NIH/GWD/04-07/1

Modelling of a Coastal Aquifer using FEFLOW

Director : Dr. K. D. Sharma

Head : Dr. N. C. Ghosh

Study Group : Mr. C. P. Kumar
Dr. A. G. Chachadi (Goa University)
Dr. B. K. Purandara
Dr. Sudhir Kumar
Mr. N. Varadarajan
Mr. Raju Juyal

National Institute of Hydrology
Jal Vigyan Bhawan
Roorkee – 247667 (Uttarakhand)

2006-2007

PREFACE

India has been blessed with a vast stretch of coastline. Many urban centres of the country are located on the coastal tract apart from thousands of villages and industrial settlements. Water resources in coastal areas assume a special significance since any developmental activity will largely depend upon availability of fresh water to meet domestic, industrial and agricultural requirements. However, fresh water resources in these coastal aquifers are likely to experience disastrous and irreversible impacts in the coming times due to overexploitation of groundwater resources and sea level rise. Groundwater withdrawals in excess of safe yields and reduced recharges to groundwater due to rapidly changing land use pattern along the coasts have increased the incidences of seawater intrusions into the coastal aquifers.

This report on "*Modelling of a Coastal Aquifer using FEFLOW*" is a part of the research activities of 'Ground Water Hydrology' division of the Institute. The purpose of this study is to simulate the seawater intrusion in a part of the coastal area in Goa and evaluate the impact of further groundwater development on seawater intrusion. This three years study (April 2004 to March 2007) has been carried out in association with Goa University. The study group includes Mr. C. P. Kumar, Dr. B. K. Purandara, Dr. Sudhir Kumar, Mr. N. Varadarajan and Mr. Raju Juyal from National Institute of Hydrology and Dr. A. G. Chachadi from Goa University.

(**K. D. Sharma**)
Director

CONTENTS

PAGE

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Coastal tracts of Goa are rapidly being transformed into settlement areas. The poor water supply facilities have encouraged people to have their own source of water by digging or boring a well. During the last decade, there have been large-scale withdrawals of groundwater by builders, hotels and other tourist establishments. Though the seawater intrusion has not yet assumed serious magnitude, but in the coming years it may turn to be a major problem if corrective measures are not initiated at this stage. It is necessary to understand how fresh and salt water move under various realistic pumping and recharge scenarios. Objectives of the present study include simulation of seawater intrusion in a part of the coastal area in Bardez taluk of North Goa, evaluation of the impact on seawater intrusion due to various groundwater pumping scenarios and sensitivity analysis to find the most sensitive parameters affecting the simulation.

1.0 INTRODUCTION

Under natural conditions, the seaward movement of freshwater prevents saltwater from encroaching coastal aquifers, and the interface between freshwater and saltwater is maintained near the coast or far below land surface. This interface is actually a diffuse zone in which freshwater and saltwater mix, and is referred to as the zone of dispersion (or transition zone). Ground-water pumping can reduce freshwater flow toward coastal discharge areas and cause saltwater to be drawn toward the freshwater zones of the aquifer. Saltwater intrusion decreases freshwater storage in the aquifers, and, in extreme cases, can result in the abandonment of supply wells. Saltwater intrusion occurs by many mechanisms, including lateral encroachment from coastal waters and vertical upconing near discharging wells. Freshwater and saltwater mix in the zone of dispersion by the processes of diffusion and mechanical dispersion. A circulation of saltwater from the sea to the zone of dispersion and then back to the sea is induced by mixing within this zone.

Indian coastal aquifers (coastline stretching over a length of more than 7000 km) constitute the second richest groundwater reservoirs after the Indo-Gangetic alluvial plain. In coastal aquifers, freshwater usually overlies the seawater separated by a transition zone. The overuse of groundwater along parts of the coastal belts of India for various purposes has affected groundwater quality and quantity. It has led to rapid decline in groundwater levels leading to salt water intrusion and water quality deterioration. Continued human interference with the coastal hydrologic system has led to pollution of coastal groundwater aquifers by salt water. Incidence of groundwater pollution due to saltwater intrusion has increased manifold in the last two decades.

National Water Policy – 2002 also stresses that "*Over exploitation of ground water should be avoided especially near the coast to prevent ingress of seawater into sweet water aquifers*". The management of groundwater resources in coastal aquifers requires special attention to minimize the extension of seawater intrusion into aquifers and upconing of seawater near pumping stations. The extent of intrusion depends on a number of factors including aquifer geometry and properties (hydraulic conductivity, anisotropy, porosity and dispersivity), abstraction rates and depth, recharge rate, and distance of pumping wells from the coastline.

Coastal tracts of Goa are rapidly being transformed into settlement areas. The poor water supply facilities have encouraged people to have their own source of water by digging or boring a well. There are also large-scale withdrawals of groundwater by builders, hotels and other tourist establishments. Rainfall recharge to groundwater has also reduced significantly due to changing land use patterns. All these factors have induced measurable changes in the coastal water dynamic equilibrium conditions. Though the seawater intrusion has not yet assumed serious magnitude, but in the coming years it may turn to be a major problem if corrective measures are not initiated at this stage. A part of the coastal area in Bardez taluk of North Goa has been selected for the present study. It is necessary to understand how fresh and salt water move in the study area under various realistic pumping and recharge scenarios.

The objectives of the present study are:

- Simulation of seawater intrusion in a region along Goa coast.
- Evaluation of the impact on seawater intrusion due to various groundwater pumping scenarios.
- Sensitivity analysis to find the most sensitive parameters affecting the simulation.

Outcome of the study includes present status of seawater intrusion in the area, likely impact of groundwater development on the extent of seawater intrusion, determination of sensitive model parameters to plan field investigations for further modelling studies. It will result in better and sustainable management of fresh water resources in the coastal area of Goa.

The study will guide in making management decisions to monitor and control seawater intrusion and planning of groundwater development in the area. Beneficiaries and users of this project would be all bodies concerned with water utilization programme, environmental programme, and basin development programme.

The following methodology has been adopted for the present study.

1. Collection of relevant meteorological, hydrogeological and geochemical data.
2. Measurement of monthly groundwater level data in selected 20 observation wells for one year.
3. Periodic (bi-monthly) groundwater sampling from selected 20 observation wells for one year.
4. Salinity measurements (electrical conductivity and TDS) in the laboratory.
5. Resistivity profiling and sounding.
6. Model conceptualization and data preparation.
7. Model simulations and calibration.
8. Model predictions and sensitivity analysis.

2.0 STUDY AREA

The Goa region is drained by nine independent rivers (42 tributaries) flowing generally from east (Western Ghats) to west (the Arabian Sea). Goa rivers are both tidal and rainfed. Mandovi and Zuari together drain about 70% of the total geographical area of Goa.

The study area lies in Bardez taluk of North Goa within the watersheds of Baga River and Nerul creek (around 74 km^2) and covered by Survey of India toposheets number 48E/10, 48E/14 and 48E/15 on 1:50,000 scale. It is bound by rivers Chapora and Mandovi in north and south directions respectively, besides Arabian Sea in the west and encompasses coastal tract from Fort Aguada in the south to Fort Chapora in the north (15 km). Around 30 km^2 area close to the coast (15 km along the coast and 2 km wide) is more prone to seawater intrusion. Layout maps of North Goa and the study area are given in figures 1 and 2 respectively.

The topography in the area consist of isolated hills of laterites ranging in height from 40 to 80 m above mean sea level surrounded by very gently sloping low elevation areas. The land elevation in the plain varies from 0 to 20 m above msl. Figure 3 shows the topographic contours in the study area. The soils are predominantly of lateritic nature. However, the coastal areas are made up of alluvial soils composed of loamy mixed sand and loamy sands. Figure 4 presents the soil map of the study area.

Land use map of the study area has been presented in figure 5. The agricultural activities are confined to the low lying plain and valley areas. Major crops are Paddy (42%), Cashew nut (38%), Coconut (17%). Low lying area is intensely developed with population density of 814 per km^2. Each household depends on groundwater.

The main occupation of the people in this area is concerned with tourism related activities, apart from fishing and agriculture. The community setup of this area is typically of mixed type, wherein both the urban and rural communities live side by side. One third tourists visit Bardez coastal areas (Anjuna, Baga, Calangute beaches). The beach is about 32 to 50 m wide and about 15 km long. The well known holiday resorts such as Taj group of hotels, Sterling resorts are also located on this track.

Climate

The general climate of the area is mainly tropical and is influenced to a large extent by the conditions in the Arabian Sea. There are four seasons, viz. winter (December to February), summer or pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to November). The climate is characterized by high humidity and less extremes of temperature. The temperature varies between 20^o C to 33^o C and the average relative humidity is between 70 to 90%.

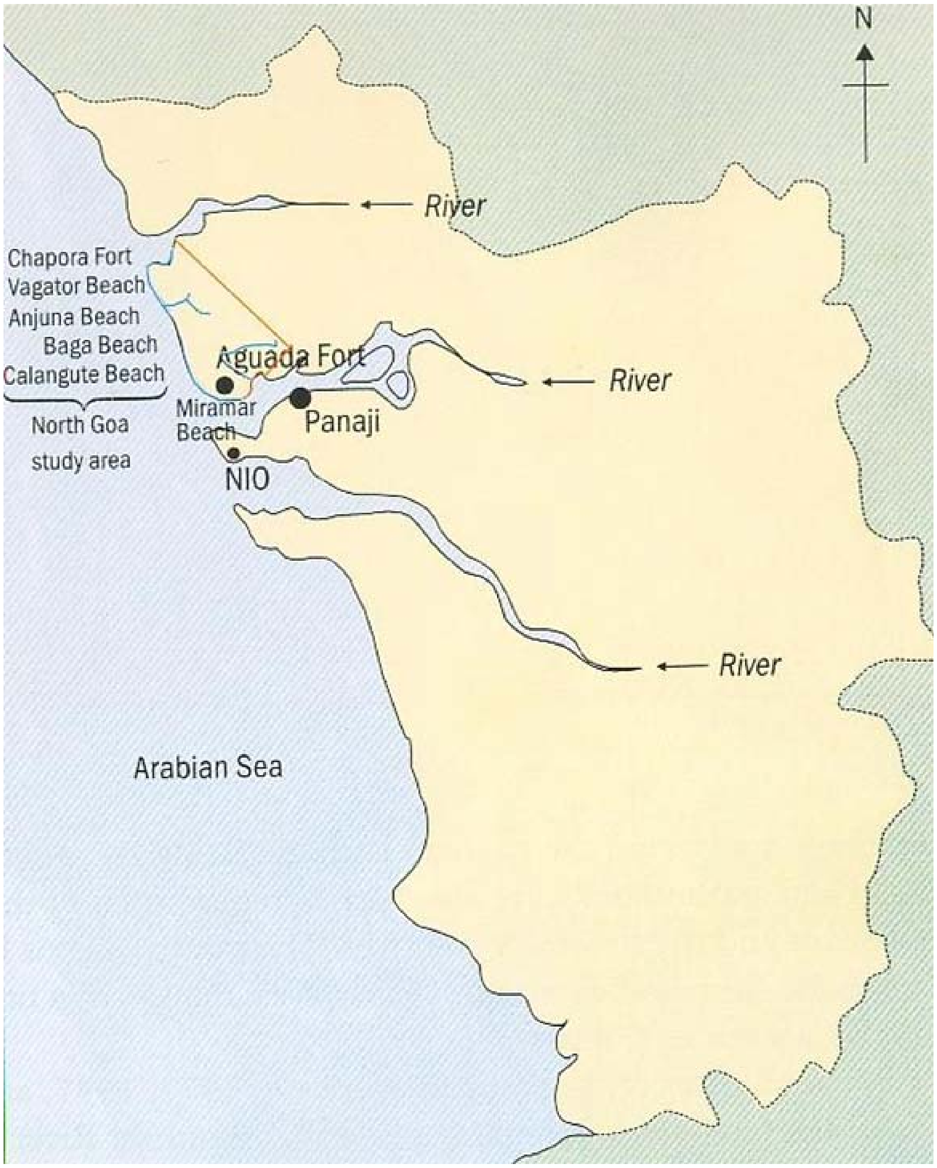


Figure 1: Location Map of Study Area in Goa

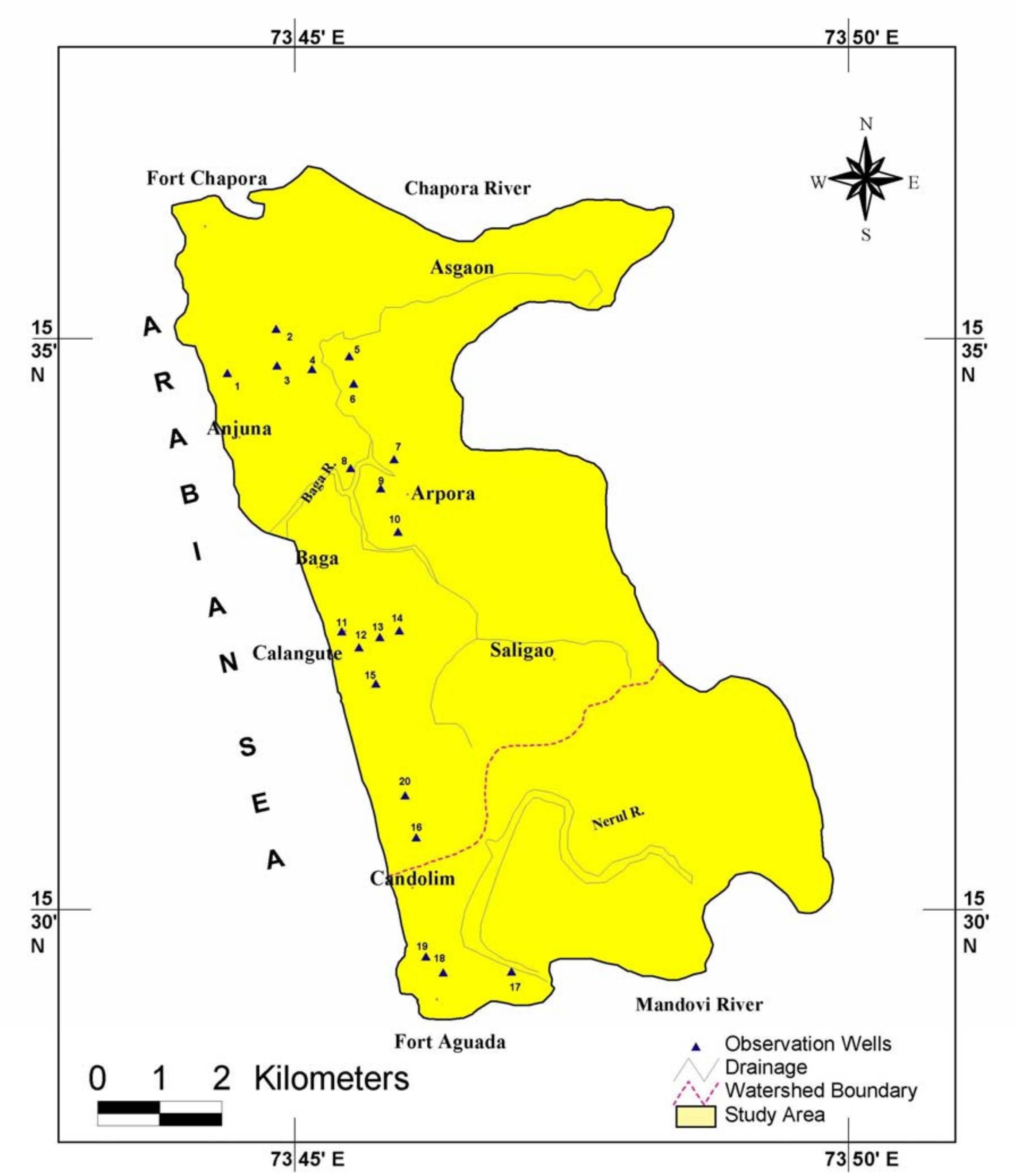


Figure 2: Layout Map of the Study Area

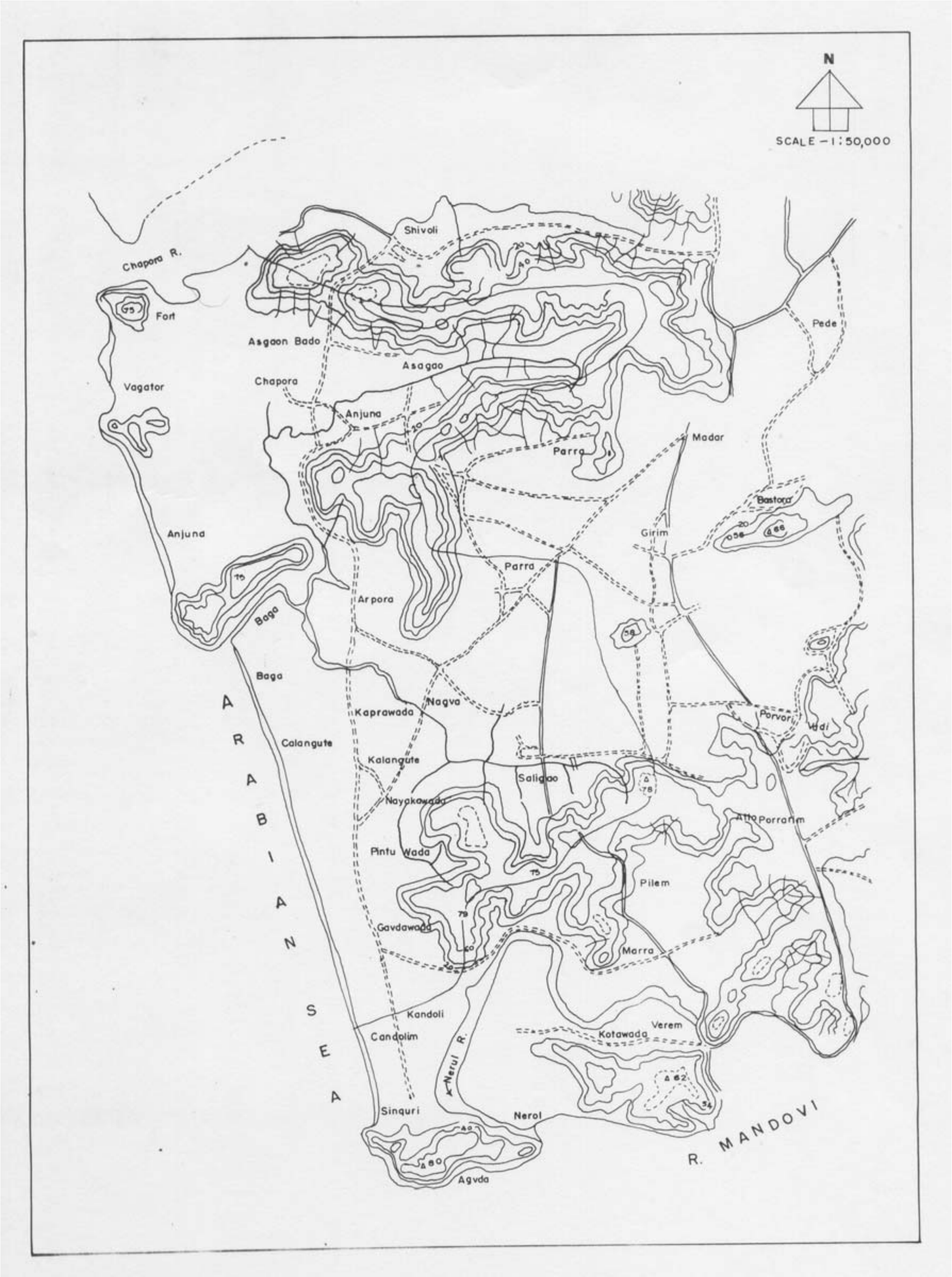


Figure 3: Topographic Contours in the Study Area

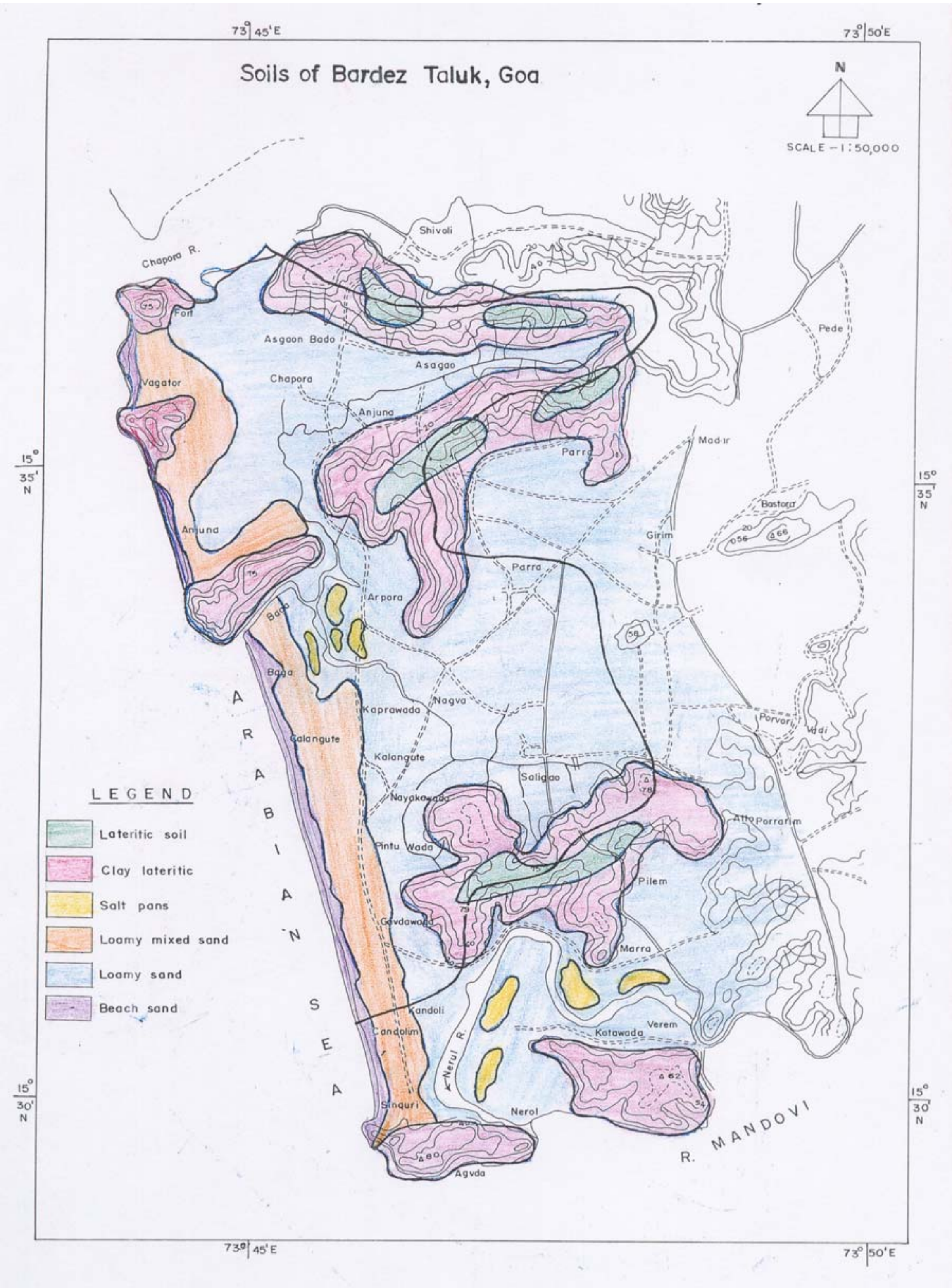


Figure 4: Soil Map of the Study Area

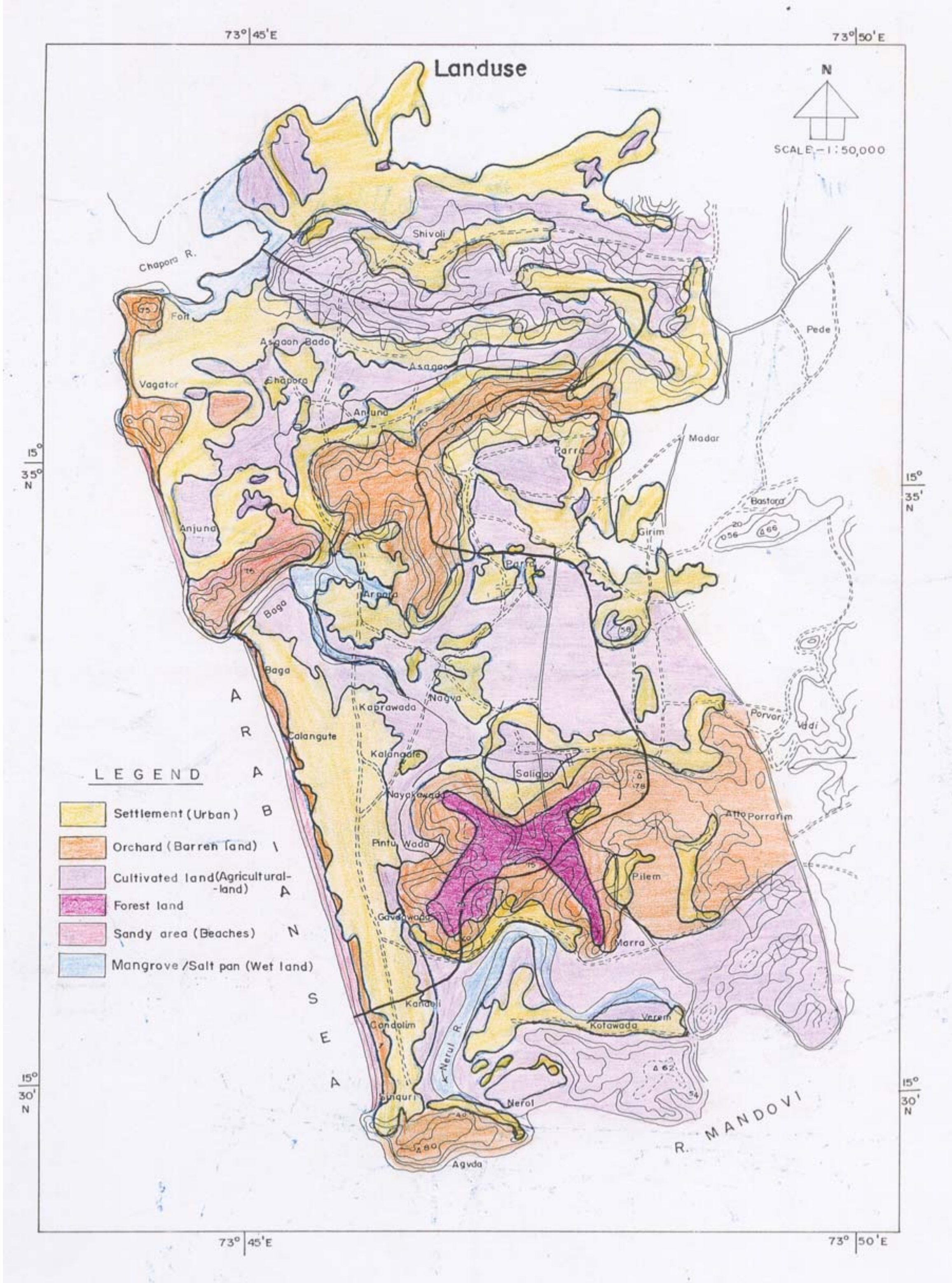


Figure 5: Land Use Map of the Study Area

The bulk of the rainfall is received during the south-west monsoon (June to October). The approximate numbers of rainy days are 110. The annual rainfall varies from 1700 mm to 3600 mm. Daily rainfall data for Panaji was available for 20 years (1984 to 2003, Table 1) and the mean annual rainfall was found to be 2714 mm during this period. Mean annual potential evapotranspiration for Panaji was found to be 1158 mm during the period May 1989 to April 1999.

Table 1: Annual Rainfall Values at Panaji

S. No.	Year	Rainfall (mm)
1	1984	2587.3
2	1985	2890.0
3	1986	1723.0
4	1987	2733.4
5	1988	3106.9
6	1989	2624.2
7	1990	2621.3
8	1991	2152.3
9	1992	2767.9
10	1993	2548.4
11	1994	2894.9
12	1995	3554.2
13	1996	2937.7
14	1997	3362.2
15	1998	3078.9
16	1999	2636.3
17	2000	2982.1
18	2001	2137.3
19	2002	2259.0
20	2003	2682.6

Geology and Hydrogeology

The rocks in the study area consist of crystalline and metamorphic rocks of the Precambrian age. The metagraywacke is a hard, compact, dark gray to green coloured rock. This rock is more prone to laterisation with the result that there are some outcrops in the area. The simplified lithological succession encountered in the area is as follows:

Recent - Beach sands, windblown sands, alluvial sands, sands and clays
Subrecent - Laterites
Precambrian - Metagraywackes

Figure 6 shows the general geology of the study area.

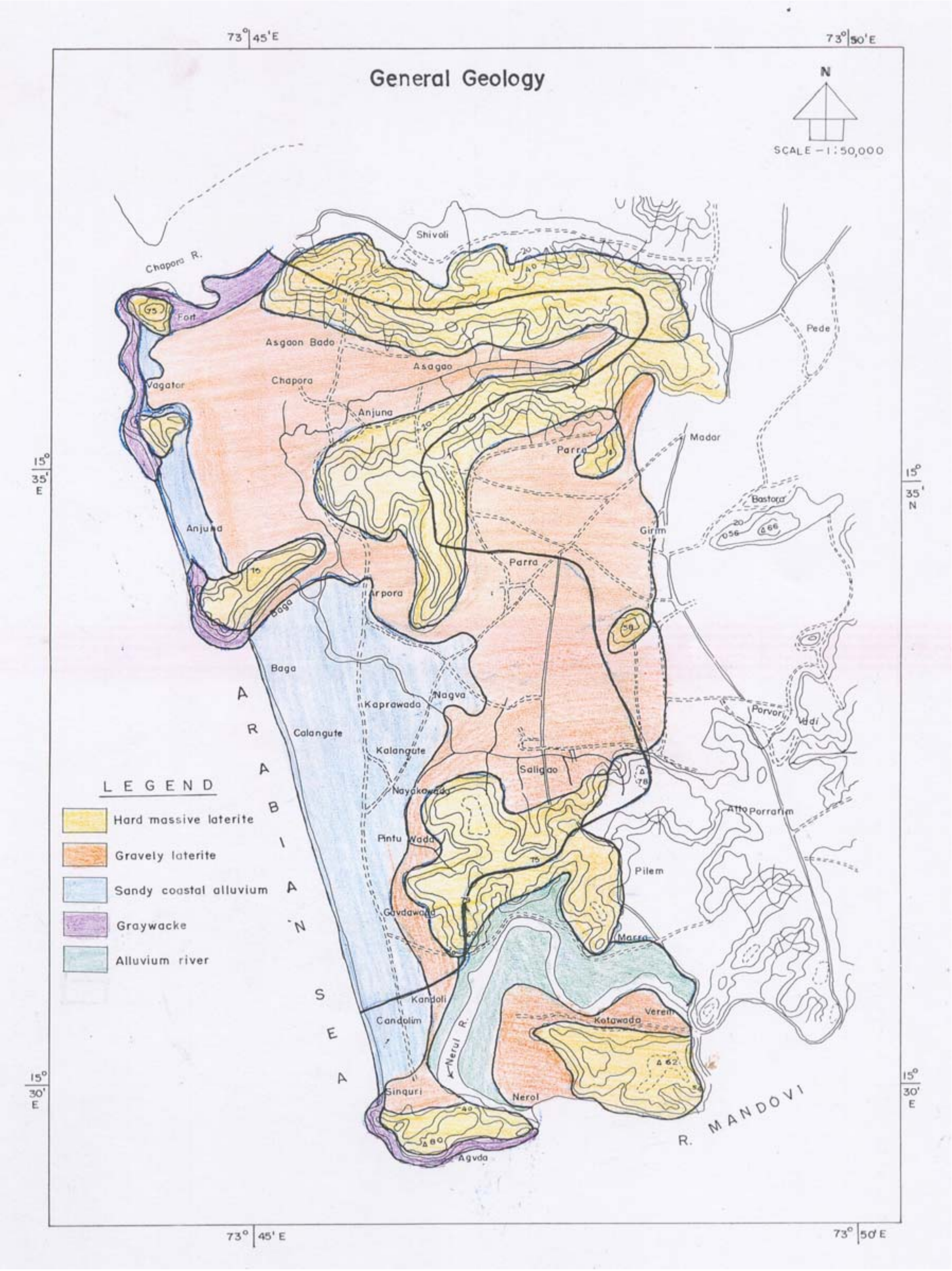


Figure 6: General Geology of the Study Area

The geological units at the low lying plain areas and on the elevated plateaus differ to some extent. Alluvial sands occupy the lowest topographic portions of the coastal tracts and extend upto 15 m below ground level. Typical geological profiles in low lying area and plateau area are as follows.

<u>Low lying area</u>

Beach sand mixed with clay : 0 – 10 m
Sandy clay / weathered laterite : 10 – 15 m
Basement rocks (phyllite, graywacke, schist etc.) : 15 m onwards

<u>Plateau area</u>

Hard compact laterite : 0 – 10 m
Laterite : 10 – 20 m
Lateritic clay : 20 – 45 m
Basement rocks : 45 m onwards

Groundwater in the study area generally occurs under unconfined conditions in the sandy aquifers of the plains and under semi-confined conditions in the aquifers constituted of laterite and graywackes. The area occupied by phyllites and laterites may contain water in joints and weathered zones under semi-confined conditions. In the sandy formation, it is the primary porosity which controls the movement of groundwater whereas in laterites and phyllites, the secondary porosity including joints, fractures and shear zones play an important role in groundwater movement.

In coastal as well as low lying flat agricultural areas, the sandy and loamy formations having moderate to good primary porosity and permeability are the main aquifers with a shallow water table. Hydrogeologically, the most important water bearing formations in Goa, covering more than 60% of its area are fractured and weathered laterites. Laterites are rich in iron oxide and derived from weathering of basalt. Excessive laterization in Goa is due to tropical moist climate, subject to vast seasonal changes. In addition to their inherent porosity, the laterites are often highly jointed and fractured which increases their water holding and transmitting capacity.

In the elevated lands, lateritic formations and the crystalline rocks constitute the main water bearing formation. The fractured and weathered crystalline rocks located below the lateritic clay sequence form a semi-confined to confined aquifer (80 to 100 m deep). Groundwater is mainly found in the fractured zones in these areas. Presently, these aquifers are not being tapped for water.

The sandy aquifers found in the flat low lying areas are under unconfined conditions (upto 15 m depth) and open wells are the common structures to withdraw the groundwater. In most places, the shallow open dug wells are used for withdrawals. However, with increased demands, few deep bore wells are also installed along the coast to meet the demands. Groundwater is withdrawn generally for domestic, construction, and industrial uses besides for agricultural use during winter season. The Taj hotel establishment and other beach resorts have been drawing water from the ground through bore holes to augment supplies from municipality for their daily use.

The main source of recharge to the aquifers is rainfall. Major part of the rainfall flows to the sea as direct surface runoff. In coastal plains, the shallow unconfined aquifers are over-used and have been showing the salt water influx, especially during summers. In the recent years, large scale urbanization along this coast has been taking place. This urbanization has inhibited the rain water recharge into the ground which is further accelerating the influx of the salt water inland due to decreased fresh groundwater flow towards the sea. Pre-monsoon TDS is observed to be greater than 1000 ppm in few wells. Wells in sandy aquifer are more prone to seawater intrusion, as compared to wells in laterite soil.

The water table is very shallow and mostly less than 10 m from ground. The minimum water level depths are generally less than 2 m below ground in most parts of the area. The aquifer transmissivity and specific yield values are moderate in both lateritic and sandy aquifers. The average hydraulic conductivity of sandy coastal alluvium and greywacke are much higher than laterites. As per the results of pumping tests carried out for 6 wells (recovery data in large diameter wells) in the study area during November 1999, the storage coefficient (S) varies from $8*10^{-7}$ (sand & clay) to 0.05 (laterite) and transmissivity (T) of the aquifer varies from 25 m^2/day (clay & laterite) to 341 m^2/day (sand & clay). Figure 7 presents the measured values of hydraulic conductivity in the study area.

Open wells are normally 10-15 m deep and 2-5 m diameter. Very few deep wells exist in the whole Goa. There are about 25 groundwater withdrawal structures (open wells) per square kilometer area in the Bardez taluk and the average annual groundwater draft per structure is 0.65 ha.m. In view of no other classified draft data being available, this information was used for estimating the present and projected draft figures.

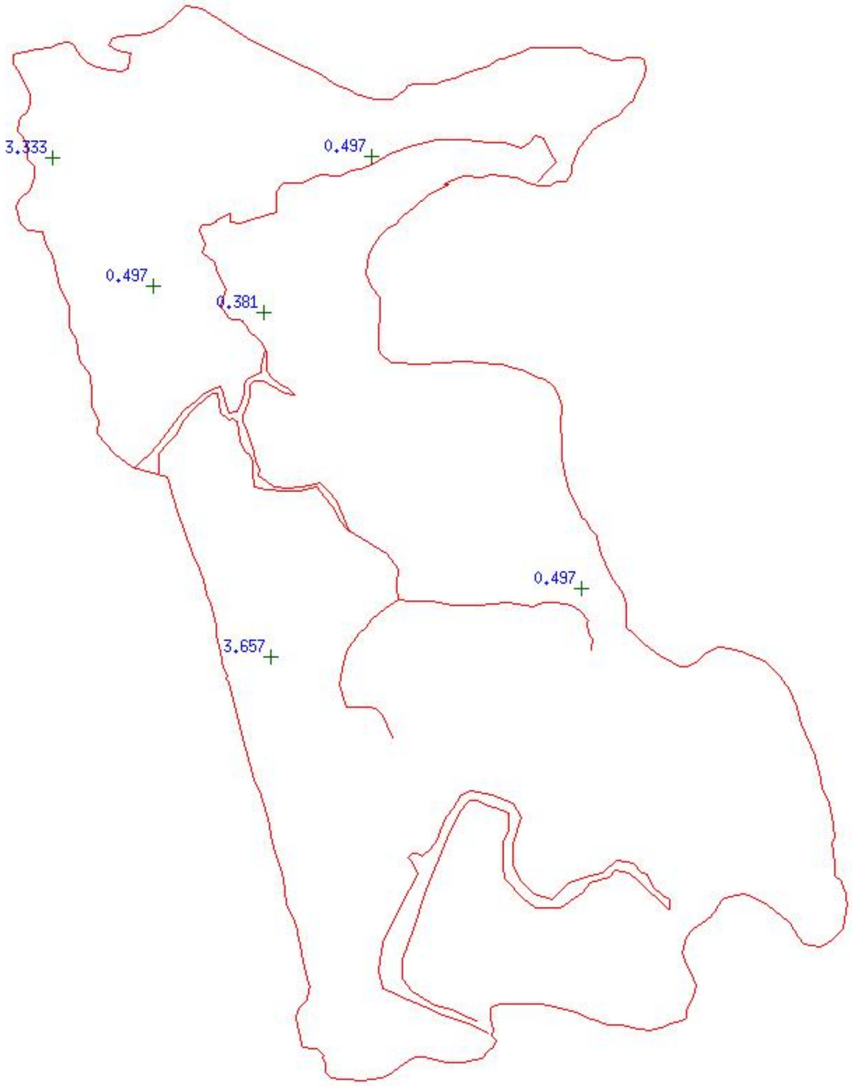


Figure 7: Measured Values of Hydraulic Conductivity (*10^{-4} m/s)

3.0 FIELD AND LABORATORY INVESTIGATIONS

A part of the coastal area in Bardez taluk of North Goa was identified for the present study. Twenty observation wells were identified in the study area. Table 2 presents the latitudes and longitudes and table 3 presents other details of groundwater monitoring wells. Figure 8 depicts the location of observation wells. Monthly groundwater level data were measured in observation wells during September 2004 to August 2005. Figure 9 shows the measurement of groundwater level being taken in an observation well. Table 4 presents the elevation of groundwater levels above Mean Sea Level. Groundwater samples were collected in September, November 2004, January, March, April, and May 2005. Salinity for groundwater samples was measured in the laboratory. Table 5 presents the total dissolved solids in water of observation wells. Figure 10 shows the hydraulic conductivity measurement by Guelph Permeameter in laterite soil.

Table 2: Latitudes and Longitudes of Groundwater Monitoring Wells in the Study Area

Observation Well Number	Latitude	Longitude	Ground Elevation above M.S.L. (m)
1	15^{0}34’98.1”	73^{0}44’33.4”	17.5
2	15^{0} 35’20.8”	73^{0}44’48.5”	19.0
3	15^{0}35’01.7”	73^{0}44’49.0”	12.5
4	15^{0}34’59.9”	73^{0}45’07.9”	14.5
5	15^{0}35’06.7”	73^{0}45’27.9”	13.5
6	15^{0}34’52.2”	73^{0}45’30.5”	13.0
7	15^{0}34’12.8”	73^{0}45’52.4”	14.0
8	15^{0}34’08.1”	73^{0}45’29.1”	7.0
9	15^{0}33’57.5”	73^{0}45’45.4”	12.0
10	15^{0}33’34.9”	73^{0}45’54.9”	12.0
11	15^{0}32’42.4”	73^{0}45’24.7”	21.0
12	15^{0}32’34.2”	73^{0}45’34.2”	15.0
13	15^{0}32’39.5”	73^{0}45’45.3”	19.0
14	15^{0}32’43.2”	73^{0}45’55.8”	10.0
15	15^{0}32’15.2”	73^{0}45’43.4”	20.5
16	15^{0}30’54.6	73^{0}46’05.6’’	10.5
17	15^{0}29’44.7’’	73^{0}46’57.4	9.0
18	15^{0}29’44.0”	73^{0}46’20.5’’	7.5
19	15^{0}29’52.3’’	73^{0}46’11.1’’	9.5
20	15^{0}31’16.7’’	73^{0}45’59.4’’	12.0

Table 3: Other Details of Groundwater Monitoring Wells in the Study Area

Well No.	Well Owner & Location	Well Type, Radius (m), & Age	Well Use	Water Quality	Summer Water Levels	M.P. above G.L. (m)	Well Depth below M.P. (m)
01	Public Well in Anjuna (Dimelowada)	Open well, Rectangular, old	Occasionally used	OK	low	0.39	7.45
02	Private well in Anjuna (Dimelowada)	Open well, Circular, old	Occasionally used	OK	low	0.80	7.80
03	Well of Vishwanber Harmalker in Anjuna (Surantowado)	Open well, Square, 2.2*2.2, old	Used Regularly	OK	low	0.25	3.15
04	Well of Filomena Vesgo in Anjuna (Mazalwado)	Open well, Circular, 1.75, old	Used Regularly	OK	low	1.00	1.90
05	Private Well in Anjuna (Gaowado)	Open well, Square, 1.8*1.8, old	Used Regularly	OK	low	0.30	2.19
06	Temple Well in Anjuna (Sonarwado)	Open well, Circular, 1.93, old	Used Regularly	OK	low	0.42	5.46
07	Well of Mogen Parrikar in Arpora (Kudozwado)	Open well, Circular, 1.83, old	Used Regularly	OK	low	0.47	3.36
08	Dhobi Well in Arpora (Baga)	Open well, Circular, 4.70, old	Used Regularly	OK	low	0.05	1.70
09	Well of Srikant DeukarIn, Arpora (Kambodki)	Open well, Circular, 0.39, old	Used Regularly	OK	dry	0.57	4.00
10	Well of Diego D'Souza, ,Arpora (DivanBati)	Open well, Circular, 3.2, old	Occasionally used	OK	low	0.85	2.22
11	Well of Leo Fernandes in Kalangute (Untawado)	Open well, Circular, 2.0, old	Used Regularly	OK	low	0.70	7.40
12	Public Well in Calangute	Open well, Circular, 2.80, old	Occasionally used	OK	low	0.50	5.89
13	Well of Eulalia D'Souza	Open well, Circular, 2.0, old	Occasionally used	Ok	dry	0.00	9.85
14	Near Bank of Baroda, Calangute (Porbawada)	Open well, Circular,old	Used Regularly	OK	low	1.02	7.45
15.	Public Well in Calangute (Tiviawado)	Open well, Circular, 2.0, old	Occasionally used	OK	low	0.42	4.63
16	Public Well in Kandole	Open well, Circular, 1.65, old	Occasionally used	OK	low	0.58	3.35
17	Public Well in Aguada	Open well, Square, old	Not used	OK	low	0.22	2.85
18	Public Well in Aguada	Open well, Circular, 2.08, old	Used Regularly	OK	low	0.51	5.28
19	Hotel Well in Aguada	Open well, Circular, 2.14, old	Used Regularly	OK	low	0.26	6.40
20	Public Well in Aguada	Open well, Circular, 1.30, old	Occasionally used	OK	low	0.65	5.80

(M.P. denotes Measuring Point and G.L. denotes Ground Level)

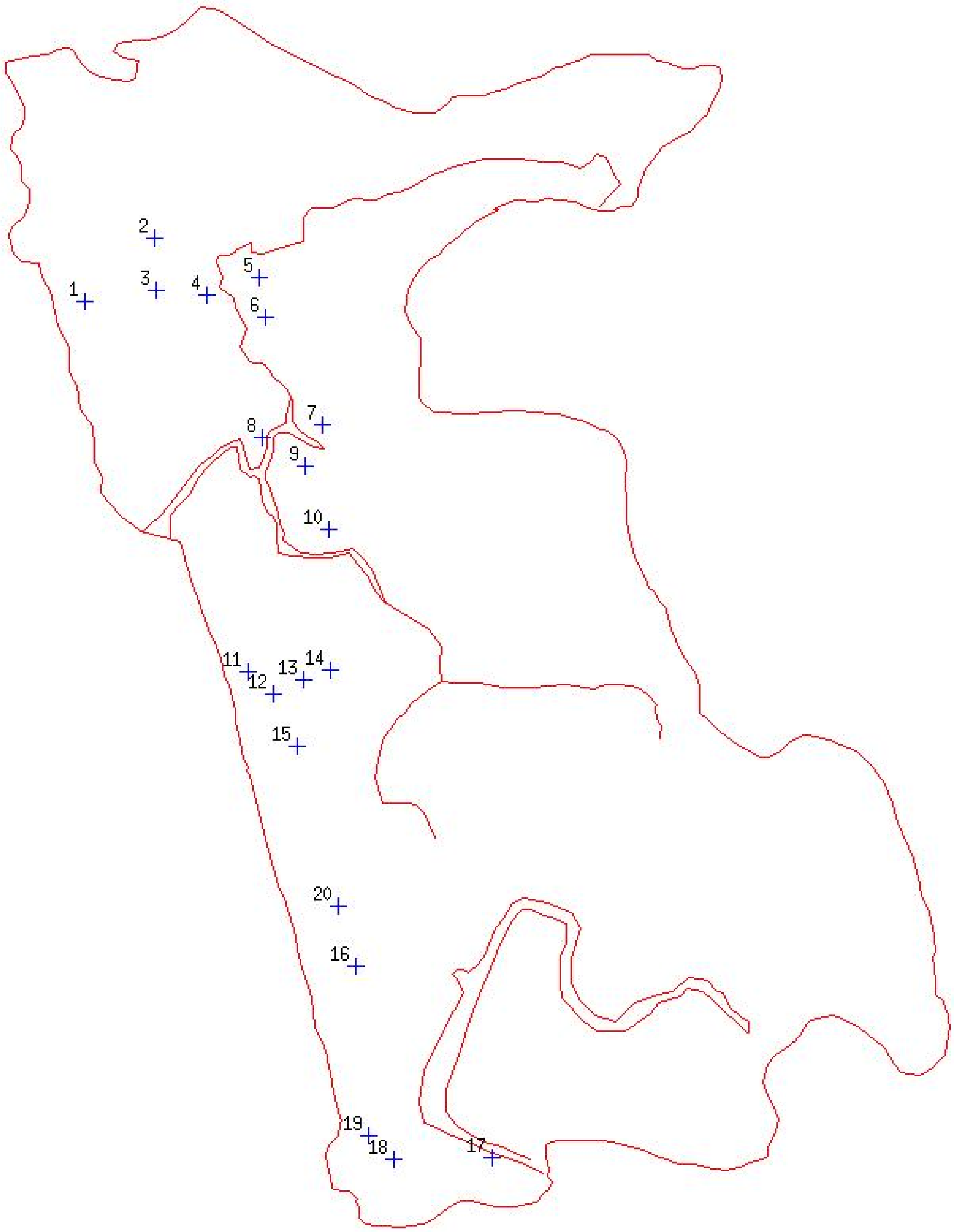


Figure 8: Location of Observation Wells

Figure 9: Measurement of Groundwater Level in Observation Well Number 10

Table 4: Elevation of Groundwater Levels above Mean Sea Level

Obser-vation Well	Elevation of Groundwater Levels above Mean Sea Level (m)											
	Sept. 2004	Oct. 2004	Nov. 2004	Dec. 2004	Jan. 2005	Feb. 2005	Mar. 2005	Apr. 2005	May 2005	June 2005	July 2005	Aug. 2005
1	10.44	10.23	10.09	9.59	8.92	8.67	8.59	8.19	7.89	7.99	11.27	11.04
2	12.00	11.60	11.13	10.50	9.80	9.78	8.62	8.98	8.95	9.00	12.28	12.19
3	9.60	9.07	8.35	7.75	7.32	7.03	6.83	6.48	6.35	6.43	10.15	9.85
4	13.60	13.60	13.10	12.50	11.65	11.30	10.93	10.50	10.30	10.38	13.78	13.69
5	11.61	11.34	10.80	10.60	10.18	9.75	9.66	9.41	9.10	9.21	12.38	12.27
6	7.96	7.34	7.07	6.82	6.76	6.63	6.67	6.62	6.06	6.14	9.46	9.37
7	11.11	10.80	10.47	10.17	9.95	9.78	9.53	9.44	9.11	9.19	11.71	11.35
8	5.35	5.05	4.85	4.85	4.50	4.45	4.30	4.15	4.10	4.18	6.02	5.83
9	8.57	8.02	7.57	6.92	6.89	6.57	6.17	6.15	6.07	6.17	9.60	9.44
10	10.63	9.70	9.37	8.55	8.45	8.65	7.85	7.75	7.66	7.73	10.74	10.45
11	14.30	13.57	13.35	13.60	12.59	12.22	12.20	12.17	12.10	12.20	15.25	14.95
12	9.61	9.12	8.70	8.20	7.74	7.25	6.28	6.65	6.50	6.68	9.43	9.16
13	9.15	9.55	9.00	8.20	7.75	7.50	7.08	6.70	6.35	6.42	9.40	9.08
14	3.57	2.72	2.37	1.62	1.27	0.52	0.22	-0.33	-0.38	-0.30	3.19	3.07
15	16.29	15.67	15.02	14.52	14.02	13.62	13.22	12.72	12.66	12.70	15.92	15.24
16	7.73	6.95	6.28	5.52	4.76	4.49	4.02	3.58	3.30	3.41	6.30	6.17
17	6.37	6.12	6.02	5.94	5.77	5.94	5.82	5.67	5.67	5.81	8.67	8.20
18	2.73	2.81	2.71	2.68	2.65	2.31	2.46	2.31	2.32	2.36	5.42	5.13
19	3.36	2.76	2.31	2.26	1.61	0.96	0.86	0.96	0.88	0.97	4.18	4.04
20	6.85	5.91	4.15	3.83	4.27	3.95	3.45	3.27	3.05	3.18	6.60	6.15

Table 5: Total Dissolved Solids in Water of Observation Wells

Observation Well	Total Dissolved Solids (mg/l)					
	September 2004	November 2004	January 2005	March 2005	April 2005	May 2005
1	120	70	90	100	100	90
2	110	60	80	70	60	80
3	120	70	90	90	80	N.A.
4	240	150	160	150	130	160
5	140	70	70	70	60	70
6	110	140	210	210	190	210
7	260	150	160	140	120	160
8	280	180	110	180	270	110
9	140	100	130	100	80	130
10	200	160	220	250	220	220
11	420	300	290	330	300	290
12	300	190	170	170	160	170
13	260	180	230	N.A.	N.A.	N.A.
14	370	270	250	280	240	N.A.
15	150	60	60	90	90	60
16	180	110	190	230	190	190
17	100	40	50	80	90	50
18	100	40	50	50	50	50
19	270	230	230	250	220	230
20	180	180	180	190	180	180

Based upon the bi-monthly measurements of salinity, groundwater quality in all the observation wells was found to be reasonably fresh, both in pre- and post-monsoon periods. It can be attributed to the fact that the transition zone of fresh water-saline water lies below the shallow open wells, as evidenced by vertical electrical soundings.

Figure 10: Measurement of Hydraulic Conductivity in Laterite Soil

Resistivity Profiling and Sounding

In surface geophysical methods of exploration, certain physical properties and parameters of subsurface formations and contained fluids are measured by instruments located on the surface. The electrical methods are most commonly employed. The geophysical surveys can provide distribution and configuration of salt-water/fresh-water interface, salt-water encroachment, pollution and contamination. In many surface methods, observations are made to obtain information on the variation of the physical field along a horizontal profile (profiling) or in the vertical section at a given location (sounding).

In electrical-resistivity survey, a known current (direct current or low-frequency alternating current) is sent into the ground through a pair of current electrodes and the potential difference created in the medium between another pair of potential electrodes is measured. The calculated resistivity represents the true resistivity of the material if the formation is homogeneous and isotropic in nature, and only the apparent resistivity if the formation is anisotropic, consisting of two or more layers of different resistivities. The apparent resistivity value depends on several variables like electrode spacing, geometry of electrode array, true resistivities and other features of underlying formations such as layer thickness, dip and anisotropic properties. The effective depth of current penetration, and hence of the investigation, increases with increase in electrode spacing.

There are two types of resistivity surveys, namely profiling or lateral traversing and vertical electrical sounding (VES). With profiling, anisotropism in the horizontal direction is distinguished while with sounding, anisotropism in the vertical direction is distinguished. In Vertical Electrical Sounding (VES) method, keeping the place of observation constant, a set of apparent resistivity values are obtained successively for different electrode spacings. The results of VES and profiling are often affected by both lateral and vertical variations in the electrical properties of the formations. Keeping the electrode spacing constant, apparent resistivity values are measured at selected stations by shifting the whole electrode array along a profile. By measuring the apparent resistivity along the same profile with different electrode spacings, lateral as well as vertical changes in apparent resistivity can be known.

Fresh water – salt water zones are readily distinguished in resistivity profiles. Resistivity of a rock depends on clay content, water saturation, quality of water and porosities. It decreases with increasing water saturation and salt content in the water saturating the medium. Resistivity is 50 ohm-m for fresh water and about 1 ohm-m for sea water. For best results, electrical resistivity profiles should be studied alongside the hydrogeological, water quality and topographic profiles.

Results of Electrical Resistivity Survey

Apparent electrical resistivity (ohm-m) was measured in four profiles along the Bardez coast (Anjuna, Baga, Calangute, Candolim) at 18 locations upto 525 metres from the coast (Table 6). The inter-electrode separation was kept at 10 meter, that is, the resistivity values measured are at 10 m depth plane. The seawater mixed zone is witnessed along Anjuna (12 to 45 ohm-m) and Baga beach (4 to 46 ohm-m) sections along the low lying sandy alluvial areas. Very close to the sea, relatively higher apparent resistivity values are due to dry sand dunes. However, along Calangute (75 to 900 ohm-m) and Candolim (142 to 700 ohm-m) beaches, there is no indication of seawater mixing at 10 m depth, as all values are higher.

Seven vertical electrical soundings were carried out at monitoring well sites 1, 3, 6, 7, 8, 15 and 17 (Table 7). These were restricted to a depth of 20 m to know any change in the quality of water vis-à-vis seawater intrusion (3 m to 20 m with 1 m interval). As seen from the apparent resistivity values, well numbers 6, 7 and 8 show low values of resistivity (2 to 33 ohm-m) below about 12 m depth, indicating the presence of seawater or mixed zone below this depth. However, at other sites, there is no indication of the seawater mixing upto 20 m depth. It is noted here that wells located in low lying sandy alluvial areas show seawater mixing than the wells located in laterites at higher altitudes. In both laterite and alluvial soils, the wells are built well above the salt water – fresh water interface and hence no change in water quality was found in summer also.

Table 6: Apparent Electrical Resistivity Values (ohm-m) in Four Profiles along the Bardez Coast

S. No.	Distance from Coast (m)	P1	P2	P3	P4
		Anjuna	Baga	Calangute	Candolim
1	15	**30**	70	150	700
2	45	**40**	**46**	820	555
3	75	**45**	**35**	612	142
4	105	**32**	**25**	360	421
5	135	**26**	**28**	110	281
6	165	**24**	**22**	75	153
7	195	**20**	**30**	125	184
8	225	**15**	**32**	242	255
9	255	**14**	**24**	410	431
10	285	**12**	**20**	623	236
11	315	**13**	**31**	531	165
12	345	**13**	**32**	415	242
13	375	**14**	**20**	324	281
14	405	**16**	**30**	470	641
15	435	**20**	**20**	684	531
16	465	**21**	**10**	650	426
17	495	**24**	**5**	835	186
18	525	**18**	**4**	900	200

Table 7: Apparent Electrical Resistivity Values (ohm-m) at Observation Well Points in the Study Area

AB/2 (m)	Apparent Electrical Resistivity Values (ohm-m) at Monitoring Well Numbers						
	1	3	6	7	8	15	17
3	410	448	80	102	231	1988	333
4	436	446	65	84	277	665	356
5	467	521	63	72	202	900	373
6	505	595	68	62	180	256	393
7	536	613	82	58	138	850	383
8	541	521	74	51	120	156	381
9	533	482	47	45	102	780	381
10	544	389	62	42	62	194	327
11	528	339	56	40	61	125	339
12	539	314	23	25	45	128	314
13	581	264	**24**	**22**	**41**	158	290
14	582	245	**19**	**18**	**31**	165	276
15	563	246	**20**	**16**	**32**	164	246
16	561	240	**21**	**17**	**33**	215	240
17	543	226	**13**	**15**	**25**	265	226
18	609	233	**16**	**12**	**10**	315	203
19	566	215	**12**	**18**	**3**	452	226
20	520	214	**9**	**17**	**2**	351	202

4.0 DESCRIPTION OF FEFLOW

For the present study, a finite-element model (FEFLOW) was selected for model simulations. The advantages of finite-element models are

- Flexibility in the spatial discretization (irregular boundaries, coarse discretization), elements can be adjusted to match the geometry, better control on numerical errors.
- Elements can be oriented along flow, which practically eliminates numerical dispersion transverse to flow.
- Coarse discretization can be chosen in areas not affected by the plume (zone of contaminated groundwater containing dissolved contaminants), but important for the flow submodel.

4.1 FEFLOW Groundwater Modelling System

The FEFLOW is an interactive finite element simulation system (Version 5.1) for three-dimensional (3D) or two-dimensional (2D), i.e. horizontal (aquifer-averaged), vertical or axi-symmetric, transient or steady-state, fluid density- coupled or linear, flow and mass, flow and heat or completely coupled thermohaline transport processes in subsurface water resources (groundwater systems).

The FEFLOW is written for modern color graphics engineering workstations under UNIX and the X-Window (11.4 and above) and OSF/Motif (1.2 and above) graphics standard as well as for Microsoft (R) Windows NT/2000/XP/2003 Server and Windows 98SE/ME. FEFLOW provides, as the primary computed results, hydraulic heads, flow patterns and solute concentrations (mass) of a contaminant or temperature distributions, as they vary with time, everywhere in the simulated subsurface study area. The FEFLOW is capable of computing:

- Groundwater systems with and without free surfaces (phreatic aquifers, perched water tables, moving meshes)
- Problems in saturated-unsaturated zones
- Both salinity-dependent and temperature-dependent transport phenomena
- Complex geometric and parametric situations

The package is fully graphics-based and interactive. Pre-, main- and post-processing are integrated. There is a data interface to GIS (Geographic Information System) and a programming interface. The implemented numerical features allow the solution of large problems. Salient features of the software are given below.

- A finite-element simulation package for 3D and 2D density-dependent flow, mass and heat transport processes in groundwater.
- Advection-dispersion balance equations.
- Both saturated and unsaturated aquifers.

- Multiple free surface (perched water table) approach using moving meshes.
- Single phase approach (salinity considered as a miscible component).
- Adsorption effects; conservation equations of mass and heat.
- Flow can be either transient or steady-state.
- Transport equations can by solved for either transient or steady-state conditions.
- Transport process can be considered as isothermal or non-isothermal processes.
- Viscosity and fluid density are affected by salinity and temperature.
- Conservation equation is solved for a single component.
- Chemical reactions and non-reactive processes.
- A Galerkin-based finite element method.
- Boundary conditions: Dirichlet, Neumann and Cauchy-type for flow, mass and heat. A 4th kind boundary condition exists for singular (pumping or injection) wells.
- Boundary conditions are node-related while material parameters are element-related. Both nodal and elemental quantities can be transient if desired.
- Rainfall or evaporation (areal groundwater recharge) is normally modeled by sink/source formulations.
- All parameter inputs are handled on an element level.
- FEFLOW is available for UNIX and PC.
- The package is fully graphics-based and interactive. Pre-, main- and post-processing are integrated.
- There is a data interface to GIS (Geographic Information System) and a programming interface.
- The implemented numerical features allow the solution of large problems.

The perceived strengths of FEFLOW are

- Interactive graphical working environment.
- Powerful numerical techniques.
- Allow very complex and large problems to be solved.
- Also appropriate for teaching purposes to study physical phenomena and effects of numerical approaches.
- Practical modeling needs a number of reruns to find out optimal design variables for remediation and to study sensitivities of parameters and boundary conditions.
- Online-help system.

4.2 FEFLOW Basic Model Equations

The simulation system FEFLOW models the flow, mass transport and heat transport processes as combined or separable phenomena for saturated or partially saturated/unsaturated porous media.

For the three-dimensional (3D) and two-dimensional (2D), vertical or axi-symmetric processes, the representative formulations of the basic equations are as follows (*ij = 1,2,3*):

$$S_o \frac{\partial h}{\partial t} + \frac{\partial q_i^f}{\partial x_i} = Q_\rho + Q_{EB}(C, T)$$

$$q_i^f = -K_{ij} f_\mu \left(\frac{\partial h}{\partial x_j} + \frac{\rho^f - \rho_o^f}{\rho_o^f} e_j \right)$$

$$\left. \begin{array}{ll} \dfrac{\partial}{\partial t}(RC) + \dfrac{\partial}{\partial x_i}\left(q_i^f C - D_{ij} \dfrac{\partial C}{\partial x_j} \right) + R\vartheta C = 0 & \text{divergence form} \\ R_d \dfrac{\partial C}{\partial t} + q_i^f \dfrac{\partial C}{\partial x_i} - \dfrac{\partial}{\partial x_i}\left(D_{ij} \dfrac{\partial C}{\partial x_j} \right) + R\vartheta C = Q_C & \text{convective form} \end{array} \right\}$$

$$[\varepsilon \rho^f c^f + (1-\varepsilon)\rho^s c^s] \frac{\partial T}{\partial t} + \rho^f c^f q_i^f \frac{\partial T}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\lambda_{ij} \frac{\partial T}{\partial x_j} \right) = Q_T$$

with the constitutive conditions:

$$\left. \begin{array}{c} \rho^f = \rho_o^f \left[1 + \dfrac{\bar{\alpha}}{C_s}(C - C_o) - \bar{\beta}(T - T_o) \right] \\ h = \dfrac{p^f}{\rho_o^f g} + x_k \qquad K_{ij} = \dfrac{k_{ij} \rho_o^f g}{\mu_o^f} \qquad \bar{\alpha} = [\rho^f(C_s) - \rho_o^f]/\rho_o^f \\ f_\mu = \dfrac{\mu_o^f}{\mu^f(C,T)} = \dfrac{1 + 0.7063\varsigma - 0.04832\varsigma^3}{1 + 1.85\omega - 4.1\omega^2 + 44.5\omega^3} \qquad \varsigma = \dfrac{(T-150)}{100}, \ \omega = \dfrac{C}{\rho^f} \\ D_{ij} = (\varepsilon D_d + \beta_T V_q^f)\delta_{ij} + (\beta_L - \beta_T)\dfrac{q_i^f q_j^f}{V_q^f} \\ R = \varepsilon + (1-\varepsilon)\chi(C) \qquad R_d = \varepsilon + (1-\varepsilon)\dfrac{\partial[\chi(C) \cdot C]}{\partial C} \\ \lambda_{ij} = \lambda_{ij}^{cond} + \lambda_{ij}^{disp} \qquad Q_T = \varepsilon \rho^f Q_T^f + (1-\varepsilon)\rho^s Q_T^s \\ \lambda_{ij}^{cond} = [\varepsilon \lambda^f + (1-\varepsilon)\lambda^s]\delta_{ij} \qquad \lambda_{ij}^{disp} = \rho^f c^f \left[\alpha_T V_q^f \delta_{ij} + (\alpha_L - \alpha_T)\dfrac{q_i^f q_j^f}{V_q^f} \right] \end{array} \right\}$$

with

h = hydraulic head;
q_i^f = vector of the fluid's Darcy-velocity;
C = concentration of the chemical component;
T = temperature;

and

ρ^f, ρ_o^f = fluid resp. reference fluid density;
ρ^s = solid's density;
S_o = specific storage ratio (compressibility);
K_{ij} = tensor of permeability;
e_j = gravitational unity vector;
f_μ = function of viscosity ratio;
Q_{EB} = Extended term of Boussinesq-Approximation;
R = factor of retardation;
R_d = derivative term of retardation;
D_{ij} = tensor of hydrodynamic dispersion;
ϑ = decay rate;
ε = porosity;
c^f, c^s = heat capacity of the fluid resp. of the solid;
λ_{ij} = tensor of hydrodynamic thermodispersion;
Q_x = source/sink function for fluid ($x = \rho$), for mass ($x = C$) and for heat ($x = T$);
$\bar{\alpha}$ = ratio of mass density;
$\bar{\beta}$ = ratio of expansion;
C_o, T_o = reference value for concentration resp. temperature;
C_s = maximum concentration;
p^f = fluid pressure;
g = gravitational acceleration;
k_{ij} = tensor of permeability;
μ^f, μ_o^f = dynamic fluid viscosity and reference viscosity
ς = normative temperature;
ω = mass fraction;
D_d = molecular medium-diffusion;
V_q^f = $\sqrt{q_i^f q_i^f}$ absolute Darcy-flux;
β_L, β_T = longitudinal resp. transversal dispersivities for chemical species;
$\chi(C)$ = concentration dependent function of sorptivity;
λ_{ij}^{cond} = tensor of conductive thermodispersion;
λ_{ij}^{disp} = tensor of dispersive thermodispersion;
λ^f, λ^s = heat conductivity of fluid resp. solid;
α_L, α_T = longitudinal resp. transversal thermodispersivities.

4.3 FEFLOW Modelling Strategy

For good and fast modelling, it is useful to follow a certain order. A typical order has been below.

- **Design super-elements**: They are biggest units of the model. It is of advantage to create more than one super-element if you have regionally changing parameters or areas of higher interest. The shape and position of the super-elements should make it possible to set the boundary conditions and material parameters as exact as needed. Background maps can be loaded and activated.

- **Generate Finite Element Mesh**: If you have designed different super-elements, you have the possibility to vary the mesh density. If you are creating a mass transport problem, be aware that the elements' width and length in the interested area should correspond to the longitudinal and transversal dispersivity of the contaminant.

- **Assign problem attribute data**: FEFLOW offers many ways to import and assign data to the model. FEFLOW uses the defaults for a parameter not specified. The borders of the model are impermeable as default.

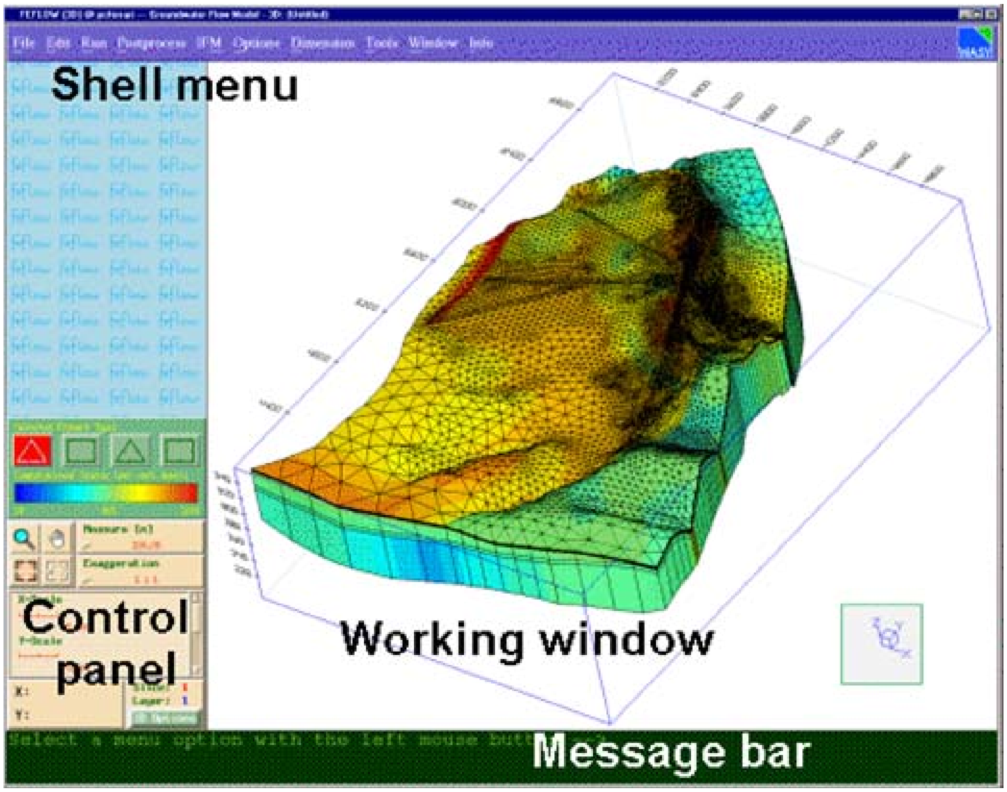
- **Run simulator**: Make a first trial with your model. The 'time step history' window will show you at which time the simulator kernel gets into trouble (if you use automatic time step control) and the hydraulic head and/or local mass windows will show where the trouble is.

- **Loop**: If the model doesn't work, restart at one of the previous items.

- **Final results:** The postprocessor offers many options for the output of results.

4.4 FEFLOW Structure

The interactive simulation system FEFLOW is hierarchically structured. The System Shell is the top level within this program hierarchy. The shell offers entries to the editors (mesh, problem), the simulator kernel with different solution strategies, presents information and pre-selected system defaults, maintains options for file handling (importing and exporting various database formats) and other items which can easily be selected by the pull down menus with the mouse. Additionally, it is possible to add own modules to FEFLOW via the FEFLOW Programming Interface.



Select a menu option with the left mouse butt

Figure 11: FEFLOW Working Window

The FEFLOW shell is subdivided in four parts:

- **The working window:** Displays your model, including FEM, boundary conditions, background maps etc.
- **The shell menus:** You can enter the shell menus either by clicking with the left mouse button on the corresponding names on the top bar of the window, or by pressing <Alt> + [underlined letter]. Generally, the shell menus can only be entered from this top level.
- **The control panel**: It is visible on every level of the system on the left side of the screen and offers information about the models and the working windows settings. The zooming is located here and additionally, you can enter the 3D Options menu for displaying your model in a 3D view.
- **The message bar**: Here context sensitive help texts are displayed, specially for the functions of the mouse buttons and the active hot keys.

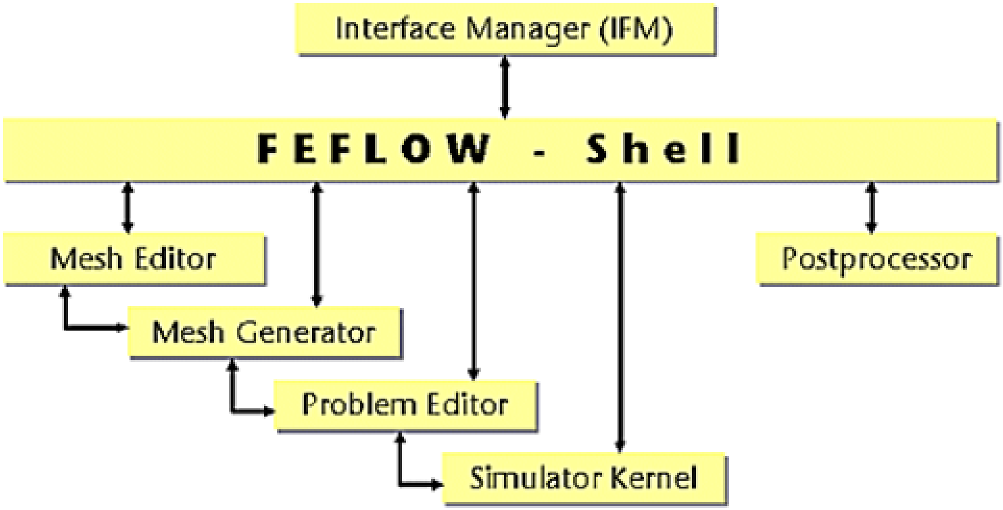


Figure 12: FEFLOW Shell

Shell menus

- **File -** Offers all options for file operations.
- **Edit -** Entry to the editors, concerning the construction of the FEM and the editing of the model parameters.
- **Run -** Starts the simulation kernel.
- **Postprocess** - Offers tools for analyzing and output of the computed data.
- **IFM -** Menu for adding and creating modules for FEFLOW.
- **Options -** Defines the parameters and adjustments for the editors and the simulation kernel.

5.0 MODEL SIMULATIONS

The FEFLOW simulation package was used to model seawater intrusion in the Bardez taluk of North Goa. Details of model setup and simulation results are given below.

5.1 Aquifer Geometry

The aquifer geometry was adopted, as defined in previous studies. The modelling region is divided into two layers with different material data. Geological profile in low lying area (ground elevation 0 – 20 m above mean sea level) was assigned as 15 – 30 m deep sandy soil (upto 10 – 15 m below mean sea level) underlain by 1 – 2 m clay layer and then basement rocks (phyllite, graywacke, schist etc). Geological profile in plateau area (ground elevation 20 – 80 m above mean sea level) was assigned as 0 - 75 m deep laterite (upto 0 – 10 m below mean sea level) underlain by 2 – 5 m clay layer and then basement rocks.

Reference zero elevation was assumed at 50 m below mean sea level. The aquifer domain of the study area (74 km^2) was discretized using 6 nodal triangular prism elements with 52,656 mesh elements and 32,053 mesh nodes. The upper layer was sub-divided into 5 equidistant layers. The vertical discretization therefore corresponds to 7 slices and 6 layers. The top slice was defined as free and movable (water table).

5.2 Boundary Conditions

The boundary conditions for the flow simulation are as follows:

- A coastal head boundary along the coastal zone (western boundary) at the top and bottom slices of the aquifer; FEFLOW uses head (h) instead of pressure with $h = (e_w / e_s) Z$, where e_w and e_s represent ambient and seawater densities respectively and Z is the depth below sea level. The head was calculated in each constant-head boundary node.

- No flow boundaries are specified in the eastern boundary and right part of the northern boundary, where it forms the watershed boundary of Baga and Nerul rivers.

- Southern boundary (Mandovi River) and left part of the northern boundary (Chapora River) are described by third-kind (Cauchy) boundary condition, Transfer. Internal flow boundaries (Baga River and Nerul River) are also described by Transfer boundary condition.

The boundary conditions and initial concentration for the transient state solute transport are dependent on the flow simulation results. For this model, solute transport concentrations are expressed in terms of total dissolved solids (TDS). A concentration of 35,425 mg/l (seawater TDS) is used along the coastal zone where simulated inflow from ocean occurs (mass boundary of 1st kind). The initial concentration of the groundwater was set to 0 mg/l.

5.3 Flow and Mass Transport Materials

Only few measured hydrodynamic data are available and incorporated in the model. Six values of hydraulic conductivity ranging from 0.381x10^{-4} to 3.657x10^{-4} m/s were measured through pumping tests. Data regionalization for hydraulic conductivity over the study area has been carried out using Akima inter/extrapolation. Figure 13 presents the distribution of hydraulic conductivity in the study area.

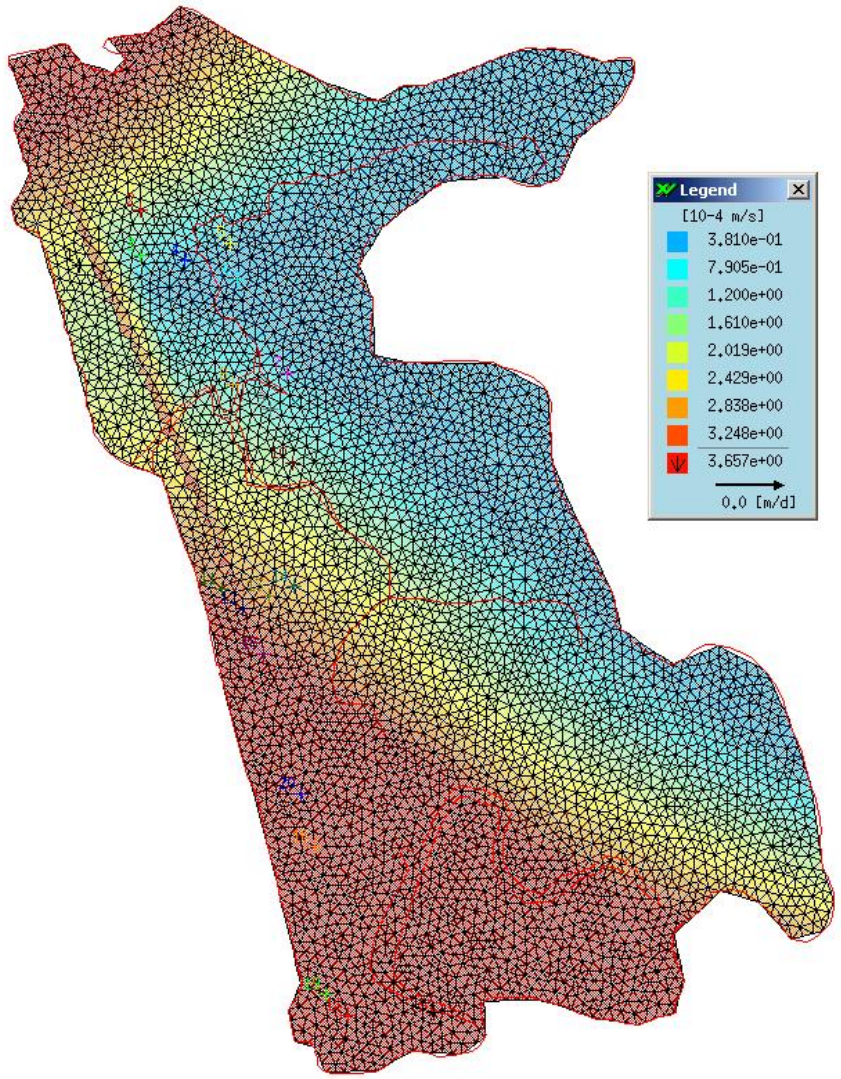


Figure 13: Distribution of Hydraulic Conductivity

No measurement of dispersivity has been made; this parameter was therefore estimated by trial and error using prior information from similar cases. Molecular diffusion was assumed as 1.00×10^{-9} m^2/s. Initial head data have been measured in 20 observation wells. Data regionalization for hydraulic heads over the study area has been carried out using Akima inter/extrapolation. Figure 14 presents the distribution of initial hydraulic heads assigned for model simulations.

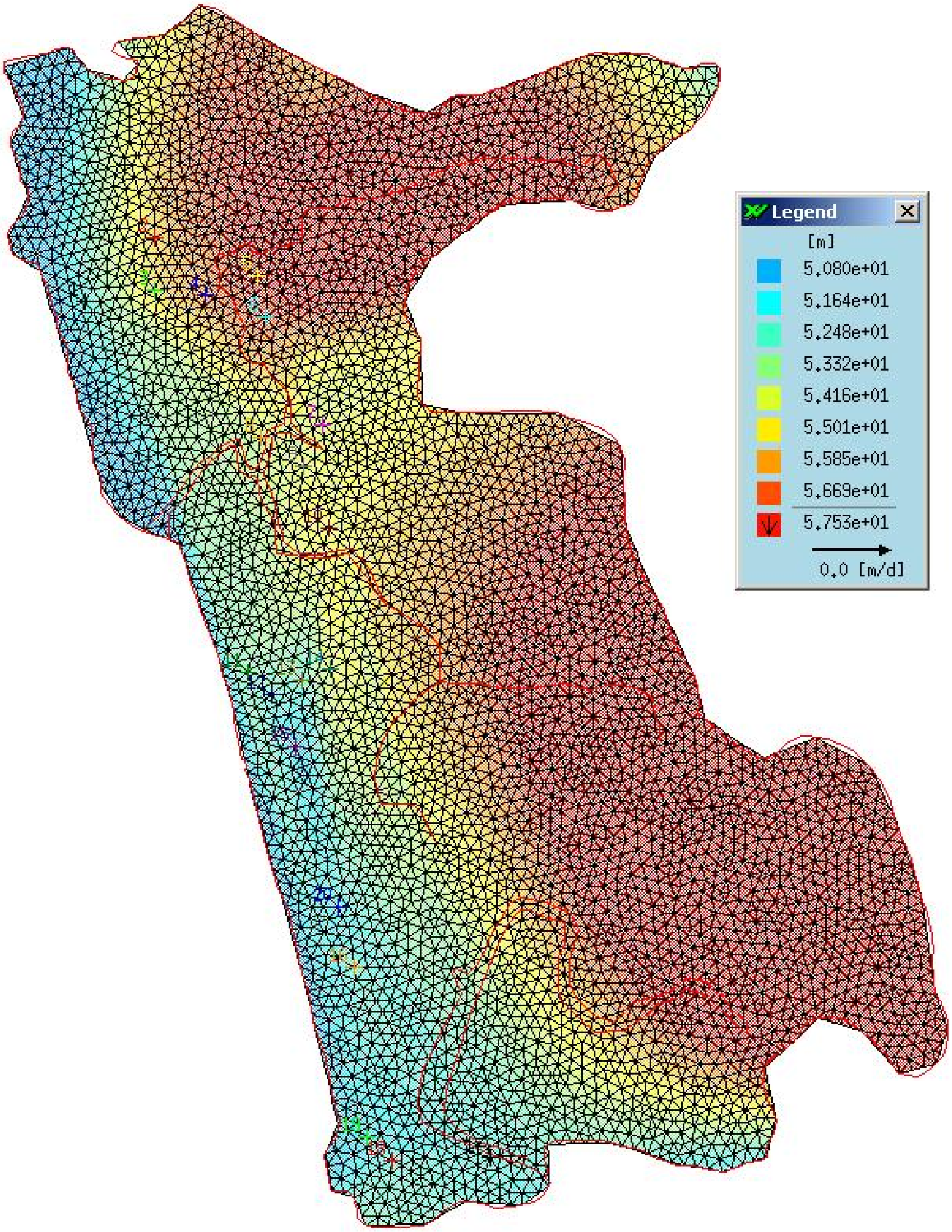


Figure 14: Distribution of Initial Hydraulic Heads

Mean annual rainfall is estimated to be 2714 mm, based upon daily rainfall data of Panaji for 20 years (1984 to 2003). Rainfall recharge values for laterite and west coast were adopted as 7% and 10% respectively, as recommended by “Groundwater Resource Estimation Methodology - 1997”. Annual groundwater draft for the study area was worked out by using the reported density of wells as 25 wells per km^2 and average annual groundwater draft per structure as 0.65 ha-m. Porosity for sandy alluvium, laterite and clay were assumed to be 0.32, 0.21 and 0.42 respectively. Specific yield for sandy alluvium, laterite and clay were assumed to be 0.16, 0.025 and 0.03 respectively.

5.4 FEFLOW Problem Summary

- Dimension : Three-Dimensional
- Type : Saturated media (groundwater)
- Number of Layers : 6
- Number of Slices : 7
- Projection : None (3D with free surface)
- Problem Class : Combined flow and mass transport
- Time Class : Unsteady flow – Unsteady mass transport
- Upwinding : Full upwinding
- Element Type : 6-noded triangular prism
- Mesh Elements : 52656
- Mesh Nodes : 32053
- Incorporate fluid viscosity dependencies
- Extended Boussinesq approximation applied to density coupling

- Time Stepping Scheme :

  Automatic time step control via predictor-corrector schemes - Forward Adams-Bashforth/backward trapezoid (AB/TR time integration scheme)

  - Initial time step length : 0.001 d
  - Final time : 3650 d

- Unconfined (phreatic) aquifer(s)

Slice No.	Status
1	Free & movable
2	Unspecified
3	Unspecified
4	Unspecified
5	Unspecified
6	Fixed
7	Fixed

5.5 Simulation Results

The transient state simulation of the solute transport was carried out using automatic time step control via predictor-corrector schemes, with initial time step length as 0.001 day and final time as 3650 days (10 years) to reach steady state conditions. Calibration objective for the mass transport was focused mainly at observation wells near Anjuna and Baga beaches and Baga River where resistivity survey has indicated the presence of brackish water.

Longitudinal and transverse dispersivity were modified uniformly by trial and error in order to match the measured salinity values from the observation wells. Several runs were carried out to approach the solution. Final calibrated longitudinal and transverse dispersivity are 50 m and 5 m respectively. The calibration process shows that the mass transport model is sensitive to the dispersivity values. Figure 15 presents the three-dimensional fringes for hydraulic head at the end of simulation period.

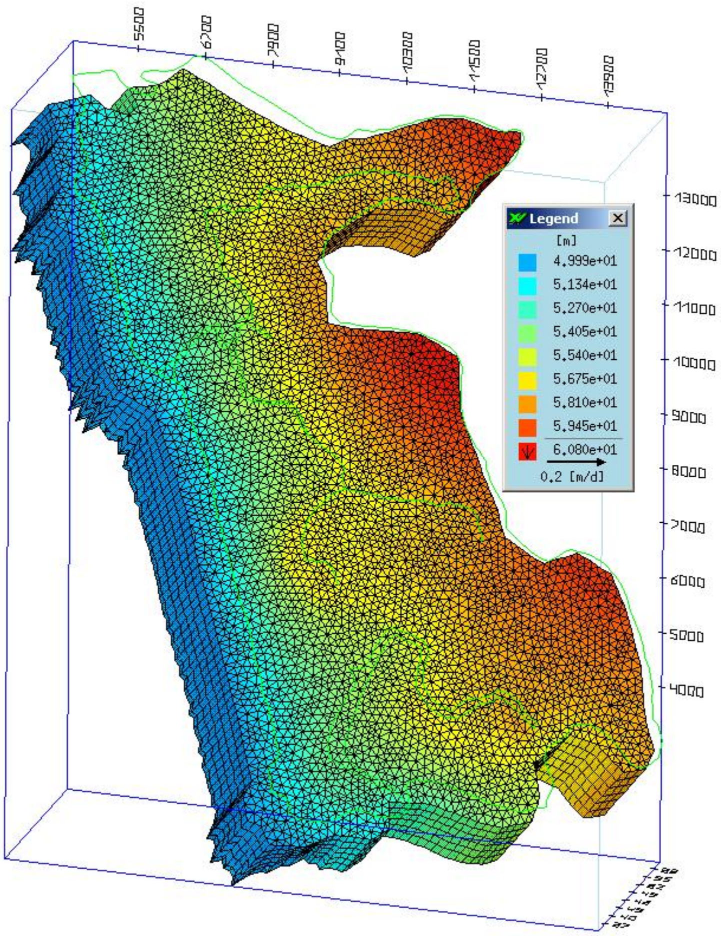


Figure 15: Three-dimensional Fringes for Hydraulic Head at the End of Simulation Period

Three-dimensional plot for mass distribution has been presented in figure 16. It indicates 3 peaks where salinity near the coast exceeds 6000 mg/l. Along these three sections, the salinity of groundwater was found to be greater than 500 mg/l upto 290 m inland, the maximum (near the coast) being 9400 mg/l, 9600 mg/l and 6800 mg/l respectively.

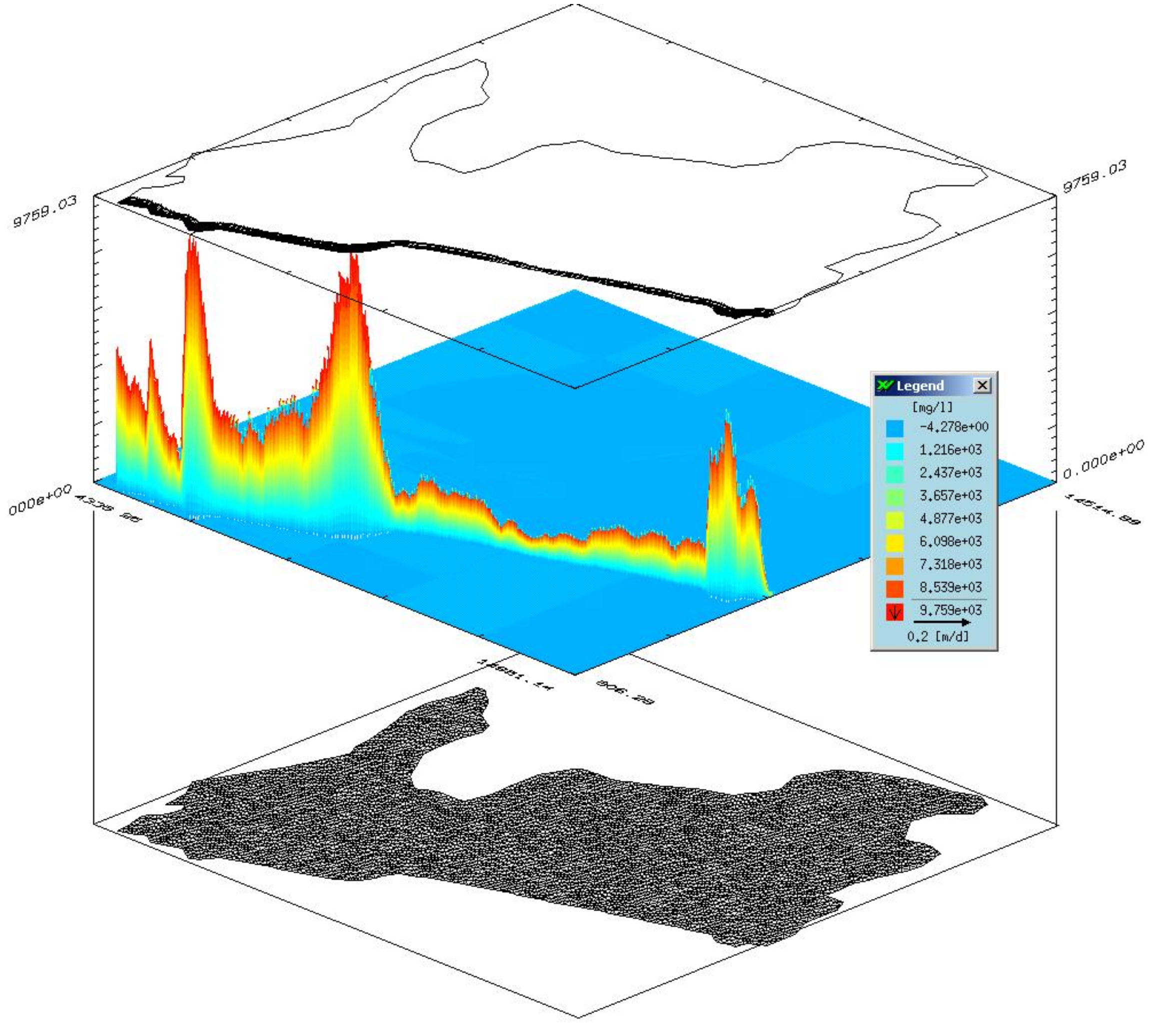


Figure 16: Three-dimensional Plot for Mass Distribution

The computed salinity in the aquifer shows a sharp decrease of salinity from the coast towards inland. As an example, for the middle section, the salinity varies from 9,600 mg/l to 500 mg/l from the coastal front to a distance 290 m, as shown in figure 17. The extent of seawater intrusion over the entire coast has been presented in figure 18. The model was not fully calibrated because of uncertainties in the hydrodynamic flow and mass transport data used. However, the results show that the density dependent 3D model is reasonable.

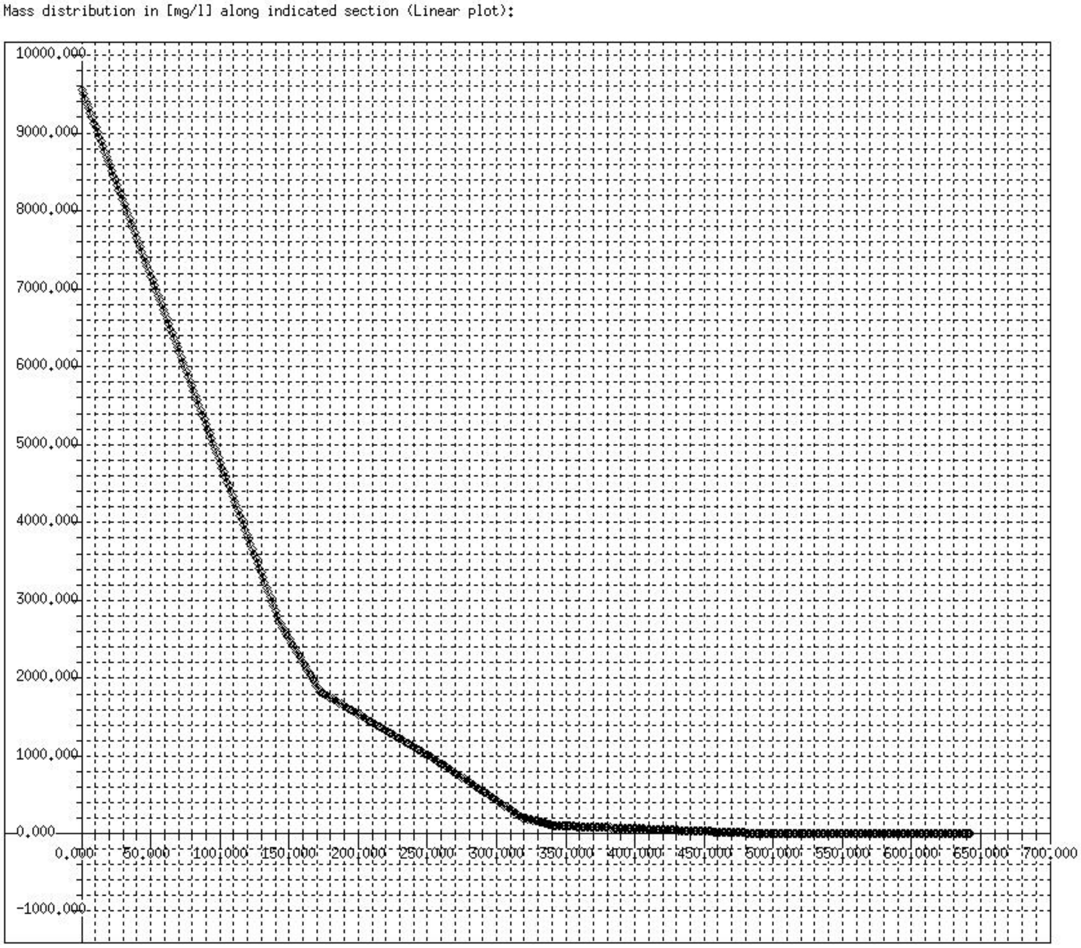


Figure 17: Mass Distribution along a Section

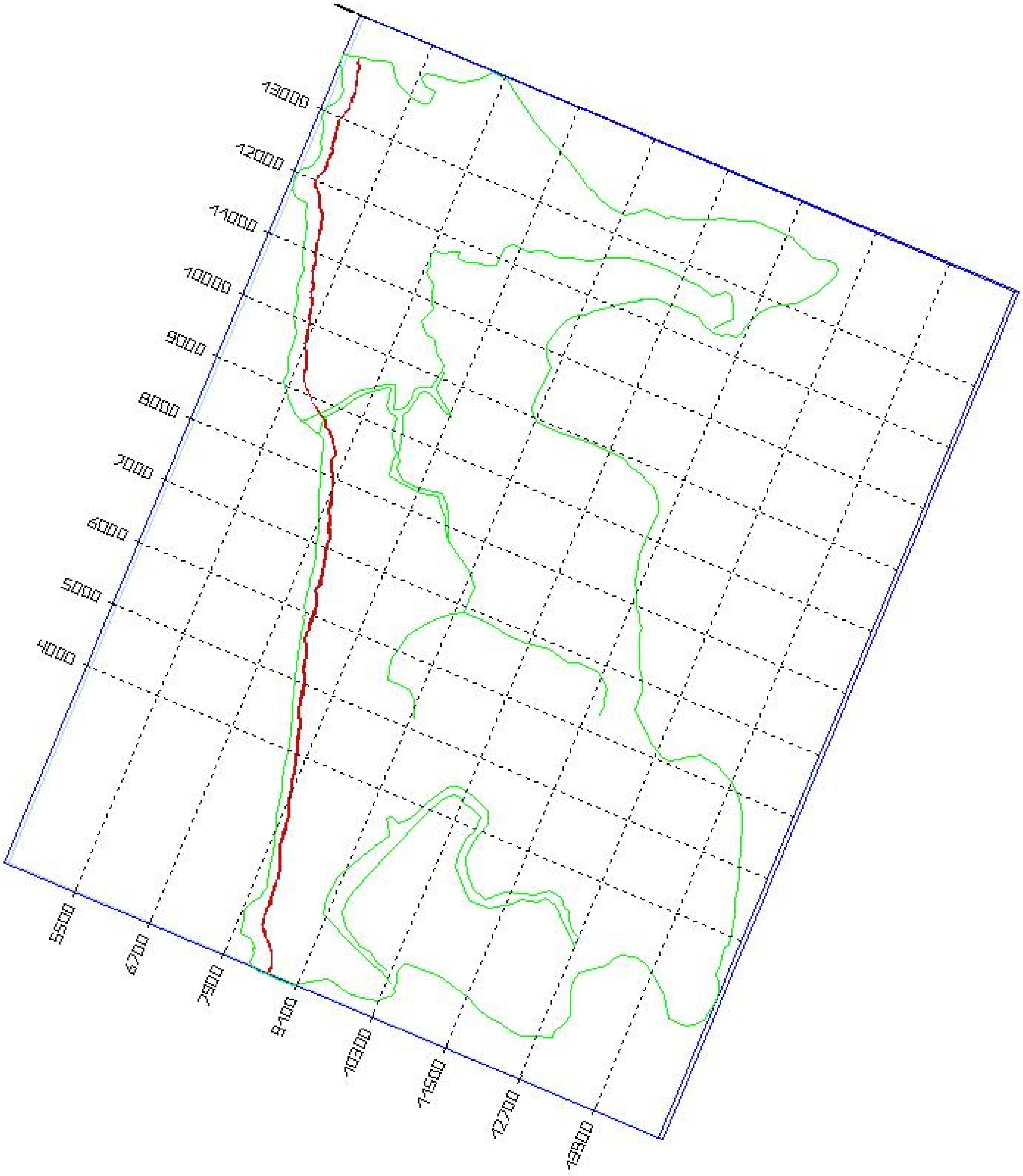


Figure 18: Simulated Extent of Seawater Intrusion

5.6 Sensitivity Analysis

Sensitivity analysis was carried out to find the most sensitive parameters affecting the simulation. The following scenarios were modeled by keeping all other parameters and conditions same.

[A] Groundwater Draft

- 10 % increase in groundwater draft
- 20 % increase in groundwater draft
- 30 % increase in groundwater draft

[B] Longitudinal and Transverse Dispersivity

- Longitudinal and transverse dispersivity reduced to 30 m and 3 m respectively.
- Longitudinal and transverse dispersivity increased to 70 m and 7 m respectively.

[C] Hydraulic Conductivity

Instead of distributed hydraulic conductivity (obtained through Akima inter/extrapolation for the measured values), uniform maximum and minimum measured values were taken over the entire study area.

- Uniform hydraulic conductivity (maximum) = 3.657 x 10^{-4} m/s
- Uniform hydraulic conductivity (minimum) = 0.381 x 10^{-4} m/s

[D] Rainfall

Instead of average annual rainfall of 2714 mm, simulations were made with lowest and highest rainfall observed during the period 1984 to 2003.

- Lowest annual rainfall observed during the period 1984 to 2003 = 1723 mm
- Highest annual rainfall observed during the period 1984 to 2003 = 3554 mm

Table 8 presents the results of sensitivity analysis for the above scenarios. It indicates the maximum salinity (near the coast) and the inland distance from the coast beyond which the salinity is less than 500 mg/l.

Table 8: Results of Sensitivity Analysis

S.No.	Parameter	Scenario	Simulated Results	
			Maximum Salinity near the Coast (mg/l)	Distance from the Coast (m) with Salinity 500 mg/l
1.	Original Calibrated Parameters (middle section)		9,600	290
2.	Groundwater Draft	10 % increase	9,900	295
		20 % increase	10,300	300
		30 % increase	10,700	300
3.	Longitudinal and Transverse Dispersivity	30 m and 3 m	10,100	275
		70 m and 7 m	9,000	305
4.	Uniform Hydraulic Conductivity	3.657 x 10^{-4} m/s	7,300	295
		0.381 x 10^{-4} m/s	12,900	145
5.	Rainfall	1723 mm	11,800	295
		3554 mm	7,800	290

The above sensitivity results indicate that the model is very sensitive to hydraulic conductivity and dispersivity values. Also, rainfall and change in draft pattern affect the seawater intrusion simulations to considerable extent.

7.0 CONCLUSIONS

- Presently, seawater intrusion in Bardez taluk of North Goa is confined only upto 290 m from the coast under normal rainfall conditions and present draft pattern. It may slightly extend farther for low rainfall years.

- Seawater intrusion may further advance inland if withdrawals of groundwater by builders, hotels and other tourist establishments continue to increase in the coming years.

- Groundwater salinity needs to be continuously monitored near the coastal area, especially within 2 km from the coast.

- Corrective measures with proper planning and management of groundwater resources in the area need to be initiated so that it may not turn to be a major water quality problem in the coming times.

- The model is very sensitive to hydraulic conductivity and dispersivity values. Field and laboratory investigations need to be undertaken for measurement of these parameters for use in further modelling studies.

- This study will guide in making management decisions to monitor and control seawater intrusion and planning of groundwater development in the area.

REFERENCES

Chachadi, A.G. (2000), "*Strategies for Water Resources Management in the Coastal Zones of Goa*", Coastal Zone Management, S.D.M.C.E.T, Dharwad & IGCP-367, Special Publication, Volume No. 2, pp. 165-168.

Chachadi, A.G. and C. Joaquim S. John (2000), "*Geoelectrical Studies in Ascertaining Fresh-Water Zones in Coastal Goa*", Coastal Zone Management, S.D.M.C.E.T, Dharwad & IGCP-367, Special Publication, Volume No. 2, pp. 169-172.

Chachadi, A. G., J. P. Lobo-Ferreira, Ligia Noronha and B. S. Choudri (2002), "*Assessing the Impact of Sea-Level Rise on Salt Water Intrusion in Coastal Aquifers using GALDIT Model*", Coastin – November 2002, TERI, pp. 27-32.

Cheng, Alexander H.-D. (2003), "*Groundwater, Saltwater Intrusion in*", Encyclopedia of Water Science, Marcel Dekker, Inc., pp. 404-406.

COASTIN (2001), "*GIS and Mathematical Modelling for the Assessment of Groundwater Vulnerability to Pollution: Application to an India Case – Study Area in Goa*", 2nd Year Report, April 2001, 69 p.

Diersch, H.-J. G. (2002), "*FEFLOW Reference Manual*", Finite Element Subsurface Flow & Transport Simulation System, WASY Institute for Water Resource Planning and Systems Research Ltd., Berlin, 278 p.

FEFLOW (Finite Element Subsurface Flow & Transport Simulation System) Demonstration Exercise, WASY Institute for Water Resource Planning and Systems Research Ltd., Berlin, 2004, 48 p.

FEFLOW 5.1 (Finite Element Subsurface Flow & Transport Simulation System) User's Manual, WASY Institute for Water Resource Planning and Systems Research Ltd., Berlin, 2004, 168 p.

Goa University (2000), "*Aquifer Testing, Observation Well Networking, Electrical Profiling and Groundwater Draft Estimation, Baga Watershed, Bardez, Goa*", Department of Geology, Goa University, Goa, 46 p.

Lobo-Ferreira, J. P., Maria C. Cunha, A. G. Chachadi, Kai Nagel, Catarina Diamantino and Manuel M. Oliveira (2003), "*Application of Optimization Models for Satisfaction of Water Resource Demand of Tourist Infrastructure*", In. Coastal Tourism, Environment, and Sustainable Local Development (Ed. Noronha et al.), Chapter 14, pp. 305-320.

DIRECTOR : K. D. SHARMA

DIVISIONAL HEAD : N. C. GHOSH

STUDY GROUP : C. P. KUMAR
A. G. CHACHADI
B. K. PURANDARA
SUDHIR KUMAR

SCIENTIFIC STAFF : N. VARADARAJAN
RAJU JUYAL