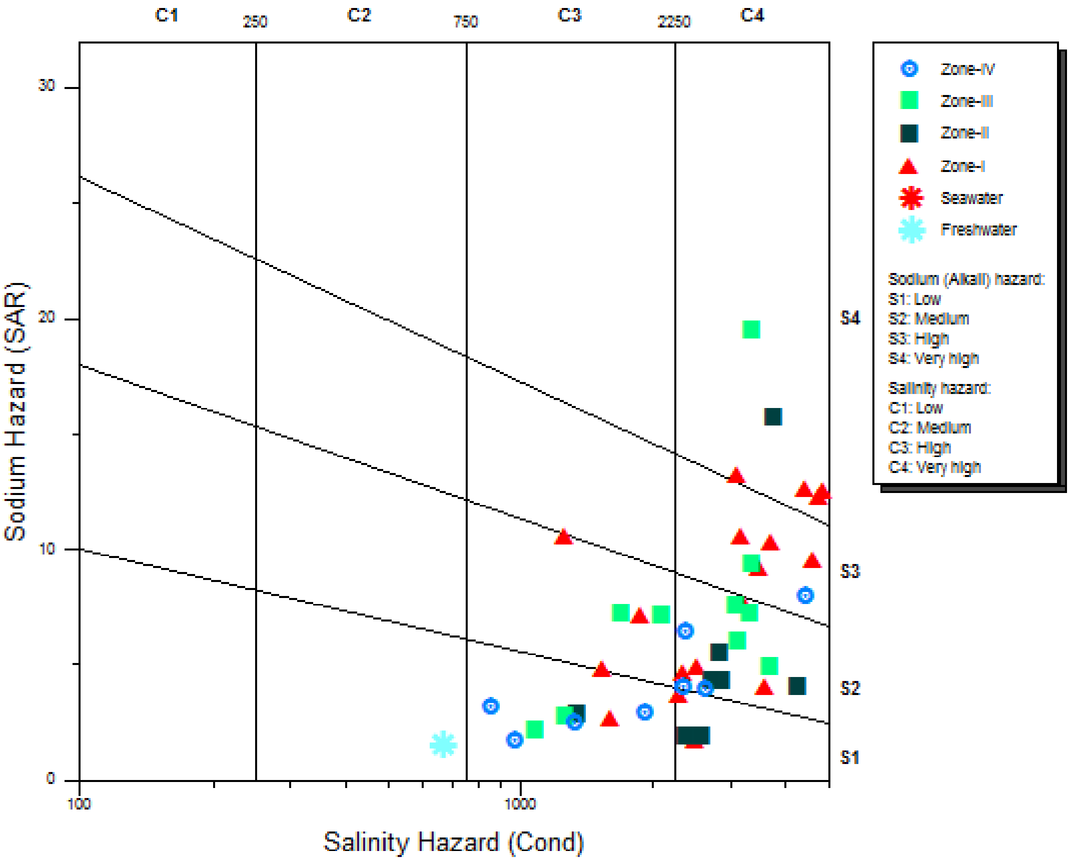


Fig. 4.32 Salinity plot for Pre Monsoon (2013)

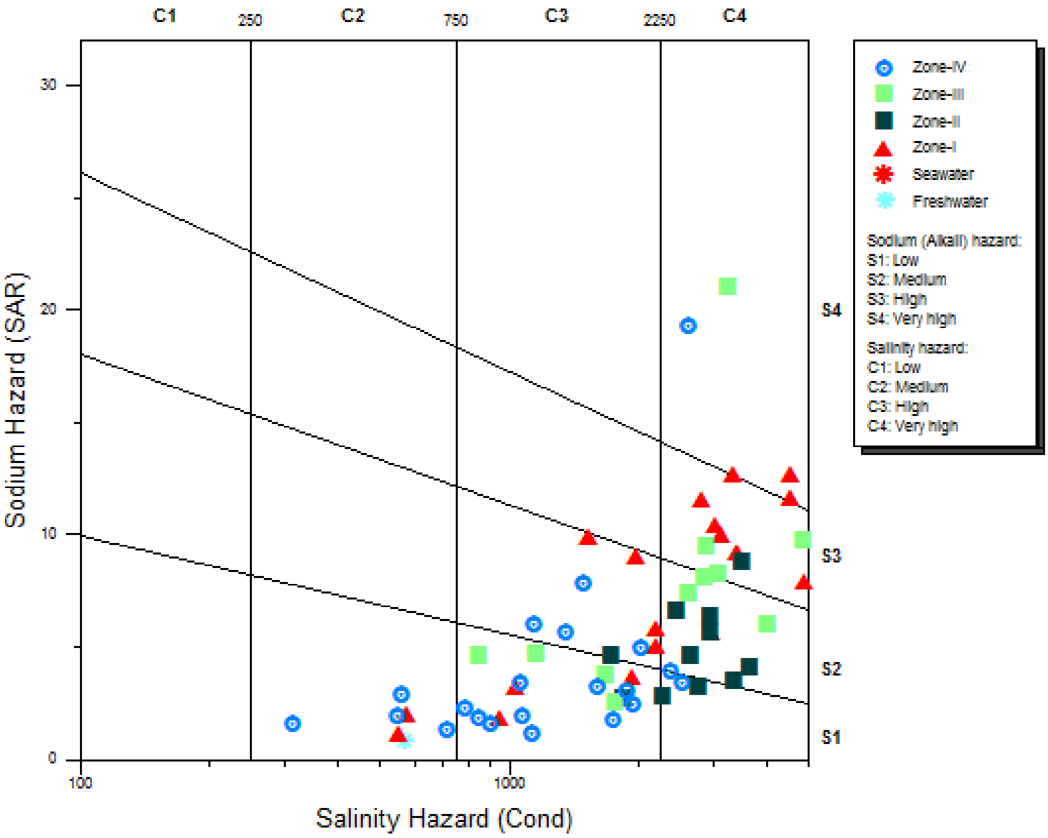


Fig. 4.33 Salinity plot for Monsoon (2013)

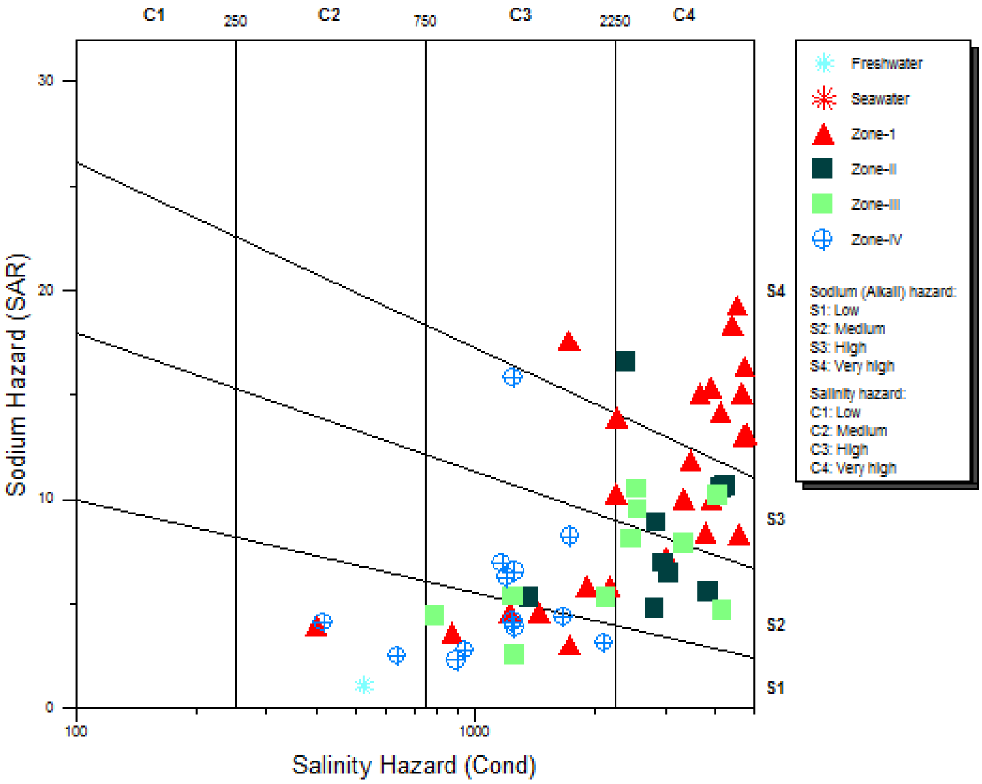


Fig. 4.34 Salinity plot for Post Monsoon (2013)

4.6.3 Combating twin problems of drought and groundwater salinity

As is evident from Sec. 4.6.1 and 4.6.2, the Minsar river basin suffers from the twin problems of recurring drought and coastal groundwater salinity. The population is mainly engaged in agricultural activities and, therefore, a judicious use of available water and crop type cultivated in the region is essential for the necessary socioeconomic development of the region. In coastal areas, salt tolerant crops can be cultivated. Table 4.7 lists some of the crops that can survive in such saline environment.

Table 4.7 Crop selection and quality of irrigation water*

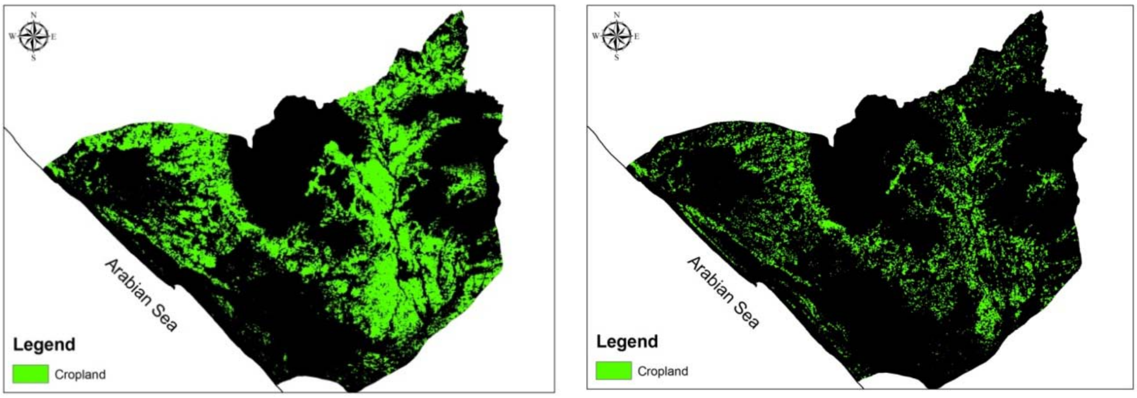
Tolerance class	Soil Type	EC of water (µS/cm)	Crops
Highly tolerant	Light to medium texture	More than 10000	Field crops: Sugarbeat and Dhaincha
	Heavy texture	5000-10000	Orchard crops: Date palm; Forest Crops: Babul shrub
Tolerant	Light to medium texture	5000-10000	Field crops: Safflower, Mustard, Barley, Wheat, Bajra, Jowar, Cotton, Castor
	Heavy texture	3000-5000	Orchard crops: Ser, Coconut and Guava; Forest Crops: Eucalyptus, hybrid Saru
Semi tolerant	Light to medium texture	3000-5000	Field crops: Rice, Sugarcane, Maize, Sunflower, Seasame, Gram and Groundnut
	Heavy texture	1500-3000	Vegetable crops: Cauliflower, Onion, and Potato; Orchard Crops: Mango and Pomegranate

***** Source: CGWB, Ahmedabad

In addition, farmers can also go in for blending of saline and fresh water for irrigating the crops. Low water-intensive crops should be the natural choice of farmers. Due to surface water irrigation schemes that have been commissioned during the last two decades, the situation has considerably improved in terms of freshwater availability. But in a drought year, the surface water schemes also dry up and groundwater salinity rises sharply with severe decline of groundwater levels. To keep the transition zone of freshwater-saltwater mixing in control, maintaining a sufficient hydraulic head gradient in the inland region of the coastal plain is essential. Therefore, suitable artificial recharge schemes and a limit on the groundwater pumping are required. It is to be mentioned here that Govt. of Gujarat has taken several such conservation measures in the region that have been quite effective in combating the problem of drought and groundwater salinity. In Chap. 6, additional recommendations are suggested keeping in view the unique features of the coastal aquifer in Minsar basin.

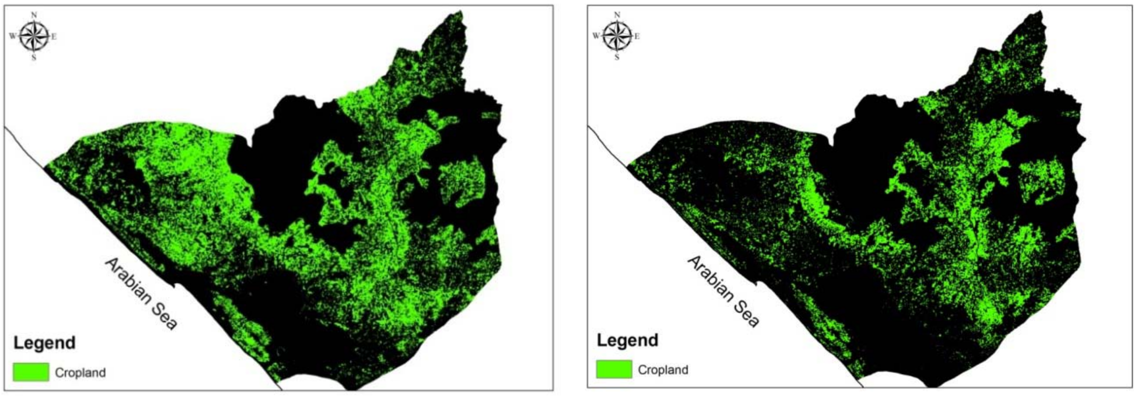
4.6.3.1 Tracking changes in cultivated land since 1970s

In order to study changes in crop cultivation due to rainfall variability and availability of water for irrigation as a result of conservation measures taken over the years, satellite data was utilized to compute the cropped land during typical low rainfall years and slightly below normal rainfall years since 1970s. Satellite data for high rainfall was not available consistently during the period 1972-90, therefore, comparison in respect of high rainfall years could not be made. Figures 4.35 and 4.36 illustrate the spatial changes in cultivated land distribution over a period of about three to four decades. It may be noted here that the figures only show the increment/ decrement in cropped land. However, over the period of last four decades, changes in type of crop being cultivated have also occurred in Minsar Basin. Moreover, during drought/ low rainfall years, fodder crop is cultivated in large areas especially in the coastal belt instead of the usual Kharif or Rabi crop.



Kharif crop for hydrological year 1972-73
Rainfall 375 mm

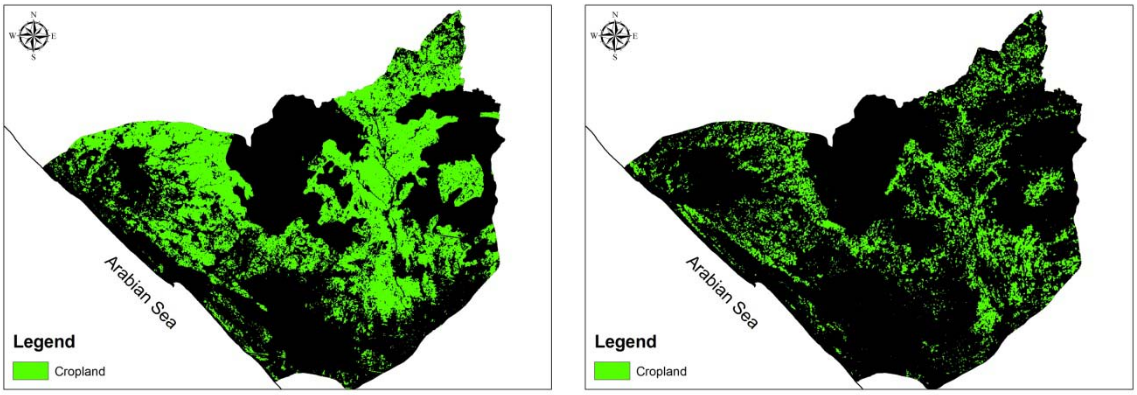
Rabi crop for hydrological year 1972-73
Rainfall 375 mm



Kharif crop for hydrological year 2012-13
Rainfall 249 mm

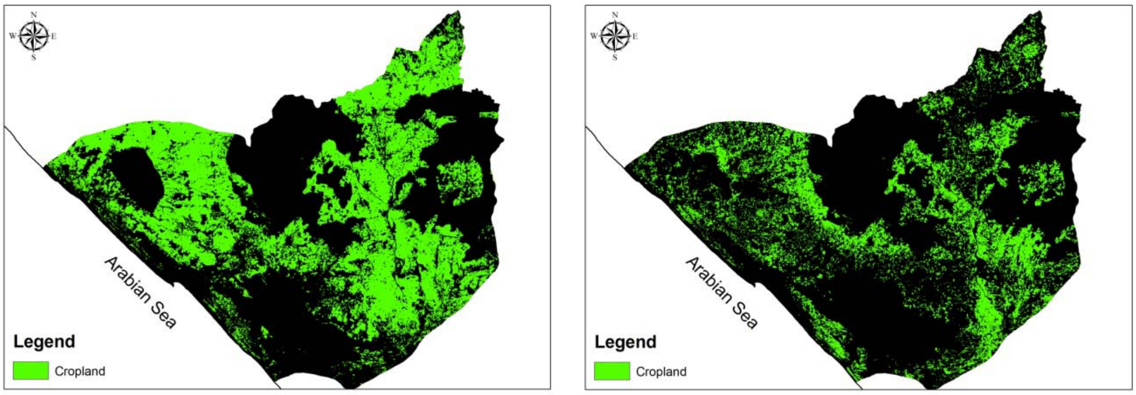
Rabi crop for hydrological year 2012-13
Rainfall 249 mm

Fig. 4.35 Comparison of cropped land for *low rainfall* (249-375 mm) years under Kharif and Rabi seasons during the period 1972-2013.



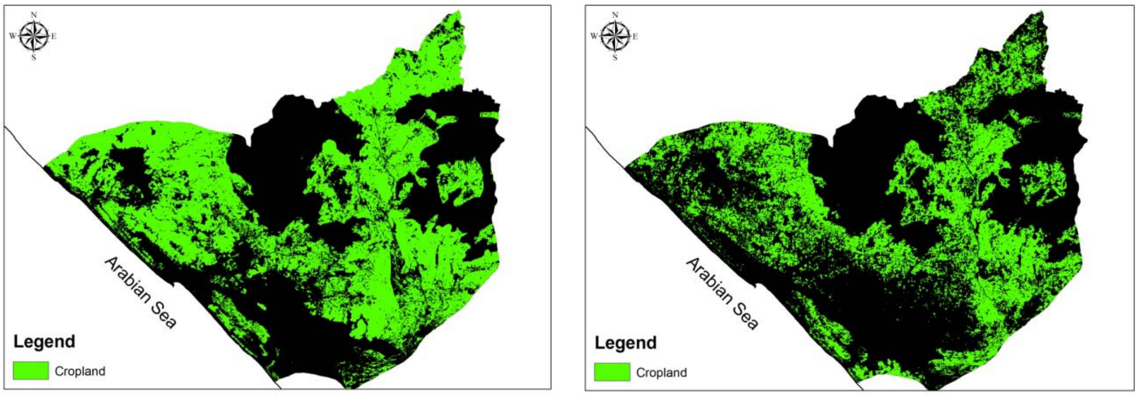
Kharif crop for hydrological year 1977-78
Rainfall 702 mm

Rabi crop for hydrological year 1978-79
Rainfall 569 mm



Kharif crop for hydrological year 2001-2002
Rainfall 623 mm

Rabi crop for hydrological year 2001-02
Rainfall 623 mm

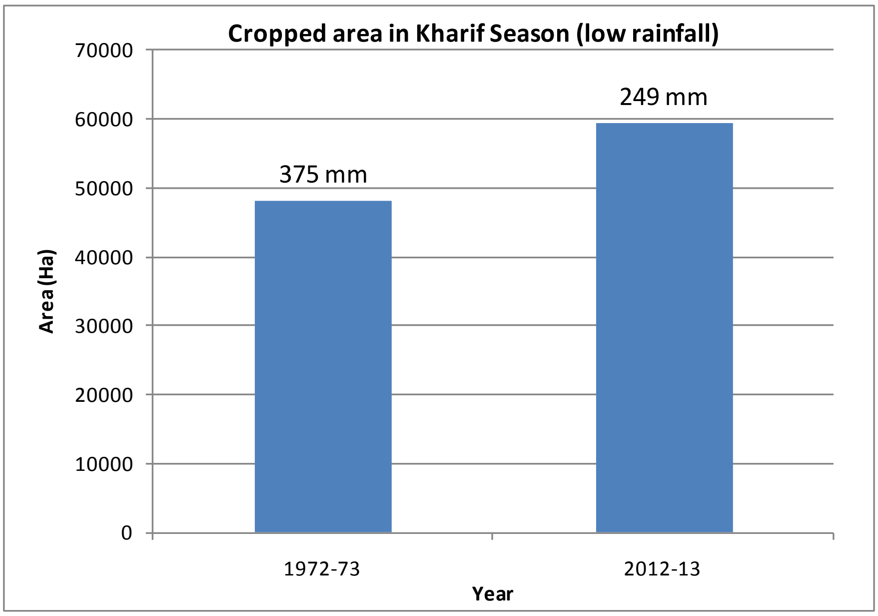


Kharif crop for hydrological year 2008-09
Rainfall 561 mm

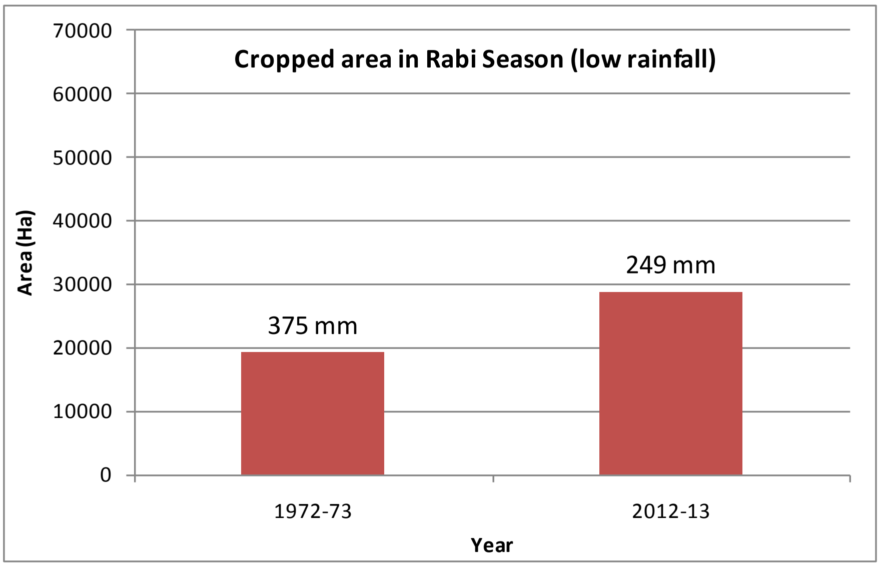
Rabi crop for hydrological year 2008-09
Rainfall 561 mm

Fig. 4.36 Comparison of cropped land for *normal to slightly below normal rainfall* (702-561 mm) years under Kharif and Rabi seasons during the period 1977-2009. For 1970s, satellite data for Kharif and Rabi seasons in the desired rainfall range was available only for the hydrological years 1977-78 and 1978-79, respectively.

In Figs. 4.35-4.36, the expansion in cropped land is very much visible especially in the coastal belt.

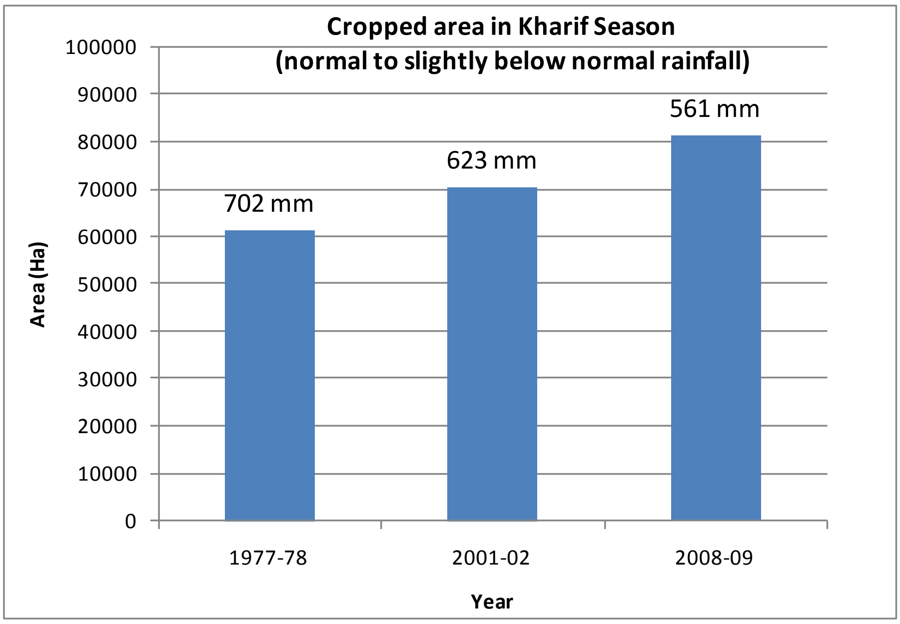


(a) Cropped area in Kharif season for low rainfall years

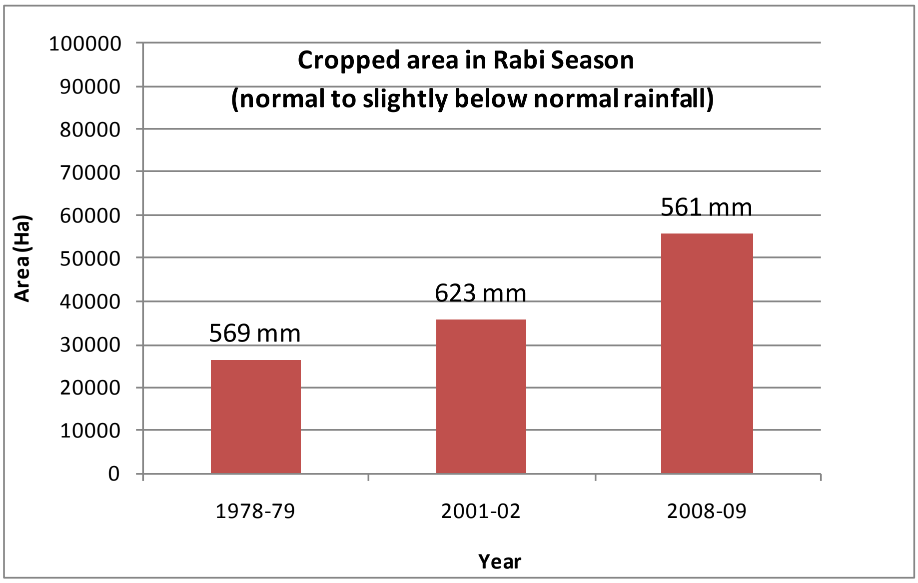


(b) Cropped area in Rabi season for low rainfall years

Fig. 4.37 Comparison of cropped land area for *low rainfall* (249-375 mm) years under Kharif and Rabi seasons during the period 1972-2013. Figures above bars depict corresponding rainfall for the year.



(a) Cropped area in Kharif season for normal to slightly below normal rainfall years



(a) Cropped area in Rabi season for normal to slightly below normal rainfall years

Fig. 4.38 Comparison of cropped land area for *normal to slightly below normal rainfall* (702-561 mm) years under Kharif and Rabi seasons during the period 1977-2009. Figures above bars depict corresponding rainfall for the year.

While comparing the cropped areas in different hydrological years, attempt has been made to utilize satellite coverage for the dates corresponding to pre-harvesting season to estimate maximum cropped land under the respective season. Figures 4.37 to 4.38 clearly reveal the expansion in cropped land area over the period of four decades, which may be attributed to water conservation measures taken in the Minsar basin.

Graphs shown in Fig. 4.39 show some of the wells that have recorded rise in groundwater levels and reduction in TDS values.

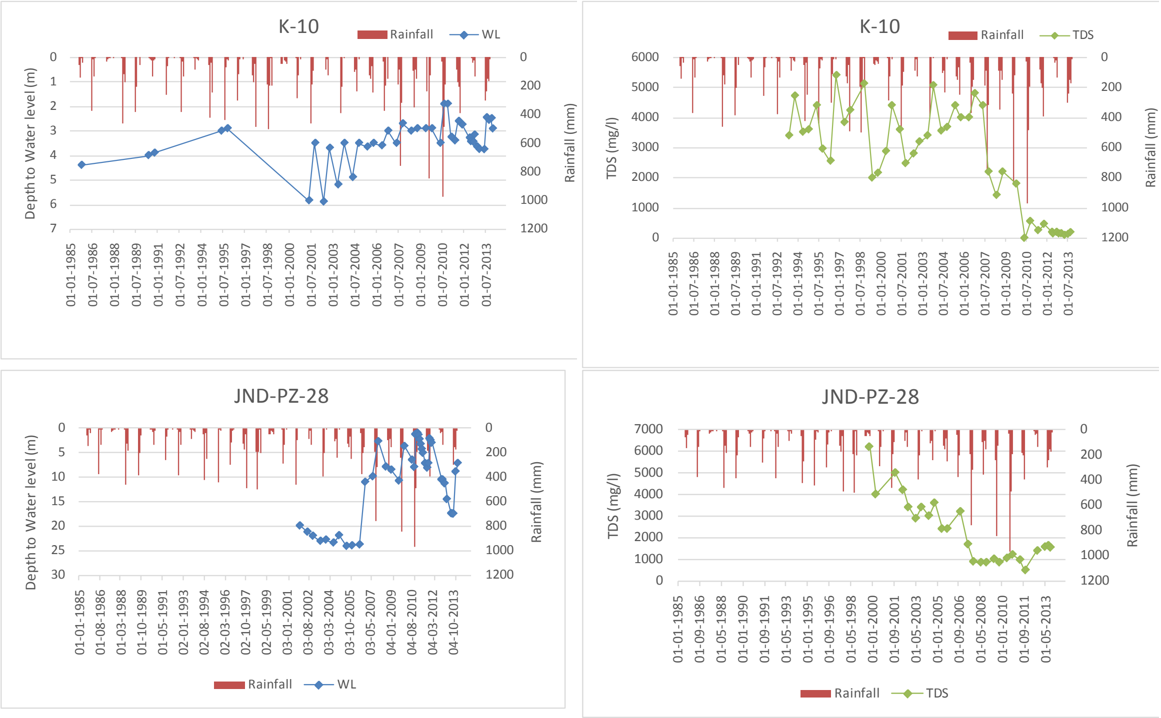


Fig. 4.39 Long terms variation in depth to groundwater level and groundwater salinity (TDS values) in some wells/ piezometers.

The improvement in groundwater levels and salinity may be attributed to comparatively higher rainfall received during the last few years as well as a consequence of water conservations measures in the region.

Chapter 5

Impact of Groundwater Salinity on Socioeconomics of Minsar Basin

Structure on Kindri creek to control salinity ingress

Large diameter dug well

5.1 INTRODUCTION

Coastal areas that fall under the semi-arid category with groundwater as the major source of water supply are susceptible to the availability and quality of groundwater for meeting the water demands for domestic, agricultural and industrial sectors. The groundwater in coastal areas is generally saline due to the proximity of the region to the sea, therefore, the vulnerability of coastal communities to groundwater quality aspects is greatly amplified. As such, the extent of salinity intrusion in the coastal area greatly influences the crop yields, soil fertility, industrial growth; and, in turn, the living status of the community. In absence of any suitable planning measures, the menace of groundwater salinity increases with indiscriminate groundwater pumpage which further destroys fertile lands forcing local population to migrate to inland areas; whereas, with sustainable development policies in place, the groundwater salinity can well be kept in control in order to encourage a thriving socioeconomic growth of the coastal community. As discussed in previous chapters, several water management strategies are already in place in the Minsar River Basin. To evaluate the impact of the water quality and these management policies on the environment and socioeconomics of the region, a comprehensive study was undertaken that involved the integration of remote sensing techniques and socioeconomic surveys within a GIS framework. The survey was undertaken in villages located within a distance of about 15 km from the coast (Fig. 5.1). The detailed socioeconomic survey was conducted with the help of a questionnaire (refer Annexure II) prepared for interaction with the villagers, by adopting a structured survey schedule in the study area, and through personal communication with the local farmers and general population in the region.

The survey revealed that the coastal villages in Porbandar taluka located near reservoir schemes (Kerly / Barda) and tanks are having both surface and groundwater resources which are used for domestic purposes and agriculture production; but the availability of surface water resources is usually limited upto February. Moreover, the quality of surface water in the reservoirs deteriorates after November and the TDS value rises from about 500 mg/l in monsoon season to more than 2000 mg/l in February-March and beyond. Radial canals taking off from reservoir schemes and underground pipes are used for supplying water to the fields. Despite the availability of surface water in these villages, in many instances villagers opt for pumping groundwater in case of leakage/ breakdown in underground pipes.

It was observed that open wells remain an important source of water for majority of the households in the coastal villages despite higher levels of groundwater salinity (Fig. 5.2). However, wells located within a distance of 500 m from the sea coast are highly saline and are utilized only for water quality monitoring purposes and are not suitable for any other purpose. In the coastal zone beyond 500 m, the water from 11% wells is used for domestic purposes and livestock, 54% wells are used for irrigation and 12% wells are used for both domestic purposes and irrigation. During the summer season, when groundwater salinity further increases, water from these wells is not used frequently. Depth of wells ranges from 4 – 40 m in the surveyed villages. Most of the dugwells near the coast (within a distance of 3 km from the coast) are shallow to minimize the possibility of tapping saline water (Fig. 5.3).

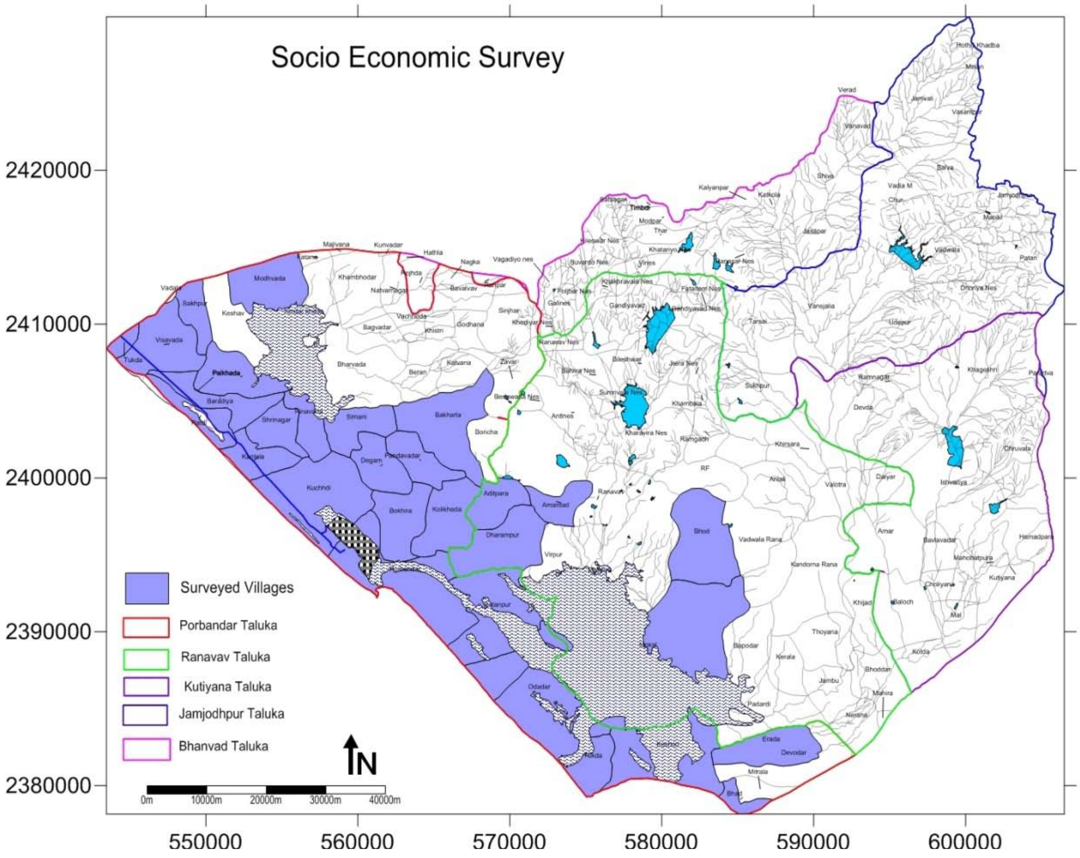
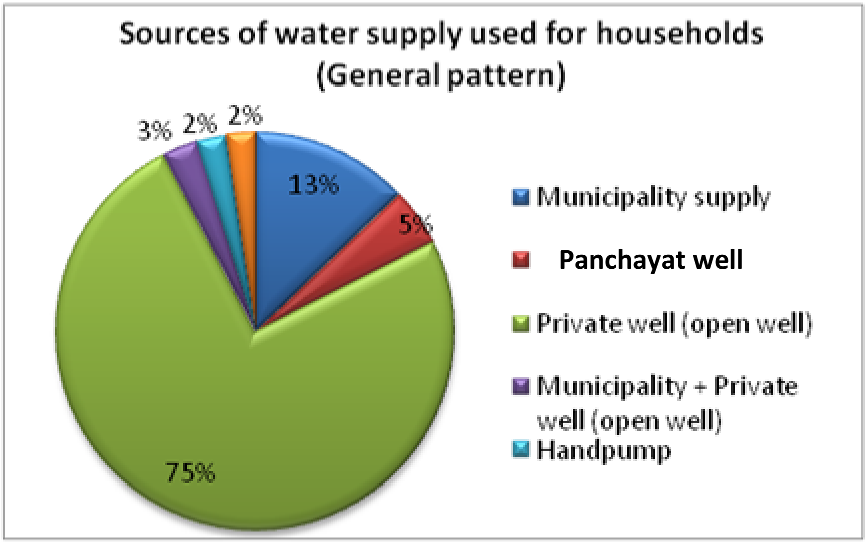


Fig. 5.1 Location map of villages in which socioeconomic survey was conducted.



*Source: field survey data

Fig. 5.2 Household water supply sources

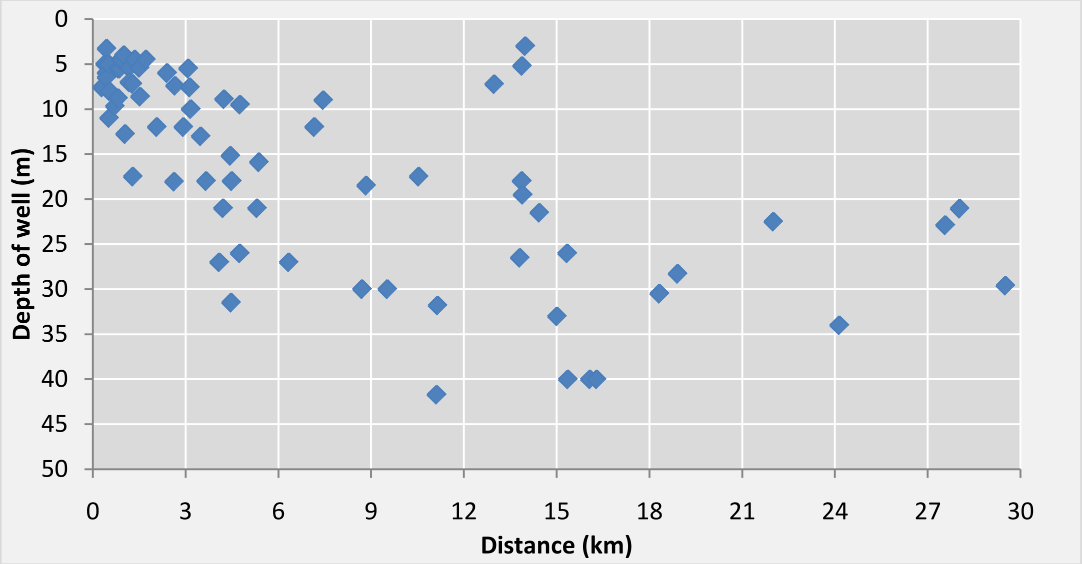


Fig. 5.3 Depth of wells versus distance from coast

Agriculture is the main occupation in the region. As a supportive economic activity, many families (nearly 80-90%) apart from farming activities, are also involved in animal husbandry, and fishing to some extent. The important crops grown in the villages are jowar, bajra, wheat, groundnut, jeera, castor, cotton, vegetables and gadab (fodder crop which is saline tolerant). These crops are grown in three different seasons: Kharif (June-October), Rabi (November-February) and Summer (March to June). However, cultivation of crops by farmers during all the three seasons in the study area varies spatially and also depends upon climatic conditions/ rainfall. Farmers who have access to water with its quality suitable for irrigation, cultivate crop in all the three seasons e.g. in the foothills of Barda region, which is a major recharge zone, fresh groundwater is available during summer season as well and so the summer crop (short term groundnut variety and vegetables etc.) is cultivated in this whole region. Otherwise, crop is cultivated during Kharif and Rabi period only. There are stretches of land, near the coast and in Mokar area (nearly Kerly TR), where soil structure is unfit and groundwater turns more saline in Rabi season. In such areas, only one crop in Kharif season is cultivated, due to non-availability of surface water. In a few villages (e.g. Tukda Gosa) near coast, farmers use saline water with TDS value of about 5000 mg/l to cultivate crop; however, quality of crop that is raised in these areas is poor and the crop yield is also low. South of Kerly Reservoir, the low-lying region gets flooded during monsoon and no crop cultivation is possible during Kharif season. This region, in which groundwater is saline, has also benefitted from the Kerly reservoir scheme and farmers are now able to cultivate good cash crop during Rabi season due to availability of surface water. It has also helped in keeping the groundwater salinity under control.

5.2 SOCIOECONOMIC SCENARIO

5.2.1 Past conditions

In 1970s, the coastal villages in Porbandar taluka and the Ghed areas were worst affected by the groundwater salinity, which was increasing due to saline water ingress through porous media as well as through tidal creeks connected to sea. The unregulated boreholes/wells and the virtually unregulated abstraction of groundwater, exacerbated the declining water quality situation. As per the HLC (High Level Committee) report, in the decade 1971-1981 the average growth rate of population was less than 27 per 1000 persons for the state as a whole but in Porbandar taluka it was less than the average i.e. between 7 and 20. An adverse impact of groundwater salinity was reflected by reduction in agricultural activity. During this period, the number of cultivators reduced in number in many villages along the coastal strip. Effects of salinity were severe and it forced the local population to migrate from rural areas to nearby urban areas and depend less and less on land cultivation as their means of livelihood. Since many families opt for animal husbandry as a supporting economic activity in the region, the impact was seen on cattle population too, with its growth rate coming down by 9% in the period 1972-77.

5.2.2 Salinity mitigation measures

To remove such socioeconomic imbalance in the area, Government of Gujarat implemented several mitigation measures to combat the groundwater salinity problem. The Salinity Ingress Prevention Cell (SIPC) set up by the Government of Gujarat under the Irrigation Department invested in building structures like tidal regulators, bhandharas, checkdams, spreading channels and surface water reservoirs. The bandharas have been instrumental in checking the ingress of sea water through the creeks during high tides and facilitated the conservation of fresh surface water runoff from the catchment of Minsar River in the low-lying Ghed area. These irrigation schemes in Kelry and Barda region have also helped in making surface water available for irrigation and in reducing stress on groundwater. Structures such as check dams and spreading channel have aided in making available the surface water through lift irrigation and in enhancing the groundwater recharge and controlling groundwater salinity. Figure 5.4 shows the sources of water for irrigation in Porbandar district.

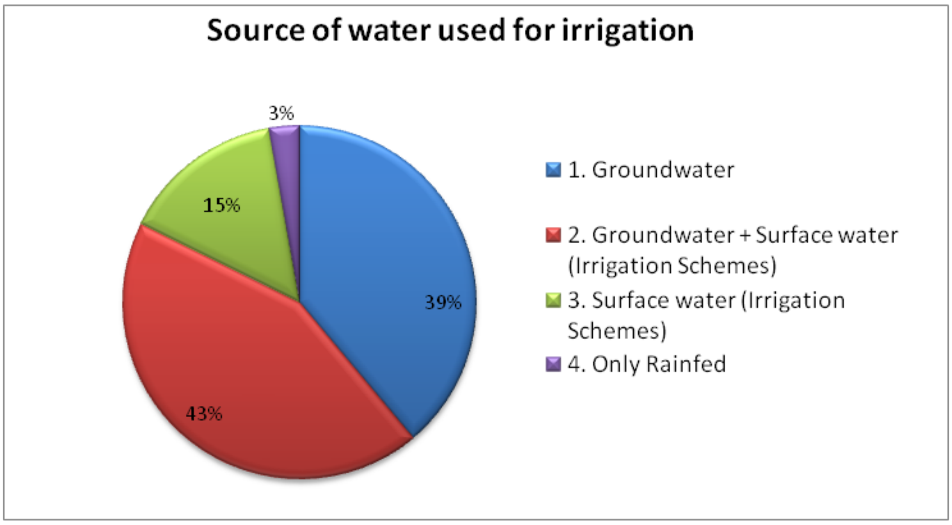


Fig. 5.4 Sources of water used for irrigation in study area

. The surface water irrigation schemes which come under SIPC are as follows:-

- Kalindri Irrigation scheme in Ranavav taluka across river Kalindri (Village:- Ishwariya of Kutiyana Taluka) ,
- Kerly Reservoir scheme in Porbandar Taluka across river Minsar (Village: - Tukda Gosa),

- Kerly tidal regulator scheme in Porbandar taluka across Minsar river and Kerly Creek (Villages:- Chhaya, Oddadar, Tukada),
- Barda Sagar Reclamation bund in Porbandar Taluka (Nearest Villages:- Rinawada and Keshav) and
- Kindri Creek - Kerly Creek spreading channel scheme in Porbandar Taluka (Villages in the stretch from Ratadi to Bokhira).

A scheme wise analysis of impact reveals that villages falling under the spreading channel and Barda Sagar schemes have witnessed increase in area under irrigated crops by 79% and 46 % respectively after the construction of these schemes (source: SIPC personal communication)

Table 5.1 Beneficiary villages under surface water schemes in coastal plain of Minsar basin

Name of scheme	Taluka	District	Year of commissioning	Beneficiary villages
Kerly TR	Porbandar	Porbandar	1993	Chhaya, Ranghavav, Ratanpar, Odadar, Tukda gosa, Pipaliya, Vanala (Virpur), Mokar, Bapodar
Barda sagar	Porbandar	Porbandar	1987	Rinavada, Modhvada, kindherkheda, Keshav, Palkhada, Srinagar, Kuchhadi, Baradiya, Kantela, Bharvada
Kerly creek Kindri creek spreading channel	Porbandar	Porbandar	2009	Ratdi, Jhavar, Srinagar, Bokhira

***Source: SIPC personal communication**

5.2.3 Present situation of drinking water supply

The drinking water is provided to the rural population by Public Health Engineering Departments (PHED) mainly through hand pump wells and piped water supply schemes by pumping of water from bore/tube wells and connecting to overhead tanks / ground level reservoirs. In some villages, water is also supplied through tankers during summer season. Municipal piped water supply from Fodarna and Khambala dams (known as ‘regional water supply scheme’ – Reg. WSS) is also available in cities/ villages/ industries.

During a normal rainfall year, 23% of households get municipal water (Fig. 5.2). In the past, during a less than normal rainfall year, municipal water supply used to get reduced with only 13% households getting municipal piped water supply; with 75% villagers depending on open wells for domestic water needs, and the remaining 12% utilizing Village Panchayat wells (Figs. 5.5 – 5.6). But the situation improved in the recent year 2012 (again a low normal rainfall year); the strategic requirement of domestic water need was additionally catered through joint water supply schemes (i.e. Narmada Municipal water supply) in a major part of area (Fig.5.7).

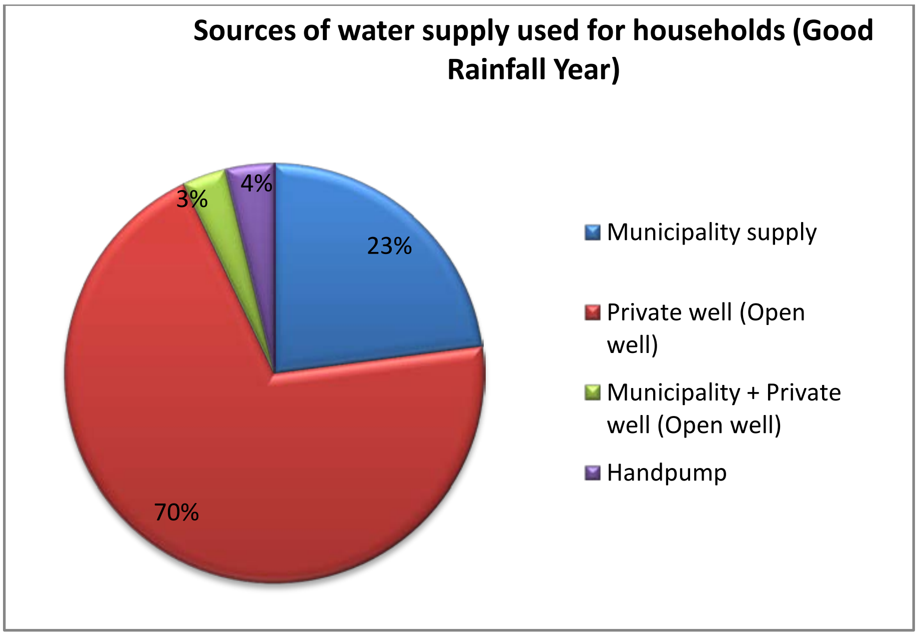


Fig. 5.5 (a) Source of water supply in households for a normal rainfall year

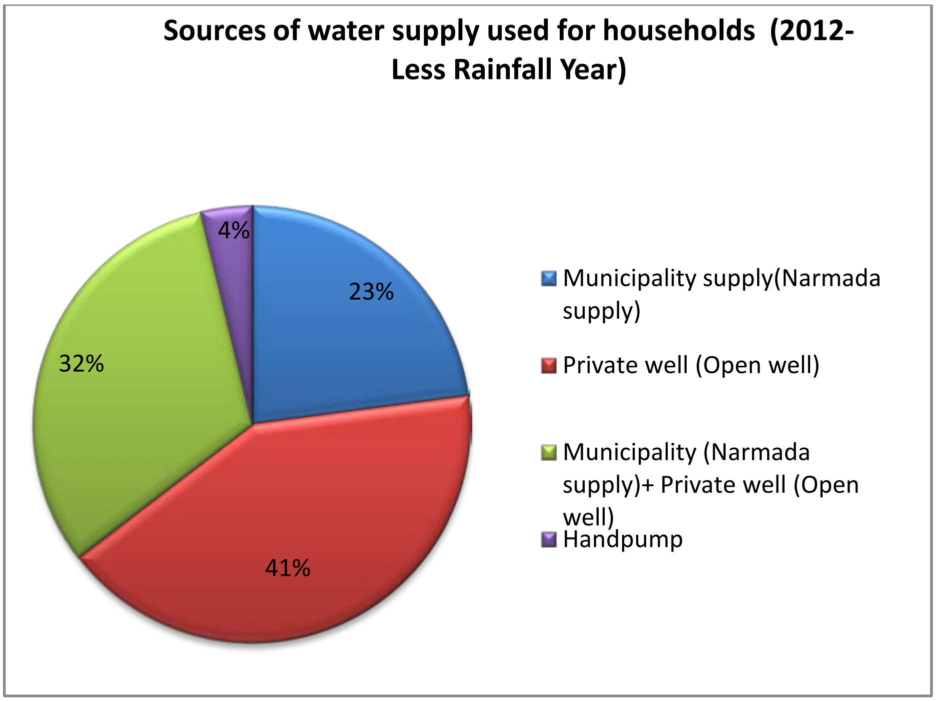


Fig. 5.5 (b) Sources of water supply in households for a less than normal rainfall year (year 2012)

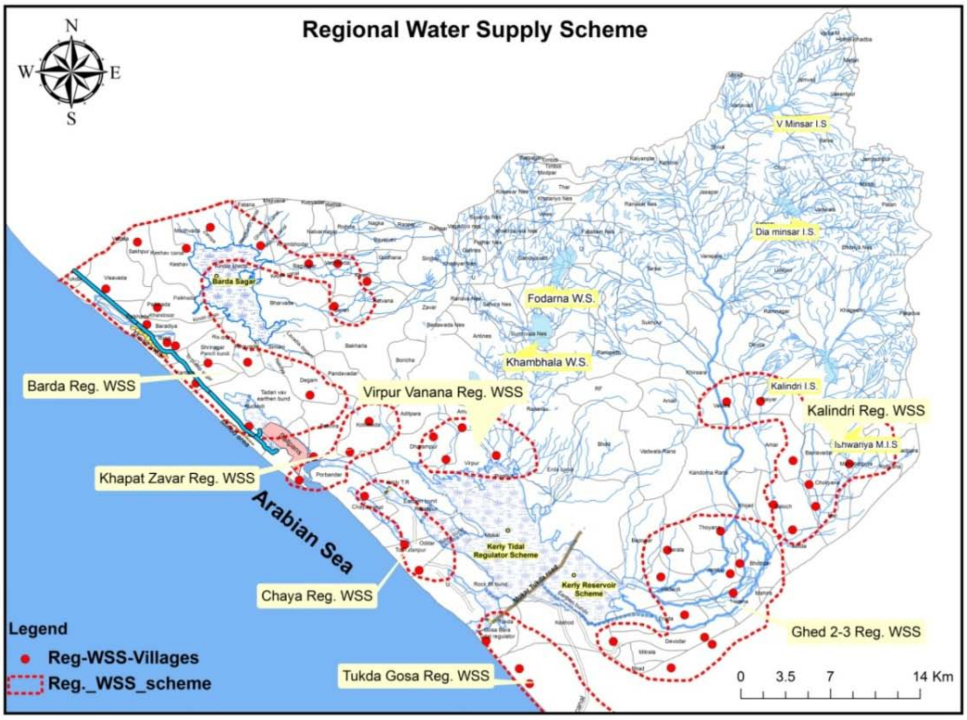


Fig. 5.6 Regional water supply scheme since 1961

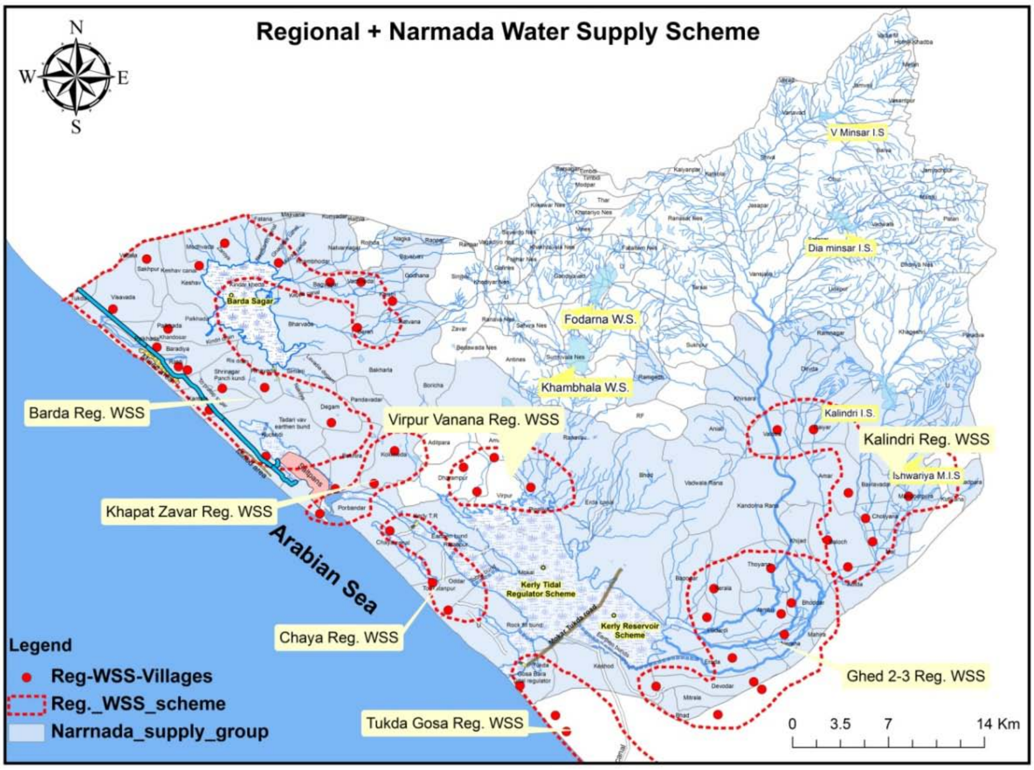


Fig. 5.7 Joint water supply scheme implemented from 2012 in the study area

In order to further mitigate the groundwater salinity, many organizations like Tata Ratan Trust, Water and Sanitation Management Organisation (WASMO), Suzlon, Bharat Buthan etc. are working, along with village panchayats, for better management of the water resources for drinking purposes for the village people. Water storage tanks and pipelines made by WASMO are present in many villages for provision of potable water. At the time of survey it was observed that the people of this region are very hard working and optimistic. Despite the poor water quality they try their utmost to get the best yield from the sown crop. While the problem of lack of drinking water in the villages has been resolved to a large extent, because of the SIPC structures, there have also been a number of other spinoff benefits for women folk like time savings in collecting water from long distances, opportunities for employment and increase in incomes. Women have started participating in Self-Help Groups (SHGs) and Pani Samities, exercising greater decision making, both within their families as well as at the village level. They have also started securing their future by saving with their SHGs and taking loans for livelihood facilities.

As part of the survey, micro biological tests were conducted on water samples collected from most frequently used wells and ponds for drinking water. The analysis showed an MPN (Most Probable No.) index < 2, which suggests that water is suitable for drinking. At some locations of Kerly creek it was found that MPN index is > 2, which suggests that water is not suitable for drinking (Fig. 5.8).

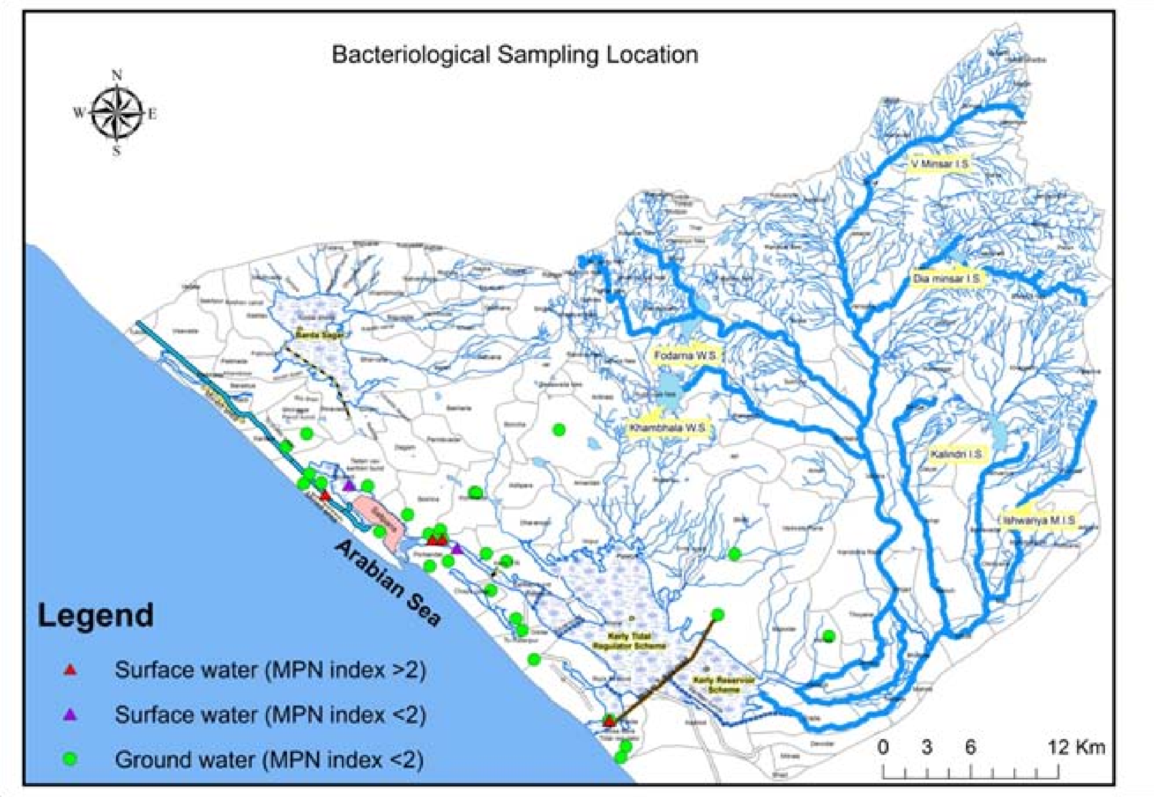


Fig. 5.8 Bacteriological sampling

5.2.4 Change in cropping pattern

As a result of initiatives taken by SIPC Govt. of Gujarat, water suitable for irrigation is annually available for a longer period over a larger region. In turn, the cropping pattern in the study area has changed over the years. Food grain crops were important in 1970s, but later on non-food grain crops became dominant. Area under coarse cereals like jowar and bajra has been replaced by cash crops such as oil seeds (castor, groundnut and cotton), spices (Jeera) and horticulture crops (brinjal, chilly, onion, etc.). Changes in cropping pattern have occurred more rapidly since last 4-5 years because of availability of fresh water and are still continuing. In many areas, old variety of single cotton crop has been replaced with two season (Kharif and Rabi) crops such as groundnut, wheat and jeera. The higher production of jawar / gadap (fodder) helps in supporting animal husbandry. According to farmers, crop yields have increased by up to 60-70% within last 4-5 yrs due to heavy rainfall (except 2012) and the measures taken by Govt. Departments and local people. At present, cotton and groundnut are the two main Kharif crops sown in coastal Porbandar. Recently, castor is also grown along with these crops. The main Rabi crops include wheat, jeera and chana. Bajari, moong, moth and udad are the summer crops. During a drought year, the cultivated crop in major areas gets replaced by fodder crop. This also results in a drastic reduction in farmers' income compared to a normal rainfall year.

The 'Krishi Mahotsav' program was initiated in the district in 2005 with the main objective to double the income of farmers within a span of 5 years in a sustainable manner. The 'Krushi Mahotsav' covered almost all the villages in the state with researchers, scientists and experts interacting and providing information to farmers on all aspects of agriculture. Such programs have helped the farmers in adopting modern technology for practicing agriculture and maximize crop yield.

In recent years, farmers have opted for modern efficient irrigation techniques such as drip and sprinkler irrigation. Figure 5.9 shows the percentage area under the investigated domain utilizing different irrigation techniques.

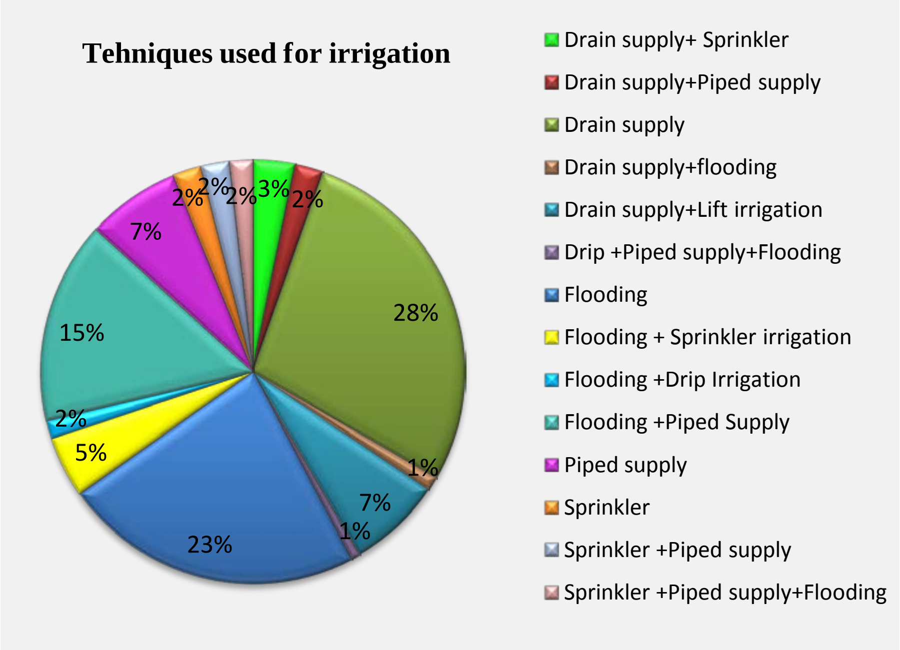


Fig. 5.9 Techniques used for irrigation in study area

In villages where new water sources are established, the number of milch animals has increased due to availability of drinking water and green fodder. Across nearly all land benefitting from water supply schemes, a positive correlation can be seen between the number of milch animals and milk production as shown in Table 5.2

Table 5.2 Increase in percentage of milch animals due to availability of fresh water

Name of scheme	% increase in no. of cows	% increase in cow's milk (lt.)	% increase in no. of buffalos	% inc. in buffalo's milk (lt.)
Kerly RR/ TR	4	3	3	8
Barda Sagar	12	24	59	155
Spreading canal (between Kindri - Kerly creeks)	9	19	111	259

***Source: SIPC**

5.2.5 Shelterbelts - protection from sea sprays

Coastal areas that receive consistent salt spray from the sea have elevated levels of soil salinity. Coastal shelterbelts significantly reduce both the direct and indirect impact of sea sprays on plants and water resources, acting as effective barriers that reduce damage from salt-laden winds in coastal areas and provide shelter to coastal life. Shelterbelt plantation (casuarinas) is an ongoing activity undertaken in the coastal region by the Forest Department of Gujarat, Porbandar.

Besides casuarinas shelterbelts, mixed plantation is also employed by farmers to increase crop yields. One of the major plantation activities along the coast is by private land owners who plant casuarinas and coconut along with castor and oreo as cash crops. Figure 5.10 shows such a plantation at Tukdagosa village-DF7.

Fig. 5.10 Nursery Plantation at Tukdagosa-DF7 (Block-2)

According to farmers this approach has change the economic scenario by increasing the land fertility due to which yield of crops (castor and oreo) increased up to 70-80% which was 20-30% before this plantation 3-4 years ago.

The study of shelterbelts in the Porbandar region indicates that vegetation around the coastal area has helped to reduce the water-logging condition of land and improve water quality by up to 10-20%, both of which benefitted castor, oreo and gadap crop production. Additional nursery plantations are planned at more places. Forest Department Gujarat, Porbandar, distributed free seedlings of Casurina sps. to public, farmers etc., to plant these seedlings in order to improve existing conditions and increase the crop yield in the coastal belt. The Forest Department is planning to bring more area under the tree cover near the coastal line.

5.2.6 General conditions

The surveyed information indicates that the majority of villages have literate population up to higher secondary level; infrastructure for primary and secondary education level is found in most of the villages (Fig. 5.11).

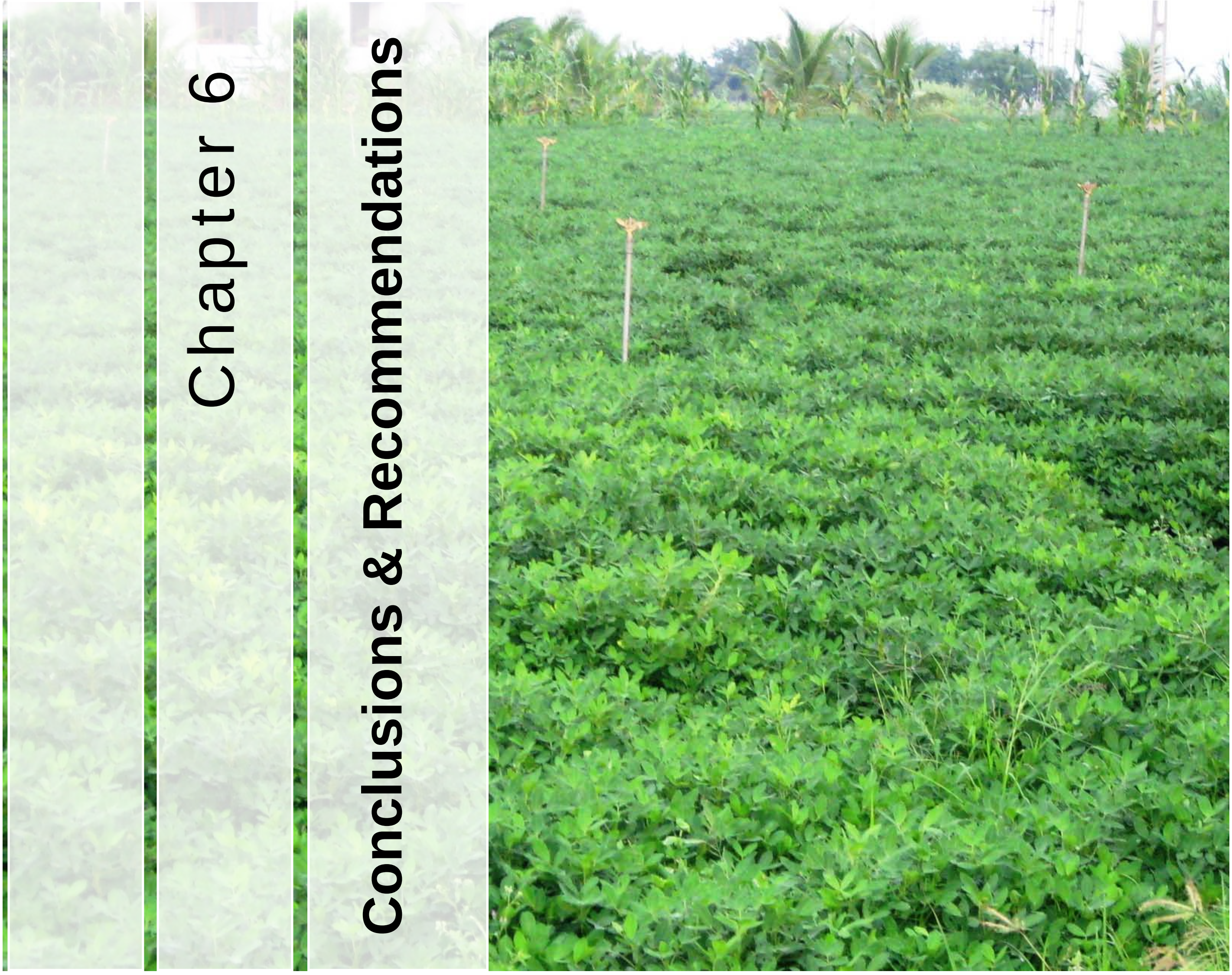
Fig. 5.11 Primary schools in villages

Almost all the villages have post office facility, entire region is well connected with land line BSNL service and all types of mobile services; primary health care centers are found in most villages, remaining use the source from nearby villages.

In a nutshell, major expansion in surface water irrigation schemes, water management, implementation of drip and sprinkler irrigation, providing Kisan Credit Cards and Soil Health Cards to farmers in the past years have spearheaded agriculture economy towards inclusive growth and has enhanced the socioeconomic growth of the region.

Chapter 6

Conclusions & Recommendations



Use of sprinkler system for crop irrigation in Barda region

Water quality monitoring in Ghed area

6.1 INFERENCES DRAWN FROM THE STUDY

The research work documented in this report, envisaging to investigate the groundwater dynamics in the coastal aquifer system of Minsar River Basin, essentially comprises the following:

- Hydrogeologic investigations
- Water quality and stable isotope investigations
- Numerical modeling of coastal aquifer system and water management aspects
- Impact of groundwater salinity on socioeconomics of the coastal river basin

Hydrogeologic investigations based on litholog study and water level data have revealed that the Miliolitic limestone forms the potential aquifer system in the coastal belt. In some areas, the limestone is more than 35 m thick. In the upland areas, the Deccan trap basalt forms the most extensive but poor aquifer due to its compactness and limited primary porosity. However, the weathered zone of the Deccan Trap, which at places is upto 30 m thick, forms a good aquifer. The water table contours in the Minsar basin, more or less follow the topography and the direction of groundwater flow is, in general, towards the sea. The region near the foothills of the steeply rising Barda Hills exhibits significant thickness of limestone and comprises a major groundwater recharge zone.

Close to the sea coast, groundwater is saline even at shallow depths. With increasing distance from the coast, the salinity in general decreases; except in the Ghed region, where the groundwater salinity is quite high (> 3000 mg/l) even at shallow depths at 12 km from the coast. Beyond a distance of 18 km from the coast, the groundwater is generally fresh (< 1000 mg/l) at shallow as well as at deeper depths. Further landward movement of salinity is curtailed by the strong seaward hydraulic gradient in the upland area. This gradient existing in both pre- and post-monsoon seasons effectively limits the freshwater-saltwater interface present in the limestone formation in the coastal zone. In the coastal belt, the groundwater salinity increases steeply with depth and at places reaches more than 10,000 mg/l. However, there are pockets of freshwater even near the coast, especially in places where a significant positive hydraulic gradient exists. During pre-monsoon, the water table gets lowered and a reverse hydraulic gradient is established near the coast leading to landward flow of seawater in some of the stretches along the sea coast. During monsoon season, the water table recovers and a positive gradient is setup which generates submarine groundwater discharge into the Arabian Sea.

Several factors contribute to groundwater salinity in the Minsar basin. Gaj beds comprising limestone, grit, sand, silt and gypseous clay of Miocene age that were formed in marine environment, have contributed to groundwater salinity both close and away from the coast in inland areas. Upconing of underlying saltwater due to groundwater pumpage for crop irrigation in the intensively cultivated region surrounding the Barda Sagar enhances the groundwater salinity for limited time periods. This increase in salinity is visible even during monsoon, when groundwater is utilized to supplement crop irrigation during a long dry spell in the monsoon period. Close to the sea coast, it is the seawater ingress in some pockets that has given rise to elevated levels of salinity. In addition, on the sea coast, high waves breaking along the seashore throw up a considerable amount of sea water in the form of spray, which gets deposited on the coastal land surface and plants and adds to soil salinity.

Chemical analyses of water samples have indicated the presence of ion exchange phenomena in the transition zone of the freshwater-saltwater interface. Stable isotope investigations have revealed that in the Ghed region (Kerly creek) the zone of transition exists at 15 m ± 3 m (approx.) altitude. For future studies, it is important to monitor this transition zone (at 12 m to 17m altitude) to understand the influence of groundwater withdrawals, climate change, land use change and other anthropogenic activities that may cause this transition zone to fluctuate.

Distributed groundwater modeling of the coastal aquifer system in Minsar river basin has been attempted in 3D at the regional-scale accounting for variable density flow. Numerical simulations for anticipated sea level rise on account of climate change do not yield any visible change in groundwater salinity near the coast; since the groundwater is already quite saline along the coastal strip. However, seawater ingress through creeks on account of higher tides needs to be investigated further.

For protection of groundwater quality, several conservation measures have been taken by the Govt. of Gujarat. The construction of bandharas at the mouth of creeks has enabled both (i) the conservation of surface water runoff from the catchment of Minsar River and Barda Sagar, and (ii) the prevention of seawater ingress through the creeks in the inland areas. The surface water irrigation schemes viz., Kerly RR/ Kerly TR and Barda Sagar, developed in the low-lying Ghed area as a byproduct of the above conservation measures, have facilitated ready access of fresh surface water for irrigation to the farmers in the Ghed area. In Ghed area, the groundwater is quite saline and the commissioning of above schemes has enhanced groundwater recharge through radial canals taking off from these schemes. As summer approaches, the water spread area of these irrigation schemes shrinks, and the fresh water turns saline due to evaporation effects. The spreading channel laid parallel to the coast between Kindri and Kerly creeks has aided groundwater recharge and has provided water for crop cultivation through lift irrigation in the coastal strip. The spreading channel, existing along the Saurashtra coast, also feeds surplus floodwater from one reservoir basin to another where rainfall is scanty. Checkdams constructed on streams and percolation tanks have also augmented the groundwater recharge.

As an outcome of the above conservation measures taken over the last two decades, relatively more freshwater is available for crop cultivation, compared to previous decades. A gradual change in cropping pattern is witnessed with more farmers opting for cash crops instead of the coarse cereals grown earlier. Major expansion in irrigation, suitable water management, implementation of drip and sprinkler irrigation, providing Kisan Credit Cards and Soil Health Cards for farmers in the past years have spearheaded the agricultural economy towards inclusive growth.

6.2 Recommendations

To combat the groundwater salinity, a multi-dimensional approach is required. Percolation tanks, check dams, rainwater harvesting systems, adoption of low water-intensive crop farming, renovation and deepening of ponds and run-off diversions systems to recharge aquifers are micro-steps that mitigate salinity ingress. Use of suitable technology, study of meteorological parameters, geography and geological factors, and capacity building of farming communities on efficient water management practices are other strategic interventions. Specific recommendations for the area under investigation are stated below.

1. Seaward hydraulic gradient needs to be maintained all along the coast to prevent inland migration of seawater.
2. Groundwater pumpage in the narrow coastal strip should be restricted.
3. For sustainable development of the sensitive coastal zone, long term monitoring of groundwater levels and salinity at regular intervals is essential to check any undesirable fall in the water table elevation and degradation in groundwater quality on account of groundwater overdraft in inland areas of the coastal zone.
4. Groundwater pumpage for irrigation can be further reduced by widespread adoption of efficient irrigation techniques such as sprinkler and drip irrigation technology. This technology is already in place in some areas of Minsar basin.
5. In areas with saline groundwater and no surface water resource, salt tolerant crops and / or low water-intensive crops can be cultivated.
6. The high evaporation rates result in significant loss of surface water storage. Moreover, the analysis of long term rainfall data has indicated that the region suffers from frequent drought years. The effect of evaporation intensifies especially during conditions of drought. In order to safeguard against the influence of droughts and to save water from being lost to the evaporative process, evaporation mitigation techniques need to be implemented.
7. Apart from evaporation mitigation techniques, sub-surface storages are not susceptible to loss of the critically important water resource through evaporation. Sub-surface storages also aid in building up the water table thereby keeping the groundwater salinity in check. Raising the water table through artificial recharge techniques in the inland region of the coastal belt will help in maintaining a healthy hydraulic gradient towards the sea, besides providing additional groundwater during drought years.
8. The low-lying area south of Kerly creek reservoir regularly gets flooded with river water during monsoon period and no crop cultivation is possible in this region during Kharif season. Studies can be taken up to divert the flood river water and utilize it for recharging the groundwater.
9. Large scale limestone mining near the sea coast may be restricted to protect the aquifer formation.
10. Shelterbelt plantation is already being taken up along certain stretches of the sea coast. Such shelterbelt plantations, including mangroves, along the coastline act as a bio-shield against coastal storm surges and needs to be taken up on a longer stretch of coastline. The coastal shelterbelts also act as a 'carbon sink' by absorbing emissions of the greenhouse gas carbon dioxide. Coastal shore protection structures also need to be planned to prevent coastal erosion.

6.3 FUTURE SCOPE

1. Groundwater salinity is a wide-spread problem along the Saurashtra coast. The investigations documented in this report are probably the first such attempts to understand the dynamics and groundwater salinity of the coastal aquifer system of Minsar river basin in coastal Saurashtra.

2. The hydrology of Minsar river basin is complex because of its transient nature. Estimation of fluid and salt fluxes in this type of transient system is difficult because the available water level and water quality data represent only small segments of time and space. Monitoring of groundwater levels and water quality as well as the flow in Minsar River needs to be continued over a longer period at a desired number of strategic representative locations in order to detect changes in the hydrologic system as well as further investigate the complex physicochemical reactions occurring in the freshwater-saltwater mixing in the limestone coastal aquifer system. Data collected during this study and the interpretations made from these have definitely added to the understanding of the hydrologic system of Minsar basin, but uncertainties remain. A significant amount of water is discharged by evapotranspiration, yet data pertaining to potential evapotranspiration was not available at sufficient number of locations. Data related to groundwater draft also was not available in sufficient detail. The effect of river-aquifer interaction also needs to be determined for optimal utilization of water resources in the basin.
3. The complex dynamics and hydrogeology of the semi-arid coastal region with limestone and Deccan trap formations demands intensive field investigations and long term monitoring of tidal creeks, groundwater levels and quality, and submarine discharges. In view of the increasing water demand and anticipated changes in climate patterns that may lead to seawater ingress through surface water bodies, further studies may be considered to plan a sustainable development of the coastal zone.

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Training course organized at Ahmedabad

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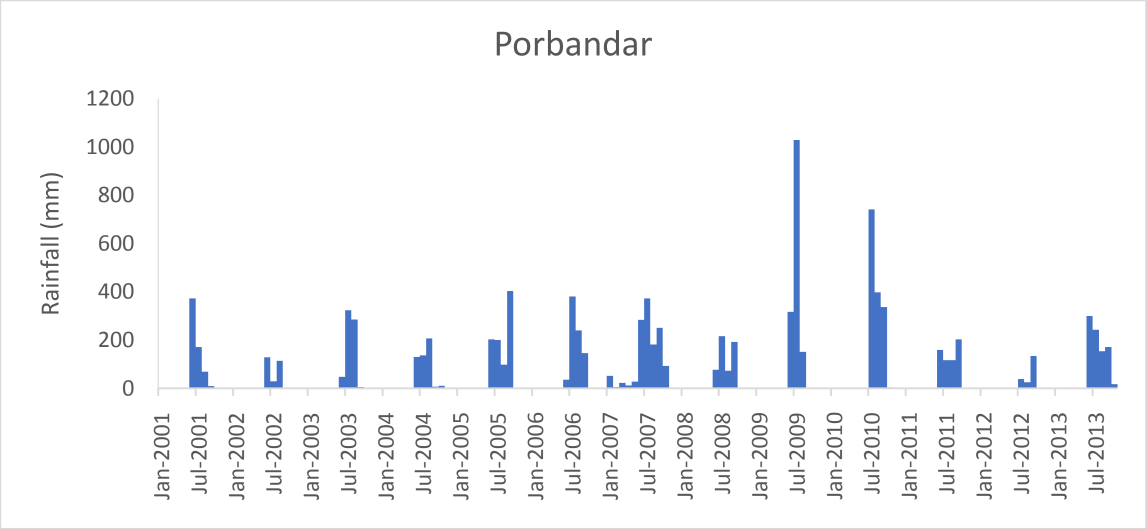
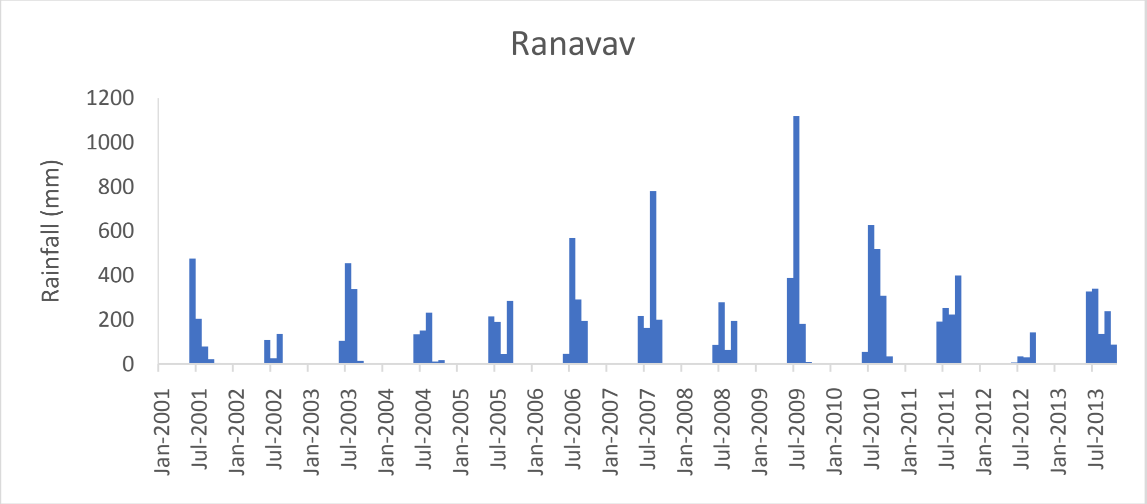
Annexure I

Monthly distribution of precipitation at raingage stations in Minsar river basin for the period 2001-2013.

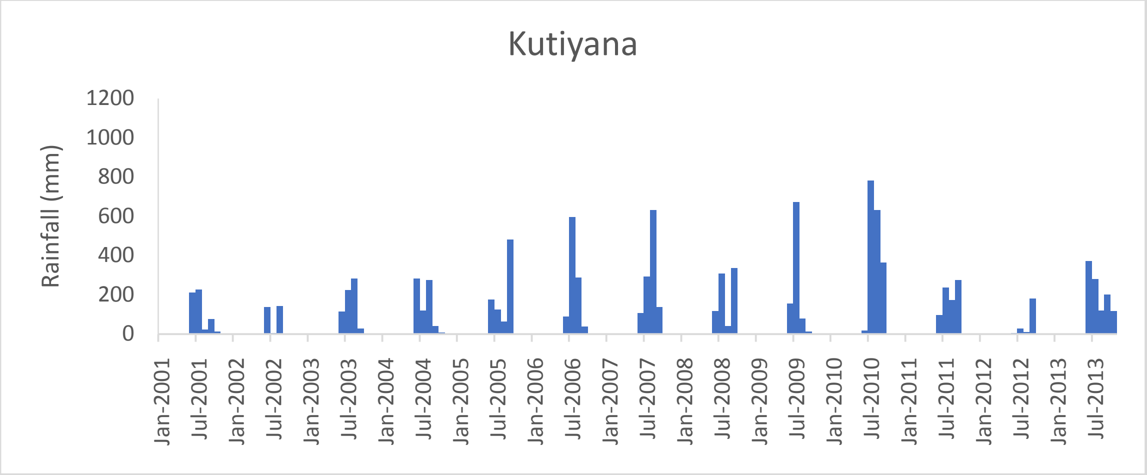
1. Porbandar



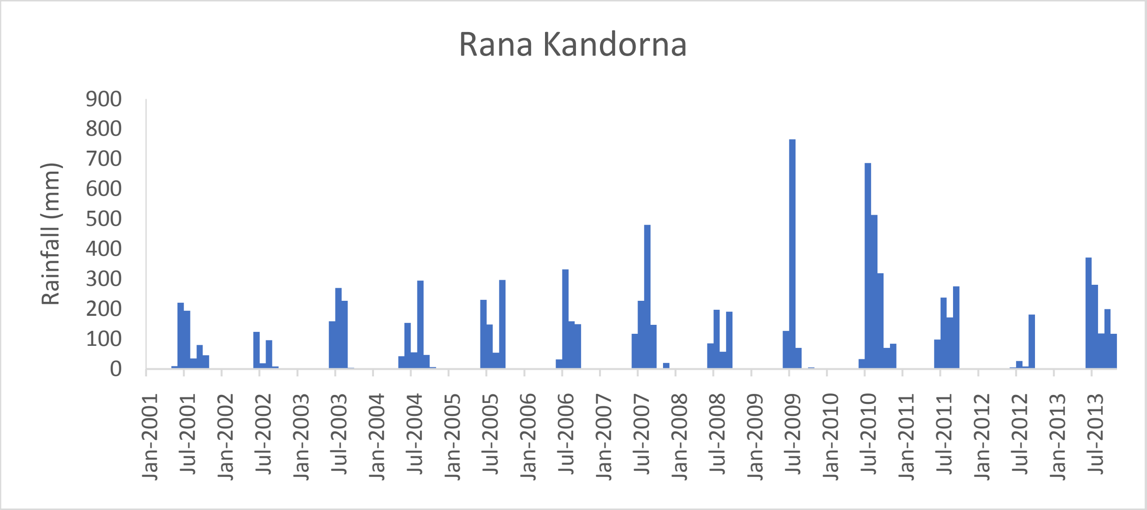
2. Ranavav



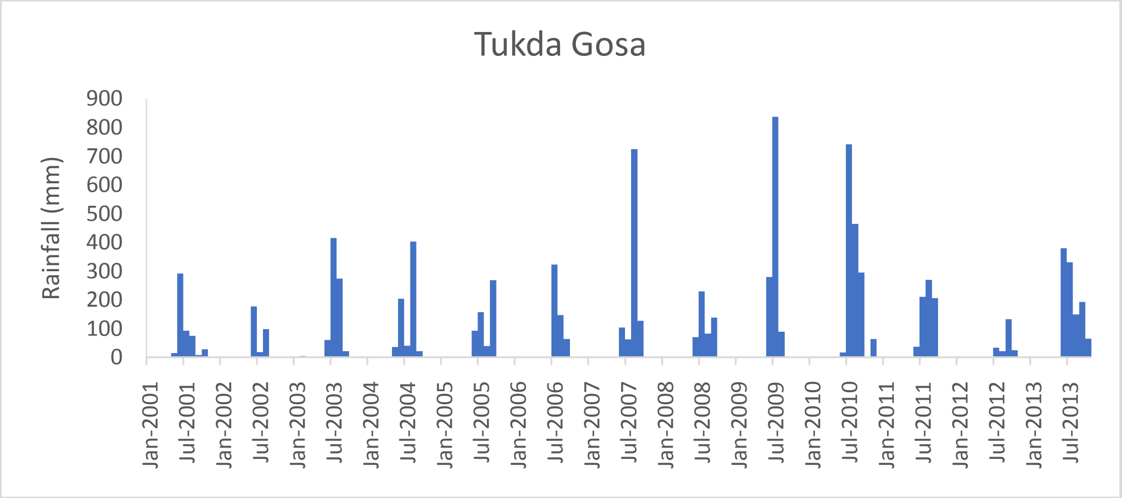
3. Kutiyana



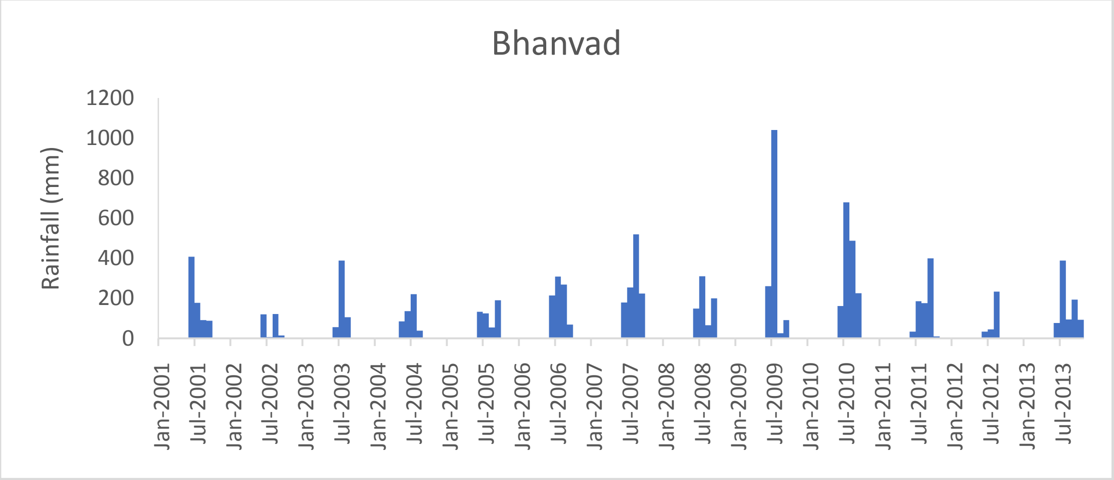
4. Rana Kandorna



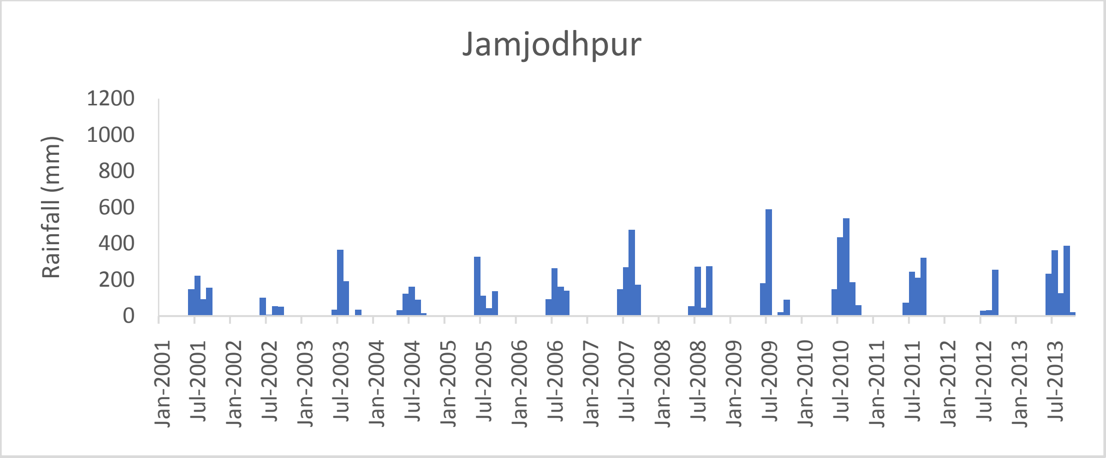
5. Tukda Gosa



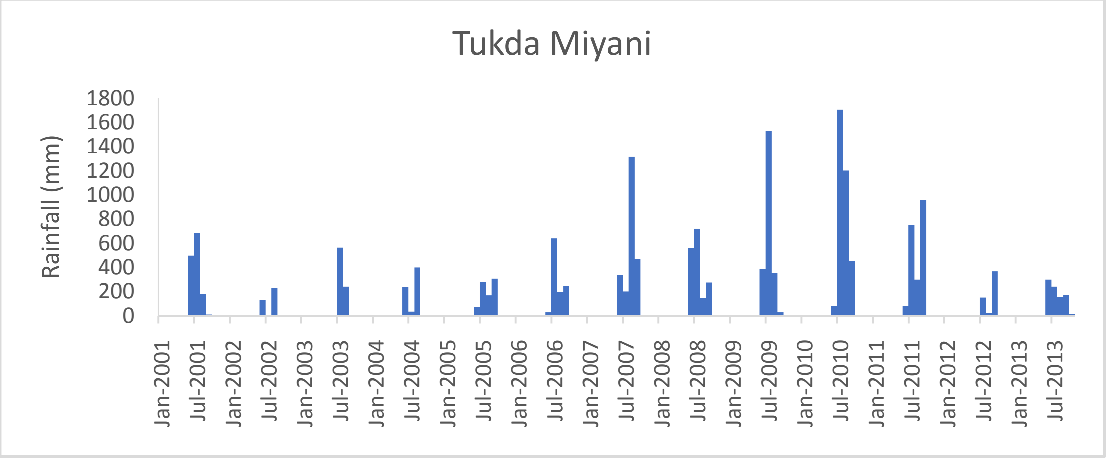
6. Bhanvad



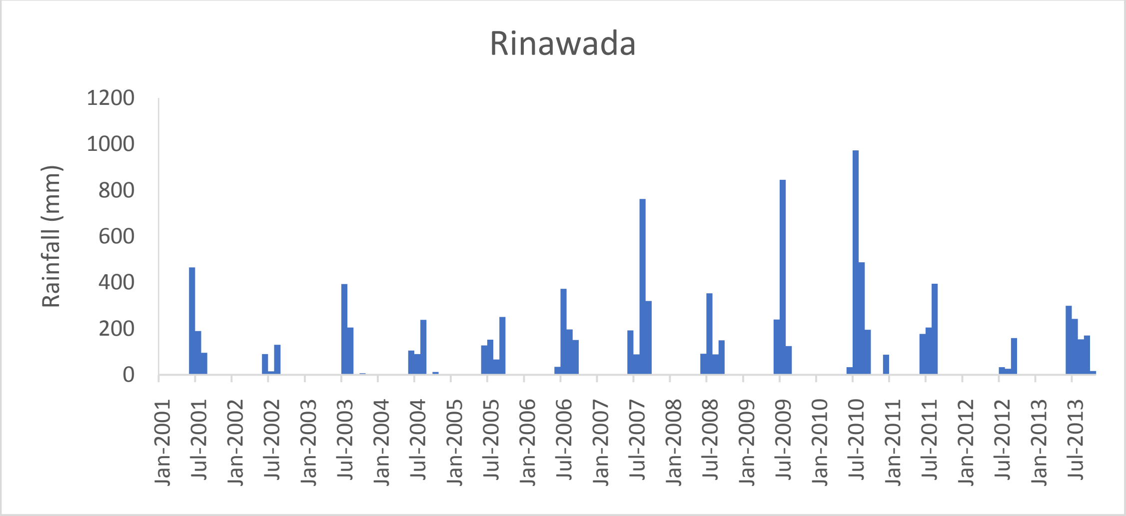
7. Jamjodhpur



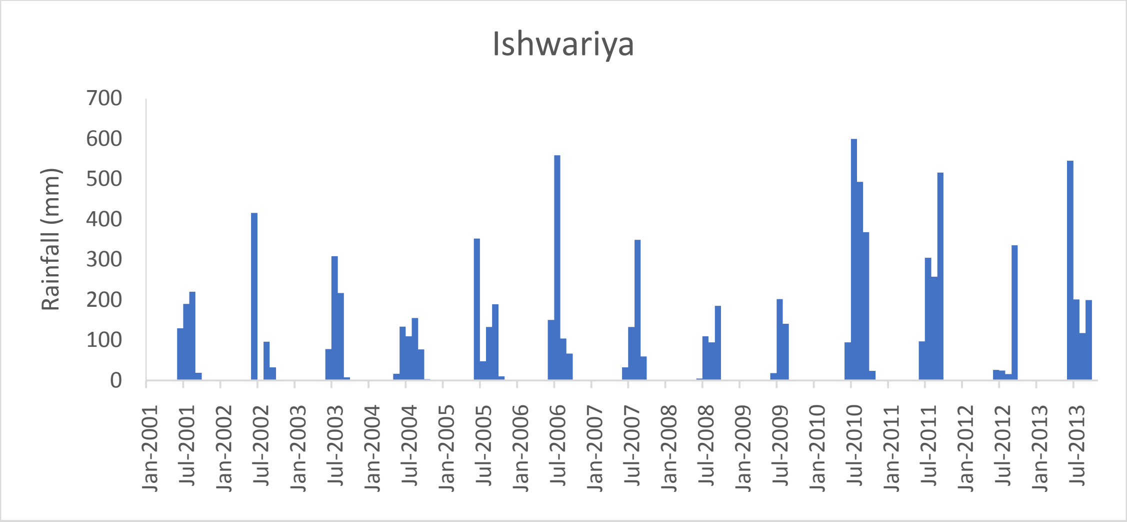
8. Tukda Miyani



9. Rinawada



10. Ishwariya



Annexure II

FORMAT FOR SOCIO-ECONOMIC SURVEY

1. Name of the Person:

2. (i) Name of Village/ Town/ City:
   (ii) Block/Taluka/District:

3. Family members and their education level.

4. House type (a) Kutcha (b) Pucca (c) Mixed

5. Source of water supply in household (municipality/ hand pump/ private well etc.). If hand pump/ private well, then its particulars (like depth, water quality etc.).

6. Occupation: Agriculture or other.
   If occupation is agriculture then land holding size/ total land under cultivation.

7. (i) Names of crops/ vegetables grown during Kharif, Rabi and Jayad.
   (ii) Cropping particulars.
   (iii) List if any salt-tolerant crops are grown?

8. Whether sufficient amount of water available for irrigation during different seasons?

9. Type of irrigation technique utilized – flooding, drip, sprinkler, piped supply.

10. Source of irrigation water - Surface water / groundwater
    If groundwater, then list the following:
    (i) Type of well – open dug well/ bore well/ dug-cum bore well/ tube well
    (ii) Status of well – community well or private well
    (iii) Depth of well
    (iv) Seasonal variations in depth of water and yield of the well.
    (v) Seasonal variation in quality/ salinity of water from well
    (vi) Type and capacity of pumpset
    (vii) Availability of power
    (viii) Pumping hours per day
    (ix) Area irrigated by each well

11. If surface water used for irrigation, then list the following:
    (i) Source of surface water – river/ estuary/ canal/ ponds/ reservoir/ lake
    (ii) Seasonal variation in availability and quality of surface water

12. How the salinity in groundwater has varied during the last 25 years or more?

13. Observations regarding impact of using saline water for irrigation on soil structure/ fertility in your agriculture land. Measures taken to restore the soil fertility.

14. Are there any salinity control or artificial recharge measures in the area
    - (i) list the type of structure such as anicut, percolation pond, spreading channel or tidal regulator etc. in the area
    - (ii) date / year of its construction/ initiation
    - (iii) impact on groundwater level and water quality since the recharge/control measure was introduced.

15. Impact on crop yield (i) prior to taking control/recharge measures
    (ii) after taking control/recharge measures.

16. Proportion of income realised from irrigated and unirrigated crops.

17. Increase in income due to increase in crop yield attributed to salinity control/ artificial recharge measures.

18. Whether any migration of population has taken place due to increase in water salinity in last 15-20 years?

19. Change in occupation from agriculture due to increasing water salinity problem/ lack of irrigation water.

20. Details of any other income-generation activities.

21. Marketing strategy - how the crops are sold?

22. Any other water quality problems besides salinity? Impact of water quality on health or knowledge about any water borne diseases in the area.

23. Availability of medical, transport and communication facilities in the area.

24. Any support from village panchayats, NGO etc. regarding water conservation activities.

25. Any community activities in the area for mass welfare.

26. Role of family women in social and economic activities - empowerment of village women by increasing their participation in agricultural production and income generation.

27. In your opinion, what measures can be taken-up by Government and local agencies to uplift the social and economic status of the community?