# HYDROGEOLOGICAL, GEOPHYSICAL AND GEOCHEMICAL STUDIES IN PARTS OF COASTAL AND MIDLAND AREAS, CENTRAL KERALA - A GIS APPROACH



*Thesis submitted to*

**COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY**

*In partial fulfilment of the requirement for the degree of*

**DOCTOR OF PHILOSOPHY**
**IN**
**MARINE GEOLOGY**

**UNDER THE FACULTY OF MARINE SCIENCES**

By

**SANTHOSH KUMAR R.**

**DEPARTMENT OF MARINE GEOLOGY AND GEOPHYSICS**
**SCHOOL OF MARINE SCIENCES**
**COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY**
**COCHIN-682016, INDIA**

**NOVEMBER 2006**

*......to my beloved daughter*

# DECLARATION

*I* ***Santhosh Kumar. R*** *do hereby declare that the thesis entitled* **"HYDROGEOLOGICAL, GEOPHYSICAL AND GEOCHEMICAL STUDIES IN PARTS OF COASTAL AND MIDLAND AREAS, CENTRAL KERALA - A GIS APPROACH"** *is an authentic record of research work done by me under the supervision of S. Rajendran, Department of Marine Geology and Geophysics, School of Marine Sciences, Cochin University of Science and Technology. This work has not previously formed the basis for the award of any degree or diploma of this or any other University/Institute.*

**Santhosh Kumar. R**

Cochin-16
November, 2006

# CERTIFICATE

*This is to certify that the thesis entitled* **"HYDROGEOLOGICAL, GEOPHYSICAL AND GEOCHEMICAL STUDIES IN PARTS OF COASTAL AND MIDLAND AREAS, CENTRAL KERALA – A GIS APPROACH"** *is an authentic record of research work done by Mr. Santhosh Kumar. R under my supervision and guidance in partial fulfillment of the requirements for the degree of Doctor of Philosophy and no part thereof has been presented for the award of any degree or diploma of this or any other University/Institute.*

Cochin-16
November, 2006

**Prof. S. Rajendran**
(Research Supervisor)
Dept. of Marine Geology and Geophysics
School of Marine Sciences
Cochin University of Science and Technology
Cochin -682016

# Acknowledgements

*I would like to express my deep sense of gratitude to my supervising guide Dr. S Rajendran, Professor, Cochin University of Science and technology for his meticulous guidance, constant encouragement, moral support and constructive criticism. Without his valuable suggestions and intellectual inputs this work would not have been completed. I acknowledge him with immense gratitude.*

*I am deeply grateful to Sri. T M. Mahadevan, former Director, Atomic Minerals Division for his constant encouragement, advice and valuable suggestions throughout the period of my research. He was always willing to provide critical and constructive comments during the preparation of the manuscript.*

*I express my sincere gratitude to Dr. Nambiar, Head of the Department of Marine Geology and Geophysics for his encouragement and valuable suggestions in this endeavour.*

*My thanks are due to Prof. (Dr.) K. T. Damodaran, Prof. (Dr.) K. Sajan, Prof. (Dr.) P. Seralathan, Dr. M. Radhakrishna and Dr. M. Ravishankar, faculty members of the department for the help and encouragement rendered by them.*

*I am beholden to Dr. Girish Gopinath for his wholehearted support right from the beginning of my research work. In every sense, this work would not have been possible without his constant inspiration, unconditional support and prayers.*

*I place on record my sincere thanks to Sri.. Pramod P. K. for his inspiring support and untiring help throughout my research work.*

*I am indebted to Sri. Pramod Lal and Sri. Subin for providing technical expertise during the course of the research work.*

*I place on record my gratitude to Sri. Ravindran. K.V, Scientist, NRSA and Sri. Nagarajan, Scientist, CGWB for providing me with invaluable guidance.*

*I am thankful to Sri. Rajan, Lecturer, M.G. University for providing technical expertise in geophysical studies.*

*I am grateful to A. S., Dr. Shadanandan, Sri. Sudhir A.S, Dr. Ajith Joseph. Dr. Rasheed, Sri. Venu G. Nair, Sri. Thomas Scaria and Sri. Ajith for their timely advice, valuable criticism and suggestions during the preparation of manuscript.*

*I would like to express my deep sense of gratitude to my beloved friends Mr. Baiju K. R., Mr. K. S. Prasad, S. R. Pradeep, Sri. Abilash S and Sri. Nilof S. Pasha for their immense help, moral support and constant encouragements.*

*I am thankful to Sri. Sreekumar, Section Officer and other non-teaching staff of the Department of Marine Geology and Geophysics for their wholehearted help throughout the period of my research.*

*Thanks are also due to the staff of the library for their help rendered during this work.*

*Words are not enough to express my feelings and emotions for the unconditional shower of care, love and affection of my beloved parents and my wife and daughter who had been the motivation in all my endeavours and I feel lucky to have them with me, always. I am deeply indebted to them for all my achievements.*

*I am grateful to Cochin University of Science and Technology for providing me an opportunity to work in this wonderful environment.*

*Santhosh Kumar R.*

CONTENTS


| | | PAGE NO |
|---|---|---|
| | **CHAPTER 1** | |
| | **GENERAL INTRODUCTION** | |
| 1.1 | INTRODUCTION | 1 |
| 1.2 | SCENARIO IN KERALA | 6 |
| 1.3 | SCOPE OF THE STUDY | 9 |
| 1.4 | OBJECTIVES | 11 |
| 1.5 | THE STUDY AREA | 12 |
| 1.5.1 | GEOMORHOLOGY OF KERALA | 12 |
| 1.5.2 | LINEAMENT PATTERN | 16 |
| 1.5.3 | DRAINAGE | 18 |
| 1.5.4 | LAKES AND BACKWATERS | 19 |
| 1.5.5 | GEOLOGY OF KERALA | 20 |
| 1.5.6 | CLIMATE AND WATER RESOURCES | 31 |
| 1.5.7 | GROUNDWATER OCCURRENCE IN THE STUDY AREA | 33 |
| 1.6 | REVIEW OF LITERATURE | 36 |
| | **CHAPTER 2** | |
| | **MATERIALS AND METHODS** | |
| 2.1 | INTRODUCTION | 42 |
| 2.1.a | FIELD OPERATIONS AND INVESTIGATIONS | 43 |
| 2.2 | GEOCHEMICAL STUDIES | 43 |
| 2.2.1 | LAB WORK | 44 |
| 2.2.2 | BACTERIOLOGICAL ANALYSIS | 47 |
| 2.4 | HYDROMETEOROLOGICAL ANALYSIS | 47 |
| 2.4.1 | Groundwater level monitoring | 47 |
| 2.4.2 | Water balance studies | 47 |
| 2.5 | GEOPHYSICAL STUDIES | 49 |
| 2.5.1 | Electrical resistivity methods | 51 |
| 2.5.2 | Data acquisition | 52 |
| 2.6 | REMOTE SENSING AND GIS | 53 |
| 2.6.1 | Digital image processing | 54 |
| 2.7 | GEOGRAPHIC INFORMATION SYSTEM | 60 |

| | | |
|---|---|---|
| 2.7 1 | Water level analysis | 61 |
| 2.7.2 | Geomchemical Zonation | 62 |
| 2.7.3 | Spatial overlay analysis | 62 |
| 2.7.4 | Drinking water quality maps | 63 |
| 2.7.5 | Saline water buffer zones | 63 |
| 2.7.6 | Deciphering prospective groundwater zones using resistivity and aquifer thickness | 63 |


**CHAPTER 3**

**HYDROGEOLOGY**

| | | |
|---|---|---|
| 3.1 | INTRODUCTION | 68 |
| 3.2 | Hdyrogeology of coastal aquifers | 69 |
| 3.3 | Fluctations in water level | 70 |
| 3.4 | Behaviour of groundwater in the study region | 72 |
| 3.5 | Hydrograph analysis | 75 |
| 3.5.1 | Hydrograph analysis of the coastal belt | 78 |
| 3.5.2 | Hydrograph analysis of the laterite terrain | 79 |
| 3.5.3 | Hydrograph analysis of charnockites | 80 |
| 3.5.4 | Basinwise analysis | 80 |
| 3.6 | Water balance studies | 80 |


**CHAPTER 4**

**GEOPHYSICAL STUDIES**

| | | |
|---|---|---|
| 4.1 | INTRODUCTION | 82 |
| 4.2 | Electrical resistivity methods | 83 |
| 4.3 | Groundwater detection using resistivity | 90 |
| 4.4 | Resistivity studies in coastal areas | 90 |
| 4.5 | Saline water intrusion | 91 |
| 4.6 | Interpretation of VES data | 91 |
| 4.6.1 | Empirical methods | 93 |
| 4.6.2 | Analytical methods | 94 |
| 4.7 | Results of VES analysis in the study area | 95 |
| 4.7 1 | Hard rock terrain | 95 |
| 4.7.2 | Coastal belt | 97 |
| 4.8 | Groundwater targeting using resistivity methods | 98 |

**CHAPTER 5**

**HYDROGEOCHEMISTRY**


| | | |
|---|---|---|
| 5.1 | INTRODUCTION | 99 |
| 5.2 | Groundwater quality an overview | 101 |
| 5.3 | Evaluation of groundwater for domestic uses | 103 |
| 5.3.1 | pH | 103 |
| 5.3.2 | Electrical Conductivity (EC) | 105 |
| 5.3.3 | Total dissolved solids (TDS) | 107 |
| 5.4 | Major cations and anions | 109 |
| 5.4.1 | Cation geochemistry | 109 |
| 5.4.2 | Anion geochemistry | 112 |
| 5.5 | Bacteriological Quality *(E.coli)* | 115 |
| 5.6 | Suitability of groundwater for various uses | 116 |
| 5.6.1 | Domestic uses | 116 |
| 5.6.2 | Suitability for irrigation | 116 |
| 5.7 | Classification by USSL diagram | 121 |
| 5.8 | Quality of groundwater for livestock and poultry | 123 |
| 5.9 | Quality of groundwater for industrial purposes | 123 |
| 5.10 | Hydrochemical diagrams | 124 |
| 5.10.a | Collins diagram | 125 |
| 5.10.b | Stiff diagram | 126 |
| 5.10.c | Schoeller diagram | 126 |
| 5.10.d | Piper diagram | 127 |
| 5.10.e | Durov's diagram | 129 |
| 5.10.f | Plotting over raster images | 130 |


**CHAPTER 6**

**REMOTE SENSING AND GEOGRAPHICAL INFORMATION SYSTEM**


| | | |
|---|---|---|
| 6.1 | INTRODUCTION | 132 |
| 6.2 | Remote sensing applications in water resources | 134 |
| 6.3 | GIS Applications in water resources | 135 |
| 6.3.1 | Groundwater analysis | 138 |
| 6.3.1a | Groundwater surface elevation contour coverages | 139 |
| 6.3.1b | 3D visualization of water level | 139 |

| | | |
|---|---|---|
| 6.3.2 | GIS Analysis of geochemical data | 140 |
| 6.3.2.1 | Drinking water quality map | 140 |
| 6.3.2.2 | Saline water buffer zones | 143 |
| 6.3.3 | Deciphering groundwater prospect zones using resistivity and aquifer thickness | 143 |
| 6.3.3.1 | Analysis of thematic maps | 145 |
| 6.3.3.2 | RT map analysis | 146 |
| 6.3.4 | Delineation of potable water zones integrating water quality data with potential groundwater zones | 147 |
| | **CHAPTER 7** | |
| | **SUMMARY AND CONCLUSIONS** | |
| | **REFERENCES** | |

# LIST OF FIGURES

**Chapter 1**
1.1 Location map of the study area
1.2 Roads and rails
1.3 Drainage map
1.4 Geological map of the study area
1.5 Subsurface geology of the study area
1.6.a Average monthly temperature Alappuzha
1.6.b Average monthly temperature Kochi
1.7.a Average monthly rainfall Alappuzha
1.7.b Average monthly rainfall Kochi
1.7.c Average monthly rainfall Trissur

**Chapter 2**
2.1 Schlumberger electrode configuration
2.2 Flow chart showing steps in the preparation potable groundwater zones using GIS

**Chapter 3**
3.1 Location of observation wells
3.2.a - j Spatial distribution of water levels from 1993 to 2003
3.3 Groundwater flow accumulation raster of the study area 2003
3.4 Groundwater flow direction raster of the study area 2003
3.5 Statistical analysis of water levels from 1993 to 2003 using GIS
3.6 Effects of sustained pumping seen on a hydrograph
3.7 Comparison of hydrographs of crystalline and coastal belt
3.8 Correlation of rainfall and water level data
3.9.a - e Hydrographs of wells in the coastal belt
3.10.a - b Hydrographs of wells in the laterite terrain
3.11.a - b Hydrographs of Aluva and Kunnathukad
3.12 Comparison of well hydrographs in the laterite terrain
3.13 Comparison of hydrographs of alluvium and laterite
3.14.a - b Hydrographs of Kizhakambalam and Kunnathukad
3.15 Comparative analysis of hydrographs in Charnockite

**Chapter 4**
4.1 Location of vertical electrical sounding points
4.2 Resistivity zones - hard rock
4.3 Aquifer resistivity - alluvium
4.4 Common types of sounding curves in three-layered formation
4.5 Interpretation of VES data and selected curve pattern of the coastal belt

**Chapter 5**
5.1 Well location
5.2.a - b Zonation maps of pH
5.3.a Zonation maps of electrical conductivity
5.4.a. - b Zonation maps of TDS
5.5.a - b Zonation maps of Ca
5.6.a - b Zonation maps of Mg
5.7.a. - b Zonation maps of Na
5.8.a - b Zonation maps of K
5.9.a - b Zonation maps of HCO3 +CO3
5.10.a - b Zonation maps of Cl
5.11.a - b Zonation maps of SO4
5.12.a - b Zonation maps of *E.coli*
5.13.a - b Zonation map of Na percentage
5.14.a Wilcox diagram of the coastal alluvium -pre-monsoon
5.14.b Wilcox diagram of the coastal alluvium -post-monsoon
5.15.a Wilcox diagram of the crystalline terrain -pre-monsoon
5.15.b Wilcox diagram of the crystalline terrain -post-monsoon
5.16 RSC of groundwater in the coastal plain and crystalline terrain
5.17.a USSL diagram of the crystalline terrain -pre-monsoon
5.17.b USSL diagram of the crystalline terrain -post-monsoon
5.17.c USSL diagram of the coastal belt -pre-monsoon
5.17.d USSL diagram of the coastal belt -post-monsoon
5.18 Collins diagram of representative samples of the study area
5.19 Schoeller diagram of the study area
5.20.a Piper diagram of the coastal belt
5.20.b Piper diagram of the crystalline terrain
5.21.a - d Durov diagram of the study area
5.22 Plotting chemical data over raster

**Chapter 6**
6.1 FCC of the study area
6.2. ETM of the study area
6.3 Classified image of the study area
6.4 Three-dimensional visualization of water levels in the study area
6.5.a - j Change in zonation for individual elements
6.6 Change in drinking water suitability zone -pH
6.7 Change in drinking water suitability zone -TDS
6.8 Change in drinking water suitability zone -*E.coli*
6.9 Change in drinking water suitability zone -Cl
6.10 Change in drinking water suitability zone -Mg
6.11 Change in drinking water suitability zone -Na
6.12 Change in drinking water suitability zone -So4
6.13 Change in drinking water suitability zone -Ca
6.14 Chemical overlay - alluvium
6.15 Chemical overlay - laterite

6.16 Saline water buffer zones
6.17 Aquifer resistivity - laterite
6.18 Aquifer resistivity - alluvium
6.19 Aquifer thickness - laterite
6.20 Aquifer thickness - alluvium
6.21 Groundwater potential zones - alluvium
6.22 Groundwater potential zones - laterite
6.23.a - l Overlay of individual elements on groundwater potential zones
6.24 Potable groundwater zones - laterite
6.25 Potable groundwater zones - alluvium

## LIST OF TABLES


**Chapter 1**

1.1 Stratigraphic succession of Kerala
1.2 Average monthly rainfall - Kerala
1.3 Details of catchment area and utilizable yield of rivers of Kerala

**Chapter 2**

2.1 Methods followed for the determination of various physical and chemical parameters of groundwater
2.2 Electrical methods employed for common hydrogeological problems
2.3 Scores assigned for different groundwater controlling parameters in GIS

**Chapter 3**

3.1 General characteristics of the Tertiary formations
3.2 Minimum, maximum, and average water levels for 10 years in the study area
3.3 Change in water availability - Kerala

**Chapter 4**

4.1 Representative resistivity values for earth materials (Mooney 1980)
4.2 Hydrogeological significance of bulk resistivity values
4.3 Ranges of resistivity values of common rocks
4.4 Analyzed vertical electrical sounding curves of the study area - hard rock
4.5 Analyzed vertical electrical sounding curves of the study area - alluvium

**Chapter 5**

5.1.a Average chemical composition (mg/L) of major rock types and groundwater
5.1.b Various sources of ions in water (Hem 1959)
5.2.a Chemical and *E. coli* analysis of groundwater (pre-monsoon)
5.2.b Chemical and *E. coli* analysis of groundwater (post-monsoon)
5.3 Ranges/upper limits of various constituents (mg/L) in drinking water
5.4 Classification of groundwater based on TDS
5.5 Potability of water in terms of TDS
5.6 Classification of groundwater for irrigation
5.7 Guide to the use of saline waters for livestock and poultry
5.8.a Categorisation of groundwater for industrial purpose - coastal belt
5.8.b Categorisation of groundwater for industrial purpose - crystalline

Chapter 1

# General Introduction

## 1.1. Introduction

Groundwater is one of the most important natural resources necessary for humanity. It is vital for the existence of mankind but faces acute shortage. Groundwater is that invisible supply of water that seeps beneath the surface of the ground, collects in natural underground reservoirs known as aquifers, and is the source of water in springs and wells. It provides almost a third of all freshwater on earth. It is threatened, however, by pollution, water mismanagement and exploding populations just as the world's remaining sources of freshwater are endangered. The increasing danger to *"Groundwater: the Invisible Resource"* was the main theme of World Water Day – 1998 and the discussions centred on groundwater management. For World Water Day 2006, the theme is Water and Culture with an emphasis on educating students and communities about the many water-related development efforts. The idea is to increase global awareness of the vital role water plays in sustainable national development. In 2005, Asia was home to 71 % of the total number of people in the world without access to improved sanitation with 58 % of these without access to safe water. Marking World Water Day on 22$^{nd}$ March the Executive Secretary of the UN Economic and Social Commission for Asia and the Pacific (ESCAP) noted that this region has the lowest per-capita fresh water availability in the world.

Groundwater resources are dynamic in nature as they grow with the expansion of irrigation activities, industrialization, urbanization etc. As it is the largest available source of fresh water, it has become crucial not only for targeting of groundwater potential zones, but also monitoring and conserving this important resource. The expenditure and labour incurred in developing surface water is much more compared to groundwater, hence more emphasis is placed on the utilization of groundwater, which can be developed within a short time. Besides targeting groundwater potential zones it is also important to identify suitable sites for artificial recharge usage cycle. When the recharge rate cannot meet the demand for water, the balance is disturbed and hence calls for artificial recharge on a country wise basis (Sameena *et al.,* 2000).

With the world's population explosion, increasing pollution and wide-scale mismanagement of freshwater supplies, a critical water shortage may occur within the next 50 years and hence counter-measures are essential. The world has seen a six-fold increase in water usage since 1900. By 2025, the amount of water for use by each individual may be only half of what it is today, and today it is only half what it was in 1960. The hydrological facts are these: Only a mere 2.5 percent of all water on earth is freshwater. Some 97.5 per cent is salt water. Glaciers, polar ice caps and permanent snow cover account for 69.9 per cent of the freshwater. Lakes and rivers provide only a tiny 0.3 per cent. Soil moisture, swamp water and permafrost furnish 0.9 per cent. The remaining 29.9 per cent, nearly a third of the total freshwater, comes from natural underground sources. This groundwater flows, albeit very slowly, as part of a hydrological cycle which involves the waters in lakes, streams and the rain. It is, however, more difficult and expensive to extract than surface water. In some desert areas, groundwater has been the only source of water for millennia. In many regions, this groundwater is the principal and only water, which feeds the plants which in turn feed animals and humankind. It is thus essential to life. It is usually more stable and reliable than any other source of water, but it is increasingly coming under threat because of greater demand. In some parts of the world, where lakes and rivers are drying out, it is the only reasonable alternative to dwindling supplies on the surface. At least one-fifth of all people in the world do not have access to safe drinking water and more than one half of humanity lacks adequate sanitation. At the same time, groundwater reservoirs are being drained faster than nature can replenish them, or are being severely contaminated by human, industrial and agricultural wastes. Excessive withdrawal of groundwater, pollution, or mismanagement can deprive future generations from using this valuable commodity. It can cause drying out of wells and land subsidence. Deep groundwater is relatively free from pollutants in many places and is excellent for drinking, domestic use and industrial purposes. But once an aquifer is contaminated, remedial measures can be long and costly, even impossible. It threatens humankind. Furthermore, because groundwater is invisible, the dangers to it are often disregarded or mishandled. In some countries it has been handled in the same manner as a mineral resource. In spite of the link between surface water and groundwater, many water laws have been changed only recently.

Another danger is that of saltwater intrusion: the displacement of freshwater in coastal aquifers by seawater. The problem is acute in some coastal regions and for small islands. India, with its long coastline is no exception to this problem.

All of these dangers need to be anticipated and dealt with. Improved monitoring of the water at industrial and waste disposal sites and in areas where fertilizers, pesticides and herbicides are used is an urgent requirement and can stave off potential disaster.

It has been estimated that out of the total precipitation of around 400 million hectare meters in India, the surface water availability is about 178 million hectare metres. Out of this about 50 % can be put to beneficial use because of topographical and other constraints. In addition there is a ground water potential of about 42 million-hectare metres. The availability of water is highly uneven in both space and time. Precipitation is confined to only about three of four months in the year and varies from 10 cm in the western parts of Rajasthan to over 1000 cm at Cherrapunji in Meghalaya. Water is also a part of larger ecological system. Floods and drought affected vast areas of the country, transcending state boundaries. A third of the country is drought prone. Floods affect an average area of around 9 million hectares per year. According to the National Commission on floods, the area susceptible to floods is around 40 million hectares. The approach to the management of drought and floods has to be coordinated and guided at the national level. Even the planning and implementation of individual irrigation or multi purpose projects, though done at the state level, involve a number of aspects and issues such as environmental protection, rehabilitation of project- affected people and livestock, public health consequences of water impoundment, dam safety, etc. On these matters, common approaches and weaknesses have affected a large number of projects all over the country. There have been substantial time and cost overruns on projects. In some irrigation commands, problems of water logging and soil salinity have emerged, leading to the degradation of good agricultural land. There are complex problems of equity and social justice in regard to water distribution. The development and exploitation of the country's groundwater resources give rise to questions of judicious and scientific resource management and conservation.

Another important aspect is water quality. Improvements in existing strategies and the innovation of new techniques resting on a strong science and technology base will be needed to eliminate the pollution of surface and ground water resources, to improve water quality and to step up the recycling and re-use of water.

Water is one of the most crucial elements in developmental planning. Water is a precious national resource and has to be conserved.

Taking into consideration these facts and after detailed deliberations Government of India the National Water Policy 2002 .The salient points are as follows.

- Water is precious national resource and its planning, development and management to be governed by national perspectives.
- Accord first priority to drinking water in allocation of water.
- Priority for drought- prone areas in planning of project development.
- Develop information system related to water data at the national and state levels and create a network of data banks.

- Plan water resources on the basis of the hydrological units such as a river basin or sub basin.
- Transfer of water from one river basin to another, especially to areas of water shortage.
- Plan water resources' projects preferably on multi-purpose projects adopting multi- disciplinary approach.
- Prepare plans having regard to human and ecological aspects including those of the disadvantaged sections in society.
- Exploitation of groundwater to be regulated with reference to recharge possibilities and avoid detrimental environmental consequences due to over exploitation.
- Management of water resources for diverse use to include users, stakeholders and governmental agencies.
- Monitor surface and groundwater for quality and effluent treatment before releasing.
- Evolve a master plan for flood- prone areas for flood control and management of each flood-prone basin.
- Educate users and stakeholders in conservation and preservation of water resources.

### 1.2. Scenario in Kerala

Kerala has a unique hydrogeological and climatic condition. The surface and groundwater resources of the state play a crucial role in the development of various activities like irrigation, industrial and domestic uses. The state experiences wide variation in the rainfall pattern (average

3107 mm) from eastern hilly areas to the western coastal regions and a major part of the rainfall goes as surface run off particularly during monsoon season. The steady base flow from the groundwater emerges as surface run off during the non-monsoon periods.

The problems faced by the coastal zone of Kerala are unique among all other states of India mainly due to its high density of population and peculiar geological setting. The hydrogeological environment along this 560 km long coast with its backwater, lagoons, estuaries and barrier islands is complex in nature. The groundwater development along the coast has been increased many fold during the last four decades to meet the increase in requirements as a result of population growth, industrial development and change in lifestyle.

Realistic estimation of surface/ groundwater and other related information for each watershed is needed to mitigate water scarcity, water pollution and ecological problems in the state.

The present study deals with the different hydrogeological characteristics of the coastal region of central Kerala and a comparative analysis with corresponding hard rock terrain. The coastal regions lie in areas where the aquifer systems discharge groundwater ultimately into the sea. Groundwater development in such regions will require a precise understanding of the complex mechanism of the saline and fresh water relationship, so that the withdrawals are so regulated as to avoid situations leading to upcoming of the saline groundwater bodies as also to prevent migration of sea water ingress further inland. Coastal tracts of Kerala are formed by several drainage systems. Thick pile of semi-consolidated and consolidated sediments from Tertiary to Recent age underlies it. These sediments comprise phreatic and confined aquifer systems. The corresponding hard rock terrain is encountered with laterites and underlined by the Precambrian metamorphic rocks. Supply of water from hard rock terrain is rather limited. This may be due to the small pore size, low degree of interconnectivity and low extent of weathering of the country rocks. The groundwater storage is mostly controlled by the thickness and hydrological properties of the weathered zone and the aquifer geometry. The over exploitation of groundwater, beyond the 'safe yield' limit, cause undesirable effects like continuous reduction in groundwater levels, reduction in river flows, reduction in wetland surface, degradation of groundwater quality and many other environmental problems like drought, famine etc.

For sustainable development of this important resource mere prospecting alone is not enough. Effective strategies for managing the available resources also have to be chalked out. Scientific management of groundwater resources requires studies relating to hydrogeology, hydrometeorology, hydro geochemistry, geophysics and remote sensing. All management policies for water resources, before the onset of remote sensing techniques, have been crippled by the limitations of conventional methods used in resources survey and monitoring. The effective management of groundwater resource can be done only when there is an adequate knowledge about its spatial and temporal distribution. Thus remote sensing techniques give a new dimension to the effective management by satisfying the primary need and helps in real time analysis of such scarce and valuable resources. This can be substantiated by studies like resources evaluation with the aid of remote sensing. Time bound conventional data and real time remotely sensed data are compared and correlated to produce the most exciting results for conservation, optimum utilization and management of the resources. In this study both conventional survey (hydrogeological characteristics, geophysical and hydro geochemistry) and remote sensing techniques have been employed to decipher the characteristics of groundwater in the study area.

### 1.3. Scope of the Study

The study is necessary because of the various threats facing the coastal groundwater resources in the area. Although a number of water resources development schemes have been taken up in the past for various purposes like irrigation, hydropower generation water supply etc most of these projects evolved in an isolated manner without giving due consideration for the development of basins as a whole. The isolated developments of projects that affect the different physical subsystems are degradation and aggradations of downstream channels, changes in soil and water quality, and salinity in the estuarine portions etc. The use of fertilizers in the low-lying area is also a threat to the shallow groundwater aquifers.

The city of Kochi falls in the study area (fig.1.1) and there are more than 20 major industries on the eastern outskirts and most of these industries depend on the river Periyar for their water requirements. Even

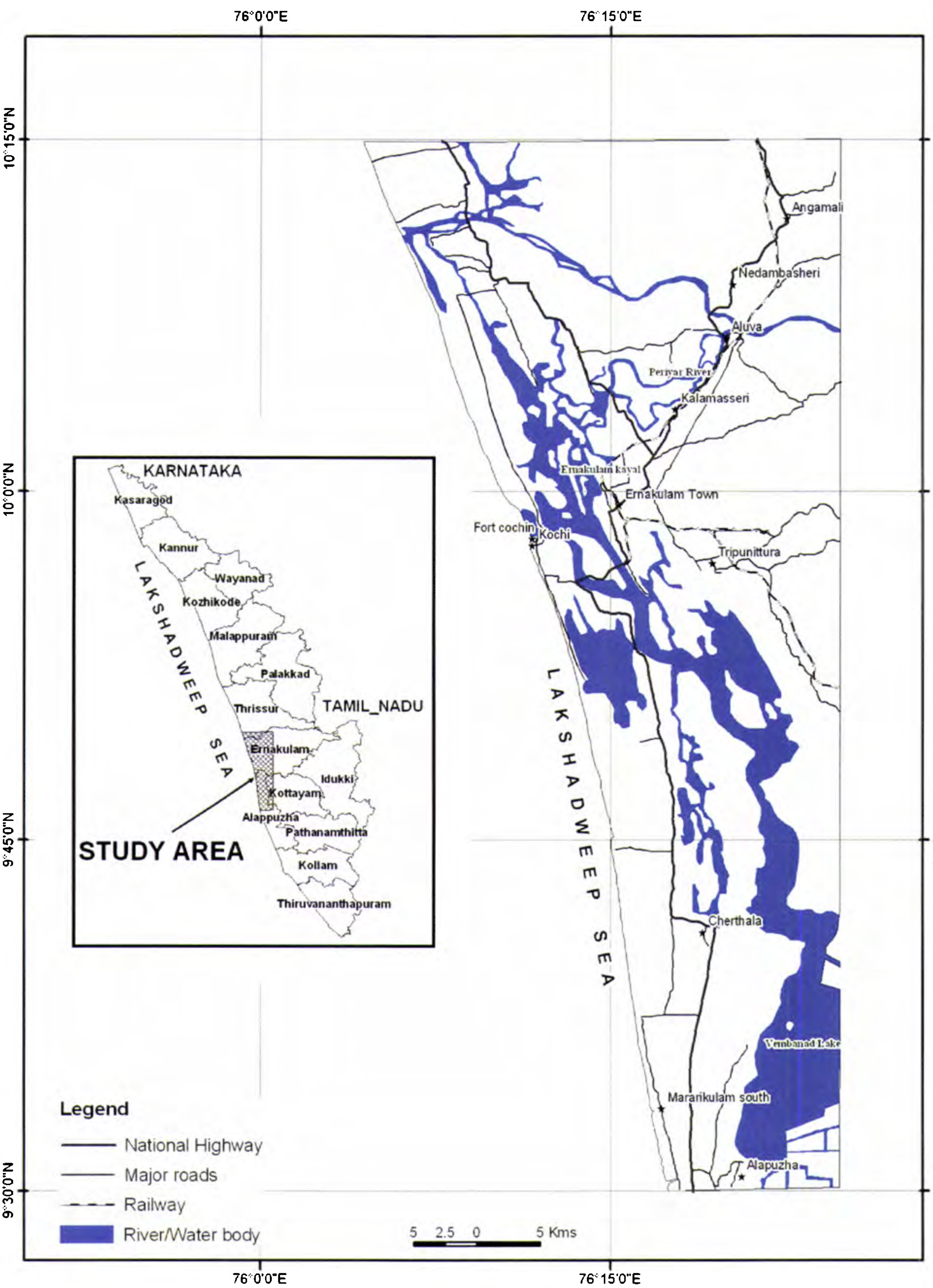



fig.1.1 LOCATION MAP ERNAKULAM - ALAPPUZHA STRETCH

then, there are a number of bore wells in the industrial areas. Effluents from these industries affect water quality and scope for further study in this field is vast. Another major problem of the area is the saline water intrusion through the river Periyar, especially when the daily flow rate through the river is less.

Groundwater is the main source of drinking water supply except in Kochi city and some major towns, and there is vast potential to develop groundwater in these areas for domestic and irrigation purposes. Proper development and management techniques are absolutely essential in the use of groundwater for agricultural purposes. The study area also offers a platform for a comparative analysis of the characteristics of the coastal area with the corresponding crystallines. The present study area has been selected as it provides immense scope to contribute to the existing knowledge and practices elsewhere in the coast.

The potential of Geographic Information Systems, (GIS) although in use for some time, has not been fully exploited and this tool in conjunction with conventional techniques like geophysical prospecting offers tremendous scope for further contributing to the existing knowledge on groundwater.

### 1.4. Objectives

Based on the problems of the study area the following objectives were drawn:

- To determine the long-term effect of rainfall on groundwater levels using hydrographs and to calculate the recharge using water balance studies.

- To carry out GIS analysis on the groundwater levels of the study area so as to decipher the seasonal fluctuation as also flow accumulation, flow direction and other statistical analyses.
- To delineate the areal extent and thickness of shallow aquifers in the coastal region and deep seated aquifers in the crystalline terrain using geophysical methods (Vertical Electrical Soundings) VES.
- To carry out the groundwater quality studies and to evaluate its suitability for various uses.To carry out GIS zonation studies for accurate and user-friendly groundwater quality management.To apply GIS methods for delineating the fresh water zones based on geochemical studies (water quality mapping).To delineate potential groundwater zones in the laterite terrain and coastal alluvium by integrating VES data (aquifer thickness & resistivity) and geology of the area using GIS.
- To decipher potable zones by applying GIS methods.
- To bring out a comparative account of the hydrogeological, geophysical and geochemical characteristics of the coastal and hard rock regions of the study area using conventional methods and spatial analysis of various data by applying GIS methods.

### 1.5. The Study Area

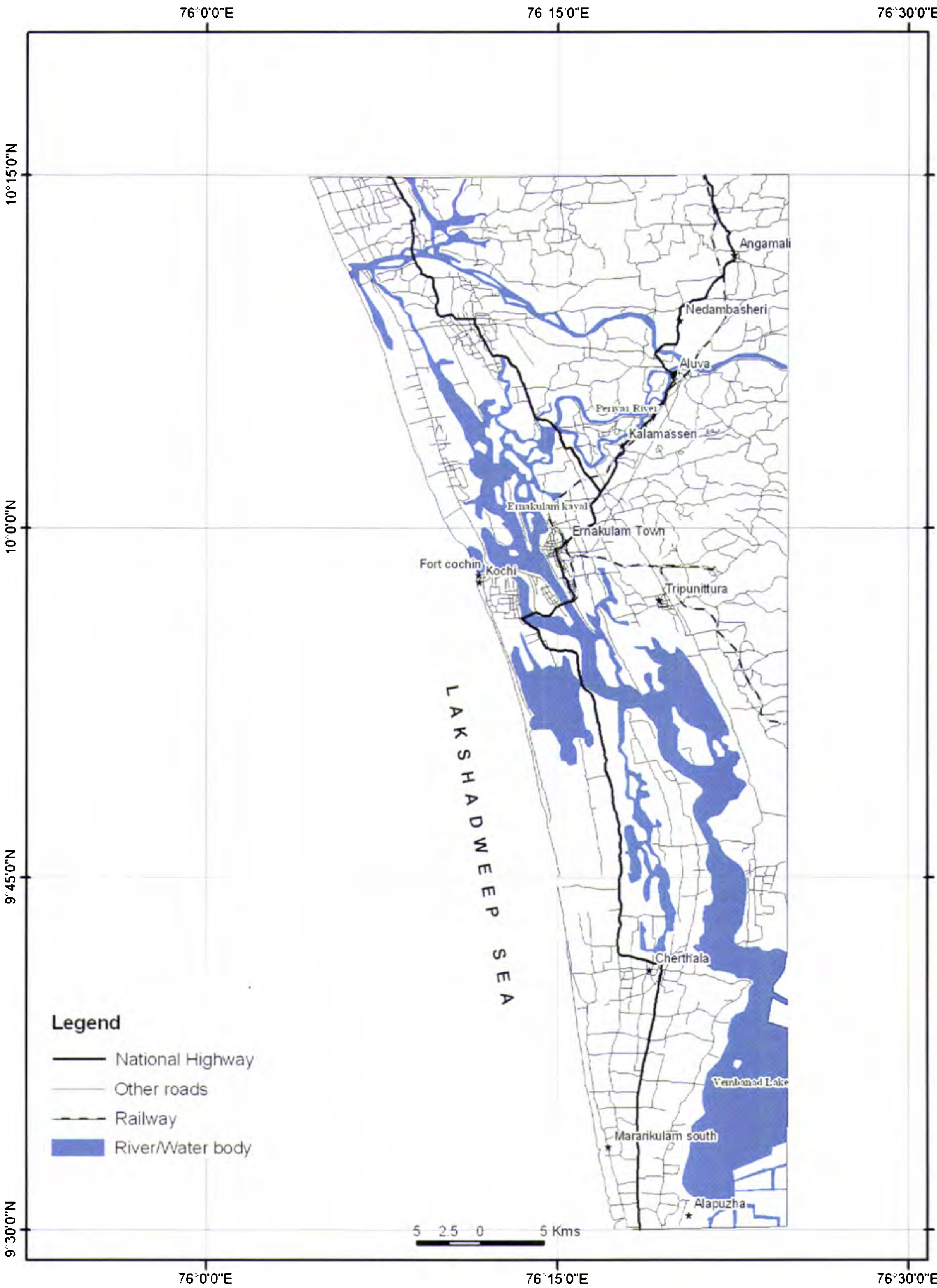
The study area lies in the Ernakulam, Alleppey and Trichur districts of Kerala (India). (North latitudes 9°5' and 10° 2 and East longitudes 76° and 76° 4'). Map showing the roads and rails is presented in fig.1.2.

### 1.5.1. Geomorphology of Kerala

Kerala state comprromises a narrow strip of land in the southwestern tip of India, extending between north latitudes 8°17'30" and 12°27'40" and east longitudes 74°51'57" and 77°24'47" with an area of 38,863 $km^2$ bordered by Karnataka and Tamilnadu. The majestic Western Ghats with the magnificient array of sky scraping pinnocks on the east and the Arabian Sea on its western side gives Kerala distinctive physical and cultural features. The shape of Kerala resembles a scalene triangle with its base on the long coast (560 km) and its apex on the Western Ghats. The width of the state ranges from a minimum of 11 km to a maximum of 124 km (Soman, 1997).

Kerala is singularly diversified in her physical features as it is in configuration. In the light of this diversity of physical feature, the state can be divided in to five physiographic zones (Soman, 1997). These are the mountain peaks above 1800 m, the high lands at latitudes of 60-1800 m, the midlands at latitudes of 300-600 m, the low lands at 10-300 m and coastal plains and lagoons below 10 m. The different physiographic zones are briefly discussed as below.

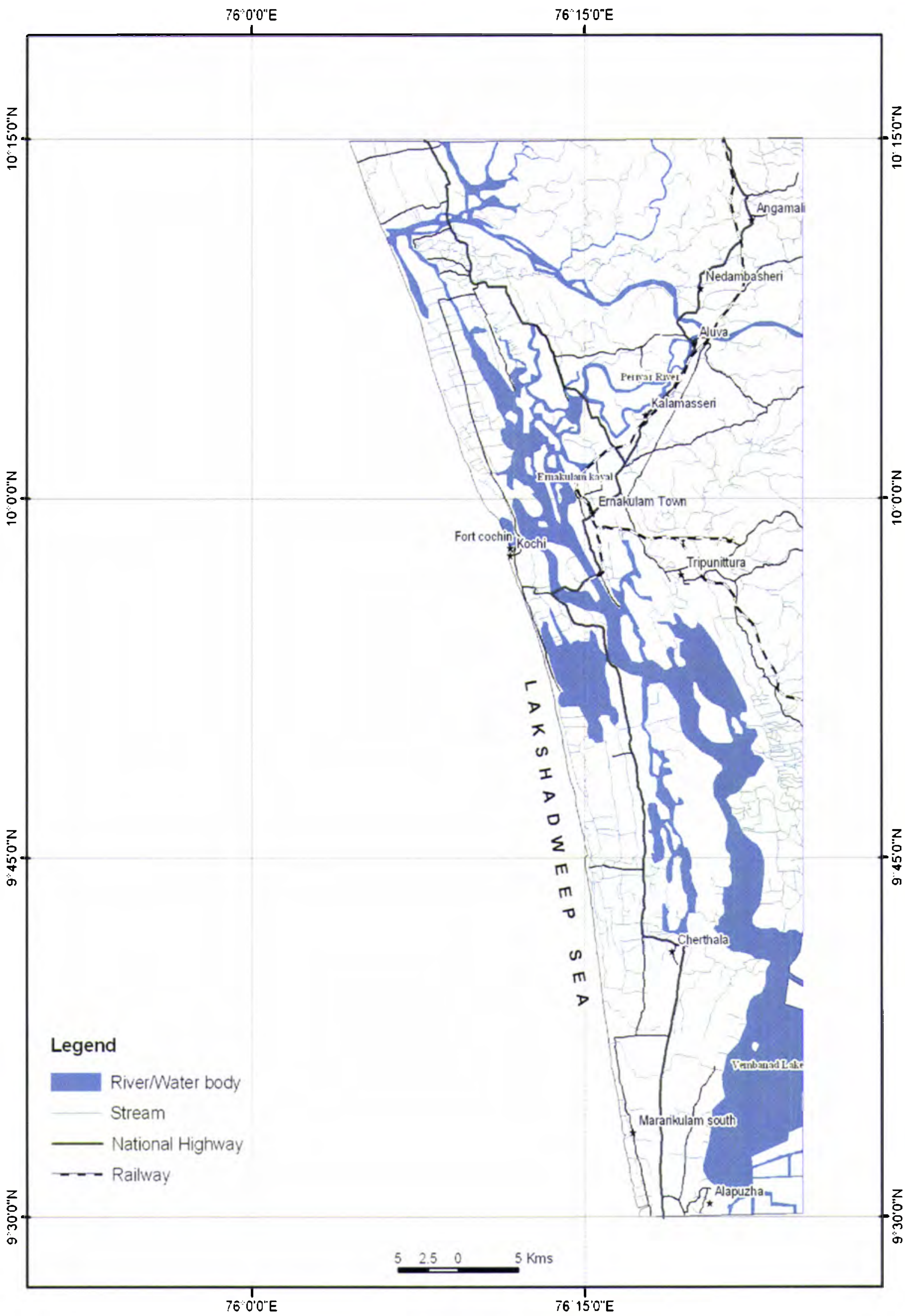
**a. Mountain peaks:** The mountain peaks above 1800 m within the Western Ghats are limited in number and constitute only 0.64% of the total area of the state. The Western Ghats, sough of the Palghat Gap, swell into a wide hill massif in the region south of the Anamalai, with arcuate projections into Tamilnadu, giving place to Munnar plateau, at 1500-2000 m altitude. It is the highest elevated surface in the Kerala region, and has




ROADS AND RAILWAYS ERNAKULAM - ALAPPUZHA STRETCH remnant laterite cappings. The highest peak in the Western Ghats, the Anamudi hill with a height of 2817 m is one among the fourteen peaks of over 2000 m situated in Kerala.

**b. Highlands:** The highlands occupying 20.35% of the area of the state form an important physiographic province. They rise at several places to an elevation of more than 900 m above mean sea level (Thiagarajan, 1980). The hill ranges run more or less continuously keeping a general fall in the elevation from north to south. The hill ranges in Cannanore and Trivandrum districts are at short distance from the shoreline having a distance less than 40 km; but in Palghat district there is a break with sinistral shift of 50 km. The Palghat gap and the Achenkovil gap give access to the hinterland in Karnataka and Tamilnadu. The presence of deeply entrenched relatively youthful streams with waterfalls and hanging valleys in the highlands of Western Ghats are considered to be evidences of the down faulting of the west coast and transgression of the sea in post-Miocene times.

**c. Midlands:** The undulating western fringe of the highlands and the lateritised rocky spurs projecting westward and parts of the crustal breaks (passes) forms the midland region. It covers nearly 8.44% of the total area of the state. While the midlands constitute most of the eastern parts of Cannanore (Kannur) district, their area shrinks towards the west of Wayanad plateau where they occupy a narrow strip, coinciding with the steep slopes. The midlands, which have an elevation of 300-600 m above mean sea level, is a surface of erosion (peneplain), having numerous




DRAINAGE ERNAKULAM - ALAPPUZHA STRETCH

streams and rivers, flood plains and rock cut terraces, cut and fill terrace, and colluvium. The peneplain is 70 to 100 km wide and shows a gradient of 6-10$^0$ from north to south. It will be of interest to note that the direction of the present day rivers is at right angles to this.

**d. Lowlands:** The area falling under the altitudinal range of 10-300m, and consisting of dissected peneplains constitute the lowlands. The altitudinal range is quite asymmetric with the maximum area of 54.17% falling within this unit. Numerous flood plains, terraces, valley fills, colluvium and sedimentary formations are part of the lowlands. In the southern most parts of the state, this unit merges with the coastal plains with discernible steeper slopes than in the rest of the state. The higher altitudinal portions of the unit are seen more in the eastern parts of the southern and northern districts. It stretches from near Kasargod in the north to Puvar in the South having a width of less than 1 km wide at extremes to 25 km in the region of Alleppey to Kottayam. The beach is discontinuous and is of three kinds viz., bar, crescent, and pocket. They show the presence of swales and beach ridges. Swales are nearly marshy and pave ways for small streams. To east of this beach, lie a chain of more or less continuous lagoons (Backwater or Kayals) followed by the deltaic plains of the several rivers form the Western Ghats.

**e. Coastal plains and lagoons:** The vast low-lying area fringing the coast, is not only an important physiographic unit of the state, but also important in terms of economic activity and demographic distribution. It constitutes 16.40% of the area of the state. Most of the area shows relief of

4 to 6m above mean sea level. Both the innermost and the present shorelines are of Atlantic types. The innermost shoreline is irregular and crenulate with several rias. The present shoreline is 580 km long and is straight for over a greater part of the length, from Kozhikode to Quilon; but in Cannanore, Thiruvananthapuram and Quilon districts, dentations, cliffs and creeks are present. It has a maximum width in the Alleppey (Alappuzha) and Aluva - Kaladi regions. A characteristic feature of this unit is the existence of numerous beach dune ridges, parallel and sub-parallel to the coast, especially in the Alleppey-Shertallai regions. Their orientation indicates that the strandlines belong to at least two ages, and the maximum width between the oldest and the youngest, close to the present shoreline is 18 km. Further, the different geomorphic units like sandbars, creeks, lagoons, estuaries, raised beaches and cliff sections could mostly be due to earth movements along and across the coast in the geologic past and, the erosional and depositional activities that have taken place in the quaternary to recent times.

### 1.5.2. Lineament pattern

The term lineament refers to natural lines, bands and anomalous zones, brought out well in the aerial photographs and Landsat imageries. These lineaments are generally, more than ten kilometres long, associated with different features like fault, fracture and shear zone, drainage, vegetation and topographic alignments, etc. It is also reasonable to expect that longer a lineament, deeper it would penetrate into the earth. (Varadarajan and Balakrishnan, 1980).

Lineament analysis on land sat-1 imageries of the Kerala coastal tract carried out by Varadarajan and Balakrishnan (1980) identified three sets of major lineaments/geofractures trending in NNW-SSE, NW-SE to WNW-ESE and NE-SW directions. These lineaments are structurally weak zones, subject to many tectonic events in the past. Evidences of dykes, veins and other intrusions of different ages seen emplaced along different lineaments indicating continued tectonic activity even after the formation of the earlier. Brief descriptions of the set of lineaments seen in Kerala are as below.

**a. NW-SE to WNW-ESE lineaments**

Many established fractures and shear zones mapped in the Archean territory of Kerala belong to the NW-SE to WNW-ESE set of lineaments. The most important ones in the WNW-ESE category are (1) Achankoil-Tamraparni shear zone, identified as major shear belt of Proterozoic age (Drury *et al.,* 1984). (2) Bavali lineament (3) Muvattupuzha-Thekadi and Palghat Gap fracture zones. Evidences of later reactivation of these shears resulting in granite/pegmatite emplacement and uplift are known during the early Palaeozoic times, as in the case of Palghat Gap fracture and Achankovil-Tenmala shears. Occurrence of late Cretaceous granitic phase at depth (as encountered in the off-shore borewell to the NW of Achenkovil shear zone) and evidence of post Eocene uplift of carbonate strata in that well may speak of continuous tectonic activity along the lineament (Soman, 1997). Recent activities along these shears are also indicated by earth tremors.

**b. NNW-SSE to N-S lineaments**

These are series of prominent, generally intermediate lineaments (around 50 km in length) identified in the Land sat imagery and seen mainly at the contact zone between the steeply rising Western Ghats and the step like coastal terraces. These are more prominent in the southern and northern extremity of the Western Ghats. It is recognized that the NNW-SSE trending lineaments define a weak zone along that, the west coast evolved by faulting, and the Western Ghats uplifted. Indirect evidences like the displacement of laterites and youthful geomorphological features indicate that these movements have extended throughout Teritiary as well as into the Quaternary period. Recent tremors along the NNW-SSE Idamalayar lineament would indicate that this is active even today.

**c. NE-SW to ENE-WSW lineaments**

Lineaments belonging to this category are seen both within the Western Ghats and in the coastal belt, and are coupled with the contemporary NNW-SSE lineaments. In the Western Ghats, the headward erosion of the West-flowing Rivers is guided by the ENE-WSW fractures and it has been proposed that the southern most parts of the Western Ghats have been uplifted along these faults. Since the ENE-WSW lineaments truncate other lineaments, this set is considered to be the youngest set (Nair, 1990).

### 1.5.3. Drainage

The state is drained by 44 rivers, of which 3 are east flowing. The streams originating from the Western Ghats are short and swift flowing, showing various stages of gradation. Cascades and waterfalls mark these streams in the upper reaches, although in the plains they show evidences of maturity of development. Some of these rivers have steep gradients (1/250 or more) in their initial reaches. Absence of delta formation is a characteristic of the Kerala rivers. Rejuvenation of the catchment area closely linked with the west coast faulting and later adjustments may, in all probability, be the reason for the youthful character of the rivers, while high-energy shoreline appears to have prevented delta formation in the river mouths.

The general drainage pattern of these rivers is dendritic, although in places, trellis, sub-parallel and radial patterns are also noticeable fig.1.3. Most river courses are straight, indicating structural control. General course of the rivers coincides with the prominent lineament directions (NW-SE and NE-SW). Many of the rivers do not have a continuous flood plain. Analysis of longitudinal profiles of different rivers indicates a high level knick-point at 500-300m, which broadly corresponds to the boundary of the highlands and midlands. Similarly another major knick-point is evident in the elevation range of 90 to 150m.

### 1.5.4. Lakes and Backwaters

One of the striking features of the state is a continuous chain of lagoons or backwaters existing along the coastal regions. These lagoons are locally known as Kayals. Natural or man-made canals facilitating internal navigation almost for the entire length of the Kerala coast mostly interconnect these. The lagoons or backwaters are connected to the sea through small opening calls Azhis or Pozhis based on the fact that the opening is permanent or temporary. A Kayal can be generally described as a body of brackish, marine or hypersaline water impounded by a sandy barrier and having an inlet connecting it with the open sea. The Kayals of Kerala coast are mostly separated from the sea by elongated sand bars and based on this they can be treated as "coastal lagoons." Since perennial rivers debouch into the sea through these water bodies, making the system compound, these can be considered as lagoonal-estuarine systems or partially mixed estuarine systems (Biggs, 1978). During monsoon, the Kayals overflow in to the sea, discharging sizeable quantities of sediments, whereas in summer, seawater flows into the Kayal over considerable distances.

Based on the geometry, geologic and geomorphic settings, the Kayals of the state can be grouped into (i) Those contained in the beach ridge and adjoining coastal plains and (ii) those occurring within the rocks of the Warkalli formation with eastern extensions. The most prominent estuaries of Kerala are Vembanad Lake and Astamudi kayal of which the earlier is situated within the study area and the later is situated south of the study area. The Vembanad Lake extends from Cochin to Alleppey for a distance of 83 km and is the largest estuary in Kerala. Its width varies from a few hundred meters to 15 km. It is elongated and oriented in NW-SE direction. Five major rivers, viz. Muvattupuzha, Meenachil, Manimala, Achankovil and Pamba discharge into the lake. The area of the Vembanad Lake in 1912 was 315 $km^2$ and by 1983, it shrank by 43.15% to 179.25 $km^2$ (Nair *et al.,* 1987). Based on the borehole data, thickness of the sediments in the lake found to vary from 34 to 63m and the sediments include mixtures of sand and clay, and occasional lignite patches. The Western part of the lake is marked by a number of beach ridges, which run parallel to the coast and lake margins.

### 1.5.5. Geology of Kerala

Geologically, Kerala forms the southwestern fringe of the South Indian Peninsular shield. It consists of two major terrains namely (1) The Cratonic part lying north of Palghat – Cauvery shear zone and (2) the mobile belt- the Pandian mobile belt formed of gneiss, charnockite and khondalite (Ramakrishnan, 1988). The Kerala state, bounded by the Western Ghats on the east and Arabian Sea on the west, is a passive margin of Indian sub-continental plate. Lineament analysis (Varadarajan and Balakrishnan, 1980) shows three sets of major lineaments/ geofractures trending NNW – SSE, NW – SE to WNW –ESE and NE – SW of which careful analysis of the available subsurface stratigraphic information along with the indication of faults as brought out by the lineament map, indicates that that the NW – SE to WNW – ESE trending fractures have acted as basin forming faults, which controls the sedimentation, NNW – SSE trending fault zone, which is associated with the uplift of the Western Ghats, is significant mainly as the source of detrital supply.

The lineament geometry of Kerala and adjoining areas are not only indicative of such tectonism, but also indicate the bearing on the lithologic distribution and other depositional features. The NW–SE trending Achenkovil shear zone, passing through the vicinity of Alleppey divides the Varkala – Cochin sector of the Kerala basin into two distinct blocks with different lithofacies. It is a clear indication of such tectonic controls (Varadarajan and Nair, 1978).

The Kerala region forms a significant portion of the southern high-grade metamorphic terrian and contains Pre-Cambrian crystalline rocks of granulite facies. The most importance rock types in Kerala are as follows:

I. Pre-Cambrian crystallines

II. Tertiary sediments and

III. Recent to sub-Recent sediments.

#### 1.5.5.1 Pre-Cambrian Crystallines

In Kerala, the oldest and the most widely spread are the Pre-Cambrian crystalline rocks and these compromises of eight groups as given below:

1. The Khondalite group
2. The Charnockite group
3. The Sargur group
4. The Dharwar group
5. The Basic and Ultra Basic rocks
6. Granites and related rocks
7 Pegmatites and quartz veins
8. Dykes

### a. The Khondalite group

A large part of South Kerala is occupied by a group of metasediments referred in earlier literature as khondalite group. In recent years, they are being referred to as Kerala Khondalite belt (KKB). Khondalite rock group are the oldest rock outcropping in Kerala region. The group included rocks like garnet – sillimanite – biotite – graphite schist, garnet – biotite graphite gneiss, calc-granulites, quartzites and patchy charnockites. Since the typical minerals do not contain water and other volatiles, they are considered as dry metamorphic rocks. In this group, sillimanite occurs as hair like needles or as broken crystals. Graphite forms an integral part of this rock type.

In Thiruvananthapuram district, the khondalites are intruded by a sworn of pegmatites and the region is highly sheared. Lenticular bands of garnet, sillimanite gneiss along with garnet – biotite gneiss and cordierite gneiss is observed in parts of Kottayam district. Lenticular bands of crystalline – limestones and calc-granulites occur interbanded with the rocks in Palghat, Quilon, Kottayam and Thiruvananthapuram districts.

### b. The Charnockite group

The charnockite group is the dominant one among the rock types in Kerala. Holland (1900) defined charnockite as hypersthene granite composed of hypersthene, microcline, quartz and accessory amounts of iron ores. It has its type area at Pallavaram, near Madras in Tamil Nadu. The charnockite bodies are discontinuous and are of variable sizes. The characteristic features of this sequence are the invariable presence of hypersthene and granulitic texture. Charnockites are well exposed in central and northern parts of Kerala. These rocks also constitute the high ranges of Western Ghats and extent to the Nilgiri massif and south Mysore. The charnockite have undergone intense folding and migmatisation. The charnockites in many places are intruded by granite dolerites and pegmatites. The charnockite groups in Kerala consist of:

(a) Lenses of hypersthene – diopside – hornblende – magnetite – biotite rocks (pyroxenites, ultra basis charnockites).

(b) Lenses, bands and schleiren of hypersthene – diopside – hornblende –granulite (basic charnockites).

(c) Hypersthene –diopside – hornblende – biotite gneiss and migmatities (intermediate charnockites).

(d) Lenticular sheets, bands and layers of hypersthene bearing quartzo – feldspathic alaskite granites (intermediate charnockites).

**c. The Sargur group**

In Kerala, the high-grade schist of Sargur and the low-grade schist of Dharwar are seen extended into Wynad from its corresponding groups in southern Karnataka. The Sargur shows high-grade metamorphism, migmatisation and more complex tectonic activity than the Dharwar.

**d. The Dharwar group**

The younger Dharwar schist overlying the Sargurs consist of Oligomictic conglomerates, current bedded quartzites quartz – mica schist and biotite – quartzites forming an interlayered sequence. The type region of Dharwar system is Mysore. The Dharwar system contains the oldest rocks so far known in South India. Formerly, all the Dharwarian types were regarded as of igneous origin. The conglomerates were derived as auto clastic from felsites and porphyrites. The hematite quartzites are altered and some other Dharwar rocks were seen as silicified amphibole rocks. This view has changed in recent years and considerable part of the Dharwarians is now recognized as of sedimentary origin.

### e. The Basic and Ultra Basic rocks

Basic and ultra basic rocks are reported to be seen at various places in Kerala. The dominant among these are pyroxenites and gabbro ultrabasic rocks of dunite composition, which has been reported to be seen in Punalur along a minor, shear zone parallel to Achenkovil shear. The basic intrusives include minor patches of anorthosite, differentiated diorites and magnesite. Mineralisation is observed along fracture planes. Different periods of basic and ultrabasic igneous activity including anorthosite and dunite are reported from Pre-Cambrian age.

### f. Granites and related rocks

Several late Proterozoic intrusions of acid and alkaline composition have invaded the Pre-Cambrian crystallines and schists. They include pink and grey granites (Ambalavayal, Angadimogoru, Chengannur, Kalpetta, Munnar etc.), Syenites (Sholayar, Peralimala, etc) and granophyres (Ezhimala). These intrusions are considered to be fault/lineament controlled and emplaced between 500-700 m.y. ago (Santhosh and Drury, 1988).

### g. Pegmatites and Quartz veins

Numerous pegmatites and quartz veins also traverse the Pre-Cambrian rocks. Few of the pegmatites are known for hosting economically importance chrysoberyl in them. K-Ar dates suggest a general age of 460 m.y. for the pegmatites (Soman, *et al.*, 1982).

### h. Dykes

Post Archaean basic magmatism is widespread in Kerala. The dykes are oriented parallel to the major lineament trending NNW-SSE, NE-SW and WNW-ESE. Generally, the dykes are doleritic in composition. Few isolated occurrences of dykes of gabbroic composition are noted near Kottayam and in north Kerala region. The age data and the tectonic interpretation suggest that the basic dyke swarms are the rift response of the late Cretaceous detachment of India from rest of the Gondwana land (Sinha Roy and Mathai, 1980).

### 1.5.5.2. Tertiary sediments

The earliest records of the tertiary beds in the coastal plains of Kerala appears in the notes of General Cullen to Carter (Carter, 1857). In that, he described two distinct formations comprising of marine carbonate and continental clastic facies, which belongs to the tertiary sequence. These have been termed as Quilon and Warkalli beds, respectively by King (1882) and Foote (1883). The lithostratigraphic classification proposed by Paulose and Narayanaswamy (1968) seems to be the further extended work of the initial classification proposed by King in 1882. They suggested a new lithostratigraphic classification of these sediments, in which the

Tertiary sediments comprised of Quilon and Warkalli beds and the Quaternery formation comprised of Recent to sub-recent sediments above the Tertiaries.

However, as explained earlier, the studies of the lithology of these sediments by the workers of the Central Groundwater Board supported by exploratory bore hole data indicate that the upper Tertiary sediments in Kerala consist of three distinct formations instead of two (Raghava Rao, 1975). The Warkallis with a thickness of nearly 80m are underlain by rocks of the Quilon formation, having a maximum thickness of 70m. These are underlain by a thick sequence of sediments called Vaikom beds.

The exploratory drilling by the Central Groundwater Board and Kerala Water Authority contributed a great deal in studying the subsurface geology of the area. The analysis of lithological and electrical logs of the exploratory borehole drilling by them revealed the presence of four distinct beds (Anon, 1992). The four beds from top to bottom are Warkalai, Quilon, Vaikom and Alleppey. Among these the Quilon beds form a marker horizon for distinguishing the various litho-units.

A narrow belt of Tertiary sediments is noted mostly between coastal and mid-land region extending from Cape Comorin in the south to Manjeshwar in the north, resting directly on Pre-Cambrian crystalline rocks. The coastal sedimentary basin of the Kerala region apparently forms the eastern edge of an apparently bigger basin extending westward over the continental shelf and is discussed in relation to the geological history of the west coast continental shelf including the better known Bombay offshore region (Desikachar, 1980). The geological history indicates that since Palaeocene upto the present, the sedimentation history is characterized by a number of transgression and regression. These results in major lateral shifts in the sedimentary facies over the continental shelf are giving rise to ideal conditions for the formation of startigraphic traps.

The Tertiary sediments are succeeded by beach, estuarine, lagoonal and alluvial deposits of Pleistocene to Recent age. The continental Warkalli beds represent the youngest formation and underlying these beds, are the marine Quilon beds, without registering any marked unconformity. The Tertiary strata of Kerala reveal two major basins of deposition viz. (i) a southern basin between Trivandrum and Ponnani in south and central Kerala and (ii) a northern basin, between Cannanore and Kasargod in north Kerala. They include mainly (1) the Quilon beds consisting chiefly of fossiliferous limestones, intercalated with thick beds of variegated sands, carbonaceous clays, calcareous and sandy clays and sands and (2) the overlying Warkalli beds of variegated sands, white plastic clays, Carbonaceous clays and associated seams of lignite.

As the stratigraphic classification proposed by many earlier workers have not fulfilled the code of stratigraphic nomenclature, it is prudent to adhere to the widely understood nomenclature proposed by King and Foote (Soman, 1997). They are briefly described as below.

**a. Quilon beds**

The Quilon beds consist of fossiliferous limestones, sandstone and clays. The type area of these sediments is Padappakkara. It was originally believed to be confined to the base of the cliff section of the type locality but later investigations carried out by Kumar and Pitchamuthu (1953), Damodaran (1955), Jacob and Sasthry (1952), Paulose and Narayanaswamy (1968) have revealed the extensive nature of Quilon beds. The Quilon limestone beds were said to have been deposited in a large lagoonal bay of the sea in this region. The foraminifera from a borehole sample near Chavara indicated a lower Miocene (Burdigalian age), (Jacob and Sasthry, 1952). Dey (1962) from his study of molluscan fauna assigned a Vindobanian age to Quilon beds. Foraminiferal and ostracod faunal studies, Rao and Datta (1976) also assigned a Burdigalian age to the Quilon deposits. Thus the known faunal assemblage indicate a Burdigalian to Vinodbanian age (Lower –Middle Miocene) for the Quilon beds.

**b. Warkalli beds**

According to King (1882) the Quilon bed, conformably overlain and overlapped by the Warkalli deposits, constitute an older group. From a lithological similarity, he treated the Warkallis as equivalent to Cuddalore sandstones of Tamil Nadu and considered the same to middle Miocene age. The type section is the location at Varkala, edging the seashore. The formation is nearly horizontal and this has been traced out in almost, the entire coastal stretch from the Cape Comorin in south to Kottayam and Ernakulam in north, bordering the backward tract on the east, but observed beneath the recent deposits of sand and silt (Prabhakar Rao, 1968) Subramaniam (1964) indicated an areal extent of over 2000 sq. km for this formation.

The Warkalli section consists of sandstones, variegated clays and lignite bands. This is considered to be a littoral facies. These sediments partially overlap the Quilon limestone. The topmost Warkalli sediments, barring the lignite band, are devoid of floral and faunal remains. MioPliocene age has been tentatively assigned for these sediments (Paulose and Narayanaswamy, 1968).

Contrary to the opinion that Warkalli sediments are barren of fossils, instead milky-white grains resembling fossil tests have been reported (Raha *et al.,* 1983; Rajendran, 1987).

### 1.5.5.3. Recent to Sub-Recent sediments

#### a. Quartenary formation

Beach sands, sticky black clays, beds of carbonised wood and alluvium are met mostly in the low-lying areas of Quilon, Kayamkulam, Kottayam, Ernakulam and Ponnani, and also between Cannanore and Nileswar. These are from the Tertiary rocks by a polymict pebble bed, extending throughout Kerala.

The accumulation of estuarine sediments and the accretion of the coastal sand bars accompanied by tectonism led to the formation of lagoons such as the Vembanad Lake in the Quartenary to Holocene time (Sinha Roy, 1981). These Quartenary –Holocene sequences are designated as the Vembanad formation.

**b. Laterite**

Laterite, a sub-aerial product of deep chemical weathering, occurs as capping on the Pre-Cambrian crystalline rocks and Tertiary sediments throughout Kerala. Laterite occurs mainly in two geomorphic levels viz.

(i) 6-140 m (N. Kerala)

(ii) 200-250 m (S. Kerala)

Sinha Roy (1979) has demarcated laterites in two geomorphic levels at 30-70 and 90-110 m in parts of Trivandrum district. However, high-level laterites are observed above 2000 m in Munnar area. Both residual and detrital laterites are represented. The latter is reconsolidated debris of old residual laterite. The unconsolidated alluvial formations occupy most of the area on the coastal plains in the western parts of the study area. It is of recent origin. It includes the sediments of backwaters and fine to medium green quartzite sand, silty sands of the plains and grey to dark grey beach sands. The porosity of sand in this region is 0.4 – 0.5. They are excessively drained with very high hydraulic conductivity of 65 m/day. The laterite formations occur all along the midland region and adjacent to the alluvium in the coastal plains. Laterite is formed due to the weathering of either crystalline or sedimentary rocks. These are porous, reddish brown to buff coloured. The porosity of laterite formations ranges from 0.27 – 0.3 and the hydraulic conductivity is 30 m/day. Quilon beds are present below the laterite formations. It is composed of calcareous clay and lateritic clay. It is having very less porosity ranging from 0.15 – 0.2 with the hydraulic conductivity of 10 – 15 m/day. The geological map of the study area is shown in fig.1.4 and the subsurface geology of the coastal belt is given in fig1.5. The stratigraphic succession of Kerala as given by CGWB is presented in table. 1.1.

### 1.5.6. Climate and water resources

Orography of the Western Ghats produce heavy rainfall of more than 300cm. in the State, 270cm of which falls during June December. Northern parts of the State receive most of the rainfall from the southwest monsoon whereas the northeast monsoon is pronounced only in the southernmost parts. pre-monsoon thunderstorms produce fairly good amount of rainfall, solving the summer water crisis to a good extend. Intensity of rainfall ranges from around 2cm/rainy day in the southern districts to around 3cm/rainy day in the north. The heavy rainfall gives birth to 44 rivers, 41 of which flow west to join the Arabian Sea. In spite of this, Kerala faces serious water shortages on certain occasions as a result of irregularities in temporal and spatial distribution of rainfall, slope of the terrain and improper water resources management. The average monthly rainfall (district wise) in the state is presented in table.1.2, which shows the marked north-south variation in rainfall. Amount, intensity and seasonality increases northward. Northeast (winter) monsoon is more active in the southern districts and southwest (summer) monsoon in the northern districts. An exception to this is the Palakkad, where the Gap in Western Ghats has a key role in controlling the climate. Table.1.3 gives the details of catchment area and utilisable yield of the rivers of Kerala.

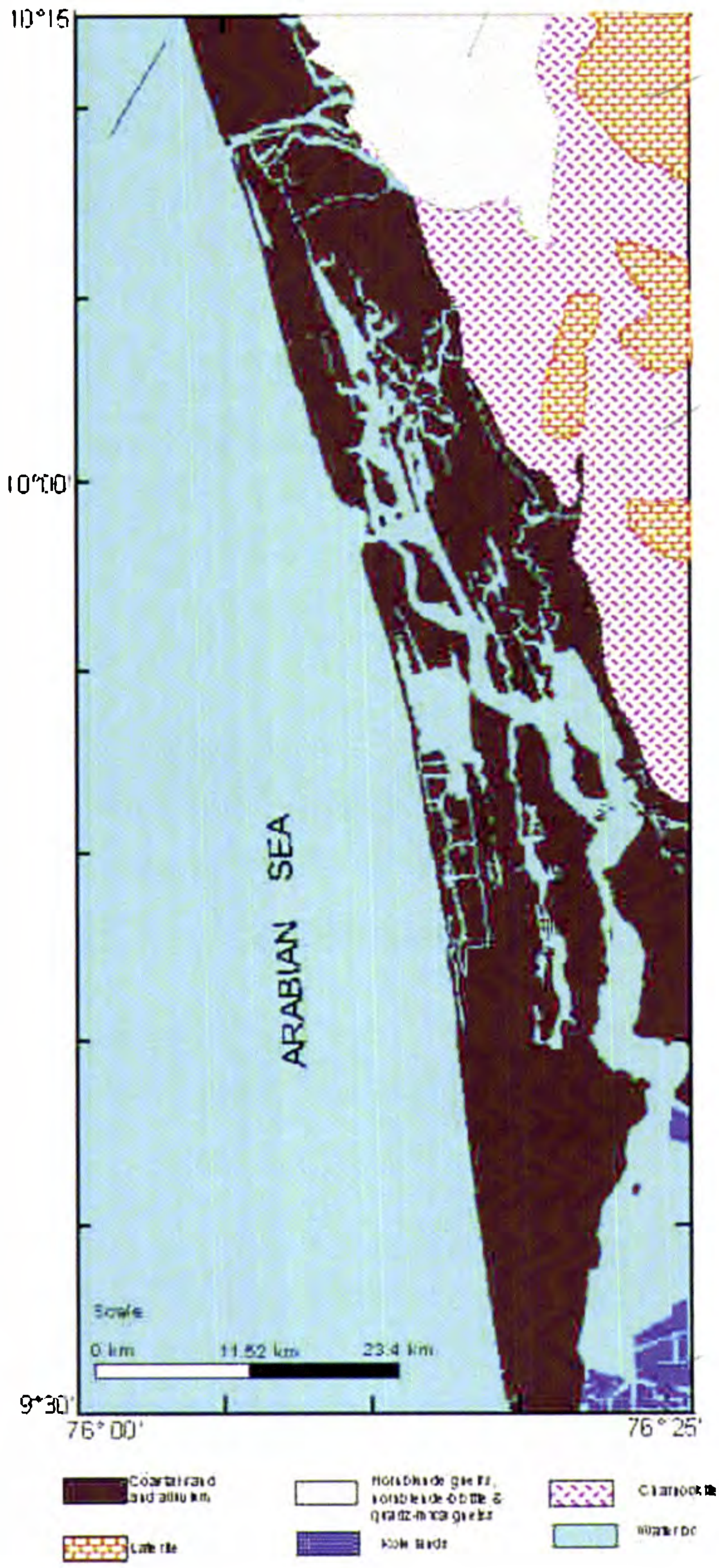



fig.1.4 **Geology map of the study area**

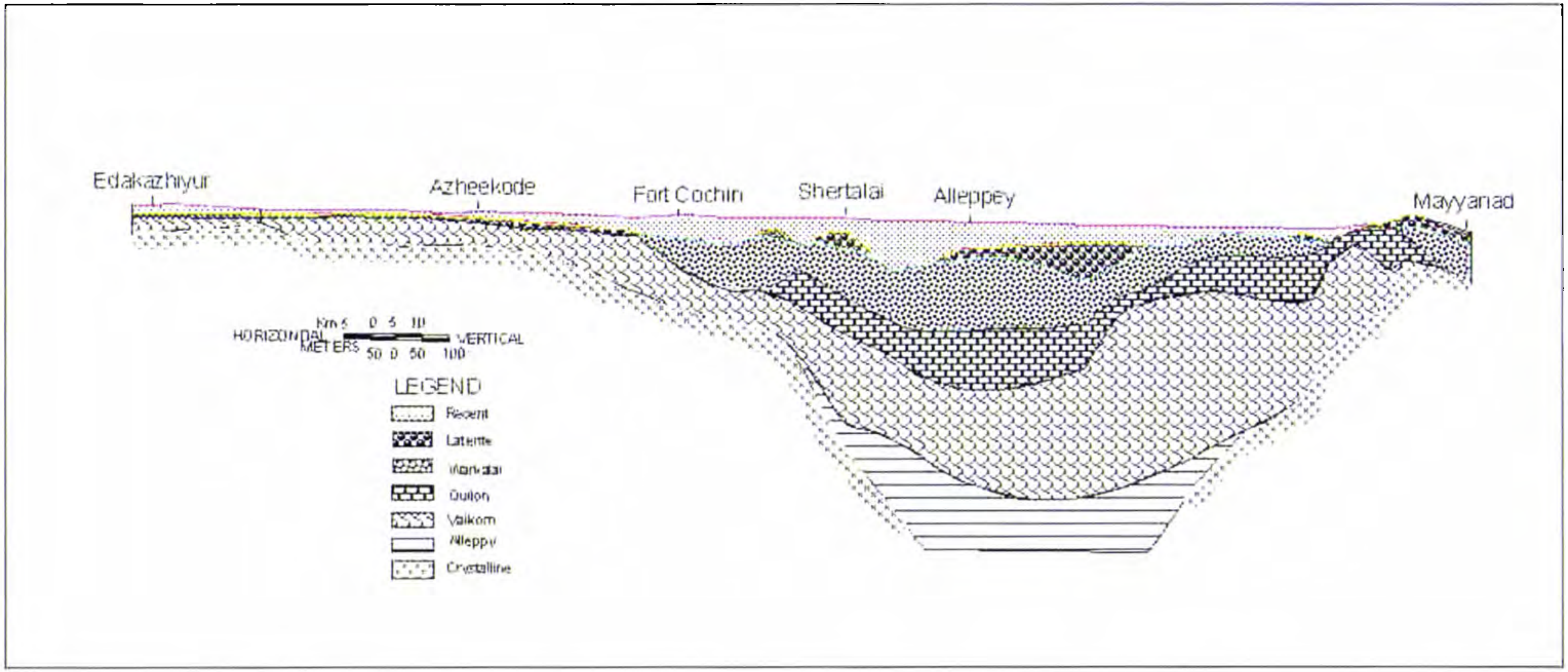



fig 1.5 **Sub-surface Geology of the coastal belt from Edakazhiyur to Mayyanad (Rahahava Rao, 1976)**

**Table.1.1. Stratigraphic succession of Kerala (CGWB)**

| Age | Formation | Lithology |
|---|---|---|
| Recent | Alluvium | Sand, Clay, riverine alluvium etc. |
| Sub-Recent | Laterite | Derived from crystallines and sedimentaries |
| Tertiary | Warkalli<br>Quilon<br>Vaikom<br>Alleppey | Sand stone, clays with lignite Lime stone, marl and clay<br>Sandstone with pebbles, clay and lignite<br>Carbonaceous clay and fine sand |
| Undated | Intrusives | Dolerite, Gabbro, Granites, Quartzo feldspathic Veins |
| Archaean | Wayanad group<br>Charnockites<br>Khondalites | Granitic gneiss, Schists etc.<br>Charnockites and associated rocks<br>Khondalite suite of rocks and its associates |

#### 1.5.6.1Climate and water resources of the selected region

The study region experiences typical coastal climate with moderate temperatures (Fig.1.6a & 1.6b). There is no considerable difference between the maximum and minimum temperatures or in the monthly averages. Summer temperatures are reduced by the monsoons and winter temperatures are modified by the proximity to the Sea. As explained earlier, the region comes under the influence of monsoons, especially the southwest monsoon and receive fairly good amount of rainfall.

Figures from 1.7a to fig. 1.7c shows the monthly rainfall pattern for the selected three stations in the study area. Two rainfall peaks for the summer and winter monsoons are clearly identifiable. There are wide interannual variations in rainfall associated with global anomalies.

### 1.5.7. Groundwater occurrence in the study area

Ground water occurs under phreatic, semi-confined and confined conditions in the above formations. The weathered crystallines, laterites and the alluvial formations form the major phreatic aquifers, whereas the deep fractures in the crystallines and the granular zones in the Tertiary sedimentary formations form the potential confined to semi-confined aquifers (CGWB).

**a. The Crystalline aquifers**: The shallow aquifers of the crystalline rocks are made up of the highly decomposed weathered zone or partly weathered and fractured rock. Thick weathered zone is seen along the midland area either beneath the laterites or exposed. In the hill ranges,

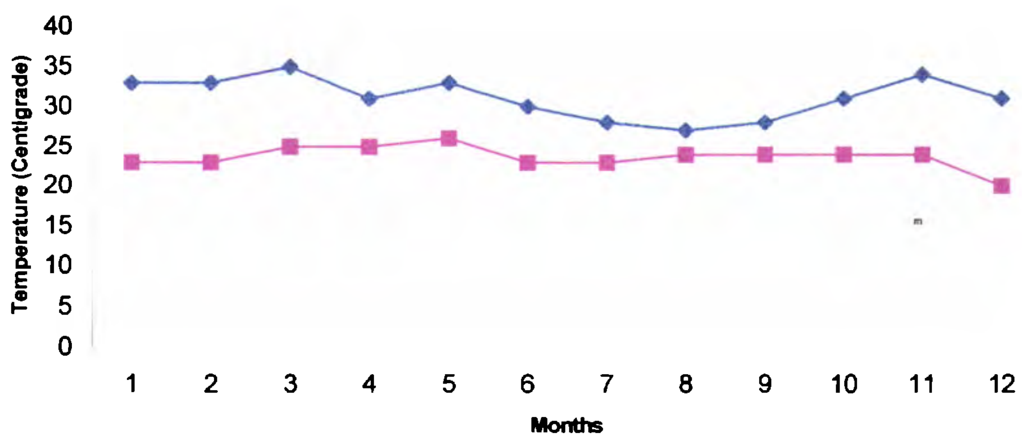



Fig.1.6a Average Monthly Temperature (maximum & minimum) - Alappuzha

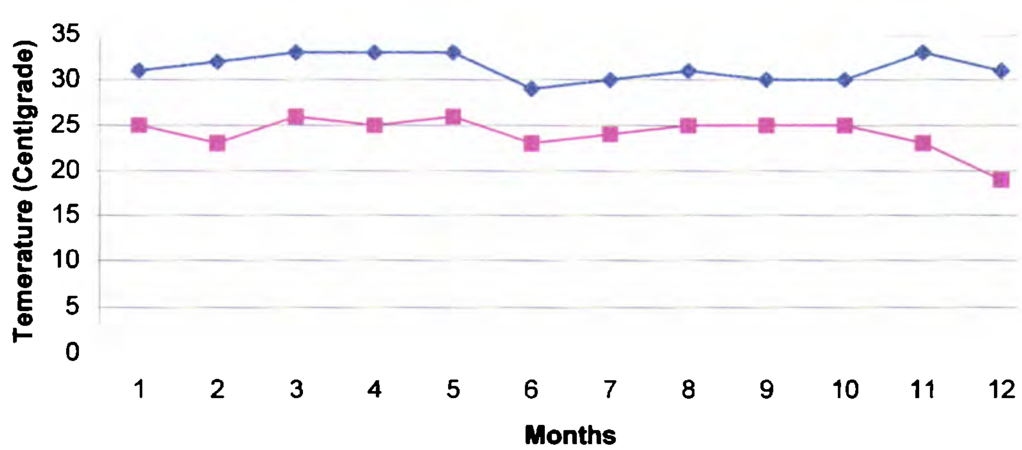



Fig1.6b. Average Monthly Temperature (maximum & minimum) - Kochi

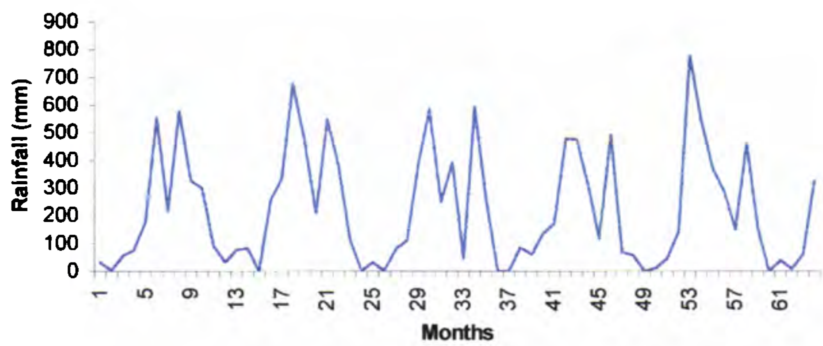



fig1.7a. Monthly rainfall - Alappuzha (2000 January - April 2005)

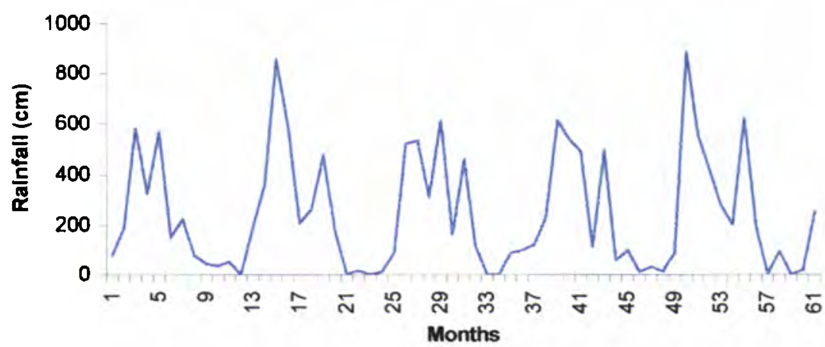



Fig1.7b. Monthly rainfall - Kochi (2000 January - 2005 April)

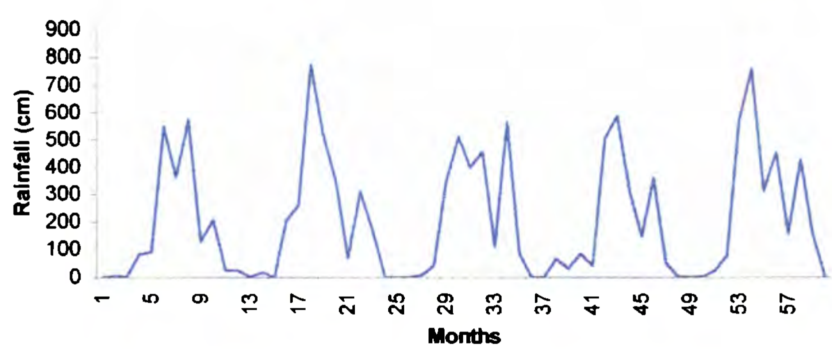



Fig1.7c. Monthly rainfall - Thrissur (January 2000 - December 2004)

**Table 1.2. Average Monthly Rainfall (mm) – Kerala (District – Wise)**

| District\month | Jan | Feb | Mar | Apl | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trivandrum | 2.9 | 10.1 | 17.8 | 63.1 | 124.6 | 265.4 | 221.4 | 122.6 | 401.2 | 227.6 | 308.2 | 115.2 | 1880.1 |
| Kollam | 1.3 | 4.6 | 75.6 | 155.4 | 229.9 | 365.1 | 431.2 | 269.1 | 311.4 | 432.2 | 265.1 | 110.4 | 2651.3 |
| Pathanamthitta | 0.0 | 13.4 | 87.8 | 80.3 | 246.2 | 310.5 | 654.4 | 401.3 | 419.8 | 456.0 | 376.8 | 106.3 | 3152.8 |
| Alappuzha | 2.1 | 2.7 | 67.2 | 94.7 | 156.7 | 465.7 | 702.9 | 425.7 | 477.4 | 362.9 | 256.4 | 161.8 | 3176.2 |
| Kottayam | 1.0 | 0.0 | 40.1 | 113.8 | 206.3 | 466.4 | 706.9 | 462.2 | 359.7 | 369.1 | 297 1 | 128.0 | 3150.6 |
| Idukki | 3.9 | 0.0 | 59.3 | 146.1 | 175.9 | 406.4 | 1111.8 | 713.9 | 345.6 | 357.4 | 438.5 | 147.9 | 3906.7 |
| Ernakulam | 5.8 | 1.0 | 48.0 | 86.3 | 130.1 | 550.6 | 942.6 | 471.8 | 415.4 | 329.0 | 377.2 | 141.7 | 3499.5 |
| Thrissur | 0.0 | 0.0 | 0.7 | 6.9 | 85.1 | 700.7 | 946.1 | 545.4 | 315.3 | 213.9 | 217.9 | 74.3 | 3106.3 |
| Palakkad | 0.0 | 14.1 | 36.8 | 30.8 | 125.1 | 337.3 | 813.9 | 380.2 | 149.3 | 215.9 | 283.1 | 26.7 | 2413.8 |
| Malappuram | 3.5 | 0.0 | 19.6 | 29.0 | 111.8 | 561.0 | 1173.9 | 575.7 | 246.0 | 317.4 | 363.1 | 52.4 | 3453.4 |
| Kozhikode | 1.6 | 0.0 | 9.5 | 1.0 | 67 1 | 1084.0 | 1495.7 | 728.7 | 158.4 | 207.4 | 238.4 | 62.7 | 4054.5 |
| Wayanad | 7.0 | 7.3 | 46.3 | 58.7 | 156.1 | 504.3 | 873.3 | 572.3 | 174.5 | 267.6 | 198.3 | 49.1 | 2914.8 |
| Kannur | 0.1 | 0.0 | 8.0 | 9.9 | 54.6 | 923.0 | 1571.5 | 803.7 | 157.2 | 134.7 | 259.6 | 68.9 | 3982.2 |
| Kasaragod | 0.0 | 0.0 | 6.1 | 4.3 | 16.5 | 929.8 | 1545.1 | 815.4 | 128.4 | 92.6 | 127.9 | 57.5 | 3723.6 |

**Source IMD**

**Table. 1.3. Details of catchment area and utilizable yield of rivers of Kerala**

| River | Length (Km) | Catchment Area (Sq km) | Annual yield/ Utilizable yield (MCM) |
|---|---|---|---|
| 1.Manjeswar | 16 | 90 | |
| 2.Uppala | 50 | 76 | 309/106 |
| 3.Shiriya | 67 | 290 | 620/358 |
| 4.Moryal | 34 | 132 | |
| 5.Chandragiri | 105 | 570 | 1718/1218 |
| 6.Chittari | 25 | 145 | |
| 7.Nileshwar | 46 | 190 | |
| 8.Karingode | 64 | 429} | 1356/937 |
| 9.Kavvayi | 31 | 143 | |
| 10.Peruvamba | 51 | 300 | 1143/603 |
| 11.Ramapuram | 19 | 52 | - |
| 12.Kuppam | 82 | 469 | 1236/786 |
| 13.Valapattanam | 110 | 1321 | 1784/1823 |
| 14.Anjarakkandy | 48 | 412 | 986/503 |
| 15.Tellicherry | 28 | 132 | 251/122 |
| 16.Mahe | 54 | 394 | 803/445 |
| 17.Kuttyadi | 74 | 583 | 1626/1015 |
| 18.Korappuzha | 40 | 624 | |
| 19.Kallayi | 22 | 96 | |
| 20.Chaliyar | 169 | 1535 | 7135/2616 |
| 21.Kadalundi | 130 | 1122 | |
| 22.Tirur | 48 | 117 | 1165/60 |

..Continued

| | | | |
|---|---|---|---|
| 23.Bharathapuzha | 209 | 4400 | 6540/3349 |
| 24.Keecheri& | 51 | 401 | |
| 25.Puzhakkal | 29 | 234 | 1024/345 |
| 26.Karuvannur | 48 | 1054 | 1887/963 |
| 27.Chalakudy | 130 | 1404 | 2591/1539 |
| 28.Periyar | 244 | 5284 | 11139/8004 |
| 29.Muvattupuzha | 121 | 1554 | 3814/1812 |
| 30.Meenachil | 78 | 1272 | 2349/1110 |
| 31.Manimala | 90 | 847 | 829/1108 |
| 32.Pamba | 176 | 2235 | 4641/3164 |
| 33.Achenkovil | 128 | 1484 | 2287/1249 |
| 34.Pallikkal& | 42 | 220 | |
| 35.Kallada | 121 | 1699 | 2270/1368 |
| 36.Ithikkara | 56 | 642 | 761/429 |
| 37.Ayroor& | 17 | 66 | |
| 38.Vamanapuram& | 88 | 687 | 1324/889 |
| 39.Mamon | 27 | 114 | |
| 40.Karamana | 68 | 702 | 836/462 |
| 41.Neyyar | 56 | 497 | 433/229 |
| 42.Kabani | | 1920 | 4333/4333 |
| 43.Bhavani | | 562 | 1019/1019 |
| 44.Pambar | | 384 | 708/708 |
| 42,43 and 44 are east flowing rivers | | | |

thin weathered zone is seen along topographic lows, area with lesser elevation and gentle slope. In areas along the hill ranges generally rock exposures are seen. The depth to water level in this aquifer varies from 2 to 16 mbgl and the yield of the well ranges between 2 to 10 $m^3$ per day.

The exploratory drilling carried out by Central Ground Water Board in the State in the crystalline formations has indicated that the potential fractures are encountered at depths ranging between 60 m. bgl to 175 m. bgl. with yield varying from less than 1 to as much as 35 litres per second (lps). In Charnockites, more than 40% of the wells have yielded more than 10 lps or above.

**b. The Tertiary aquifers**: Ground water occurs under phreatic condition in the shallow zone and under semi-confined to confined conditions in the deeper aquifers. The Tertiary formation of Kerala coast is divided into four distinct beds viz. Alleppey, Vaikom, Quilon and Warkalli. These formations except the Alleppey beds are seen as outcrops and are lateritised wherever they are exposed. The maximum thickness of Tertiary sediments is found between Karunagapally and Kattoor and all the four beds are encountered in this area.

Ground water is commonly developed through dug wells tapping the sandy zones at shallow depth in the Tertiary sediments. The depth to water level in this shallow zone ranges from 3.0 to 27 m. bgl and the yield of the well ranges from 500 lpd to 10 $m^3$ per day.

The Vaikom and Warkali beds form the most potential aquifers in the Tertiary group. The Alleppey beds have been encountered at deeper levels in the bore holes drilled in the coastal tract of Alleppey district and the formation water is found to be saline and hence, no tube well has been constructed by tapping this formation.

In the Vaikom aquifers, the piezometric level is between 2 m and 20 m above msl. The yield of the tube wells constructed in this formations ranges from 1 to 57 lps. This bed forms 'auto flow' zones along the coast between Karunagapally in Quilon district and Nattika in Trichur district. Recent exploration by CGWB has proved good quality ground water zone in this formation in and around Cochin area.

Warkali aquifers are the most developed aquifer system among the Tertiary group. The urban and rural water supply in the coastal area between Quilon and Shertallai is mostly dependent on this. The piezometric head is about 3 m. above msl along the eastern part of the sedimentary basin whereas it is 10 m. below msl in and around Alleppey. The yield of the wells tapping this formation ranges from 3lps to 14 lps.

The hydrogeological information on the Quilon beds is very limited. The formation is considered to be a poor aquifer compared to Vaikom and Warkali beds.

**c. Laterites**: Laterites are the most widely distributed lithological unit in the State and the thickness of this formation varies from a few meters to about 30m. The depth to water level in the formation ranges from less than a meter to 25 mbgl. Laterite forms potential aquifers along valleys and can sustain medium duty irrigation wells with the yields in the range of 0.5 - 6 $m^3$ per day. The occurrence and movement of ground water in the laterites are mainly controlled by the topography. Laterite is a highly porous rock formation, which can form potential aquifers along topographic lows. However, due to this same porous nature, groundwater is drained from elevated places and slopes at shortest duration after monsoon due to which scarcity is experienced in the elevated places and slopes. This is the most extensive hydrogeologic unit in the State. The thickness varies generally from less than a meter to above 20 m. and thicker zones are seen along Malappuram and other northern districts.

**d. Alluvium**: The alluvium forms potential aquifer along the coastal plains and ground water occurs under phreatic and semi-confined conditions in this aquifer. The thickness of this formation varies from few meters to above 100 m. and the depth to water level ranges from less than a meter to 6 m. bgl. Filter point wells are feasible wherever the saturated thickness exceeds 5 m. This potential aquifer is extensively developed by dug wells and filter point wells throughout the state and the yield ranges from 5 to 35 $m^3$ per day.

## 1.6 Review of Literature

Awareness on the importance of groundwater for mankind has shown a tremendous increase and this has resulted in increased research using latest technologies in this field. In India, earlier groundwater investigations were confined mostly to the unconsolidated and semi-consolidated sedimentary tracts (Singhal, 1984). In the recent years, however, emphasis is being given equally to the groundwater resources in hard rock area also (Gopinath, 2003).

Groundwater exploration is carried out using one or a combination of methods (Karanth, 1987) namely, geological and hydrogeological methods (geology, drainage density, lineament, hydrogeomorphology etc.), surface geophysical methods (electrical, seismic, magnetic, gravity and radiometric), hydrogeological well logging (inventory of existing wells, rainfall infiltration etc.) and tracer techniques as stated by Sarma and Sharma (1987).

Water level studies form an important part in any groundwater research. A.Crimnisi and T.Tucciarelli (2003) have spelt out the points to be considered in the selection of water level measurement locations for coastal aquifer management. Studies by Philip and Singhal (1991) revealed that wells located in the erosional valleys have deeper water levels as compared to other landforms. Chen *et al.* (2002) predicted the average annual groundwater levels from climatic variables using an empirical model. Matson *et al.* (1996) has enumerated the approaches to automated water table mapping. Groundwater level forecasting in a shallow aquifer using artificial neural network approach has been carried out by Nayak *et al.* (2006) and kriging of groundwater levels has been undertaken by Kumar and Remadevi (2006).

Geophysical studies are of paramount importance in geological research. Variations in the geophysical properties of rocks have been put to effective use for a multitude of purposes by authors around the globe (eg. Zohdy *et al.*, 1974; Barker, 1980; Beeson and Jones, 1988; Bernard and Valla, 1991; Mohammed *et al.,* 2005). Of the many electrical methods available Vertical Electrical Soundings (VES) using Schlumberger configuration appear to be quite popular among geologists. Schlumberger soundings are processed by computer modelling of the sounding data as a series of horizontal layers (Zohdy, 1989 and Zohdy and Bisdorf, 1989). More detailed explanations of processing and automatic interpretation procedure can be found in Bisdorf, 1985 and Zohdy and others 1993. Geoelectrical soundings are useful in predicting aquifer properties (Kossinski and Kelly, 1981), which in turn can be used for the estimation of dynamic, and static groundwater reserves (Paliwal and Khilnani, 2001). Contouring the apparent resistivity is an important method through which one can easily identify the groundwater potential areas, movement pattern etc (Sarma and Sarma, 1982; Balakrishna *et al.,* 1978, Balasubramanian *et al.,* 1985). VES have also been used in groundwater quality studies. Frolich and Urish, 2002 applied geoelectrical methods for the assessment of groundwater quality of coastal industrial sites. Kaya, 2001, carried out investigation of groundwater contamination at an open waste disposal site in Turkey. Delineating zones affected by saline water intrusion is another major application of VES (eg. Arora and Bose, 1981; Satyamurthy *et al.,* 1985; El-Waheidi *et al.,* 1992; Melanchthon *et al.,* 1988; Choudhury *et al.,* 2001).

Hydrogeochemical studies form another important aspect in groundwater research. Hydrochemical data helps in estimating the extent of mixing, the circulation pathways and residence time of groundwater (Edmunds, 1994). The type and concentration of salts in groundwater depend on the geological environment and movement of groundwater (Raghunath, 1987). Laluraj *et al.,* 2005 studied the groundwater chemistry of the coastal zones of Cochin and highlighted the necessity of proper sanitation and waste disposal to sustain the groundwater quality. Sakthimurugan, 1995 has also described that anthropogenic activities like improper construction of wells, disposal of animal waste and sewage disposal can have deleterious effects on groundwater quality. Munir Hussain *et al.,* 2005 carried out hydro-chemical analysis of groundwater of Hajiganj in Bangladesh with a view to discuss some of the elements relevant to human health. The study emphasized the need for evolving hydro-geo-chemical databases for nationwide safe drinking water supply. Manivel and Aravindan, 1997 studied the hydrogeochemistry of Sempattu are, Tiruchirappalli and concluded that disposals from the tanneries are the main cause for the change in physical, chemical and biological characteristics of groundwater in the area. Gopinath, 2003 studied the chemistry of groundwater in the lateritic formations of the Muvattupuzha river basin, Kerala and found that the groundwater, except in zones having high content of total iron and low pH is fit for domestic use. The study further reveals that the sodium adsorption ratio (SAR), residual sodium concentration (RSC) and sodium percentage indicated that the groundwater in general is good for irrigation purposes. N. Rajmohan, and L. Elango, 2006 carried out an investigation to understand the role of water level fluctuation on major-ion chemistry of groundwater in the Palar and

Cheyyar river basins, southern India. The study revealed that the major-ion chemistry of groundwater in this region is greatly influenced by mineral dissolution, anthropogenic activities and water level fluctuations in different geological formations. Various methods of depicting water quality data have been given by Zaporec (1972), Freeze and Cherry (1979), Mathess (1982) and Lloyd and Heathcote (1985). Kelley (1940), Eaton (1950) and Wilcox (1955) have proposed indices to find out the alkali hazards and Residual Sodium carbonate which in turn can be used to find out the suitability of groundwater for irrigation.

One of the greatest advantages of using remote sensing data for hydrological monitoring and modelling is its capability to generate information in spatial and temporal domain, which is important for water management as observed by Sanjay *et al.* (2004). Aerial photographs have been used to map aquifer systems and lineament pattern for groundwater targeting in earlier studies (Howe, 1956; Ray, 1960; Lattman and Parizek, 1974; Boyer and Maguer, 1964; Setzer, 1966 and Mollard, 1988). Digital image processing is used for extracting information from digital data and its application in geology has been discussed by Drury (1987), Sabins (1987), Gupta (1991) and Lillesand and Kiefer (1994). Various applications in water resources studies wherein remote sensing may substitute, complement, or supplement the conventional methods are given by Ramalingam and Venugopal (2004). Many workers have used raw and digitally enhanced satellite multi-spectral data for hydrogeological, structural and hydrogeomorphological interpretations (Brakeman and Fernandaz, 1973; Bowder and Pruit, 1975; Moore and Duestsch, 1975; Ottle *et al.*, 1989). An integrated approach involving geology, geomorphology and land use pattern using remotely sensed data could give significant information for groundwater targeting (Ramaswamy and Bakliwal (1983). The interpretation of satellite data in conjunction with sufficient ground truth information makes it possible to identify and outline various ground features such as geology, structure, geomorphic features and their hydraulic characters (Das *et al.*, 1997), that may serve as direct or indirect indicators of the presence of groundwater (Ravindran and Jayaram, 1997). In their work in eastern Chad, Firoz and Alain, 2006 used the latest geo-spatial analytical method "WATEX" which is a proprietary groundwater exploration process used to locate renewable groundwater reserves in arid and semiarid environments. WATEX minimizes the need for costly, time consuming and often hazardous ground surveying and this study provides a promising example of how geo-spatial analysis could be utilized to remotely assess the availability of water potential.

Geographic Information System (GIS) has wide applications in groundwater studies and also act as tool for integrating various data. Integrated approach using remote sensing and GIS to decipher groundwater prospecting zones has been attempted in many earlier works (Saraf and Choudhury, 1998; Pratap *et al.*, 2000, and Pankaj and Amit, 2006). GIS finds important applications in groundwater quality studies. Bajjali, W. 2002 studied the groundwater quality in the

Sultanate of Oman using GIS. Groundwater pollution can be effectively evaluated by GIS (Aller *et al.*, 1987; Halliday and Wolfe, 1991). Salinity mapping is an important application of GIS and has been attempted by many workers (Tickell, 1994, Srivastava, 1997; Bajjali, 1999). Kiran and Anji Reddy (2006) carried out mapping of saline water affected villages in the Pennar river basin the East Coast of India.

Chapter 2

# Materials and Methods

## 2.1. Introduction

Groundwater acts as a reservoir from which good quality water can be drawn for drinking and for use in industry and agriculture. It maintains wetlands and river flows, acting as a buffer through dry periods. Groundwater provides base flow to surface water systems, feeding surface water systems all through the year. So groundwater quality has a direct impact on the quality of those surface waters as well as that of associated aquatic and terrestrial ecosystems.

Thus the study of quality and quantity of water is essential for the survival of human beings and aquatic life. Environmental degradation and human activities have greatly affected the groundwater quality in many countries. A thorough understanding of the hydrogeology, meteorological aspects, water level, geology and land use of the area is essential for proper management of regional water resources. Effective management of regional water resources so as to avoid adverse environmental impacts is the basis for sustainable groundwater development.

Taking into consideration all the above factors as also the latest trends in groundwater studies, quality analysis of groundwater in the area has been substantiated by hydrogeological, geophysical and remote sensing studies and integration of all data has been made using GIS.

This chapter deals with the materials and methods adopted for the present study both in the field and laboratory. As a first step a base map of the study area was prepared, after gathering information from various maps including Geological Survey of India and the sampling points were fixed approximately. Based on these reference points open wells were identified and samples collected. The exact locations of the wells were identified and these were then transferred into the base map. Resistivity locations were also identified and fixed in the map.

### 2.1.a. Field Operations and Investigations

Although during the study emphasis has been given for the coastal area, a comparison of the various hydrogeological characters with the corresponding crystallines has also been made. Hence site selection for groundwater sampling, geophysical survey and hydrogeological studies have been made accordingly. Field investigation has been carried out based on the existing information like land use, topography, geologic formation and hydraulic property of the system. During fieldwork attention was also given to record the local hydrogeology of the area, geological set up, local demand of groundwater and the problems faced by the local community etc.

## 2. 2. Geochemical Studies

Sample collection was carried out following the well laid out procedures in Standard Methods for the Examination of Water and Waste Water (APHA, 1985) Sampling was done during the year 2003 covering both pre-monsoon (April) and post-monsoon (December) periods. Groundwater samples have been collected from 41 dug wells from both coastal and crystalline terrain of the study area. Samples from the open wells were collected by lowering the sampling can without touching the sides of the well. Water samples were collected in pre cleaned plastic polyethylene bottles. Prior to sampling, the sampling containers were rinsed two to three times with the respective groundwater under sampling. After taking the Ph and EC the samples were neatly labelled. For bacteriological analysis the samples were collected aseptically in sterilized bottles and transported to the laboratory in icebox maintaining the temperature at $4^0$ C. Coliform tests were done within 12 hours of sampling. The samples were analysed following the standard procedure of water analysis (ISI, 1983), standard methods for the examination of water and waste water (Lenores, *et al.*, 1989) and standard analytical procedures for water analysis (Anon, 1998).

### 2.2.1. Laboratory Work

Pre-monsoon and post-monsoon values for concentrations of various anions and cations of the groundwater were chemically analysed (tab.2.1) using standard procedures (APHA, 1985). TDS, EC and pH measurements were carried out in the field using TDS meter (CM-183), conductivity meter (CM-183) and pH meter (pH scan1) respectively. The values of TDS and EC were validated using the following relationship 1µS/cm = 0.65 mg/l. Sodium and potassium in groundwater samples were analysed using Flamephotometer (Systronics FPM digital model). Carbonate and bicarbonate concentrations of the groundwater were determined titrimetrically against standard hydrochloric acid (0.01N). Sulphate concentration was carried out following turbidity method using

Spectrophotometer. Calcium, Magnesium and total hardness were estimated by EDTA (0.01M) titrimetric method, whereas Chloride was determined by argentometric titration using standard silver nitrate as reagent.

Table. 2.1. Methods followed for the determination of various physical and chemical parameters of groundwater

| Sl. No. | Parameters | Methods |
|---|---|---|
| 1 | pH, TDS & conductivity | Electrolytic |
| 2 | $Na^+$ and $K^+$ | Flame photometry |
| 3 | $Ca^{++}$ $Mg^{++}$ $HCO_3^-$, $CO_3^{- -}$ $Cl^-$ and total hardness | Titrimetry |
| 4 | $SO_4^-$ | Spectrophotometry |

**2.2.2. Precision and Accuracy of Analysis**

Some errors are unavoidable in analytical work and these may be due to the reagents employed, limitations of the methods or instruments used, the presence of impurities even in distilled water and finally the personal errors of the analyst himself. To minimize these errors analytical grade reagents were used. Also the instruments were periodically calibrated to assure the quality of generated data. Certain procedures have been listed to check the precision and completeness of the analysis. Cation-Anion balance is especially important in the case of ground water analysis. Cation-Anion balance check is a convenient technique to assess the reliability of measurements and the accuracy of data. The accuracy in the chemical analysis of water samples can be checked by calculating the cation-anion balance. There the sum of major cations should be equal to the sum of major anions, which is expressed in meq $l^{-1}$ To account for source dependency an allowable error limit of 10% is acceptable. The percentage error termed as ion balance error (e) can be determined following the equation given by Matthess (1982).

E= εγc - εγa / εγc + εγa

γc = cation sum in meq/l

γa = anion sum in meq/l

The concept of GIS zonation has been effectively employed in the study to delineate the accurate areal extent of all the elements in area. Zonation has been utilized since it is more scientific and accurate than isocone maps.

Tables showing results of analyses of chemical quality of groundwater are difficult to interpret, particularly where numerous analyses are involved. Hydrochemical diagrams such as Durov's diagram and Hill Piper diagram are useful for comparative analysis and for emphasizing similarities and differences. Graphical representation is also helpful in identifying chemical processes that occur when groundwater moves. These have been utilized in the present study also. Suitability of water for irrigation has been determined using U.S.S.L diagram. Suitability Zones for drinking water as per international standards have been delineated using GIS .The methodology is detailed under the subheading Geographic Information System.

## 2.3. Bacteriological Analysis

The groundwater samples were analysed for *E. coli* by streaking on Mac Conkey agar plates. The brick red bacterial colonies in the agar plate after incubation indicates the presence of *E. coli*. The resultant data has been spatially analysed using GIS to get the extent of *E. coli* percolation in the area.

## 2.4. Hydrometeorological Analysis

### 2.4.1. Groundwater Level Monitoring

Monitoring of water level has been carried out to understand the fluctuation during the post-monsoon and pre-monsoon periods. Data from the observation wells of the CGWB and State Groundwater Board has been utilized to understand the seasonal water level fluctuations. Representative wells have been selected from the significant localities for the short term (5years) and long term (15 years) trend analysis by preparing hydrographs. This has been achieved by making use of the GWDES software by combining with the rainfall data collected from IMD during the respective months. The behaviour of groundwater over the years could be easily visualized form the prepared comparative hydrographs.

### 2.4.2. Water Balance Studies

A detailed analysis of the water balance of the selected study region has been carried out using the method developed by Thornthwaite (1948) and modified by Thornthwaite & Mather (1955). This method helps to assess the water yield and water availability. According to the concept of this method, the water surplus represents the excess water after the actual evapo-transpiration and soil moisture recharge and is the water available for exploitation.

Soil water is controlled by the difference between precipitation (P) and potential evapo-transpiration (PE). If water remains after the atmospheric demand has been satisfied (P>PE), then the water is retained in the soil. If, on the other hand, PE exceeds P, then water is removed from the soil in order to meet the atmospheric demand. The potential evapo-transpiration is accurately estimated by Thornthwaite's empirical equation:

$$PE = 1 \cdot 6\left(\frac{10T}{I}\right)^m$$

Where PE is the uncorrected monthly evapo-transpiration (cm) and T is the monthly mean temperature in (°C). The annual heat index (I) is given by summing-up the monthly heat indexes, as follows:

$$I = \sum_{k=1}^{12} i_k$$

The monthly heat index, $i_k$ can be calculated by:

$$i_k = \left(\frac{T}{\alpha}\right)^\beta$$

Where $\alpha$ and $\beta$ are empirical constants ($\alpha$=5, $\beta$=1.514). The exponent m actually depends on I but it can be estimated as a series expansion of I, as follows

$$m = ai^3 + bi^2 + c^i + d$$

where

$a = 6.75 * 10^{-7}$

$b = -7.7 * 10^{-5}$

$c = 1.79 * 10^{-2}$

$d = .492$

The above equation for PE is valid only for the temperature below 26.5°C for the area. Where temperature is above 26.5°C, then the equation is

$$PE = -41.586 + 3.2233 * T - .043254T^2$$

Water surplus occurs when precipitation is more than potential evapo-transpiration (P.E) and deficiency occurs when precipitation and change in soil moisture together falls short of (P.E.). The surplus water appears either as surface runoff or as subsurface runoff that percolates down to join groundwater. All the surplus water do not immediately run off but a part of it is detained in the underground regions for further contribution to runoff and detention later, depending on the slope, soil type and vegetation.

### 2.5. Geophysical Studies

The role of geophysical methods in groundwater exploration is vital. Its chief aim is to understand the hidden subsurface hydrogeological conditions accurately and adequately. Since the base of any geophysical methods is the contrast between the physical properties of the target and the environs, the better the contrast or anomaly, better would be the geophysical response and hence the identification. So, the efficacy of any geophysical techniques lies in its ability to sense and resolve the hidden subsurface hydrogeological heterogeneities or variation. Hence for groundwater exploration a judicious application or integration of techniques is most essential to become successful in exploration, technologically as well as economically. It is to be clearly conceptualised that groundwater cannot be detected directly by any one of the geophysical methods and therefore the interpretation is contextual and a broad understanding of the subsurface hydrogeological condition is a prerequisite. Some of the important techniques which have proven effective in resolving horizontally layered aquifers (and confining beds) are resistivity soundings, electromagnetic (EM) soundings in the frequency domain or time domain (TEM), high-resolution shallow seismic reflection, seismic refraction, and controlled-source audiomagnetotellurics (CSAMT). Electrical methods (resistivity, EM, TEM, CSAMT) which measure the electrical conductivity contrast between sedimentary layers, dependent on the grain size, mineralogy (sand/clay ratio), and water content (saturated versus unsaturated). Seismic methods rely on acoustic velocity contrasts, which again dependent on grain size, degree of consolidation, density, and water content of a formation.

Sufficient physical property contrast between lithological units of interest must exist in order for specific geophysical methods to be of use.

Hence there are limitations to which geophysical methods can be used in groundwater prospecting. For example, the ionic content of pore water within the saturated zone of a granular aquifer may not allow it to be distinguished from the overlying unsaturated zone using electrical methods, however, an alternate method like seismic refraction might be successful. Conversely, a lithologic variation from silty sand to sandy silt may be significant to groundwater flow, might be identifiable with a resistivity survey and not seismic refraction. Hence multiple geophysical methods are usually recommended. Often a combination of different geophysical methods can provide a more comprehensive picture of hydrogeological variation in the subsurface. This expansion of related information can often be critical in solving regional groundwater problems. The depth of investigation and resolution of specific geophysical methods are often a significant limitation. As a general rule, greater the depth of investigation, lesser the resolution or detail, which can be obtained about the target. In addition, often higher the required resolution at depth, higher the cost of obtaining that resolution.

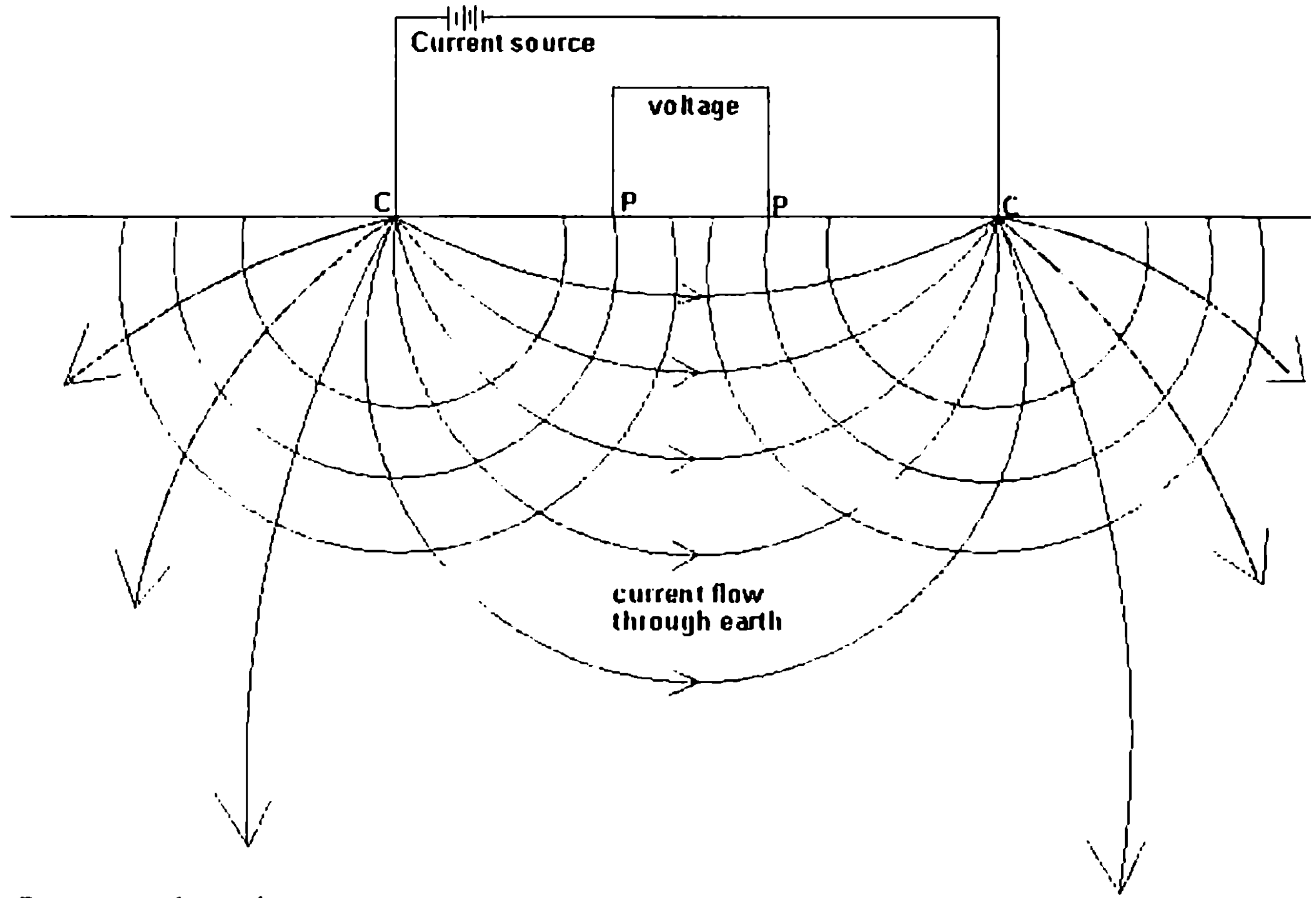
### 2.5.1. Electrical Resistivity Methods

Surface Resistivity methods measure the electrical resistivity of the subsurface, which then reflect the soil and groundwater characteristics. Ground resistivity) can be used to study lateral changes and can provide vertical cross sections of the natural hydrogeologic setting. Electrical resistivity can also be used to study contamination of soil and groundwater. Geophysical survey and test drilling are also helpful for determining transmissivity and storativity in relation to artificial recharge of subsurface water (Mukherjee and Das, 1996). Electrical resistivity finds applications in studying soil or rock lithology, soil and groundwater contamination, saltwater/freshwater interface, mapping clay layers or sand deposits, mapping water table and fracture location and in mineral exploration.

The various electrical methods commonly employed to solve different geological problems (Bhimashankaram and Gour, 1977; Patangay, 1977) are listed in Table 2.2. The electrode configuration used in this study is Schlumberger arrays (fig.2.1).

### 2.5.2. Data Acquisition

VES was carried out in the study area with a CRM 50 Terrameter unit. The equipment is light and powerful for deep penetration. The resistivity survey was completed with 36 sounding stations. Field survey was carried out between April to June 2003. The electrical sounding in this study was conducted by using the Schlumberger array, which is popular method but time consuming. The field data acquisition was generally carried out by moving two or four of the electrodes used, between each measurement against electrode spacing. The apparent resistivity for each of the VES was plotted against the electrode separation. Computer programs for reducing geoelectrical sounding curves into values of thickness and resistivity of individual layers are described by Zohdy and Bisdorf (1989). The field curves were interpreted by the well-known method of curve matching with the aid of Russian software IPI7.63. However, thickness and characteristics of the aquifer are fairly well known due to the number of dug wells in the




C = current electrode

P = potential electrode

fig.2.1 **Electrical circuit for resitivity determination and electrical field for a homogeneous subsurface stratum**

**Table.2.2 Electrical Methods employed for common Hydrogeological problems**

| Nature of the problem | Methods used |
|---|---|
| 1. Assessment of subsurface structure | VES, DES, FEMS,RIS |
| 2. Study of horizontal and vertical distribution of aquifers | VES, DES, FEMS, RIS |
| 3. Tracing Salt water – Fresh water interface | VES, FEMS, RIS, IP, EP |
| 4. Estimating groundwater quality | VES, FEMS, RIS, IP |
| 5. Mapping valley fills | VES, FEMS |
| 6. Mapping thick sediments over Impermeable substratum | VES, RIS, IPVES |
| 7 Tracing groundwater movement | SP |
| 8. Depth to the water table | VES, IPVES, RIS, FEMS |

EP – Electrical profiling
DES – Dipole Electrical Sounding
FEMS – Frequency EM sounding
IP- Induced Polarisation
SP- Spontaneous Polarisation
RIS – Radio Interference Sounding
RP – Radiowave profiling
VES – Vertical Electrical Sounding

centre of the aquifer. A number of geoelectric stations were purposely located near about the 16 wells. The key to success of any geophysical survey is the calibration of the geophysical data with hydrogeological and geological ground truth information. VES success must rely on the careful interpretation and integration of the results with the other geologic and hydrogeologic data for the site. Therefore, lithologic information obtained from log could be used to calibrate the VES field curves. Where test hole-log information was available, the solution to automatic interpretation procedure was constrained by keeping known layer thickness constant during the program computations. In final, the results of the Schlumberger electrical soundings have been compared with the available geological sections. These results are in a good agreement with the geological sections. The boundary of the aquifer, thickness and resistivity of subsurface layers are also determined by the electrical survey in this research.

### 2.6. Remote sensing and GIS

The satellite data of IRS-ID LISS III (2002), geocoded FCC for visual interpretation and digital data for digital classification were used. Digital data were processed in the laboratory using ERDAS Imagine 8.6 DIP software.

Image rectification and preparation of a GIS file through visual interpretation of standard FCC data is performed to extract surfacial expression of subsurface water accumulation. Edge enhancement is done mainly for structural interpretation; vegetal cover, land use, lithology and structural lineaments influence infiltration of water into subsurface condition (Perry *et al.,* 1988). Hydrogeological land use classification through supervised classification technique provides very good thematic information regarding different types of hydro geomorphic features including vegetation pattern, burried channels, flood plain areas, shallow to deep surface water bodies, surface drainage and areas with moisture content, dry sandy soil or surface material with higher reflectance (Das *et al.,* 1992). Band rationing gives vegetation index map (Jensen, 1986). Spectral band (0.6-0.7um) gives valuable information regarding fracture pattern in the rock and drainage pattern in the study area. Observations from the satellite data must be complemented by field checks, and existing geologic maps and topographic sheets are very much useful as supplementary data sources. Data integration and composite map generation may be performed through GIS technique (1:50,000 scale). Delineation of pertinent area (such as open deep seated fractures, weathered residuum, alluvial fans, old channel courses etc.) in the composite map is one of the most desired tasks for groundwater development, for construction of artificial recharge structure and for surface water storage augmentation (Geomorphic depression with impermeable layer) by water impounding structure.

### 2.6.1. Digital Image Processing

A digital image is an array of numbers depicting spatial distribution of certain parameter such as reflectance, temperature, geophysical data, elevation data etc. Each point on the image is represented by an integer DN (digital number) whose value varies from 0 to 255. Digital image defines any scene in numerical terms on a 3-axis coordinate system in which x and y define the location of each pixel and z gives the DN which can be displayed as gray scale intensity value. The main objectives of digital image processing are:

- Remove distortions of the image.
- Enhance the quality of image
- Extraction of information that cannot be displayed. Automatic mapping

  Measures and defines the degree of statistical similarity in different images of a scene.

**DIP Techniques**

Image processing techniques are grouped under different heads:

A. Image Statistical Analysis

B. Image Restoration

   - Radiometric corrections
   - Geometric Corrections
   - Image Registration

C. Image Enhancements

   - Radiometric Enhancement

     Contrast Stretching

     Histogram Equalisation

     Special stretching

       - Spatial Enhancement: Spatial filtering
       - Spectral Enhancement

     Band Ratio

Vegetation Indices

Principal Component Analyses

HSI Transformation

D. Information Extraction

Image Classification: Supervised and Unsupervised

Textural analysis

Change Detection

E. Image Manipulations

Image merging

Image mosaicing

Enlargement and Reduction

Image rotation, translation etc

Image enhancement is the modification of an image to alter its impact on the viewer. The purpose of enhancement is to allow for improved image interpretation by amplification of the desired spectral or spatial characteristics while suppressing non-essential characteristics. Enhancement should be designed to improve the visual quality of the image for specific interpretation. It may result in improved appearance of one feature but could result in suppression of some other features. Enhancement technique to be used depends on the objective of the study, experience of the user and the type and quality of the data. There are various enhancement techniques available in image processing packages. They may be broadly grouped into the following categories.

Digital classification is the process of dividing the scene into different classes. The classification assigns each pixel in a multi-spectral image to a discrete class based on its spectral signature. If a pixel satisfies a certain set of criteria, it is assigned to the class that corresponds to that criterion. The output is a thematic map.

Digital classification involves pattern recognition. Arrangement of features in an image constitutes the pattern. Pattern can be spatial or spectral. Enhanced images help pattern recognition even with naked eyes. Human brain can sort several colours and textures. But a computer system can recognize pattern more scientifically, based on statistics and mathematical criteria. There are basically two approaches in classification: Supervised and Unsupervised classification.

Classification involves four steps:

Training

- Classification using decision rules
- Accuracy estimation
- Output generation

Training the computer to recognize pattern in the data is the first step. In Supervised classification, training is controlled by the analyst in which sample sites (training sites) are selected and computer is instructed to identify similar pixels. In unsupervised classification training is computer automated, based on statistical patterns, eg. clustering.

Decision Rules are rules (mathematical algorithms) based on which the pixels are sorted into classes. There are parametric decision rules (statistical) and Nonparametric decision rules (independent properties). Supervised training uses pattern recognition skill and apriori information about data such as types of classes present in the area and spectral characteristics of each class. Supervised classification involves the following steps

- •Defining Classification classes
- •Selection of training sites
- •Estimation of universal statistics of the training sites
- •Classification of the image using appropriate algorithm
- •Post classification smoothing
- •Classification accuracy estimation

**Training stage**

Training (sample) sites are selected by using a vector layer from a map, user-defined polygons in the image, or through seed pixels or ground truth. Number of training sites for each class depends on its variability. Homogenous classes require fewer samples while more heterogenous classes require more samples. Universal statistical parameters such as mean, standard deviation, variance-covariance, correlation etc are calculated for the samples of each class.

**Classification stage**

Appropriate algorithm (mathematical formula) for the classification is selected. There are mainly 3 algorithms in use. They are:

Minimum Distance to mean classifier

Parallelepiped classifier

Maximum likelihood classifier

**Minimum Distance to mean classifier**

In this case the mean of all DN values of each training class is computed first. Then the Euclidian distance of each pixel from the mean values of each class is calculated and assigned to the class to which it is nearest.

**Parallelepiped Classifier.**

Mean and standard deviation of each class for each band is calculated. Two-dimensional rectangular feature spaces (boxes) are defined using a range (eg. Mean +/- 1 Std. dev) in each class. All pixels falling into a box are assigned to that class. When rectangles overlap, the box boundaries are tapered into steps. All the pixels falling outside the boxes are left unclassified.

**Maximum likelihood Classifier**

It is assumed that the DN values of each class have a Gaussian distribution. The mean and standard deviation for each training class are calculated. For each pixel, the computer calculates the probability for belonging to each class and then the pixel is assigned to the class to which it has the maximum probability. The analyst sets a threshold value. If the probability value for any pixel is below this value, it is left unclassified. Probability is maximum near to the mean value and decreases away from the mean. So equi-probability contours take the shape of distribution. Accuracy is high for this method, but it takes more computational time.

**Accuracy Estimation**

Classification accuracy is estimated by comparison of classified data with true geographical data (ground truth). Reference pixels of actual data are randomly selected and used for comparison. A defined window size of reference pixels are selected. Error matrix is constructed and Omission errors (how many pixels of a class have been misclassified into other classes) and Commission errors (how many pixels of other classes have been misclassified into this class) are calculated. Finally the overall accuracy percent is calculated.

## 2.7. Geographic Information Systems

The Geographic Information Systems provides an effective tool for integrating the various data collected from the field and through remote sensing. This helps in better utilization of the available data in a scientific and accurate manner. The major advantage of GIS is that large volumes of data can be analysed easily, accurately and also displayed in user-friendly maps. In the present study also these advantages of GIS have been fully utilized. GIS has been used for integrating various geological data in many early works. (Chaterjee and Bhattacharya, 1995; Krishnamurthy and Srinivas,1995 ; Krishnamurthy *et al.,*1996; Tiwari and Rai, 1996; Ravindran and Jeyaram, 1997; Saraf and Choudhary,1998; Srivastava and

Bhatacharya, 2000; Sankar, 2002; Srinivasa Vittala *et al.*, 2004 and .Srinivasa Vittala *et al.*, 2005).

In the present study GIS has been utilized for analysis and presentation of data in all the stages right from water level analysis to the final potential potable water zone map.

a. Water level analysis
b. Geochemical analysis
c. Water quality mapping
d. Saline water buffer zones
e. Deciphering prospective groundwater zones using resistivity and aquifer thickness
f. Integration of water quality data with the potential groundwater zones to identify possible potential potable groundwater zones. The methodology adopted for each study area detailed below.

### 2.7.1. Water Level Analysis

Water level variations were analysed for a period of ten years. Data from the 26 observation wells of State Groundwater Board falling in the study area were used for this purpose. pre-monsoon and post-monsoon variation of each year has been studied in detail using GIS. Also statistical analysis of the water level for ten years were carried out using GIS. For the creation of water level contour, first water level surface was developed using topo to raster tool available in Spatial Analyst. From the water level, surface water level contours were generated using the contour-generating tool in the Spatial Analyst. By using the water level contours, flow direction raster and flow accumulation raster etc were generated by using the hydrology tools in the Arc GIS 9.

### 2.7.2. Geochemical Zonation

The base map of study area is digitized edited, formatted and geo-referenced (using ArcMap module of Arc GIS). The Well location points are digitized and corresponding location number given for each location. The well data in excel format is converted into (.dbf) format and linked with the spatial data (base map) by the Join option in ArcMap. The grid is prepared using ArcScene module of Arc GIS. Isolines are prepared by contour option in ArcScene. The range is given in contour option. The contour interval is polygonized and the different zones are created using ArcMap option. The range for each polygon is given in the attribute table. The pre-monsoon and post-monsoon zonation of each chemical parameters are prepared to know the spatial distribution of each parameters within the study area. Area of each zones are prepared using ArcMap area calculation option (using VBA Script code) and shown in the map. Percentage area to the total area of each map is also calculated.

### 2.7.3. Spatial Overlay analysis

Spatial overlay maps are prepared to know the change in the zonation area of each element between the pre-monsoon and post-monsoon periods. In the geo-processing wizard (in Arc Tool box) the Union option is employed and overlay is done. Another field is added in the attribute table to calculate the area. Bar diagrams are prepared and exhibited in the map to show the changes. The change is also presented in tables. The overlay map of each element showing the variation in the concentration during the pre-monsoon and post-monsoon period is thus prepared.

### 2.7.4. Drinking Water Quality Maps

Range of chemical quality parameters as per WHO standards are input in Arc Map and suitability zones delineated. Pre-monsoon and post-monsoon are overlain for suitability. Overlay maps of each element for suitability zones have been overlain to find out the final chemical high suitability zones.

### 2.7.5. Saline Water Buffer Zones

One km buffer zone is prepared around the well sample point location having salinity. The saline water buffer zones are overlain on the drinking water suitability zone. It has been found that none of the buffer zones are falling within the high drinking water suitability zone. For the creation of buffer zone geographic analysis tools were used. Input feature was given as saline water affected wells and the buffer distance specified as 1 km.

### 2.7.6. Deciphering prospective groundwater Zones using resistivity and aquifer thickness

The present study makes a comparison of all aspects of coastal alluvium and the crystalline terrain. In the crystalline terrain laterite outcrops are a significant feature. Hence GIS has been used to integrate aquifer thickness and resistivity to delineate groundwater prospect zones only in the alluvium and laterite terrains of the study area. The method followed by Shamsuddin Shahid and Sankar Kumar Nath (2003) in their study in Midnapur District, West Bengal has been applied to integrate geophysical data with geology to bring out groundwater prospect zones.

In the present investigation, for the estimation of hydrogeological condition, data obtained from VES surveys are interpreted for the estimation of the subsurface parameters viz. electrical resistivity of the aquifer and aquifer thickness. These parameters at different survey points are contoured using Kriging method (deMarsily 1986) and the corresponding thematic maps are prepared. The resistivity and thickness of aquifer media are directly related to transmissivity and hydraulic conductivity of the aquifer. Therefore, integration of these two data can give the groundwater potential of an area. However, different types of lithology with different resistivity ranges have different groundwater prospect. Therefore, different range of values or features should have a different score in a scale according to its importance in accumulating groundwater. An overlay operation would then evaluate the intersected regions by a sum of the scores, so that each resulting region is characterised by a score measuring its potential. Based on this method groundwater condition of the study area is estimated. In the present study, feature of an individual geophysical theme has been scored in the 1-10 scale in the ascending order of hydrogeologic significance. To ensure that no layer exerts an influence over the other, the raw score for each feature is then normalized using the following relation.

$$X_J = \frac{R_j - R_{min}}{R_{MAX} - R_{MIN}}$$

Where $X_j$ is the normalized score

$R_j$ is the raw score

$R_{min}$ is the minimum score, and

$R_{max}$ is the maximum score of a layer.

The groundwater condition of the study area is then estimated as,

Groundwater Prospect = $R_s + T_s$

where $r_s$ represents score of aquifer resistivity

$T_s$ represent score for aquifer thickness

Equal weightages have been assigned to aquifer resistivity and thickness since the importance of hydraulic conductivity and transmissivity in groundwater exploration are the same. Different rock types may have same resistivity values but the groundwater prospects may be different. Hence assigning score based solely on the resistivity value may lead to misinterpretation of groundwater prospect. So different scores for resistivity have to be assigned for different rock types. This is done by overlaying the thematic map of resistivity on the geological map.

In the present study groundwater prospect maps have been prepared separately for the coastal belt and the lateritic terrain. It is well known that hydraulic conductivity increases with the resistivity. Hence, a higher yield is expected from an aquifer with higher resistivity. A higher rating is therefore assigned to the maximum resistivity range and least to the lowest one. In the lateritic terrain hard cap laterites, which do not hold any water, register high resistivity values and the associated lithomargic clay shows low resistivity (Shamsuddin Shahid, 2003). Hence the positive correlation between the resistivity of the aquifer materials and the hydraulic conductivity cannot be applicable in this terrain. Roy and Niyogi (1961) also pointed out that the lateritic formation does not have significant ground water potential. Therefore, different scores are required to assign to the same resistivity ranges in the lateritic zone to that in the Alluvium zone. This is done by overlaying the thematic map of aquifer resistivity over the thematic map of geology which is shown. According to Patra *et al.* (1972) only the fine sand formation in the lateritic zone with a resistivity range between 40 and 70 ohm-m has a little prospect of groundwater. It is well known that transmissivity increases with the thickness of the aquifer. The scores have been assigned keeping the above facts in mind and are shown in tab.2.3. The resistivity location points are digitized and geo-referenced. The corresponding resistivity and aquifer thickness values are integrated (in .dbf format) with resistivity point data. Preparation of Isolines have been done in the range specified in the tab2.3.The regions in between are polygonized to get the aquifer resistivity and aquifer thickness zones. In the case of the coastal belt the present study was restricted only to the shallow aquifers because it was noticed that the clay layer present in the area acted as a barrier for accurate resistivity survey. Overlay operation of the thematic maps of aquifer resistivity and aquifer thickness results in groundwater prospect zones. RT maps (Resistivity Thickness Map) have been used by many scientists in deciphering the potential of aquifers

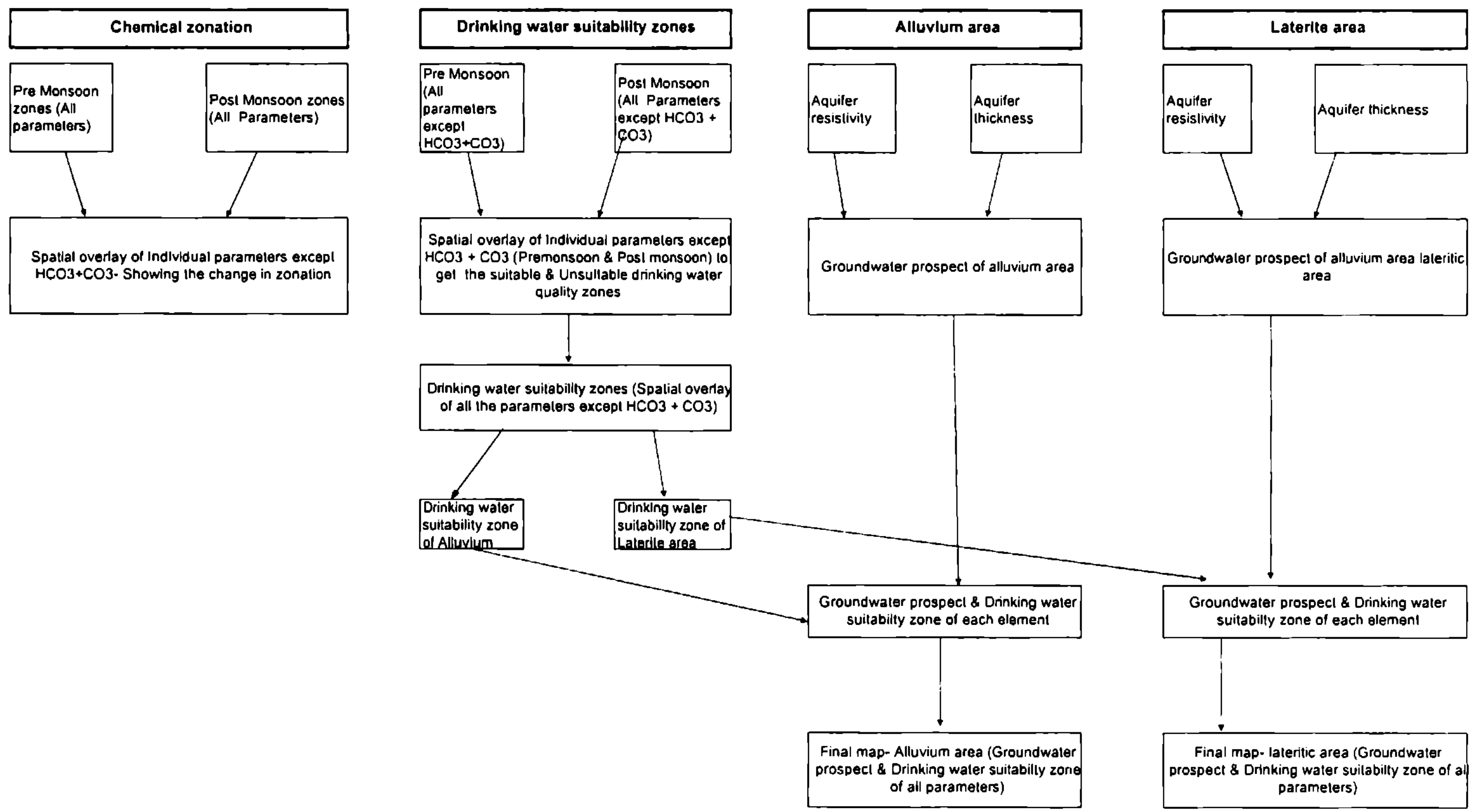



**Fig. 2.2. Flow chart showing steps in the delineation of potable groundwater zones using GIS**

**Table. 2.3. Scores assigned for different groundwater controlling parameters in GIS**

| Score - Alluvium area | | | |
|---|---|---|---|
| | Attribute | Raw score | Normalized score |
| Resistivity of Aquifer | <35 | 1 | 0.00 |
| | 36-55 | 2 | 0.25 |
| | 56- 75 | 3 | 0.50 |
| | 76-90 | 4 | 0.75 |
| | >90 | 5 | 1.00 |
| Aquifer thickness | <2.5 | 1 | 0.00 |
| | 2.5-5.0 | 2 | 0.50 |
| | >5.0 | 3 | 1.00 |

| Score - Laterite | | | |
|---|---|---|---|
| | Attribute | Raw score | Normalized score |
| Resistivity of Aquifer | <40 | 1 | 0.00 |
| | 40-70 | 4 | 0.75 |
| | 70-200 | 3 | 0.50 |
| | >200 | 2 | 0.25 |
| Aquifer thickness | <25 | 1 | 0.00 |
| | 25-75 | 2 | 0.50 |
| | >75 | 3 | 1.00 |

**Groundwater prospect - Alluvium**

| Zone | Score | Aquifer resistivity | Aquifer thickness | Average transmissivity& Hydraulic conductivity | Groundwater condition |
|---|---|---|---|---|---|
| 1 | 0.75-1 | >75 | >5 | High | Good |
| 2 | 0.5-0.75 | 55-75 | 2.5-5.0 | Moderate | Moderate |
| 3 | <0.5 | <55 | <2.5 | Poor | Poor |

**Groundwater prospect - Laterite**

| Zone | Score | Aquifer resistivity | Aquifer thickness | Average transmissivity& Hydraulic conductivity | Groundwater condition |
|---|---|---|---|---|---|
| 1 | 0.75 | 40-70 | >75 | High | Good |
| 2 | 0.25-0.75 | >70 | 25-75 | Moderate | Moderate |
| 3 | <. 25 | <40 | <25 | Poor | Poor |

(Lashkaripour, 2005). Another overlay operation of the drinking water suitability map with the groundwater potential map resulted in potential potable water zones of the area. This has been created separately for alluvium and the hardrock terrain of the study area. The flow chart showing the steps in the preparation of potable groundwater zones are given in fig.2.2.

Chapter 3

# Hydrogeology

### 3.1. Introduction

Hydrogeology is the part of hydrology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust. The term Geohydrology is often used interchangeably. Some make the minor distinction between a hydrologist or engineer applying themselves to geology (geohydrology), and a geologist applying themselves to hydrology (hydrogeology). Hydrogeology is an interdisciplinary subject and difficult to account fully for the chemical, physical, biological and even legal interactions between soil, water, nature and man. Although the basic principles of hydrogeology are very intuitive (e.g., water flows "downhill"), the study of their interaction can be quite complex. Taking into account the interplay of the different facets of a multi-component system, it often requires knowledge in several diverse fields at both the experimental and theoritical levels. Traditionally the movement of groundwater has been studied separately from surface water, climatology, and even the chemical and microbiological aspects of hydrogeology (the processes are uncoupled). As the field of hydrogeology matures, the strong interactions between surface water, water chemistry, soil moisture and even climate are becoming more clear.

Hydrometeorological and hydrological study plays an important role in understanding the groundwater system. Compilation, analysis and interpretation of hydro meteorological and hydrological data are vital in assessing the surface water balance, groundwater resource estimation and quantification of ground water recharge. Rainfall, runoff and evapo-transpiration are the important components of the hydrological cycle. So an estimation of these three parameters is helpful in the quantification of the groundwater recharge correctly. Depending on the purpose and scope of the study, hydro meteorological data of the study area is compiled and studied. The data on rainfall (annual, seasonal, monthly, weekly and daily) and rainfall intensity, temperature, humidity, wind speed and direction, evapo-transpiration and sunshine hours are generally compiled for hydro meteorological and hydrological studies.

### 3.2. Hydrogeology of Coastal Aquifers

India has a very long coastline of about 6000 km of which the eastern coast is 2600 km and the western counter part is 3400 km. The high population and the modern living standards demand more water, which has given a higher stress to the coastal aquifers. Most of the coastal aquifers are sedimentary in nature even though there are a few outcrops of hard rocks along the coast.

#### 3.2.1. The Tertiary Sediments of Kerala

Groundwater occurs under phreatic condition in the shallow zone and confined condition in the deeper zones in the Tertiary sedimentary rocks. Depth of water level in the shallow aquifers ranges from 3 to 26.75mbgl and the depth of wells range from 6 to 27m. Deep aquifers comprise of Alleppey beds, Vaikom beds, Quilon beds and Warkallai beds.

Vaikom and Warkallai beds are the most potential aquifer among the four Tertiary formations.

The general characteristics of the above beds are given in table 3.1.

Table. 3.1. General characteristics of Tertiary formations.

| **Beds** | **Depth of piezometric surface** | **Yield of the wells** | **Quality** |
|---|---|---|---|
| Vaikom beds | Varies from 19.96mbgl in Vaiyenkara to 4.97mbgl in Karuvatta | 0.73lps to 57lps | Saline north of Karuvatta in Alleppey district |
| Quilon beds | The hydrological particulars are very limited and the thickness of the granular zone ranges from 6 to 16m | | |
| Warkali beds | 2.8mamsl to 10mbgl | 3lps to 14lps | Brackish north of Shertallai in Alleppey district |

(Source: CGWB report)

### 3.3. Fluctuations in Water Level

Changes in the water level in wells indicate fluctuations of the water table, and thus indicate whether the groundwater reservoir is being depleted or replenished. In general, the water table rises when the rate of recharge exceeds the rate of discharge and declines when the rate of discharge exceeds the rate of recharge. Interpretation of fluctuations in water levels is complicated by the interrelation of several factors. Declines in water level are caused by various factors like prolonged periods of deficient rainfall, increased transpiration of plants, increased evaporation, increased pumping and seepage into streams, ground water outflow and withdrawal. Whereas rise in the water level may be caused by factors such as increased precipitation, decreased evapo-transpiration, decreased pumping, artificial recharge and seepage from streams.

The controlling factors for the change in water level are divided as time dependent and time independent. The time dependent factors are rainfall, surface water bodies, ground water pumping, change in river stage, induced recharge, atmospheric pressure, evapo-transpiration, ocean and earth tides and lunar effect. The time - independent factors are topography, geology, physical properties of aquifers viz, areal extension, thickness, grain size and shape, inter-granular porosity and unconfined or confined nature. The water levels in recharge area are characterized by deep levels, higher fluctuation range, steep limbs in hydrograph, depth to water table increases with depth, phreatic level is higher than piezometric level.

Similarly, water levels in discharge area is characterized by shallow levels, low fluctuation range and gentle slope of the hydrograph.

The major factors that affect ground-water storage are described by Taylor and Alley (2001). Winter frost conditions may also lead to water level fluctuations (Schneider, 1961). Many authors elsewhere have studied fluctuations of the water table. Fluctuations in the Sedgwick County have been determined by periodic measurements of the depth to water in selected wells by Fishel and others (Fishel and Mason, 1957; Fishel and Broeker, 1960; Broeker and Fishel, 1961; Mohammed, 1992; Grimaldi *et al.,* 2004). Chen *et al.* (2002) predicted the average annual groundwater levels from climatic variables using an empirical model. Matson *et al.*

(1996) have enumerated the approaches to automated water table mapping. Groundwater level forecasting in a shallow aquifer using artificial neural network approach has been carried out by Nayak *et al.* (2006) and kriging of groundwater levels has been undertaken by Kumar and Remadevi (2006).

### 3.4. Behaviour of Groundwater in the study region

Groundwater levels of phreatic aquifers and peizometric levels of confined to semiconfined aquifers have been used for the analysis by means of maps, graphs and sections. Important among them are the water table contour mapping, water level fluctuation mapping, water level profiles and well hydrographs. If the details of well construction and aquifer geometry are known, water level contour maps can be classified more precisely as peizometric maps, water table maps or potentiometric maps (Davis and De Wiest, 1966). Long term and short term fluctuations of groundwater level study helps us to understand the recharge and discharge conditions of aquifers. Well hydrographs represent variation of water level with rainfall.

The Groundwater levels have been studied in detail over a period of ten years (1993 –2003) to get a clear trend of the water level. Short-term variations have also been dealt with and detailed analysis of the data in the year 2003 with respect to 2002 has been done. A groundwater surface elevation contour coverage was made for each year from 1993 to 2003 for both pre-monsoon and post-monsoon periods. Separate data files including well identification, groundwater surface elevation, depth to water, and year provided the information. Twenty six wells of the State Groundwater Board were used for this purpose and are shown in fig. 3.1. Contouring was created using ArcInfo's TIN (Triangulated Irregular Network) procedure. The TINs were then converted to grids for presentation. The maps showing the seasonal water level fluctuations for the 10-year period were also prepared using the same method and are presented in figs. 3.2.a – 3.2.j. From the figures (fig.3.2a to 3.2.j) it is observed that the water levels show a decline in the pre-monsoon period when compared to the post monsoon period. Since the coastal area is also a discharge zone, the effect is less towards west. During post-monsoon, the water column shows a sharp increase which is indicated by the thickening of contours towards the west.

The study area comprise of alluvium in the western side and charnockites towards the east. Laterite cappings in the area also act as potential aquifers. The average water levels are given in table no. 3.2, which show values of 5.92 m for laterite, 5.71 m for charnockites and 1.07 m for alluvium. The maximum water levels are 14.45m for laterite, 10.77 m for charnokite and 4.32 m for alluvium and their minimum values are 0.42 m, 2.31m and 0.07 m respectively. Trend analysis of the data for pre-monsoon for ten years shows that the maximum rise of 0.643 m/yr is shown by an observation well towards the northern point of the study area where as the maximum fall of 0.233 m is shown by a well towards the southern point of the study area. The post-monsoon data shows interesting values and the same well in the southern most point shows a rise of 0.009 m. The maximum rise of 0.346 m is observed again in the northern side

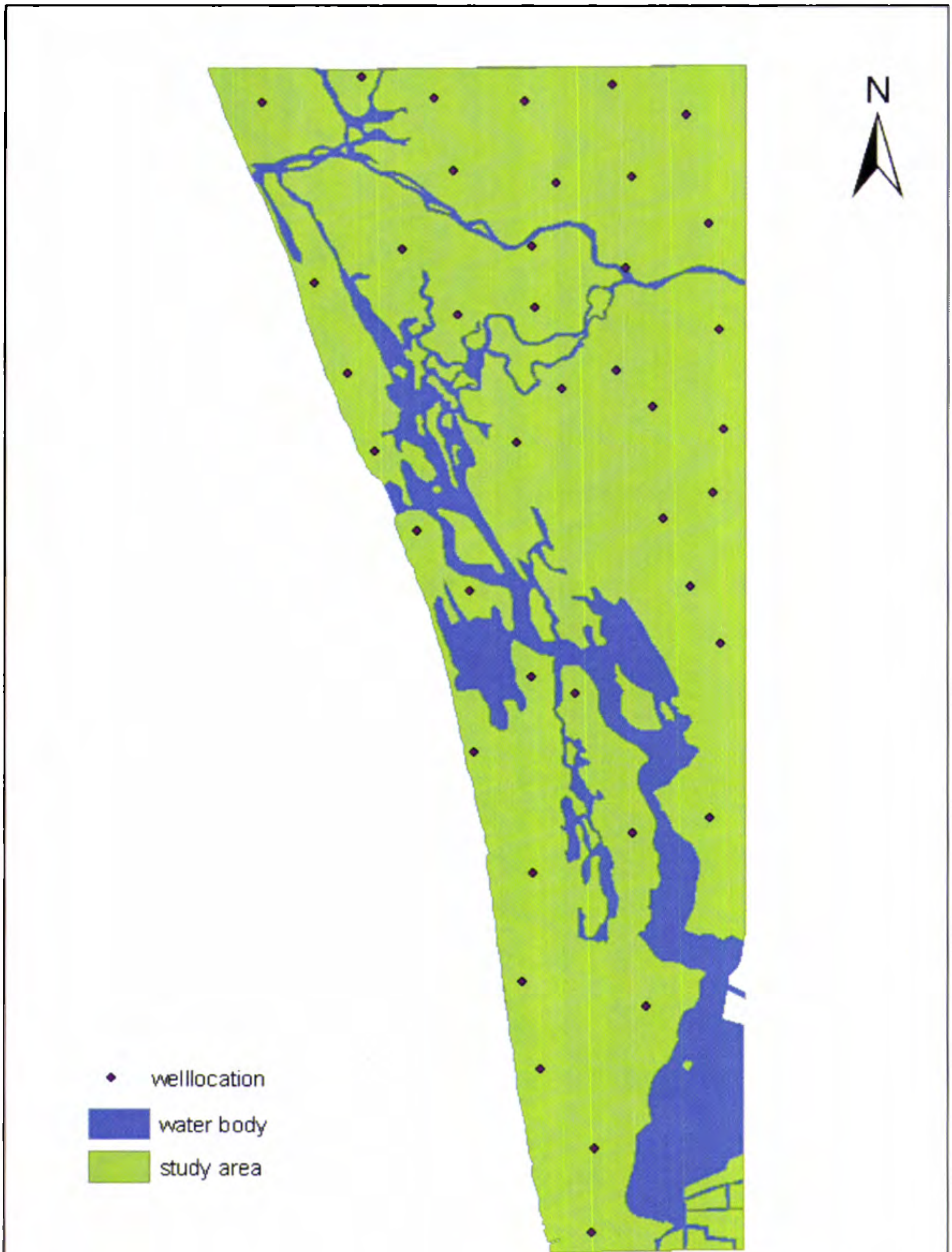
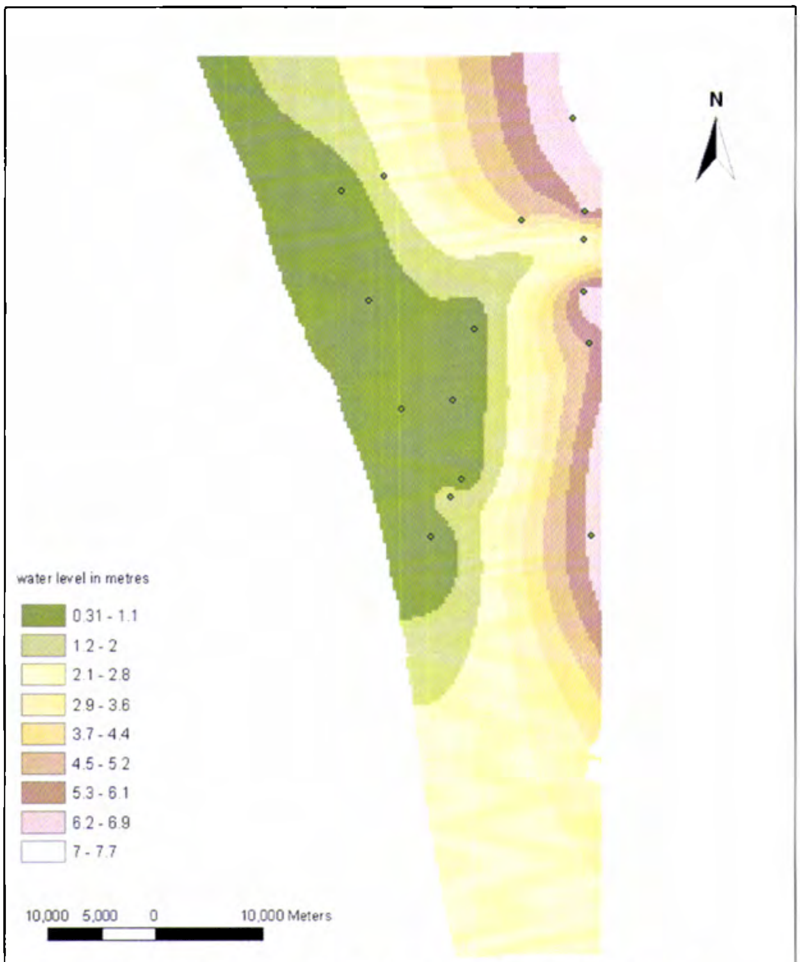



fig.3.1 Location of observation wells in the study area




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-1993-POST MONSOON

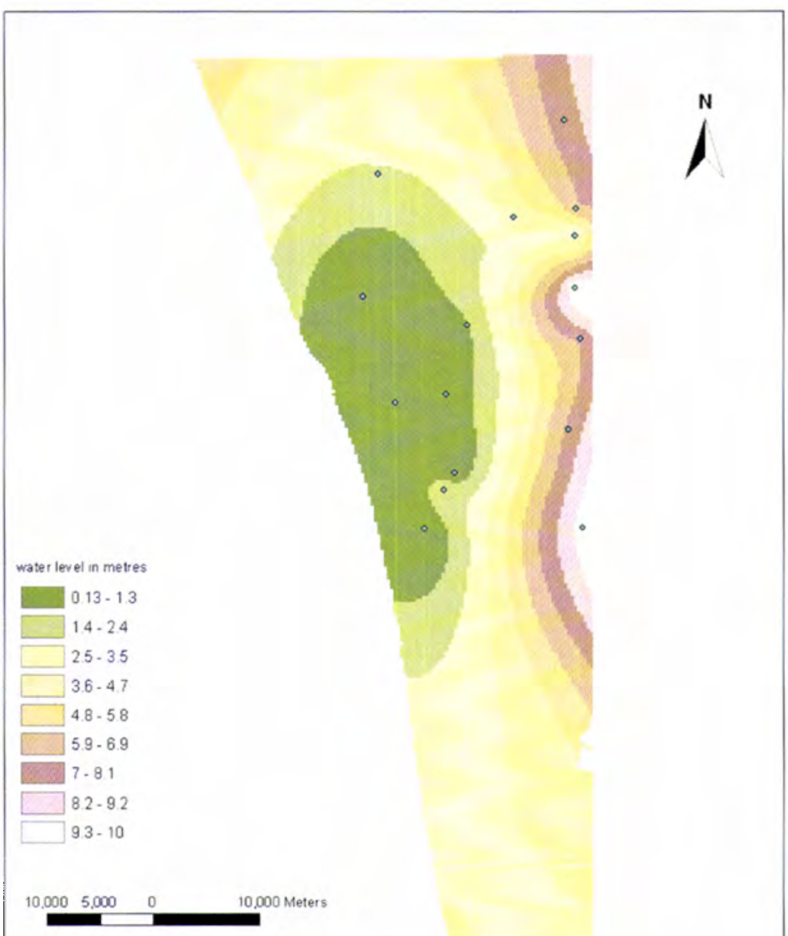
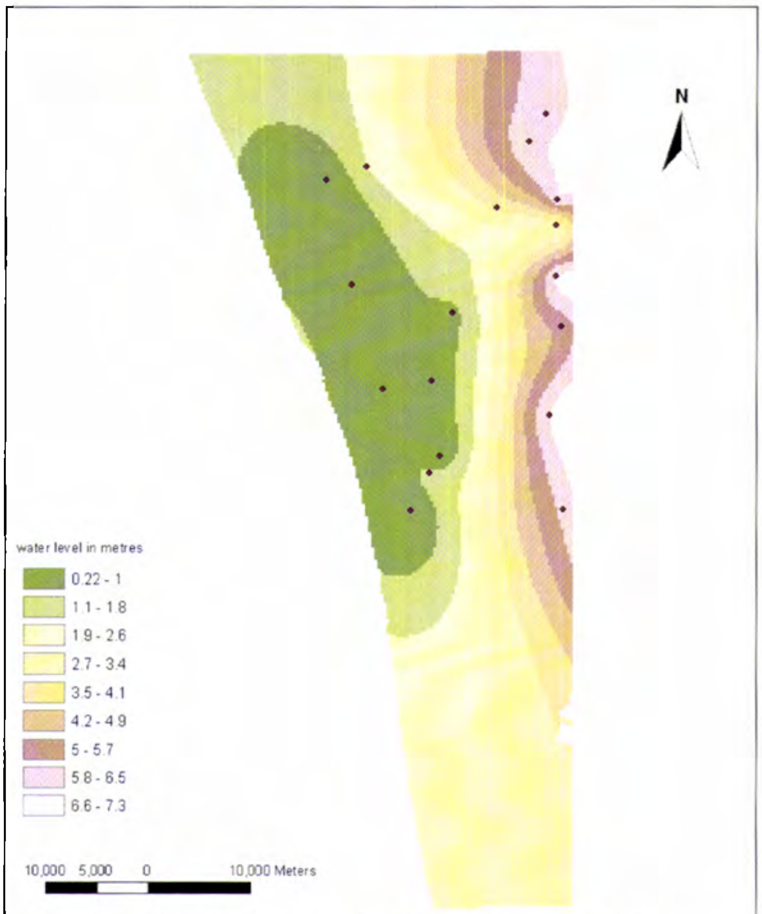



fig.3.2a SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-1993-PRE MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA 1994-POST MONSOON

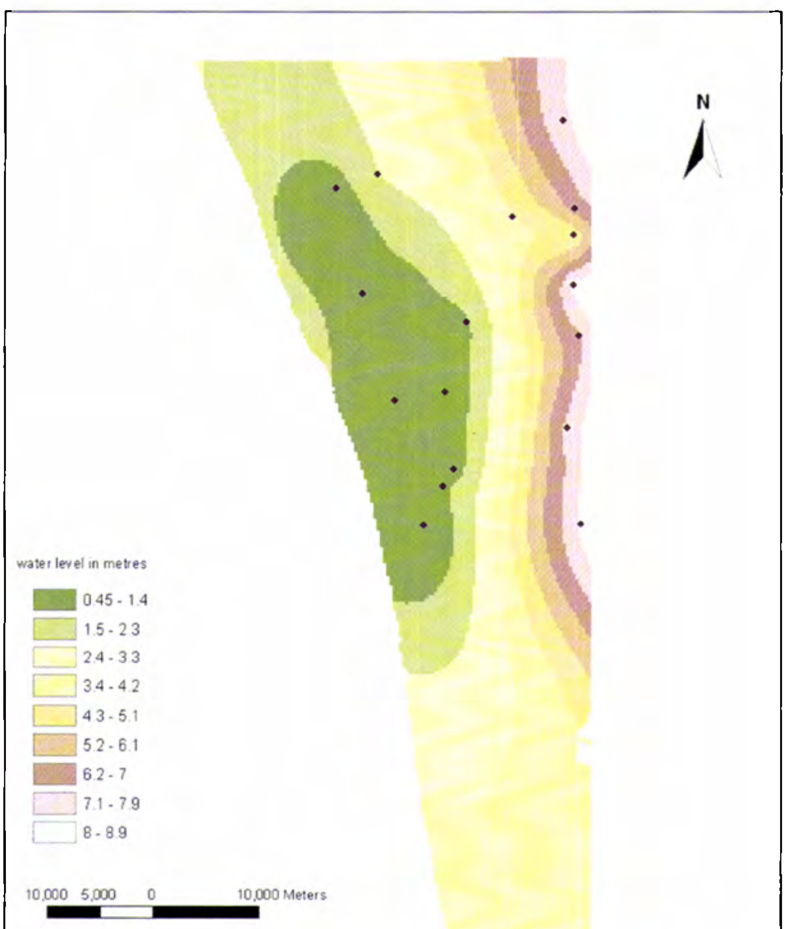
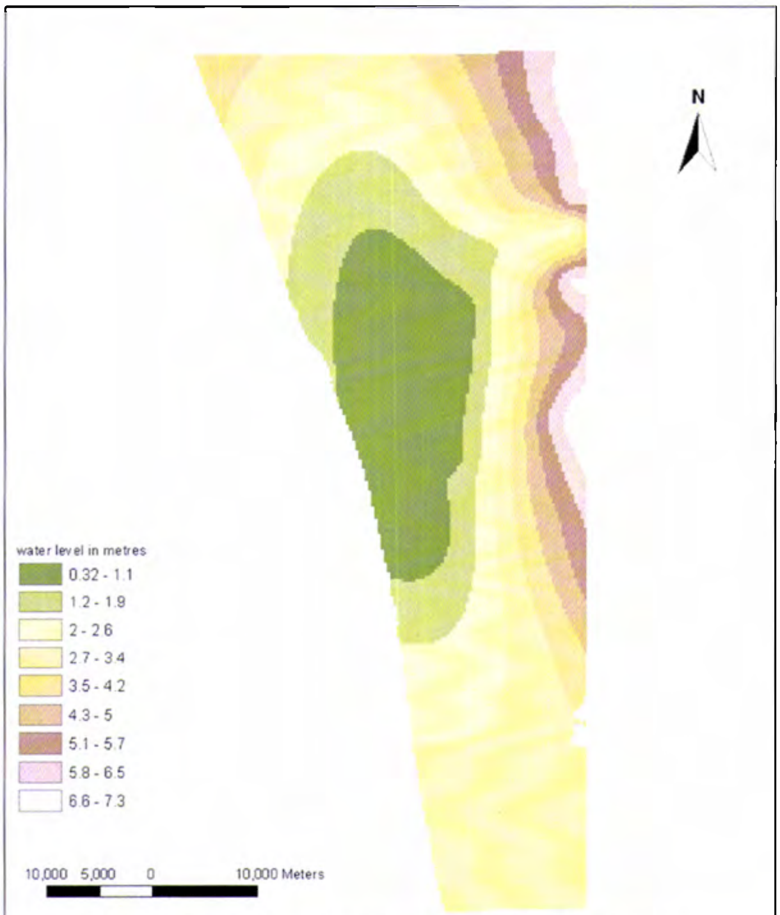



fig.3.2b SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA 1994-PRE MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-1995-POST MONSOON

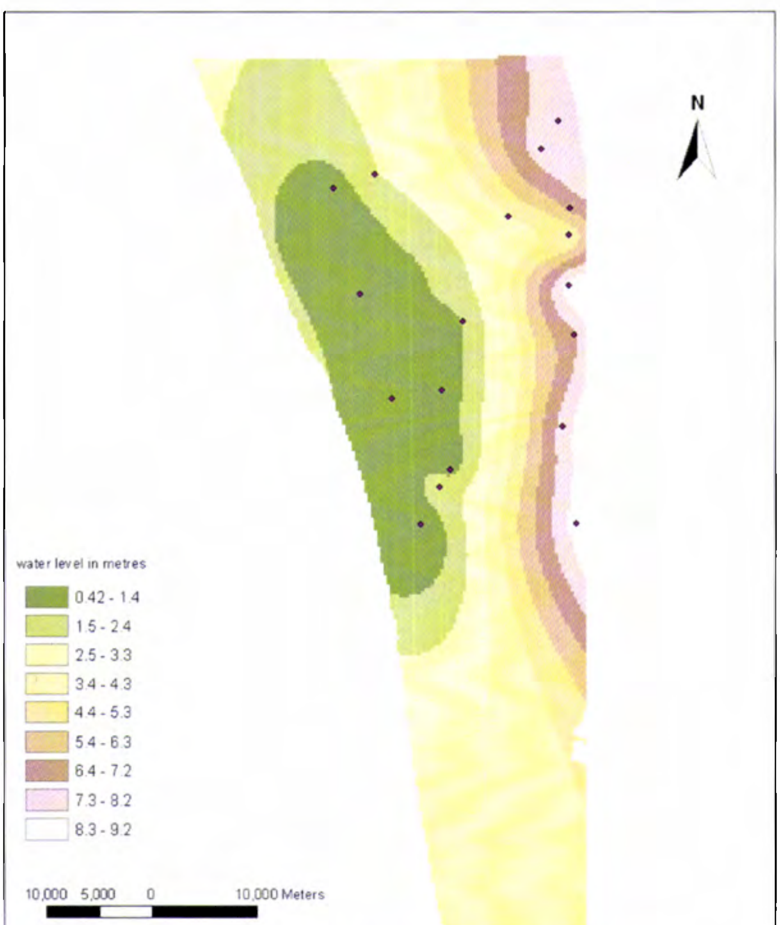
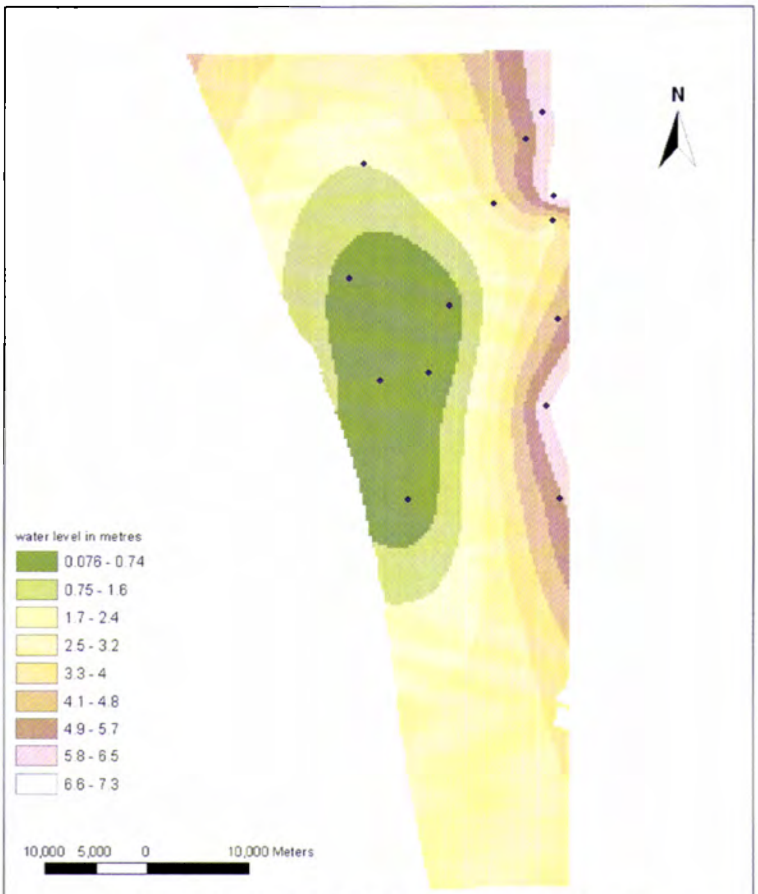



fig.3.2c SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-1995-PRE MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA 1996-POST MONSOON

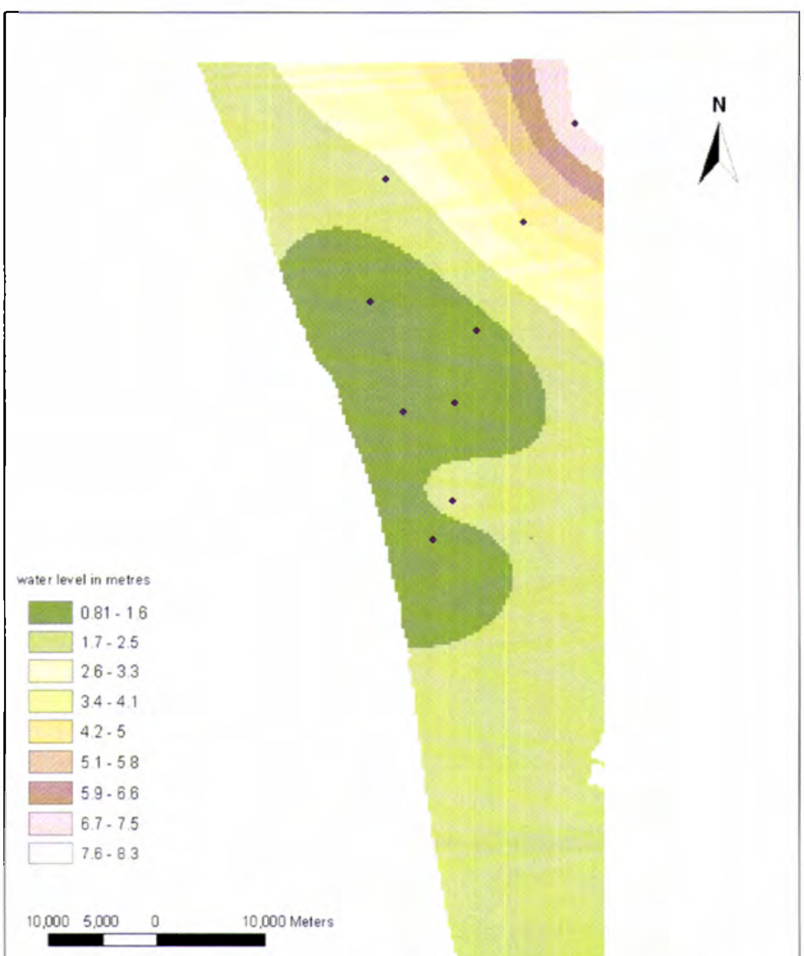
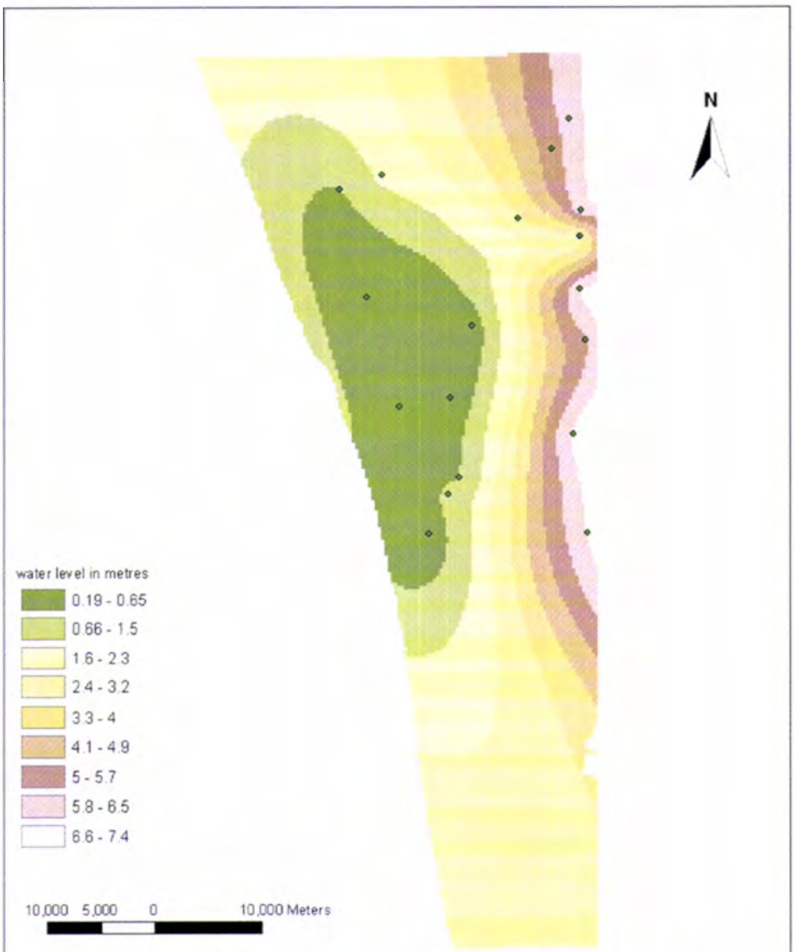



fig.3.2d SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA 1996-PRE MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-1997-POST MONSOON

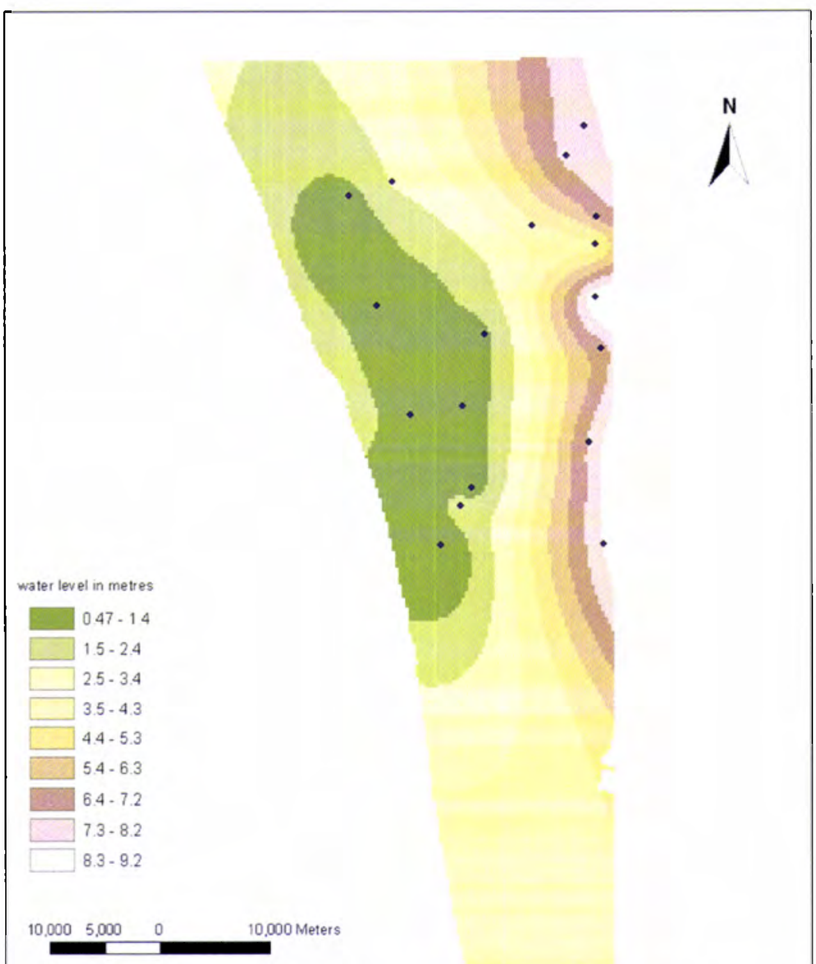
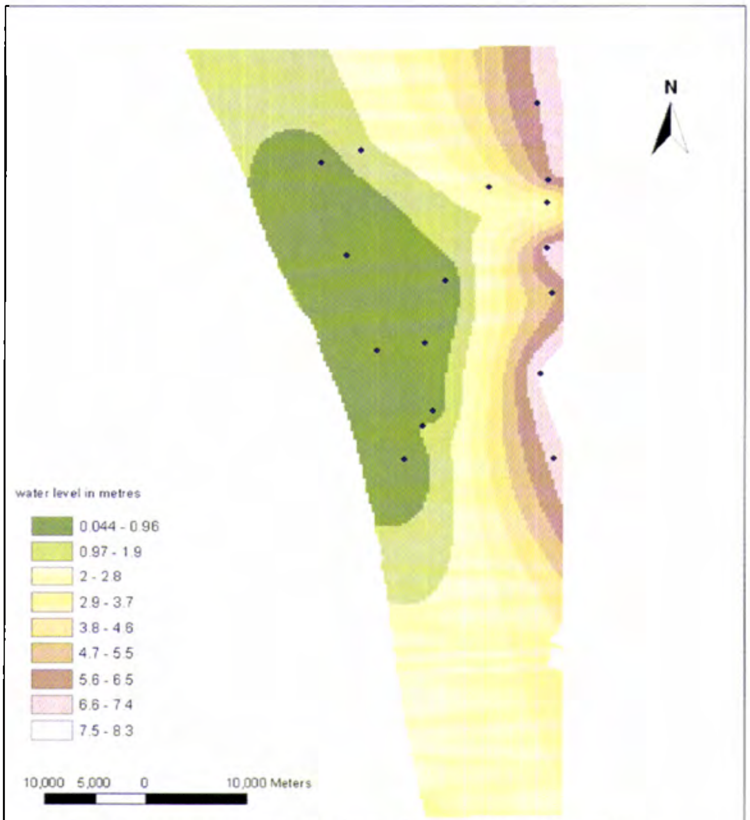



fig.3.2.e SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-1997-PRE MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-1998-POST MONSOON

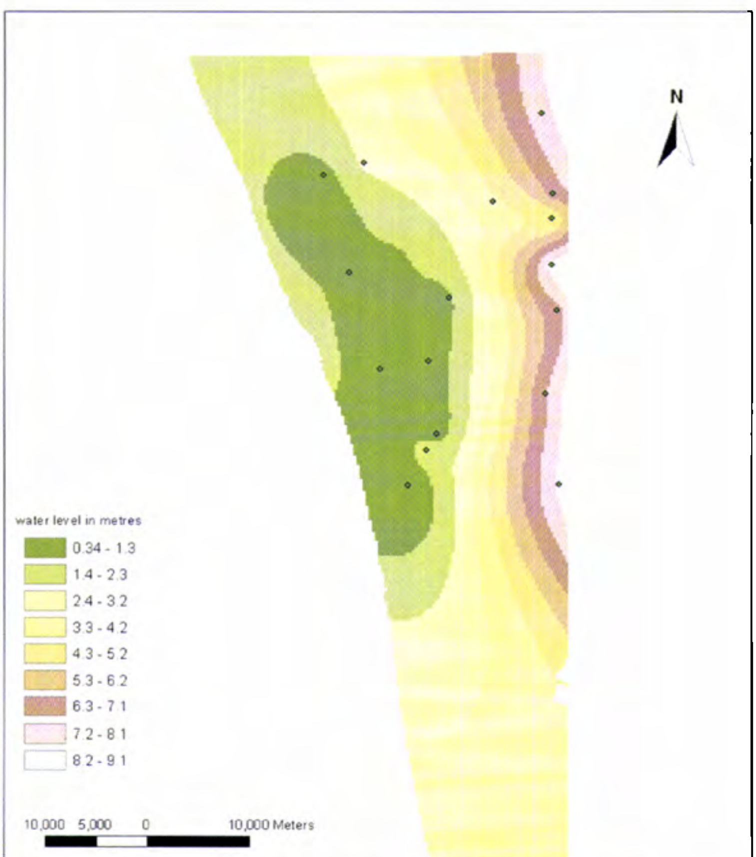
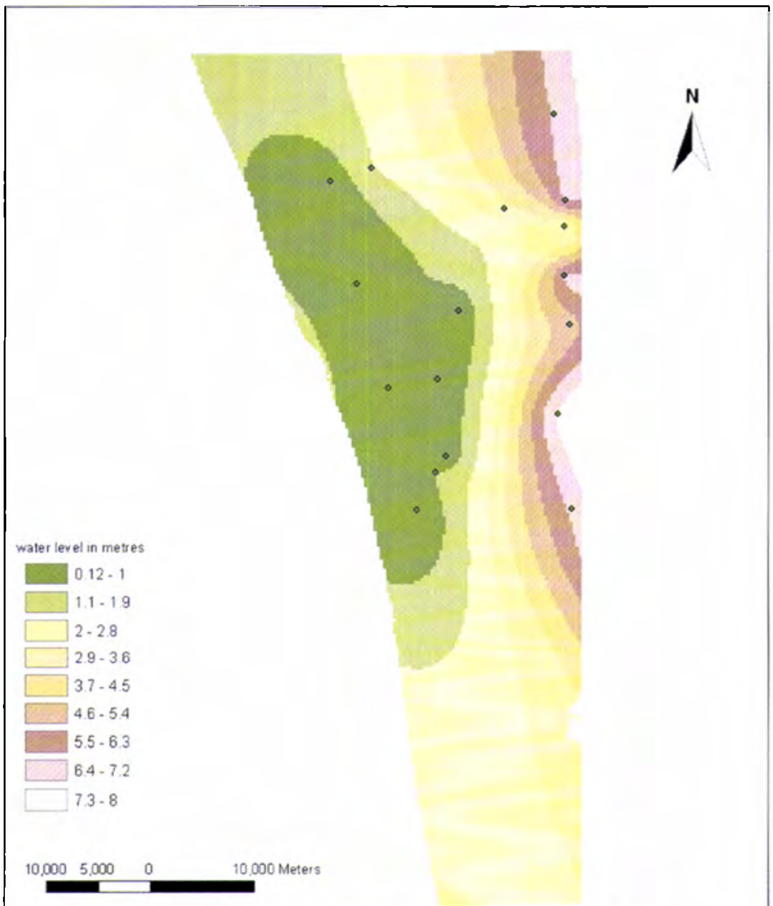



fig.3.2f SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-1998-PRE MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA 1999-POST MONSOON

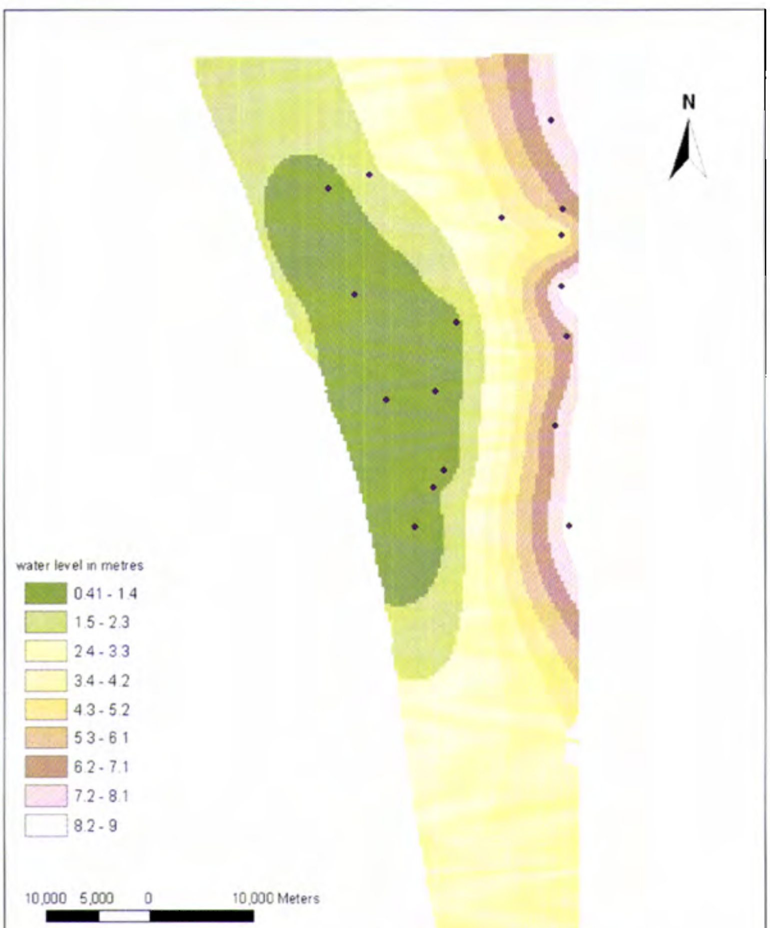
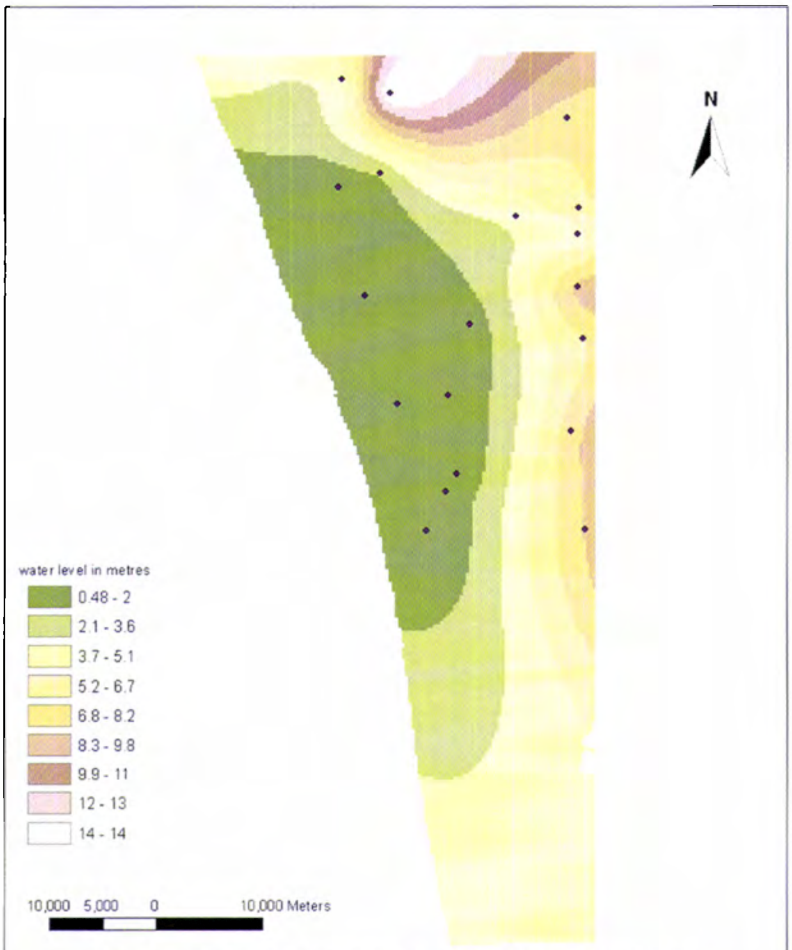



fig.3.2g SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA 1999-PRE MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-2000-PRE MONSOON

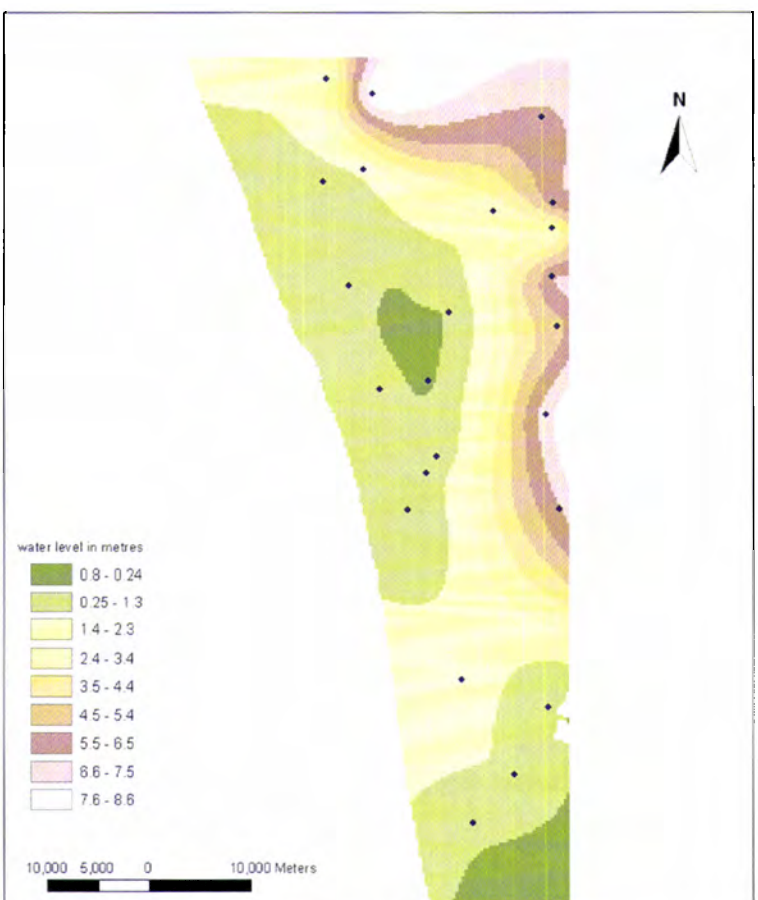
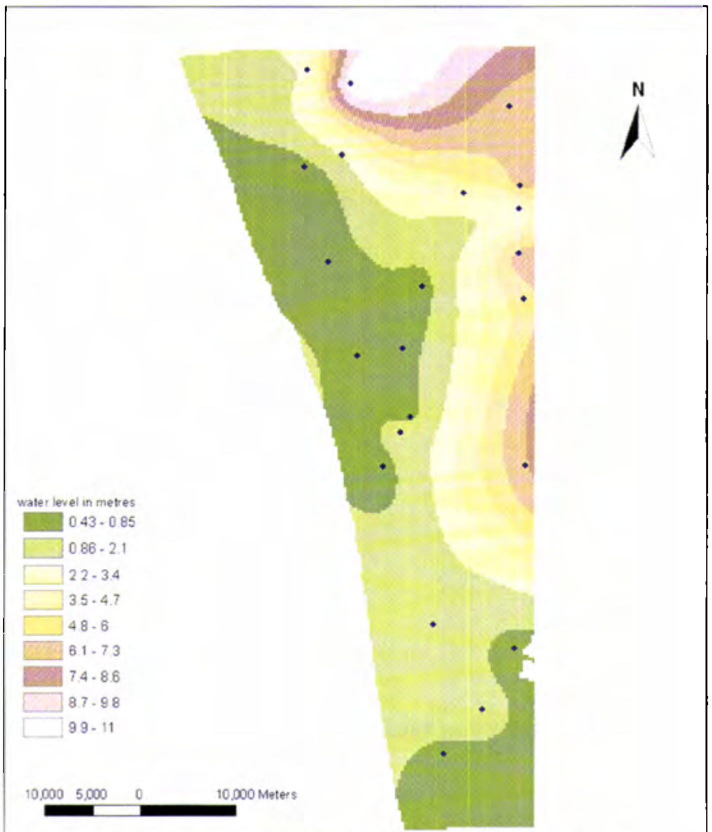



fig.3.2h SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-2000-POST MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-2001-POST MONSOON

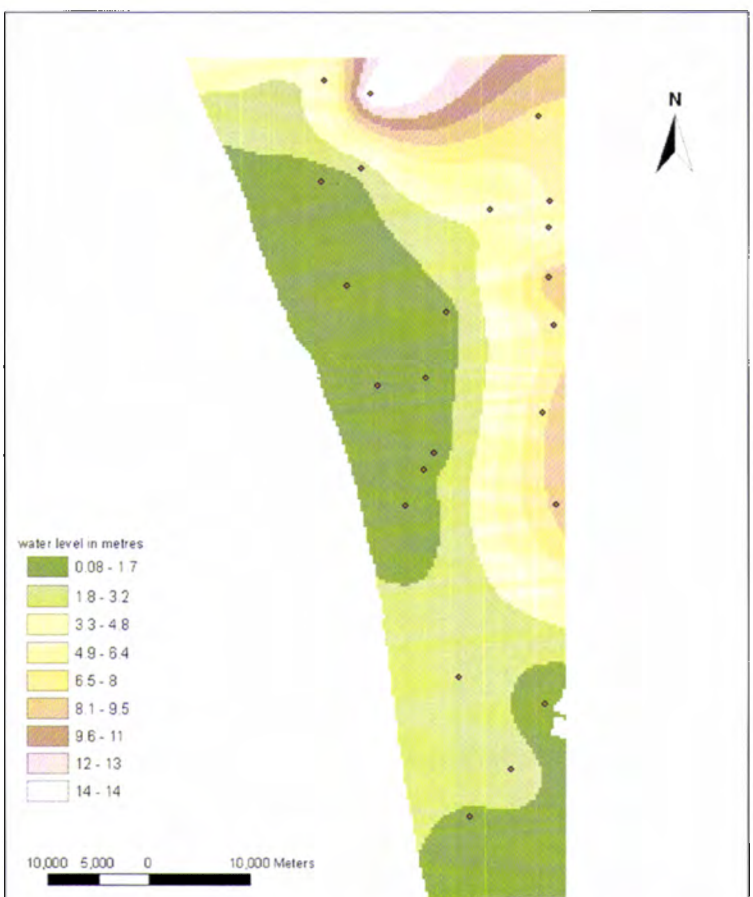
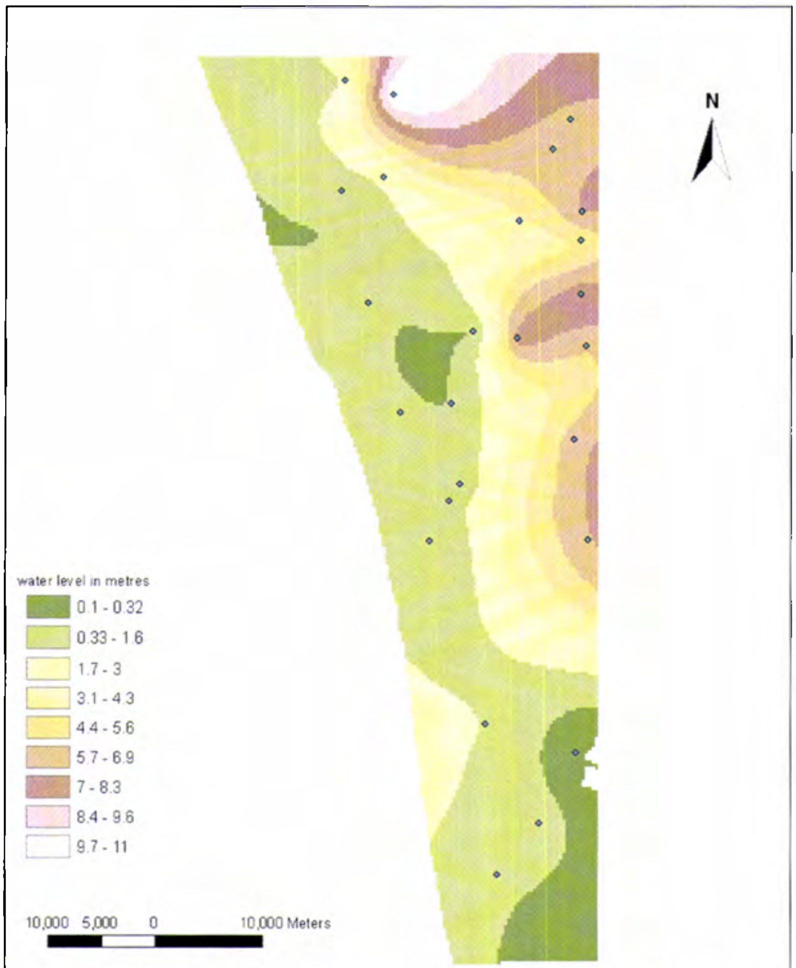



fig.3.2i SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-2001-PRE MONSOON




SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-2003-POST MONSOON

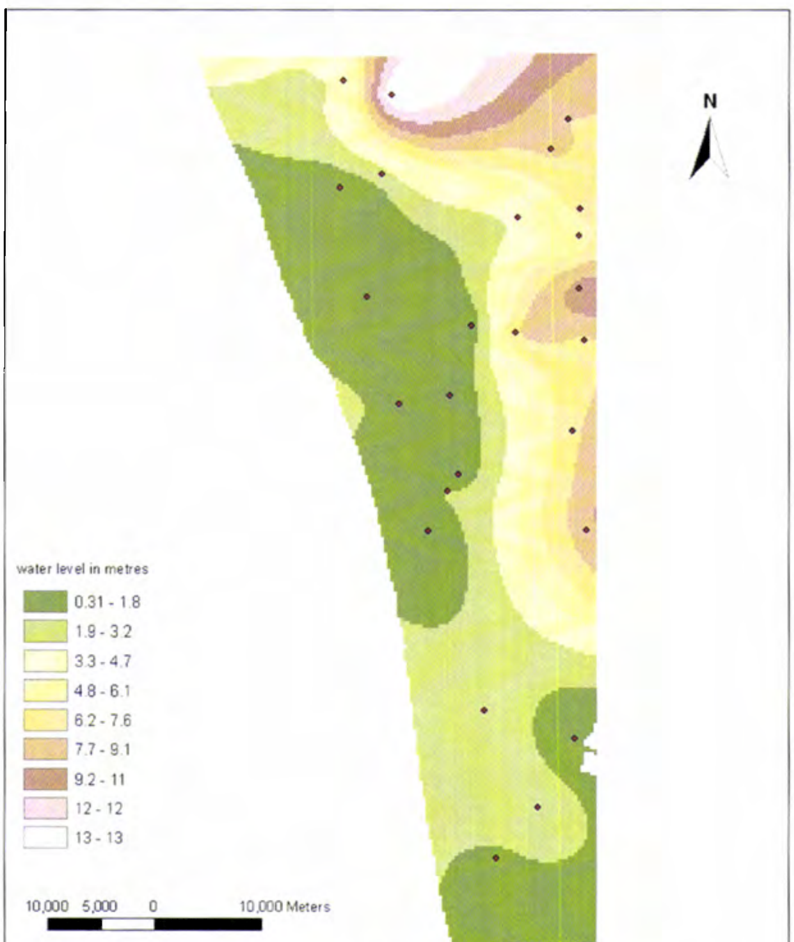



fig.3.2k SPATIAL DISTRIBUTION OF WATER LEVELS IN THE STUDY AREA-2003-PRE MONSOON

Kodungalloor but interestingly the observation well which showed the maximum rise during the pre-monsoon shows a fall of 0.053 m. This can be attributed to the presence of clay lenses in the area, which act as perched aquifer showing different characteristics from the surrounding.

GIS also has been extensively used in the water level study to bring out the statistical analysis of water level fluctuations and flow characteristics like water level contours, flow accumulation, flow direction, flow length and basin analysis between 1993 and 2003. Several recent developments have made the process of interfacing GIS and hydrologic models easier. First, the development of ArcView Spatial Analyst tool provided raster-modeling capabilities on the desktop, where most of the hydrology work is done. ArcView Spatial Analyst also led to the adoption of a simple, open standard vector format the ESRI shape file, which facilitates data exchange and conversion. In the present study various extensions of the spatial analyst in GIS has been utilized to undertake comprehensive study of the area. The flow accumulation raster of the study region is displayed in the figure 3.3, which gives the number of cells upstream of any given cell in the drainage network. A flow accumulation function is applied to get the flow accumulation grid by calculating the accumulated flow as the accumulated weight of all cells flowing into each down slope cell in the output raster. Many authors have used the flow accumulation function for representing field data in a user-friendly manner (Stube and Johnston (1990), Santasmita and Paul (2006).

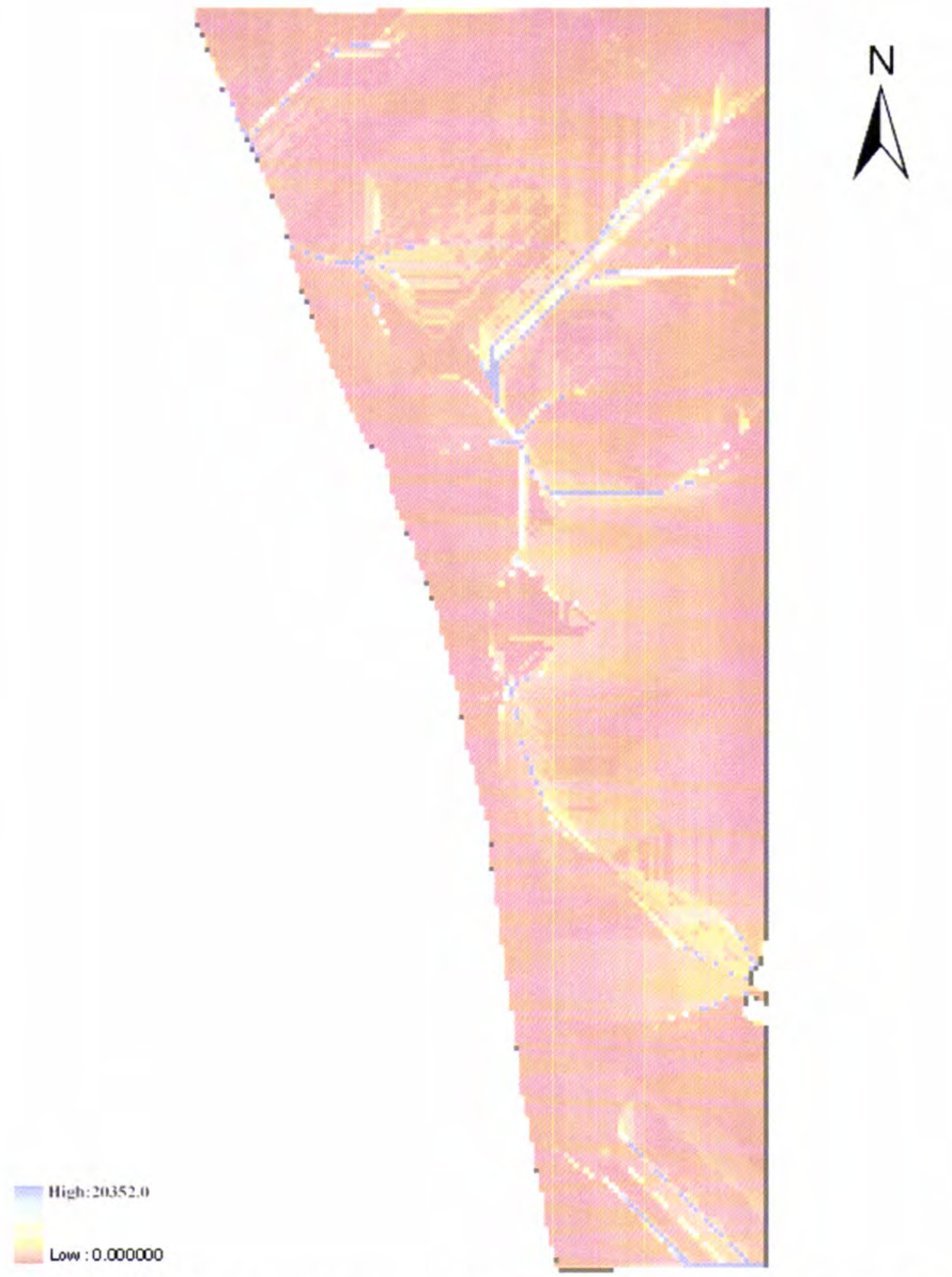



fig.3.3 Groundwater flowaccumulation raster of the study area - 2003

Figure.3.4 shows the flow direction raster of the study region which represents direction of flow length upstream represents the flow length from each cell to the top of the drainage divide whereas flow length downstream represents the flow length from each cell to a sink or outlet. Fig. 3.5 gives the statistical analysis of the water level data over ten years.

### 3.5. Hydrograph analysis

A hydrograph is a two-dimensional graph representing change of some property of water with time. It is a record of hydraulic head through time at a well or the changes in hydraulic head (drawdown) recorded during the pumping of a well in a test. Hydraulic head is a measure of the amount of energy exerted per unit weight by the groundwater, flowing through an aquifer. The word head indicates that the quantity is expressed in terms of a length of water (1ft of head is equal to 0.43 psi of pressure). In hydrogeology, it is convention to use gauge pressure (pressure measured greater than atmospheric pressure) when speaking of pressure head (unless absolute pressure is explicitly specified). Changes in hydraulic head ($h$) are the driving force which causes water to move from one place to another. Hydraulic head is a directly measurable property and can be measured with a pressure transducer. Commonly, in wells tapping unconfined aquifers the water level in a well is used as a proxy for hydraulic head, assuming there is no vertical gradient of pressure. Often only changes in hydraulic head through time are needed, so the constant elevation head term can be left out.

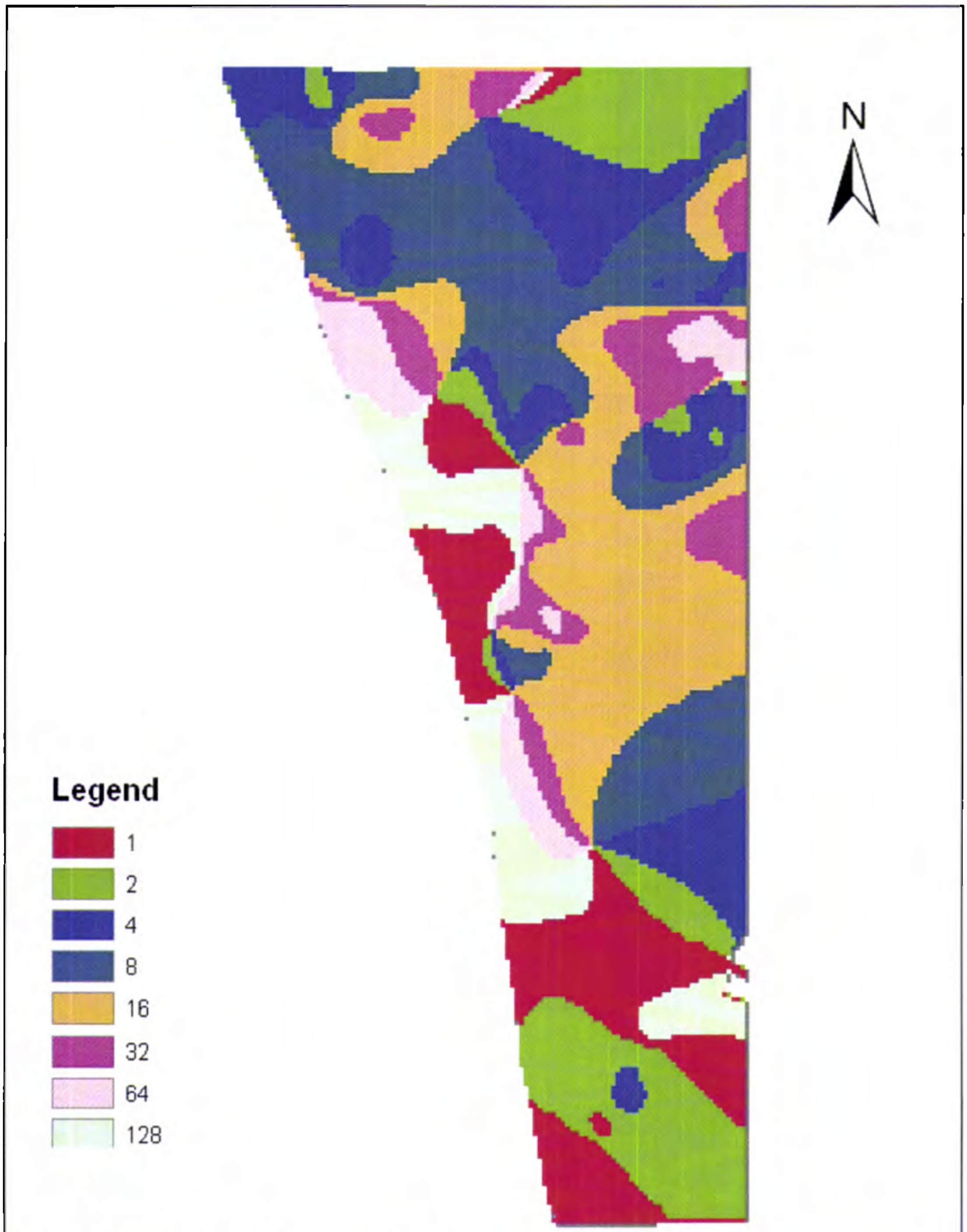



fig.3.4 Groundwater flow direction raster of the study area - 2003

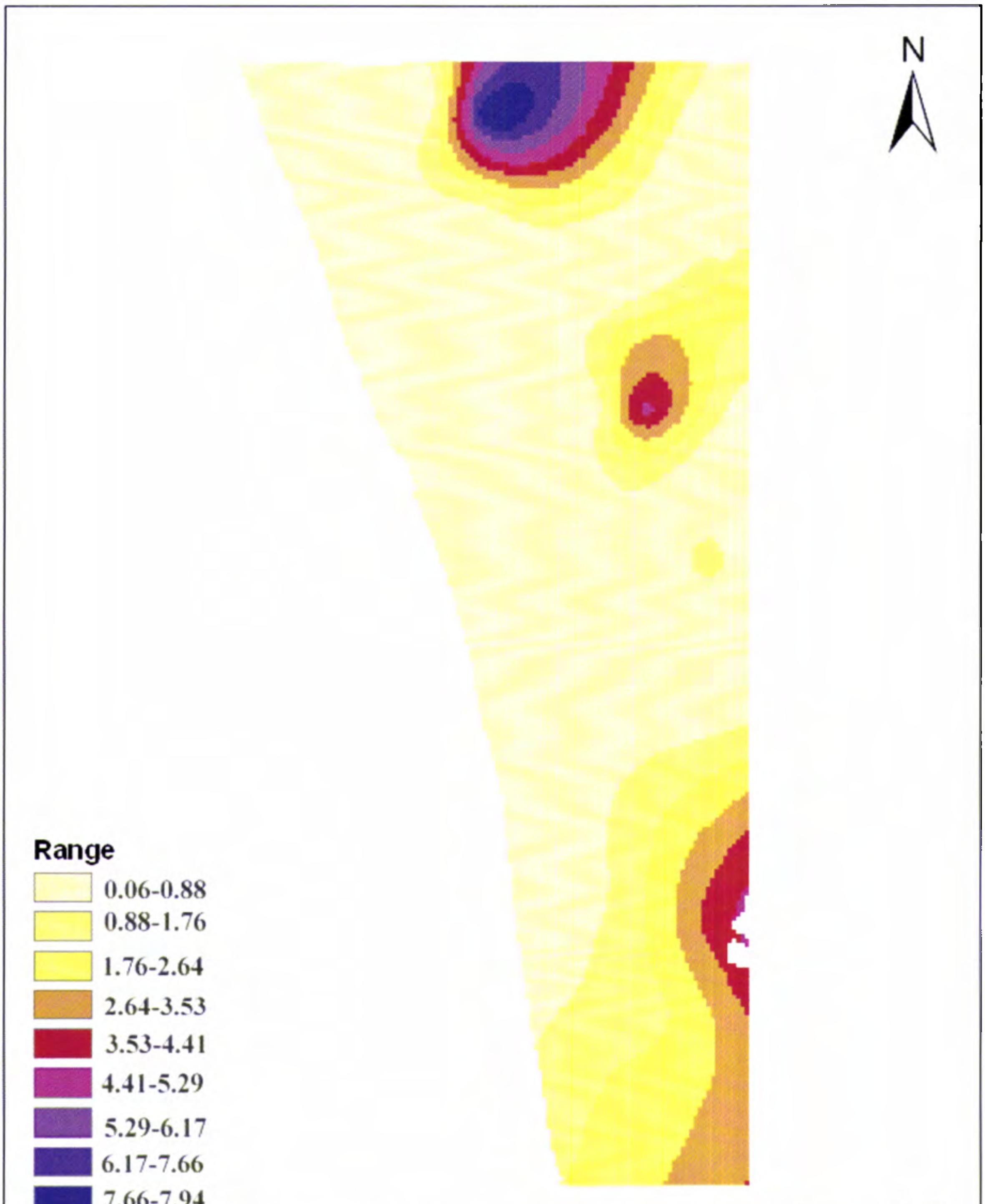



fig.3.5 Statistical analysis of water levels from 1993 to 2003 using GIS

Hydrograph helps in analyzing behavior of water table with time, period of recharge and discharge, providing warning signal to indicate groundwater over-development, cautioning to take remedial measures to prevent water-logging, ground water recharge and discharge areas and estimation of ground water resources.

Hydrographs allow comparison of water levels over time. Comparative hydrographs can show how ground water levels vary between wells screened in the same aquifer or different aquifers. The hydrograph of the groundwater level is the most important and quite frequently the only means to gather some information of the hydrological and, to a certain extent, the geological conditions of the subsoil. Monitoring changes in groundwater levels in response to management practices is helpful in indicating the degree of threat faced and the necessary timing and scale of preventative treatments. Ruhi *et al.*, 2000 and Shao *et al.*, 1999 suggested an approach based on fitting different linear trends in different segments of the data over the duration of the records. Their approach has the advantage that it allows for differences in rainfall levels in different periods. It is also a useful method for classifying the hydrographs of a region into similar groups for further investigation.

Trend analysis of groundwater gives the secular variations of water levels over several wet and dry periods. Recharge is the governing factor of groundwater level change and it depends on rainfall intensity, distribution and amount of surface runoff. Several authors have studied trend analyses to get a clear picture of water level variations in groundwater studies. Lal

(2004) studied fluctuations of water level using hydrographs in Alleppey. In the present study, hydrographs of ten years were analyzed to monitor the response of water level to groundwater recharge. The method of least square for best fitting was adopted to find out the slope of the trend line. In general, a well hydrograph should follow a definite trend like a stream flow hydrograph with a peak followed by a recession limb in response to the recharge and discharge. The trend line indicates the general behaviour of water levels.

The GIS maps and hydrographs provide an overview of ground-water levels of the aquifers in the study area during 2003. In addition, the hydrographs provide a visual summary of ground-water conditions for the past 10 years (1993–2002) compared to the period of record. Inspection of the hydrograph shows the water table to be sensitive to changes in the hydrologic regimen of the area. Water levels in aquifers in the study area typically follow a cyclic pattern of seasonal fluctuation, with rising water levels during post monsoon due to greater recharge from precipitation, and declining water levels during summer due to less recharge. Greater evapo-transpiration and pumping also contribute to the decline. The magnitude of fluctuations can vary greatly from season to season and from year to year in response to varying climatic conditions. Generally a cyclic pattern can be observed in the hydrographs. Ground water pumping is the most significant human activity that affects the amount of ground water in storage and the rate of discharge from an aquifer (Taylor and Alley, 2001). As ground-water storage is depleted within the radius of influence of pumping, water levels in the aquifer decline, forming a cone of depression around the well. In areas having a high density of pumped wells, multiple cones of depression can form and produce water level declines over a large area. These declines may alter ground-water-flow directions, reduce flow to streams, capture water from a stream or adjacent aquifer or alter ground-water quality.

The effects of sustained pumping can be seen on a hydrograph of observation well in Kalady by fig. 3.6. Comparison of hydrographs of wells of the crystalline terrain and coastal plains has been made and is shown in fig.3.7 It is seen that the hydrographs follow a similar pattern. Correlation of rainfall and water level is done by superimposing the rainfall data and water level data. The results for a period of ten years from 1993 to 2002 are shown in Fig.3.8. It is seen that the water levels follow rainfall pattern. Hence it can be concluded that rainfall is the major controlling factor of water level in the study region. The trend of the water level generally varies from –0.2 to 0.146. However no generalization could be made on the basis of geology as far as trend in water level is concerned. But a comparative analysis of the hydrographs on the basis of the geology has been made and is discussed below.

### 3.5.1. Hydrograph analysis of the Coastal Belt

The wells at Mattancherry, Kumbalngi, Chellanam, Paravur and Njarakkal (fig.3.9a-3.9e) fall in the coastal belt of the study area and are in alluvium. Of these wells, apart from the well at Chellanam all others show a declining trend varying from -0.2 to – 0.027. All these wells fall in the

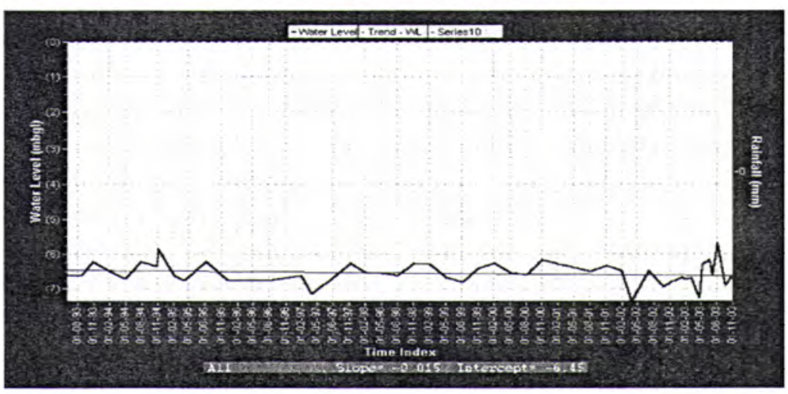



Fig 3.6 well showing depletion

Periyar basin. Long-term fall in the water level may be attributed to decrease in rainfall, overdraft of water and environmental impacts of urbanization. The well at Chellanam falls in the Muvattupuzha basin and this well shows an increasing trend of 0.04. The long-term water level rise is due to recharge, which depends on rainfall intensity, distribution and amount of surface runoff assuming annual withdrawal is constant. (Ground Water Year Book, Ernakulam District, State Groundwater Department, Kerala-2003).

A comparative analysis of these wells is presented in the figure. 3.10. It is very clear from the figure that the hydrographs of these wells follow an almost similar pattern. The general pattern in the distribution of peaks and limbs of hydrographs suggest that steep peaks and limbs characterize open wells in majority of the places along the coastal belt. This sharp rise may be attributed to the dominant vertical recharge of the shallow aquifers.

### 3.5.2. Hydrograph analysis of the Laterite terrain

Laterite is one of the most important water bearing formation in the study area and occurs as outcrops in many parts as shown in the geological map. Wells in the following places namely Aluva, Ankamaly, Mulamthuruthy and Thrikkakkara falls in laterite terrain and all these wells show an increasing trend from 0.05 to 0.403 as observed in fig.3.10.a-3.10d. But this cannot be taken as a general feature amongst all wells in the laterite terrain in the study area. The observation well in Aluva and in Kunnathukad shows a declining trend ranging from –0.022 to –0.015 as

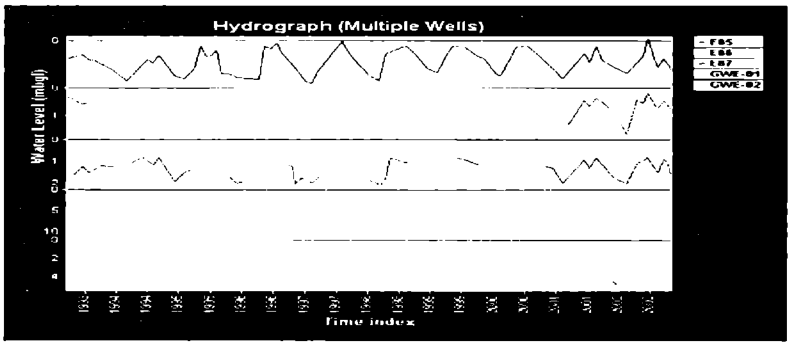



fig.3.7 Comparison of hydrographs of crystalline and coastal belt

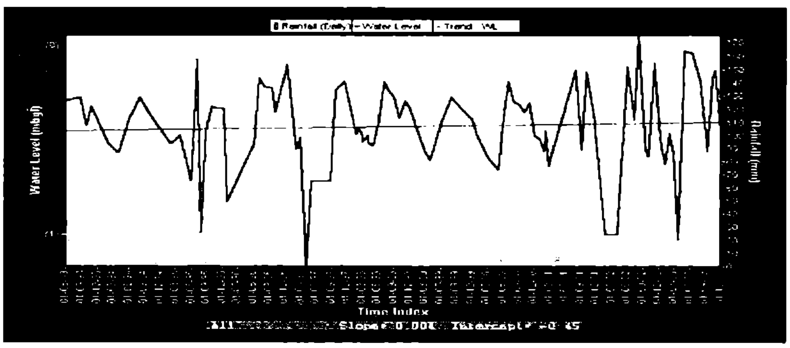



fig.3.8 Correlation of rainfall and water level data

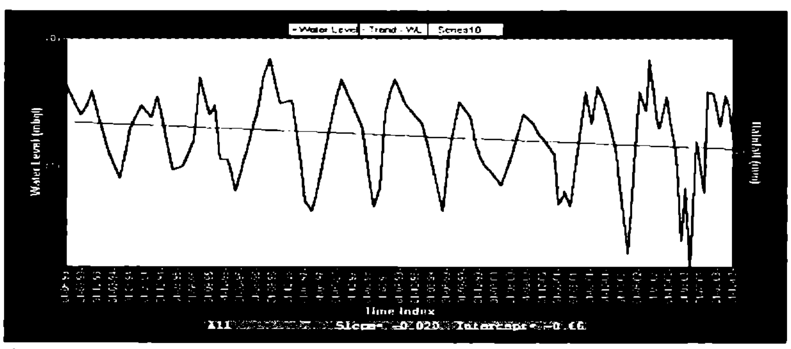



fig.3.9a hydrograph of well at Mattancherry

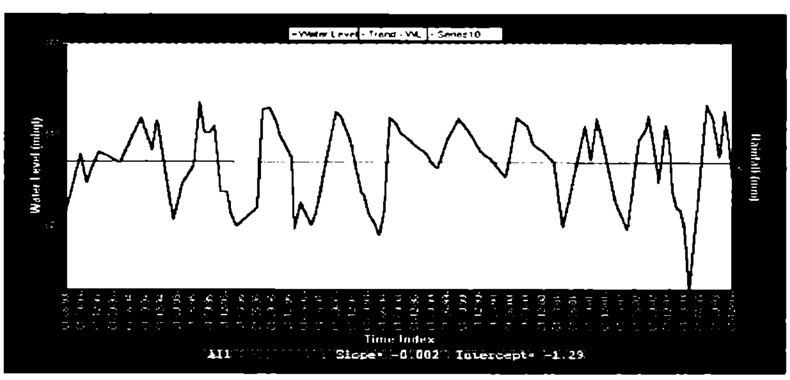



fig.3.9b hydrograph of well at Kumbalangi

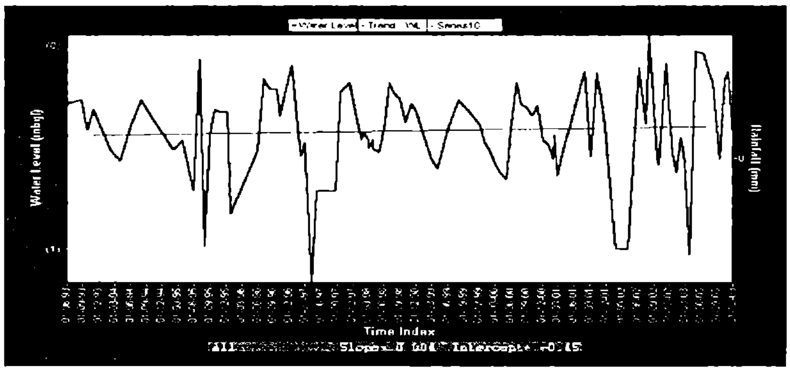



fig3.9c hydrograph of well at Chellanam

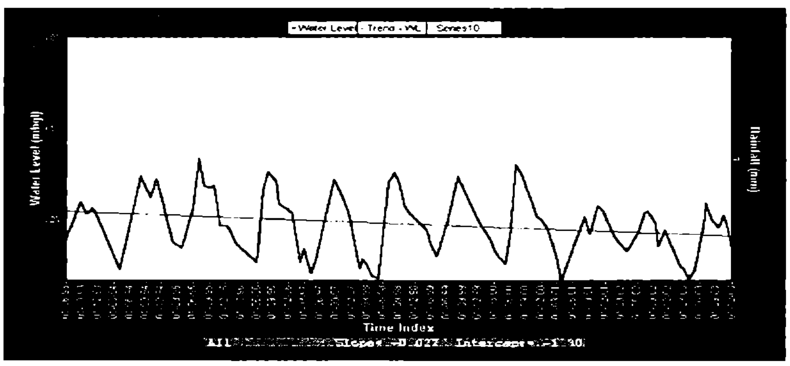



fig.3.9d hydrograph of well at Paravur

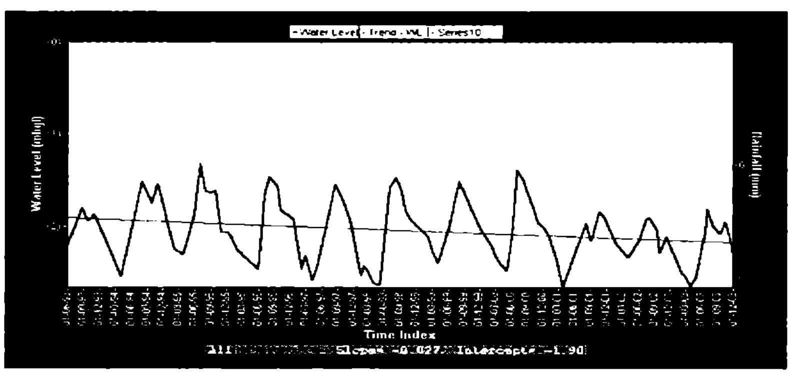



fig.3.9e hydrograph of well at Njarackal

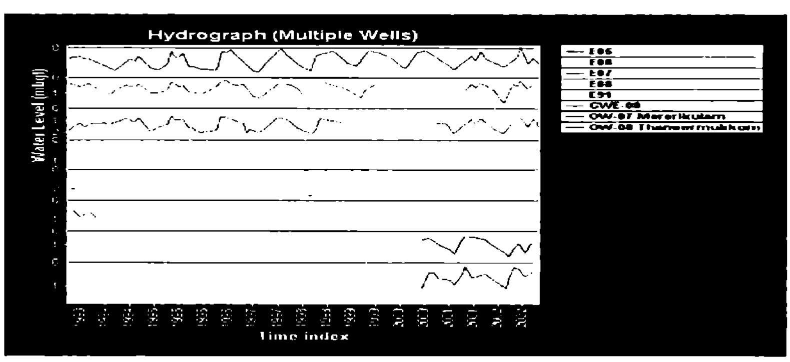



fig .3.10 Comparison of well hydrographs of the coastal belt.

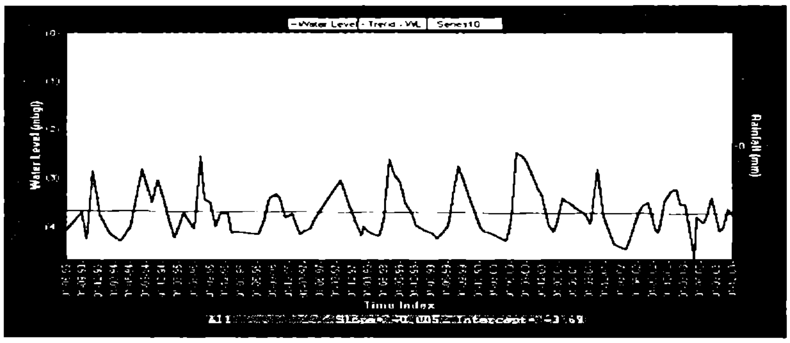


fig 3.10a hydrograph of well at Aluva

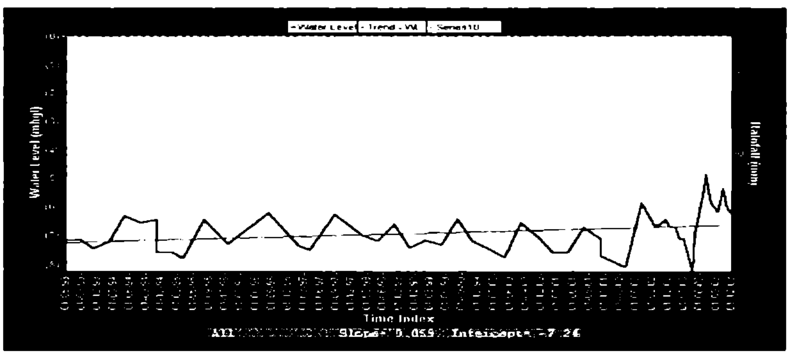


fig 3.10b hydrograph of well at Ankamally

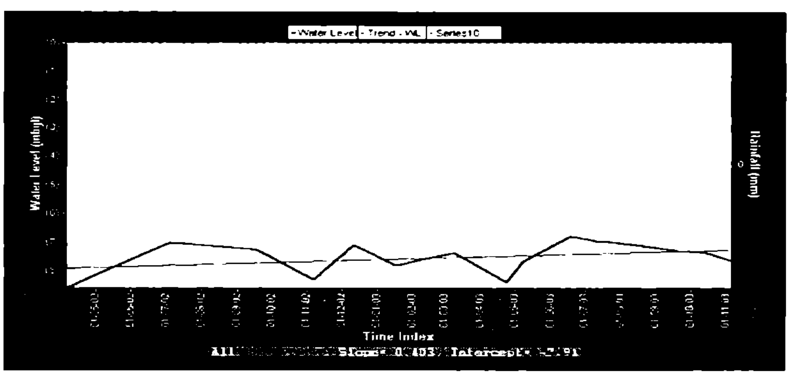


fig 3.10 c well hydrograph of Mulamthuruthy

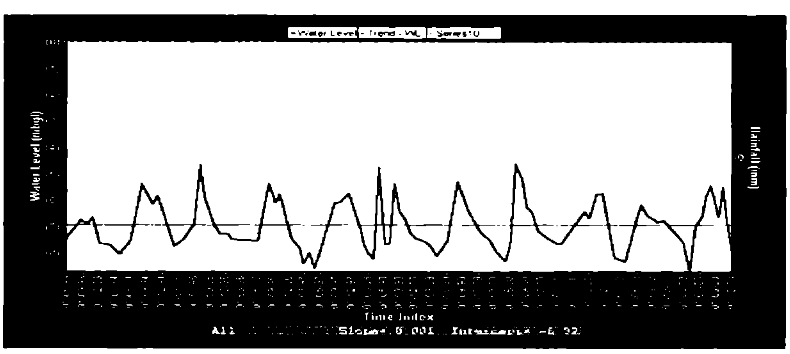


fig.3.10d hydrograph of well at Thrikkakara

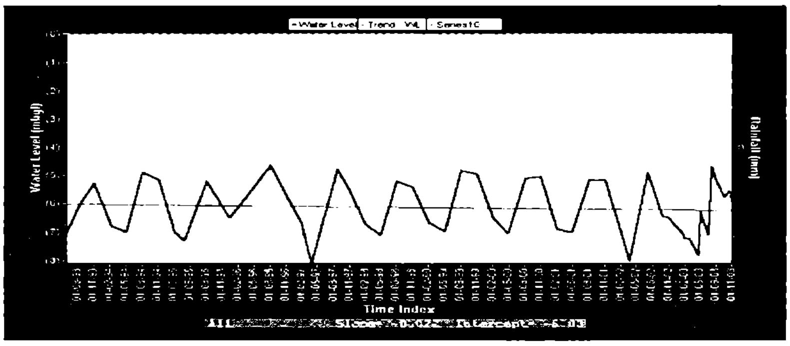


fig.3.11a well hydrograph of Aluva

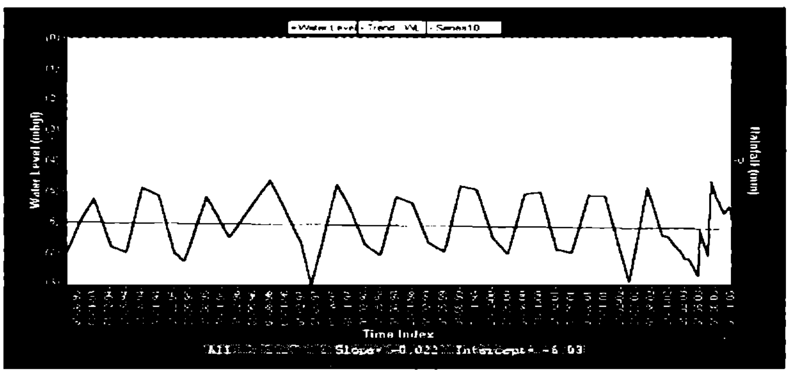


fig.3.11b well hydrograph of Kunnathukad

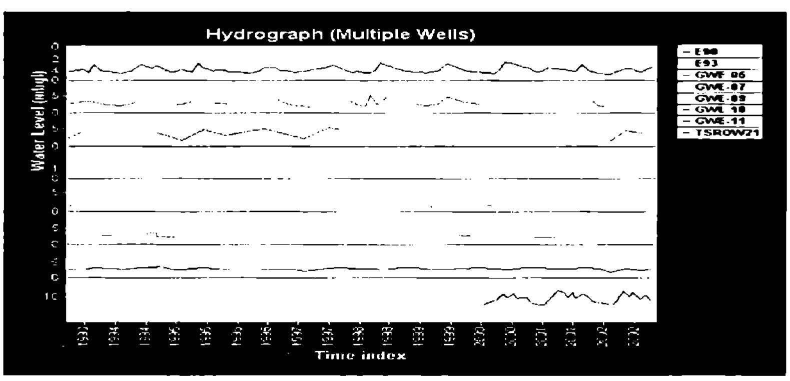


fig.3.12 comparison of hydrographs in laterite

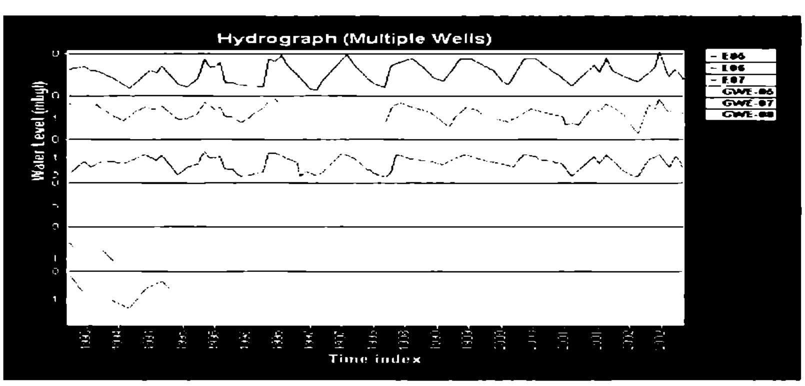


fig 3.13 Comparison of hydrographs of alluvium and laterite

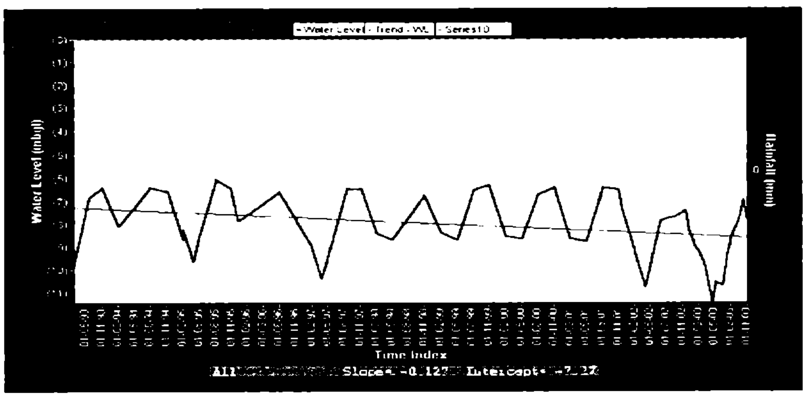



fig.3.14a Hydrograph of well at Kizhakkambalam

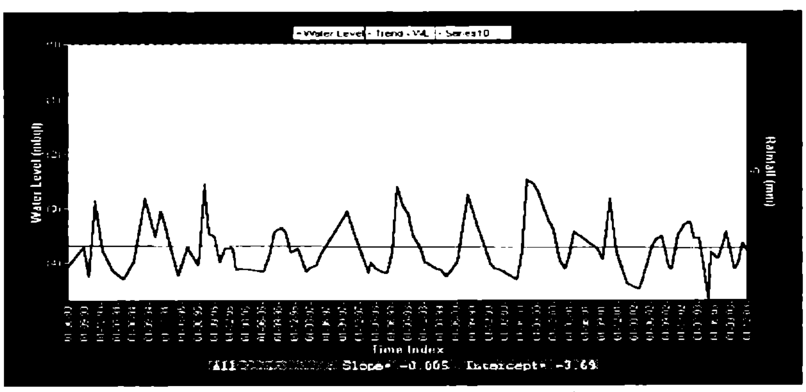



fig.3.14b hydrograph of well at Kunnathukad

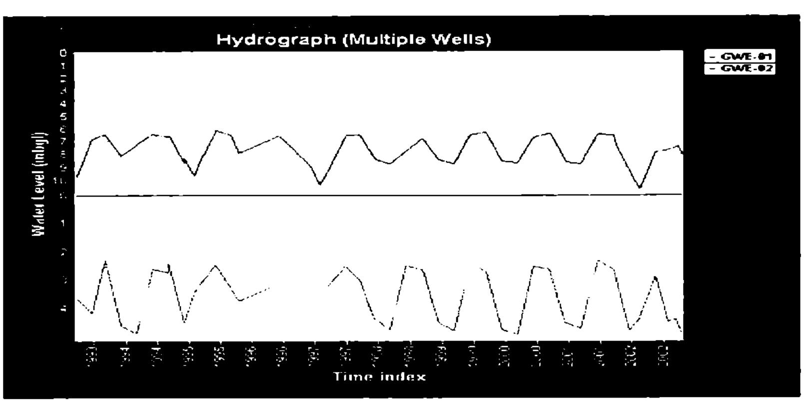



fig.3.15 comparative analysis of wells in charnockites

seen in fig.3.11.a & 3.11.b. This area is also affected by pumping of water for tanker lorries to cater to city needs. A comparative analysis of all the wells in the laterite terrain is shown in the fig.3.12. Fig.3.13 shows a comparison of the hydrographs of alluvium and laterite of the study region

### 3.5.3. Hydrograph analysis of Charnockites

Fig.3.14a and 3.14b shows the hydrograph analysis of wells in Kizhakkambalam and Kunnathukal falls in charnockites terrain and is in the Muvattupuzha basin. Both these wells show declining trend of –0.0127 to –0.037 A comparative analysis of the hydrographs of the wells in the charnockites is shown in Fig.3.15.

### 3.5.4. Basin wise Analysis

The wells in the study area falls in three river basins namely Muvattupuzha, Periyar and Pampa. Majority of the observation wells in the study area falls in the Periyar basin. A comparative analysis of the hydrographs of wells in the three different basins shows that there is not much control of river basins on the hydrograph pattern in the study area.

## 3.6. Water balance studies

Water balance condition as well as changes in annual water yield and per capita water availability in the study region by the year 2025 have been estimated considering the population growth and increase in rainfall and temperature pattern. Present decadal growth of population is 14% and the population is expected to be stabilised by 2025. Changes in hydrological parameters (surpluses and deficiencies) have been computed using the water balance.

Table. 3.3. Changes in water availability - Kerala.

| **District** | **Area ($Km^2$)** | **Population ('01Census)** | **Per capita water availability (present level)** | **Per capita water availability (after 3 decades)** |
|---|---|---|---|---|
| Alappuzha | 1256 | 1990603 | 1010 | 593 |
| Ernakulam | 2408 | 2797779 | 1499 | 881 |
| Thrissur | 3032 | 2734333 | 1897 | 1115 |

The study reveals that in the coming decades there will be considerable reduction in water yield if the temperature increases and considerable reduction in per capita water availability if the present rate of growth of population continues, in the study region. To meet the requirements of the huge population in the domestic, agricultural and industrial sectors, utilization of more groundwater will become essential which may lead to lowering of water table and salinity intrusion along the coasts. Water resources in these regions face contamination not only from local sources but also from the eastern, mid and highlands carried by the rivers.

Proper land use, protection of topsoil, reduction of pollution, better agricultural practices and water conservation from the domestic level all needs attention. Basis of development lies in the protection and proper management of the resources in watersheds.

Chapter 4

# Geophysical Studies

## 4.1. Introduction

Geophysical exploration is the scientific measurement of physical properties of the earth's crust for investigation of mineral deposits or geologic structures. Geophysical methods detect differences, or anomalies of physical properties within the earth's crust. Density, magnetism, elasticity and electrical resistivity are properties most commonly measured. Geophysical techniques are generally sub-divided into

- Static
  - Magneto metric
  - Gravimetric
  - Telluric
- Dynamic techniques
  - Geo-electrical
  - Electro-magnetic
  - Seismic

The static techniques measure the resident physical parameters of subsurface rocks. In the dynamic technique rock parameters are measured as a response to energy fluxes injected into the earth.

Geophysical surveys provide information on geological structures like; fractures, joints, fissures, and faults. In addition to these nature and physical characteristics of sub-surface lithological units, extent and degree of weathering and the nature and extent of underlying bedrocks, which exercise a great control, on the occurrence and movement of groundwater can also be deciphered using geophysical exploration. Thus, the use of geophysical methods in ground water exploration has proved very important as they provide better understanding of many parameters of sub-surface lithology, type, vertical and horizontal extent of aquifers and geological structures etc. Further the geophysical data provides information of local geological environment, which influence ground water occurrence and movement. The main geophysical methods that have been used to solve some of the problems of hydrogeology are the electrical, seismic, gravity and magnetic method. In the present study electrical resistivity methods were put to use.

### 4.2. Electrical Resistivity Methods

Electrical resistivity is the most commonly used method in groundwater investigations as it employs simple technique, which is easy to operate. This technique is economically viable and time saving. Further the resistivity data involves simple interpretation and gives rise to fairly reliable results. The variation in moisture content of rocks, the changes in sub-surface litho units, the secondary porosity created by joints, fractures, and faults reflect the corresponding variations in electrical resistivity parameters.

These techniques are based on the injection of an electric current into the earth by means of two current electrodes. The electrical resistivity of a rock formation limits the amount of current passing through the formation. It may be defined as the resistance in ohms between opposite faces of a unit cube of the material. If a material of resistance R has a cross sectional area A and length L then its resistivity can be expressed as

$$\rho = RA/L$$

Resistivity of rock formations vary over a wide range depending on the material, density, porosity, pore size and shape, water content and quality and temperature. Resisitivity studies can be used either in the form of vertical electrical soundings (VES) or horizontal profiling to search for groundwater in both porous and fissured media (e.g. Barker, 1980; Van Overmeeren, 1989).

Vertical electrical sounding (VES) constitutes a particular field procedure for determining the various electrical properties with depth. In this method, apparent resistivity values are measured corresponding to successively increasing electrode separation at the same reference point called as sounding point. VES method is used to determine resistivity distribution in vertical direction. The subsurface is assumed to occur from horizontally stratified layers that are laterally homogeneous and isotropic (Zohdy, 1989; Telford *et al.,* 1992; Loke, 1997).

Schlumberger introduced the VES methods in 1934. Since then, a wide variety of VES arrays were developed (Keller and Frischknecht, 1966) but the Schlumberger array remained as the best array for depth sounding. However, application of the VES techniques were limited to shallow investigations until recently mainly because electronic measuring devices of sufficient sensitivity were not available except in bulky forms, and partly because deeper penetration would have meant a wider variety of resistivity layers than could possibly be incorporated in any set of standard resistivity curves. These standard curves provided the only means of interpretation by the curve matching techniques. The recent advances in electronics and the advent of high-speed computers made it possible to penetrate to large depths while using portable equipment, and to interpret the results without the limitations imposed by the standard resistivity curve albums. However, the interpretation of VES data as well as all other resistivity data is ambiguous. It is important to keep in mind that a unique interpretation can be made only when good control is available through wells which were drilled by means of modern drilling practices and logged by calibrated logging devices. Modern drilling practices ensure minimal changes in the properties of the strata penetrated by the well and calibrated logging provides the true resistivities of the strata in absolute units.

The use of geophysics for both groundwater resource mapping and for water quality evaluations has increased dramatically over the last 10 years in large part due to the rapid advances in microprocessors and associated numerical modelling solutions. The vertical electrical sounding (VES) has proved very popular with groundwater studies due to simplicity of the technique. Traditional methods for characterizing protective layers include test hole drilling and analyses of log with the objective being to characterize thickness and/or lateral extent of the protective layer. Disadvantage of such investigations are that they can be labour-intensive and expensive (Kalinski *et al.,* 1993). The principle of Vertical electrical sounding was established in the 1920's (e.g. Gish and Rooney, 1925). The electrical resistivity survey involved in VES is based on measuring the potentials between one electrode pair while transmitting direct current (DC) between another electrode pair. The depth of penetration is proportional to the separation between the electrodes, in homogeneous ground, and varying the electrode separation provides information about the stratification of the ground (Dahlin, 2001). The resistivity method is carried out to solve more problems of groundwater in the types alluvium, karstic and another hard formation aquifer as an inexpensive and useful method. Some uses of this method in groundwater are determination of depth, thickness and boundary of an aquifer (Zohdy, 1989 and Young *et al.,* 1998), determination of interface saline water and fresh water (El. Waheidi *et al.,* 1992, and Choudhury et al., 2001), porosity of aquifer (Jackson *et al.,* 1978), hydraulic conductivity of aquifer (Yadav, 1998, Troisi *et al.,* 2000), transmissivity of aquifer (Kosinski and Kelly, 1981), specific yield of aquifer (Frohlich and Kelly, 1987), hydrogeological mapping in karst terrains (Sumanovac and Weisser, 2001), contamination of groundwater (Kelly, 1976 and Kaya, 2001). Contamination usually reduces the electrical resistivity of pore water due to increase of the ion concentration (Frohlich and Urish, 2002). However, when resistivity methods are used, limitation can be expected if ground inhomogenities and anisotropy are presented (Matias, 2002).

The electrical resistivity of rock is a property that depends on lithology and fluid content. The resistivity of coarse-grained well-consolidated sandstone saturated with fresh water is higher than that of unconsolidated silt of the same porosity saturated with the same water. Also the resistivities of identical porous rock samples vary considerably according to the salinity of the saturating water. The higher the salinity of the water the lower the resistivity of the rock. Thus it is quite possible for two different types of rock such as shale and sandstone to be of essentially the same resistivity when the sandstone is saturated with saline water and the shale with fresh water. For this reason the number and thickness of the geoelectric units as determined from VES measurements at a locality may not necessarily be the same as the geological ones. In this respect, geoelectric units define parastratigraphic units (Krumbein and Sloss, 1963) whose boundaries may be discordant with the stratigraphic boundaries.

The ultimate objective of a VES at some locality is to obtain a true resistivity log similar to, for example, the induction log of a well at the locality, without actually drilling the well. However because of the inherent limitations the resolution of the VES methods is not as high as that of the induction log. Nonetheless, the VES methods remain as the most inexpensive methods of subsurface exploration. They surpass the more expensive seismic method in one major respect. The seismic signal associated with a sandstone body would be the same whether its pores are saturated with fresh or with brackish water. On the other hand its resistivity varies according to small changes in water salinity. This property together with the low cost makes the VES methods very suitable for groundwater exploration.

In resistivity sounding the electrode spacing is changed while maintaining a fixed location for the centre of the spread. Since depth of investigation increases in a general way with increasing electrode spacing the resistivity sounding is preferred to find out the resistivity variation with depth. Various standard electrode spacing arrangements have been adopted amongst which the most common are the Wenner and Schlumberger arrangements. In the present study Schlumberger configuration has been used.

Geophysical imaging of aquifers is useful because such surveys are more time and cost effective than collecting sediment cores and well data. Also geophysical surveys provide noninvasive spatial images of the aquifer while borehole data only provides information of the aquifer in close proximity to the well. However interpretation of the geophysical data can be ambiguous if clear correlations are not established between the geophysical attributes and the hydrological and stratigraphic properties of the aquifer. (Koster and Harry 2005). Given the usual scarcity of core and geophysical logs, establishing such a correlation is often problematic. As an alternative geophysical study of outcrops of the aquifer strata are often used. (eg, Wolf and Richard, 1996; Hubbard and Rubin, 2000). Water content affects a variety of geophysical attributes including electrical resistivity and seismic and radar velocity and reflectivity (Heigold *et al.*, 1979; Kelly and Frohlich, 1985; Mazac *et al.*, 1988; Ahmed *et al.*, 1988; Smith and Jol, 1995; Doser *et al.*, 2004).

Tab.4.1 gives the representative resistivity values for earth materials given by Moony (1980). Igneous and metamorphic rocks typically have high resistivity values. The resistivity of these rocks is greatly dependent on the degree of fracturing, and the percentage of the fractures filled with ground

**Table.4.1. Representative resistivity values for Earth materials (Mooney, 1980)**

| | |
|---|---|
| Low resistivity materials | < 100 ohm- m |
| Medium resistivity materials | 100 to 1000 ohm- m |
| High resistivity materials | > 1000 ohm- m |
| **1. Regional soil resistivities** | |
| Wet regions | 50 - 200 ohm- m |
| Dry regions | 100 – 500 ohm- m |
| Arid regions | 200 – 1000 ohm- m |
| (Some times as low as 50 ohm- m if the soil is saline) | |
| **2. Waters** | |
| Soil water | 1 – 100 ohm- m |
| Rain water | 30 – 100 ohm- m |
| Sea water | order of 0.2 ohm- m |
| Ice | $10^5$ - $10^8$ ohm- m |
| **3. Rock types below the water table** | |
| Igneous and metamorphic | 100 to 10,000 ohm- m |
| Consolidated sediments | 10 to 1000 ohm- m |
| Unconsolidated sediments | 1 to 100 ohm- m |
| **4. Ores** | |
| Massive sulphides | $10^{-4}$ to 1 ohm- m |
| Non-metallic | order of $10^{10}$ ohm- m |

**Table.4.2. Hydrogeological significance of bulk resistivity values**

| Bulk resistivity (Ohm-m) | Aquifer characteristics or significance | Source |
|---|---|---|
| < 1 | Clay/ sand saturated with salt water | Zohdy *et al.* (1974) |
| 15 – 600 | Sand and gravel saturated with fresh water | Zohdy *et al.* (1974) |
| < 10 | Delineates sediments enriched with salt water | Steward *et al.* (1983) |
| < 20 | Indicates a chloride ion concentration of 250 ppm (aquifer fine sand and limestone) | Steward *et al.* (1983) |
| 20 – 30 | Pore fluid conductivity dominant | Steward *et al.* (1983) |
| 30 – 70 | Affected by both water quality and lithology | Steward *et al.* (1983) |
| 50 – 70 | Porosity is the principal determinant of resistivity | Steward *et al.* (1983) |
| < 19 | Clay / clay mixed with kankar | Singhal (1984) |
| 64- 81 | Weathered sandstone | Singhal (1984) |
| 57-111 | Weathered granite | Singhal (1984) |
| < 10 | Saline coastal zone sand (sedimentary) | Balasubramanian *et al.* (1985) |
| 10 – 20 | Clay with or without diffused water | Balasubramanian *et al.* (1985) |
| 20 - 60 | Freshwater zones | Balasubramanian *et al.* (1985) |
| 0.2 – 0.8 | Clay | Sathiyamoorthy and Banerjee (1985) |
| 0.6 – 5 | Dry sand (contaminated) | Sathiyamoorthy and Banerjee (1985) |
| 0.3 – 3 | Brine bearing sand | Sathiyamoorthy and Banerjee (1985) |
| 3 – 6 | Red clay | Sathiyamoorthy and Banerjee (1985) |

Source: Sakthimurugan and Balasubramanian (1991).

water. Tab.4.2 gives the range of resistivity values of common hard rocks and their water bearing weathered products of peninsular India tabulated by Sakthimurugan and Balasubramanian (1991). Table. 4.3 gives the range of resistivity values of common rocks under dry and saturated conditions (Singhal and Gupta, 1999).

Tab.4.3. Ranges of resistivity values (ohm-m) of common rocks (Singhal and Gupta, 1999)

| Rocks/material | Almost dry | Saturated with water |
|---|---|---|
| Quartzite | $4.4\text{x}\ 10^{3}$ - $2\text{x}10^{8}$ | 50 – 500 |
| Granite | $10^{3}$- $10^{8}$ | 50 – 300 |
| Limestone | 600 - $10^{7}$ | 50 –1000 |
| Basalt | $4\text{x}10^{4}$- $1.3\text{x}\ 10^{8}$ | 10 – 50 |
| Gneiss | $6.8\text{x}10^{4}$ - $3\text{x}10^{8}$ | 50 – 350 |
| Sand | 150 - $2\text{x}10^{3}$ | 10 – 100 |

Sedimentary rocks, which usually are more porous and have higher water content, normally have lower resistivity values. Wet soils and fresh ground water have even lower resistivity values. Clayey soil normally has a lower resistivity value than sandy soil. However there may be overlap in the resistivity values of the different classes of rocks and soils. This is because the resistivity of a particular rock or soil sample depends on a number of factors such as the porosity, the degree of water saturation and the concentration of dissolved salts. The resistivity of ground water varies from 10 to 100 ohm-m· Depending on the concentration of dissolved salts. The low resistivity (about 0.2 ohm-m) of seawater is attributed to the relatively high salt content. This makes the resistivity method an ideal technique for mapping the saline and fresh water interface in coastal areas, (Loke (1997).

### 4.3. Groundwater Detection Using Resistivity

To identify the presence of groundwater from resistivity measurements, one can look to the absolute value of the ground resistivity, through the Archie law. Generally target for aquifer resistivity can be between 50 and 2000 ohm-m. Most of the time it is the relative value of the ground resistivity that is considered for detecting groundwater. In a hard rock (resistant) environment, a low resistivity anomaly will be the target, while in a clayey or salty (conductive) environment it is a high resistivity anomaly, which will most probably correspond to fresh water. Resistivity studies are often used for groundwater exploration in sedimentary environments also (Emenike, 2001). In sedimentary layers, the product of the aquifer resistivity by its thickness has been considered by many authors as representative of the interest of the aquifer. However, electrical methods cannot give estimation of the permeability but only of the porosity.

### 4.4. Resistivity Studies in Coastal Areas

Resistivity studies are useful in the coastal areas for a multitude of purposes like finding out the seawater intrusion as also water quality in the sedimentary aquifers. Because electrical conductivity is affected by Salinity (Archie, 1942), electrical methods such as electromagnetic induction and resistivity imaging lend themselves particularly well to coastal ground-water investigations because of the sharp contrast in conductivity between saltwater and freshwater. The presence of clay layer underneath the shallow aquifers may act as a hindrance to resistivity surveys in many areas.

### 4.5. Saline water intrusion

One of the principal characteristics of seawater is its high concentration of dissolved ions approximately 35,000 mg/l (Freeze and Cherry, 1979). These dissolved ions enhance the ability of seawater to conduct electricity. Seawater, which is a very good conductor, has a specific conductance (SC) of 50µS/cm (Hem, 1970). Freshwater suitable for domestic purposes has much lower dissolved ion concentrations (0 to 1000 mg/l) and lower SC in the range of 50 to 500 µS/cm (Freeze and Cherry, 1979; Hem, 1970, Hearst *et al.,* 2000). This large difference in the electrical properties of fresh and saline water means that the presence of saline water in an aquifer can be detected by various electromagnetic geophysical measurements either in boreholes, or on the surface.

### 4.6. Interpretation of VES Data

Interpretation is the process in which we determine the layering parameters of the model that describes the geoelectric properties of the earth, which is called inverse problem. The parameters of the geoelectric layer are resistivity, thickness, longitudinal conductance and transverse resistance. These parameters are determined by interpretation of vertical electrical sounding curves. The task of a geoelectrical survey is to assess the extent of individual elements of a hydrogeological structure and classify them on the basis of their electrical properties. A bed is a geological unit defined by its lithology. A geophysical layer is a tabular body differing from its surrounding in physical properties such as resistivity or polarizability for a geoelectrical layer. A geological bed and geophysical layer need not be identical, and frequently are not. In some cases, the geoelectrical method is able to separate a geological bed into several geoelectrical layers, whereas in other cases an entire geological complex appears as a single geoelectrical layer. Accordingly the surfaces separating individual geological beds need not correspond to boundaries between physically homogeneous layers.

The criterion used for the classification of a geoelectrical layers is the difference in resistivity. A layer having the same resistivity parallel and transverse to its bedding throughout is considered a homogeneous isotropic geoelectric layer with a resistivity $\rho$. The geoelectrical parameters of such a layer are resistivity, thickness, longitudinal conductance (S), and transverse resistance (T). These parameters are determined by interpreting vertical electrical sounding (VES) curves. Where the layer thickness is sufficiently great relative to the thickness of the overlaying complex the above parameters can be determined unambiguously. For layers that are thin relative to the thickness of the overlaying layers, the principle of equivalence will affect the interpretation. This means that sounding curves measured above layers of identical longitudinal conductance, where the conductivity of the underlying complex is lower, or of identical transverse resistance, where the conductivity of the underlying complex is higher, do not differ. One other disadvantage of geoelectric tool is that if the thickness of the layer is very small relative to that of the overlying complex, its indication on the sounding curve may, in an extreme case, be completely absent due to the principle of suppression (Koefoed, 1979).

Recently the interpretation of VES curves is fully computerized. A correct interpretation, however, requires that two conditions be satisfied. First, the calculation must be precise and second, a reasonable geological concept or model must be incorporated in the interpretation process. Present-day interpretation procedures are based on the assumption of a one-dimensional medium. If this assumption is not satisfied the results of the interpretation will be incorrect and a two- or three-dimensional approach must be utilized (Dey and Morrison, 1979). Like other geophysical techniques geoelectric sounding survey should be interpreted to express geological terms. This interpretation needs practical experience and enough knowledge about the geological background of the area under investigation. This is important because different structures may lead to nearly the same set of measured data. Geoelectric data curves can be solved through "indirect interpretation" or "direct interpretation"

There are two main categories of indirect interpretation techniques: the empirical methods and the analytical methods.

### 4.6.1. Empirical methods

There are at least two empirical techniques that are frequently mentioned in the literature, namely, the Moore Cumulative Resistivity method and the Barnes Layer method (Burger, 1992), Zohdy *et al.* (1974) reported that the Barnes method appears to work well for two layer cases, where the resistivity contrast is not too great. Both methods are good when the data are collected at equal electrode spacing intervals on a linear scale.

### 4.6.2. Analytical Methods

Albums of pre-calculated theoretical curves called "Master Curves" are used as curve-matching procedure to interpret the data curves. Hundreds of apparent resistivity curves have been published for the two-, three- and four-layer cases (Orellana and Mooney, 1966). The master curve method is used in conjunction with the auxiliary-point method, which relies on partial curve matching (Orellana and Mooney, 1966). These methods are significant, but need much practice and experience.

In a direct interpretation method the measured potential or measured apparent resistivities are used in some mathematical process to determine directly the actual resistivities of the earth as a function of depth. The direct interpretation or inversion of vertical electrical sounding (VES) curves into layer thicknesses and resistivities had attracted the attention of geophysicists for the past 60 years. Generally these methods propose a horizontally stratified, isotropic, laterally homogeneous media. In the present work, the use of direct interpretation methods through the computer IPI2WIN, utilized in the processing and interpretation of the measured data has been applied.

The sounding locations are shown in fig 4.1 and tables 4.4 & 4.5 show the analysed VES data for the crystalline terrain and the coastal belt the study area respectively. Interpretation of the data for the study area has been done separately for the coastal belt and the hard rock terrain so as to

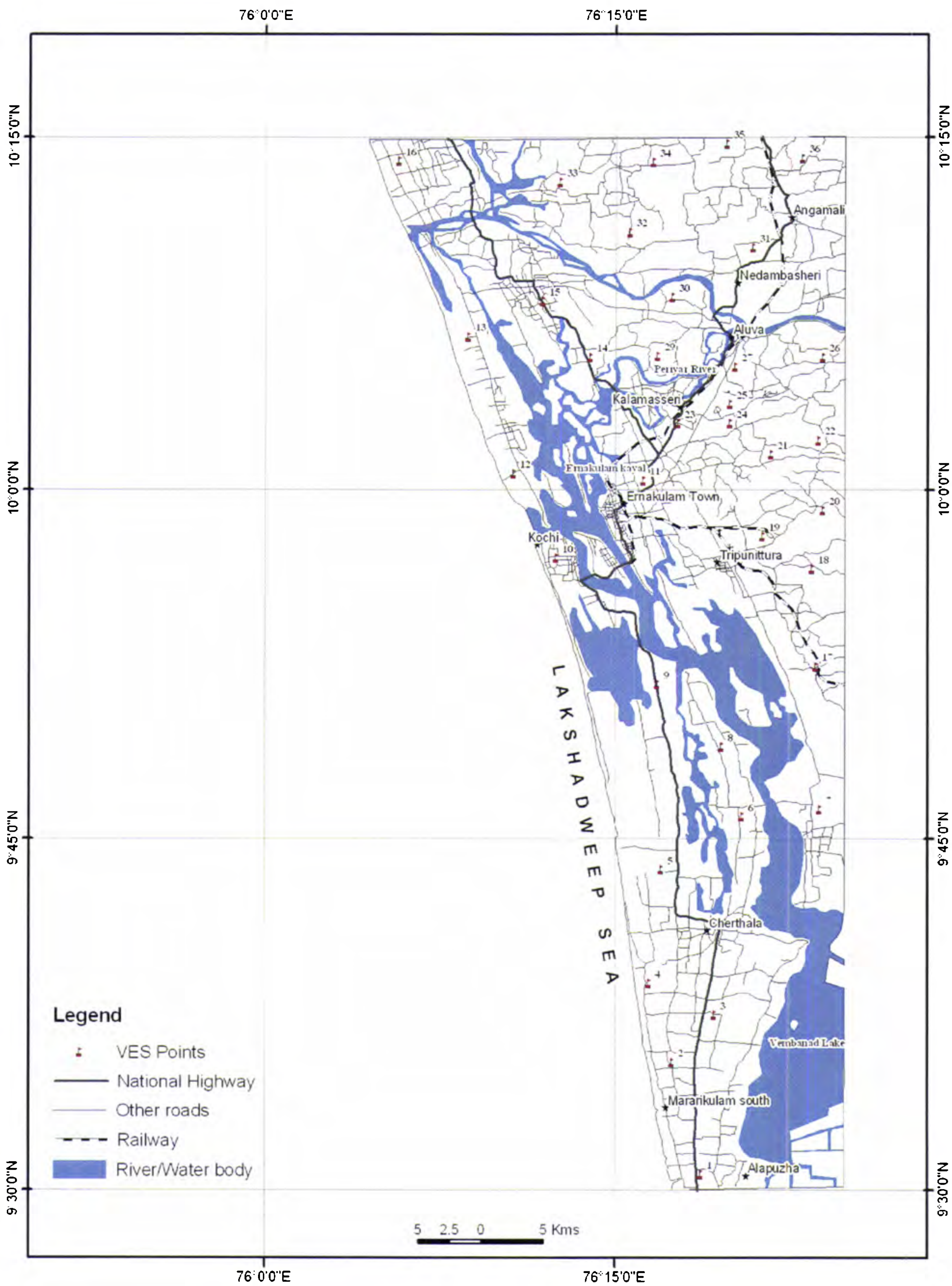



Fig.4.1 LOCATION OF VERTICAL ELECTRICAL SOUNDING POINTS
ERNAKULAM - ALAPPUZHA STRETCH

Table 4.4 Analysed Vertical Electrical Sounding (VES) Data of the Study Area (Hardrock Area)

| Location | h1 (m) | h2 (m) | h3 (m) | h4 (m) | $P^1$ | $P^2$ | $P^3$ | $P^4$ | $P^5$ | Curve Type | Geology |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | 0.8 | 3.4 | 3.4 | 24.6 | 4941 | 970 | 187 | 1323 | high | QHA | C |
| 18 | 1.8 | 8.0 | 33 | - | 2331 | 391 | 2297 | 3777 | - | HA | C |
| 19 | 1.1 | 2.9 | 1.4 | 43.8 | 988 | 126 | 675 | 109 | high | HKH | C |
| 20 | 2.3 | 38.1 | - | - | 537 | 200 | high | - | - | H | L |
| 21 | 3.4 | 10.6 | 4.5 | - | 1281 | 133 | 632 | high | - | HA | C |
| 22 | 1.6 | 20 | - | - | 1200 | 300 | high | - | - | H | C |
| 23 | 1.8 | 6.0 | 52.3 | - | 2611 | 1174 | 514 | high | - | QH | C |
| 24 | 2.9 | 76.3 | 22.3 | - | 395 | 110 | 201 | - | - | H | L |
| 25 | 1.8 | 20.1 | - | - | 600 | 300 | high | - | - | H | L |
| 26 | 1.0 | 70.6 | 61 | - | 480 | 153 | 230 | high | - | HA | L |
| 27 | 3.0 | 10.1 | 9 | - | 383 | 97 | 1250 | 50 | - | HK | L |
| 28 | 2.6 | 1.8 | 3.4 | - | 974 | 372 | 4211 | 595 | - | HK | C |
| 29 | 1.3 | 1.2 | 50.7 | - | 1348 | 388 | 1678 | high | - | HA | C |
| 30 | 1.5 | 1.2 | 13 | 12.0 | 1676 | 9598 | 810 | 173 | high | KQH | C |
| 31 | 2.4 | 30 | - | - | 100 | 500 | high | - | - | A | HG |
| 32 | 0.9 | 8.0 | 9.9 | 21.2 | 518 | 2500 | 188 | high | - | KH | HG |
| 33 | 1.0 | 4.1 | 16.6 | - | 5587 | 1496 | 148 | high | - | QH | HG |
| 34 | 2.4 | 23 | 32 | - | 1821 | 224 | 134 | high | - | QH | C |
| 35 | 1.4 | 4.5 | 27.2 | - | 1920 | 1038 | 539 | high | - | QH | C |
| 36 | 1.6 | 12.9 | 60.8 | - | 521 | 183 | 233 | high | - | HA | L |

C- Charnockite L- Latertite HG- Hornblende gneiss

**Table 4.5 Analysed VES Data of the Study Area ( Coastal Belt )**

| Location | Thickness | Resistivity |
|---|---|---|
| 1 | 2.29 | 3.76 |
| 2 | 6.2 | 3.9 |
| 3 | 5.54 | 179 |
| 4 | 5.9 | 3.49 |
| 5 | 2.2 | 1.32 |
| 6 | 3.84 | 55.8 |
| 7 | 5.4 | 4.01 |
| 8 | 3.03 | 119 |
| 9 | 2.52 | 0.809 |
| 10 | 7.7 | 0.731 |
| 11 | 2.66 | 166 |
| 12 | 2.47 | 5.7 |
| 13 | 3.2 | 2.4 |
| 14 | 2.2 | 4.2 |
| 15 | 3.03 | 33.4 |
| 16 | 4.36 | 44.1 |

bring out the results more clearly. In the qualitative interpretation, analysis of isoapparent resistivity curves are made use of (Gnanasundar and Elango, 1999). This method helps in learning the general information about the geologic structure and the changes in the geoelectrical section of an area, (Gopinath 2003). The spatial distribution of resistivity for the crystalline terrain and the coastal belt of the study area, prepared using GIS, are presented in figs 4.2 and 4.3 respectively.

### 4.7. Results of VES in the study area

#### 4.7.1. Hard Rock Terrain

The resistivity of the first layer $\rho 1$ of the hard rock terrain of the study area ranges widely from 100 ohm-m at station 31 to 5587 ohm-m at station 33. Sixteen locations gave resistivity values above 500 ohm-m of which locations 17,18,23 and 33 gave values above 2000 ohm-m. Weathered outcrops in hard rock areas usually give higher resistivity values. Charnockite and Hornblende Gneiss are the major rock types of the area with many places showing lateritic outcrops.

The second layer shows resistivity value ranging from 97 ohm-m to 9598 ohm-m. Fourteen stations show values below 500 ohm-m. As mentioned earlier, in the present study, prospect zones identification has been carried out only for laterite in the hard rock terrain. Laterite is a major feature in the study area. The zones showing resistivity values below 500 ohm-m in the laterite were considered as potential phreatic aquifers (Gopinath, 2003). Laterites with resistivities ranging from 500 ohm-m to few thousand ohm-m is considered as favourable tapping ground for

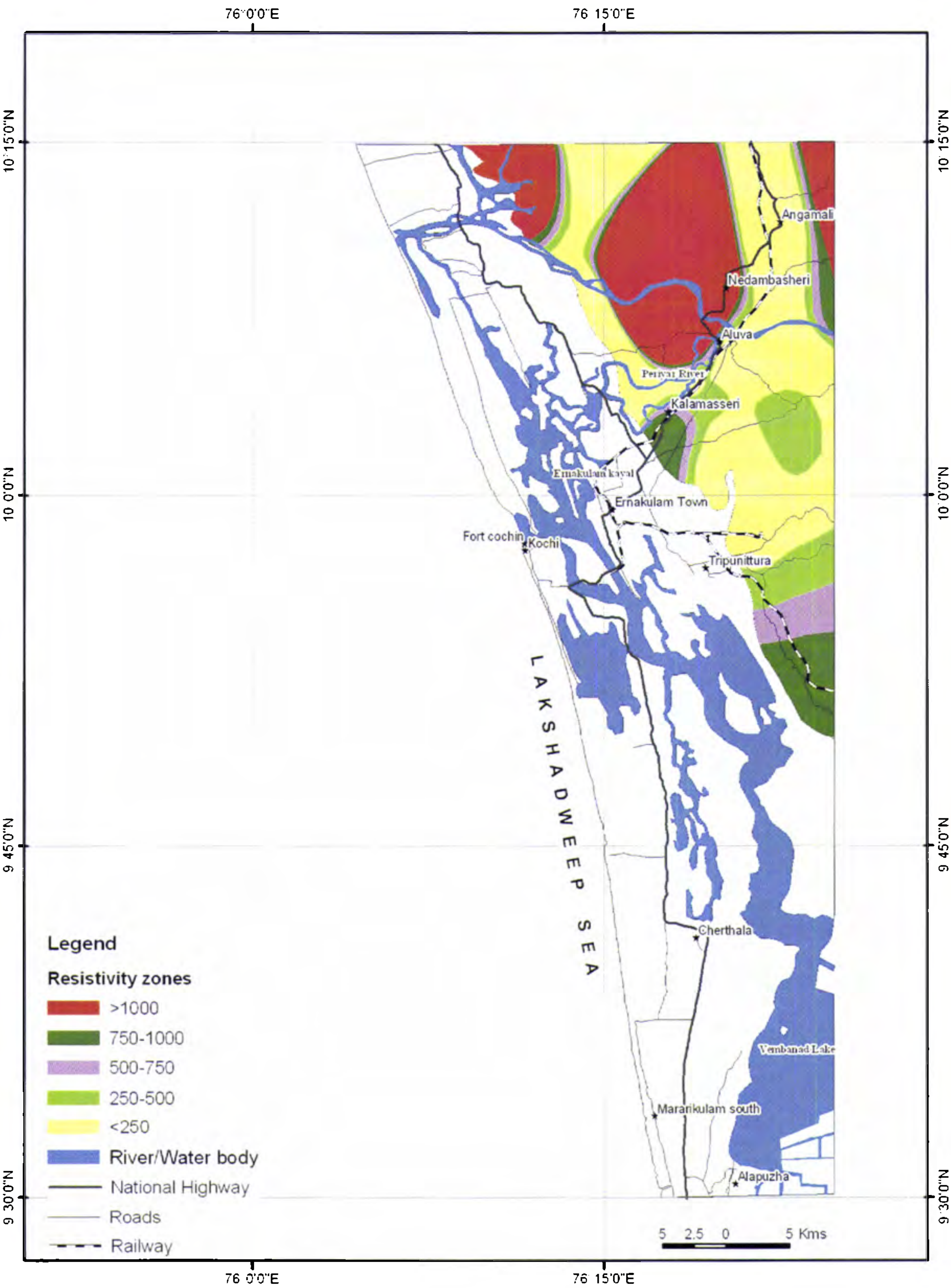
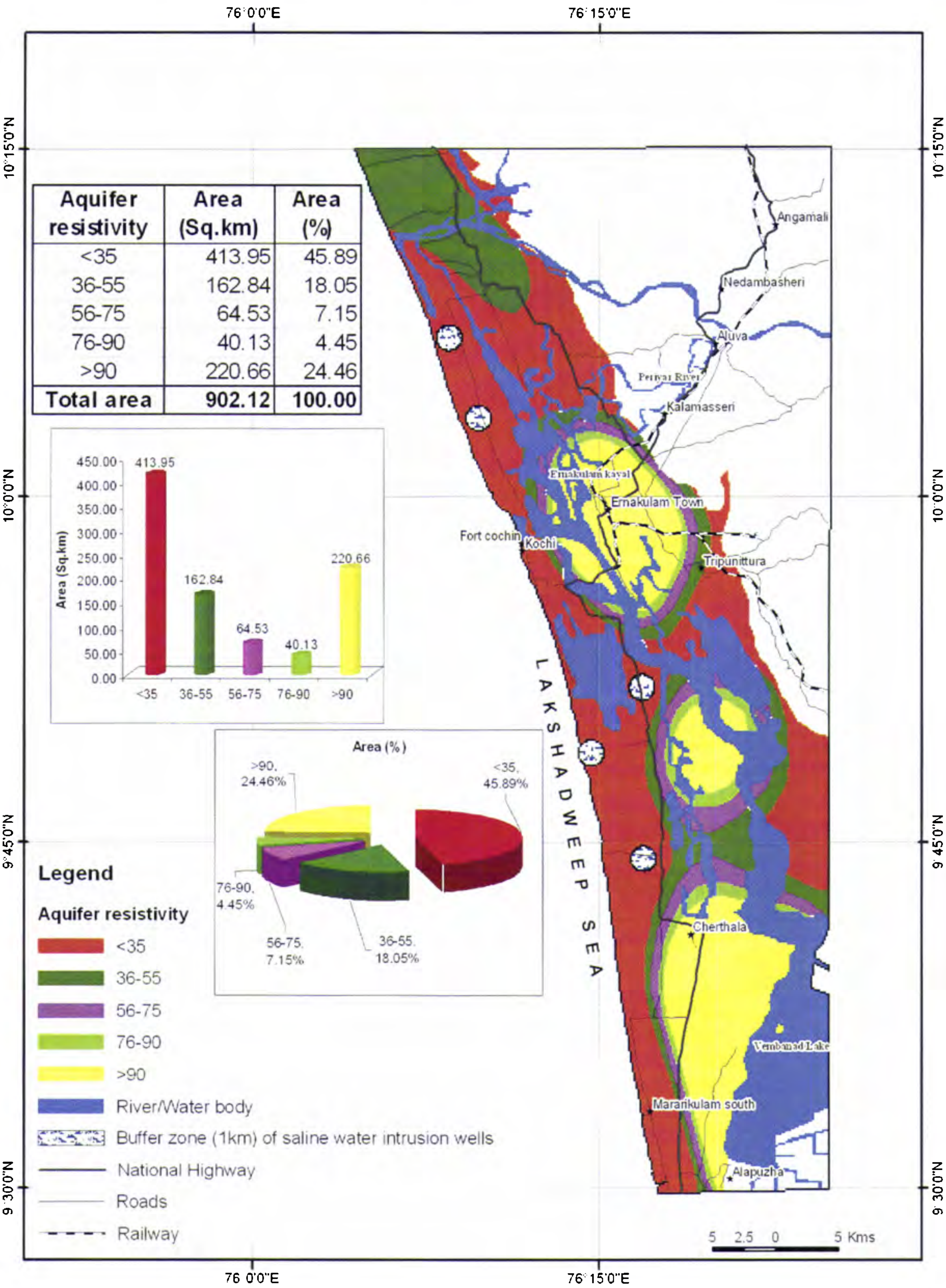



fig.4.2 RESISTIVITY ZONES - HARD ROCK AREA (2003)
ERNAKULAM - ALAPPUZHA STRETCH



| Aquifer resistivity | Area (Sq.km) | Area (%) |
|---|---|---|
| <35 | 413.95 | 45.89 |
| 36-55 | 162.84 | 18.05 |
| 56-75 | 64.53 | 7.15 |
| 76-90 | 40.13 | 4.45 |
| >90 | 220.66 | 24.46 |
| **Total area** | **902.12** | **100.00** |



fig.4.3 AQUIFER RESISTIVITY - ALLUVIUM(2003)
ERNAKULAM - ALAPPUZHA STRETCH

groundwater (Ramanucharya and Balakrishna, 1985), as laterites are usually porous and can accumulate enormous water.

**Quantitative Interpretation**

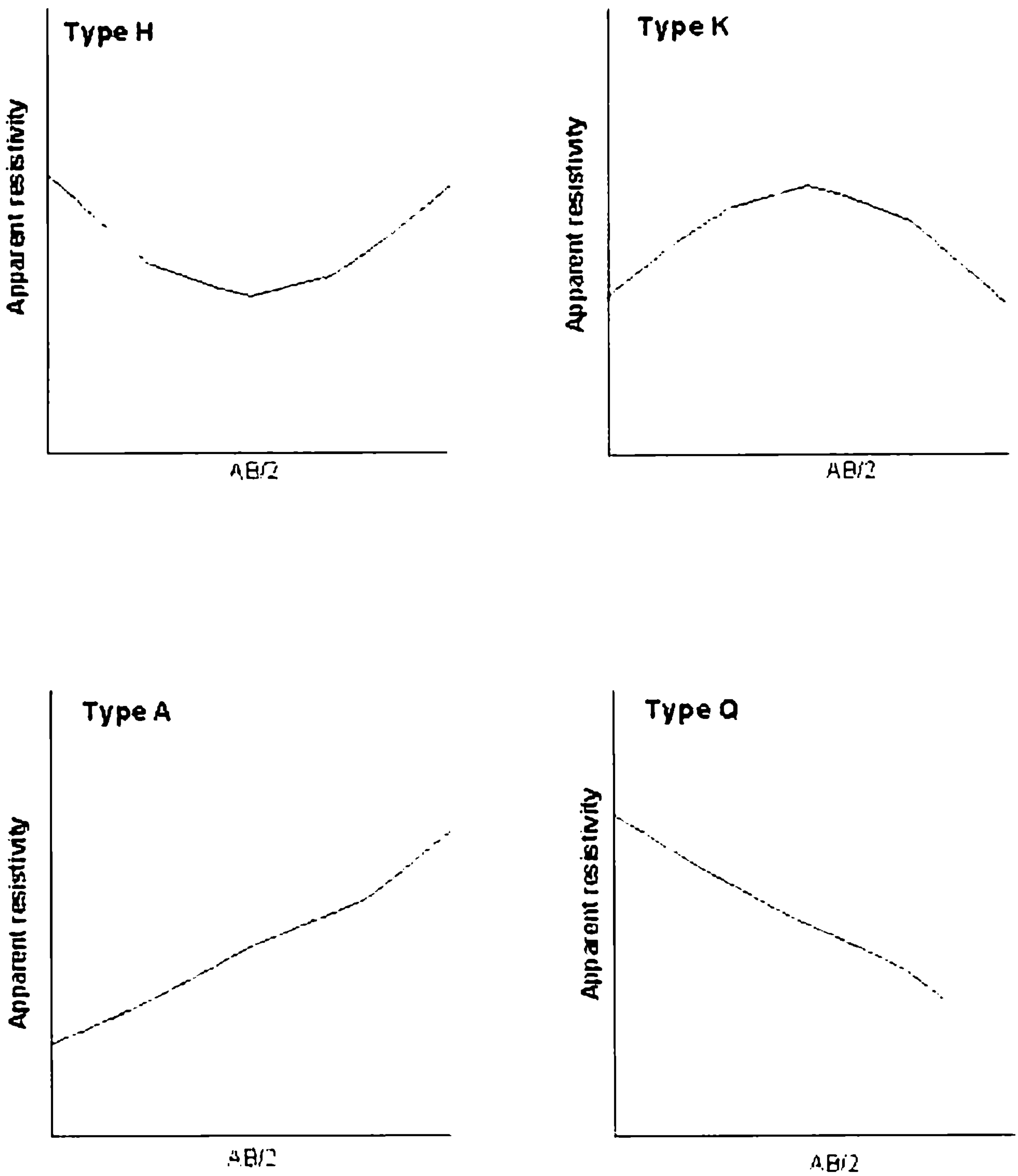
Quantitative interpretation allows getting the real numbers of layers, their resistivities and thicknesses. The 4 different types of curves for a three-layered surface are presented in the fig 4.4.

A Type: ($\rho 1 < \rho 2 < \rho 3$) 'A' type curves are obtained in typical hard rock terrain with thin topsoil and hence the resistivities of layers increase continuously with depth.

Q Type: ($\rho 1 > \rho 2 > \rho 3$) A resistivity curve with a continuously decreasing resistivity is called 'Q' type curves. Usually seen in coastal areas. fig.4.5 represents a typical curve of the coastal belt of the present study area.

H Type: ($\rho 1 > \rho 2 < \rho 3$) Seen generally in hard rock terrains consisting of top soil of high resistivity followed by either a water saturated or weathered layer of low resistivity and then a compact hard rock of very high resistivity at the bottom.

K type: ($\rho 1 < \rho 2 > \rho 3$) Seen usually in basaltic areas such the 'K' type curves show a peak with values lowering towards the sides. Also present in coastal areas where freshwater aquifer occurs between clayey layer at the top and a saline zone in the bottom. In the study area 4 stations show 'H' type curve, 4 stations 'QH' type, and others show a combination of curves.




AB/2 = Electrode spacing

Fig.4.4 Common types of sounding curves in three layered formation

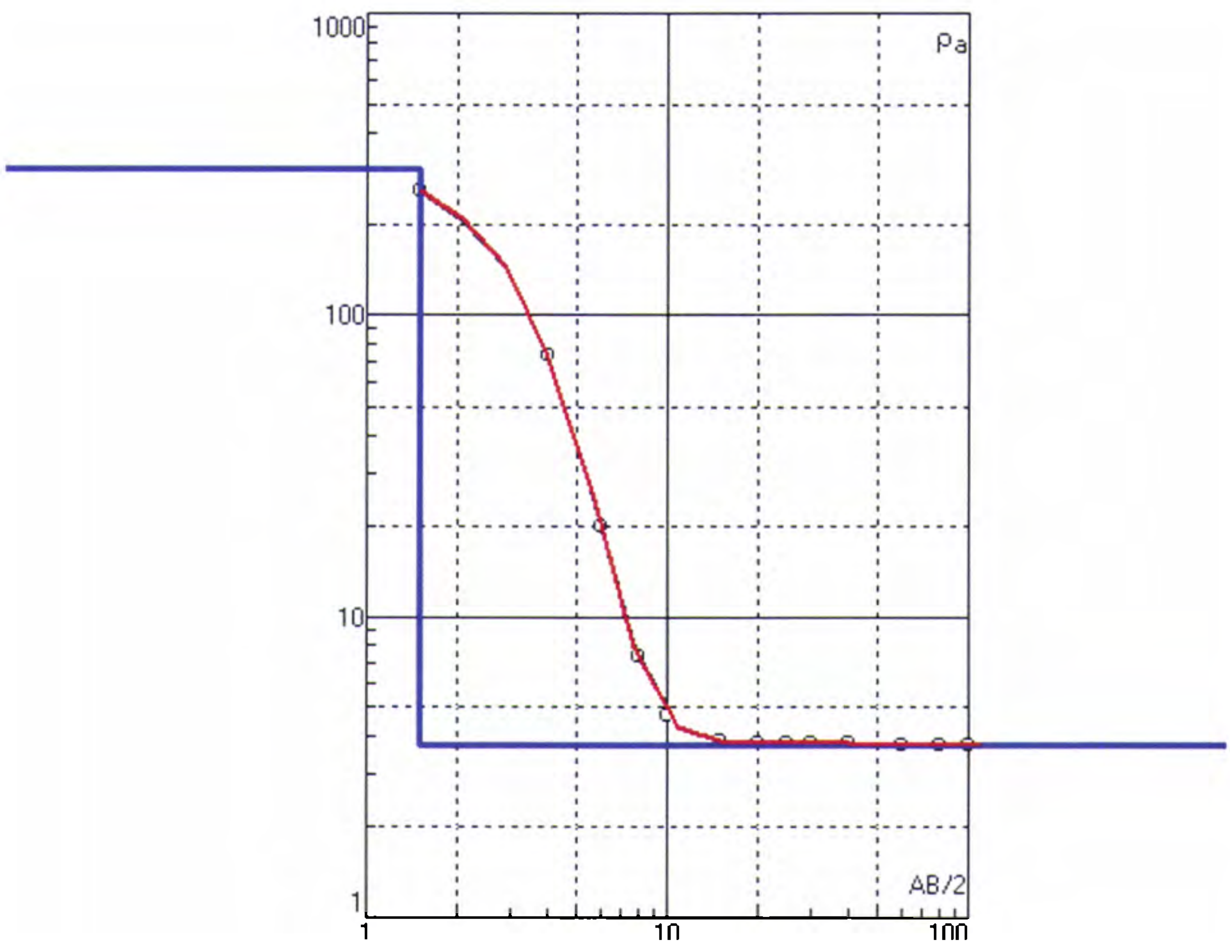



fig.4.5 Interpretation of VES data and selected curve pattern of the coastal belt

Most of the sounding curves are of H, QH and KH types, which are considered as the most suitable types of resistivity curves to estimate the hydraulic parameters where current flow is approximately horizontal. The occurrence of a significant typical H type curve indicates the presence of a highly resistive top lateritic soil followed by a saturated zone and then the basement topography (Gopinath, 2004). In the present study also the prevalence of 'H' type and its combinations can be taken as indicator of the top lateritic layer followed by saturated zone and then the basement. Additionally, inspection of the field curves reveals that, the H curve type is dominant allover the entire area indicating that, most of the sounding curves have the same number of layers. However, the thicknesses of those layers may differ from one locality to another.

### 4.7.2. Coastal Belt

The coastal belt of the study area presents an entirely different picture. The resistivity surveys have been used by authors around the globe in coastal areas to bring out characteristics of shallow aquifers as also effects of anthropogenic stress on these aquifers that may manifest as seawater intrusion (Gnanasundar and Elango, (1999), Richard Whittecar *et al.* (2005). In the present study only the shallow aquifers were considered in the coastal belt since the clay layer was found to influence the resistivity survey. The coastal belt of the study area faces acute water shortage and many areas rely on water tanker lorries of the municipal corporation. A major issue of the study area is the salinity of groundwater samples in many wells. The geochemical analysis of well samples in these areas had revealed the predominance of salinity in many wells as described in Chapter 5. This has rendered many wells in the coastal area useless for domestic purposes. Resistivity locations were purposely selected near the areas where geochemical analyses were conducted so as to study the variations of resistivity with salinity. It was noticed that many VES surveys gave very low values suggesting presence of saline water in the shallow aquifer in many places. The saline zones were buffered using GIS. The study indicated that saline water zones are localized and may be inferred to be the effects of tidal inlets in the area. Illegal sand mining of the riverbeds is rampant in the study area and this leads to morphologic changes of the riverbeds which in turn aid saline water intrusion.

### 4.8. Groundwater Targeting Using Resistivity Analysis

Resistivity data has been incorporated as one of the parameters in the integration of various data for groundwater targeting in the area. Thematic maps of the resistivity of coastal belt, and the laterite terrain of the hardrock area were prepared using GIS and utilized in the integrated approach for groundwater targeting in the study area. The weightages assigned to each layers are described in Chapter 2 where as groundwater targeting is described in chapter 5.

Chapter 5

# Hydro Geochemistry

## 5.1 Introduction

Water is often referred to as a universal solvent as it has the ability to dissolve many substances that it comes in contact with. The composition of groundwater is dependent upon the amount of rainfall, the degree of evapo-transpiration, and on biological and chemical reactions occurring in the sub-surface. The changes in concentrations of conservative chemical species along flow paths have been used to determine the relative magnitude of recharge, discharge and leakage between aquifers.

The quality of water plays a prominent role in promoting both the standards of agricultural production and human health. The term 'Quality' as applied to water embraces the combined physical, chemical and biological characteristics. Water quality is a dominant factor in determining the adequacy of any supply and to satisfy the requirements of all uses.

Natural rainwater is pure. But during surface runoff and filtration through the ground, water acquires many kinds of dissolved and suspended materials. Such dissolved salts may profoundly modify the chemical properties of water and its usefulness. Water passes through many spheres in a complex path called hydrological cycle. Atmosphere is a significant pathway for movement and redistribution of several elements in the water body. Under natural conditions water tends to distribute and deposit its pollutants across the surface of the earth but when the contamination becomes extensive, water is no longer able to disperse the contaminants. Various chemical contents in the earth determine the quality of groundwater and the kind of influence it has on living processes. The quality and composition of dissolved salts in water depend upon the nature of the rock or soil with which it has come in contact. Thus groundwater has generally a higher salt content as compared to surface water.

Quality of groundwater is dependent on the physical and chemical parameters. The characteristics of groundwater (hard or soft; mineralised or non-mineralised) depend on the extent of reactions it made with the country rock (Edmunds, 1994). Hence it is important to know the mineral characteristics of the country rock, which will vary from place to place. Various international bodies such as the World Health Organization (WHO), European Economic Community (EEC) and Bureau of Indian Standard (BIS) have given certain standards for drinking water. For a hydrogeologist, an understanding of the geochemical characteristics of groundwater systems is very important in determining the physical properties of flow system. Hydrochemical data can help to estimate such properties like the amount of recharge, the extent of mixing, the circulation pathways, maximum circulation depth, and temperature at depth and residence time of groundwater (Edmunds, 1994). The concentration of salts in groundwater depends on the geological environment and movement of groundwater (Raghunath, 1987). Groundwater has higher concentrations of dissolved constituents than surface water because of its greater exposure to soluble minerals of the geological formations (Todd, 1980). The primary anion in groundwater namely Bicarbonates, are derived from carbon dioxide released by organic decomposition in soil (Langmuir, 1997). Because of the relative insolubility of the rock composition groundwater passing through igneous rocks dissolve only a small quantity of mineral matter (Todd, 1980). The average chemical composition of rocks (igneous, metamorphic and carbonates rocks) and groundwater (Chebotarev, 1950; Hem, 1959) are given in Tab.5.1a while the sources of various ions in water (Hem, 1959) are given in Tab.5.1b. In addition to the natural mineralization, human influence in the form of sewage pits and industrial wastes also adversely affect water quality. In essence, dissolved solutes in groundwater can provide information about various components of the water budget that would not be possible using traditional hydrogeological approaches.

### 5.2 Groundwater Quality An Overview

Groundwater quality of southern India is strongly dependent on bedrock geology and climate but may also be impacted in parts by pollution particularly from agricultural and industrial sources. The most important agricultural pollutants are nitrate and pesticides, though it is recognized that fertilizer and pesticide applications are not as intrusive as in many western nations (Agrawal, 1999). Phosphate and Potassium fertilizers are also used though the mobility of these beyond the small zone is much less than that of Nitrate. Another impact of pollution is likely to be the increased values of total dissolved salts (TDS). By far the most serious problem in water quality in India derives from high flouride concentrations which are dissolved from the bedrocks by geochemical processes and have resulted in severe flourosis in large populations. High iron concentrations have also been reported in some aquifers (Handa, 1984), particularly in confined aquifers, which are typically anaerobic. High iron concentrations are not detrimental

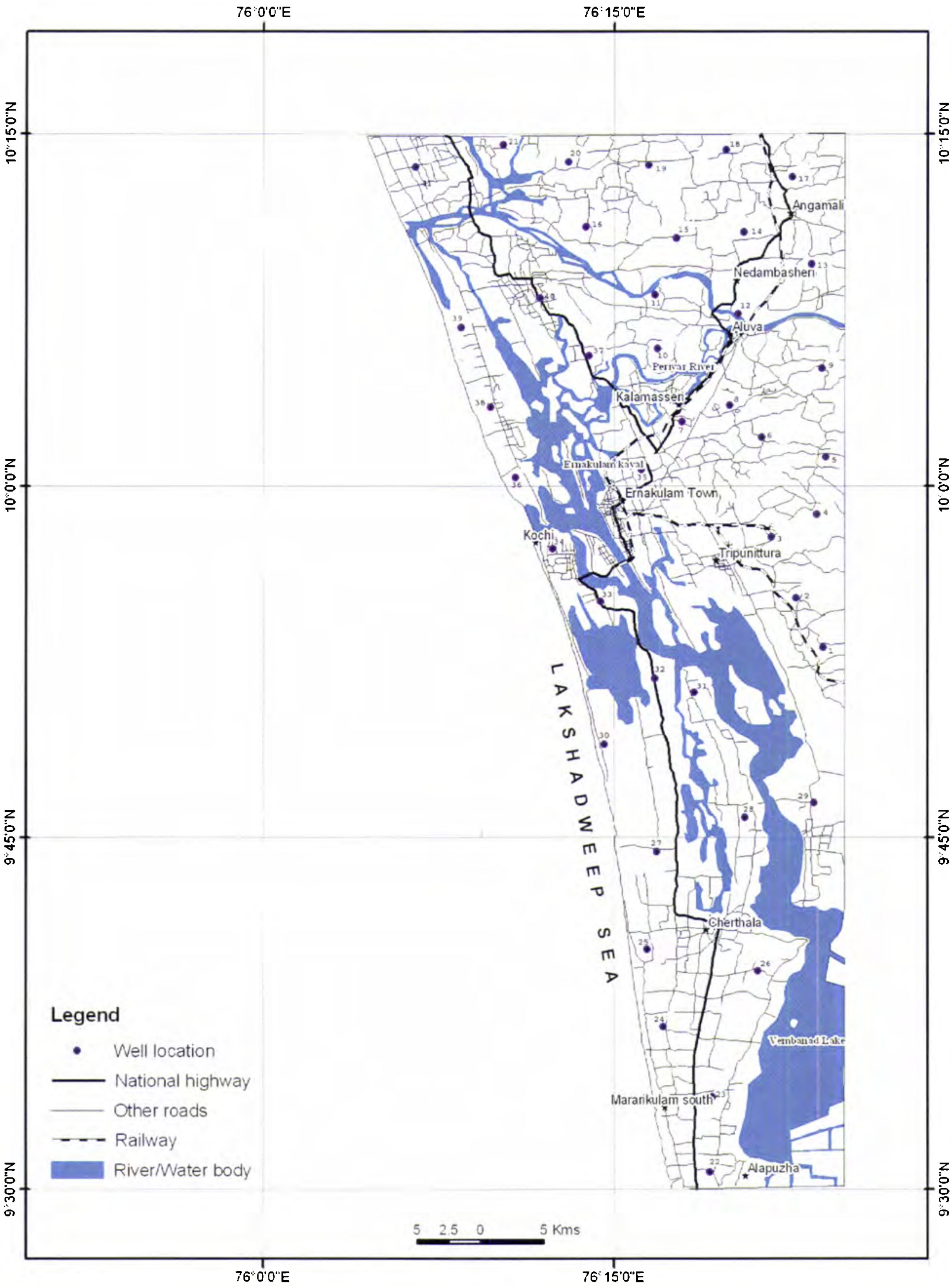



FIG - WELL LOCATIONS ERNAKULAM - ALAPPUZHA STRETCH

**Table: 5.1a Average chemical composition (mg/l) of three major rock types and groundwater (after Chebotarev, 1950; Hem, 1959)**

| Constituents | Igneous rocks | Sandstone | Carbonates | Groundwater |
|---|---|---|---|---|
| $SiO_2$ | 285000 | 359000 | 34 | 1-30 |
| Al | 79500 | 32000 | 8970 | 1-2 |
| Fe | 42200 | 18600 | 8190 | 0-5 |
| Ca | 36200 | 22 | 272000 | 10-200 |
| Mg | 17600 | 400 | 45300 | 1-100 |
| Na | 28100 | 8100 | 393 | 1-300 |
| K | 25700 | 13200 | 2390 | 1-20 |
| Sr | 368 | 28 | 617 | <10 |
| $HCO_3$ | | | | 80-400 |
| $SO_4$ | | | - | 10-100 |
| Cl | 200 | 150 | | 1-150 |
| F | 715 | 220 | 112 | 0.1-2 |
| Br | 2.4 | 1 | 606 | <0.5 |
| B | 7.5 | 90 | 16 | <2 |
| TDS | | | - | 100-1000 |

**Table 5.1b Various sources of ions in water (Hem, 1959)**

| Major ions (> 1 mg/l) | Sources |
|---|---|
| Calcium $Ca_2^+$ | Carbonates, gypsum |
| Magnesium $Mg^{2+}$ | Olivine, pyroxene, amphibole |
| Sodium $Na^+$ | Clays, feldspars, evaporates, industrial waste |
| Potassium $K^+$ | Feldspar, fertilizers, K-evaporates |
| Bicarbonate $HCO_3^-$ | Soil and atmospheric $CO_2$, carbonates |
| Chloride $Cl^-$ | Windborne rain water, sea water and natural brines, evaporates deposits; pollution |
| Sulphate $SO_4^{2-}$ | Gypsum and anhydrite, sea water, windborne, oxidation of pyrite |
| Nitrate $NO_3^-$ | Windborne, oxidation of ammonia or organic nitrogen, contamination |
| Silica, $SiO_2$ | Hydrolysis of silicates |
| Minor ions (1 to 0.1 mg/l) | |
| Iron $Fe_2^{2-}$ | Oxides and sulphides, e.g. heamatite and pyrite; corrosion of iron pipes |
| Manganese $Mn_2^{2-}$ | Oxides and hydroxides, |
| Boron B | Tourmaline, evaporates, sewage, sea water |
| Flouride $F^-$ | Flourine-bearing minerals, viz. fluorite, biotite |
| Trace elements (<0.1 mg/ 1) | |
| As | Arsenic minerals, eg arsenopyrite, arsenic insecticides |
| I | Marine vegetation, evaporates |
| Zn | Sphalerite, industrial waste |
| Heavy metals (Hg, Pb, Cd, Cr) | Industrial waste and igneous rock weathering, under mild reducing conditions |
| Radioactive elements (U, Ra, etc.) | Uraniferous minerals, nuclear tests and nuclear power plants. |

to health but may deter use of the groundwater due to aesthetic problems and lead to use of alternative less safe sources of water.

Results of the chemical analysis of the samples collected from both the crystalline terrain and coastal alluvium are discussed in this chapter. Groundwater samples collected from 41 dug wells during pre-monsoon and post-monsoon periods fig.5.1 were analysed for physical parameters, major cations and anions. The results are given in Tables 5.2a & 5.2b. The concentrations of various elements in the samples are represented using different diagrams like Collins' diagram, Schoeller diagram and Stiff diagram. Groundwater types were deciphered using other important diagrams like Hill Piper diagram and Durov's diagram. Groundwater has been categorised for various uses like drinking, domestic, irrigation, livestock etc by analysing the data using various geochemical diagrams like Wilcox diagram, and U.S.S.L diagram. The spatial and temporal variation of each element (pre-monsoon and post-monsoon) has been analysed using Geographic Information System (GIS) for accurate representation of data in maps. GIS has been used to analyse the geochemical data and also to bring out water quality maps, which are then linked, with the groundwater potential maps created using resistivity data and GIS to decipher potable groundwater maps. The Zonation figures are also described in this chapter whereas the overlay analysis and water quality maps are discussed in the chapter no.6.

**Table 5.2.a. Chemical and biological characteristics of groundwater and various ratio/ percentage in the study area (Pre monsoon)**

| Well No. | meq/l | | | | | | | µS/cm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ca | Mg | Na | K | HCO3+C03 | SO4 | Cl | EC | pH | TDS | SAR | Na% | RSC | CR | *E.coli* |
| **Eastern crystalline terrain** | | | | | | | | | | | | | | | |
| 1 | 0.405 | 0.191 | 0.920 | 0.085 | 0.962 | 0.118 | 0.232 | 149 | 7.4 | 95.36 | 2.38 | 57.48 | 0.37 | 0.004 | - |
| 2 | 0.721 | 0.036 | 0.224 | 0.141 | 0.950 | 0.098 | 0.145 | 119 | 7.2 | 79.36 | 0.51 | 19.91 | 0.19 | 0.003 | + |
| 3 | 0.204 | 0.125 | 0.292 | 0.026 | 0.194 | 0.082 | 0.312 | 53 | 6.3 | 33.92 | 1.02 | 45.22 | -0.13 | 0.025 | - |
| 4 | 0.802 | 0.247 | 0.258 | 0.018 | 1.003 | 0.159 | 0.319 | 190 | 7.3 | 121.60 | 0.50 | 19.48 | -0.05 | 0.005 | + |
| 5 | 0.200 | 0.126 | 0.181 | 0.028 | 0.264 | 0.098 | 0.145 | 51 | 6.6 | 32.64 | 0.63 | 33.77 | -0.06 | 0.010 | + |
| 6 | 1.042 | 0.186 | 0.129 | 0.049 | 0.774 | 0.185 | 0.174 | 150 | 7.2 | 96.00 | 0.23 | 9.17 | -0.45 | 0.004 | - |
| 7 | 0.200 | 0.126 | 0.138 | 0.018 | 0.246 | 0.124 | 0.203 | 53 | 6.6 | 33.92 | 0.48 | 28.58 | -0.08 | 0.014 | - |
| 8 | 0.040 | 0.251 | 0.163 | 0.023 | 0.174 | 0.111 | 0.261 | 53 | 6.2 | 33.92 | 0.61 | 34.21 | -0.12 | 0.024 | - |
| 9 | 0.321 | 0.004 | 0.211 | 0.028 | 0.282 | 0.146 | 0.145 | 55 | 7.2 | 35.20 | 0.74 | 37.38 | -0.04 | 0.010 | + |
| 10 | 0.080 | 0.065 | 0.176 | 0.018 | 0.149 | 0.048 | 0.189 | 41 | 6.0 | 26.24 | 0.93 | 51.97 | 0.00 | 0.020 | + |
| 11 | 0.160 | 0.057 | 0.224 | 0.010 | 0.194 | 0.111 | 0.203 | 57 | 5.8 | 36.48 | 0.96 | 49.59 | -0.02 | 0.018 | + |
| 12 | 0.080 | 0.065 | 0.155 | 0.033 | 0.144 | 0.117 | 0.145 | 46 | 7.0 | 29.44 | 0.81 | 46.47 | 0.00 | 0.018 | + |
| 13 | 0.080 | 0.028 | 0.327 | 0.090 | 0.194 | 0.128 | 0.290 | 86 | 6.7 | 55.04 | 1.98 | 62.22 | 0.09 | 0.025 | + |
| 14 | 0.281 | 0.008 | 0.292 | 0.059 | 0.158 | 0.139 | 0.290 | 81 | 6.2 | 51.84 | 1.09 | 45.68 | -0.13 | 0.030 | + |
| 15 | 0.481 | 0.279 | 0.400 | 0.028 | 0.512 | 0.137 | 0.435 | 165 | 6.6 | 105.60 | 0.92 | 33.65 | -0.25 | 0.013 | - |
| 16 | 0.842 | 0.332 | 0.817 | 0.231 | 0.800 | 0.181 | 0.957 | 211 | 7.4 | 135.04 | 1.51 | 36.76 | -0.37 | 0.018 | - |
| 17 | 0.200 | 0.089 | 0.181 | 0.026 | 0.246 | 0.069 | 0.178 | 55 | 8.1 | 35.20 | 0.67 | 36.43 | -0.04 | 0.012 | - |
| 18 | 0.842 | 0.061 | 0.318 | 0.075 | 0.493 | 0.112 | 0.487 | 140 | 6.6 | 89.60 | 0.67 | 24.57 | -0.41 | 0.015 | + |
| 19 | 0.361 | 0.036 | 0.860 | 0.036 | 0.496 | 0.137 | 0.493 | 139 | 6.6 | 88.96 | 2.73 | 66.50 | 0.10 | 0.015 | + |
| 20 | 1.924 | 0.024 | 1.161 | 0.100 | 2.042 | 0.271 | 1.131 | 349 | 7.3 | 223.36 | 1.66 | 36.18 | 0.09 | 0.008 | + |
| 21 | 0.481 | 0.134 | 0.417 | 0.188 | 0.336 | 0.146 | 0.580 | 123 | 7.1 | 78.72 | 1.06 | 34.21 | -0.28 | 0.027 | + |

**Western costal plain**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 | 3.405 | 1.502 | 17.733 | 0.758 | 4.642 | 0.048 | 17.110 | 517 | 8.2 | 330.88 | 16.01 | 75.79 | -0.27 | 0.052 | + |
| 23 | 1.525 | 0.340 | 5.513 | 0.594 | 3.234 | 0.046 | 5.759 | 300 | 7.9 | 192.00 | 8.07 | 69.15 | 1.37 | 0.025 | + |
| 24 | 9.820 | 2.258 | 20.257 | 3.110 | 5.131 | 0.136 | 28.200 | 938 | 8.2 | 600.32 | 11.66 | 57.15 | -6.95 | 0.078 | + |
| 25 | 6.770 | 1.255 | 22.218 | 2.245 | 6.230 | 0.090 | 25.699 | 1100 | 8.3 | 704.00 | 15.69 | 68.39 | -1.79 | 0.058 | + |
| 26 | 12.700 | 11.967 | 33.385 | 1.740 | 6.113 | 0.142 | 50.286 | 5300 | 8.5 | 3392.00 | 13.44 | 55.84 | -18.55 | 0.116 | + |
| 27 | 3.390 | 1.643 | 5.392 | 1.063 | 5.014 | 0.059 | 5.498 | 222 | 7.7 | 142.08 | 4.81 | 46.94 | -0.02 | 0.016 | + |
| 28 | 4.835 | 1.967 | 15.798 | 2.957 | 4.422 | 0.083 | 20.816 | 314 | 7.5 | 200.96 | 12.11 | 61.81 | -2.38 | 0.066 | + |
| 29 | 5.500 | 1.004 | 21.079 | 1.347 | 3.362 | 0.076 | 23.786 | 595 | 7.7 | 380.80 | 16.53 | 72.86 | -3.14 | 0.100 | + |
| 30 | 4.365 | 0.560 | 2.144 | 0.740 | 3.364 | 0.028 | 3.766 | 1122 | 7.6 | 718.08 | 1.93 | 27.45 | -1.56 | 0.016 | + |
| 31 | 3.390 | 0.307 | 4.784 | 0.774 | 4.464 | 0.054 | 4.170 | 550 | 7.2 | 352.00 | 4.98 | 51.69 | 0.77 | 0.013 | + |
| 32 | 3.565 | 0.056 | 5.243 | 0.532 | 4.033 | 0.045 | 4.540 | 211 | 7.2 | 135.04 | 5.51 | 55.80 | 0.41 | 0.016 | + |
| 33 | 3.365 | 0.112 | 4.833 | 0.501 | 2.265 | 0.036 | 6.046 | 440 | 8.0 | 281.60 | 5.18 | 54.85 | -1.21 | 0.038 | + |
| 34 | 7.900 | 1.071 | 22.029 | 2.338 | 6.267 | 0.058 | 24.775 | 2090 | 7.9 | 1337.60 | 14.71 | 66.08 | -2.70 | 0.056 | + |
| 35 | 2.280 | 0.440 | 6.248 | 0.422 | 2.700 | 0.059 | 7.159 | 666 | 8.0 | 426.24 | 7.58 | 66.54 | -0.02 | 0.037 | + |
| 36 | 3.365 | 0.336 | 4.829 | 0.358 | 4.582 | 0.068 | 3.885 | 414 | 7.6 | 264.96 | 5.02 | 54.33 | 0.88 | 0.012 | + |
| 37 | 3.540 | 0.056 | 5.775 | 0.311 | 3.678 | 0.062 | 7.258 | 457 | 7.7 | 292.48 | 6.09 | 59.65 | 0.08 | 0.028 | - |
| 38 | 3.395 | 0.357 | 6.261 | 0.350 | 3.463 | 0.026 | 6.946 | 399 | 7.5 | 255.36 | 6.46 | 60.42 | -0.29 | 0.028 | + |
| 39 | 0.510 | 0.282 | 0.520 | 0.206 | 0.930 | 0.178 | 0.290 | 160 | 6.7 | 102.40 | 1.17 | 34.27 | 0.14 | 0.005 | + |
| 40 | 0.321 | 0.113 | 0.593 | 0.180 | 0.229 | 0.128 | 0.754 | 124 | 6.5 | 79.36 | 1.80 | 49.15 | -0.21 | 0.049 | - |
| 41 | 0.802 | 0.138 | 0.817 | 0.211 | 0.546 | 0.139 | 0.870 | 161 | 6.4 | 103.04 | 1.69 | 41.54 | -0.39 | 0.024 | - |

EC Electrical Conductivity
TDS Total Dissolved Solids
SAR Sodium adsorption ratio

Na% Sodium percentage
RSC Residual sodium carbonate
CR Corrosivity ratio

\+ Presence of *E. Coli* (*Escherichia coli*)
\- Absence of *E. Coli*

**Table 5.2b Chemical and biological characteristics of groundwater and various ratio/ percentage in the study araea (Post monsoon)**

| Well No. | meq/l | | | | | | | µS/cm | | mg/l | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ca | Mg | Na | K | HCO3+C03 | SO4 | Cl | EC | pH | TDS | SAR | Na% | RSC | CR | *E.coli* |
| **Eastern crystalline terrain** | | | | | | | | | | | | | | | |
| 1 | 0.485 | 0.033 | 0.181 | 0.028 | 0.451 | 0.044 | 0.209 | 30 | 6.2 | 19.20 | 0.50 | 24.84 | -0.07 | 0.105 | - |
| 2 | 0.150 | 0.042 | 0.323 | 0.049 | 0.304 | 0.060 | 0.264 | 74 | 6.0 | 47.36 | 1.47 | 57.30 | 0.11 | 0.050 | - |
| 3 | 0.205 | 0.125 | 0.305 | 0.057 | 0.530 | 0.055 | 0.264 | 56 | 6.6 | 35.84 | 1.06 | 44.16 | 0.20 | 0.062 | + |
| 4 | 0.705 | 0.100 | 0.224 | 0.013 | 0.994 | 0.055 | 0.128 | 95 | 7.3 | 60.80 | 0.50 | 21.48 | 0.19 | 0.463 | + |
| 5 | 0.170 | 0.050 | 0.232 | 0.031 | 0.402 | 0.044 | 0.136 | 46 | 7.1 | 29.44 | 0.99 | 48.09 | 0.18 | 0.088 | + |
| 6 | 0.640 | 0.075 | 0.215 | 0.028 | 0.830 | 0.046 | 0.081 | 84 | 7.2 | 53.76 | 0.51 | 22.44 | 0.12 | 0.176 | - |
| 7 | 0.200 | 0.083 | 0.211 | 0.023 | 0.355 | 0.046 | 0.107 | 47 | 6.5 | 30.08 | 0.79 | 40.77 | 0.07 | 0.108 | - |
| 8 | 0.105 | 0.100 | 0.206 | 0.026 | 0.178 | 0.026 | 0.244 | 45 | 6.2 | 28.80 | 0.91 | 47.26 | -0.03 | 0.050 | - |
| 9 | 0.195 | 0.108 | 0.262 | 0.028 | 0.523 | 0.062 | 0.151 | 48 | 6.2 | 30.72 | 0.95 | 44.20 | 0.22 | 0.127 | + |
| 10 | 0.110 | 0.042 | 0.254 | 0.049 | 0.163 | 0.052 | 0.325 | 39 | 6.3 | 24.96 | 1.30 | 55.88 | 0.01 | 0.032 | - |
| 11 | 0.155 | 0.042 | 0.267 | 0.028 | 0.128 | 0.050 | 0.302 | 57 | 5.8 | 36.48 | 1.20 | 54.26 | -0.07 | 0.048 | + |
| 12 | 0.105 | 0.042 | 0.185 | 0.031 | 0.104 | 0.080 | 0.122 | 40 | 6.8 | 25.60 | 0.97 | 51.04 | -0.04 | 0.054 | + |
| 13 | 0.155 | 0.216 | 0.563 | 0.129 | 0.365 | 0.054 | 0.641 | 112 | 6.4 | 71.68 | 1.85 | 53.01 | -0.01 | 0.021 | + |
| 14 | 0.110 | 0.100 | 0.219 | 0.242 | 0.362 | 0.058 | 0.238 | 48 | 6.1 | 30.72 | 0.96 | 32.71 | 0.15 | 0.011 | + |
| 15 | 0.310 | 0.075 | 0.292 | 0.033 | 0.517 | 0.122 | 0.128 | 75 | 6.2 | 48.00 | 0.94 | 41.15 | 0.13 | 0.132 | - |
| 16 | 0.300 | 0.008 | 0.512 | 0.208 | 0.525 | 0.160 | 0.409 | 142 | 6.8 | 90.88 | 1.84 | 49.77 | 0.22 | 0.024 | - |
| 17 | 0.115 | 0.100 | 0.206 | 0.046 | 0.288 | 0.024 | 0.139 | 44 | 6.3 | 28.16 | 0.89 | 44.17 | 0.07 | 0.040 | - |
| 18 | 0.510 | 0.149 | 0.224 | 0.164 | 0.783 | 0.082 | 0.270 | 97 | 6.6 | 62.08 | 0.55 | 21.35 | 0.12 | 0.032 | + |
| 19 | 0.255 | 0.100 | 0.568 | 0.049 | 0.374 | 0.164 | 0.429 | 112 | 6.2 | 71.68 | 1.91 | 58.45 | 0.02 | 0.087 | - |
| 20 | 1.695 | 0.747 | 0.636 | 0.103 | 2.456 | 0.060 | 0.397 | 260 | 8.0 | 166.40 | 0.81 | 20.01 | 0.01 | 0.133 | - |
| 21 | 0.605 | 0.091 | 0.206 | 0.054 | 0.821 | 0.064 | 0.110 | 50 | 6.6 | 32.00 | 0.49 | 21.57 | 0.12 | 0.096 | + |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Western costal plain** | | | | | | | | | | | | | | | |
| 22 | 2.890 | 1.668 | 15.162 | 0.596 | 4.291 | 0.040 | 13.537 | 446 | 8.3 | 285.44 | 14.20 | 74.629 | -0.27 | 0.044 | + |
| 23 | 1.030 | 0.199 | 4.833 | 0.491 | 2.467 | 0.042 | 4.797 | 197 | 7.4 | 126.08 | 8.72 | 73.752 | 1.24 | 0.027 | + |
| 24 | 2.130 | 1.278 | 4.270 | 0.722 | 3.219 | 0.048 | 3.660 | 110 | 7.7 | 70.40 | 4.63 | 50.831 | -0.19 | 0.016 | + |
| 25 | 3.490 | 0.423 | 1.428 | 0.586 | 2.542 | 0.022 | 3.164 | 845 | 7.4 | 540.80 | 1.44 | 24.087 | -1.37 | 0.018 | + |
| 26 | 1.710 | 0.033 | 3.874 | 0.499 | 3.042 | 0.032 | 3.837 | 144 | 7.5 | 92.16 | 5.87 | 63.346 | 1.30 | 0.018 | + |
| 27 | 8.510 | 1.876 | 20.567 | 2.801 | 6.082 | 0.106 | 21.611 | 765 | 8.2 | 489.60 | 12.76 | 60.932 | -4.30 | 0.050 | + |
| 28 | 3.430 | 0.033 | 5.113 | 0.252 | 3.118 | 0.048 | 6.128 | 383 | 7.2 | 245.12 | 5.49 | 57.916 | -0.34 | 0.028 | + |
| 29 | 0.612 | 0.042 | 0.512 | 0.260 | 0.990 | 0.052 | 0.325 | 126 | 7.3 | 80.64 | 1.27 | 35.915 | 0.34 | 0.005 | + |
| 30 | 7.100 | 0.921 | 23.448 | 1.830 | 5.576 | 0.072 | 21.912 | 795 | 8.1 | 508.80 | 16.56 | 70.416 | -2.45 | 0.055 | + |
| 31 | 2.765 | 0.174 | 4.175 | 0.630 | 3.379 | 0.042 | 3.506 | 497 | 7.0 | 318.08 | 4.87 | 53.915 | 0.44 | 0.015 | + |
| 32 | 5.895 | 5.569 | 28.088 | 1.000 | 4.083 | 0.238 | 32.376 | 2796 | 8.5 | 1789.44 | 16.59 | 69.264 | -7.38 | 0.112 | + |
| 33 | 2.720 | 0.075 | 4.137 | 0.401 | 1.746 | 0.024 | 5.095 | 336 | 7.3 | 215.04 | 4.95 | 56.417 | -1.05 | 0.041 | + |
| 34 | 5.895 | 0.847 | 19.574 | 1.922 | 5.091 | 0.042 | 18.511 | 1112 | 7.5 | 711.68 | 15.08 | 69.318 | -1.65 | 0.051 | + |
| 35 | 1.755 | 0.324 | 5.083 | 0.357 | 2.642 | 0.044 | 6.067 | 530 | 7.7 | 339.20 | 7.05 | 67.601 | 0.56 | 0.032 | + |
| 36 | 1.935 | 0.241 | 4.180 | 0.285 | 3.443 | 0.054 | 3.199 | 310 | 7.3 | 198.40 | 5.67 | 62.940 | 1.27 | 0.013 | + |
| 37 | 4.360 | 1.884 | 13.304 | 2.421 | 4.563 | 0.066 | 14.364 | 216 | 7.5 | 138.24 | 10.65 | 60.558 | -1.68 | 0.044 | + |
| 38 | 2.905 | 0.241 | 4.653 | 0.311 | 2.853 | 0.026 | 5.867 | 340 | 7.2 | 217.60 | 5.25 | 57.374 | -0.29 | 0.029 | + |
| 39 | 3.505 | 0.905 | 17.123 | 1.133 | 2.866 | 0.124 | 17.374 | 514 | 7.3 | 328.96 | 16.31 | 75.544 | -1.54 | 0.086 | - |
| 40 | 0.760 | 0.125 | 0.520 | 0.182 | 0.291 | 0.068 | 1.511 | 140 | 7.2 | 89.60 | 1.11 | 32.780 | -0.59 | 0.074 | + |
| 41 | 0.890 | 0.116 | 0.611 | 0.180 | 0.382 | 0.180 | 1.282 | 182 | 7.0 | 116.48 | 1.22 | 33.985 | -0.62 | 0.050 | - |

EC Electrical Conductivity
TDS Total Dissolved Solids
Na% Sodium percentage
RSC Residual sodium carbonate
\+ Presence of *E. Coli*
Absence of *E. Coli*

### 5.2.1 Evaluation of groundwater for domestic uses

Quality standards for water vary with the purpose for which it is used. Also different countries have prescribed different limits for the quality. Depending on the impact of concentration of various ions in water on human health, standards have been laid down by the different agencies. Drinking water standards as prescribed by WHO (1984), EEC (Lloyd and Heathcote, 1985) and ISI (1983) are given in Table 5.3.

Groundwater used for drinking should be subjected to detailed chemical analysis to avoid the presence of toxic substances beyond certain levels although they may be beneficial at lower amounts (Singhal and Gupta, 1999).

### 5.3.1. pH

pH, originally defined by Danish biochemist Soren Peter Lauritz Sorensen in 1909, is a measure of the concentration of hydrogen ions. The term pH was derived from the manner in which the hydrogen ion concentration is calculated and it is the negative logarithm of the hydrogen ion ($H^+$) concentration. The concentration of hydrogen ions in a solution is very important for living things. Since the hydrogen ions are positively charged they alter the charge environment of other molecules in solution. By putting different forces on the molecules, their normal shape changes. This is particularly important for proteins in solution because the shape of a protein is related to its function. The concentration of hydrogen ions is commonly expressed in terms of the pH scale.

**Table 5.3 Ranges/ upper limits of various constituents (mg/l) in drinking water**

| Parameters | WHO (1984) | EEC (1985) | ISI (1983) |
|---|---|---|---|
| TDS | 1000 | 1500 | 500 |
| pH | 6.5-8.5 | 6.5-9.0 | 6.5-8.5 |
| Total hardness ($CaCO_3$) | 500 | 2-10 meq/l | 300 |
| Ca | 75-200 | 75-200 | 75 |
| Mg | | 50 | 30 |
| Na | 200 | 150 | No limit |
| Cl | 250 | 250 | 250 |
| $SO_4$ | 400 | 250 | 150 |
| $NO_3$ | 45 | 50 | 45 |
| Fe | 0.3 | 0.2 | 0.3 |
| F | 1.5 | 1.5 | 0.6-1.2 |
| Pb | 0.05 | 0.05 | 0.1 |
| Hg | 0.001 | 0.001 | 0.001 |
| Zn | 5.0 | 5.0 | 5.0 |
| Cu | 1.0 | 0.05 | 0.05 |
| Cd | 0.005 | 0.005 | 0.01 |
| As | 0.01 | 0.05 | 0.05 |
| Cr (hexavalent) | 0.05 | 0.05 | 0.05 |
| CN (Cyanides) | 0.05 | 0.05 | 0.05 |
| Overall radioactivity ($\alpha$) | 3 pCi/l | 3 pCi/l | 1 pCi/l |
| Overall radioactivity ($\beta$) | 30 pCi/l | 30pCi/l | 10 pCi/l |
| Coliforms | No fecal coliforms | No fecal coliforms | 100 coliforms/litre |

WHO- World Health Organisation
EEC-Europeans Economic Community
ISI-Indian Standard Institutions

Low pH corresponds to high hydrogen ion concentration and vice versa. A decrease in pH by one pH unit means a tenfold increase in the concentration of hydrogen ions. Low pH acid waters clearly accelerate corrosion by providing a plentiful supply of hydrogen ions. Although even absolutely pure water contains some free hydrogen ions, free carbon dioxide in the water can multiply the hydrogen ion concentration many times. When carbon dioxide dissolves in water, it reacts with the water to form carbonic acid, a so-called weak acid, but an effective source of acidity. Even more acidity is sometimes encountered in acid mine waters or in those contaminated with industrial wastes.

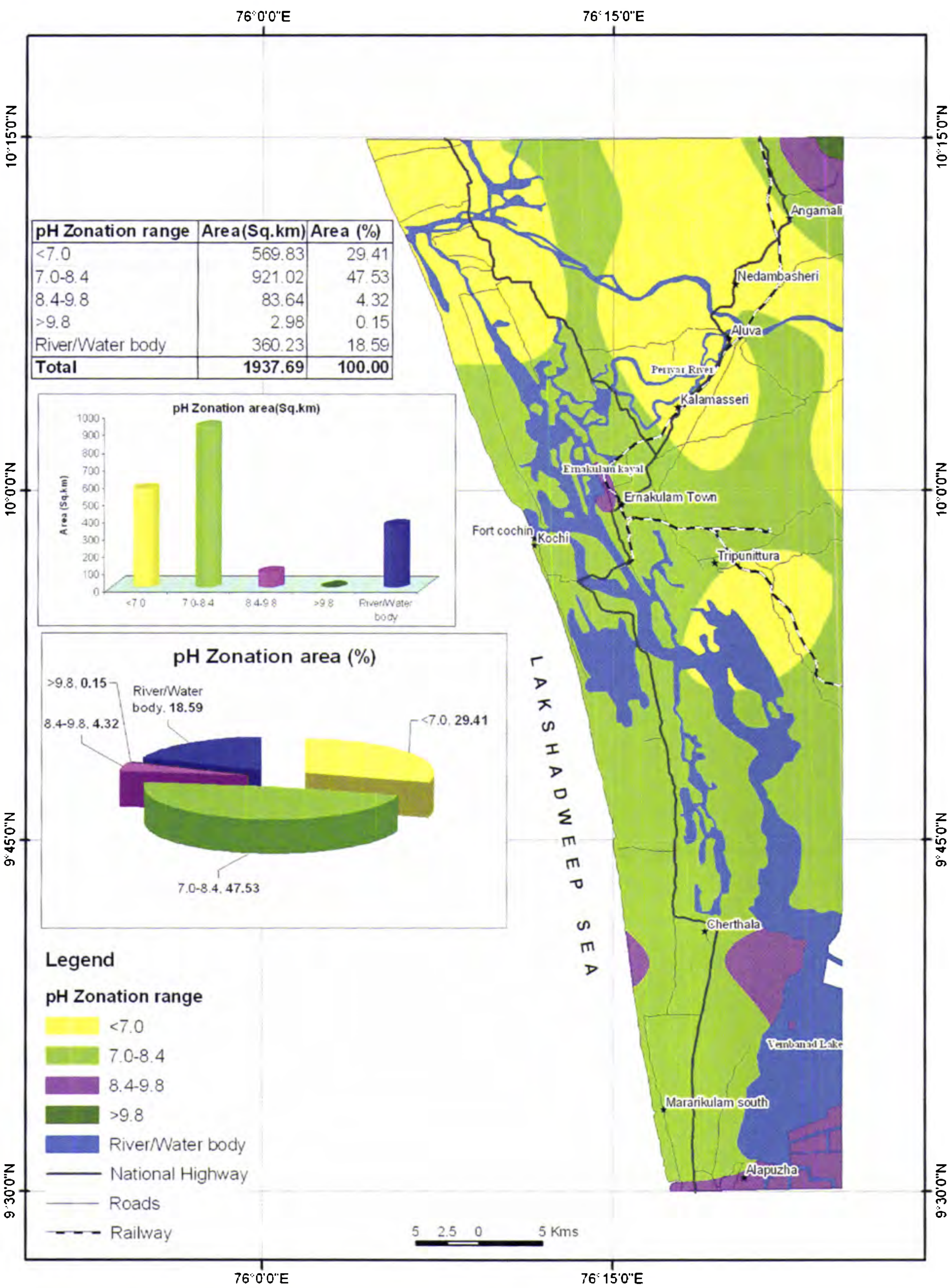
The pH of natural waters is slightly acidic (5.0 –7.5) and is caused by the dissolved carbon dioxide and organic acids (fulvic and humic acids) which are derived from the decay and subsequent leaching of plant materials (Langmuir, 1997). Waters with pH value above 10 are exceptional and may reflect contamination by strong base such as NaOH and $Ca(OH)_2$. The range of desirable limit of pH of water prescribed for drinking purpose by ISI (1983) and WHO (1984) is 6.5-8.5 while that of EEC (Lloyd and Heathcote, 1985) is 6.5-9.0.

In the present study, a comparison of the results of both eastern crystalline terrain and coastal tracts has been made. No general trend in the value of pH has been noticed. The pH in general shows higher values for the coastal area than the eastern crystallines for both pre-monsoon and post-monsoon periods. In the eastern crystallines of the study area pH value as low as 5.8 is recorded in a considerable part of the study area. In an unconfined aquifer system (like that of the present study) the pH will be often below 7 (Langmuir, 1997).

The acidic nature of the groundwater can be attributed to the dissolution of $CO_2$, which is being incorporated into the groundwater system by bacterial oxidation of organic substances (Matthess and Pekdeger, 1981) and addition of $CO_2$ through rainwater. Moreover, the low pH of the groundwater in the eastern crystallines can be related to the wide distribution of lateritic soil whose pH is always acidic (CESS, 1984). In most of the wells the values are within the admissible limits in both pre-monsoon and post-monsoon periods. A low pH of below 6.5 can cause corrosion to water carrying metal pipes thereby releasing toxic metals such as zinc, lead, cadmium, copper etc. (Trivedy and Goel, 1986). The pH distributions of groundwater of the study area for both seasons are represented by zonation maps in fig.5.2a & 5.2b.

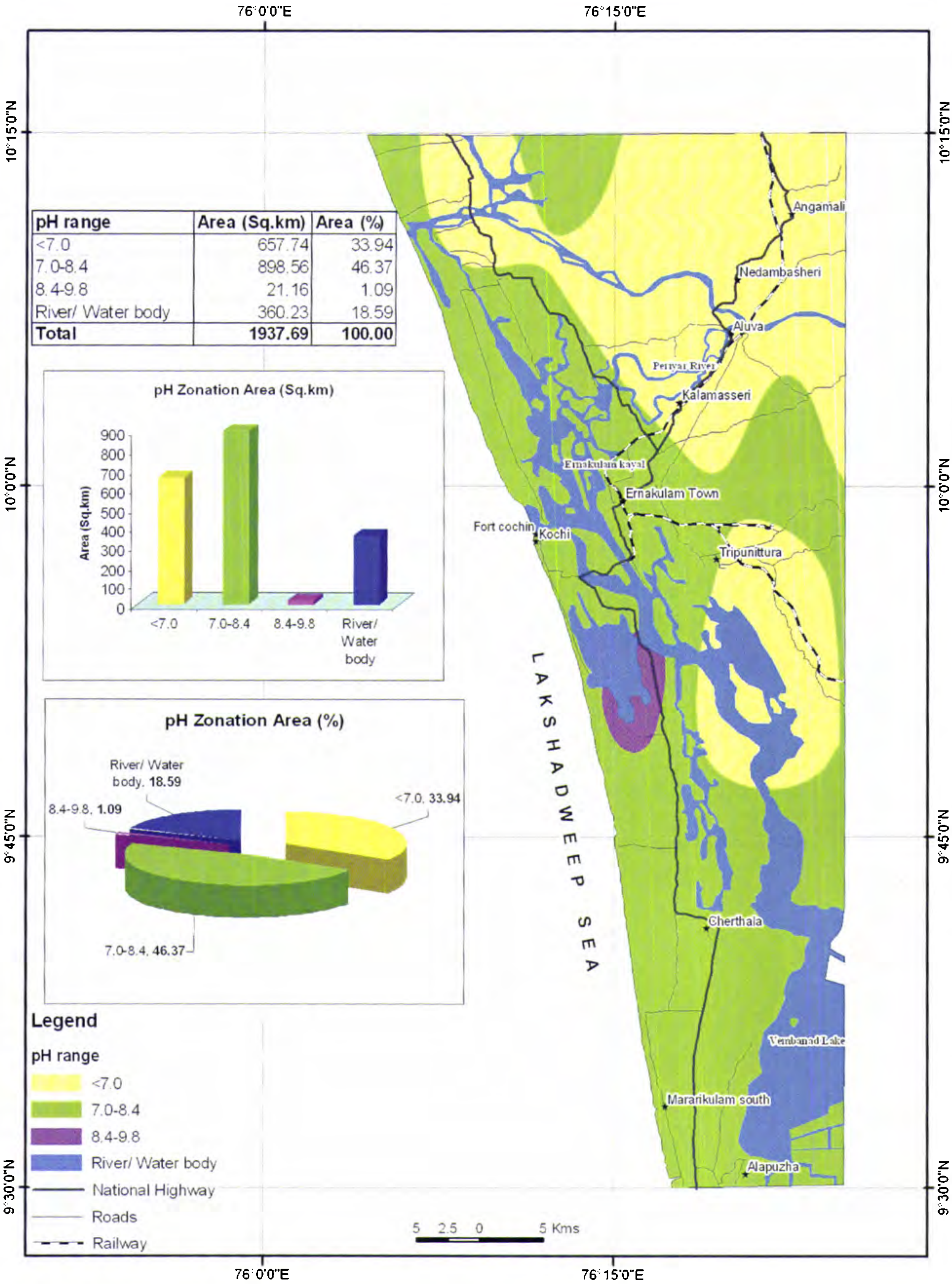
### 5.3.2. Electrical Conductivity (EC)

Electrical Conductivity (EC) is a measure of water's ability to conduct an electric current and is directly related to the total dissolved salt content of the water. This is because the salts dissolve into positive and negative ions that can conduct an electrical current proportionately to their concentration. EC is measured in Micro Siemens per centimetre. EC is temperature sensitive and increases with temperature. Most modern probes automatically correct for temperature, standardize all readings to 25°C and then refer to the data as specific EC. Electrical conductivity is very useful for determining water quality because it is an indicator of salinity




| pH Zonation range | Area(Sq.km) | Area (%) |
|---|---|---|
| <7.0 | 569.83 | 29.41 |
| 7.0-8.4 | 921.02 | 47.53 |
| 8.4-9.8 | 83.64 | 4.32 |
| >9.8 | 2.98 | 0.15 |
| River/Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.2a ZONATION - pH (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



| pH range | Area (Sq.km) | Area (%) |
|---|---|---|
| <7.0 | 657.74 | 33.94 |
| 7.0-8.4 | 898.56 | 46.37 |
| 8.4-9.8 | 21.16 | 1.09 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |



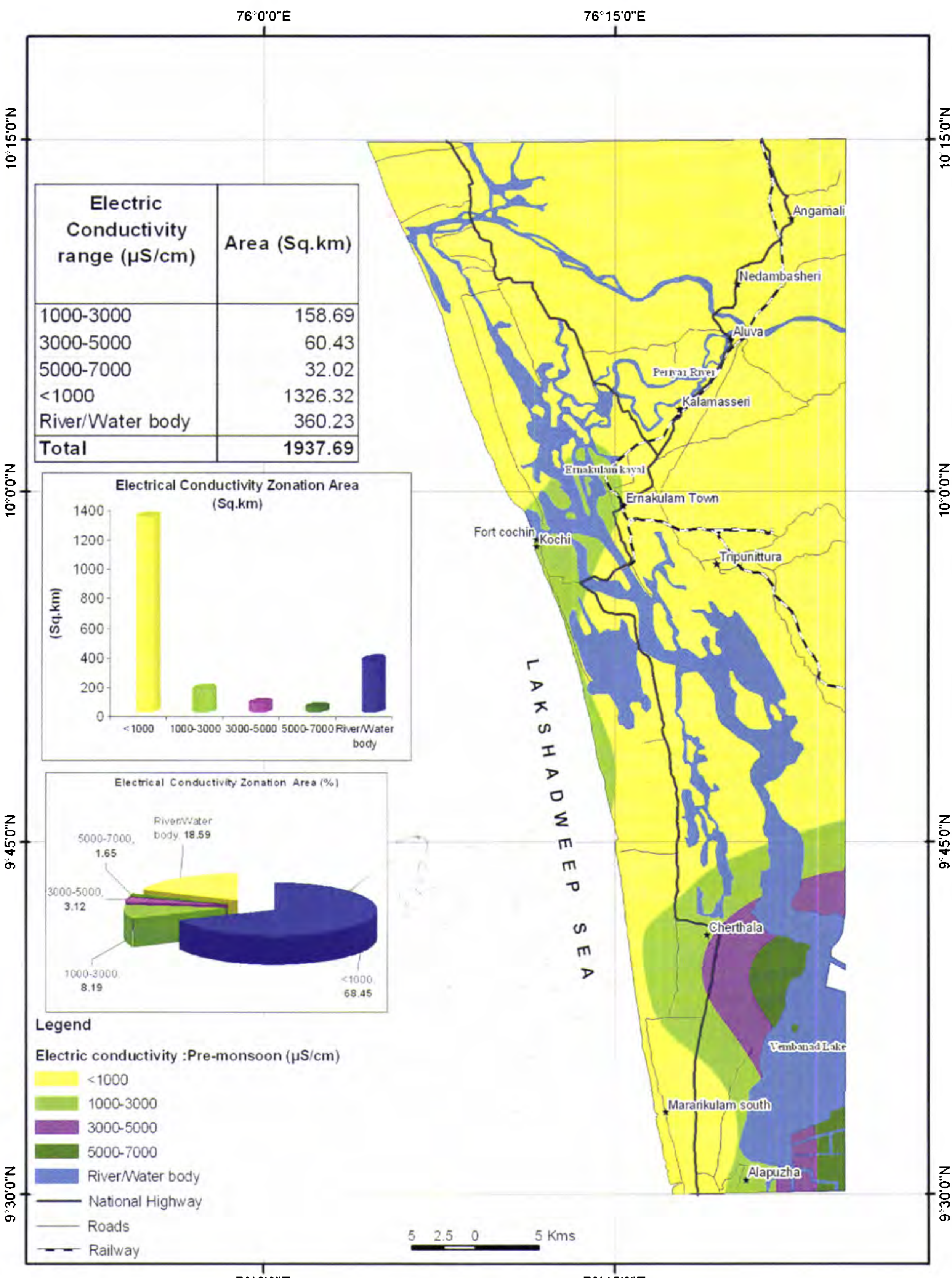
fig.5.2b ZONATION - pH (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

in water, which affects the taste and has an impact on the user acceptance of water as potable. The major chemical constituents, which contribute to the electrical conductance, are components of hardness ($Ca^{++}$ and $Mg^{++}$). Other components that also contribute to the electrical conductance are Nitrate, Chloride and Sulphates. In the present study the EC values are found to vary from 124 microseimens/cm to 530microseimens/cm during pre-monsoon season for the samples taken from the coastal belt where as the crystalline terrain shows values between 41 microseimens/cm and 349 microseimens/cm (fig.5.3.a). In the post-monsoon the values for the coastal belt ranges from 110 microseimens/cm to 2796 microseimens/cm whereas the crystallines show values ranging from 30 microseimens/cm to 260 microseimens/cm (fig.5.3.b).

**Classification of groundwater based on Ec- WHO (1984)**

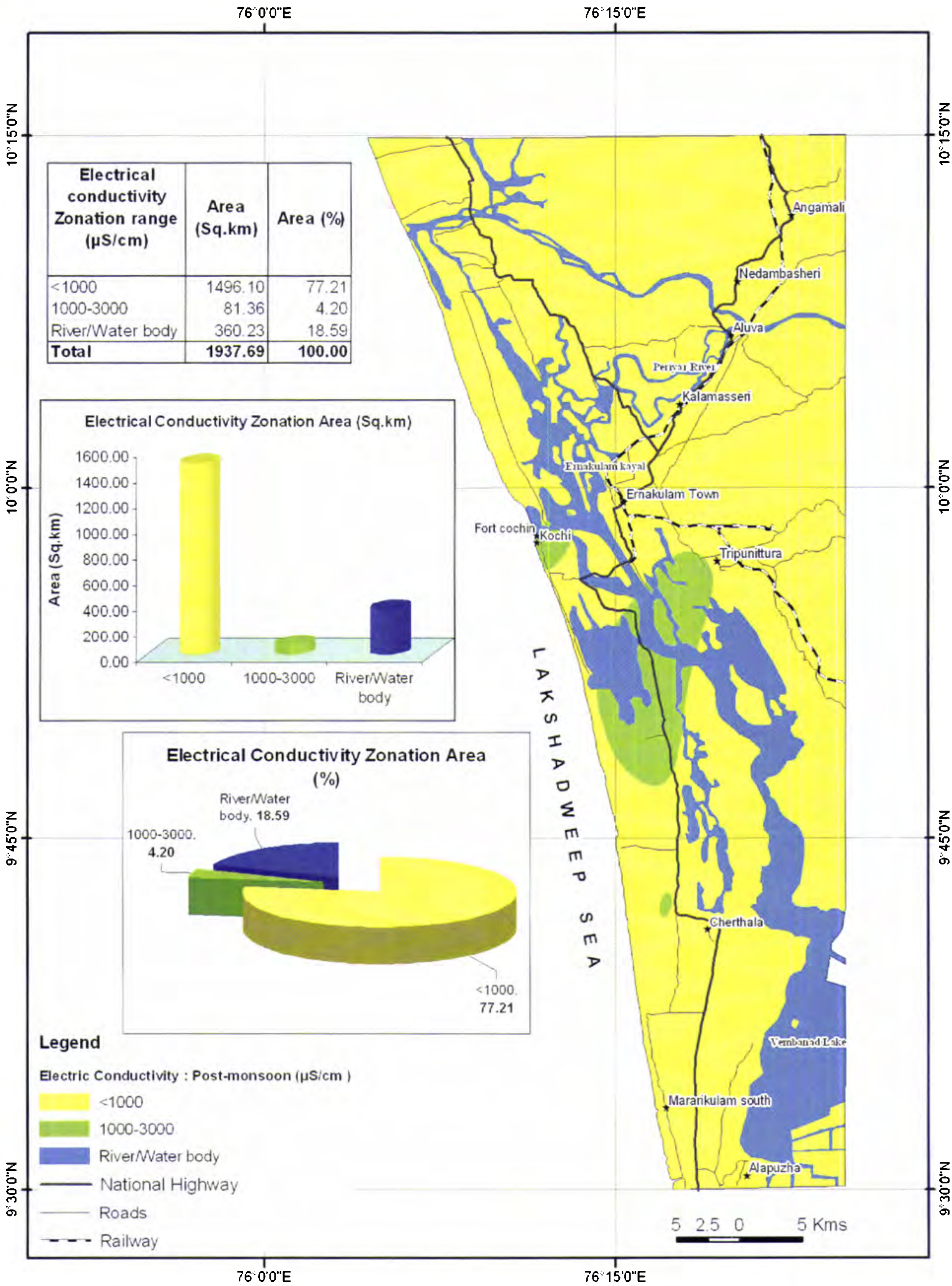
| Sl. No. | Range of EC micro mhos/cm at 25°C | Quality |
|---|---|---|
| 01 | <333 | Excellent |
| 02 | 333 – 500 | Good |
| 03 | 500 – 1000 | Permissible |
| 04 | 1000 – 1500 | Brackish |
| 05 | 1500 – 10000 | Saline |

The comparative study clearly reveals that in both pre-monsoon and post-monsoon periods wells in the crystalline terrain shows low EC values and hence these are suitable for drinking and other domestic purposes. In the coastal belt higher values are noticed and the quality of water ranges from excellent to saline.




| Electric Conductivity range (µS/cm) | Area (Sq.km) |
|---|---|
| 1000-3000 | 158.69 |
| 3000-5000 | 60.43 |
| 5000-7000 | 32.02 |
| <1000 | 1326.32 |
| River/Water body | 360.23 |
| **Total** | **1937.69** |

fig.5.3a ZONATION - ELECTRIC CONDUCTIVITY (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH




| Electrical conductivity Zonation range (µS/cm) | Area (Sq.km) | Area (%) |
|---|---|---|
| <1000 | 1496.10 | 77.21 |
| 1000-3000 | 81.36 | 4.20 |
| River/Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.3b ZONATION - ELECTRIC CONDUCTIVITY (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

### 5.3.3. Total Dissolved Salts (TDS)

The total concentration of dissolved minerals in water is a general indication of its suitability for any particular purpose. This may be calculated by adding the concentration of all ions in water or from the weight of dry residue remaining after a sample of water has evaporated.

**Table 5.4 Classification of groundwater based on TDS**

| Sl.No | Category | TDS (ppm) |
|---|---|---|
| 01 | Fresh Water | 0 – 1000 |
| 02 | Slightly Saline | 1000 - 3000 |
| 03 | Moderately Saline | 3000 - 10000 |
| 04 | Very Saline | 10000 - 35000 |
| 05 | Brine | More than 35000 |

Groundwater with a TDS value of less than 300 mg/l (Table 5.4) can be considered as excellent for drinking purpose according to WHO (1984). The distributions of TDS values for both seasons are shown in (fig.5.4a & 5.4b). The TDS values for the crystallines fall well below 300mg/l. The value ranges from 26mg/l to 223mg/l. But in the case of the coastal belt, the values are pretty high in many wells and ranges from 79mg/l to 3392 mg/l. According to Venugopal (1998) and Aravindan (1999) the TDS values are higher during pre-monsoon than the post-monsoon season. In the present study also this feature is very evident from the isocone map of TDS. The contours show considerable thickening in the pre-monsoon when compared to the post-monsoon. This can be attributed to the dilution resulting from the rainfall. As discussed earlier, total dissolved solids (TDS) are a measure of the dissolved minerals in water and also a measure of drinking water quality. There is a secondary drinking water standard of 500

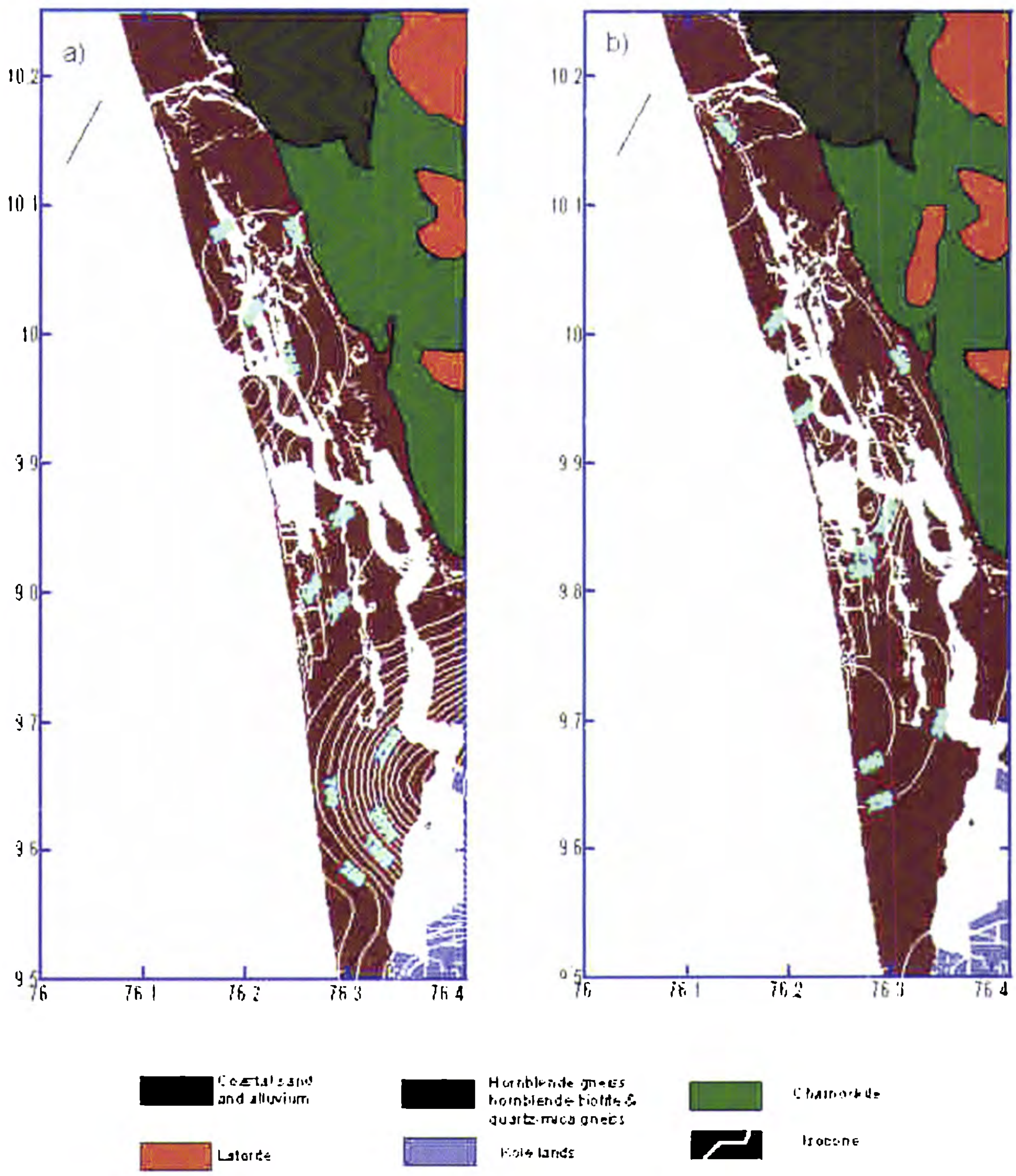



Fig 5.4a Isocone map of TDS in the coastal plain (a) pre monsoon and (b) post monsoon

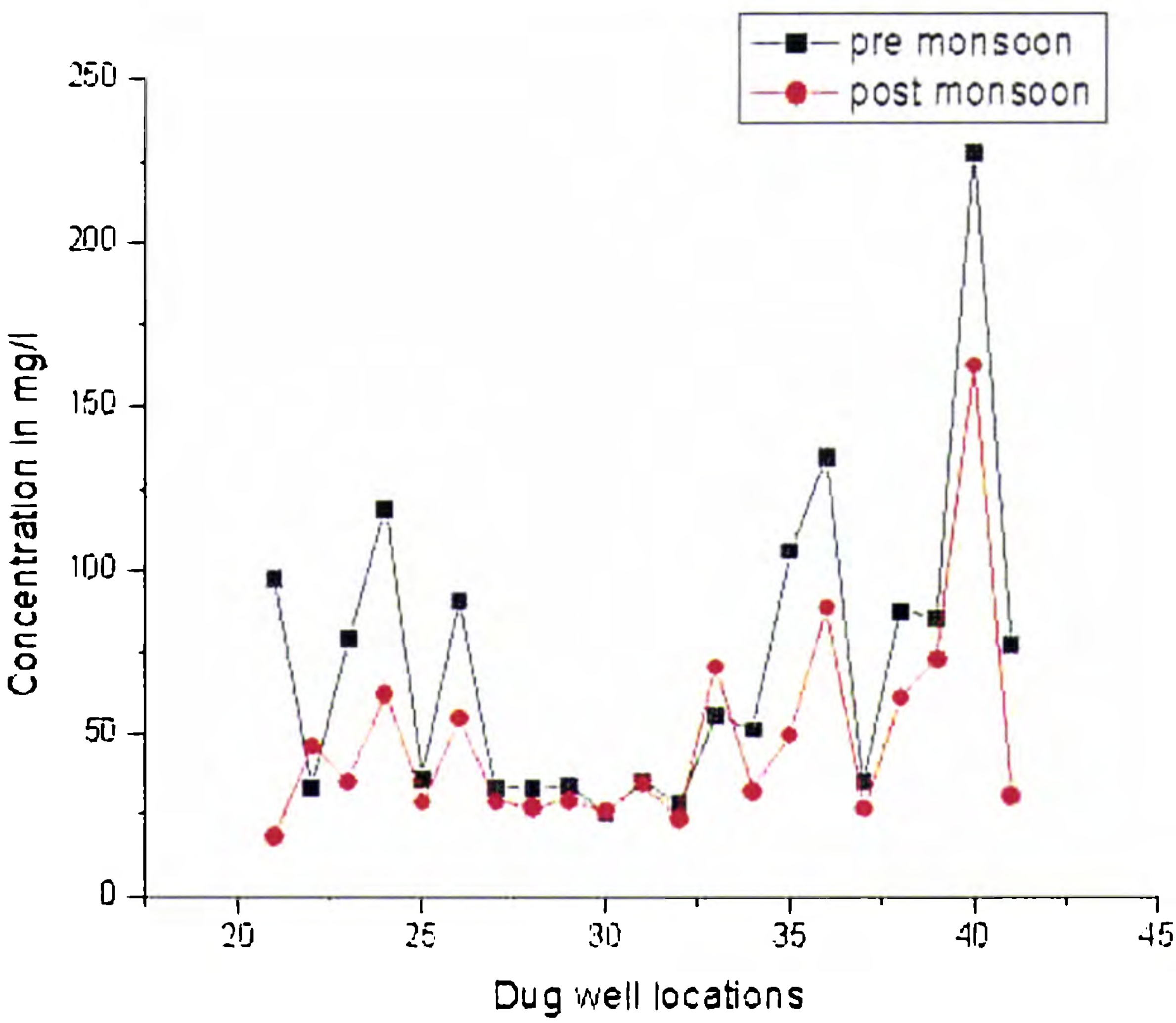



fig 5.4b Variation of TDS in crystalline terrain during pre and post monsoon

milligrams per litre (mg/l) TDS; water exceeding this level tastes salty. Groundwater with TDS levels greater than 1500 mg/l is considered too saline to be a good source of drinking water. (Kelly and Wilson, 2003).

Table.5.5 The potability of water in terms of TDS (mg/l) as per WHO (1984).

| **Water class** | **TDS mg/l** |
|---|---|
| Excellent | <300 |
| Good | 300-600 |
| Fair | 600-900 |
| Poor | 900-1200 |
| Unacceptable | >1200 |

Concentrations in 5 wells exceeded 500 mg/l. A high TDS value of 3392mg/l is shown by a well at located in Chellanam in the coastal belt where salt water intrusion has been reported earlier by many authors. This value is well above the I.S.I standard of 1500mg/l. Groundwater at 4 locations belongs to brackish water type as per the TDS classification (Twart et al. 1974). All these locations fall in the coastal belt. Rainwater is relatively pure distilled type water with very low TDS levels.

As rainwater comes in contact with materials (soils, sediments and bed rocks) soluble minerals (salts) are dissolved and carried in solution with the water during surface water flow or groundwater flow. Therefore TDS levels tend to increase in the down streams direction of the surface water flow and in the down gradient direction of ground water flow. The lowest TDS levels observed in groundwater generally present within the outcrop areas of the bedrock formation located along the eastern part of the study area.

From the analysis of EC and TDS values it can be safely inferred that wells in the crystalline terrain of the study area are much suitable for drinking purposes than those in the coastal belt.

**5.4. Major cations and anions**

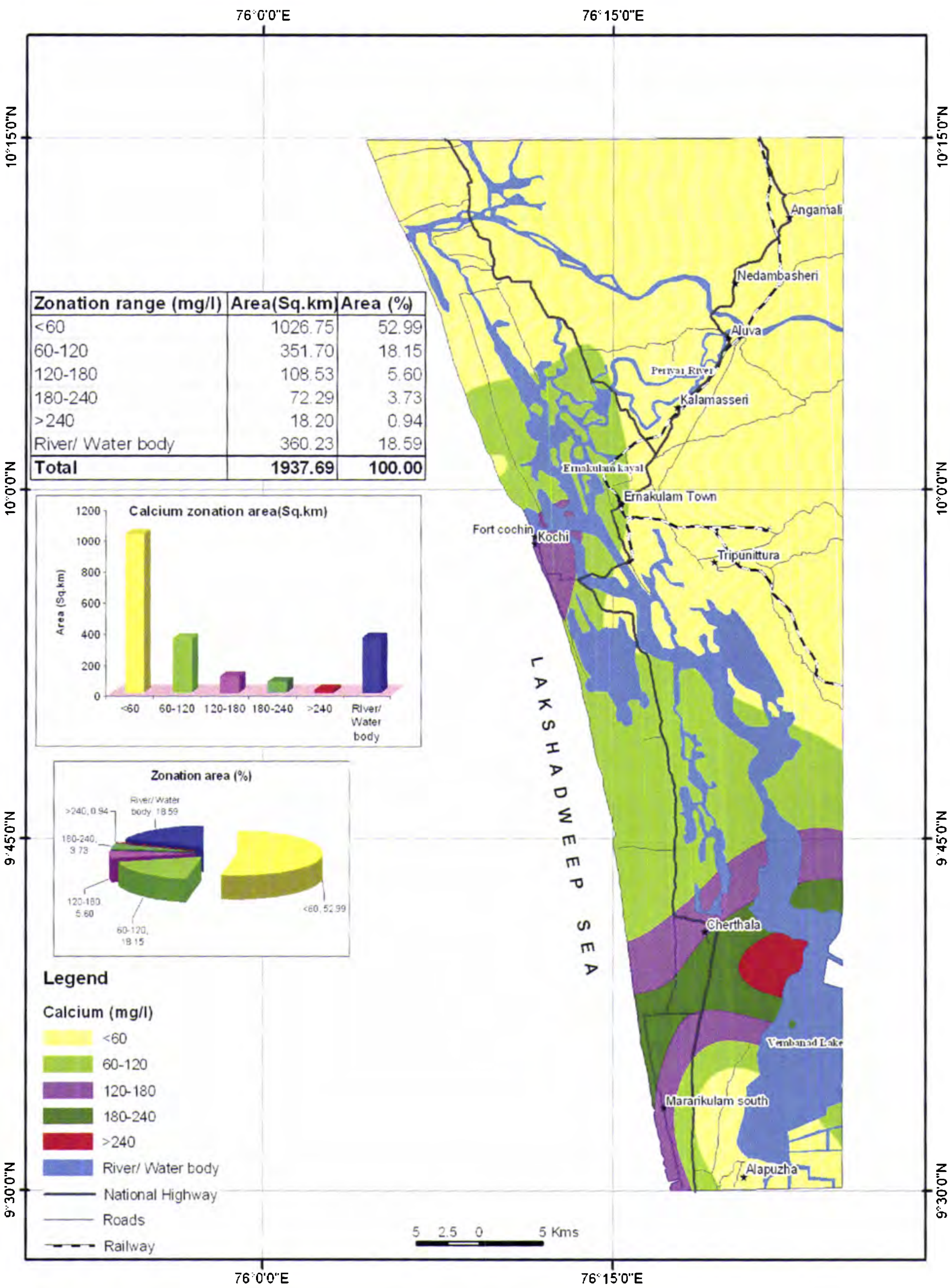
The spatial variation of the major cations and anions were deciphered using GIS zonation and are described below. The pre-monsoon and post-monsoon data of each element was analysed using GIS and is described below. Overlay analyses of the pre-monsoon and post-monsoon data has been carried out to clearly demarcate the seasonal variation in a scientific and accurate manner and explained in Chapter-6. These data were also used to prepare hydro chemical diagrams and facies classification.

**5.3.1. Cation Geochemistry.**

**Ca**: Ca is one of the freely dissolving ions from many rocks and soils. The principal sources of calcium in groundwater are some members of silicate mineral groups like plagioclase, pyroxene and amphibole among igneous and metamorphic rocks and limestone, dolomite and gypsum among sedimentary rocks. Calcium is present in water as $Ca^{++}$, which forms complex with some organic anions. The presence of K and Na also influences the solubility of calcium. Concentration of calcium in normal potable groundwater generally ranges between 10 and 100 ppm. Calcium in this concentration has no effect on the health of humans. Indeed as much as 1000 ppm of calcium may be harmless. The zonation map of Ca is given in fig 5.5a& 5.5b. In the present study the value for Ca is found to vary between 6.4 and 254 mg/l in the coastal area during pre-monsoon period where as it ranges from 1.6 to 38.5mg/l for the crystalline terrain during the same period. During the post-monsoon Ca value is found to vary between 12.2 and 170.2 mg/l for the coastal belt and between 2.1 and 33.9 mg/l for the crystalline terrain. The WHO standard prescribed for Ca in groundwater is 75-200mg/l. All the wells except the well at chellanam in the coastal belt falls within the limit prescribed. Very low values are noticed towards the eastern part of the study area where the wells are in the crystalline terrain.

**Mg:** Mg is commonly associated with calcium and causes hardness of water. The Geochemical behaviour of Mg is altogether different from that of Ca. In igneous and metamorphic rocks, magnesium occurs in the form of insoluble silicates; weathering breaks them down into more soluble carbonates, clay minerals and silica. Concentration of magnesium in groundwater attains a rather wide range. Magnesium is relatively non toxic to man. Magnesium salts act as cathartics and diuretics (Manivasakam, 1996) among animals as well as human beings. Magnesium is essential to normal plant growth. Calcium and magnesium ions in irrigation water tend to keep soil permeable and in good tilth.

The zonation map of Mg is given in fig 5.6a & 5.6b. In the present study it is found that in all the wells except the one at Chellanam, the Mg value is well below the permissible limit of 30mg/l set by ISI. The crystalline terrain of the study area shows very low values of Mg when




| Zonation range (mg/l) | Area(Sq.km) | Area (%) |
|---|---|---|
| <60 | 1026.75 | 52.99 |
| 60-120 | 351.70 | 18.15 |
| 120-180 | 108.53 | 5.60 |
| 180-240 | 72.29 | 3.73 |
| >240 | 18.20 | 0.94 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

Fig.5.5a ZONATION - CALCIUM (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

| Zonation range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <60 | 1264.98 | 65.28 |
| 60-120 | 216.13 | 11.15 |
| 120-180 | 85.17 | 4.40 |
| >180 | 11.19 | 0.58 |
| River/Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

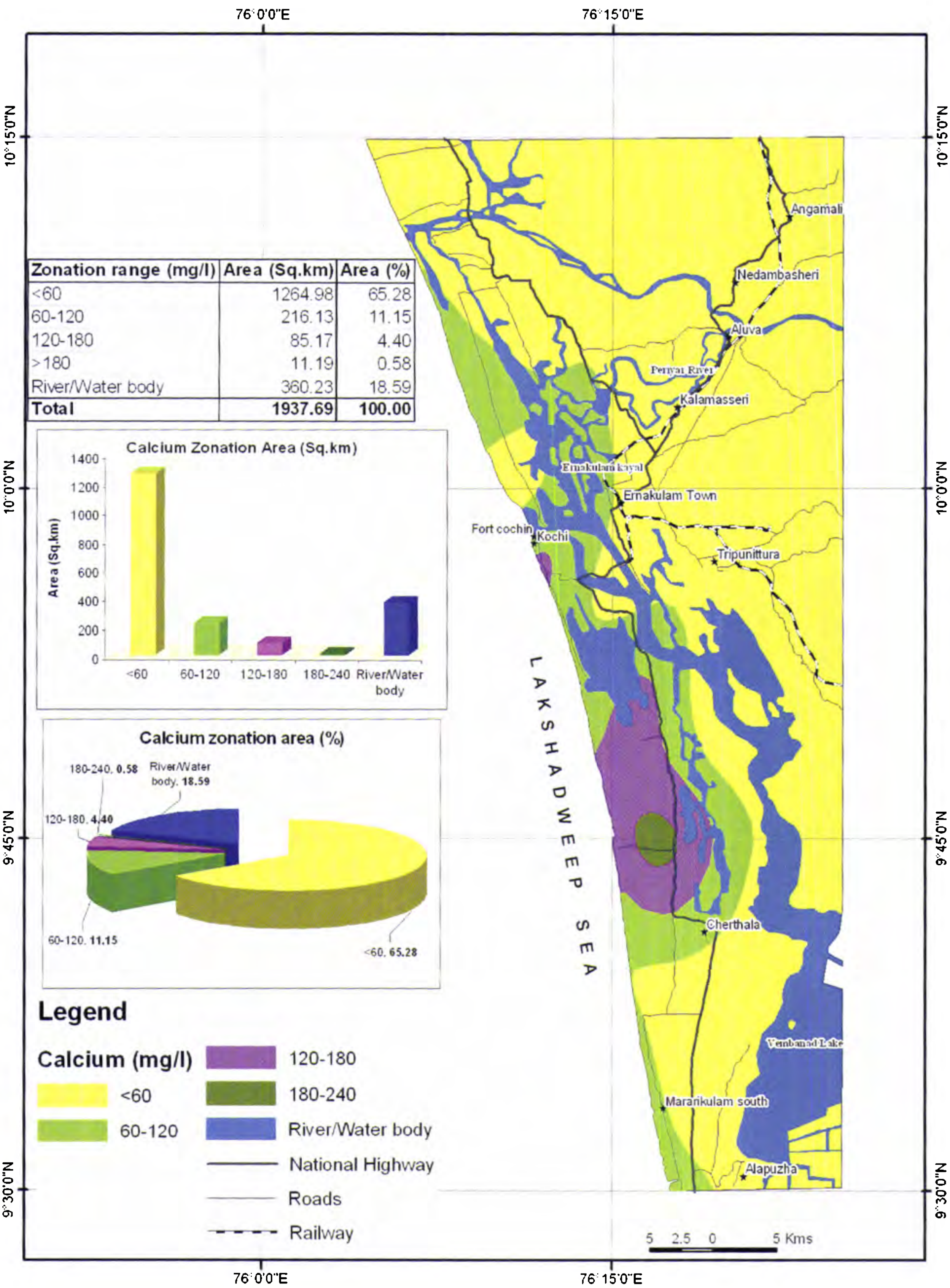
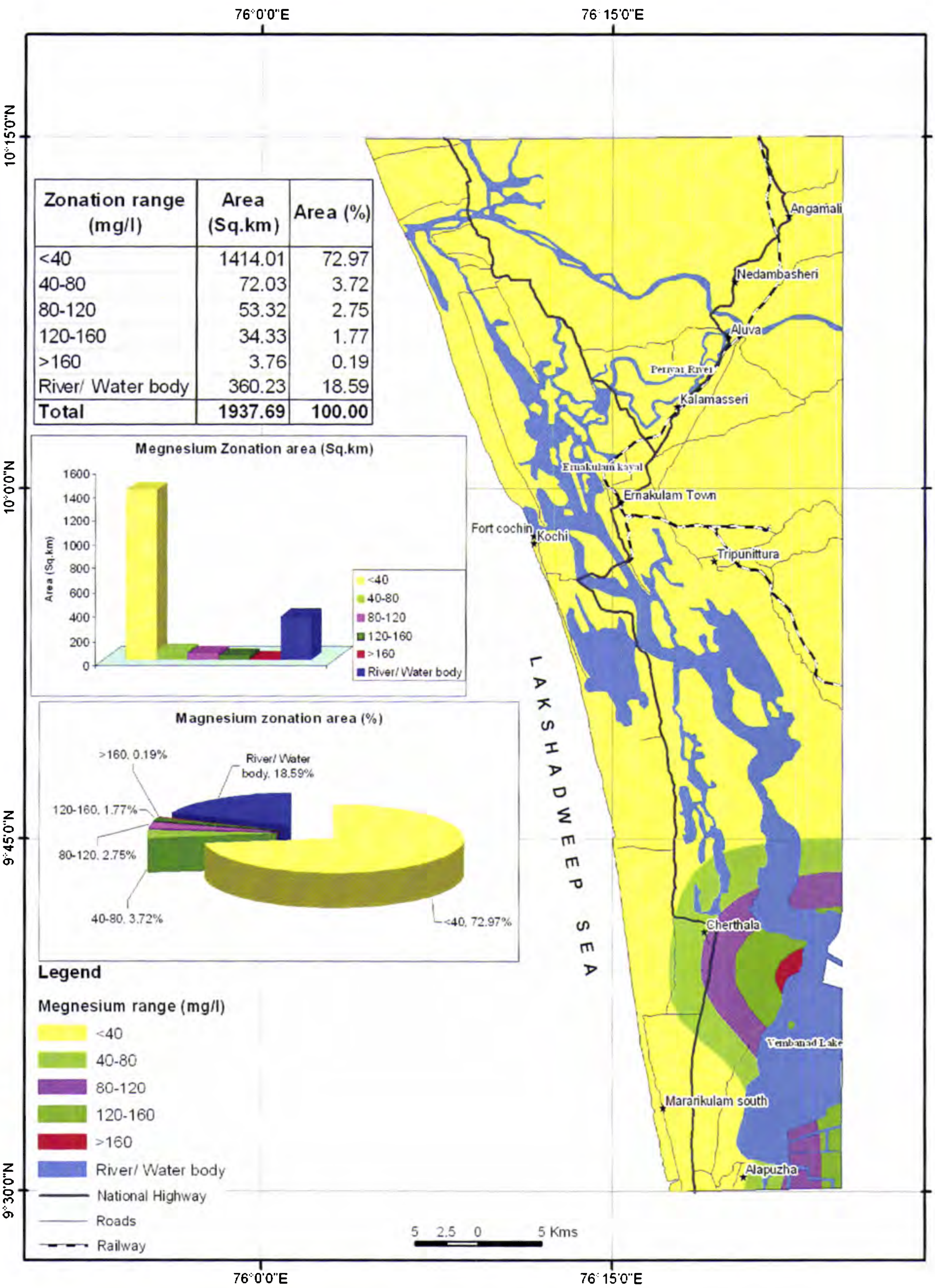
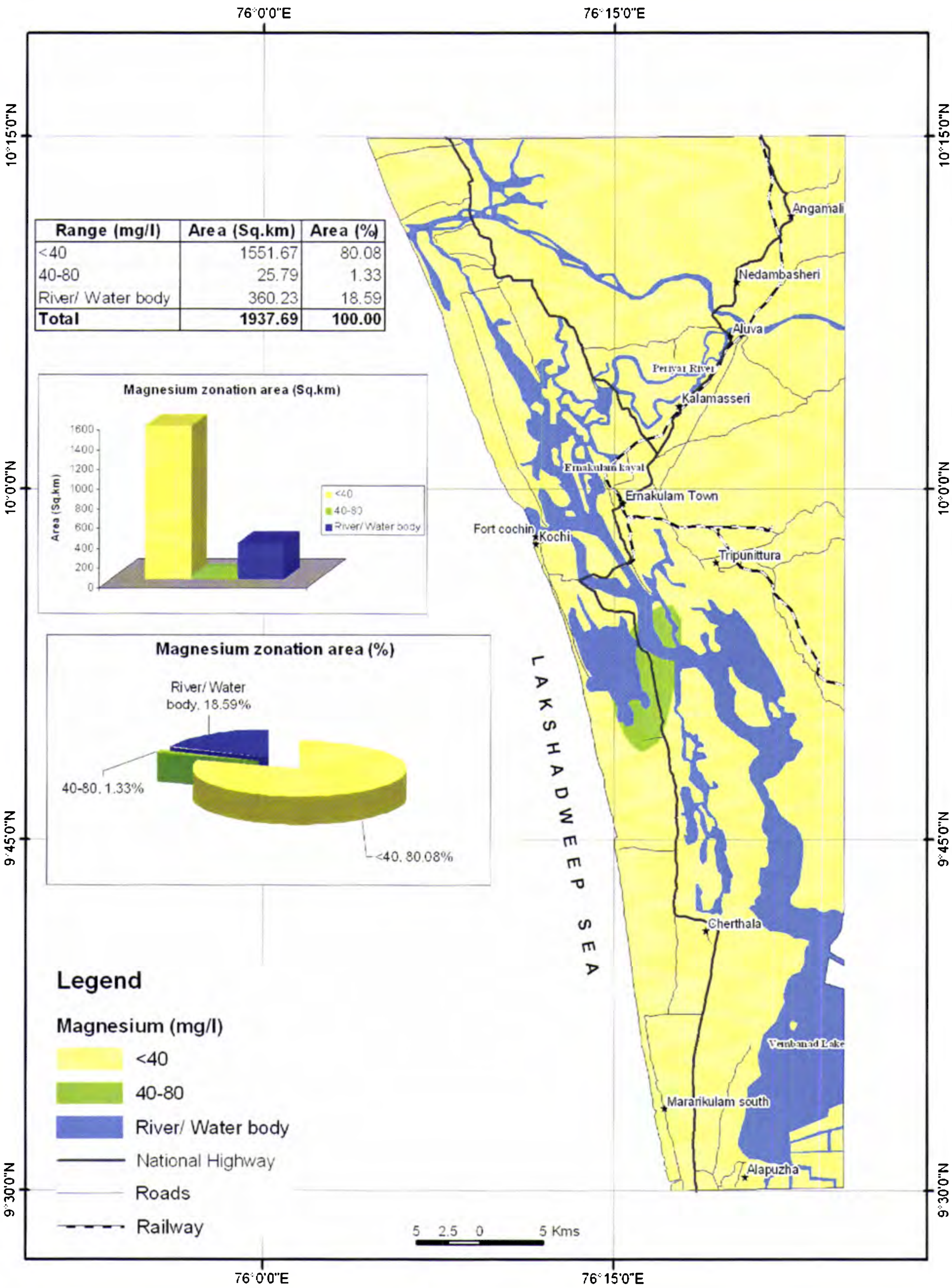



Fig.5.5b ZONATION - CALCIUM (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH




| Zonation range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <40 | 1414.01 | 72.97 |
| 40-80 | 72.03 | 3.72 |
| 80-120 | 53.32 | 2.75 |
| 120-160 | 34.33 | 1.77 |
| >160 | 3.76 | 0.19 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.6a ZONATION - MAGNESIUM (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

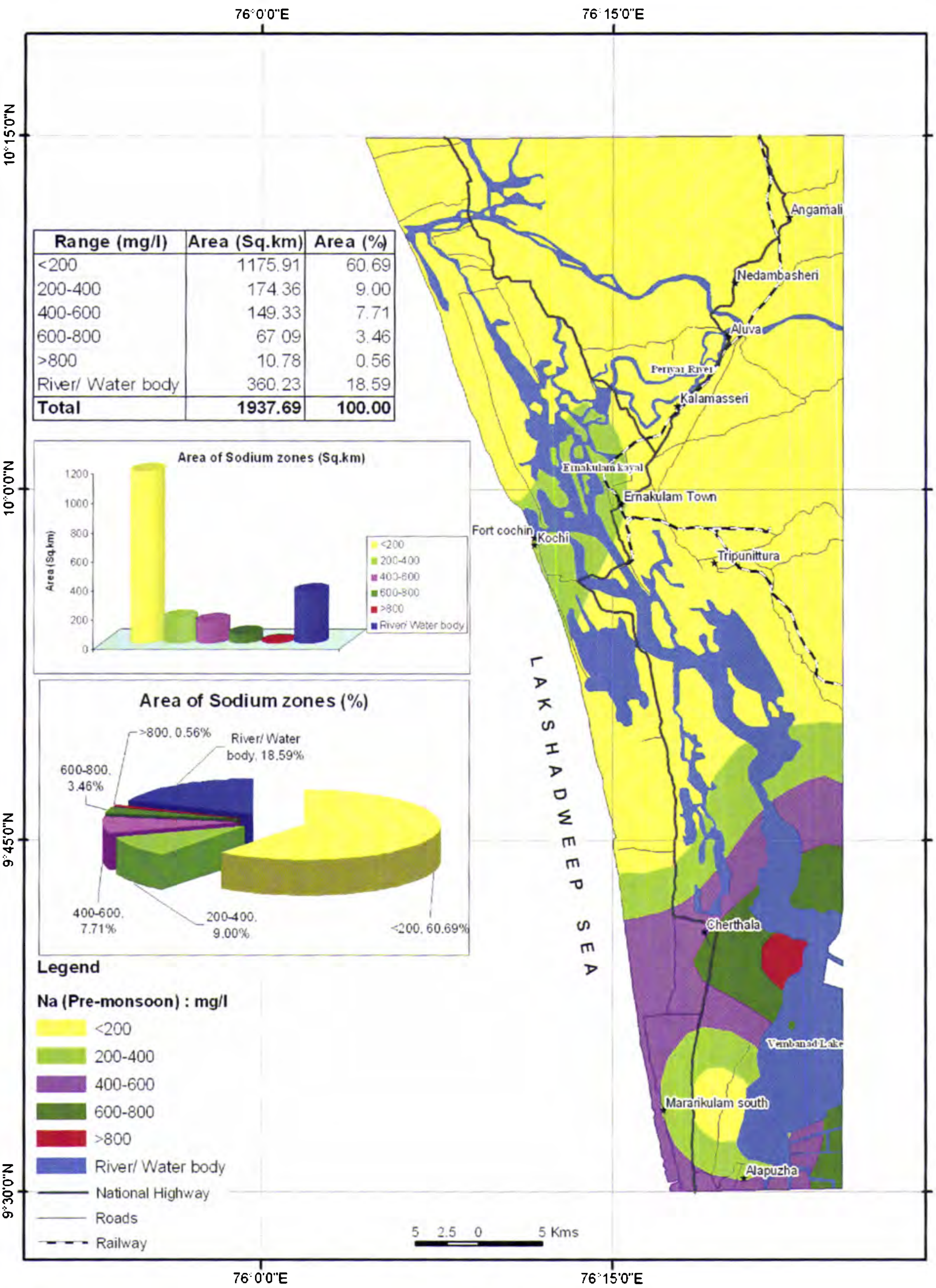



| Range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <40 | 1551.67 | 80.08 |
| 40-80 | 25.79 | 1.33 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.6b ZONATION - MAGNESIUM (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

compared to the coastal belt ranging from 0.1mg/l to 4mg/l during pre-monsoon and 0.5mg/l to 9.0 mg/l during post-monsoon. The wells in the coastal belt show values ranging from 0.7mg/l to 144.2 mg/l for pre-monsoon and from 0.4 mg/l to 22.7 mg/l for post-monsoon.

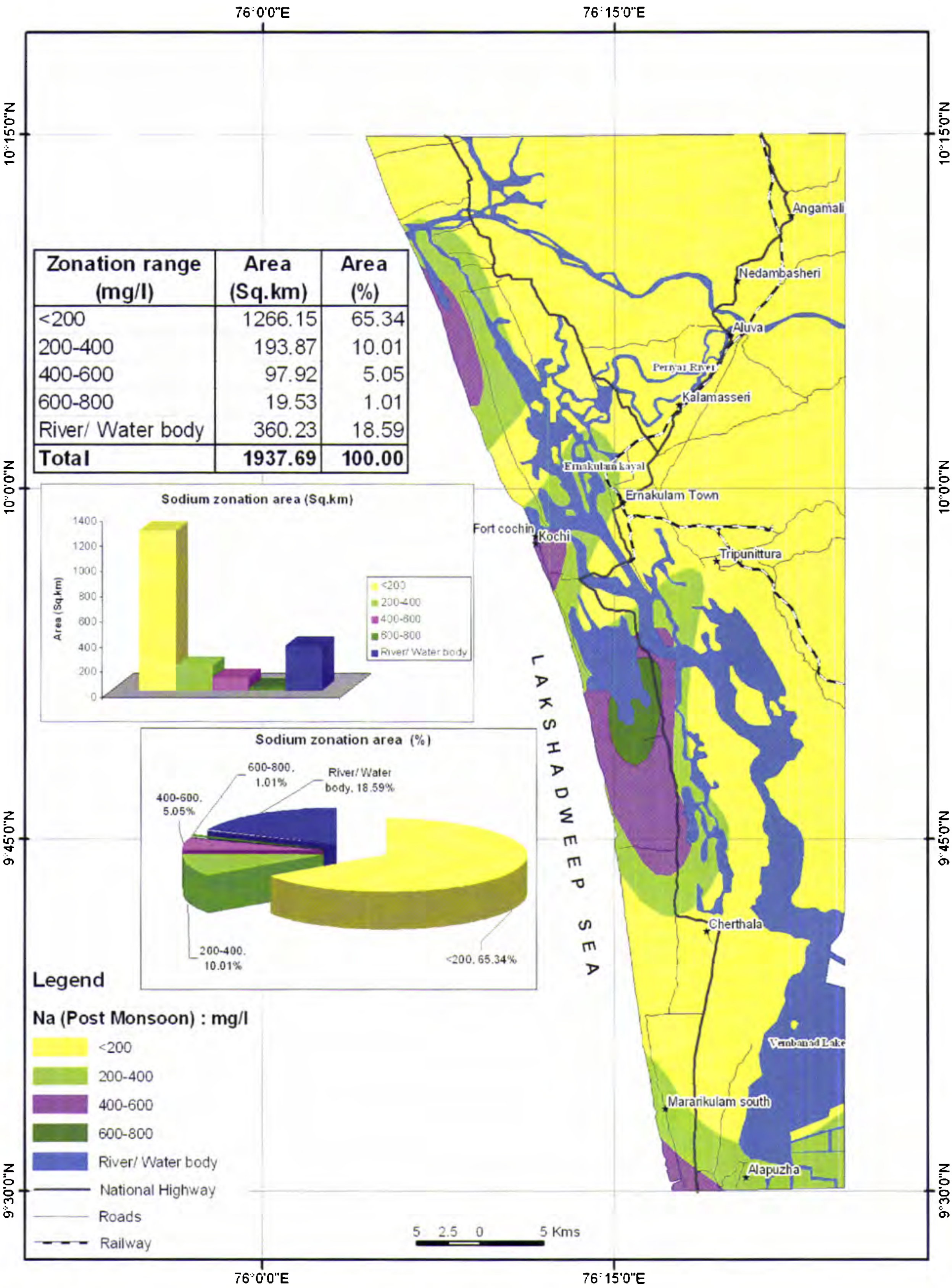
**Na:** Na unlike calcium, magnesium and silica is not found as an essential constituent of many of the common rock-forming minerals. The primary source of most sodium in natural water is from the release of soluble products during the weathering of plagioclase feldspars. The most important source of sodium in groundwater, with concentration of over 50 ppm of sodium is the precipitation of sodium salts impregnating the soil in shallow water tracks, particularly in arid and semi-arid regions. The zonation map of Na in the study area is given in fig5.7a & 5.7b. The Na values for the crystalline terrain in the study area fall between 3.0 mg/l and 27 mg/l during pre-monsoon and between 4.2 mg/l and 14.8 mg/l for post-monsoon, which is well below the WHO standard of 200mg/l. But the coastal belt shows wide variation in Na values and abnormally high values were observed in some wells in this belt. Certain clay minerals and zeolites can increase the sodium content in groundwater by base exchange reactions. Sodium is associated with high blood pressure and heart disease in persons genetically predisposed to essential hypertension. In addition, certain diseases are aggravated by a high salt intake including heart failure, cirrhosis and renal disease (Hussain et al. 2005). The spatial distribution of Na are given in fig.5.7a 5.7b



| Range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <200 | 1175.91 | 60.69 |
| 200-400 | 174.36 | 9.00 |
| 400-600 | 149.33 | 7.71 |
| 600-800 | 67.09 | 3.46 |
| >800 | 10.78 | 0.56 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |



fig.5.7a ZONATION - SODIUM (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH




| Zonation range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <200 | 1266.15 | 65.34 |
| 200-400 | 193.87 | 10.01 |
| 400-600 | 97.92 | 5.05 |
| 600-800 | 19.53 | 1.01 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.7b ZONATION - SODIUM (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

**K:** The sources of K are the products formed by the weathering of orthoclase, microcline, biotite, leucite, and nepheline in igneous and metamorphic rocks. The abundance of Potassium in the earth's crust is about the same as Sodium, Potassium is commonly less than one -tenth the concentration of Sodium in natural water. It was also found that elevated levels of Potassium and or Nitrate in groundwater serve as a reliable indicator of the groundwater susceptibility to pesticide contamination. (Lampman, 1995). In the coastal belt, the value of K ranges from 7 mg/l to 121mg/l during pre-monsoon whereas during the same period, the values for the crystalline terrain range from 0.7 mg/l to 9 mg/l. During the post-monsoon period the corresponding values are 7 mg/l to 109 mg/l for the coastal belt and 0.5 mg/l to 9.4 mg/l for the crystalline terrain. Fig5.8a & 5.8b represents the zonation of K.

### 5.3.2. Anion Geochemistry

The negatively charged ions or anions usually determined in routine water analysis are carbonates and bicarbonates sulphates and chlorides.

**Bicarbonates and Carbonates**:

Most of the carbonates and bicarbonates ions in groundwater are derived from the carbon dioxide in the atmosphere, carbon dioxide in soil and solution of carbonate rocks. These two constituents along with hydroxides are responsible for the alkalinity of water. The relative amounts of these two anions depend on the pH of the water and other factors. Bicarbonates increase as pH decreases. The zonation is given in fig.5.9a & 5.9b.

| Range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <30 | 1162.24 | 59.98 |
| 30-60 | 176.93 | 9.13 |
| 60-90 | 125.03 | 6.45 |
| 90-120 | 102.38 | 5.28 |
| >120 | 10.88 | 0.56 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

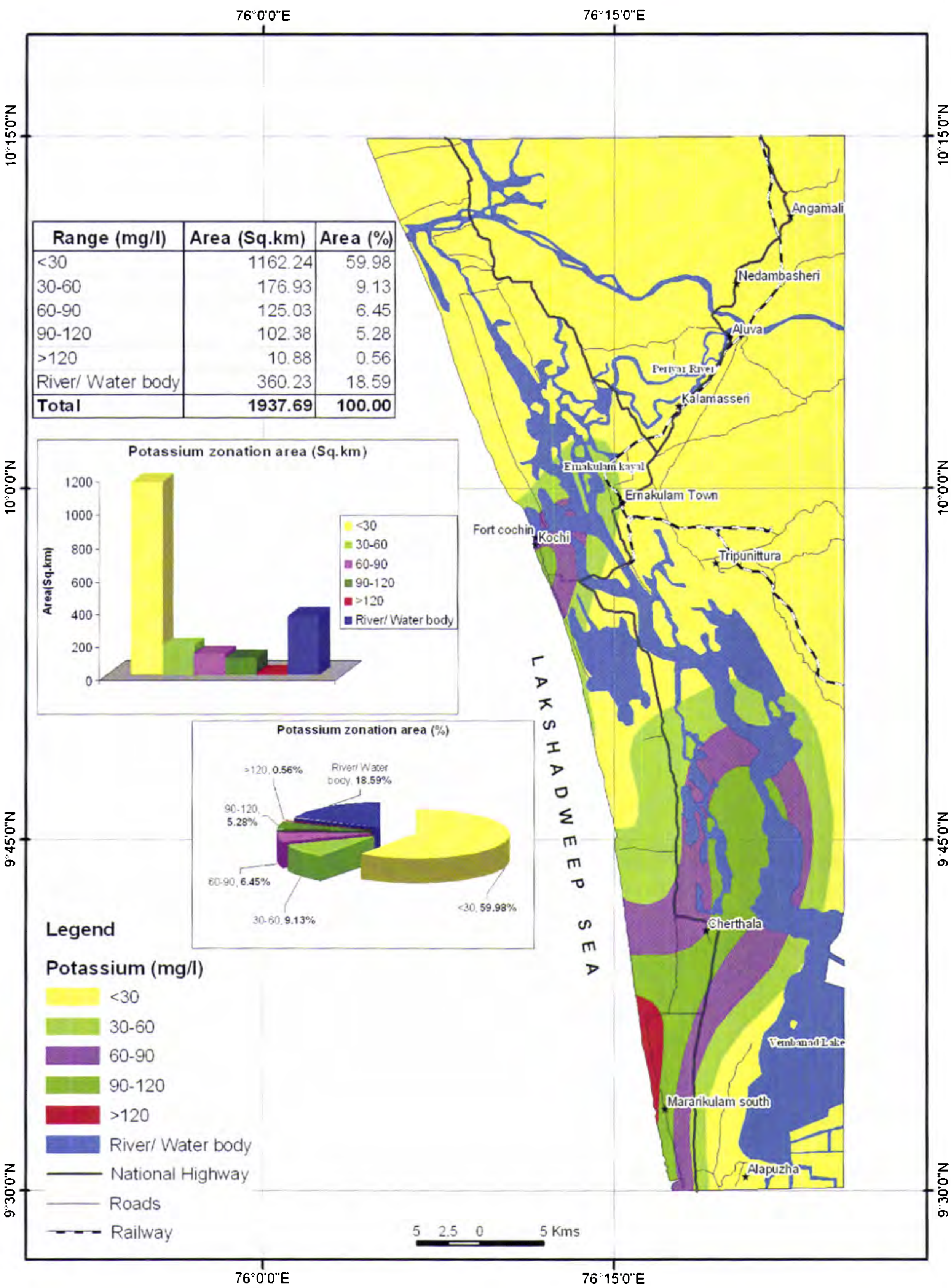
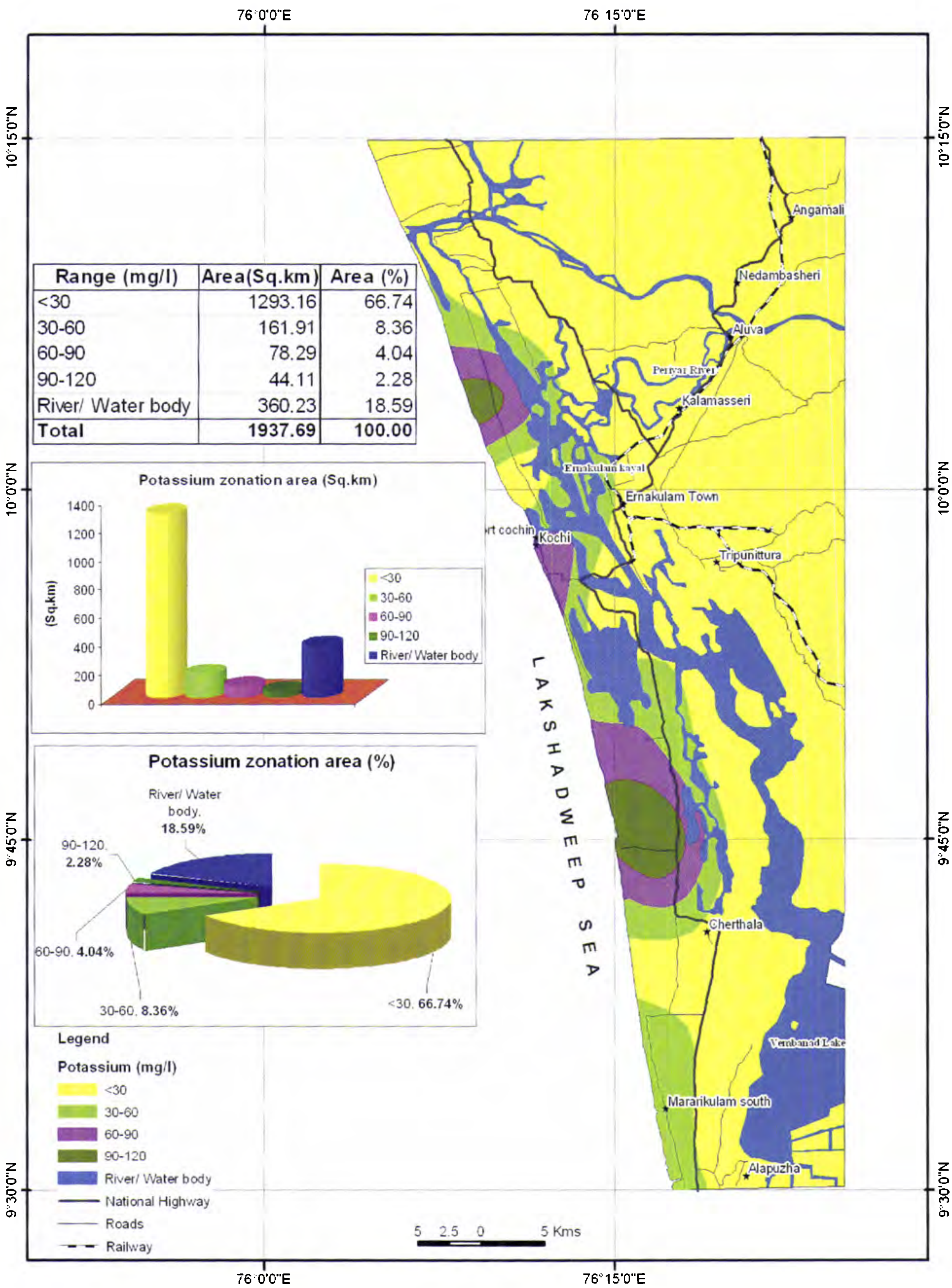
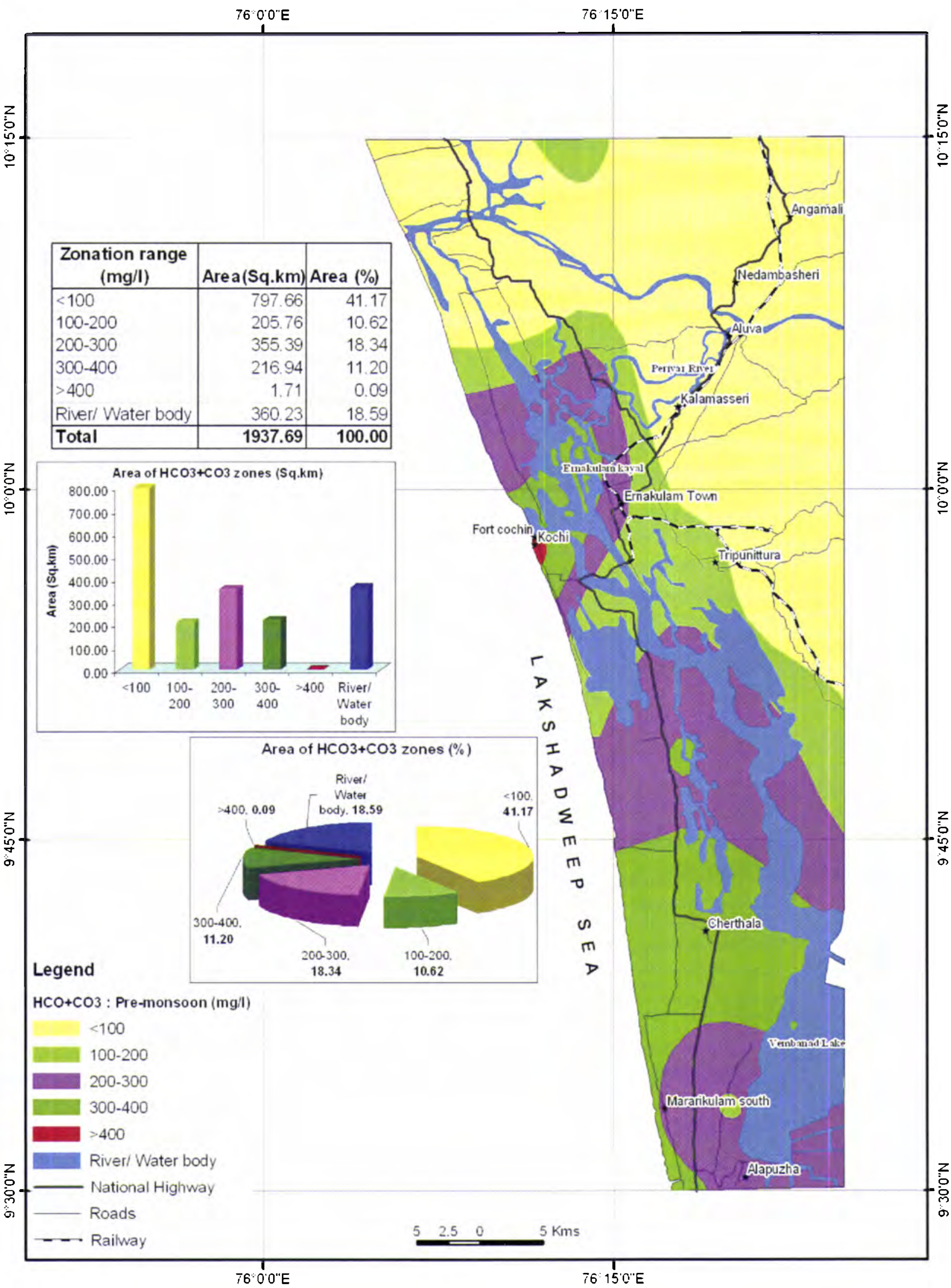



Fig.5.8a ZONATION - POTASSIUM (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



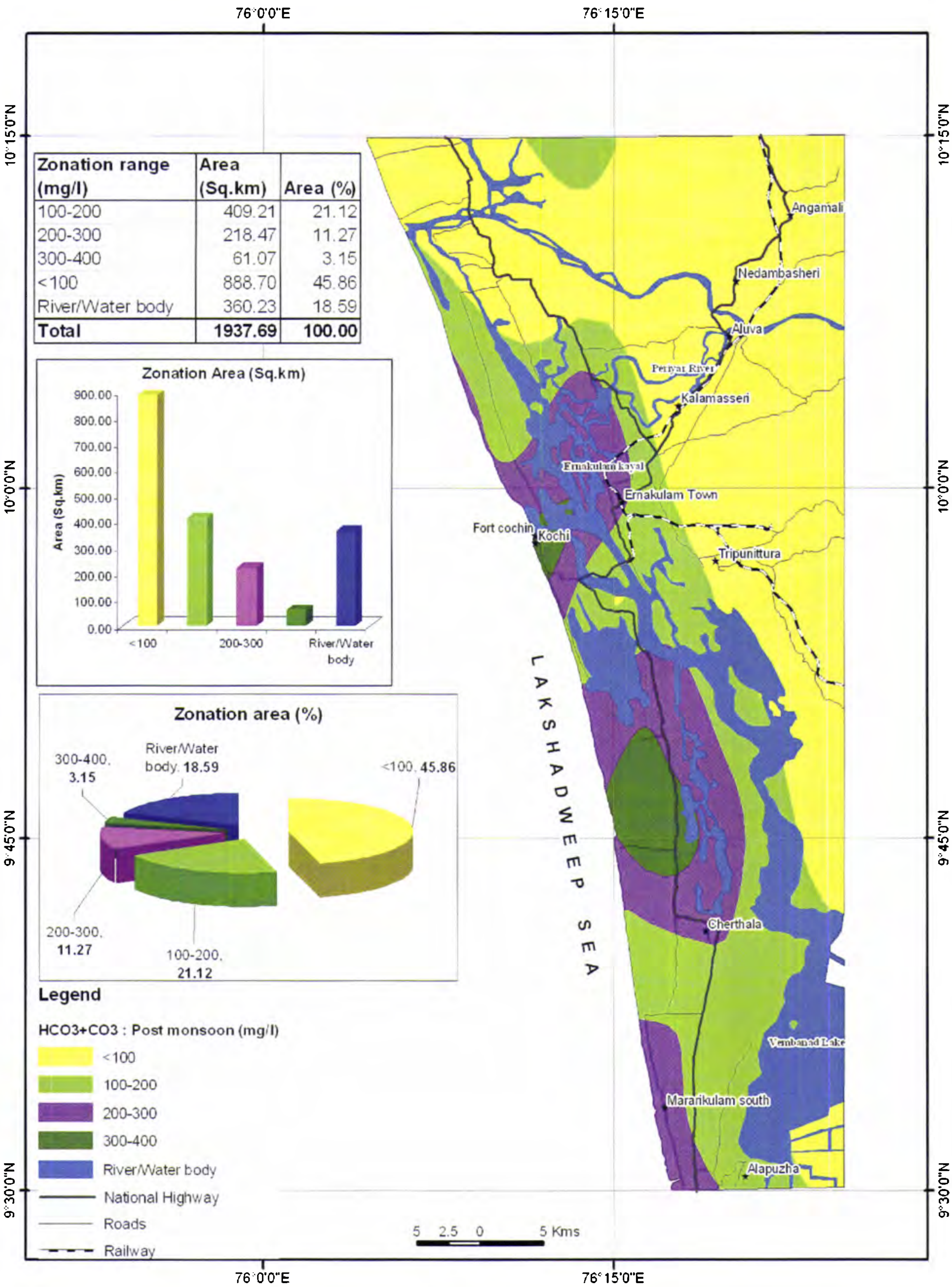

| Range (mg/l) | Area(Sq.km) | Area (%) |
|---|---|---|
| <30 | 1293.16 | 66.74 |
| 30-60 | 161.91 | 8.36 |
| 60-90 | 78.29 | 4.04 |
| 90-120 | 44.11 | 2.28 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.8b ZONATION - POTASSIUM (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH




| Zonation range (mg/l) | Area(Sq.km) | Area (%) |
|---|---|---|
| <100 | 797.66 | 41.17 |
| 100-200 | 205.76 | 10.62 |
| 200-300 | 355.39 | 18.34 |
| 300-400 | 216.94 | 11.20 |
| >400 | 1.71 | 0.09 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.9a ZONATION - HCO3+CO3 (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

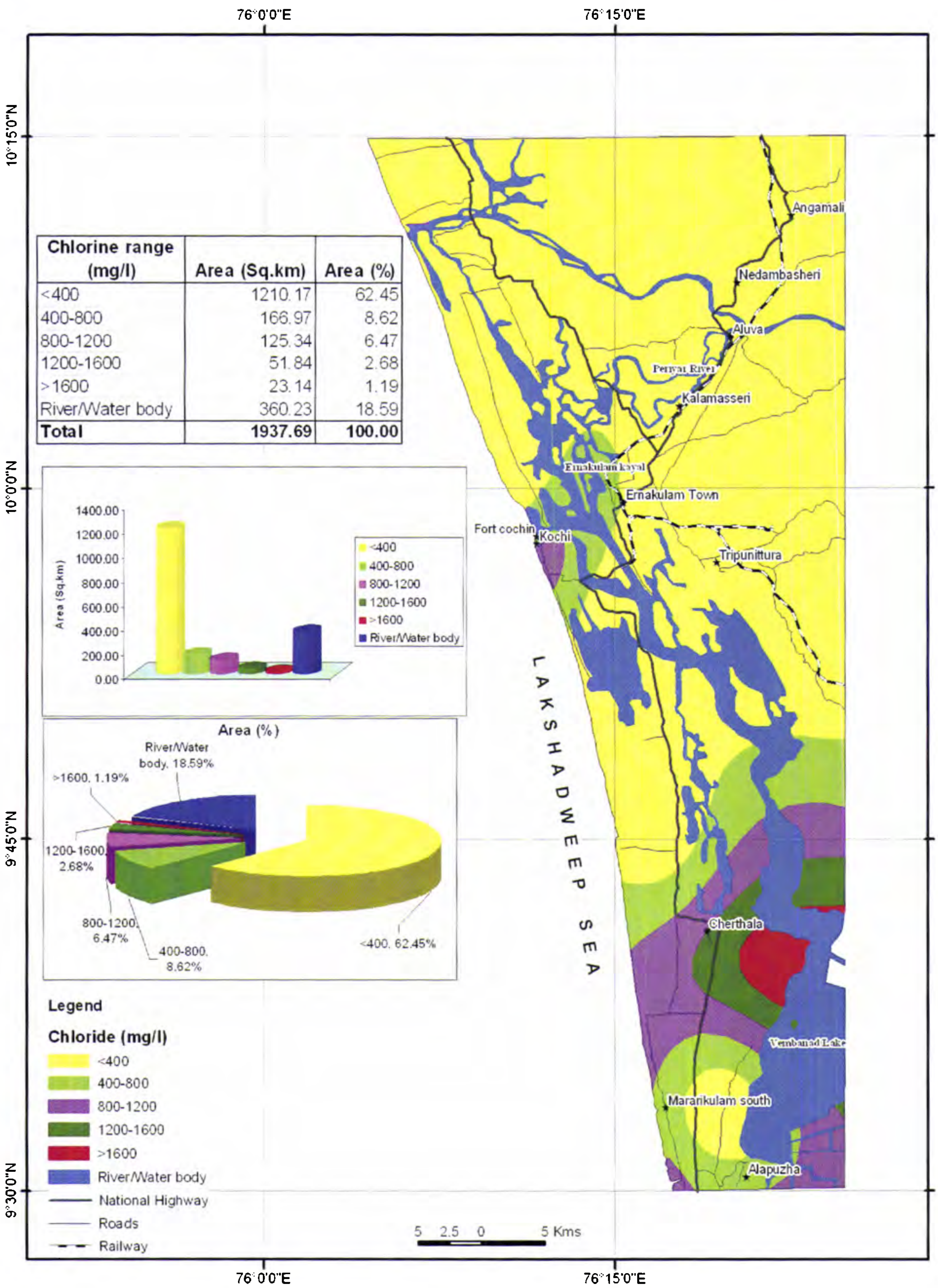



| Zonation range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| 100-200 | 409.21 | 21.12 |
| 200-300 | 218.47 | 11.27 |
| 300-400 | 61.07 | 3.15 |
| <100 | 888.70 | 45.86 |
| River/Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.9b ZONATION - HCO3+CO3 (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

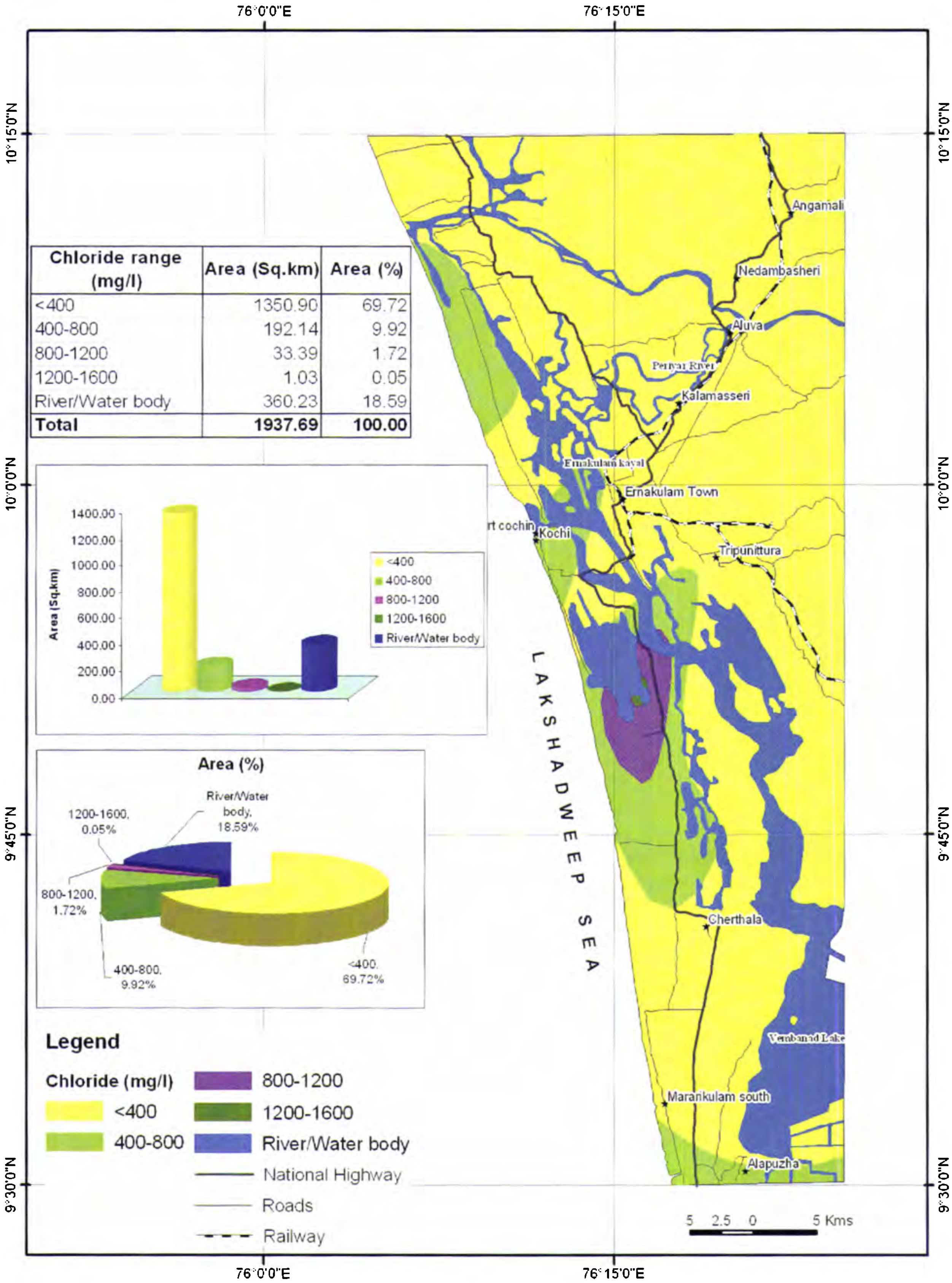
Hardness is essentially the amount of Calcium and Magnesium carbonates dissolved in water. Increased hardness can have negative effects like scaling of plumbing, heating vessels, and spotting of dishware. But beneficial relationship between high levels of hardness (calcium and magnesium carbonates) and the development of stronger bone structure, as well as the prevention of some cardiovascular disorders including hardening of the arteries are also reported. The hardness of groundwater in majority of the wells in the crystalline terrain of the study area for both pre-monsoon and post-monsoon falls well below the 75 mg/l ('soft' in the classification by Sawyer and McCarty, 1967) whereas wells in the coastal belt show very high values classifiable under 'hard' to 'very hard' as per Sawyer and McCarty's (1967) classification. Hardness of water for domestic purposes does not particularly become objectionable until it exceeds 100 ppm (Hem, 1959).

**Chloride:** Chloride is a minor constituent of the earth's crust, but a major dissolved constituent of most natural water. Chloride bearing minerals such as sodalite and chlorapatite, which are very minor constituents of igneous and metamorphic rocks, and liquid inclusions which comprise very significant fraction of rock volume, are minor source of chloride in groundwater. Most of the chloride in groundwater is present as sodium chloride but chloride concentration may exceed the sodium due to base exchange phenomena. Chloride in water is a stronger oxidising agent than Oxygen and Chlorine with Oxygen slowly decompose water. The zonation map of chloride in the study area is given in fig5.10a & 5.10b.




| Chlorine range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <400 | 1210.17 | 62.45 |
| 400-800 | 166.97 | 8.62 |
| 800-1200 | 125.34 | 6.47 |
| 1200-1600 | 51.84 | 2.68 |
| >1600 | 23.14 | 1.19 |
| River/Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.5.10a ZONATION - CHLORIDE (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



| Chloride range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <400 | 1350.90 | 69.72 |
| 400-800 | 192.14 | 9.92 |
| 800-1200 | 33.39 | 1.72 |
| 1200-1600 | 1.03 | 0.05 |
| River/Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |



fig.5.10b ZONATION - CHLORIDE (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

Wells in the crystalline terrain show values ranging from 5 mg/l to 39 mg/l during pre-monsoon and 2.8mg/l to 22.1mg/l for post-monsoon which are well within the permissible limits prescribed by WHO (1984), Lloyd and Heathcote, (1985) and ISI (1983). But the coastal belt presents an entirely different scenario with seven wells showing values above the permissible limit in both pre-monsoon and post-monsoon periods. High concentrations of chloride in groundwater is attributed to rainwater, seawater, natural brines, evaporate deposits and pollution (Junge and Wrby, 1958; Johnston, 1987). The very saline groundwater found at depths below the actively circulating zone are formed by the gradual solution of soluble constituents in aquifers and also by the modification, concentration and migration of the seawater that was present in many rocks when they formed. Some hydrogeologists believe that some groundwater have been concentrated by the filtering action of clays which act as semi-permeable membranes. The well at Chellanam shows an extremely high value of Cl during pre-monsoon. Here saltwater intrusion has been reported earlier by different agencies. A comparison of the isocone maps of Chloride for pre-monsoon in the coastal area shows that the contours thicken towards the southern part of the study area during Pre-monsoon.

Elevated levels of Chloride are noticed in wells influenced by tidal inlets. Most of the Chloride found in groundwater that is actively circulating at relatively shallow depths is derived from rain or, near coastlines, from sea spray. In built-up areas, leaching from waste sites and sewage systems may result in elevated chloride levels. Another source is corrosion in underground pipes, which, due to the effects on taste, may also limit the usefulness of groundwater for drinking purposes. In coastal areas, large-scale extraction of groundwater from wells located in sand, porous sedimentary rocks and highly fractured crystalline bedrock can result in the intrusion of salt water that affects groundwater quality even at great distances from the shoreline. The best removal techniques for excess chloride are reverse osmosis and deionisation.

**Sulphate**: Usually in waters, sulphate is found in smaller concentrations than chloride. The sources of sulphate in rocks are sulphur minerals and sulphides of heavy metals, which are of common occurrence in the igneous and metamorphic rock, and gypsum and anhydrite found in some sedimentary rocks. An important source of Sulphate in groundwater is the oxidation of Pyrite (ferrous sulphide), which is widely distributed, in sedimentary rocks. Sulphuric acid is a product of the reaction and this reacts with any Carbonate present to form Calcium and Magnesium sulphates. Sulphur-oxidising bacteria may promote the reaction. The Sulphate content of atmospheric precipitation is only about 2 ppm but a wide range in Sulphate content in groundwater is made possible through reduction, precipitation, solution and concentration as the water traverses through rocks. The Sulphate concentration in the study area is shown in the fig.5.11a & 5.11b. The sulphate concentration falls well within the desirable limits.

**Bacteriological Quality**

Bacteriological analysis carried out in the study area indicates the presence of *E.coli* in the groundwater in most of the locations. The spread

| Range (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <3 | 391.60 | 20.21 |
| 3-6 | 572.08 | 29.52 |
| 6-9 | 528.67 | 27.28 |
| 9-12 | 69.17 | 3.57 |
| >12 | 15.94 | 0.82 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

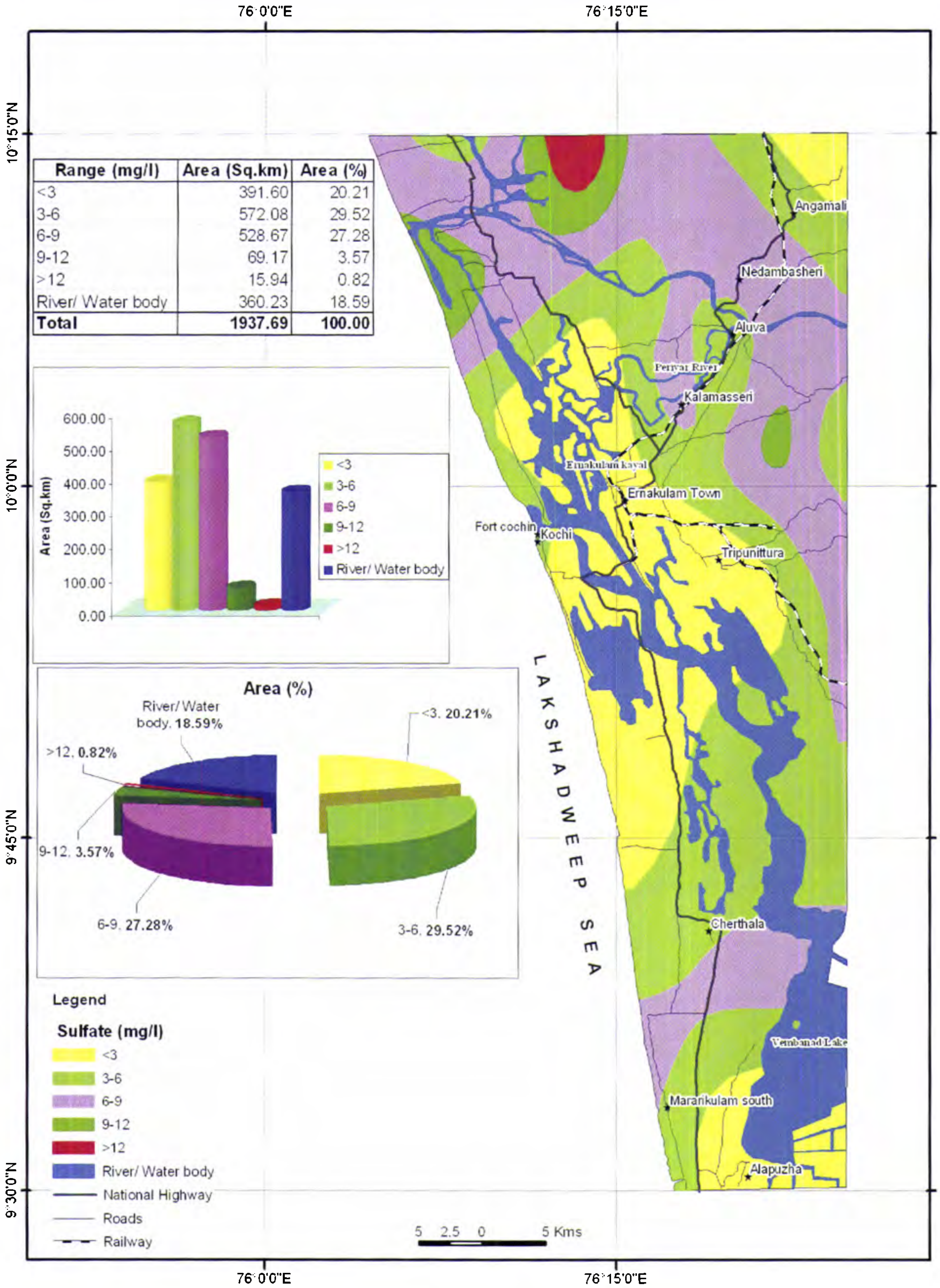
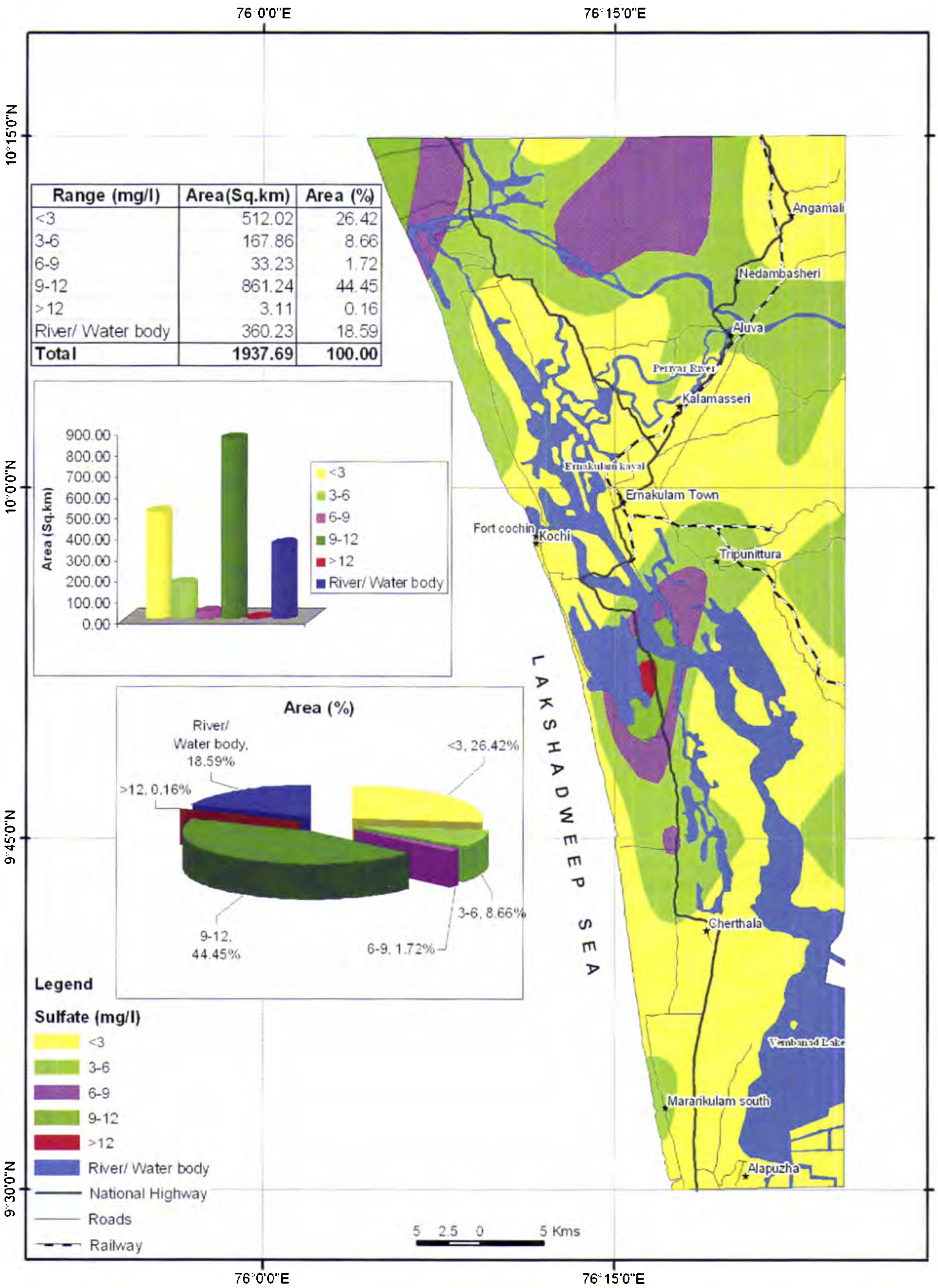



fig.5.11a ZONATION - SULFATE (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



| Range (mg/l) | Area(Sq.km) | Area (%) |
|---|---|---|
| <3 | 512.02 | 26.42 |
| 3-6 | 167.86 | 8.66 |
| 6-9 | 33.23 | 1.72 |
| 9-12 | 861.24 | 44.45 |
| >12 | 3.11 | 0.16 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |



fig.5.11b ZONATION - SULFATE (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

of e.coli is very evident from the zonation map in fig.5.12a & 5.12b. Coliforms are naturally present in the environment. E.coli comes only from human and animal fecal waste. During rainfalls e.coli may be washed into rivers, streams or ground water. When these waters are used as sources of drinking water and the water is not treated e.coli may end up in drinking water.

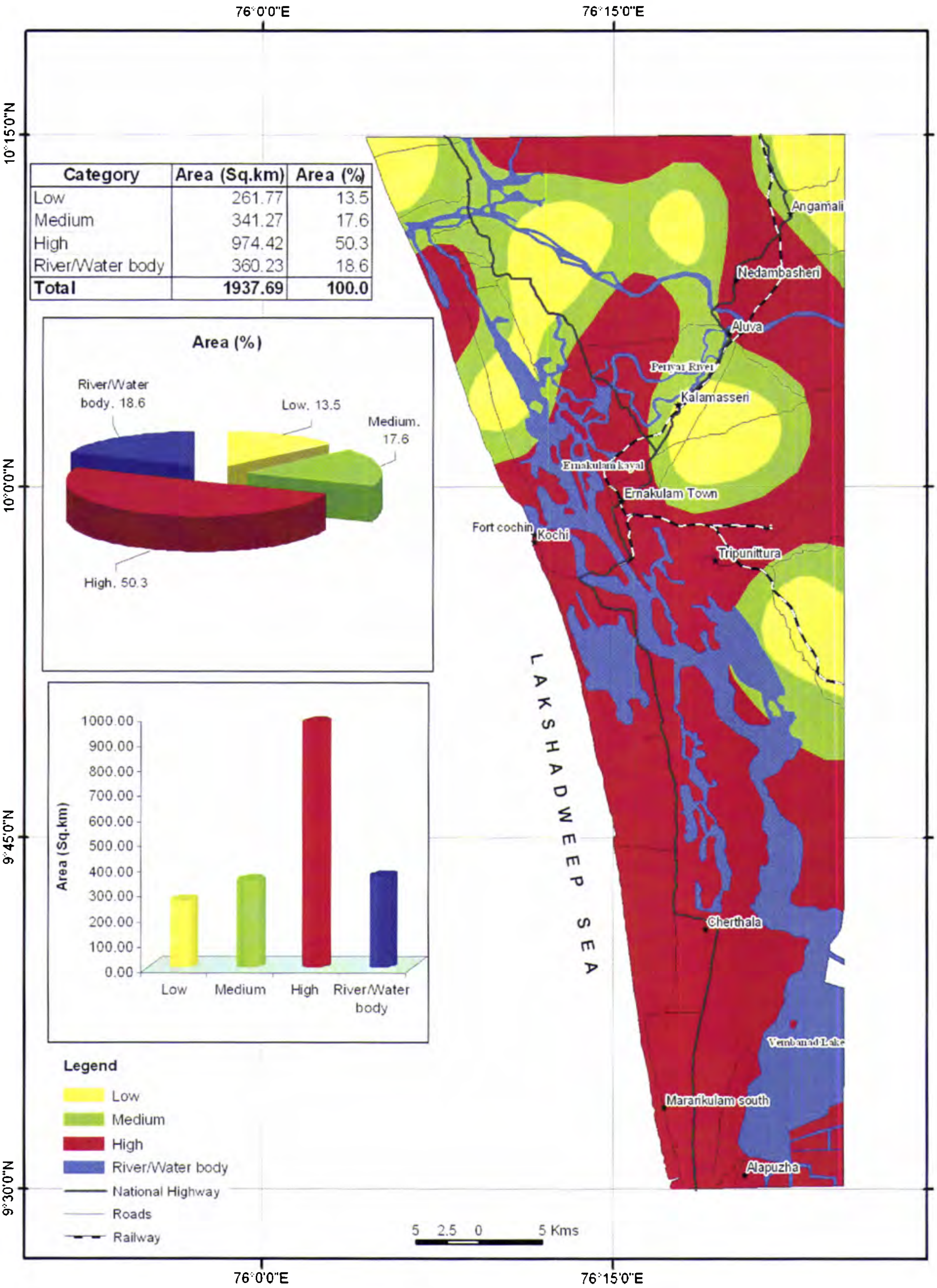
## 5.5. Suitability of Groundwater for Various Uses

### 5.5.1. Domestic Uses

Water supplied for domestic and municipal purposes should satisfy the physical, chemical and bacterial criteria, which indicate the safety of water for ingestion, culinary and sanitary purposes. Municipal or public water supply for drinking purposes is essentially required to be potable. A potable water is necessarily one which is safe and good to drink and is colourless, odourless and of pleasant taste. Quality criteria for various uses are published by number of organizations. The main standards used are those recommended by World Health Organisation, European Economic Community and United States Environmental Protection agency. As discussed earlier, under each parameter, generally water in most of the crystalline terrain in the study area is found to be suitable for drinking purpose. The coastal belt gives entirely different results and most of the wells are unsuitable for drinking purpose.

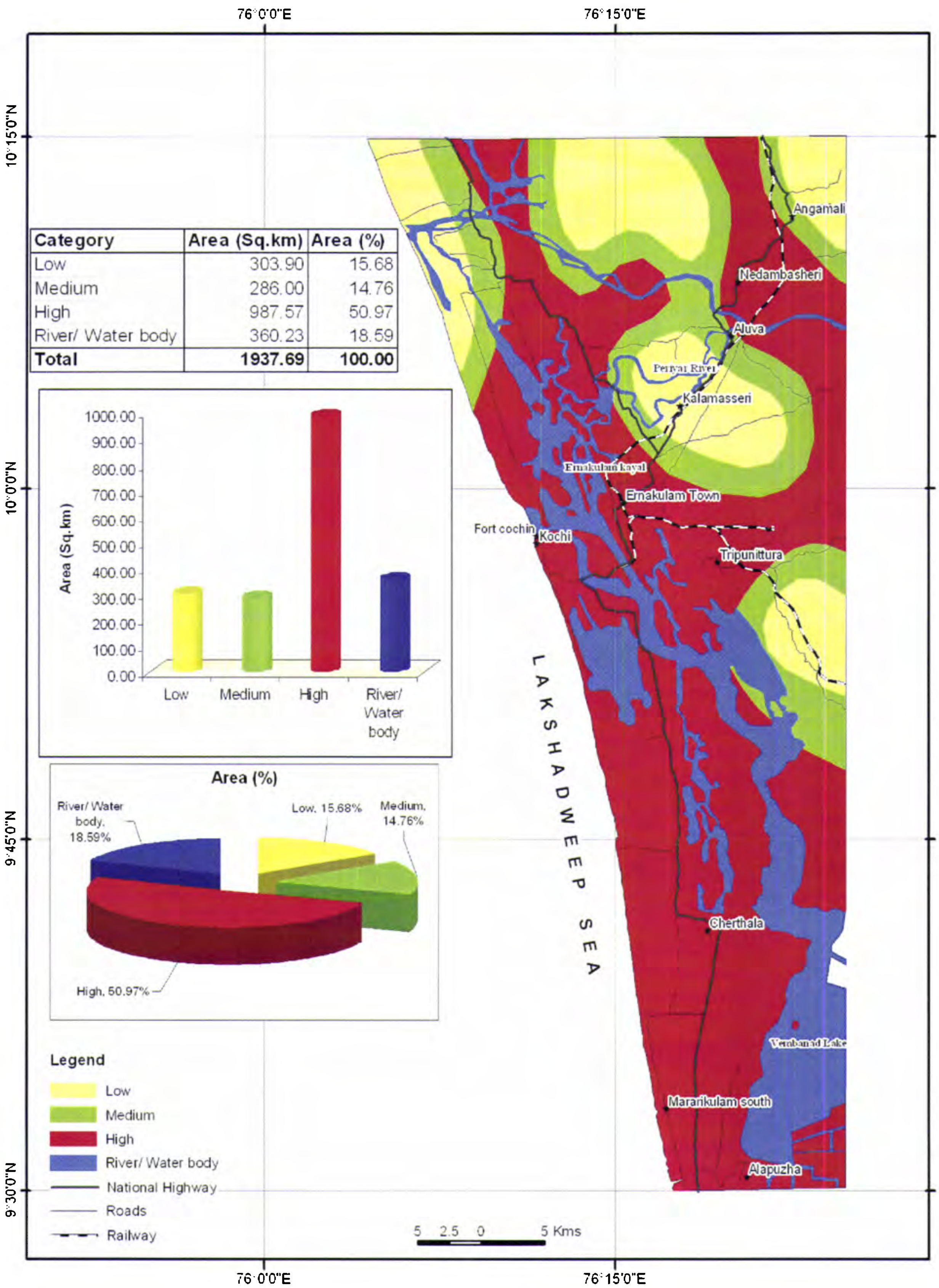
### 5.5.2. Suitability for Irrigation

Large-scale irrigation projects can bring prosperity to an area but less desirable changes can also occur as a result of increased intensity of




| Category | Area (Sq.km) | Area (%) |
|---|---|---|
| Low | 261.77 | 13.5 |
| Medium | 341.27 | 17.6 |
| High | 974.42 | 50.3 |
| River/Water body | 360.23 | 18.6 |
| **Total** | **1937.69** | **100.0** |

fig.5.12a ZONATION - ECOLI (PRE MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



| Category | Area (Sq.km) | Area (%) |
|---|---|---|
| Low | 303.90 | 15.68 |
| Medium | 286.00 | 14.76 |
| High | 987.57 | 50.97 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |



fig.5.12b ZONATION - ECOLI (POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

land and water use. One important change in the hydrological regime is that of an alteration or degradation in quality that takes place as water is used and re-used within the hydrological basin. In addition, wastewater generated by agricultural and urban sources can degrade water quality and must be considered when developing a river basin management plan. Agricultural subsurface drainage water presents the single greatest threat to water quality. The need for drainage is often quoted as a mechanism to eliminate the hazards from water logging and salinity in irrigated land. A drainage scheme can be implemented for engineering or economic reasons but in either case the drainage water created by the scheme will contain a high concentration of salts. Careful consideration must be given to its disposal so that the water supplies downstream are not polluted.

The disposal of highly saline drainage water into river courses may need to be controlled in order to meet certain minimum standards of water quality for irrigated agriculture in downstream areas. Changes in downstream agricultural practices may be necessary to adapt to the inferior water quality, or alternative schemes may need to be implemented where the drainage or other wastewater is isolated from the main water supply. Due to the high cost of transporting wastewater to a disposal site (ocean, salt-sink or river discharge), the maximum number of uses of that water should be made before discharge. At that time, disposal must be in such a way that the river basin water quality is protected and agricultural development is not jeopardized. All wastewater should be used and re-used until no longer fit for use. Of equal importance when protecting the quality of water supplies that are to be used as a source of irrigation water is the utilization of effluent water from domestic sources or from an agricultural processing activity. Re-using wastewater can remove a potential cause of ground or surface water pollution and, at the same time, release higher quality water for other uses. Rising demands for good quality water for domestic and industrial uses in countries with highly developed economies have already created the necessity to re-use wastewater. Many developing countries are now facing a similar situation, especially in arid and semi-arid regions where limited water availability is already a severe constraint on development. Agriculture is the major user of water and can accept lower quality water than domestic and industrial users. It is therefore inevitable that there will be a growing tendency to look toward irrigated agriculture for solutions to the overall effluent disposal problem. Because wastewater contains impurities, careful consideration must be given to the possible long-term effects on soils and plants from salinity, sodicity, nutrients and trace elements that occur normally manageable if associated problems with these impurities are understood and allowances made for them. Also high concentration of trace elements such as boron, selenium, cadmium etc. is toxic to the growth of plants (Todd, 1980).

In classifying water as to its suitability for irrigation, the most important factors to be considered are the total dissolved salts, the concentration of some individual constituents, particularly of boron and the relative concentration of Sodium (Trescott, 1969). The quality of water used for irrigation is an important factor in productivity and quality of the irrigated crops. The distribution of soluble salts depends on factors like; chemical composition of water, nature and composition of the soils and sub-soils, topography, amount of water used and method of its application, kind of crop grown, the climate and rainfall etc. The sodium or alkali hazard is indicated by the soluble sodium percentage (SSP), which is defined by

$$SSP=100(Na+K)/(Ca+Mg+Na+K)$$

Or by the Sodium Adsorption Ratio (SAR) which is defined by

$$SAR = \frac{Na}{\sqrt{Ca+Mg/2}}$$

Where all ions are expressed in eqm. (Trescott, 1969).

Table. 5.6 Classification of groundwater quality for irrigation ( after Wilcox, 1955)

| Class of water | EC at 25° C (μS/cm) | TDS (mg/l) | Sodium % | Boron (mg/l) (Tolerant crop) |
|---|---|---|---|---|
| Excellent | <250 | <175 | <20 | < 1 |
| Good | 250-750 | 175-525 | 20-40 | 1-2 |
| Permissible | 750-2000 | 525-1400 | 40-60 | 2-3 |
| Doubtful | 2000-3000 | 1400-2100 | 60-80 | 3-3.75 |
| Unsuitable | >3000 | >2100 | >80 | >3.75 |

**Soluble Sodium (%Na)**

Sodium is very important from agricultural point of view because sodium reacts with soil to reduce its permeability. Soil containing a large proportion of Sodium with Carbonates as the predominant anion is termed alkali soils while those with chloride or sulphate as the predominant anion are saline soils.

$$Na\,\% = \frac{(Na + K)\,100}{Ca+Mg+Na+k}$$

The isocone maps of sodium percentage in the study are given in the fig.5.13. The Na percentage and EC can be effectively used for categorising groundwater for irrigation using Wilcox diagrams.

Wilcox diagram for the study area during pre-monsoon and post-monsoon are shown in fig.5.14a&b and fig.5.15a & b. It is noticed that a majority of the wells fall in the excellent to good category during both pre-monsoon and post-monsoon periods. Not much variation could be deciphered between the two seasons. But in the pre-monsoon one well of the coastal belt falls in the unsuitable range. A comparison of the Wilcox diagrams for the crystalline terrain and coastal belt is given in fig (...). The wells in the crystalline terrain of the study area fall in the excellent to good category during both pre-monsoon and post-monsoon as can be seen from the diagrams. In the coastal belt, although a majority of wells fall in the excellent to good category one well falls in the good to permissible category and three wells fall in the permissible to doubtful category.

**Residual Sodium Carbonate (RSC)**

When the total of carbonates and bicarbonates exceeds the sum of calcium and magnesium present, the excess amount of such salts gets precipitated as Residual Sodium Carbonate and is determined by using the formula given by Eaton (1950)

$$RSC = (C03+HCO3)-(Ca+Mg)$$

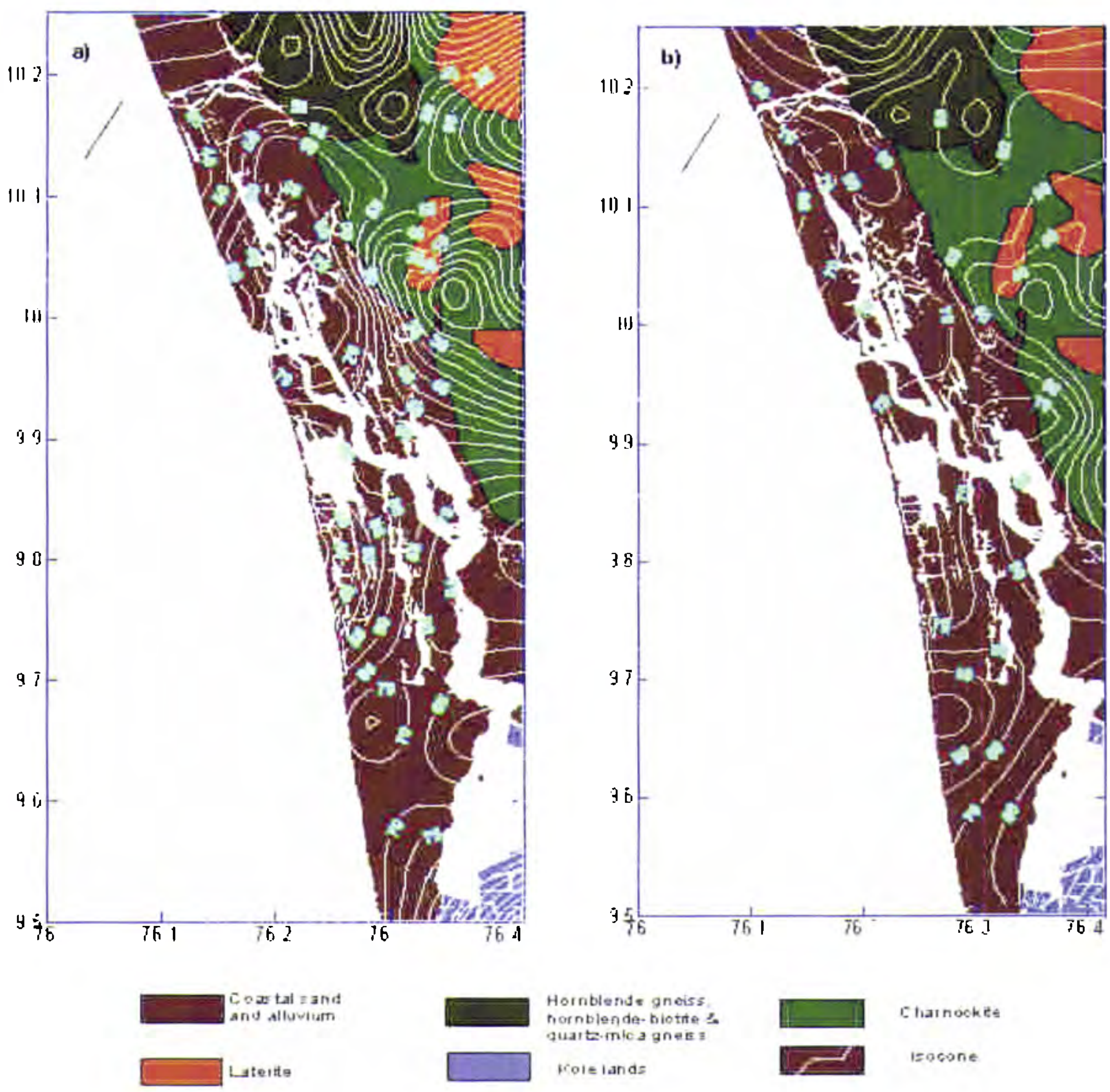


fig.5.13a-5.13b

**Sodium percent of groundwater in the coastal plain and crystalline terrain (a) pre monsoon and (b) post monsoon**

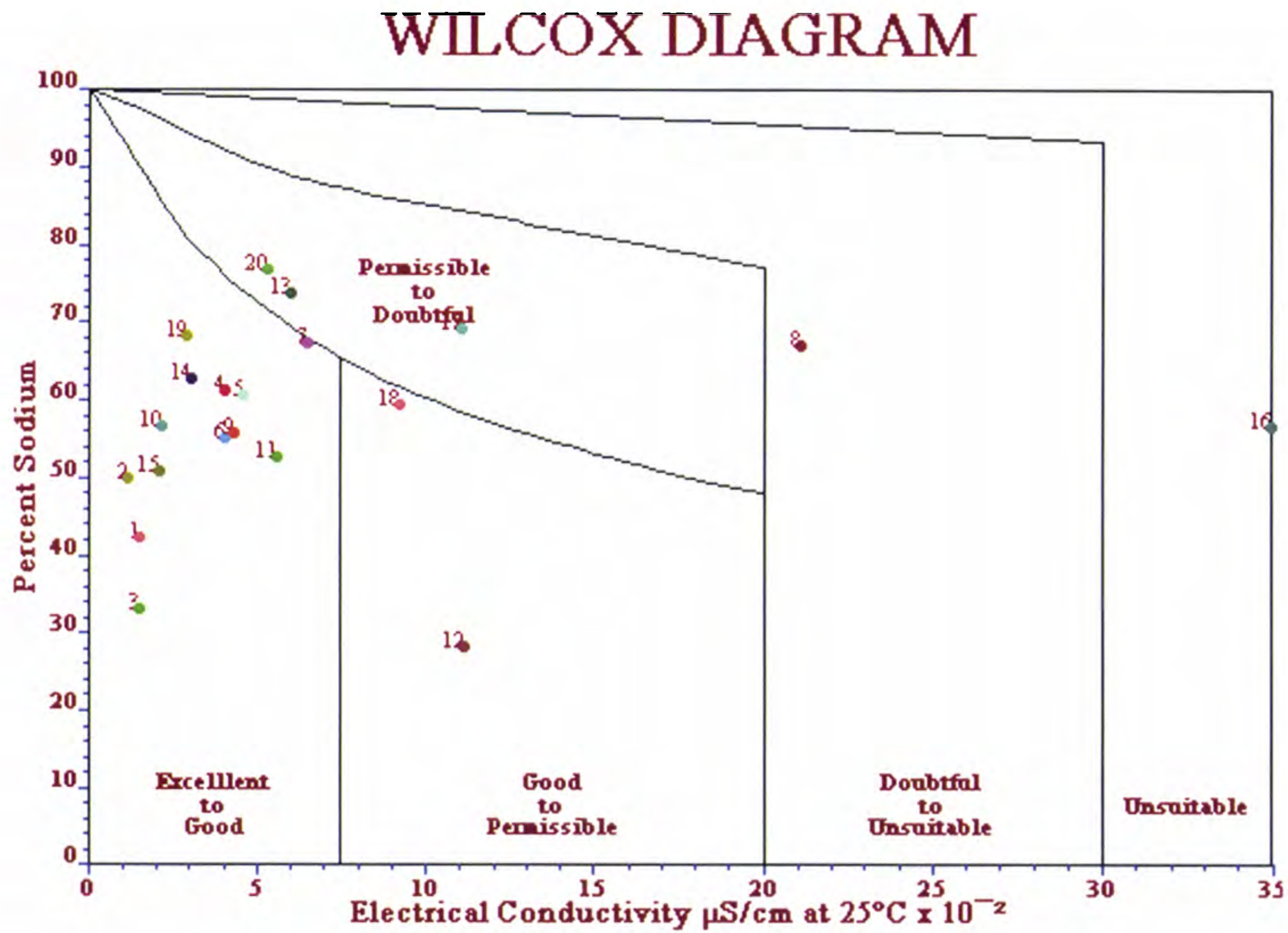
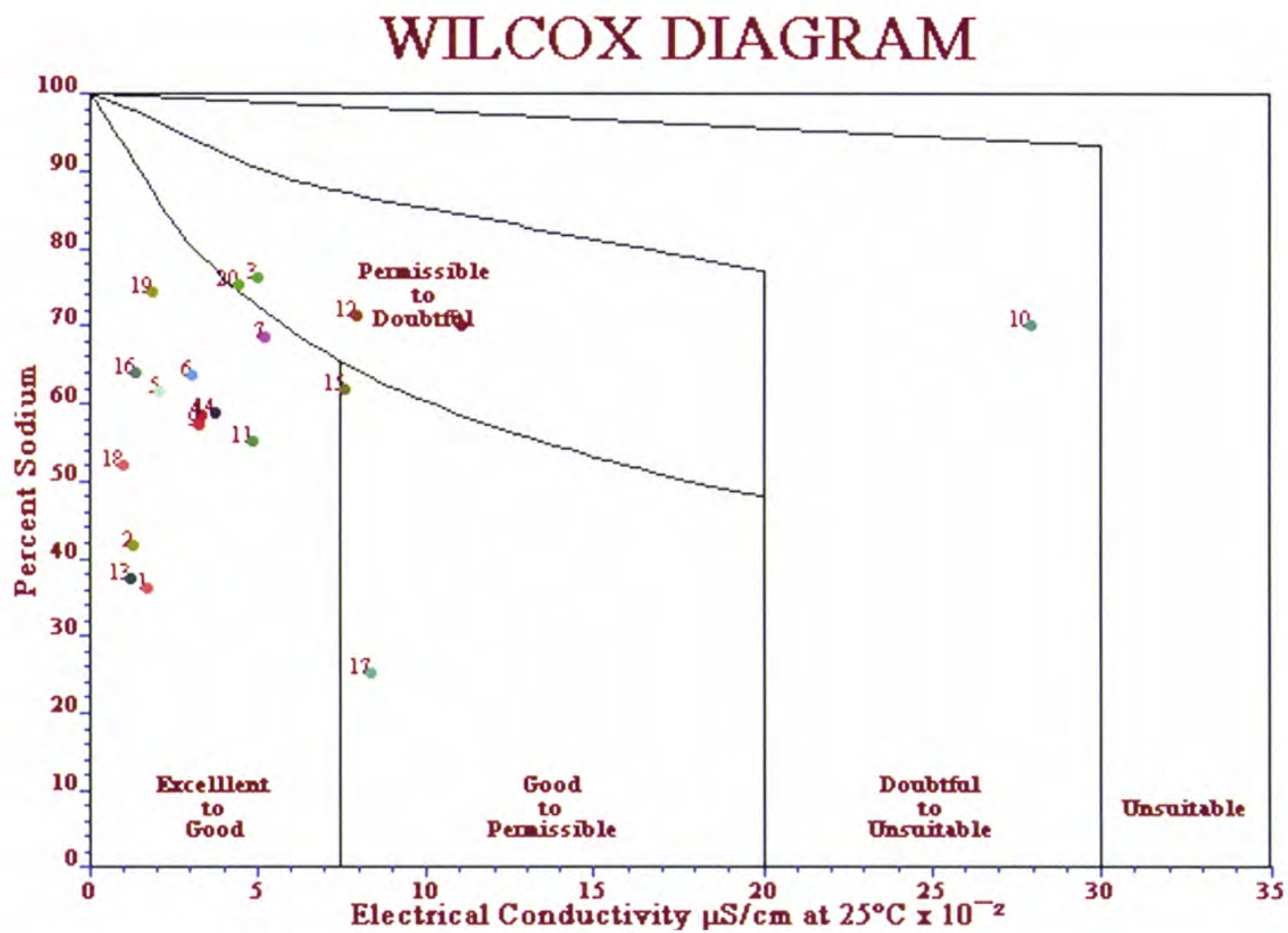

WILCOX DIAGRAM
Percent Sodium
Electrical Conductivity µS/cm at 25°C x 10⁻²
Excelllent to Good
Good to Permissible
Permissible to Doubtful
Doubtful to Unsuitable
Unsuitable
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35

fig.5.14a



WILCOX DIAGRAM
Percent Sodium
100
90
80
70
60
50
40
30
20
10
0
Electrical Conductivity µS/cm at 25°C x 10⁻²
0
5
10
15
20
25
30
35
Permissible to Doubtful
Excelllent to Good
Good to Permissible
Doubtful to Unsuitable
Unsuitable


fig.5.14b

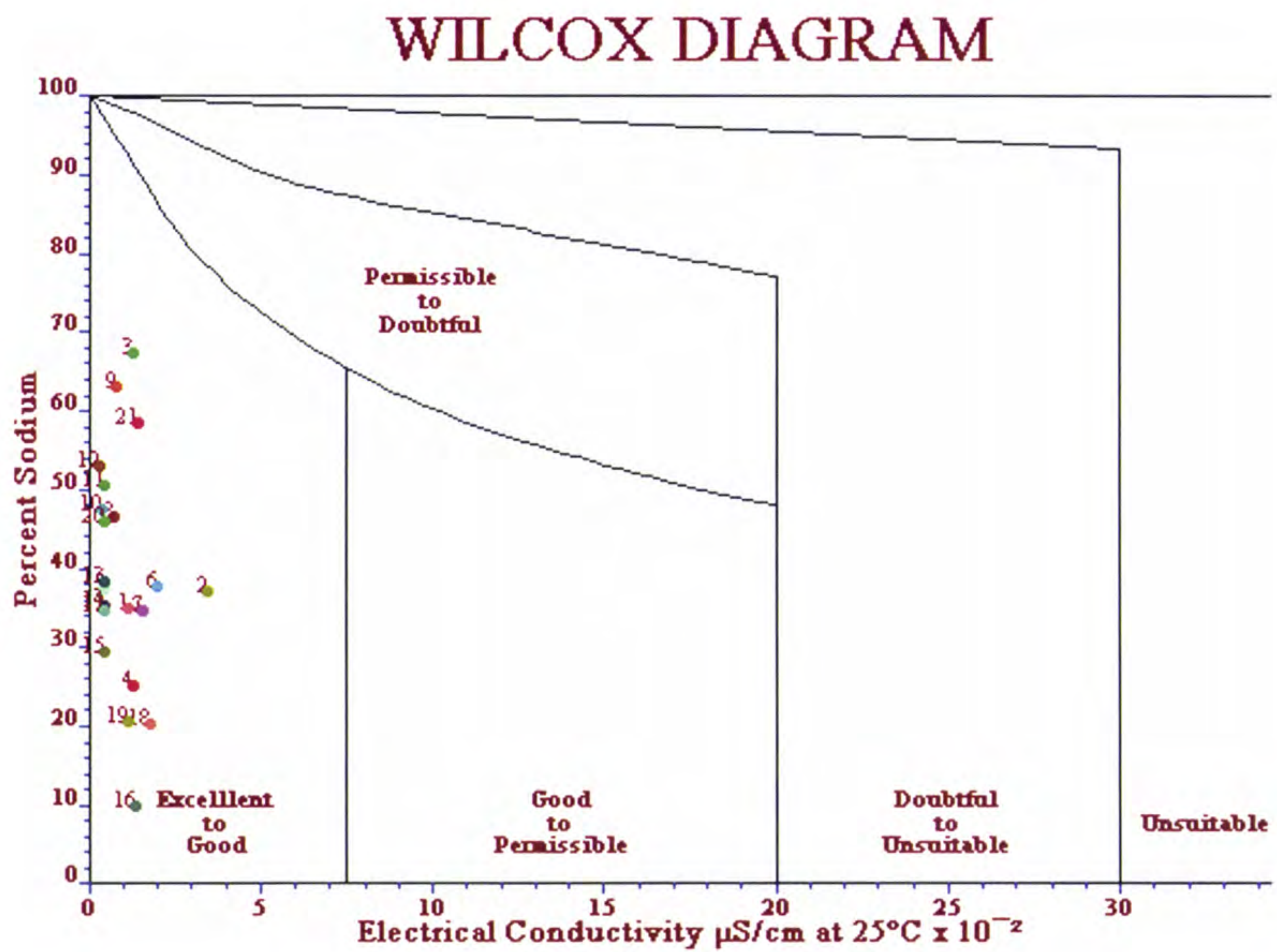

WILCOX DIAGRAM
Percent Sodium
100
90
80
70
60
50
40
30
20
10
0
Electrical Conductivity µS/cm at 25°C x 10⁻²
0
5
10
15
20
25
30
Permissible to Doubtful
Excelllent to Good
Good to Permissible
Doubtful to Unsuitable
Unsuitable

fig.5.15a

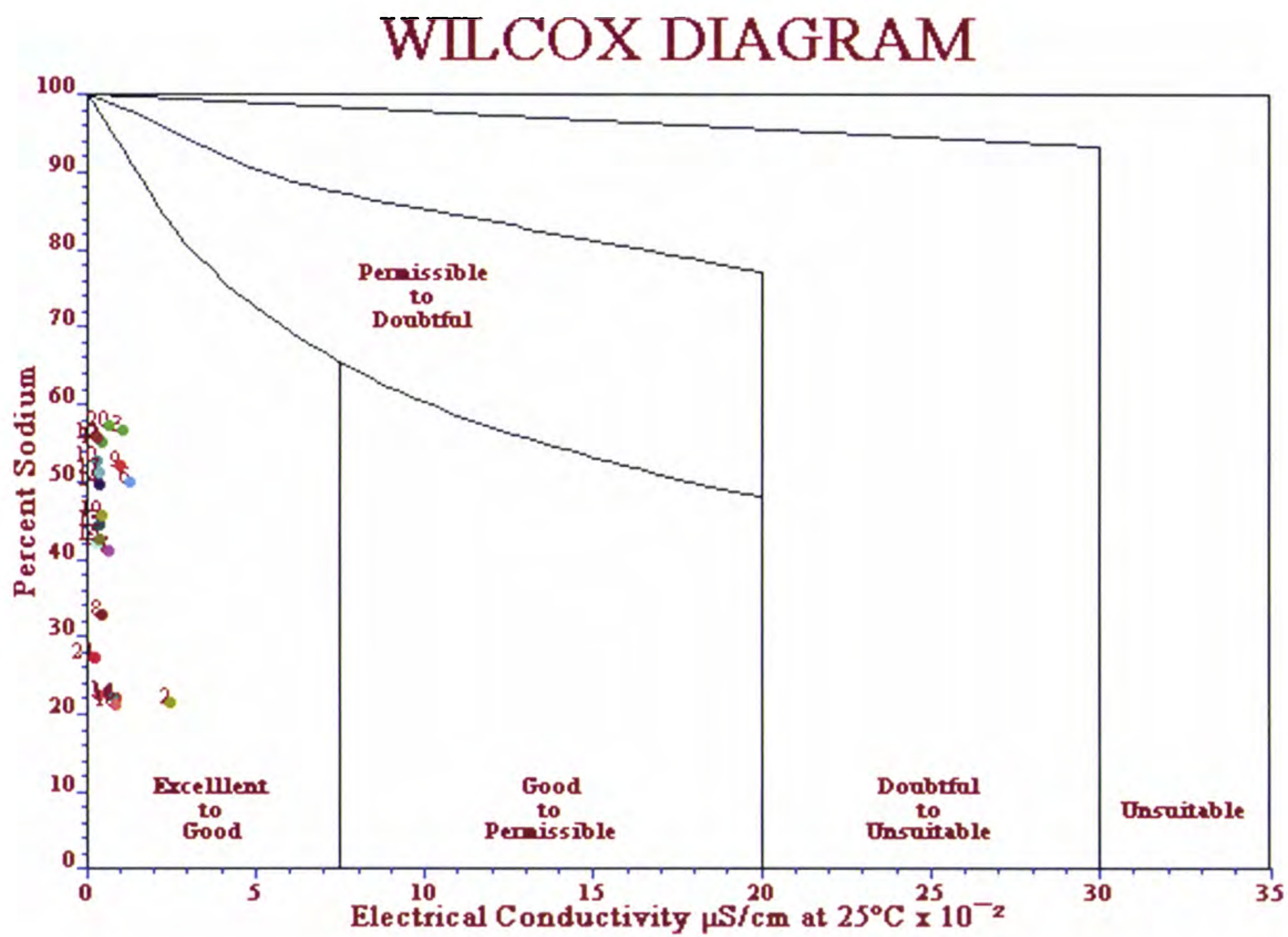

WILCOX DIAGRAM
Percent Sodium
Electrical Conductivity µS/cm at 25°C x 10⁻²
Excelllent
to
Good
Good
to
Permissible
Permissible
to
Doubtful
Doubtful
to
Unsuitable
Unsuitable
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35

fig.5.15b

Where the concentration are expressed in mill equivalent per litre. Water for irrigation (Lloyd and Heathcote, 1985) can be classified as suitable if the RSC is less than 1.25meq/l, marginal if between 1.5 meq/l and 2.5 meq/l and not suitable if above 2.5 meq/l. In the study area the RSC falls in the suitable range for irrigation in both pre-monsoon and post-monsoon periods. The isocone maps of RSC for both the seasons are shown in fig.5.16. The RSC for both the crystalline terrain and coastal belt is well below 1.25meq/l (suitable range in Lloyd and Heathcote's classification).

### 5.6. Classification by U.S.S.L diagram

There is a significant relationship between SAR values of irrigation water and the extent to which sodium is adsorbed by the soil. If the water used for irrigation is high in Sodium and low in Calcium, the cation-exchange complex may become saturated with Sodium. This can destroy the soil structure owing to dispersion of clay particles. Data is plotted on the U.S Salinity diagram in which EC is taken as salinity hazard and SAR is taken as alkalinity hazard. This diagram is used in interpreting the analysis of irrigation water. Water can be grouped into 16 classes. It uses SAR in the vertical axis and conductance in the horizontal axis.

| | |
|---|---|
| C1 (EC<250 micromho/cm) | Low salty water. It can be used for each type soil and plant. |
| C2 (EC 250-750 micromho/cm) | Medium salty water. It is suited for all plants. But natural drainage should be good. |

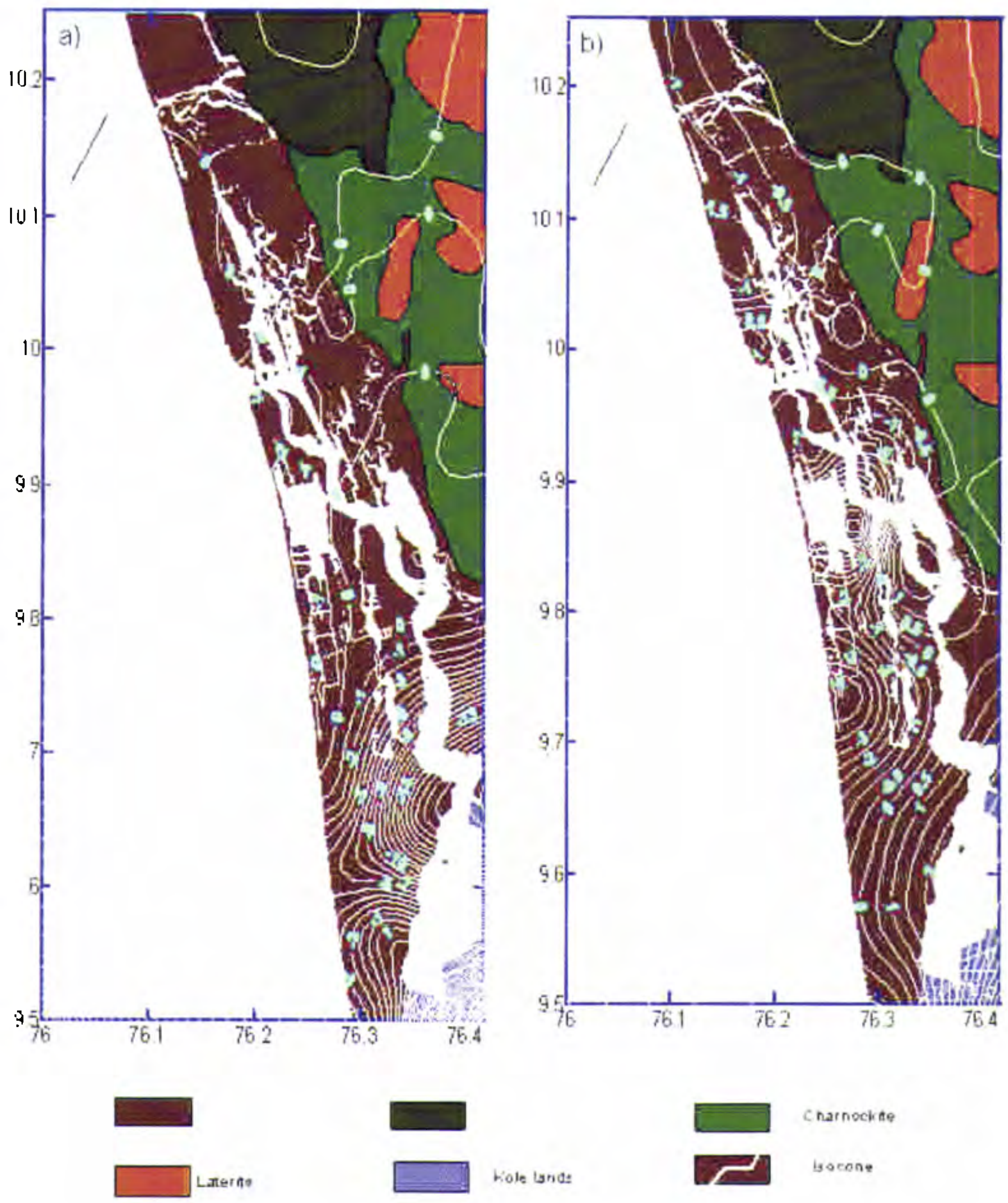



fig.5.16 **Residual sodium carbonate of groundwater in the coastal plain and crystalline terrain (a) pre monsoon and (b) post monsoon**

| | |
|---|---|
| C3 (750-2250 micromho/cm | High salty water. It should require drainage. Some plants tolerate. |
| C4 (EC>2250 micromho/cm) | Very high salty water. Soil should be permeable and drainage should be rich. In addition to this, plants tolerating salinity should be chosen. |
| S1 | Low sodium content water. It can be used in each type soil. |
| S2, S3 | Medium and high sodium content water. It may be dangerous for soil. That's why soluble matters should be leached and organic matters should be added to soil. |
| S4 | Very high sodium content water. It is unsuitable for irrigation. |

In general,

| Class | Status for irrigation |
|---|---|
| C1S1, C2S1, C3S1 | suitable |
| C4S1, C3S2 | suitable in specific conditions |
| C4S2, C4S3 | unsuitable. |

The U.S.S.L salinity diagrams for both the crystalline terrain and the coastal belt are shown in fig.5.17a to 5.17d. From the diagrams it is evident that in the crystalline terrain all the wells fall in the low salinity hazard area during the post-monsoon period. Only one well falls in the medium salinity

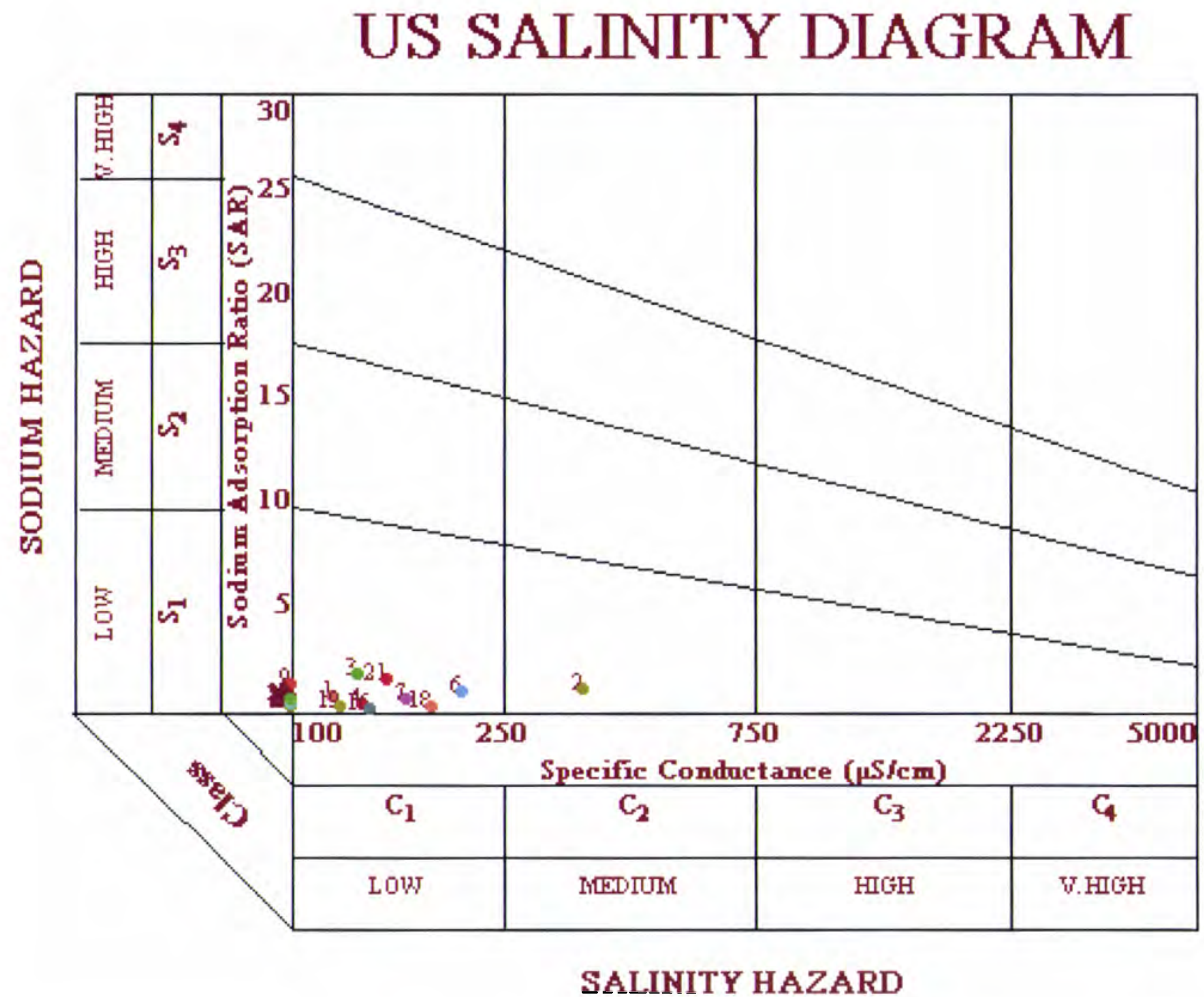
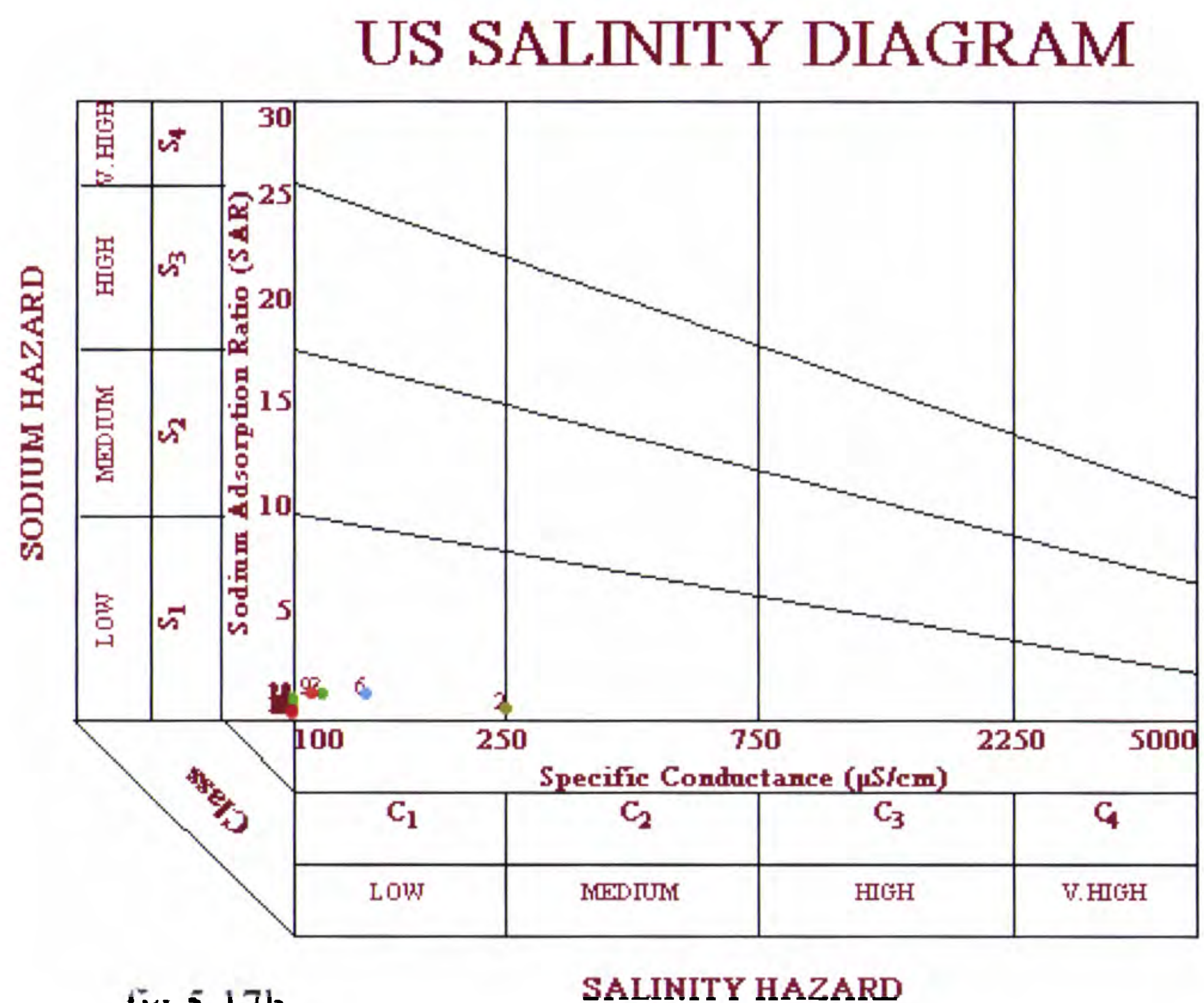
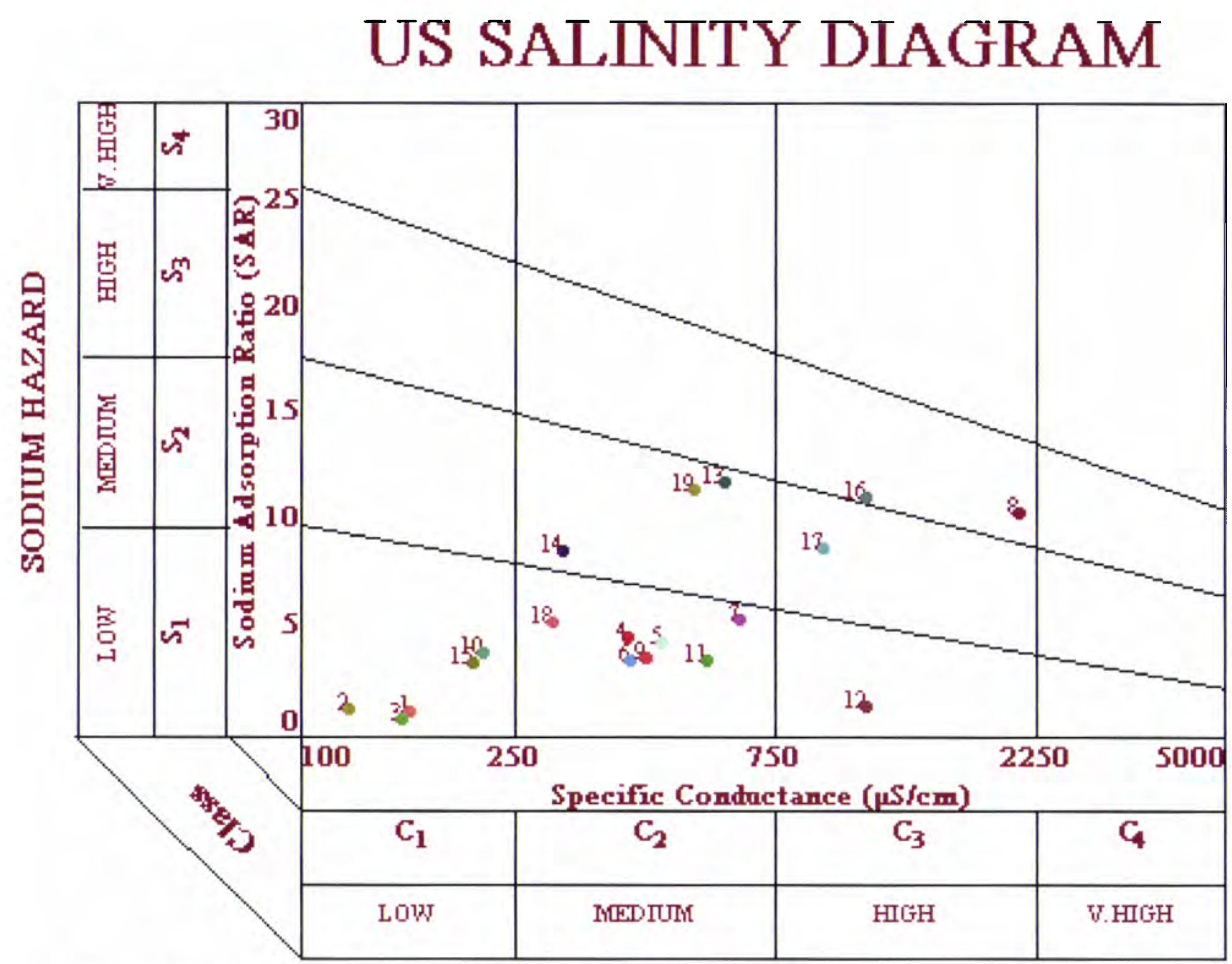

US SALINITY DIAGRAM
SODIUM HAZARD
V.HIGH
HIGH
MEDIUM
LOW
S4
S3
S2
S1
Sodium Adsorption Ratio (SAR)
30
25
20
15
10
5
100
250
750
2250
5000
Specific Conductance (μS/cm)
Class
C1
C2
C3
C4
LOW
MEDIUM
HIGH
V.HIGH
SALINITY HAZARD

fig.5.17a



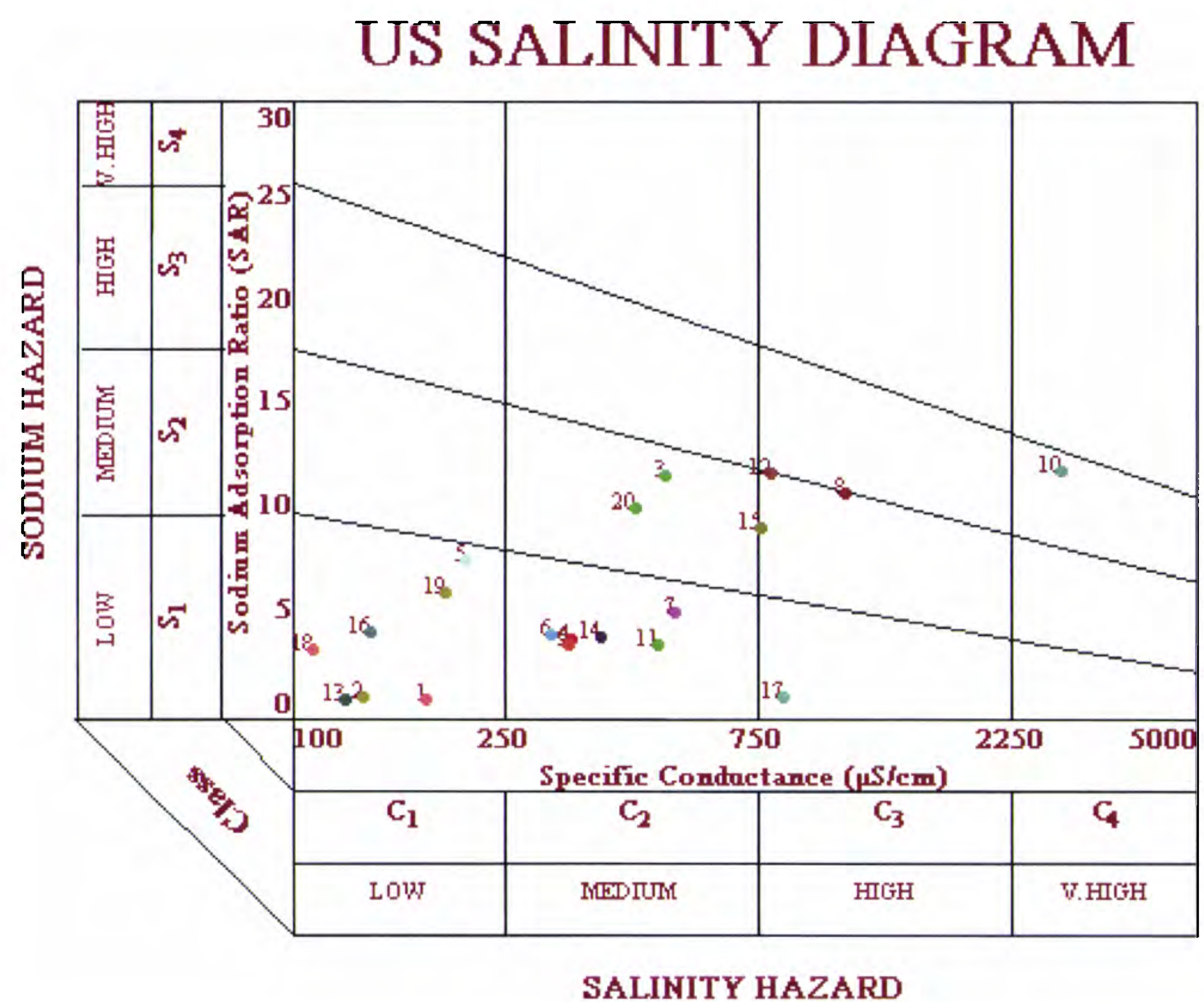
US SALINITY DIAGRAM
SODIUM HAZARD
V.HIGH
HIGH
MEDIUM
LOW
S4
S3
S2
S1
Sodium Adsorption Ratio (SAR)
30
25
20
15
10
5
100
250
750
2250
5000
Specific Conductance (µS/cm)
Class
C1
C2
C3
C4
LOW
MEDIUM
HIGH
V.HIGH
SALINITY HAZARD


fig.5.17b



US SALINITY DIAGRAM
SODIUM HAZARD
LOW
MEDIUM
HIGH
V.HIGH
$S_1$
$S_2$
$S_3$
$S_4$
Sodium Adsorption Ratio (SAR)
0
5
10
15
20
25
30
100
250
750
2250
5000
Specific Conductance (µS/cm)
Class
$C_1$
$C_2$
$C_3$
$C_4$
LOW
MEDIUM
HIGH
V.HIGH
SALINITY HAZARD


fig.5.17c


US SALINITY DIAGRAM
SODIUM HAZARD
V.HIGH
HIGH
MEDIUM
LOW
S4
S3
S2
S1
Sodium Adsorption Ratio (SAR)
30
25
20
15
10
5
0
Class
100
250
750
2250
5000
Specific Conductance (μS/cm)
C1
C2
C3
C4
LOW
MEDIUM
HIGH
V.HIGH
SALINITY HAZARD
fig.5.17d

hazard category in the pre-monsoon. Hence it can be inferred that the water in the crystalline terrain of the study area is very good for irrigation. In the case of the coastal belt it is seen in the diagrams that the wells are scattered mainly in the low and medium salinity hazard zones. Some wells are seen in the high zone and one well shows very high salinity hazard. Thus from the study it is inferred that the groundwater in the coastal belt is far inferior in quality than the crystalline terrain in terms of quality for irrigation.

### 5.7. Quality of Groundwater for Livestock and Poultry

The evaluation of the groundwater for livestock and poultry uses is based on the National Academy of Science (1972) limitations. The standards are given in the table. 5.7

According to the classification of National Academy of science, 1972 the groundwater in the study area can be classified as follows. All the wells except four samples from the coastal belt fall in the excellent range (category 1) for livestock and poultry. Other three wells fall in the very satisfactory category. One well falls in the fourth category, which cannot be used for poultry but can be used for livestock with reasonable safety.

### 5.8. Quality of Groundwater for Industrial Purposes

Industrial water quality criteria range widely depending on the use. For example, for boilers of very high pressure, water exceeding the quality of commercial distilled water is sometimes required. Fish plants on the other hand often need large amounts of seawater, Trescott (1969). The BIS

**Table. 5.7 Guide to the use of saline waters for livestock and poultry.**

| Total soluble salts content of waters | Uses |
|---|---|
| Less than 1,000 mg/L (EC < 1.5 mmhhos/cm) | Relatively low level of salinity. Excellent for all classes of livestock and poultry. |
| 1,000-3,000 mg/L (EC = 1.5-5 mmhos/cm) | Very satisfactory for all classes of livestock and poultry. May cause temporary and mild diarrhoea in livestock not accustomed to them; may cause watery droppings in poultry. |
| 3,000-5,000 mg/L (EC = 5-8 mmhos/cm) | Satisfactory for livestock, but may cause temporary diarrhoea or be refused at first by animals not accustomed to them. Poor waters for poultry, often causing watery faeces, increased mortality, and decreased growth, especially in turkeys. |
| 5,000-7,000 mg/L (EC = 8-11 mmhos/cm) | Can be used with reasonable safety for dairy and beef cattle, sheep, swine, and horses. Avoid use for pregnant or lactating animals. Not acceptable for poultry. |
| 7,000-10,000 mg/L (EC = 11-16 mmhos/cm) | Unfit for poultry and probably for swine. Considerable risk in using for pregnant or lactating cows, horses or sheep, or for the young of these species. In general, use should be avoided although older ruminants, horses, poultry, and swine may subsist on them under certain conditions. |
| Over 10,000 mg/L (EC > 11-16 mmhos/cm) | Risks with these highly saline waters are so great that they cannot be recommended for use under any condition. |

Sources: Environmental Studies Board, Nat. Acad. of Sci., Nat. Acad. of Eng., Water Quality Criteria, 1972. Ayers, R.S. and D.W. Westcot. Water Quality for Agriculture. Food and Agriculture Organization of the United Nations, Rome, 1976.

standards for industry have been utilized for categorising the groundwater in the study area for different industries. The four categories are given below.

| | |
|---|---|
| **Category I** | Chemical and Pulp Industry<br>Leather Technology<br>Hydraulic Cement Industry<br>Canned, Dried, Frozen Foods – Vegetables |
| **Category II** | Wood, Chemical<br>Synthetic Rubber and Petroleum Products |
| **Category III** | Textile Industry |
| **Category IV** | Soft Drinks |

The suitability of groundwater samples from different wells of the study area in relation to these categories (industrial use) is presented in tables 5.8. a. and 5.8.b. From the tables, it is very clear that the groundwater of the hard rock area is much suitable than that of the coastal belt for use in the industrial categories described above.

### 5.9. Hydro Chemical Diagrams

The representation of geochemical data in diagrams helps in easy visualisation of the geochemistry of an area. A robust classification scheme for partitioning water chemistry samples into homogeneous groups is an important tool for the characterization of hydrologic systems as suggested by Cüneyt Güler et al (2002). Most of the graphical methods are designed to simultaneously represent the total dissolved solid concentration and the

**Table.5.8.a. Categorisation of groundwater for industrial purpose - coastal belt**

| Well location | Category I | Category II | Category III | Category IV |
|---|---|---|---|---|
| 22 | No | No | No | No |
| 23 | No | Yes | No | No |
| 24 | No | No | No | No |
| 25 | No | No | No | No |
| 26 | No | No | No | No |
| 27 | No | Yes | No | No |
| 28 | No | No | No | No |
| 29 | No | No | No | No |
| 30 | No | Yes | No | No |
| 31 | No | Yes | No | No |
| 32 | No | Yes | No | No |
| 33 | No | No | No | No |
| 34 | No | No | No | No |
| 35 | No | Yes | No | No |
| 36 | No | Yes | No | No |
| 37 | No | Yes | No | No |
| 38 | No | Yes | No | No |
| 39 | No | Yes | No | Yes |
| 40 | No | Yes | No | Yes |
| 41 | No | No | No | No |

**Table. 5.8.b. Categorisation of groundwater for industrial purpose – crystalline**

| Well location | Category I | Category II | Category III | Category IV |
|---|---|---|---|---|
| 1 | Yes | Yes | Yes | Yes |
| 2 | Yes | No | Yes | Yes |
| 3 | Yes | Yes | Yes | Yes |
| 4 | Yes | Yes | No | Yes |
| 5 | No | Yes | Yes | Yes |
| 6 | No | Yes | Yes | Yes |
| 7 | Yes | Yes | Yes | Yes |
| 8 | No | No | Yes | Yes |
| 9 | Yes | Yes | Yes | Yes |
| 10 | No | No | Yes | Yes |
| 11 | No | No | Yes | Yes |
| 12 | Yes | Yes | Yes | Yes |
| 13 | Yes | Yes | Yes | Yes |
| 14 | No | No | Yes | Yes |
| 15 | Yes | Yes | No | Yes |
| 16 | Yes | Yes | No | Yes |
| 17 | Yes | Yes | Yes | Yes |
| 18 | Yes | Yes | Yes | Yes |
| 19 | Yes | Yes | Yes | Yes |
| 20 | No | Yes | No | No |
| 21 | Yes | Yes | Yes | Yes |

relative proportions of certain major ionic species (Hem 1989). All the graphical methods use a limited number of parameters, usually a subset of the available data, unlike the statistical methods that can utilize all the available parameters. Authors around the globe are using a large number of hydro chemical diagrams. These diagrams also help in identifying the mixing of water of different compositions and also the chemical processes that take place as the water moves. The important hydro chemical diagrams that have been put to use in the present study are Collins diagram, Pie diagram, Piper diagram, Durov's diagram, Wilcox diagram, Schoeller diagram and Stiff diagram. GIS has been used to create quality maps of the study area by plotting geochemical data over Georeferenced Raster Images. Groundwater classification using the Wilcox diagram has been described in detail above. The data analyses of the groundwater study area using the other diagrams are given below.

**5.8. a. Collins Diagram**

The Collins bar diagram (Collins, 1923) and the pie diagram are easy to construct and present relative major ion composition expressed in percent milli equivalents per litre (relative % meq L–1). The constituents can be plotted in meq with an appropriate scaling. For the Collins bar diagram, major cations are plotted on the left and major anions are plotted on the right. For the pie diagram, the cations are plotted in the upper half and an-ions are plotted in the lower half of the circle. The pie diagram is usually drawn with a radius proportional to TDS. The Collins diagram for representative samples from the coastal belt and crystalline terrain in pre-monsoon and post-monsoon are given in the fig.5.18.

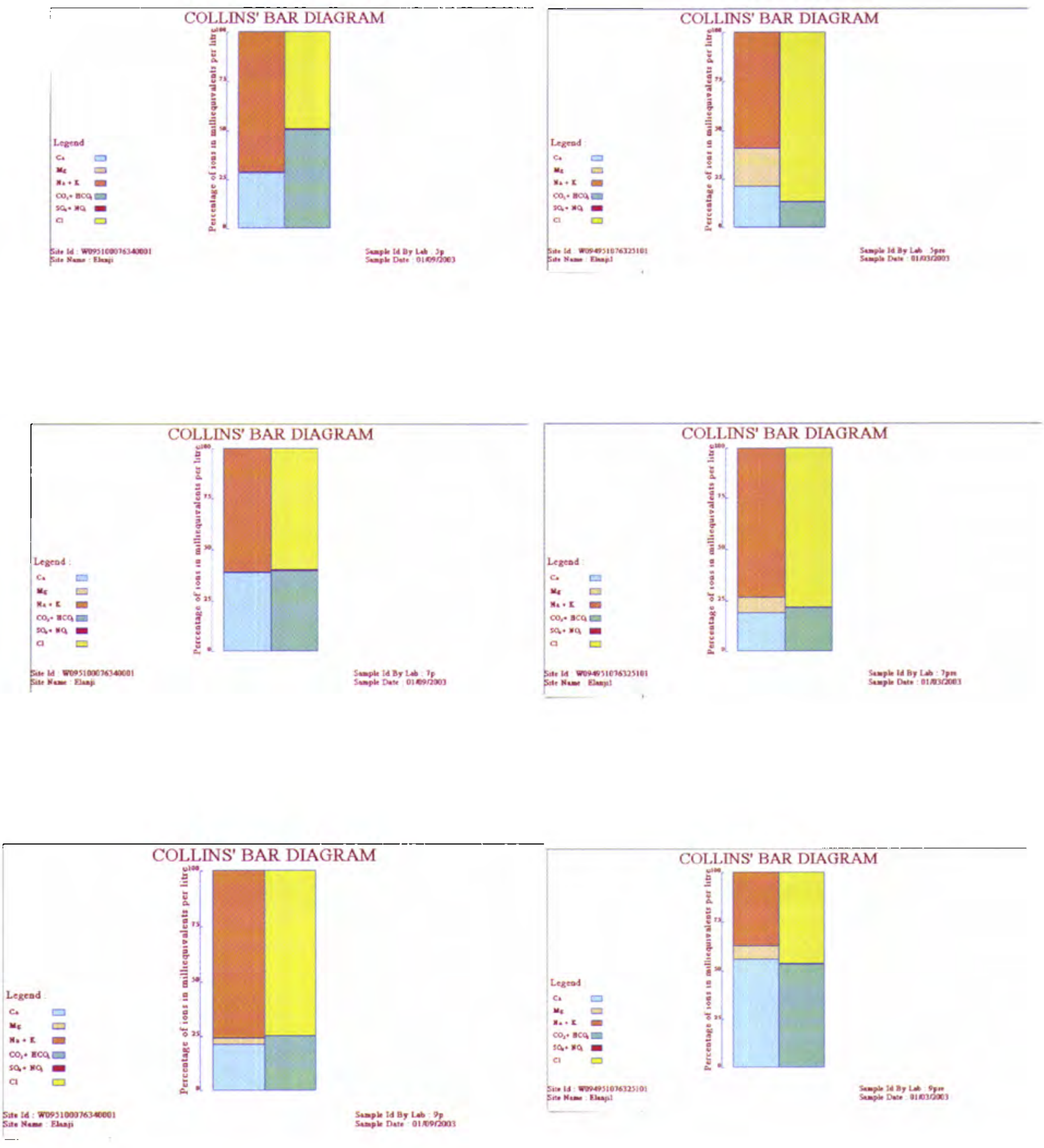



fig.5.18 Collins diagram of representative samples

### 5.8.b. Stiff Diagram

Stiff diagrams are plotted for individual samples as a method of graphically comparing the concentration of selected anions and cations for several individual samples. The shape formed by the Stiff diagrams will quickly identify samples that have similar compositions and are particularly useful when used as map symbols to show the geographic location of different water facies. The Stiff pattern is a polygon that is created from three (or four) parallel horizontal axes extending on either side of a vertical zero axis (Stiff, 1951). In this diagram, cations are plotted on the left of the axes and anions are plotted on the right, in units of milli equivalents per litre (meq L–1). The Stiff diagram is usually plotted without the labelled axis and is useful making visual comparison of waters with different characteristics. The patterns tend to maintain its shape upon concentration or dilution, thus visually allowing us to trace the flow paths on maps (Stiff, 1951).

### 5.8. c. Schoeller Diagram

The Schoeller semi-logarithmic diagram allows the major ions of many samples to be represented on a single graph, in which samples with similar patterns can be easily discriminated. The Schoeller diagram shows the total concentration of major ions in log-scale. These semi-logarithmic diagrams were developed to represent major ion analyses in meq/l and to demonstrate different hydro chemical water types on the same diagram. This type of graphical representation has the advantage that unlike the trilinear diagrams, actual sample concentrations are displayed and compared. The Schoeller diagram can be used to plot all samples in the open database or selected sample groups only. Up to 10 different parameters can be included along the x-axis and the symbols representing the sample points can be customized according to shape and color. The highlighted lines indicate specific samples that are selected in the database and are also highlighted on all other open graphical displays. The Scholler diagram for the study area is given in fig.5.19.

### 5.8. d. Piper Diagram

The Piper diagram plots the major ions as percentages of milli-equivalents in two base triangles. The total cations and the total anions are set equal to 100% and the data points in the two triangles are projected onto an adjacent grid. This plot reveals useful properties and relationships for large sample groups. The main purpose of the Piper diagram is to show clustering of data points to indicate samples that have similar compositions. The Piper diagram can be used to plot all samples in the open database or selected sample groups. In addition, the symbols representing the sample values can be customized according to shape and color. Other options include individual multiplication factors for each selected ion to prevent data point accumulation along a base line. The highlighted sample points indicate samples that are selected in the database and are also highlighted on all other open graphical displays.

The Piper diagram (Piper, 1944) is the most widely used graphical form and it is quite similar to the diagram proposed by Hill (1940, 1942). The diagram displays the relative concentrations of the major cations and anions on two separate trilinear plots, together with a central diamond plot

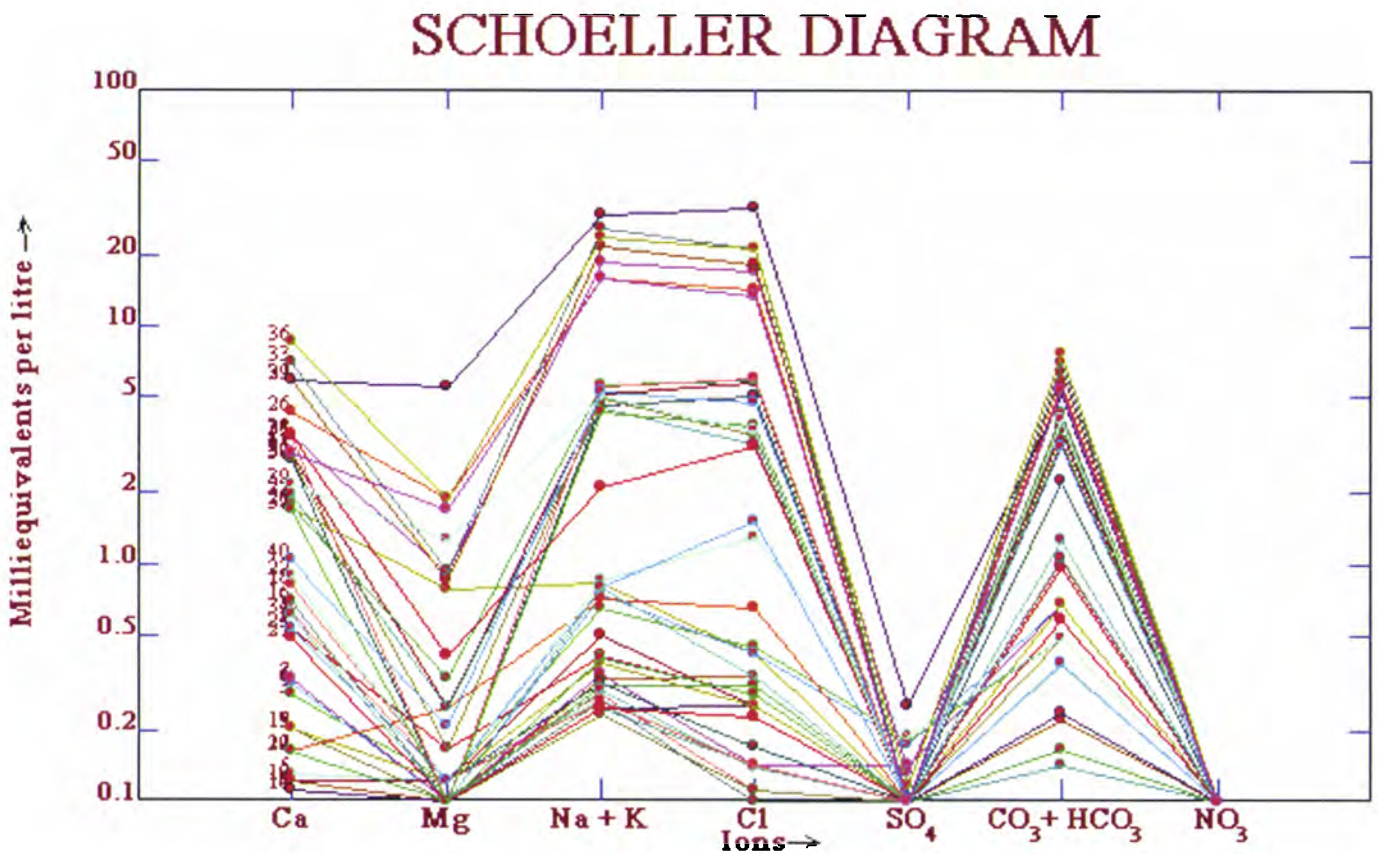

SCHOELLER DIAGRAM
Milliequivalents per litre →
100
50
20
10
5
2
1.0
0.5
0.2
0.1
Ca
Mg
Na + K
Cl
SO4
CO3 + HCO3
NO3
Ions→

fig.5.19b

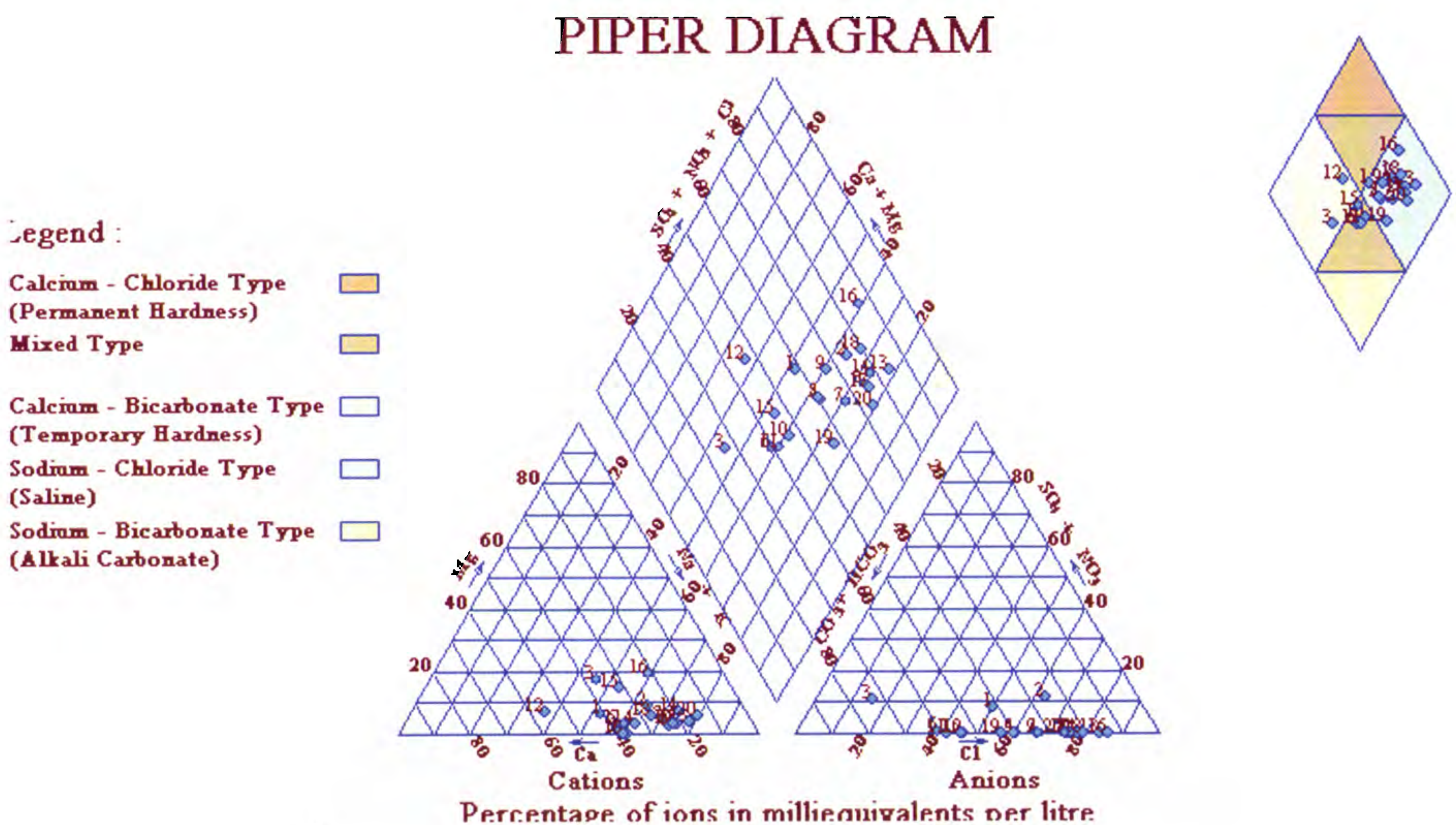

PIPER DIAGRAM
Legend :
Calcium - Chloride Type
(Permanent Hardness)
Mixed Type
Calcium - Bicarbonate Type
(Temporary Hardness)
Sodium - Chloride Type
(Saline)
Sodium - Bicarbonate Type
(Alkali Carbonate)
Ca
Cl
Cations
Anions
Percentage of ions in milliequivalents per litre

fig.5.20a

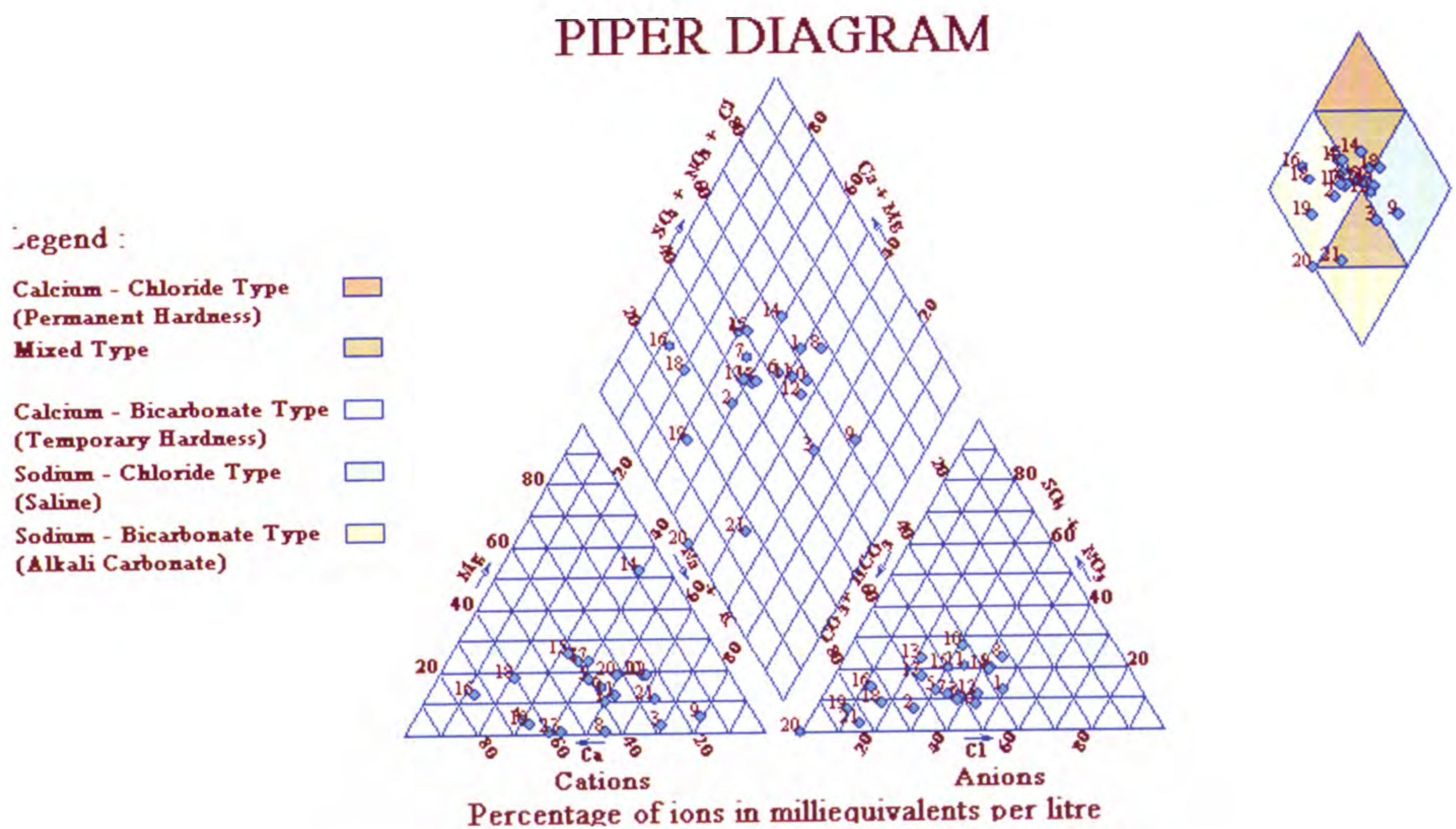

PIPER DIAGRAM
Legend :
Calcium - Chloride Type
(Permanent Hardness)
Mixed Type
Calcium - Bicarbonate Type
(Temporary Hardness)
Sodium - Chloride Type
(Saline)
Sodium - Bicarbonate Type
(Alkali Carbonate)
Cations
Anions
Percentage of ions in milliequivalents per litre

fig.5.20b

where the points from the two trilinear plots are projected. The central diamond-shaped field (quadrilateral field) is used to show overall chemical character of the water (Hill, 1940; Piper, 1944). Back (1961) and Back and Hanshaw (1965) defined subdivisions of the diamond field, which represent water-type categories that form the basis for one common classification scheme for natural waters. Morgan and Winner (1962) have also developed the concept of hydrogeochemical facies. The mixing of water from different sources or evolution pathways can also be illustrated by the Piper diagram (Freeze and Cherry, 1979). Symbol sizes can be scaled to TDS on the diamond-shaped field to add even more information (Domenico and Schwartz, 1997).

From the Piper diagrams for the study area the classifications are clearly evident from the figures themselves. (fig.5.20a & fig.5.20b). In the crystalline terrain Calcium Bicarbonate (temporary hardness) type dominates in the pre-monsoon period. Groundwater from lateritic terrain should be of bicarbonate type as the ground waters have high HCO3 ions than SO4 and Cl ions, Chandrasekharan (1989). In the post-monsoon also Calcium Bicarbonate is the dominant type but some samples move towards the mixed type category. From this shift it can be inferred that rainfall is the main controlling element in the area rather than geology. Gopinath (2003) has also reported the role of rainfall in the shift of chemistry in the Muvattupuzha basin, which is near the present study area.

The Piper diagrams of the coastal belt present a clearly different picture. Here the dominant type is the saline or sodium chloride type with some samples in the mixed type and a few samples in the calcium bicarbonate type. Not much difference could be noticed in the Piper diagrams of the coastal belt for Pre-monsoon and post-monsoon.

### 5.8. e. Durov diagram

The Durov diagram is an alternative to the Piper diagram. The Durov diagram plots the major ions as percentages of milli-equivalents in two base triangles. The total cations and the total anions are set equal to 100% and the data points in the two triangles are projected onto a square grid which lies perpendicular to the third axis in each triangle. This plot reveals useful properties and relationships for large sample groups. The main purpose of the Durov diagram is to show clustering of data points to indicate samples that have similar compositions. The Durov diagram can be used to plot all samples in the open database or selected sample groups. In addition the symbols representing the sample values can be customized according to shape and color. Other options include individual multiplication factors for each selected ion to prevent data point accumulation along a base line. The highlighted sample points indicate samples that are selected in the database and are also highlighted on all other open graphical displays. The advantage of this diagram is that this diagram displays some possible geochemical processes that could affect the water genesis (Lloyd and Heathcoat, 1985). The plot of the coastal belt and the crystalline terrain of the study area for pre-monsoon and post-monsoon in Durov diagram (fig.5.21a to fig. 5.21d) support the explanation for water types given in Piper diagram.

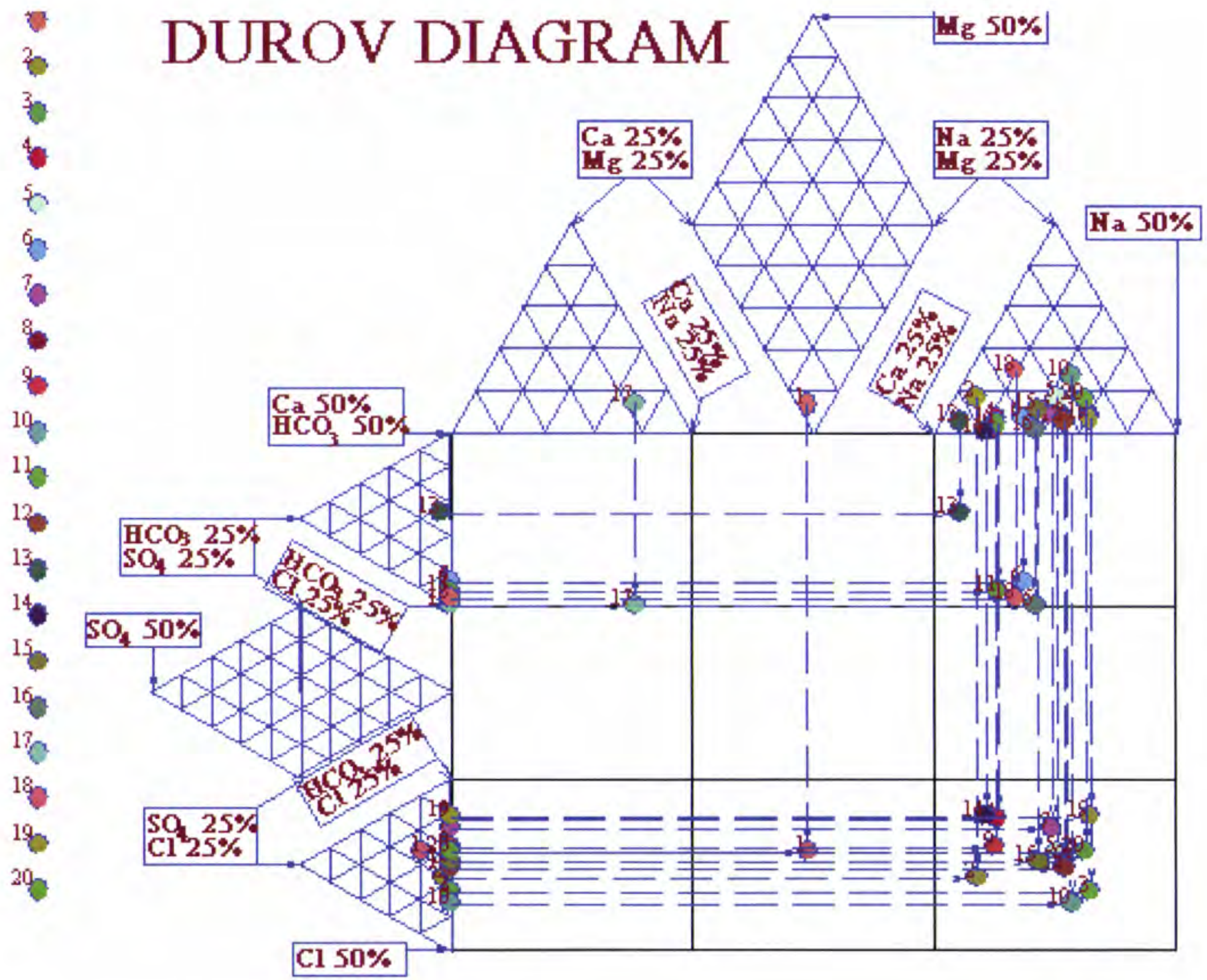
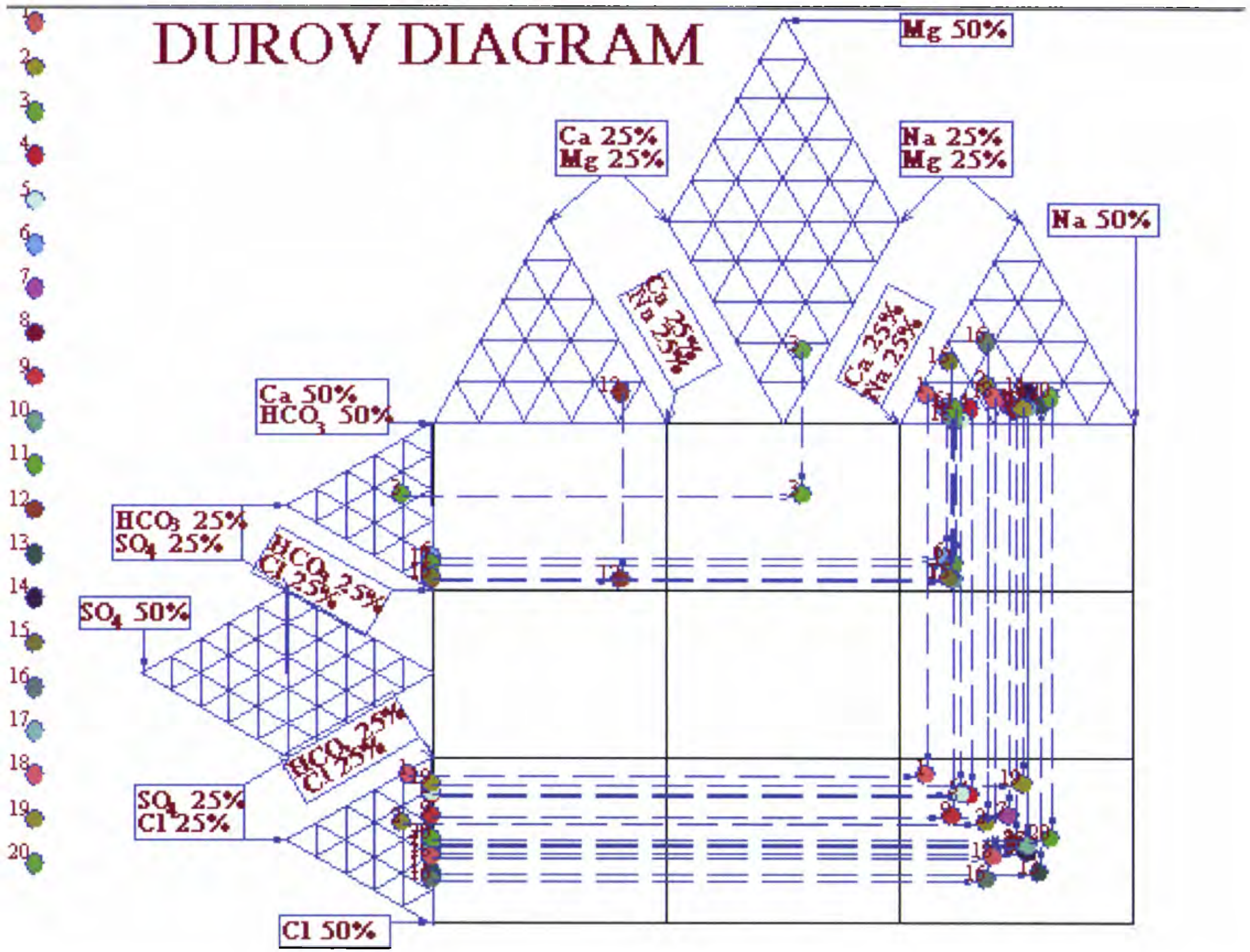

DUROV DIAGRAM
Mg 50%
Ca 25%
Mg 25%
Na 25%
Mg 25%
Na 50%
Ca 25%
Na 25%
Ca 25%
Na 25%
Ca 50%
HCO3 50%
HCO3 25%
SO4 25%
HCO3 25%
Cl 25%
SO4 50%
HCO3 25%
Cl 25%
SO4 25%
Cl 25%
Cl 50%
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

fig.5.21a



DUROV DIAGRAM
Mg 50%
Ca 25%
Mg 25%
Na 25%
Mg 25%
Na 50%
Ca 25%
Na 25%
Ca 25%
Na 25%
Ca 50%
$HCO_3$ 50%
$HCO_3$ 25%
$SO_4$ 25%
$HCO_3$ 25%
Cl 25%
$SO_4$ 50%
$HCO_3$ 25%
Cl 25%
$SO_4$ 25%
Cl 25%
Cl 50%
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20


fig.5.21b

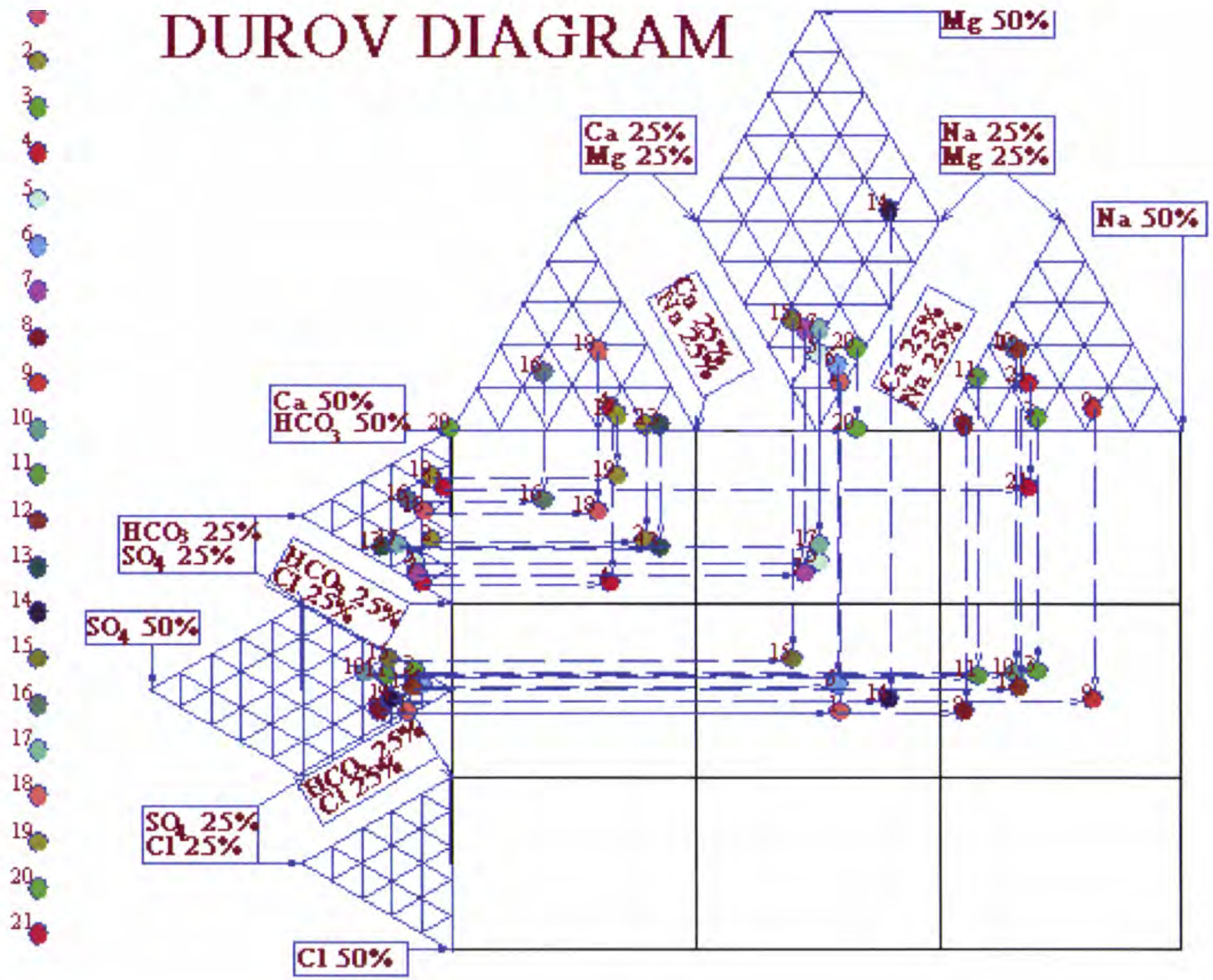

DUROV DIAGRAM
Mg 50%
Ca 25%
Mg 25%
Na 25%
Mg 25%
Na 50%
Ca 25%
Na 25%
Ca 25%
Na 25%
Ca 50%
HCO3 50%
HCO3 25%
SO4 25%
HCO3 25%
Cl 25%
SO4 50%
HCO3 25%
Cl 25%
SO4 25%
Cl 25%
Cl 50%
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

fig.5.21c

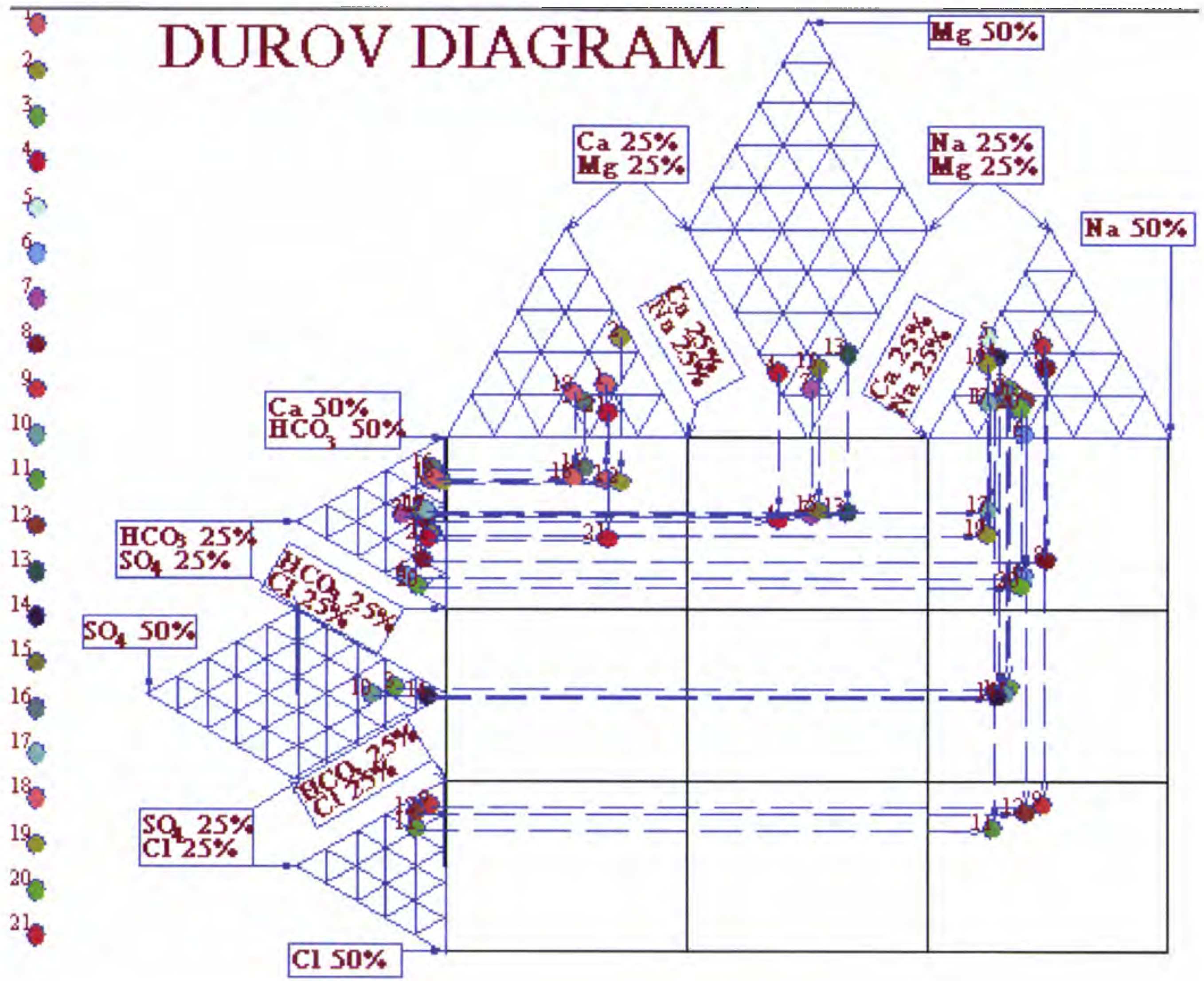

DUROV DIAGRAM
Mg 50%
Ca 25%
Mg 25%
Na 25%
Mg 25%
Na 50%
Ca 25%
Na 25%
Ca 25%
Na 25%
Ca 50%
HCO3 50%
HCO3 25%
SO4 25%
HCO3 25%
Cl 25%
SO4 50%
HCO3 25%
Cl 25%
SO4 25%
Cl 25%
Cl 50%
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

fig.5.21d

## PIE CHART OF CHEMICAL PARAMETERS -POSTMONSOON GIS MAP

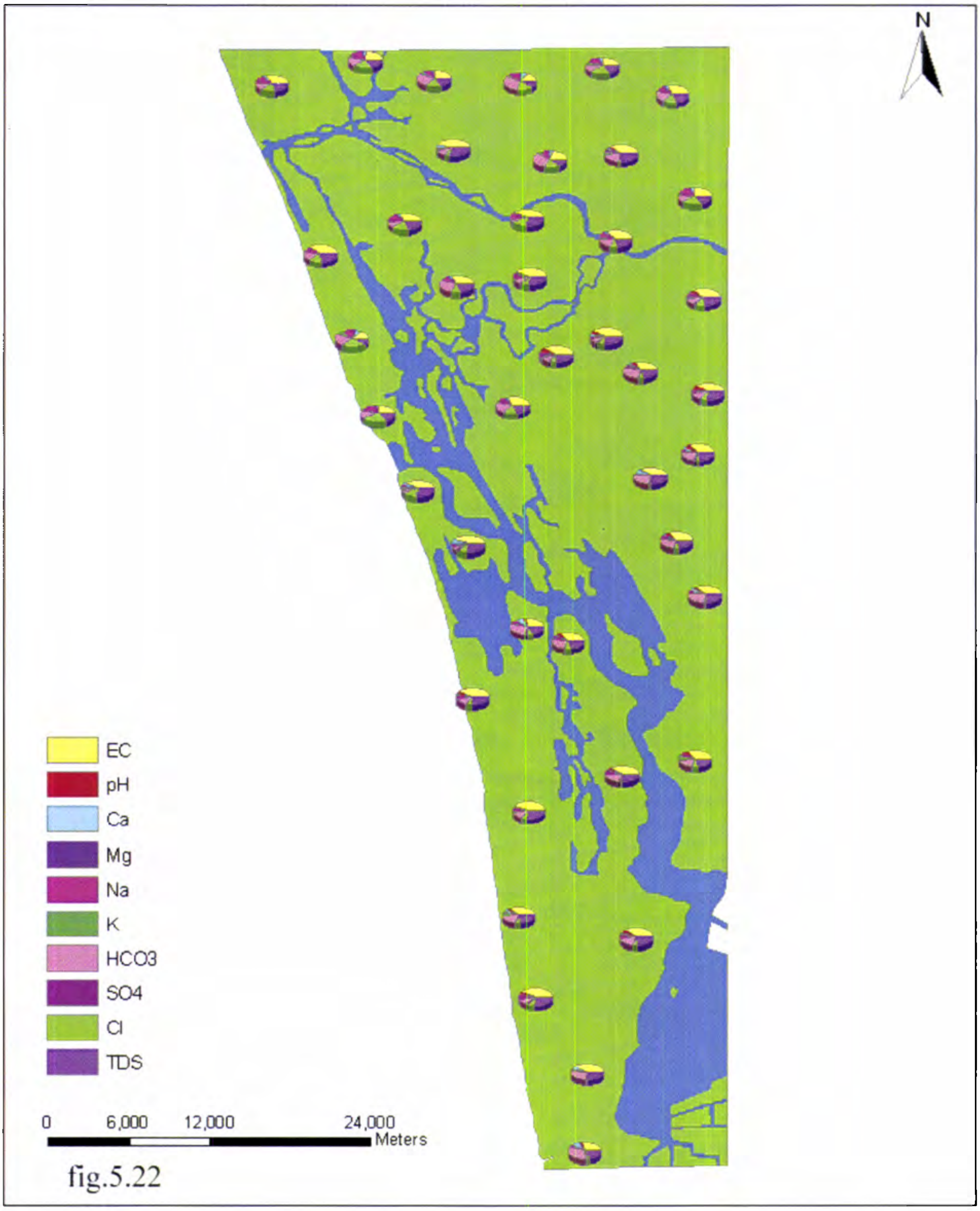



fig.5.22

### 5.9. Plotting Over Raster images

Sample locations are displayed on an X-Y graph and a detailed site map imported from raster images (fig. 5.22) to provide a familiar point of reference for analyzing sample data. The symbols representing the sample locations are customized according to shape. In addition, the map plot is used to display the location of different water types, and the symbols can be scaled in color according to the concentration of a selected measured element

Chapter 6

# Remote Sensing and Geographic Information System

## 6.1. Introduction

Remote sensing has been defined as the acquisition of data of an object or scene by a sensor that is far from the object (Colwell, 1983). Remote sensing with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within short time has become a very handy tool in assessing, monitoring and conserving groundwater resources. Satellite data provides quick and useful baseline information on the parameters controlling the occurrence and movement of groundwater like geology, lithology/structural, geomorphology, soils, landuse/ cover, lineaments etc. However all the controlling parameters have rarely been studied together because of non-availability of data, integrating tools and modeling techniques. Hence a systematic study of these factors leads to better delineation of prospective zones in an area, which is then followed up on the ground through detailed hydrogeological and geophysical investigations.

Visual interpretation has been the main tool for evaluation of groundwater prospective zones for over two decades. It has also been found that remote sensing besides helping in targeting potential zones for groundwater exploration provides inputs towards estimation of the total groundwater resources in an area, the selection of appropriate sites for artificial recharge and the depth of the weathering area. By combining the remote sensing information with adequate field data, particularly well inventory and yield data, it is possible to arrive at prognostic models to predict the ranges of depth, the yield, the success rate and the types of wells suited to various terrain under different hydrogeological domains. Based on the status of groundwater development and groundwater irrigated areas (though remote sensing), artificial recharge structures such as percolation tanks, check dams and subsurface dykes can be recommended upstream of groundwater irrigated areas to recharge the wells in the downstream areas so as to augment groundwater resources.

Remote sensing has multifarious applications in the field of geology. The satellite remote sensing has the ability to provide a synoptic view of large area and is very useful in analyzing drainage morphometry as studied by Chopra *et al.* (2005). Srivastava (1997) studied the drainage pattern of Jharia coalfield using remote sensing technology. Nag (1998) carried out morphometric analysis of Chaka sub-basin in Purulia district, while Nag and Chakraborty (2003) deciphered the influence of rock types and structures in the development of drainage network in hard rock area. Satellite remote sensing provides an opportunity for better observation and more systematic analysis of various hydrogeomorphic units/ landforms/ lineament, features following the synoptic, multispectral repetitive coverage of the terrain (Horton, 1945; Kumar and Srivastava, 1991; Sharma and Jugran, 1992; Chatterjee and Bhattacharya, 1995; Tiwari and Rai, 1996; Ravindran, 1997; Nag, 2005). The interpretation of satellite data in conjunction with sufficient ground truth information makes it possible to identify and outline various ground features such as geology, structure, geomorphic features and their hydraulic characters (Das.*et al.,* 1997), that may serve as direct or indirect indicators of the presence of groundwater (Ravindran and Jayaram, 1997).

Apart from visual interpretation, digital techniques are used by many researchers for deriving geological, structural and geomorphological details. The various thematic layers generated using remote sensing data like lithology/structural, geomorphology, land use/cover, lineaments etc, can be integrated with slope, drainage density and other collateral data in a Geographic Information System (GIS) framework and analysed using a model developed with logical conditions to derive groundwater zones as well as artificial recharge sites. Digital enhancement techniques are found to be suitable since they improve the feature sharpness and contrast for simple interpretation.

Remote sensing is a tool permitting accurate and real-time evaluation, monitoring or surveillance and forecasting of inland water resources. Remote sensing systems are used to observe the earth's surface from different platforms such as satellites and aircrafts, and make it possible to collect and analyse information about resources and environment over large areas. Remote sensors record electromagnetic energy reflected or emitted from earth's surface. Different kinds of objects or features such as soil, vegetation and water reflect and emit energy differently. This characteristic makes it possible to measure, map and monitor the objects and features using satellite or aircraft-borne remote sensing systems. Satellite images provide a low cost and potentially rapid means to monitor and map different land cover features. One of the greatest advantages of using remote sensing data for hydrological monitoring and modelling is its capability to generate information in spatial and temporal domain, which is important for water management as observed by Sanjay *et al.* (2004).

### 6.2. Remote Sensing Applications in Water Resources

Various applications wherein remote sensing may substitute, complement, or supplement the conventional methods are given below as quoted by Ramalingam and Venugopal (2004)

a) Hydrological studies include rainfall estimation, forecasting and monitoring, hydrological modelling, urban hydrology and water balance models.

b) Watershed conservation, planning and management include, watershed delineation, quantitative analysis of drainage network, watershed geology, and soil mapping, lake and reservoir sedimentation studies.

c) Flood plain management includes flood mapping, flood estimation and forecasting, disaster warning system and flood damage assessment.

d) Water Resources development studies include i) location of potential site for storage reservoir, ii) location of cross drainage works, iii) development of digital terrain model and iv) interbasin transfer of flood/surplus flow.

e) Water management in command area includes i) assessment of surface water resources, ii) reservoir operation, iii) identification, inventorying and assessment of irrigated crops, iv) soil moisture exposure estimation, v) irrigation scheduling, vi) conjunctive use of surface and ground water, vii) detection of canal seepages,

viii) artificial recharge, ix) detection of hydraulic leakages from dams, and x) monitoring performance of irrigation projects.

f) Groundwater studies include i) groundwater exploration and targeting, ii) detection of springs, fresh water discharge to inland rivers and "seabed" iii) detection of hydrogeomorphological features like abandons/buried channels and channel aquifer.

g) Drought monitoring includes i) identification of drought affected areas and monitoring, ii) drought impact assessment and iii) drought prediction and monitoring.

Other applications such as water quality mapping and monitoring, river morphology, land capability studies, saline water intrusion and estuarine studies, and coastal management etc. are also the thrust areas in which remote sensing and GIS can be properly utilized.

## 6.3. GIS Application in water resources

For many water-related studies, remote-sensing data alone are not adequate; they have to be merged with data from other sources. Hence a multitude of spatially related (i.e. climatic and geographic) data about rainfall, evaporation, vegetation, geomorphology and soil has to be considered. In addition, information is also required such as location and type of wells, rainfall, river gauges etc. Thus the fast storage, retrieval, displays and updating of maps are important functions. A system that can store data, select and classify the stations and perform mathematical, sorting operations is called a database, and information could be extracted for a given purpose. A complete set of information forms the Geographic

Information Systems (GIS). GIS is an effective tool for storing, managing and displaying spatial data encountered in hydrology and water resources management. GIS technology integrates common database operations, such as queries and statistical analysis, with the unique visualization and geographic analysis from maps and spatial databases. A GIS is defined by Goodchild (1993) as a "general-purpose technology for handling geographic data in digital form with the following capabilities: (i) the ability to preprocess data from large stores into a form suitable for analysis (reformatting, change of projection, re-sampling, and generalization), (ii) direct support for analysis and modeling, and (iii) post processing of results (reformatting, tabulation, report generation, and mapping)." The Advantages of GIS in its application to general spatial problems include "the ease of data retrieval; ability to discover and display information gained by testing interactions between phenomena; ability to synthesize large amounts of data for spatial examination; ability to make scale and projection changes, remove distortions, and perform coordinate rotation and translation; and the capability to discover and display spatial relationships through the application of empirical and statistical models" (Walsh,1988).

As cited earlier,Geographic information systems (GIS) can facilitate analysis required for more efficient management of groundwater resources. This function of GIS has been used to enhance the understanding of groundwater resources and their management worldwide. The spatial nature of groundwater data makes it possible to use GIS to input, store, organize, and analyze the data. Then the spatial analysis, visualization, and query capabilities of GIS can be employed to make decisions, taking account of the spatial relationship between the relevant elements in a given location. Finally, GIS modeling capacity can be used to develop effective management strategies to minimize water shortages.

GIS is an effective tool for integration of various data and hence has multifarious uses in geological studies. The GIS offers unique opportunities to integrate spatial data from different sources with the natural resources management models (Goodchild, 1993). GIS has been put to effective use in delineating groundwater potential zones in many earlier studies. (Chaterjee and Bhattacharya, 1995; Krishnamurthy and Srinivas,1995; Krishnamurthy *et al.,* 1996; Tiwari and Rai, 1996; Ravindran and Jeyaram, 1997; Saraf and Choudhary,1998; Srivastava and Bhatacharya, 2000; Sarkar *et al.,* 2001; Khan and Moharana, 2002; Sankar, 2002; Srinivasa *et al.,* 2004. Geographic information system can be used for storing hydrogeological data as well as their spatial locations in relational database (Shahid and Nath, 2000). For the assessment of groundwater resources of Northwest Florida water management district, Richards et.al., 1996 took the advantage of GIS for spatial analysis and data visualization. Krishnamurthy *et al.,* 1996 developed a GIS based model for delineating ground water potential zones of Marvdaiyar basin Tamilnadu, India by integrating different thematic layers derived from remote sensing data. The field verification of this model established the efficacy of GIS in demarcating the potential groundwater reserves. Application of GIS for groundwater resource assessment has also been reported by Sander (1997), Teeuw (1999) and others.

The satellite data of IRS-ID LISS III (2002), geocoded FCC for visual interpretation and digital data for digital classification were used. Digital data were processed in the laboratory using ERDAS Imagine 8.6 DIP software. The FCC of the study area is given in fig.6.1 and the enhanced terrain model is given in fig.6.2. The classified image is given in fig. 6.3. From the classified image it is possible to easily bring out the various features in the study area.

In the present study GIS has been utilized for analysis and presentation of data in all the stages right from water level analysis to the final potential potable water zone map under the following themes viz, Water level analysis, Geochemical analysis, Water quality mapping, Saline Water Buffer Zones, Deciphering prospective groundwater Zones using resistivity and aquifer thickness and Delineation of potable water zones integrating water quality data with the potential groundwater zones.

### 6.3.1. Groundwater Level Analysis

Under groundwater level analysis GIS has been made use of in creating elevation contour coverages, statistical analysis of the water level data of ten years, flow accumulation raster, flow direction raster and basin analysis, which are described in the Chapter 3 on hydrology. Three dimensional visualization of water level has been attempted using GIS and is described below.

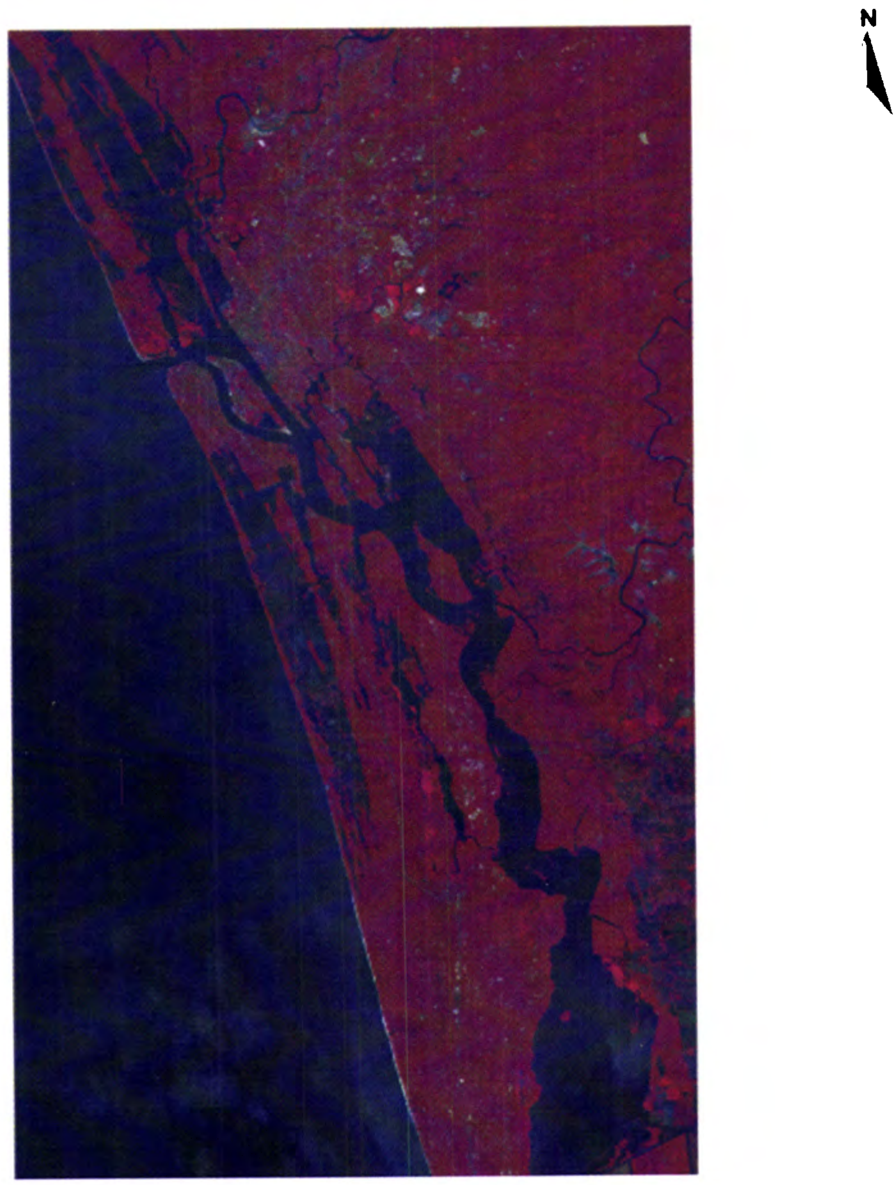



fig.6.1 False colour composite of the study area-IRS - 1D LISS-III

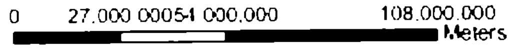



fig.6.2 ETM data of the study area

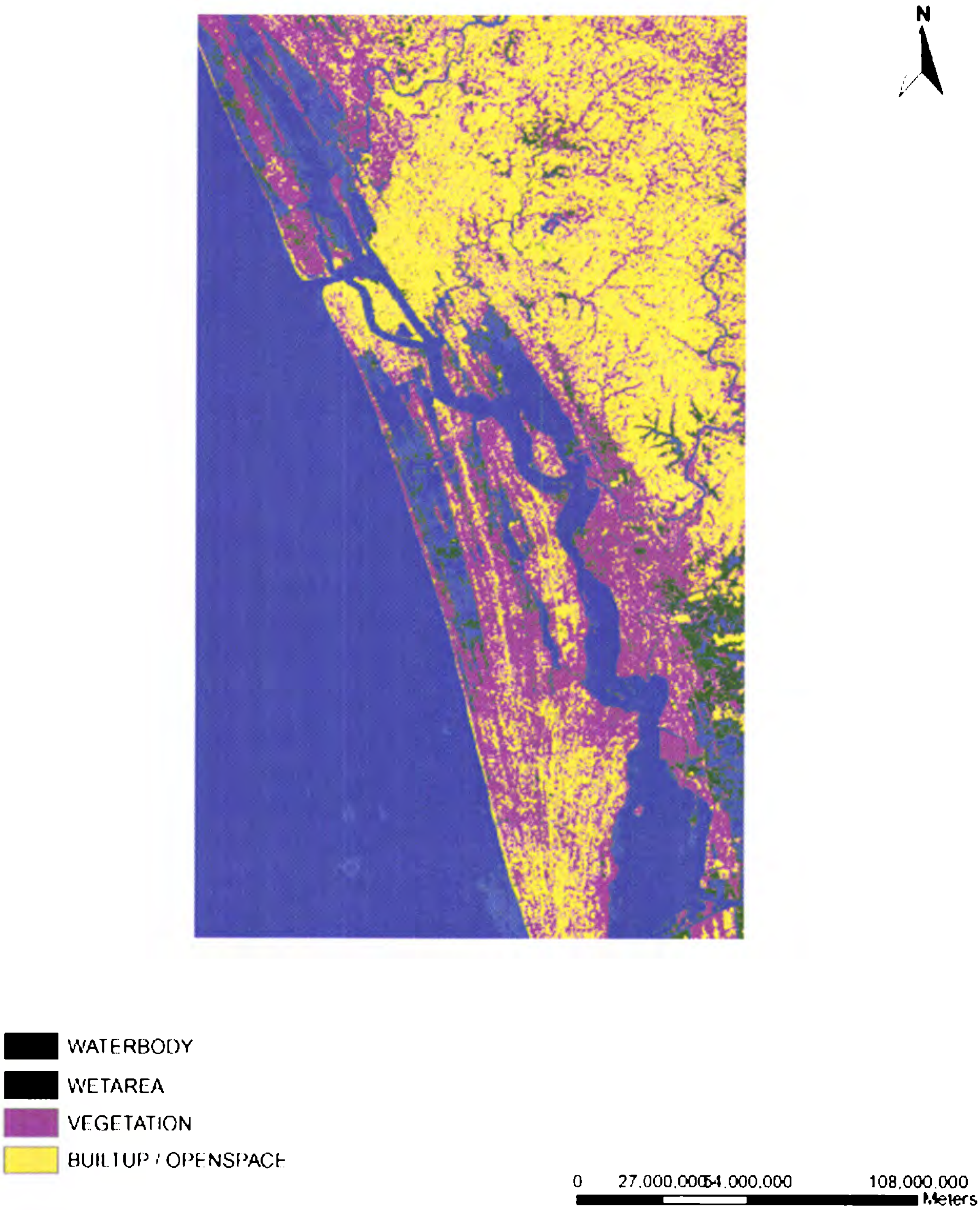



fig.6.3 Classified satellite imagery of t he study area

### 6.3.1a. Groundwater Surface Elevation Contour Coverages

A groundwater surface elevation contour coverage was made for each year from 1993 to 2003 for both pre-monsoon and post-monsoon periods. Separate data files including well identification, groundwater surface elevation, depth to water table and year of observation were provided to get the contour coverage. 26 wells of the State Groundwater Board were used for this purpose. Contouring was created using ArcInfo's TIN procedure. The TINs were then converted to grids for presentation. The maps showing the water level change for the 10-year period was also prepared using the same method. All the maps were discussed in the Chapter No.3 on Hydrogeology.

### 6.3.1.b. 3D Visualization of Water level

Amongst many modules, the ArcInfo based 3D Analyst module provides faster solution for rapidly selecting the sites for recharge. In the present study, mean water level data derived from monthly-observed data of 26 wells were plotted and contoured. The same contours were imported into ArcView 3D Analyst. The values were entered for each contour and the TIN generated by 3D Analyst module that is presented as 3D view of mean water level in figure 6.4. From this, the groundwater valleys, basins, ridges and domes were brought out and the groundwater valleys and basins were identified as suitable sites for artificial recharge as groundwater is occurring at deeper levels in these zones. Thus these techniques can be used for rapidly selecting the sites for artificial recharge.

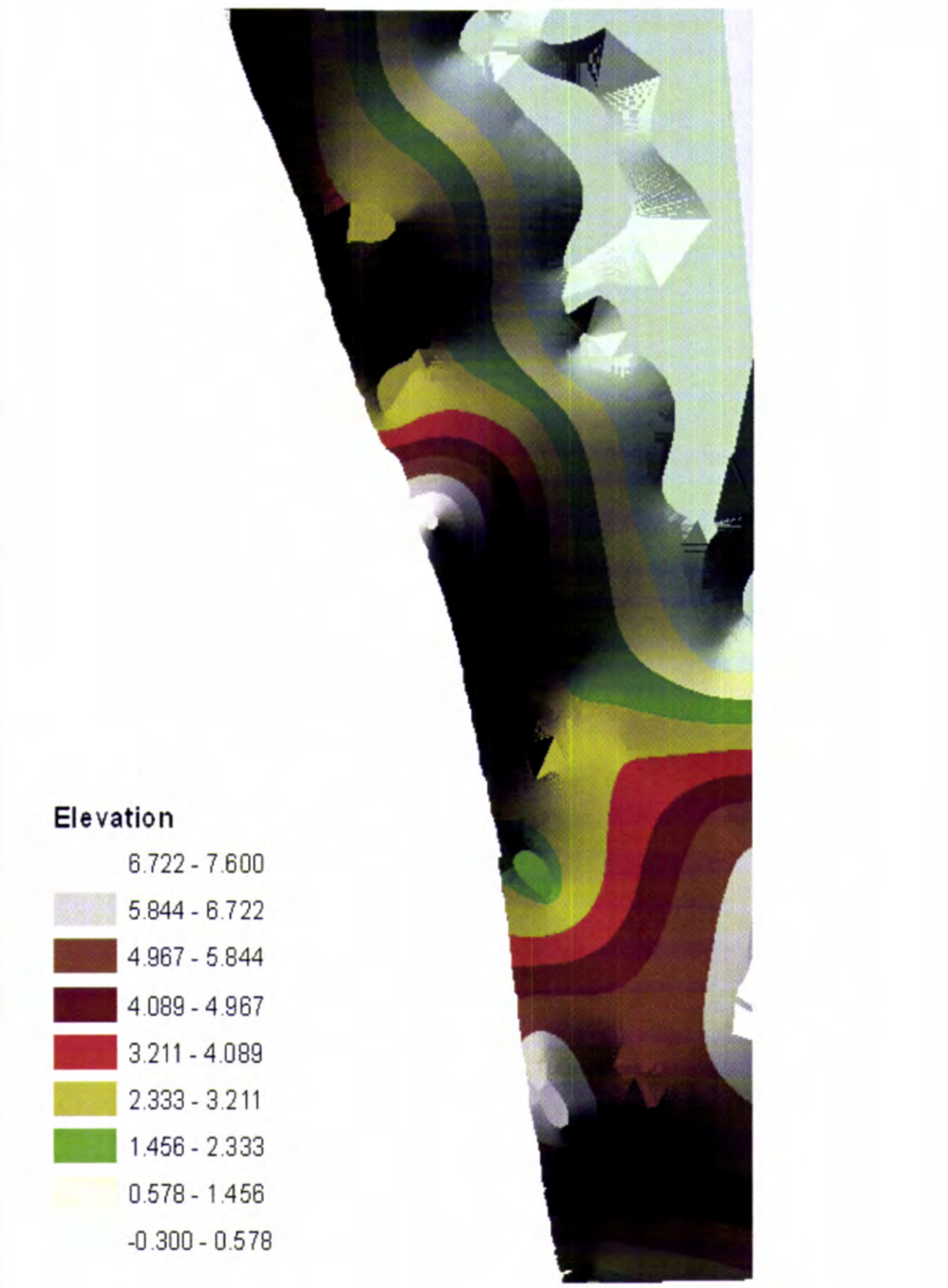



fig.6.4 Three dimensional visualization of water level of the study area

### 6.3.2. GIS Analysis of Geochemical data

In geochemical analysis, GIS has been used to create spatial distribution of each element and also for its overlay analysis to generate zonation maps and spatial overlay maps.

**6.3.2.a. Zonation maps** of each element, which are accurate and user friendly gives the areal extent of each element as also the variation between the two seasons (pre-monsoon and post-monsoon). The Zonation maps of each element were already described in the chapter no.5 on Geochemistry.

#### 6.3.2.b. Spatial Overlay analysis

Spatial overlay maps are prepared to know the change in the zonation area of each element between the pre-monsoon and post-monsoon periods. In the geo-processing wizard (in Arc Tool box) the Union option is employed and overlay is done. Another field is added in the attribute table to calculate the area. Bar diagrams are prepared and exhibited in the map to show the changes. The overlay map of each element showing the variation in the concentration during the pre-monsoon and post-monsoon period is given (fig.6.5a to fig.6.5j). The variations were discussed in detail in the chapter no.5 on Geochemistry.

**6.3.3. Drinking Water Quality Maps** Suitability maps of each element as per drinking water standards prescribed by WHO and the overlay showing variations between the two seasons are prepared.

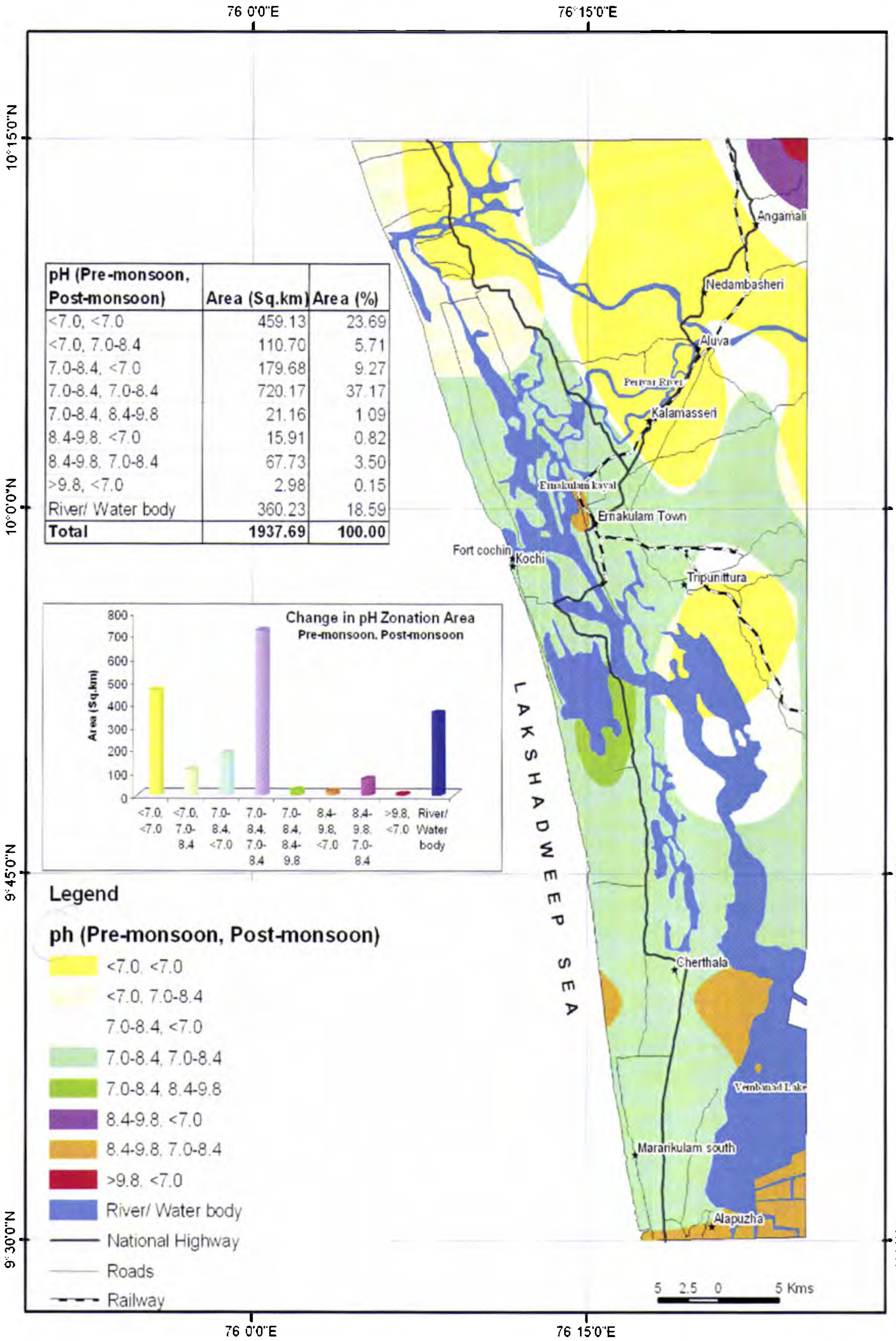
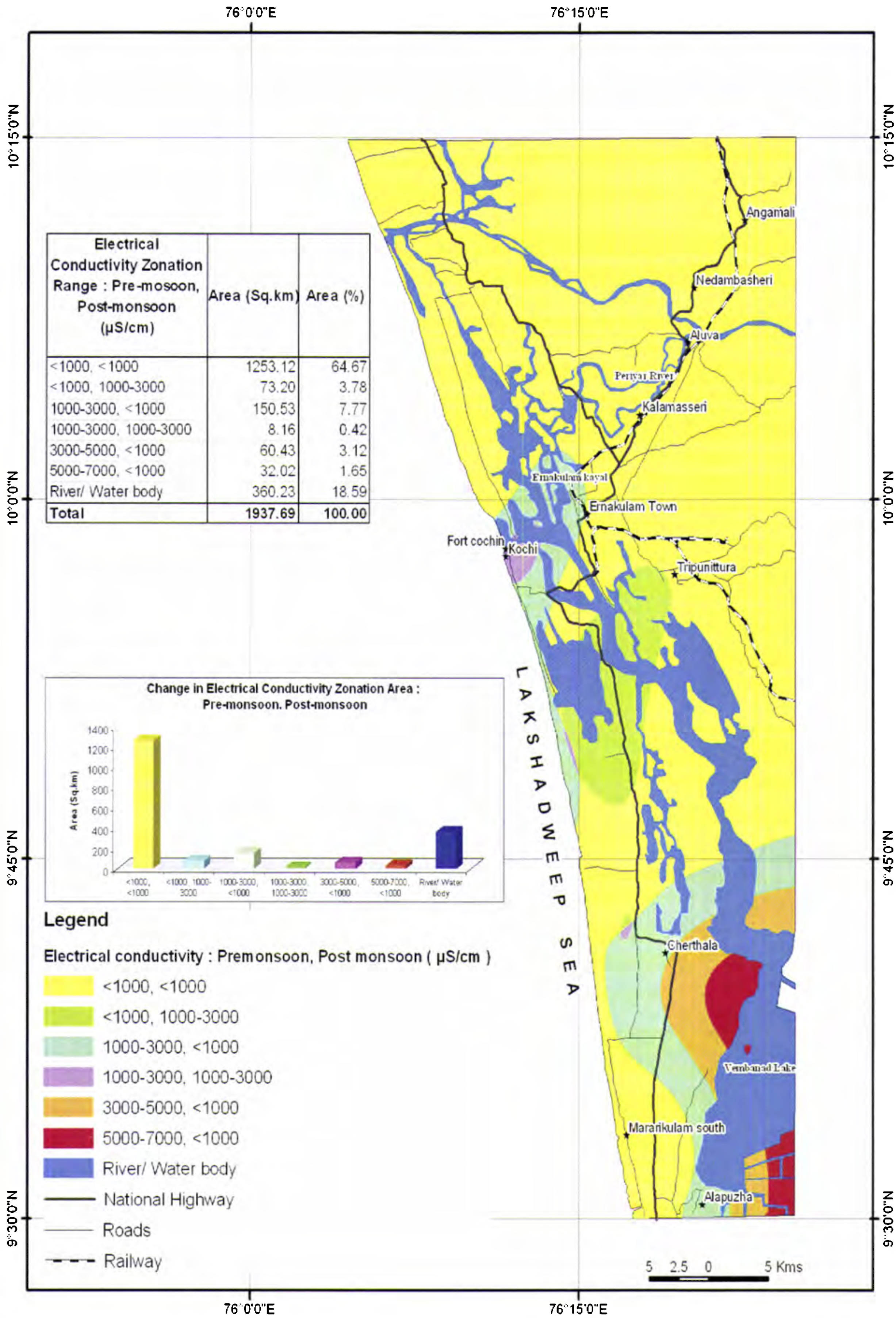
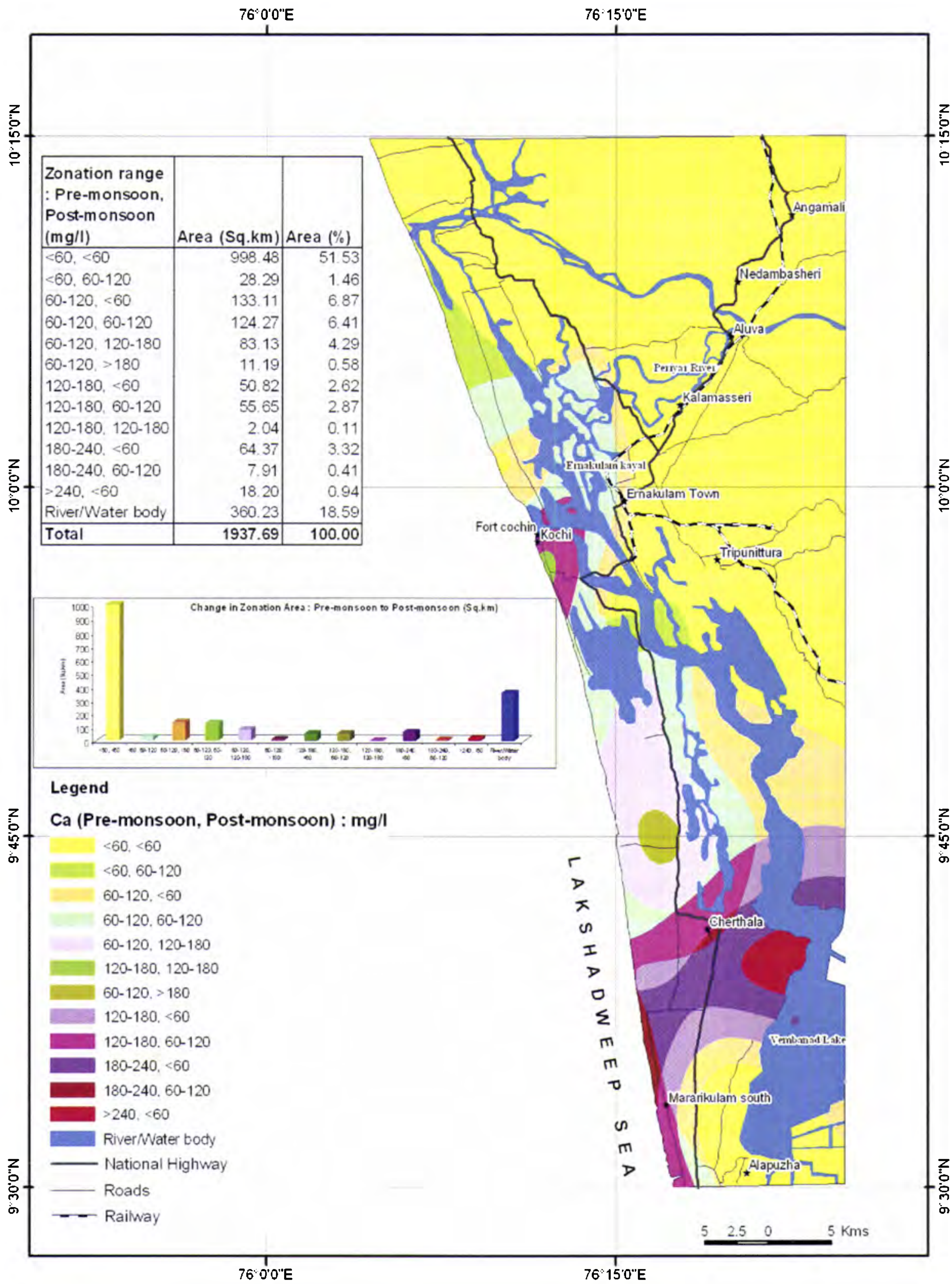



fig.6 5a CHANGE IN pH ZONES (PRE MONSOON POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



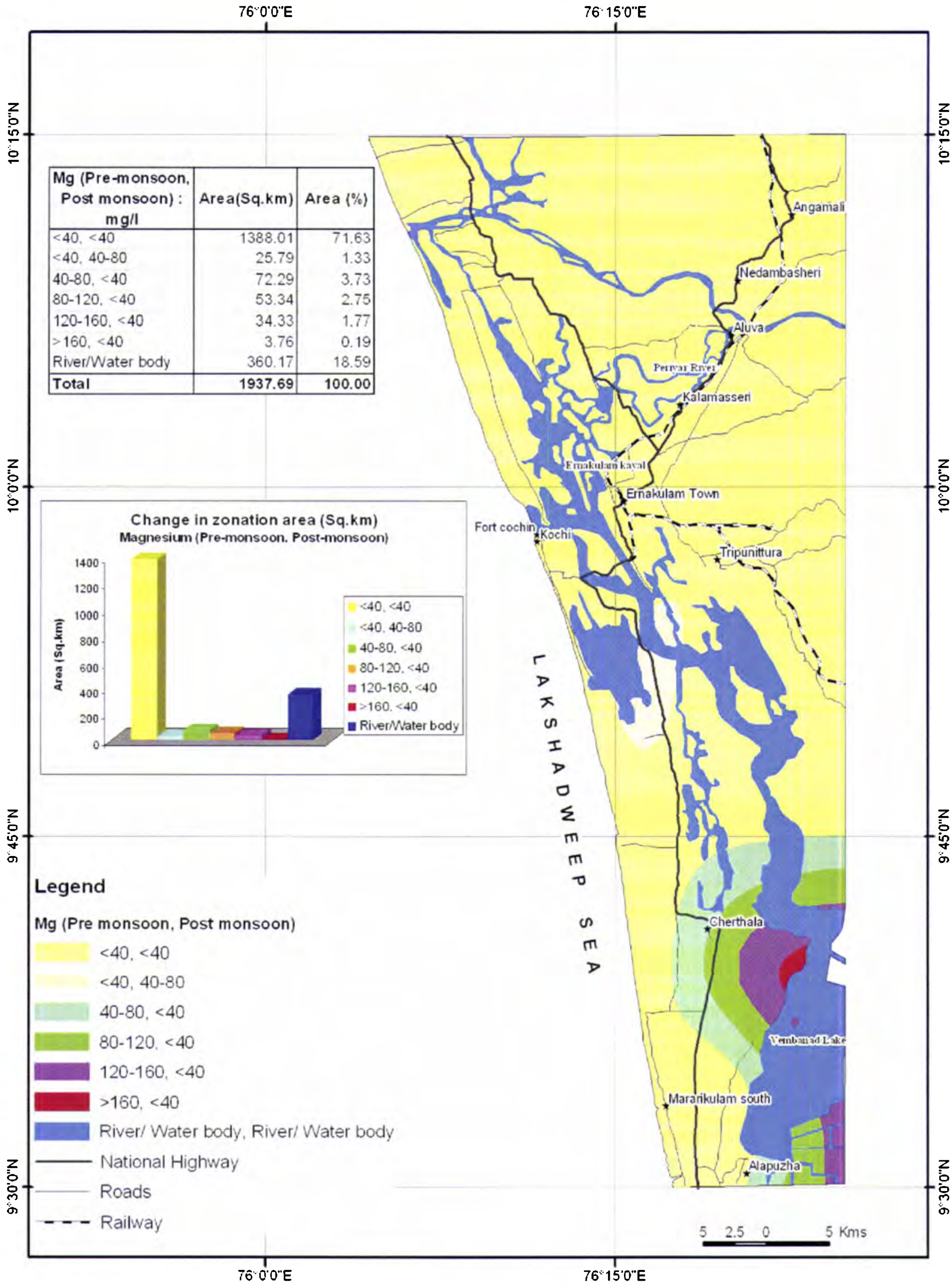

| Electrical Conductivity Zonation Range : Pre-mosoon, Post-monsoon (µS/cm) | Area (Sq.km) | Area (%) |
|---|---|---|
| <1000, <1000 | 1253.12 | 64.67 |
| <1000, 1000-3000 | 73.20 | 3.78 |
| 1000-3000, <1000 | 150.53 | 7.77 |
| 1000-3000, 1000-3000 | 8.16 | 0.42 |
| 3000-5000, <1000 | 60.43 | 3.12 |
| 5000-7000, <1000 | 32.02 | 1.65 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.6.5b CHANGE IN ELECTRICAL CONDUCTIVITY ZONES (PRE MONSOON, POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



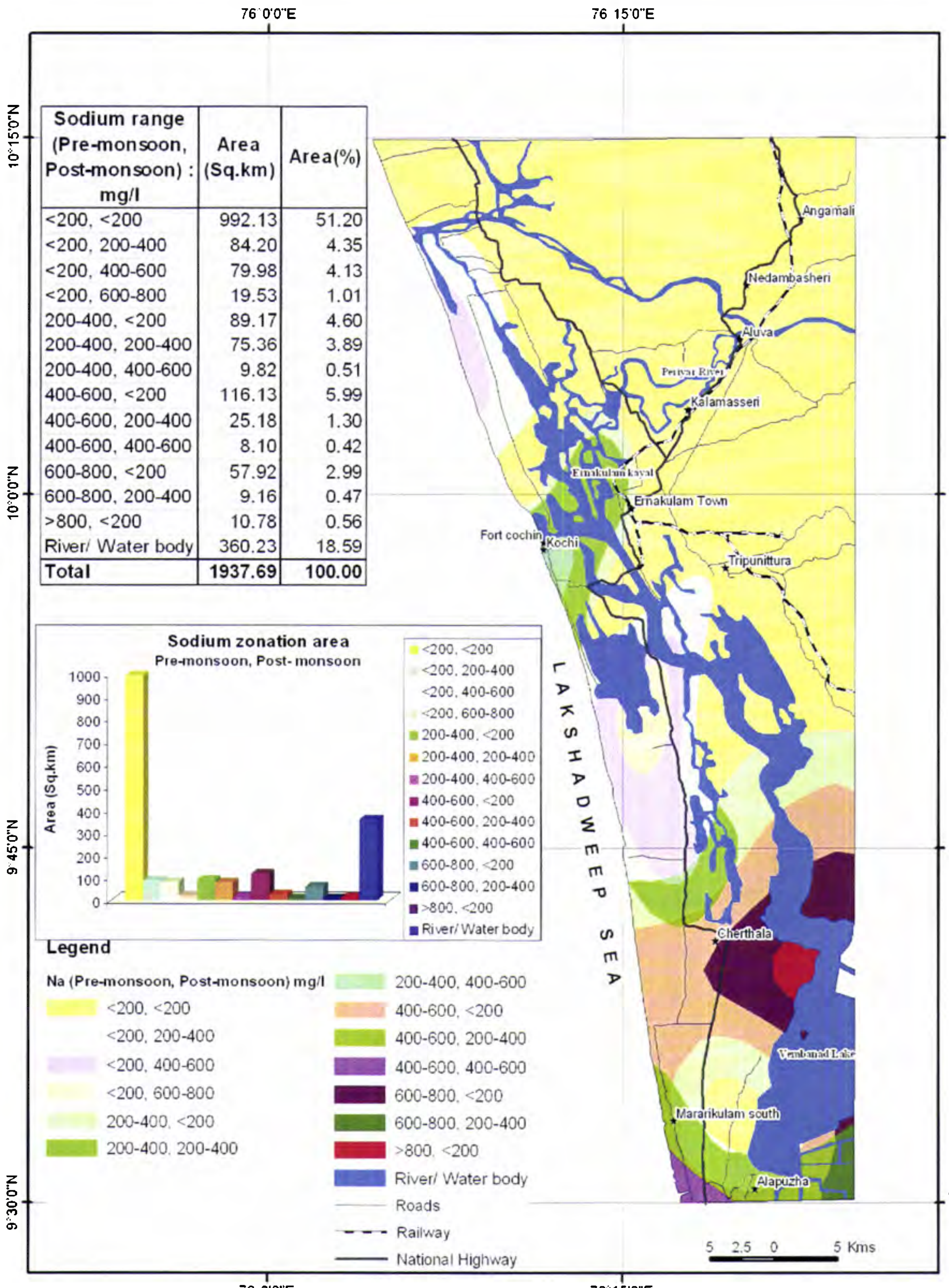

| Zonation range : Pre-monsoon, Post-monsoon (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <60, <60 | 998.48 | 51.53 |
| <60, 60-120 | 28.29 | 1.46 |
| 60-120, <60 | 133.11 | 6.87 |
| 60-120, 60-120 | 124.27 | 6.41 |
| 60-120, 120-180 | 83.13 | 4.29 |
| 60-120, >180 | 11.19 | 0.58 |
| 120-180, <60 | 50.82 | 2.62 |
| 120-180, 60-120 | 55.65 | 2.87 |
| 120-180, 120-180 | 2.04 | 0.11 |
| 180-240, <60 | 64.37 | 3.32 |
| 180-240, 60-120 | 7.91 | 0.41 |
| >240, <60 | 18.20 | 0.94 |
| River/Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.6.5c CHANGE IN CALCIUM ZONES (PRE MONSOON, POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH




| Mg (Pre-monsoon, Post monsoon) : mg/l | Area(Sq.km) | Area (%) |
|---|---|---|
| <40, <40 | 1388.01 | 71.63 |
| <40, 40-80 | 25.79 | 1.33 |
| 40-80, <40 | 72.29 | 3.73 |
| 80-120, <40 | 53.34 | 2.75 |
| 120-160, <40 | 34.33 | 1.77 |
| >160, <40 | 3.76 | 0.19 |
| River/Water body | 360.17 | 18.59 |
| **Total** | **1937.69** | **100.00** |

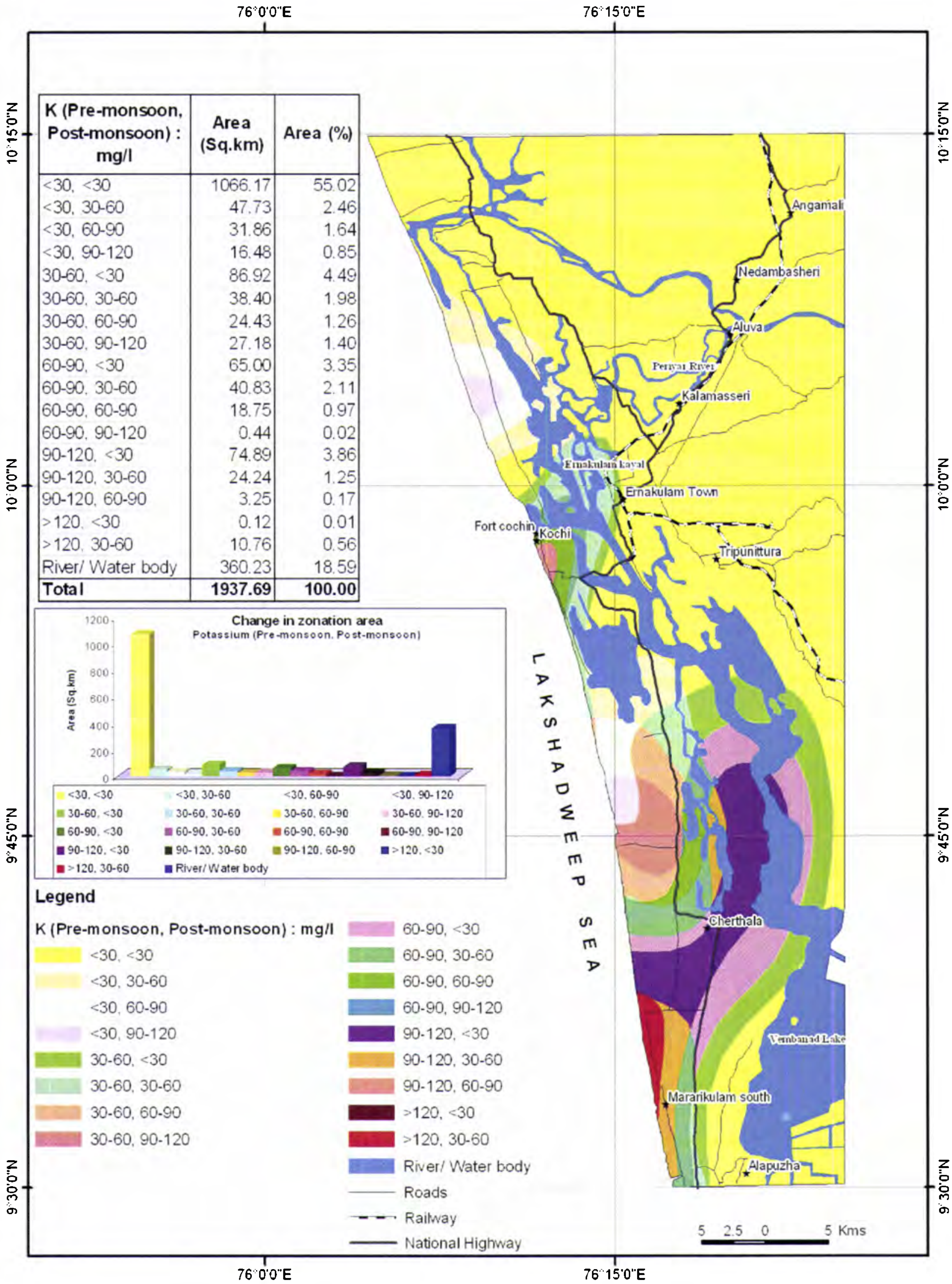
fig.6.5d CHANGE IN MAGNESIUM ZONES (PRE MONSOON POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



| Sodium range (Pre-monsoon, Post-monsoon) : mg/l | Area (Sq.km) | Area(%) |
|---|---|---|
| <200, <200 | 992.13 | 51.20 |
| <200, 200-400 | 84.20 | 4.35 |
| <200, 400-600 | 79.98 | 4.13 |
| <200, 600-800 | 19.53 | 1.01 |
| 200-400, <200 | 89.17 | 4.60 |
| 200-400, 200-400 | 75.36 | 3.89 |
| 200-400, 400-600 | 9.82 | 0.51 |
| 400-600, <200 | 116.13 | 5.99 |
| 400-600, 200-400 | 25.18 | 1.30 |
| 400-600, 400-600 | 8.10 | 0.42 |
| 600-800, <200 | 57.92 | 2.99 |
| 600-800, 200-400 | 9.16 | 0.47 |
| >800, <200 | 10.78 | 0.56 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

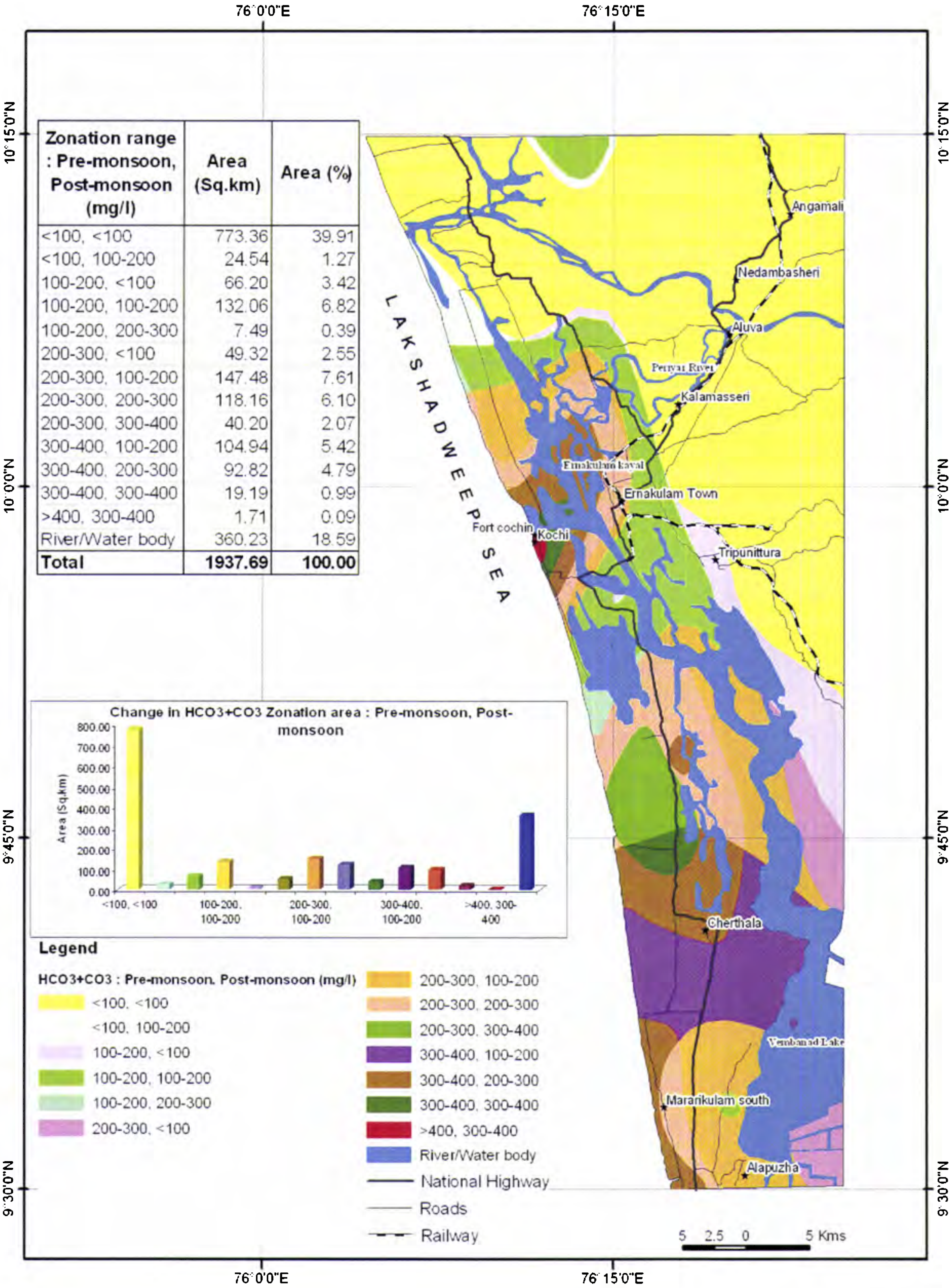


fig.6.5e CHANGE IN SODIUM ZONES (PRE MONSOON POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH



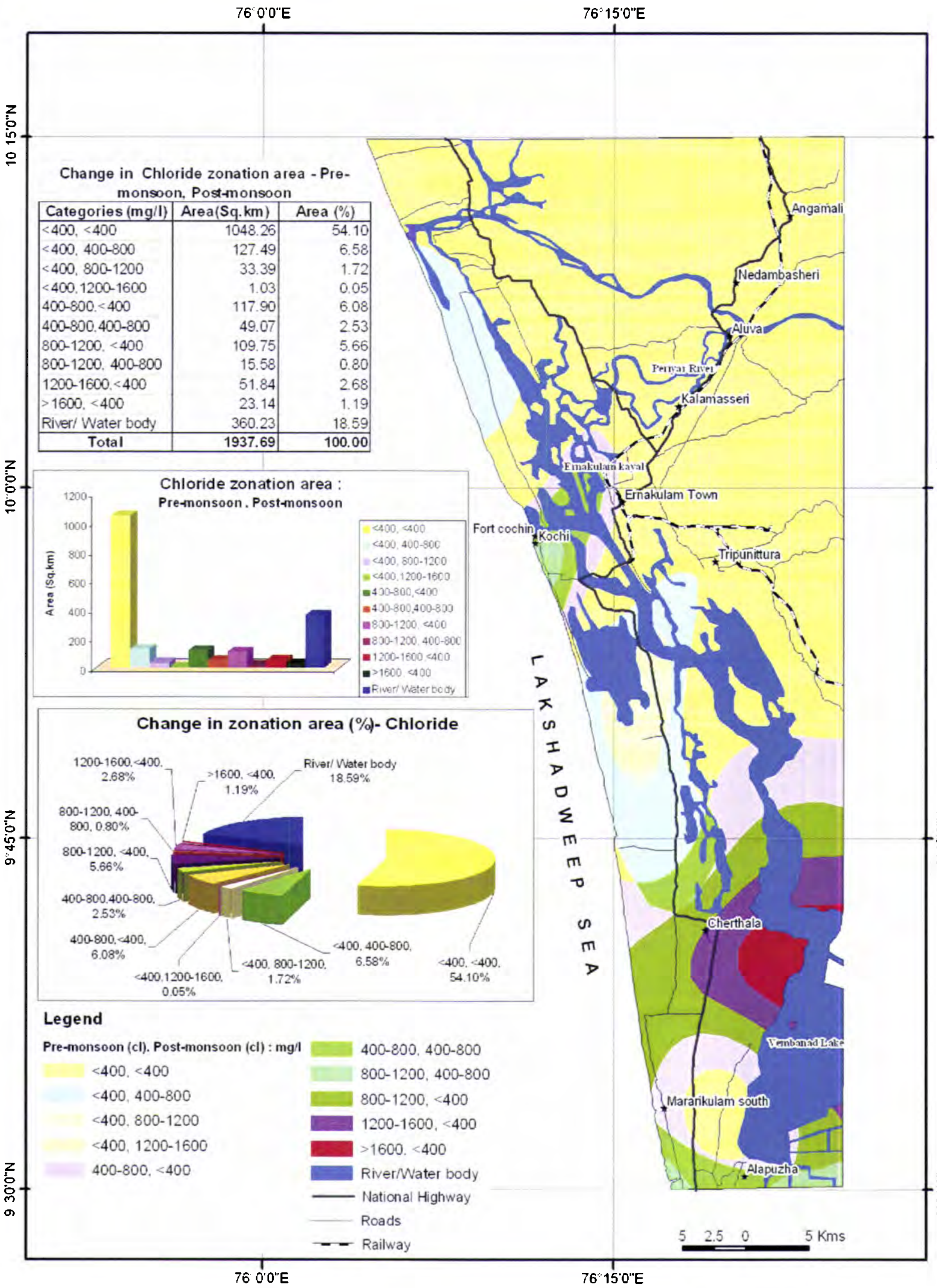

| K (Pre-monsoon, Post-monsoon) : mg/l | Area (Sq.km) | Area (%) |
|---|---|---|
| <30, <30 | 1066.17 | 55.02 |
| <30, 30-60 | 47.73 | 2.46 |
| <30, 60-90 | 31.86 | 1.64 |
| <30, 90-120 | 16.48 | 0.85 |
| 30-60, <30 | 86.92 | 4.49 |
| 30-60, 30-60 | 38.40 | 1.98 |
| 30-60, 60-90 | 24.43 | 1.26 |
| 30-60, 90-120 | 27.18 | 1.40 |
| 60-90, <30 | 65.00 | 3.35 |
| 60-90, 30-60 | 40.83 | 2.11 |
| 60-90, 60-90 | 18.75 | 0.97 |
| 60-90, 90-120 | 0.44 | 0.02 |
| 90-120, <30 | 74.89 | 3.86 |
| 90-120, 30-60 | 24.24 | 1.25 |
| 90-120, 60-90 | 3.25 | 0.17 |
| >120, <30 | 0.12 | 0.01 |
| >120, 30-60 | 10.76 | 0.56 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.6.5f CHANGE IN POTASSIUM ZONES (PRE MONSOON, POST MONSOON) ERNAKULAM - ALAPPUZHA STRETCH




| Zonation range : Pre-monsoon, Post-monsoon (mg/l) | Area (Sq.km) | Area (%) |
|---|---|---|
| <100, <100 | 773.36 | 39.91 |
| <100, 100-200 | 24.54 | 1.27 |
| 100-200, <100 | 66.20 | 3.42 |
| 100-200, 100-200 | 132.06 | 6.82 |
| 100-200, 200-300 | 7.49 | 0.39 |
| 200-300, <100 | 49.32 | 2.55 |
| 200-300, 100-200 | 147.48 | 7.61 |
| 200-300, 200-300 | 118.16 | 6.10 |
| 200-300, 300-400 | 40.20 | 2.07 |
| 300-400, 100-200 | 104.94 | 5.42 |
| 300-400, 200-300 | 92.82 | 4.79 |
| 300-400, 300-400 | 19.19 | 0.99 |
| >400, 300-400 | 1.71 | 0.09 |
| River/Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

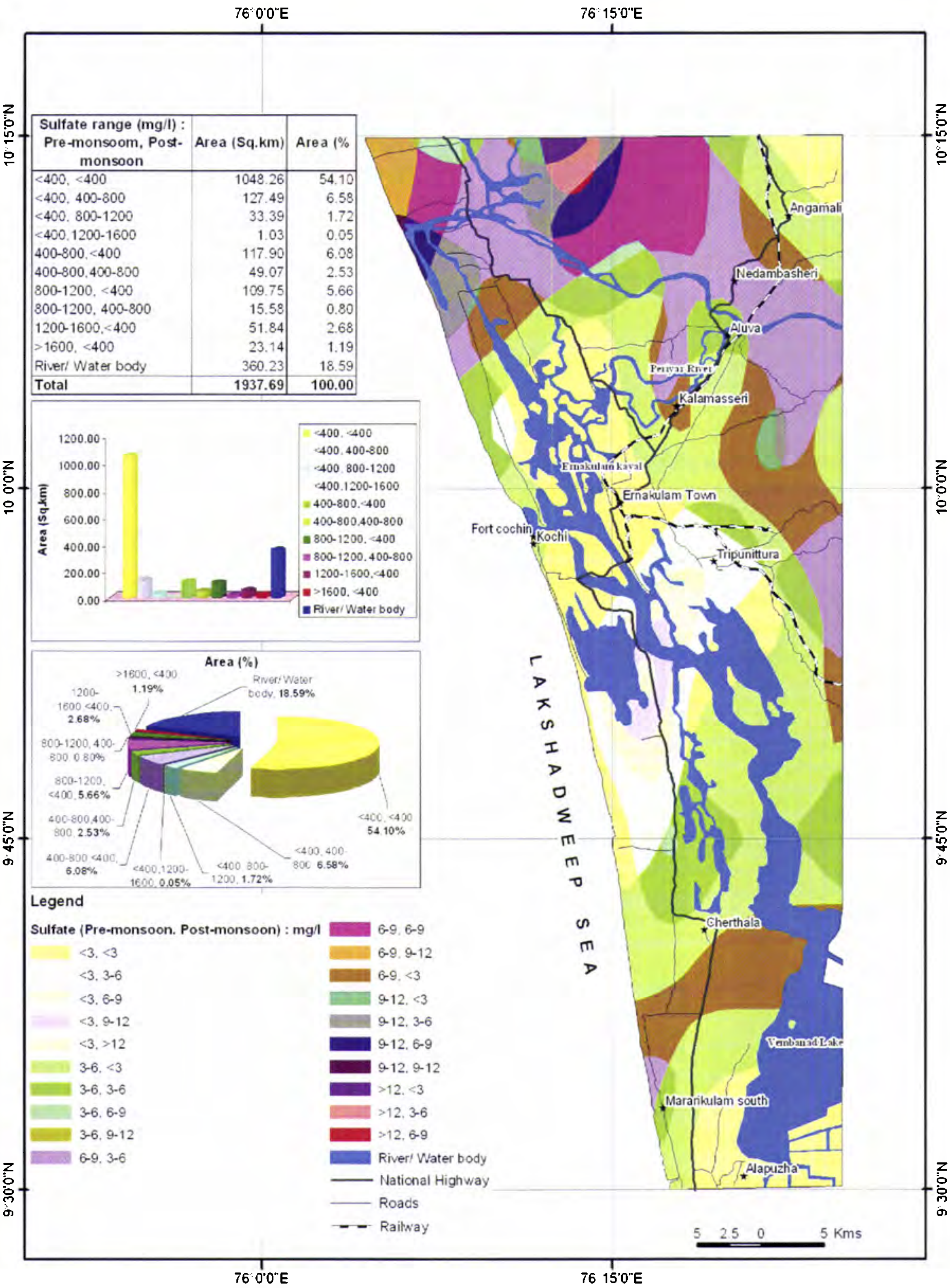
fig.6.5g CHANGE IN HCO3-CO3 ZONES (PRE MONSOON, POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH




Change in Chloride zonation area - Pre-monsoon, Post-monsoon

| Categories (mg/l) | Area(Sq.km) | Area (%) |
|---|---|---|
| <400, <400 | 1048.26 | 54.10 |
| <400, 400-800 | 127.49 | 6.58 |
| <400, 800-1200 | 33.39 | 1.72 |
| <400, 1200-1600 | 1.03 | 0.05 |
| 400-800, <400 | 117.90 | 6.08 |
| 400-800, 400-800 | 49.07 | 2.53 |
| 800-1200, <400 | 109.75 | 5.66 |
| 800-1200, 400-800 | 15.58 | 0.80 |
| 1200-1600, <400 | 51.84 | 2.68 |
| >1600, <400 | 23.14 | 1.19 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

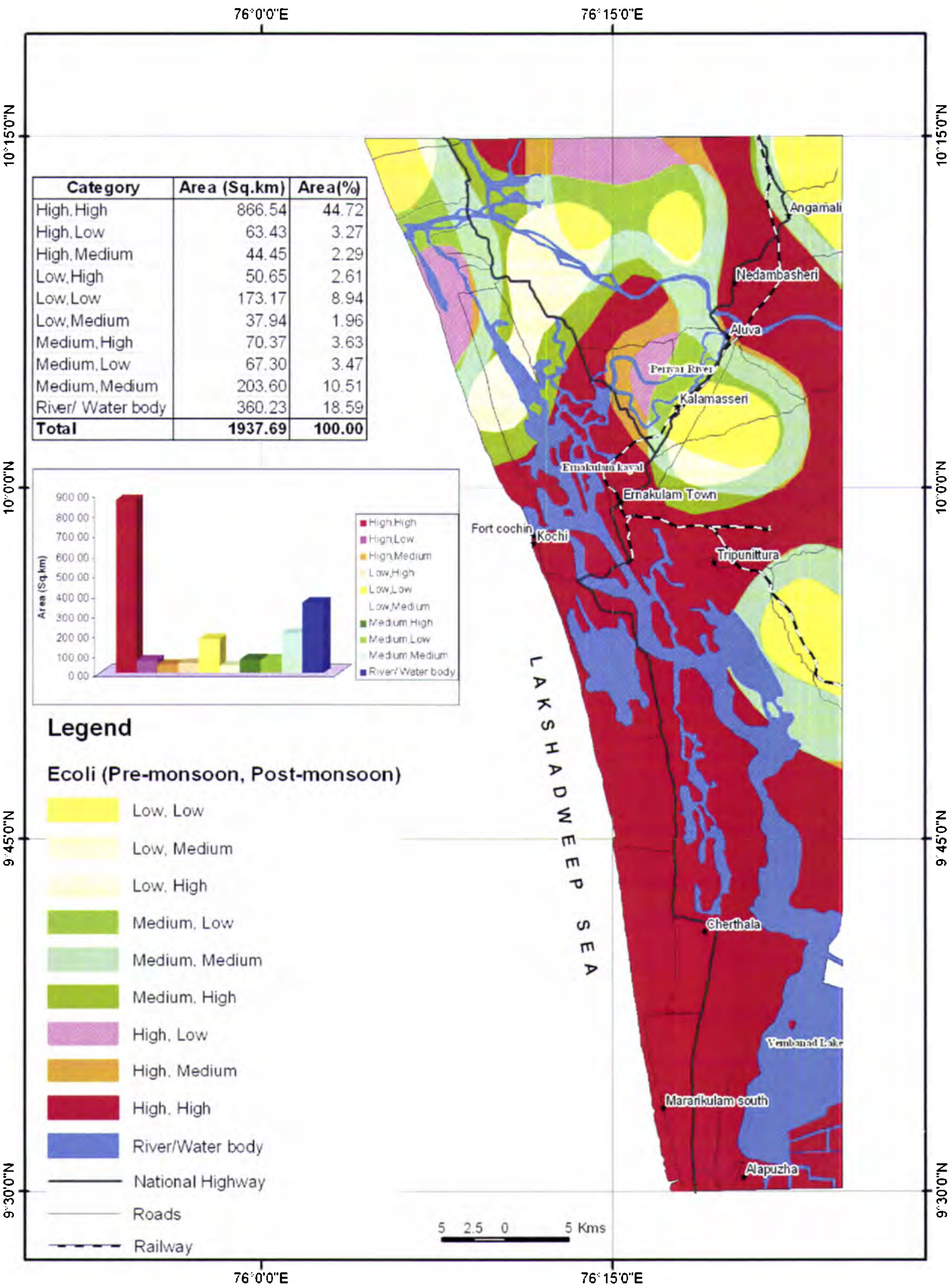
fig.6.5h CHANGE IN CHLORIDE ZONES (PRE MONSOON, POST MONSOON) ERNAKULAM - ALAPPUZHA STRETCH



| Sulfate range (mg/l) : Pre-monsoon, Post-monsoon | Area (Sq.km) | Area (% |
|---|---|---|
| <400, <400 | 1048.26 | 54.10 |
| <400, 400-800 | 127.49 | 6.58 |
| <400, 800-1200 | 33.39 | 1.72 |
| <400,1200-1600 | 1.03 | 0.05 |
| 400-800,<400 | 117.90 | 6.08 |
| 400-800,400-800 | 49.07 | 2.53 |
| 800-1200, <400 | 109.75 | 5.66 |
| 800-1200, 400-800 | 15.58 | 0.80 |
| 1200-1600,<400 | 51.84 | 2.68 |
| >1600, <400 | 23.14 | 1.19 |
| River/ Water body | 360.23 | 18.59 |
| Total | 1937.69 | 100.00 |



fig.6.5i CHANGE IN SULFATE ZONES (PRE MONSOON, POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH




| Category | Area (Sq.km) | Area(%) |
|---|---|---|
| High, High | 866.54 | 44.72 |
| High, Low | 63.43 | 3.27 |
| High, Medium | 44.45 | 2.29 |
| Low, High | 50.65 | 2.61 |
| Low, Low | 173.17 | 8.94 |
| Low, Medium | 37.94 | 1.96 |
| Medium, High | 70.37 | 3.63 |
| Medium, Low | 67.30 | 3.47 |
| Medium, Medium | 203.60 | 10.51 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

fig.6.5j CHANGE IN ECOLI ZONES (PRE MONSOON, POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH

Range as per WHO standards are input in Arc Map and suitablity zones for each element are delineated and are described below. Pre-monsoon and post-monsoon are overlain for suitability. Overlay maps of each element for suitability zones have been overlain to find out the final chemical high suitability zones. All the maps are self explanatory and userfriendly. But a brief explanation of all maps are given below before each map.

Fig 6.6 show the suitability map for pH of the area for both pre-monsoon and post-monsoon and the variation. The range of 6.5 – 8.5 has been taken as standard for the pH. In the pre-monsoon it is noticed that 64.8 % of the area falls in the suitability range where as it falls to 62.7 % in the post-monsoon. Also from the overlay map it is clear that 54.07% of the area remains in the suitable zone for both seasons, 10.7% change from suitable to unsuitable, 8.7% from unsuitable to suitable and 7.86% remains unsuitable during both seasons.

In the case of TDS the suitability range has been taken as less than 1000. The suitablity map for TDS is given in fig.6.7 From the overlay map it is evident that 70.47% remains in the suitability zone in both the seasons, 1.9% changes from suitable to unsuitable and 9.04% changes from unsuitable to suitable zone.

The suitability map for ecoli in the study area is given in fig 6.8. The suitability range has been taken as low to medium ecoli and high ecloi has been taken as unsuitable. 24.88% of the area falls in the suitable range in

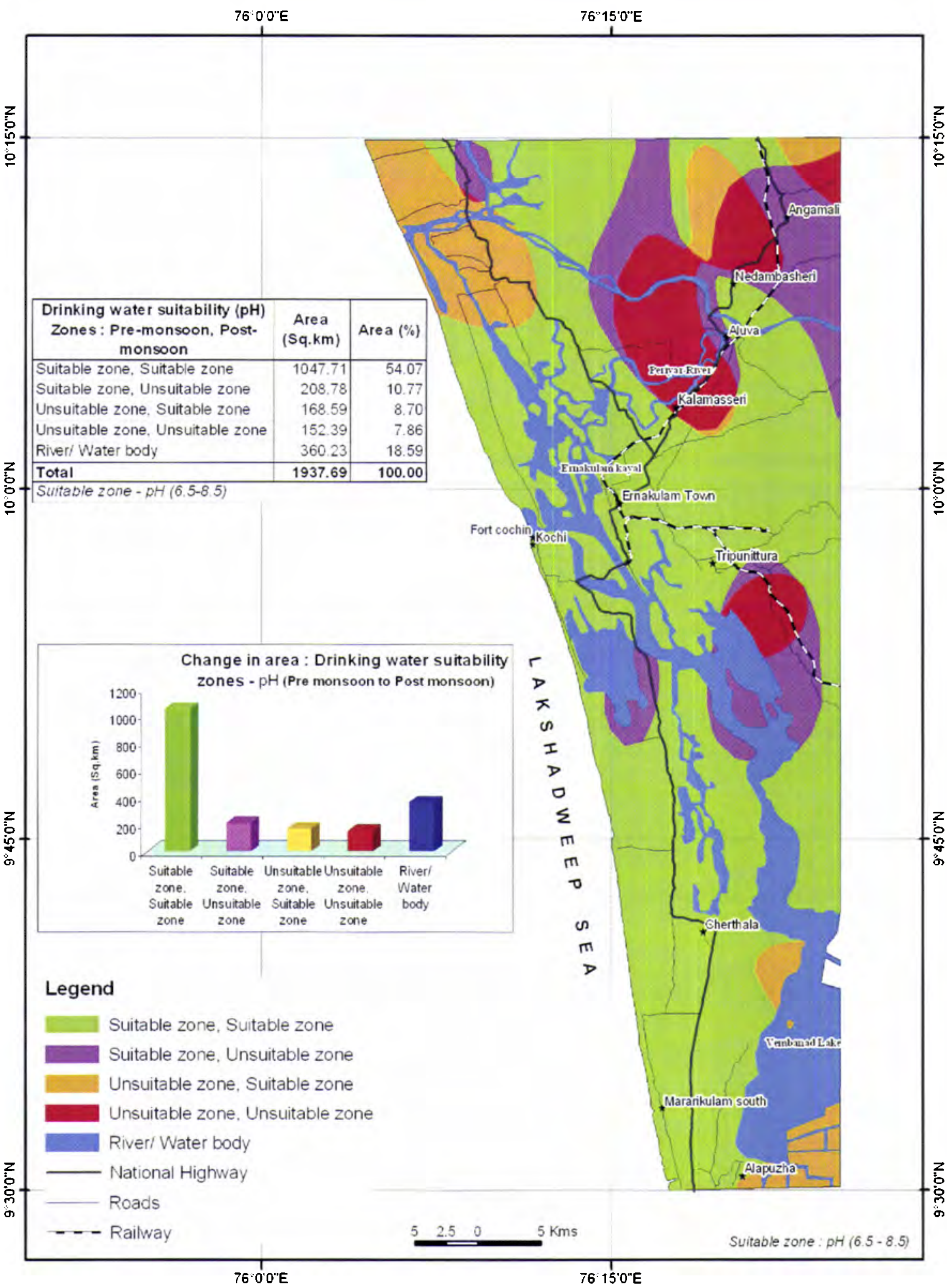



fig.6.6 CHANGE IN DRINKING WATER SUITABILITY ZONES - pH (PRE MONSOON TO POST MONSOON    ERNAKULAM - ALAPPUZHA STRETCH

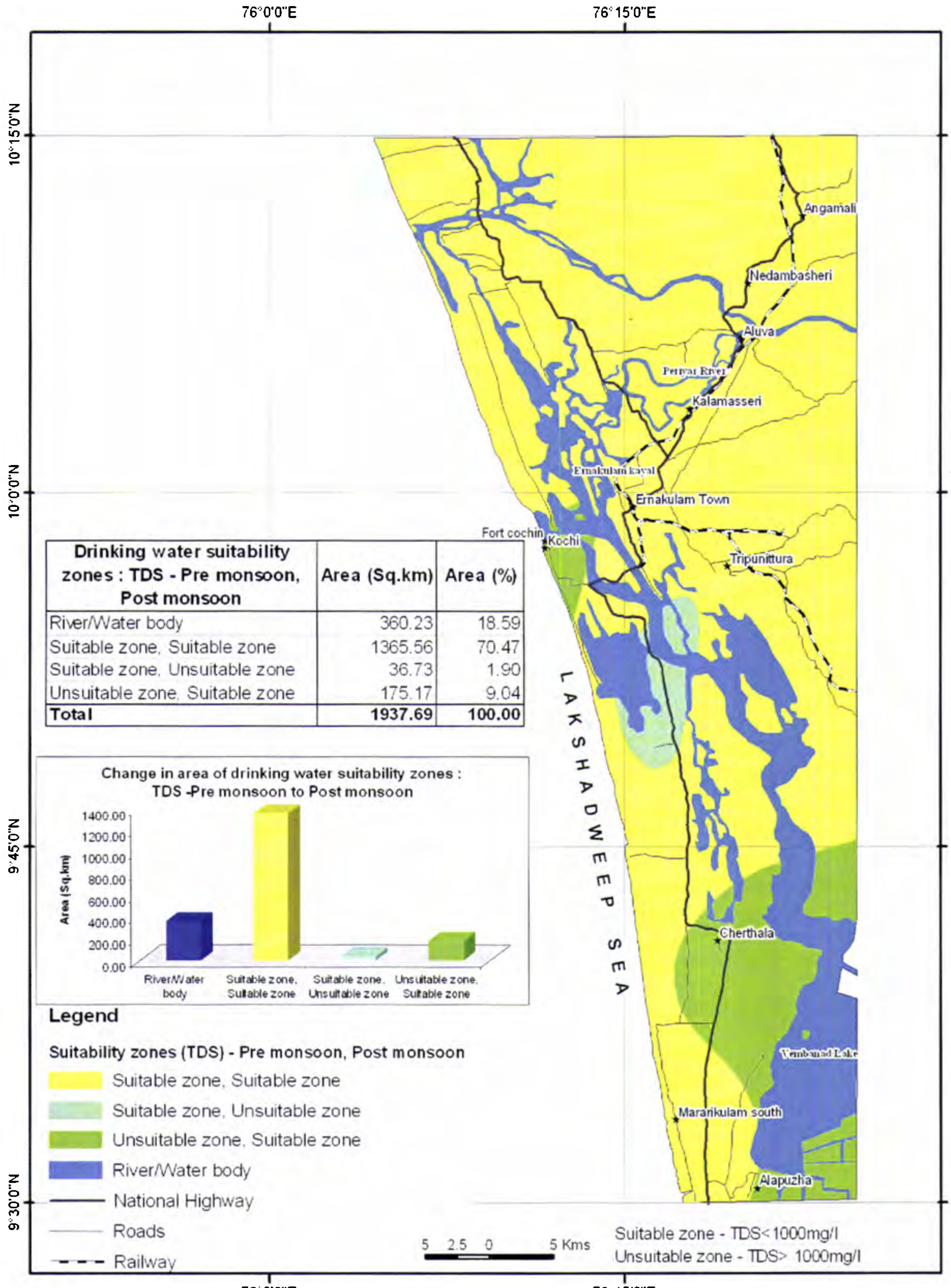
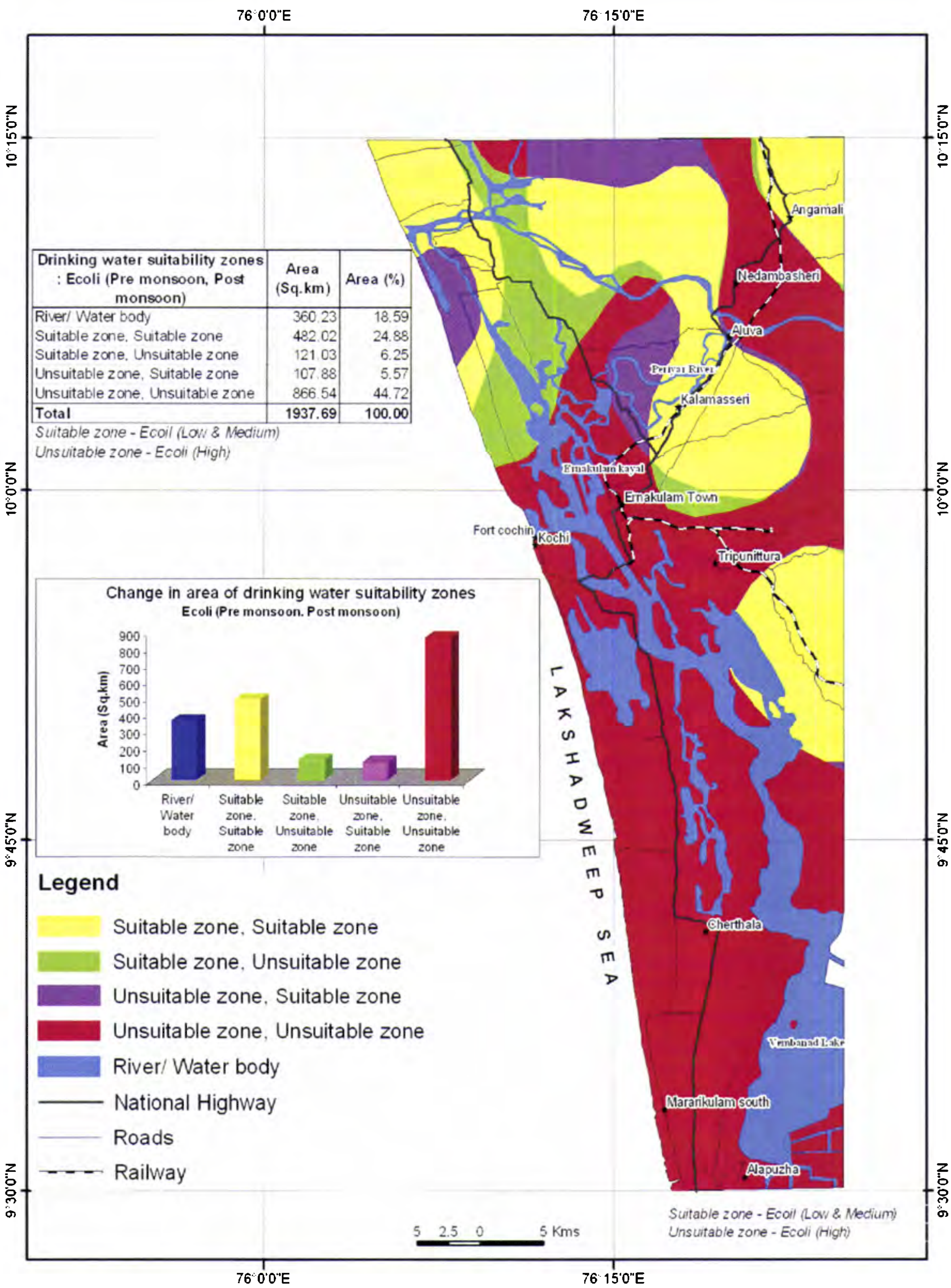



fig.6.7 CHANGE IN DRINKING WATER SUITABILITY ZONES -TDS (PRE MONSOON TO POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH




| Drinking water suitability zones : Ecoli (Pre monsoon, Post monsoon) | Area (Sq.km) | Area (%) |
|---|---|---|
| River/ Water body | 360.23 | 18.59 |
| Suitable zone, Suitable zone | 482.02 | 24.88 |
| Suitable zone, Unsuitable zone | 121.03 | 6.25 |
| Unsuitable zone, Suitable zone | 107.88 | 5.57 |
| Unsuitable zone, Unsuitable zone | 866.54 | 44.72 |
| **Total** | **1937.69** | **100.00** |

*Suitable zone - Ecoli (Low & Medium)*
*Unsuitable zone - Ecoli (High)*

fig.6.8 CHANGE IN DRINKING WATER SUITABILITY ZONES - ECOLI (PRE MONSOON TO POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH both the seasons, 6.25% changes from suitable to unsuitable and 5.57 changes from unsuitable to suitable zone.

The suitability range for chloride has been fixed below 250. 46.94% of the area falls in the suitablity range in both the seasons, 10.35% changes from suitable to unsuitable, 14.56% from unsuitable to suitable and 9.56% remains unsuitable in both the seasons .fig. 6.9.

In the case of Mg 80.89% remains in the suitablity zone below 150 mg in both the seasons whereas 0.51% changes from unsuitable to suitable range.fig 6.10.

The suitability map for Na is given in fig6.11.The suitability range has been fixed below 200. 51.13% falls in the suitability range in both the seasons, 9.56% changes from suitable to unsuitable, 14.14 %changes from unsuitable to suitable and 6.58 remain unsuitable in both the seasons.

$SO_4$ suitability map is given in fig.6.12. In this case the suitability range is fixed below 500 and 81.41% remains in the suitability range in both seasons.

In the case of Ca suitability map is shown in fig.6.13. 78.72 % remains in the suitable zone whereas 2.69% changes from unsuitable to suitable range.

An overlay operation of all the drinking water suitability maps resulted in the final water quality maps. Groundwater prospect using resistivity has been done for the whole of alluvium and only the lateritic

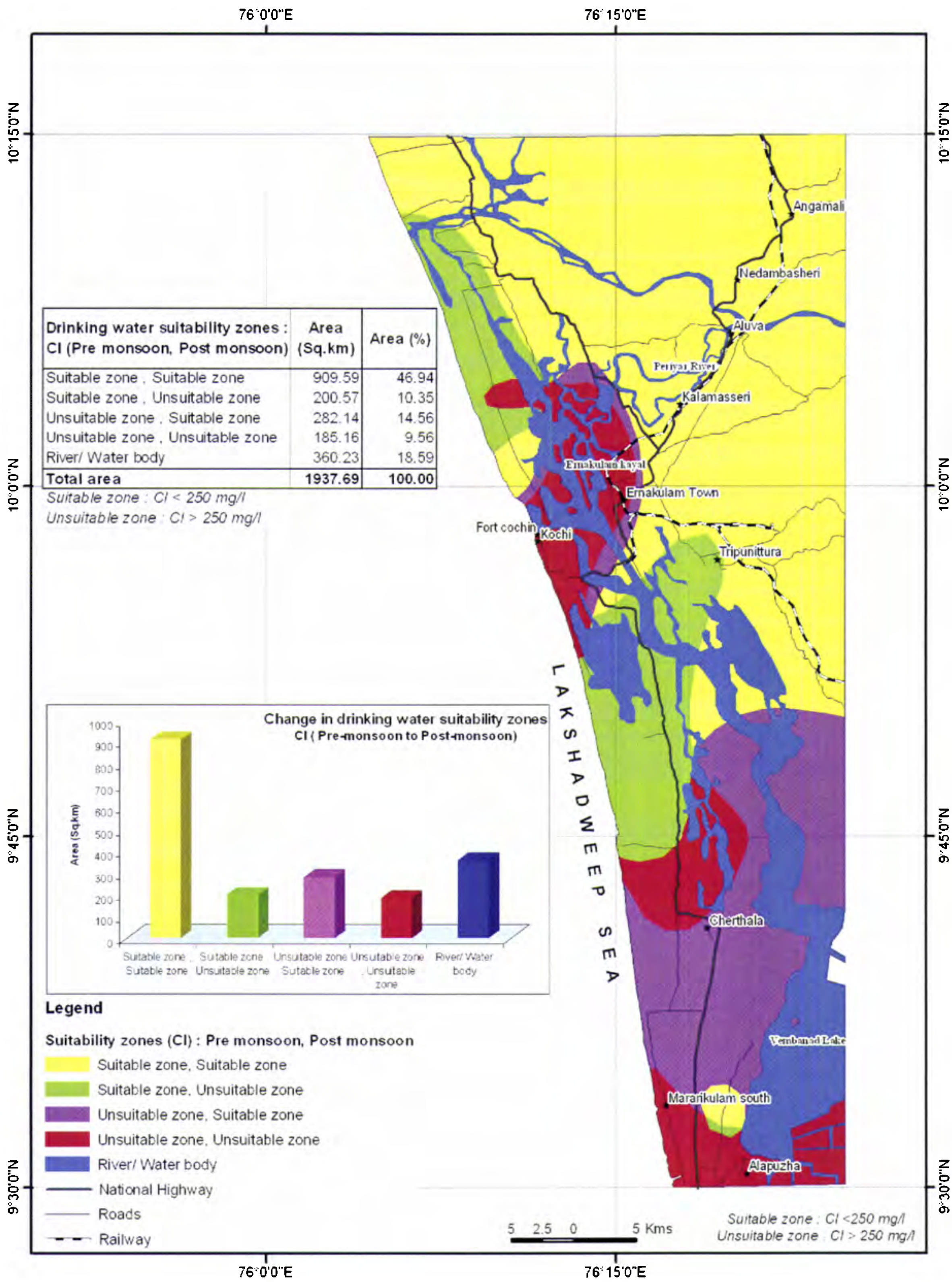



fig.6.9 CHANGE IN DRINKING WATER SUITABILITY ZONES - Cl (PRE MONSOON TO POST MONSOON - 2003) - ERNAKULAM - ALAPPUZHA STRETCH

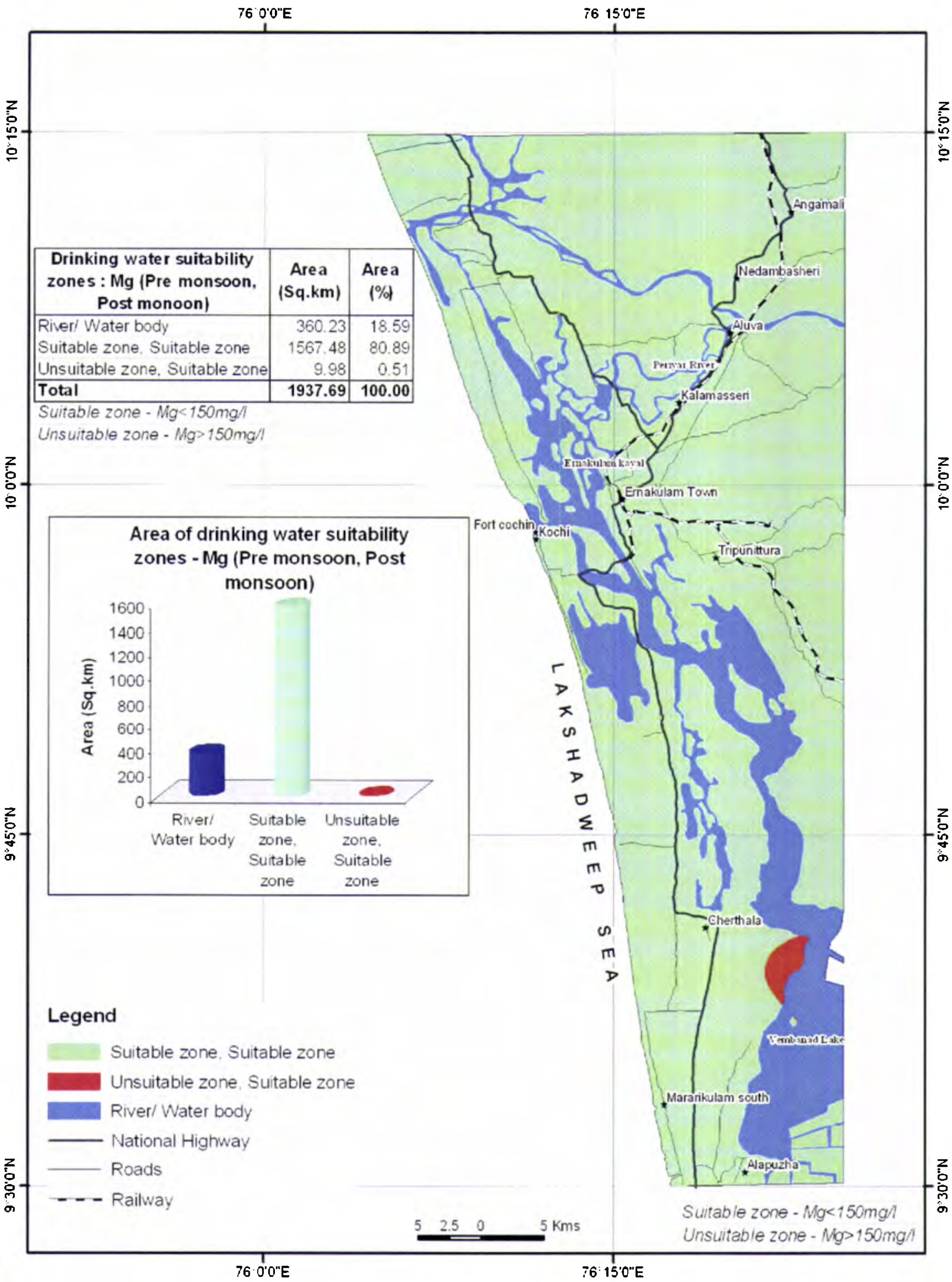



fig.6.10 CHANGE IN DRINKING WATER SUITABILITY ZONES - Mg (PRE MONSOON TO POST MONSOON) ERNAKULAM - ALAPPUZHA STRETCH

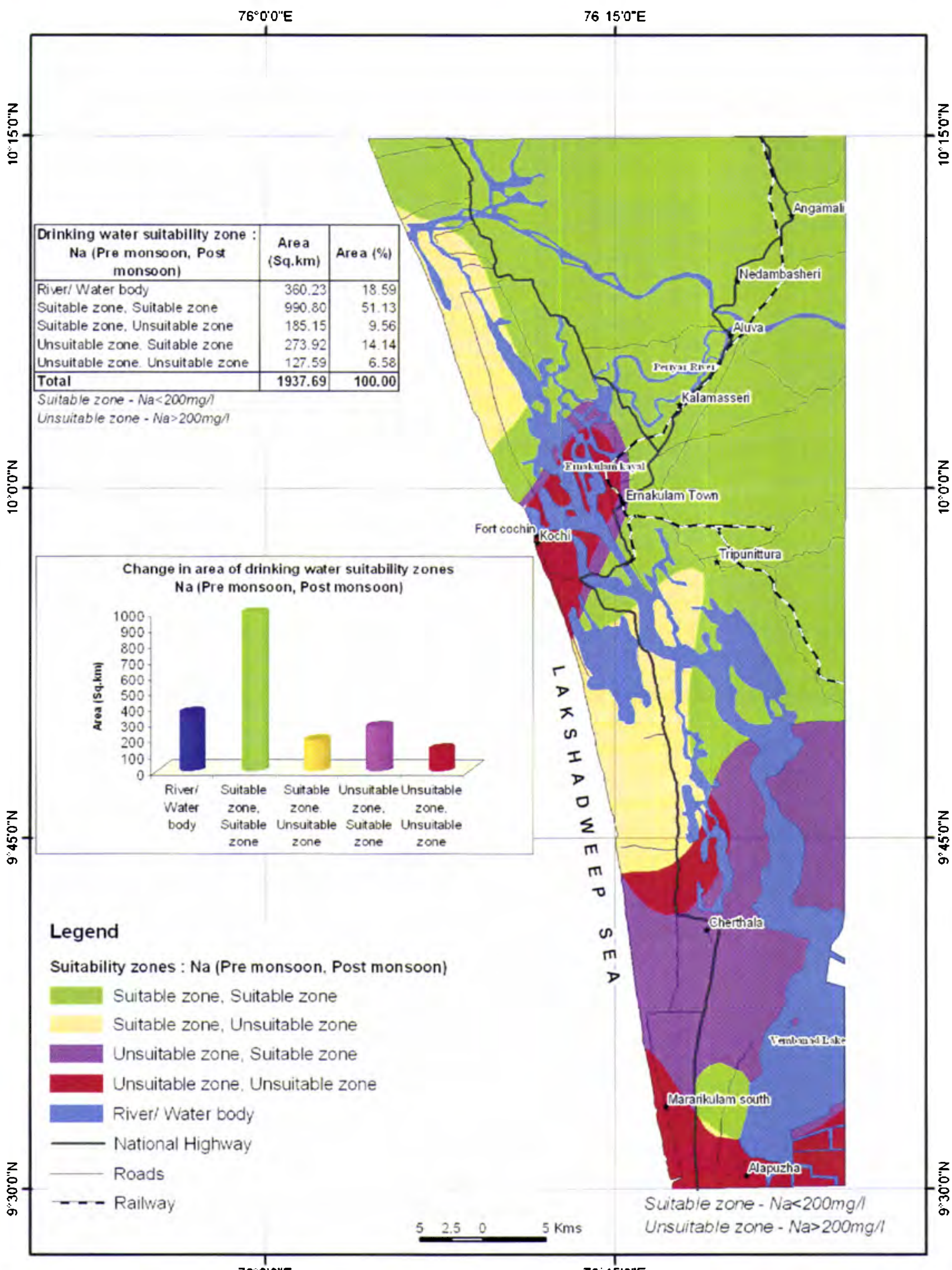
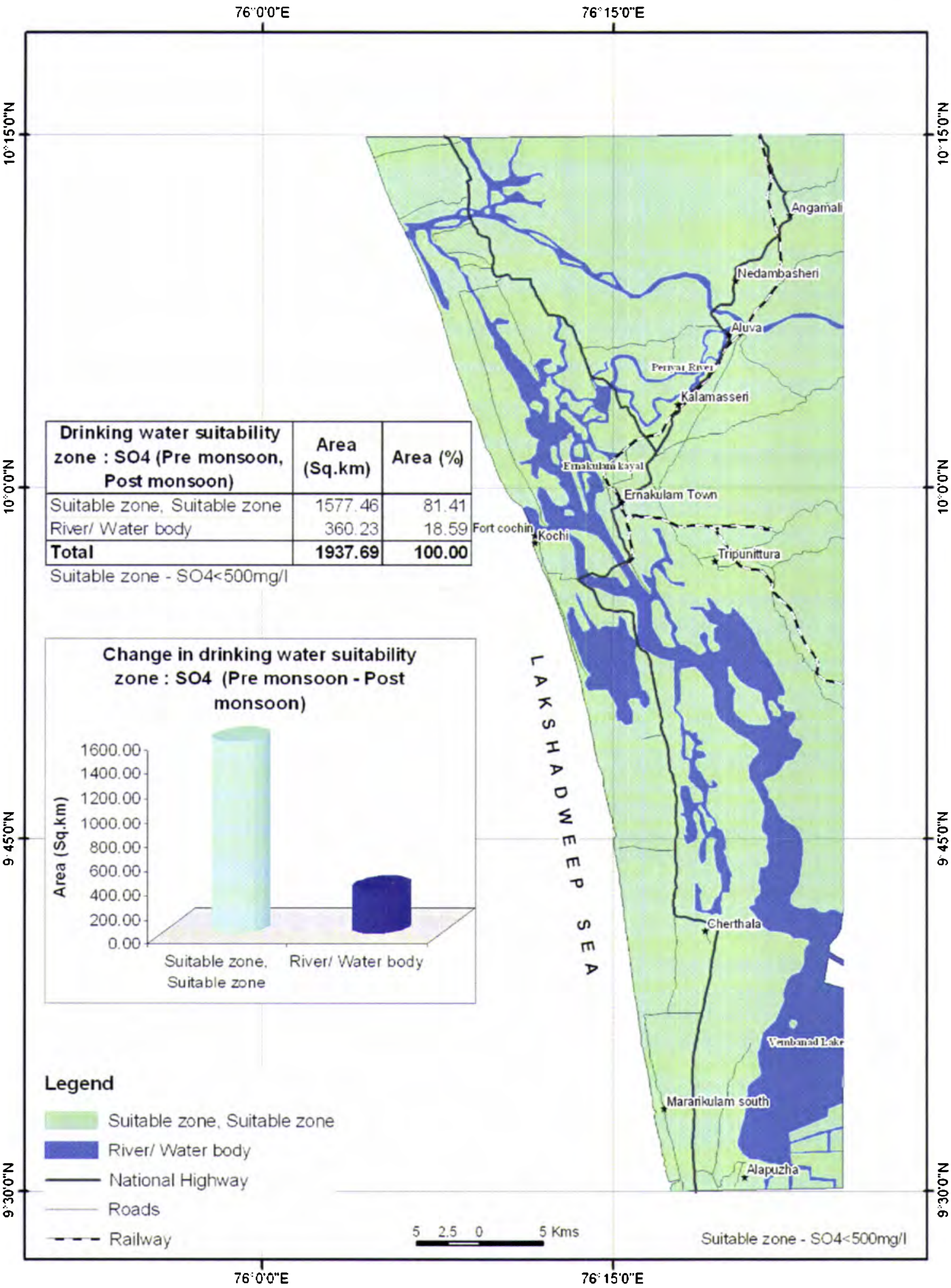


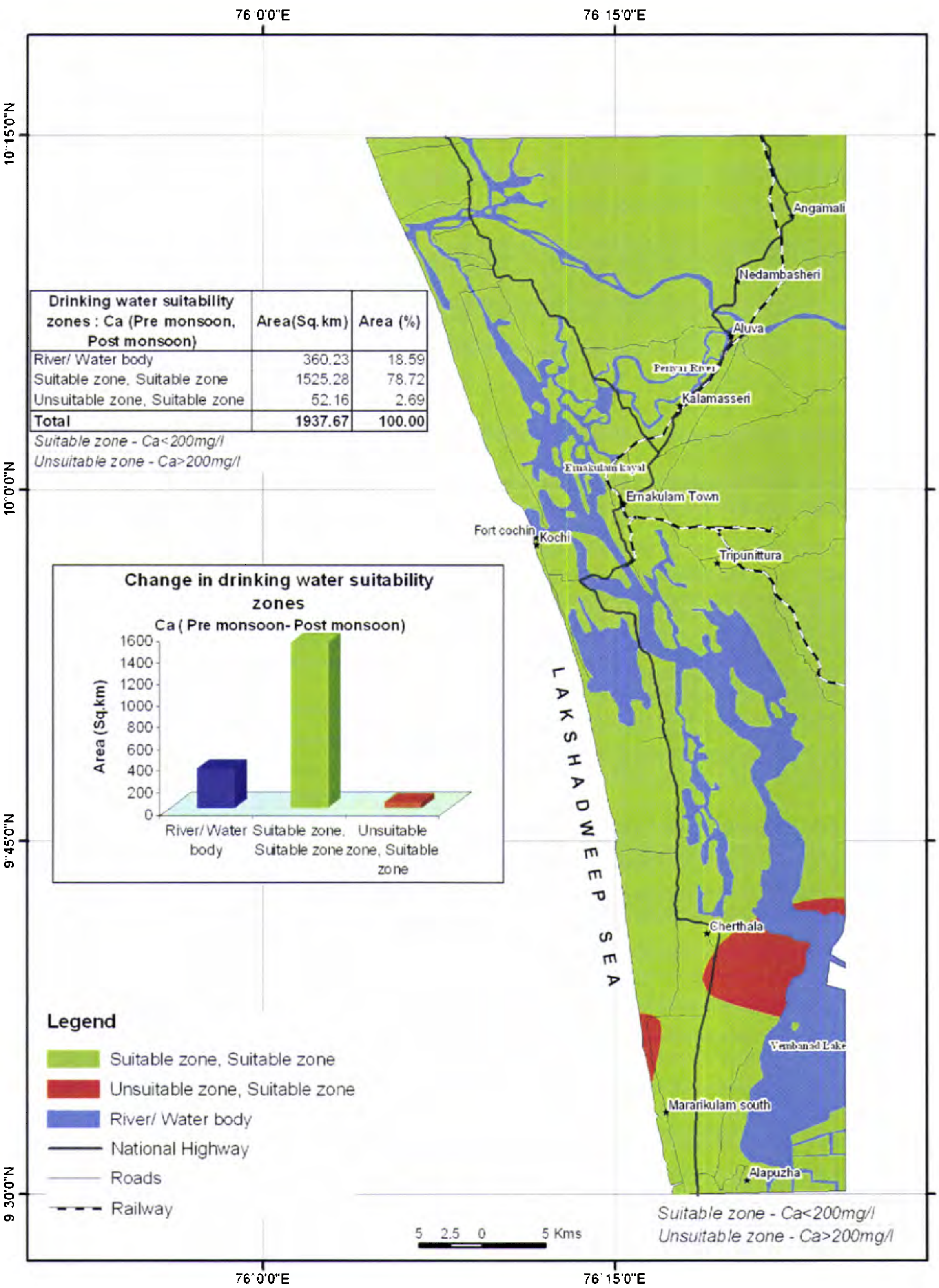

fig.6.11 CHANGE IN DRINKING WATER SUITABILITY ZONES - Na (PRE MONSOON TO POST MONSOON) ERNAKULAM - ALAPPUZHA STRETCH




| Drinking water suitability zone : SO4 (Pre monsoon, Post monsoon) | Area (Sq.km) | Area (%) |
|---|---|---|
| Suitable zone, Suitable zone | 1577.46 | 81.41 |
| River/ Water body | 360.23 | 18.59 |
| **Total** | **1937.69** | **100.00** |

Suitable zone - SO4<500mg/l

CHANGE IN DRINKING WATER SUITABILITY ZONES - SO4 (PRE MONSOON TO POST MONSOON) ERNAKULAM - ALAPPUZHA STRETCH




| Drinking water suitability zones : Ca (Pre monsoon, Post monsoon) | Area(Sq.km) | Area (%) |
|---|---|---|
| River/ Water body | 360.23 | 18.59 |
| Suitable zone, Suitable zone | 1525.28 | 78.72 |
| Unsuitable zone, Suitable zone | 52.16 | 2.69 |
| **Total** | **1937.67** | **100.00** |

*Suitable zone - Ca<200mg/l*
*Unsuitable zone - Ca>200mg/l*

fig.6.13 CHANGE IN DRINKING WATER SUITABILITY ZONES - Ca (PRE MONSOON TO POST MONSOON 2003) ERNAKULAM - ALAPPUZHA STRETCH terrain of the hard rock area for want of authentic references. Hence the chemical overlay maps also have been prepared seperately for alluvium and the lateritic terrain. The maps are shown in figs.6.14 (alluvium) and fig.6.15 (laterite). From the maps, the conclusion drawn in the geochemistry chapter that the groundwater quality in general in the coastal belt is inferior to that of the hard rock terrain is again reiterated. Whereas only 0.85% (7.66 sq.km) of the alluvium falls in the 'good' zone, 13.41%(17.02 sq.km) of the lateritic terrain falls in the 'good' zone. 83.71% (106.27 sq.km) of the lateritic terrain falls in the 'moderate' zone. In the alluvium 99.15% (894.46) falls in the 'moderate/poor' zone.

### 6.2.4. Saline Water Buffer Zones

One km buffer zone is prepared around the well sample point location having salinity. Fig 6.16. The saline water buffer zones are overlain on the drinking water suitability zone. It has been found that none of the buffer zones fall within the high drinking water suitability zone.

### 6.2.5. Deciphering groundwater prospect Zones using resistivity and aquifer thickness.

GIS has been utilized by researchers around the globe to integrate Hydrogeological data to arrive at the groundwater potential of an area. Different parameters like lineament density, slope, and land use pattern, geophysical data etc have been utilized during such studies.

The present study makes a comparison of all aspects of coastal alluvium and the crystalline terrain. In the crystalline terrain laterite

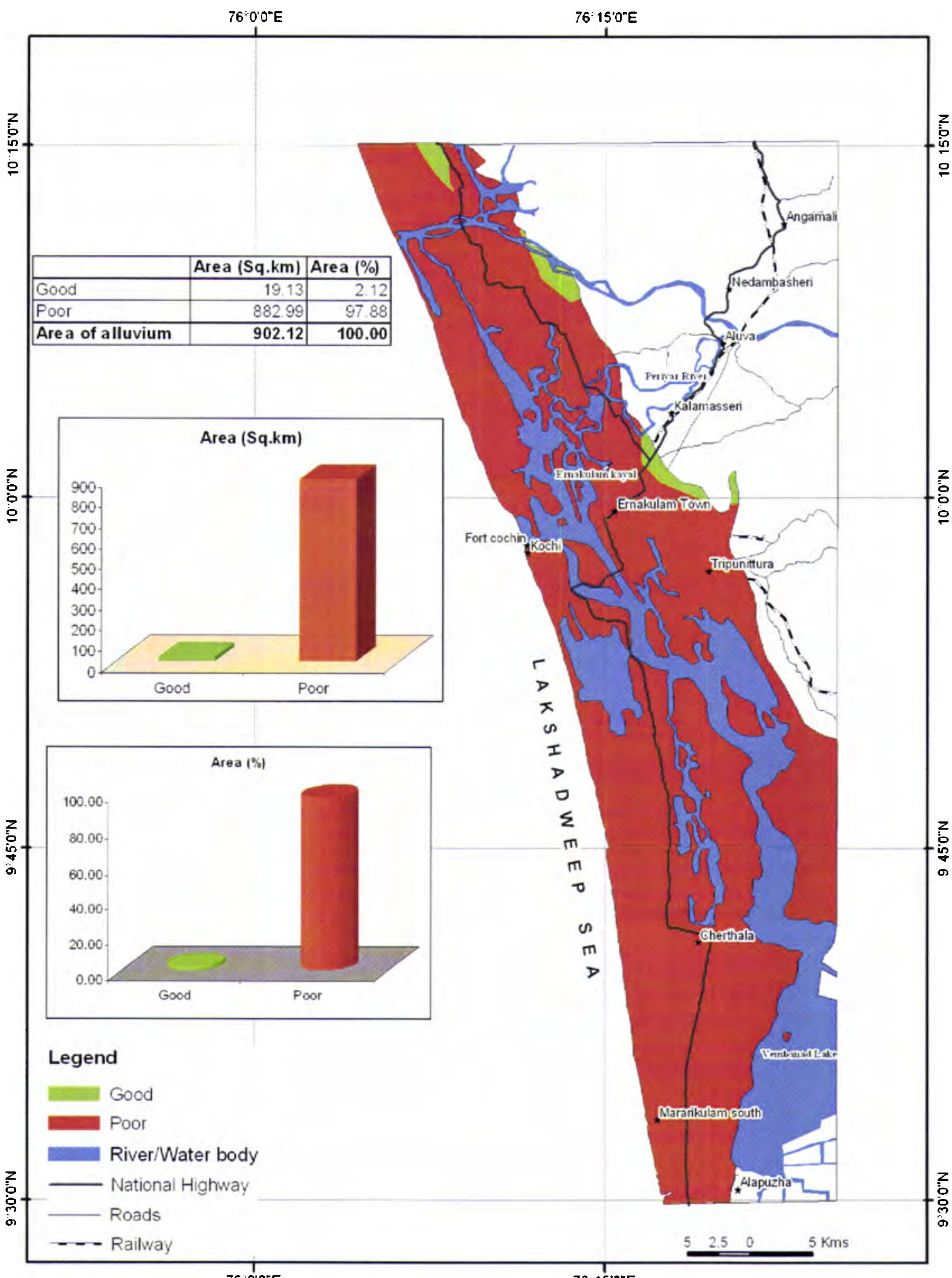



fig.6.14 SPATIAL OVERLAY OF DRINKING WATER QUALITY ZONES- ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH

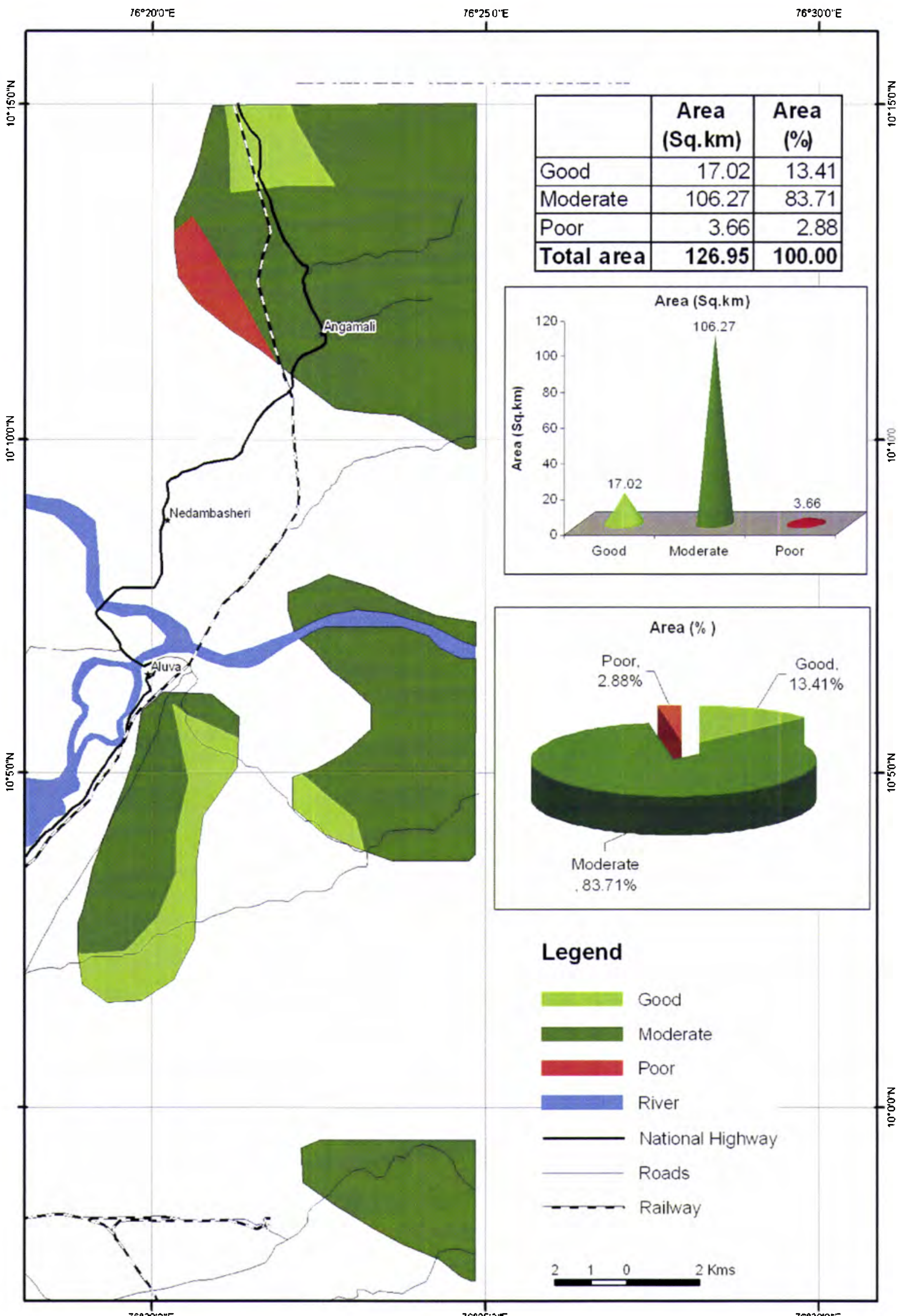



fig.6.15 SPATIAL OVERLAY OF DRINKING WATER QUALITY ZONES - LATERITE (2006)
[illegible]

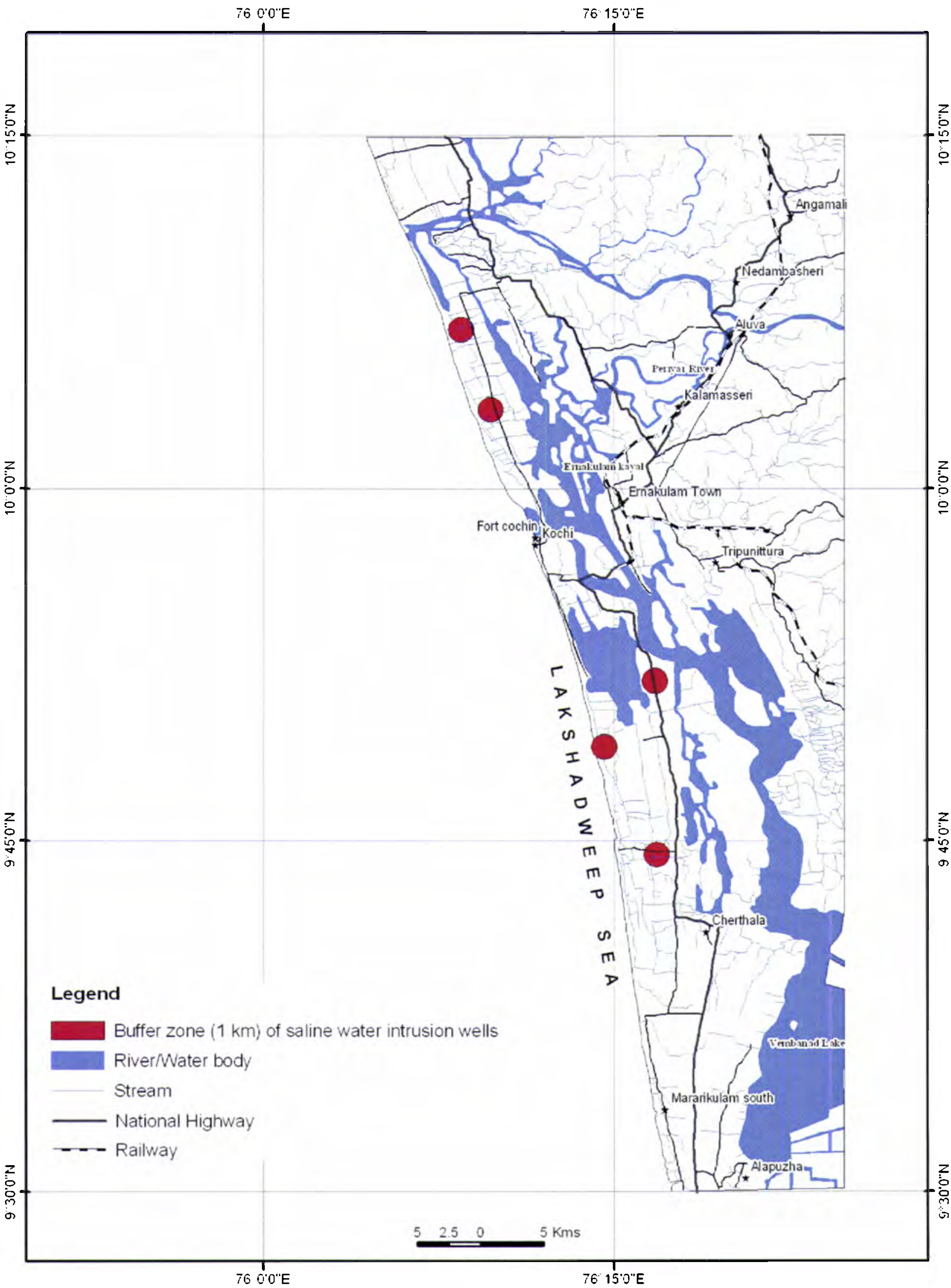


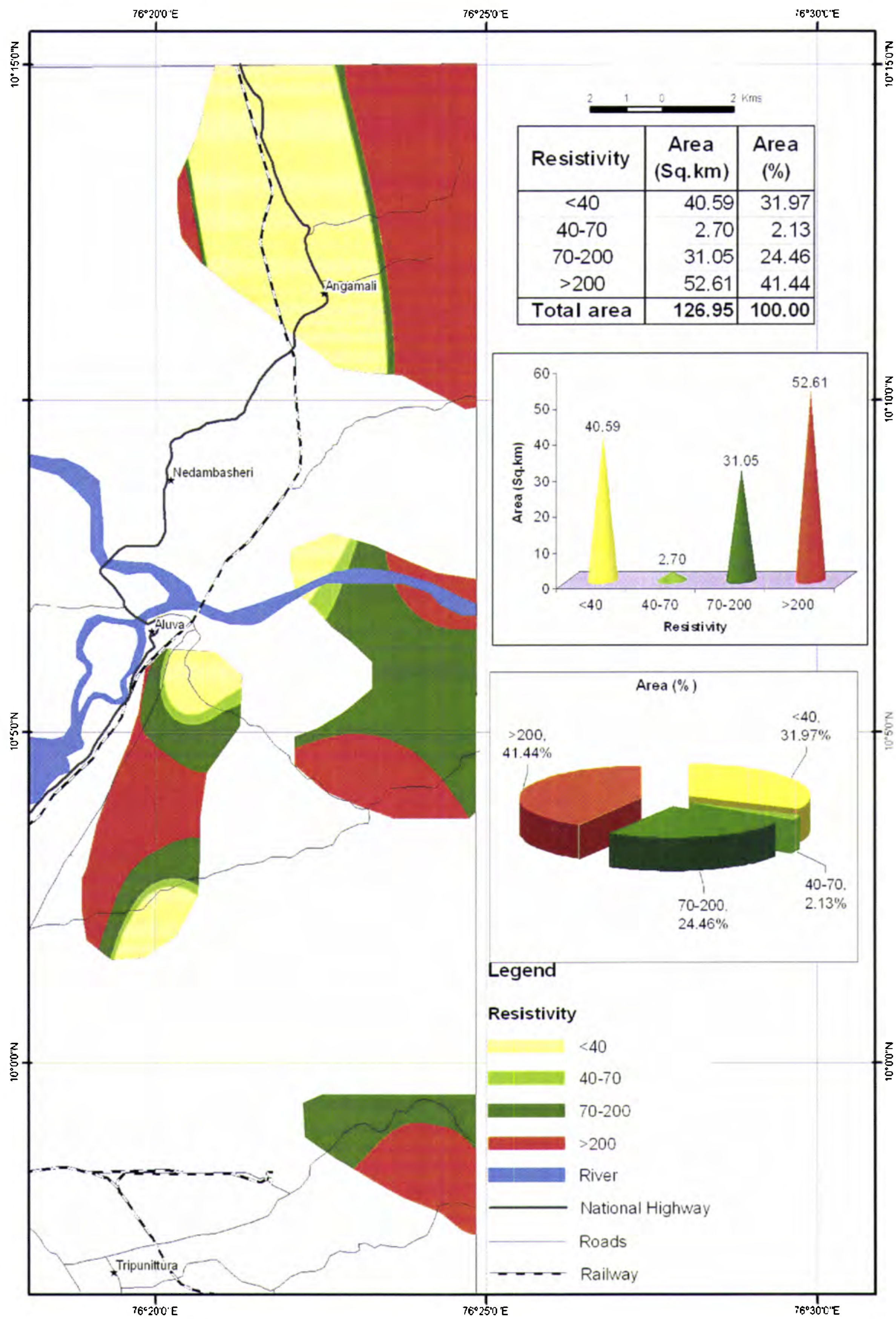

FIG 6.16
FIG DRAINAGE WITH SALINE BUFFER ZONE (2003) ERNAKULAM - ALAPPUZHA STRETCH

outcrops are a significant feature. Hence GIS has been used to integrate aquifer thickness and resistivity to delineate groundwater prospect zones only in the alluvium and laterite terrains of the study area. The method followed by Shamsuddin and Sankar (2003) in their study in Midnapur District, West Bengal has been applied to integrate geophysical data with geology to bring out groundwater prospect zones. The success of a particular strategy can be tested using a time series analysis for any given area (Baban 1997; 2000). Geophysical data greatly help in locating the ground water potential in any Hydrogeological setup. The property and thickness of various litho-units obtained from geophysical survey at different location if integrated can yield a ground water potential model of higher reliability and precision. Shamsuddin and Shankar (2004). Venkateswara and Briz-Kishore (1991) proposed a method for the interpretation of geophysical data and estimation of ground water potential index (GWPI) at various survey locations. Edet and Okereke (1997) used a similar approach for Oban massif, Nigeria and calculated the ground water potential. In both the cases they used VES data for the estimation of layer parameters, namely, aquifer resistivity and thickness at different points. They assigned weights to different layer parameters and ratings to the features of the parameters according to the performance of the existing water wells in the vicinity and estimated the GWPI of the survey points. As the GWPI obtained in this process is derived from the physical properties of the subsurface layers, they showed that it gives an accurate measurement of ground water potential. In the present investigation, for the estimation of hydrogeological condition, data obtained from VES surveys are interpreted for the estimation of the subsurface parameters viz. electrical resistivity of the aquifer and aquifer thickness. These parameters at different survey points are contoured using Kriging method (deMarsily, 1986) and the corresponding thematic maps are prepared. The resistivity and thickness of aquifer media are directly related to transmissivity and hydraulic conductivity of the aquifer. Therefore, integration of these two data can give the groundwater potential of an area. However, different types of lithology with different resistivity ranges have different groundwater prospect. Therefore, different range of values or features should have a different score in a scale according to its importance in accumulating groundwater. An overlay operation would then evaluate the intersected regions by a sum of the scores, so that each resulting region is characterized by a score measuring its potential. The detailed methodology, flow chart and the scores assigned were described in the chapter Methodology.

#### 6.2.5.1. Analysis of Thematic Maps

**Aquifer Resistivity – Laterite**

The Aquifer resistivity map of the lateritic terrain is given in the Fig.6.17 In the aquifer resistivity zone for the laterite terrain of the study area 31% falls in the zone of aquifer resistivity below 40Ωm, 2.13% between 40-70Ωm, 24.45% between 70-200Ωm and 41.44 %above 200Ωm. The aquifer thickness map of the laterite terrain (fig.6.12.) shows that 44.03% falls below 25m, 45.18 %between 25-75m and 10.78 % above 75m.




| Resistivity | Area (Sq.km) | Area (%) |
|---|---|---|
| <40 | 40.59 | 31.97 |
| 40-70 | 2.70 | 2.13 |
| 70-200 | 31.05 | 24.46 |
| >200 | 52.61 | 41.44 |
| Total area | 126.95 | 100.00 |

fig.6.17 AQUIFER RESISTIVITY - LATERITE(2003) ERNAKULAM - ALAPPUZHA STRETCH

**Aquifer Resistivity – Alluvium (Shallow Aquifers)**

Fig.6.18 shows the aquifer resistivity zone for the alluvium. Here it is seen that 45% shows a resistivity value below 35Ωm, 18%between 36-55Ωm, 7 15 %between 56-75Ωm, 4.45 %between 76-90Ωm and 24.46% above 90Ωm. The geochemical data is again validated with resistivity and it is seen that all the saline water buffer zones created using geochemical data fall in the range below 35Ωm. This is clear from the overlay map of aquifer resistivity and saline water buffer zones.

**Aquifer thickness- Laterite**

The Aquifer thickness map of the lateritic terrain is given in the Fig.6.19.In the laterite terrain 44.03 (55.9 sq.km) has a thickness below 25m, 45.18 (57.36 sq.km) between 25m and 75m and 10.78 (13.69 sq.km) of the lateritic terrain has an aquifer thickness above 75m.

**Aquifer Thickness – Shallow aquifers – Alluvium**

Fig-6.20 shows the thickness zone of shallow aquifers of the alluvium. In the shallow aquifers of the alluvium 49.44 % of the area has a thickness between 2.5 m and 5 m, 14.09 % greater than 5m and 36.46 % below 2.5 m.

**6.2.5.1.a. RT Map - analysis**

As discussed earlier overlay operation of the thematic maps of aquifer resistivity and aquifer thickness results in groundwater prospect zones. RT maps (Resistivity Thickness Map) have been used by many

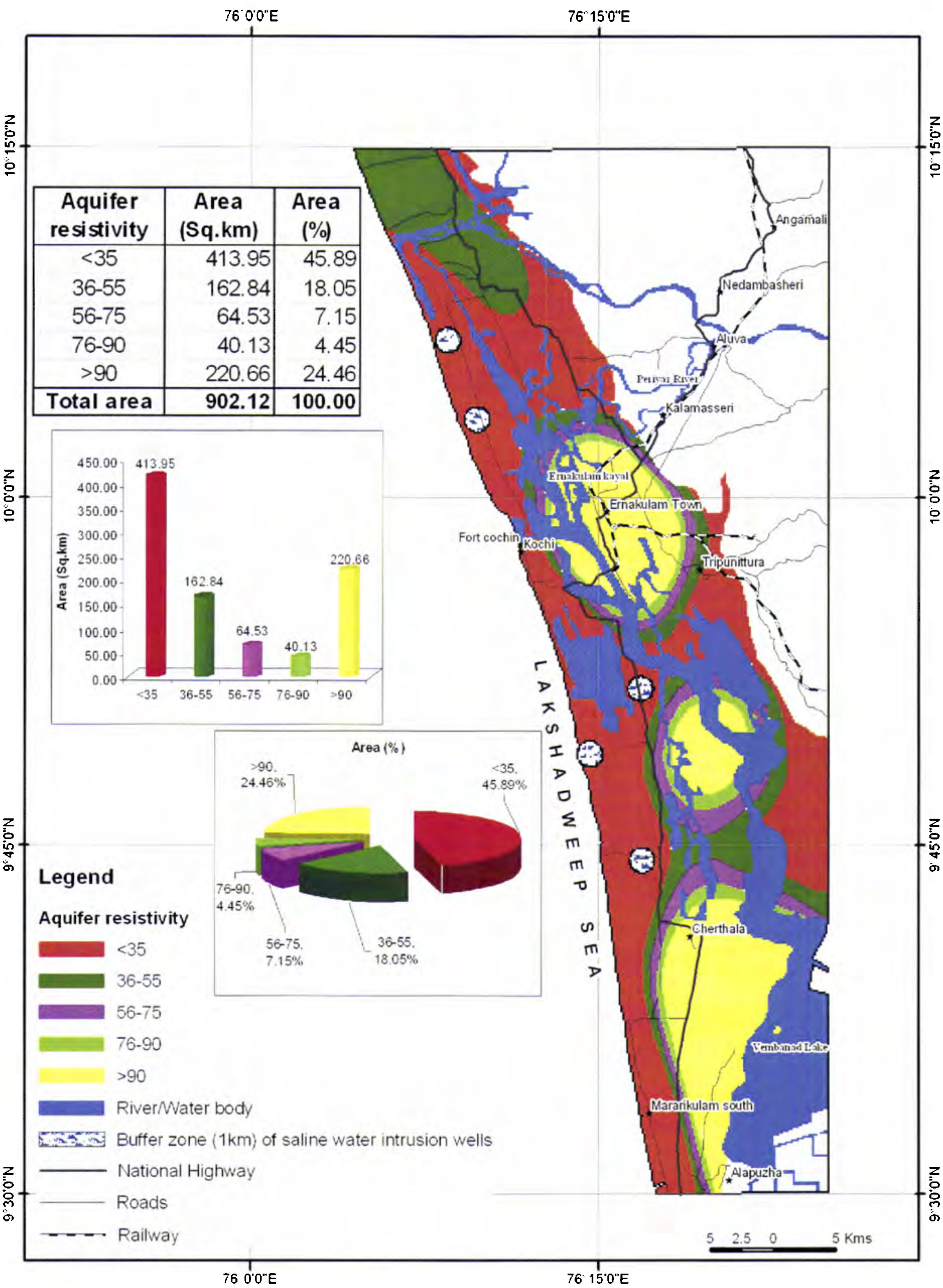



fig.6.18 RESISTIVITY OF SHALLOW AQUIFERS- ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH

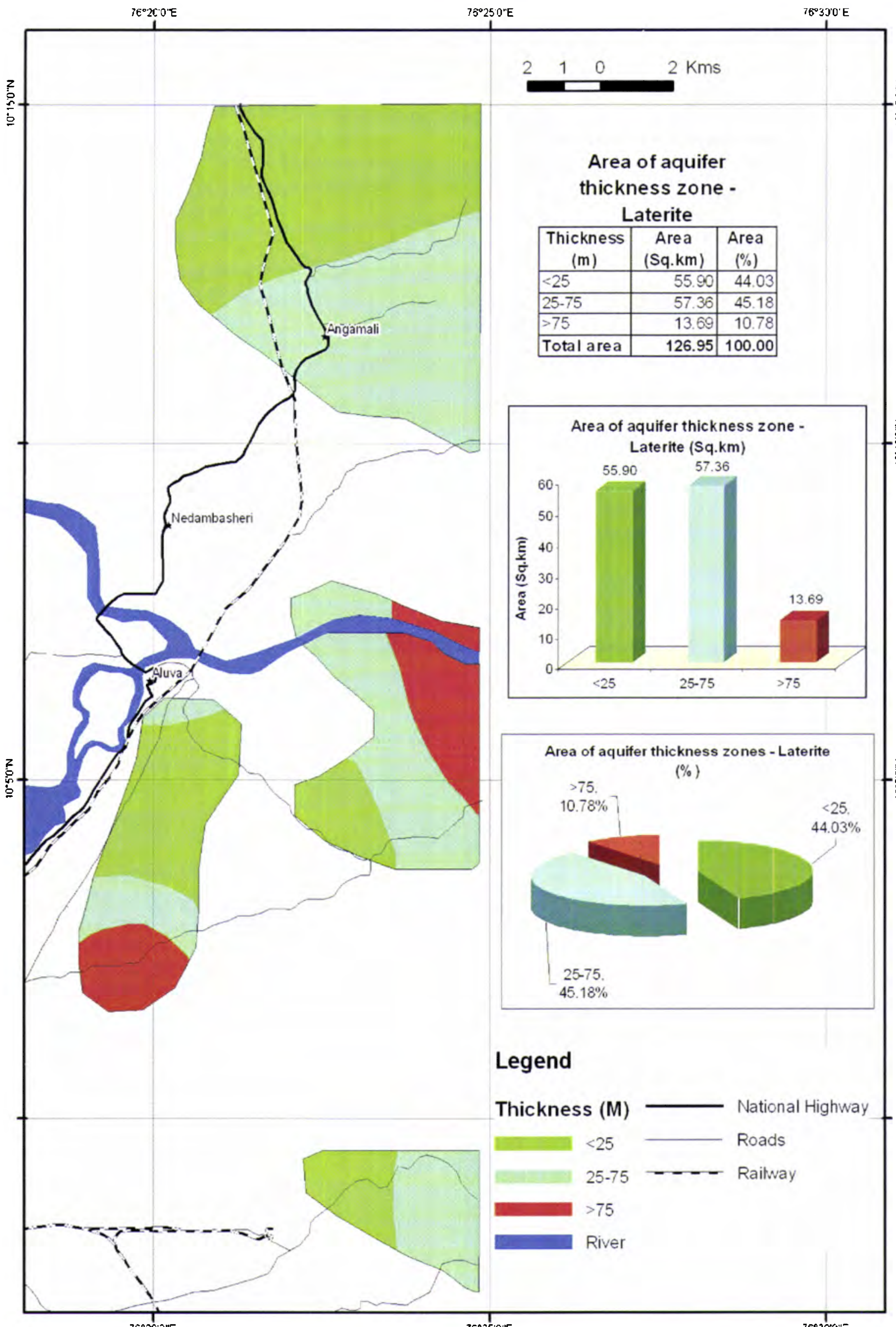



fig.6.19 AQUIFER THICKNESS - LATERITE ERNAKULAM - ALAPPUZHA STRETCH

| Aquifer thickness (m) | Area (Sq.km) | Area (%) |
|---|---|---|
| <2.5 | 329.01 | 36.46 |
| 2.5-5.0 | 446.13 | 49.44 |
| >5.0 | 127.15 | 14.09 |
| **Total** | **902.29** | **100.00** |

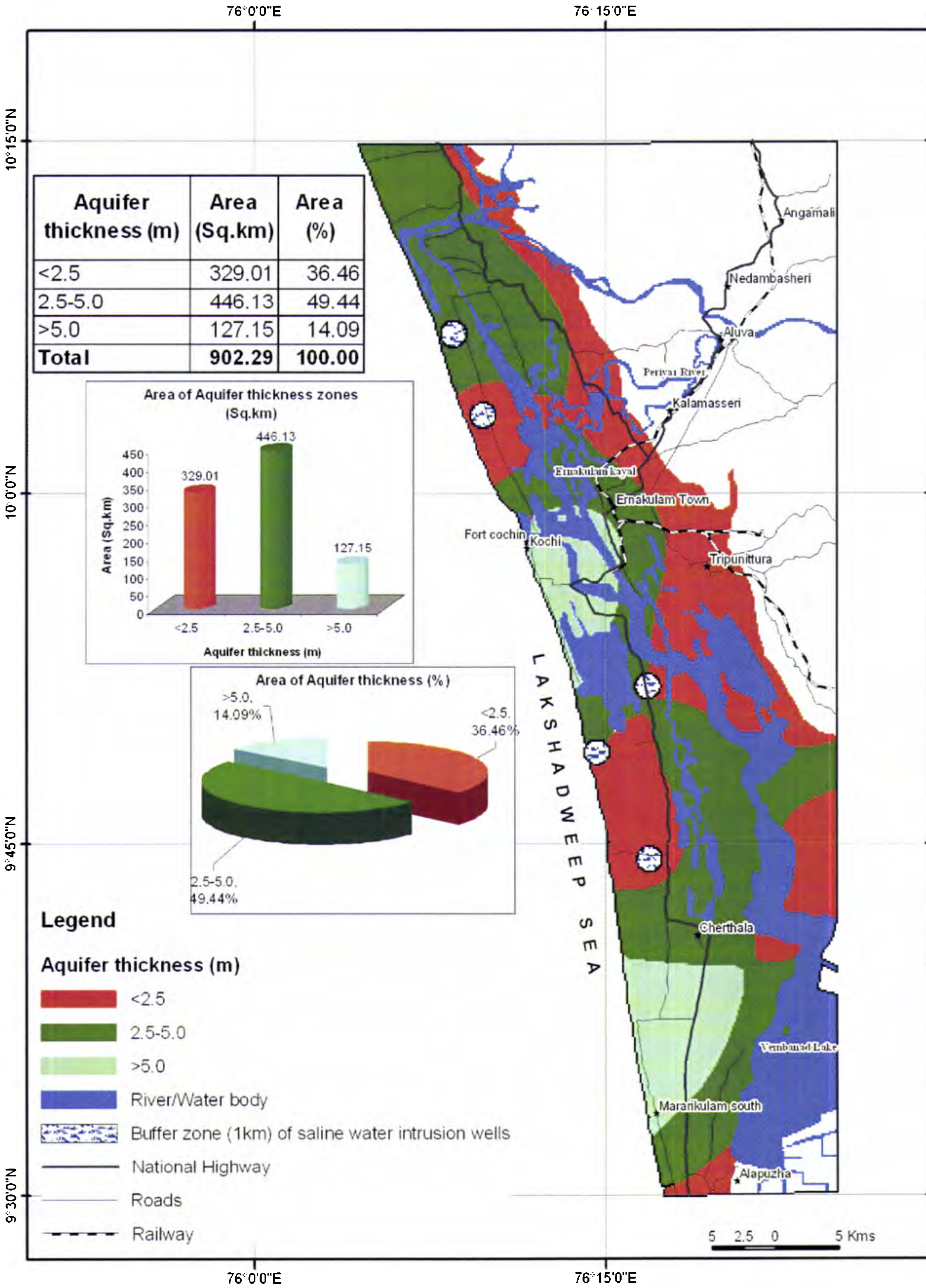



fig.6.20 THICKNESS OF SHALLOW AQUIFERS - ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH

scientists in deciphering the potential of aquifers, Lashkaripour (2005). Fig. 6.21 shows the groundwater prospect map of the alluvium and fig6.22 represents the groundwater prospect zone of the lateritic terrain of the study area.

Examination of the groundwater prospect map for the lateritic terrain prepared on the basis of criteria explained above for resistivity and aquifer thickness, reveals that 0.31 % (0.39 sq.km) falls in the very good zone, 82.13 % (104.24 sq.km) in the moderate zone and 17.57 % (22.3 sq.km) in the poor zone. In the case of alluvium the groundwater prospect map shows that 6.31 % (56 sq.km) of the area falls in the good zone, 65.6 % (591.94 sq.km) in the moderate zone and 28.08 % (253.39 sq.km) in the poor zone.

### 6.2.6. Delineation of potable water zones integrating water quality data with the potential groundwater zones.

Thematic maps of drinking water suitability zones, of each element was overlain on the groundwater prospect map for alluvium and laterite to delineate probable potable prospect zones, where the groundwater prospect as per resistivity and aquifer thickness are good and also where all the chemical parameters are within recommended limits. (Fig.6.23a to 6.23t shows the overlay of individual element on the groundwater prospect map).

An overlay operation of the drinking water suitability map with the prospect maps results in the final maps for both the alluvium and laterite

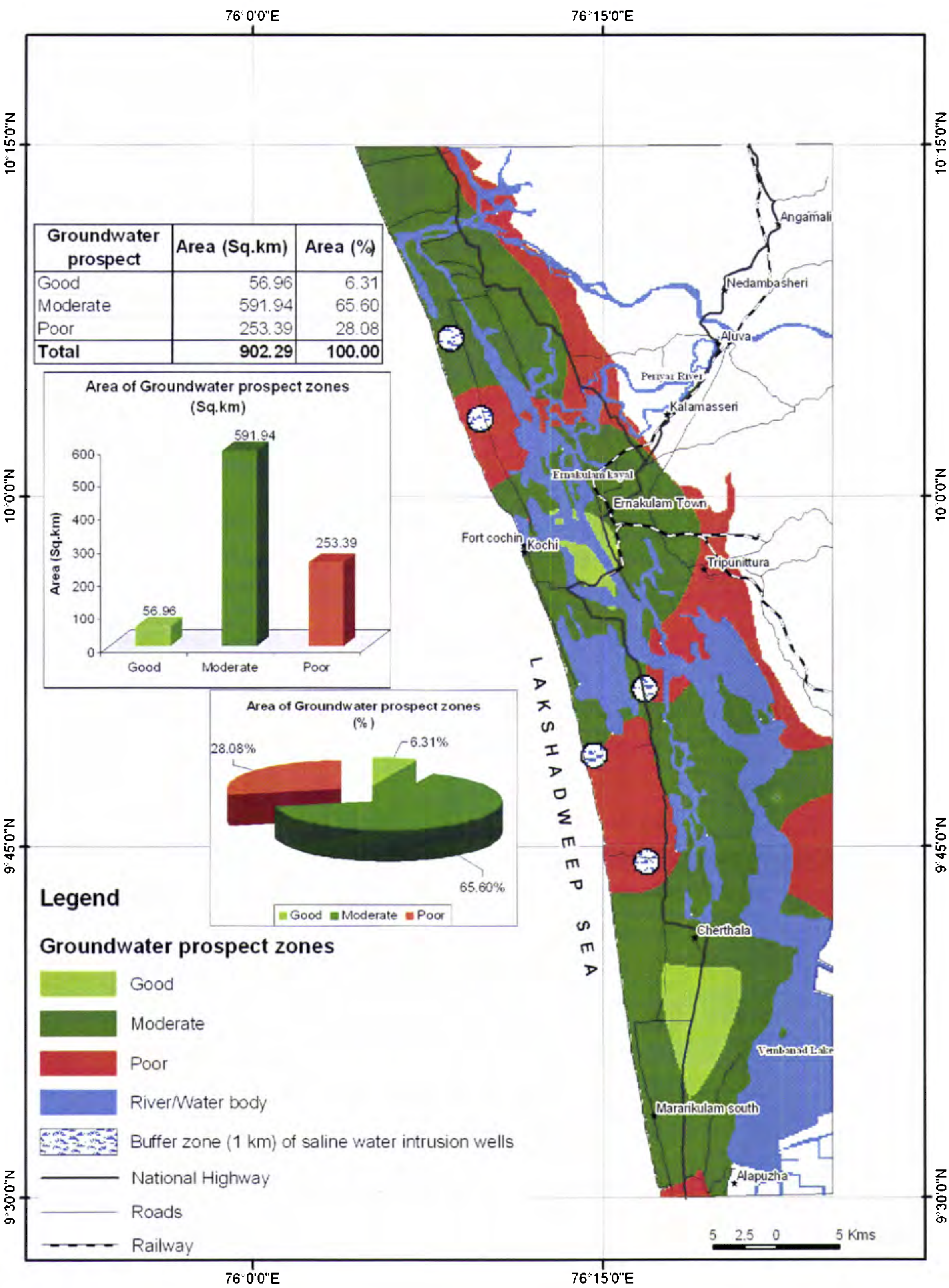



fig.6.21 GROUNDWATER PROSPECT ZONES OF SHALLOW AQUIFERS - ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH

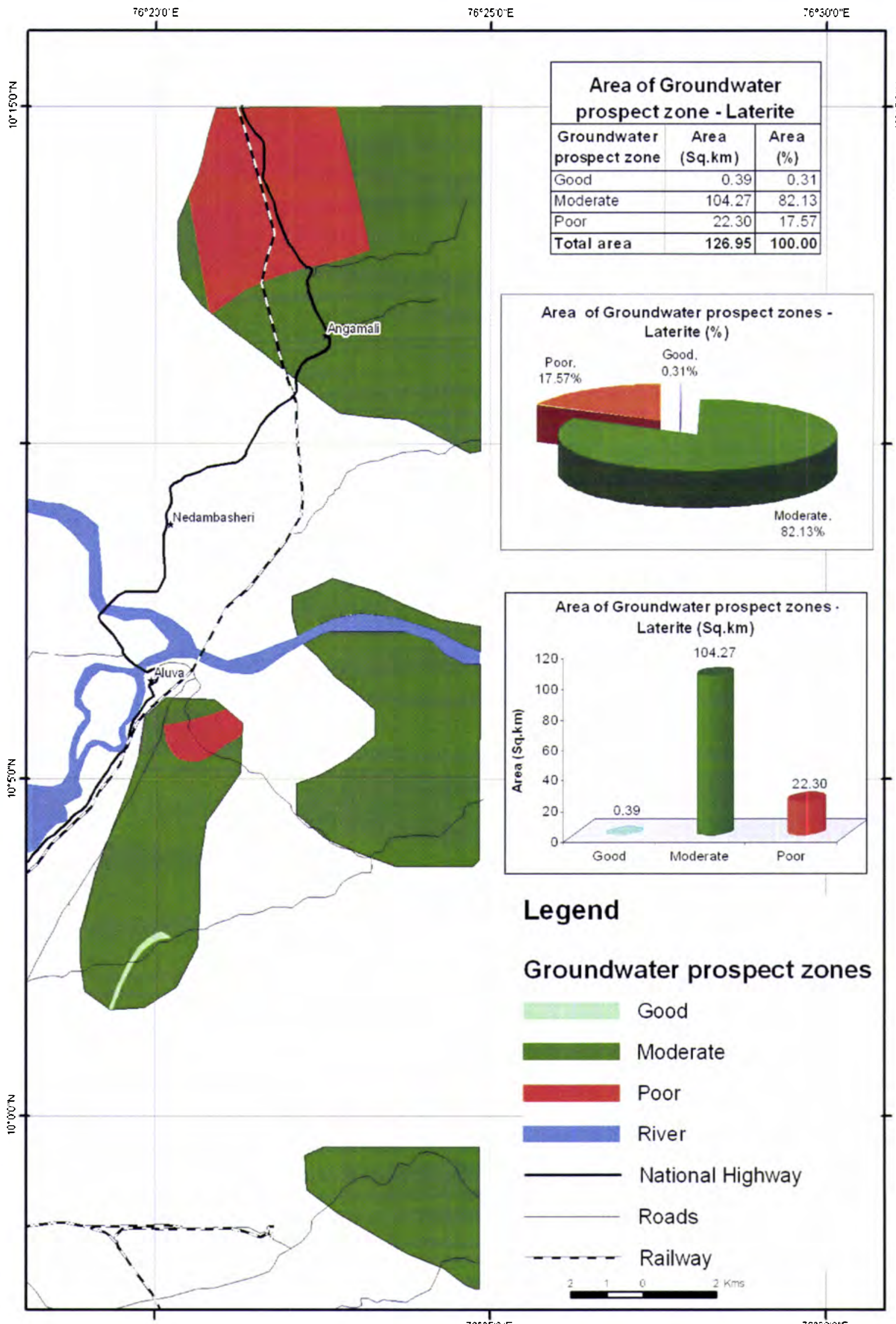



Fig.6.22 GROUNDWATER PROSPECT ZONES LATERITE(2003) ERNAKULAM ALAPPUZHA STRETCH

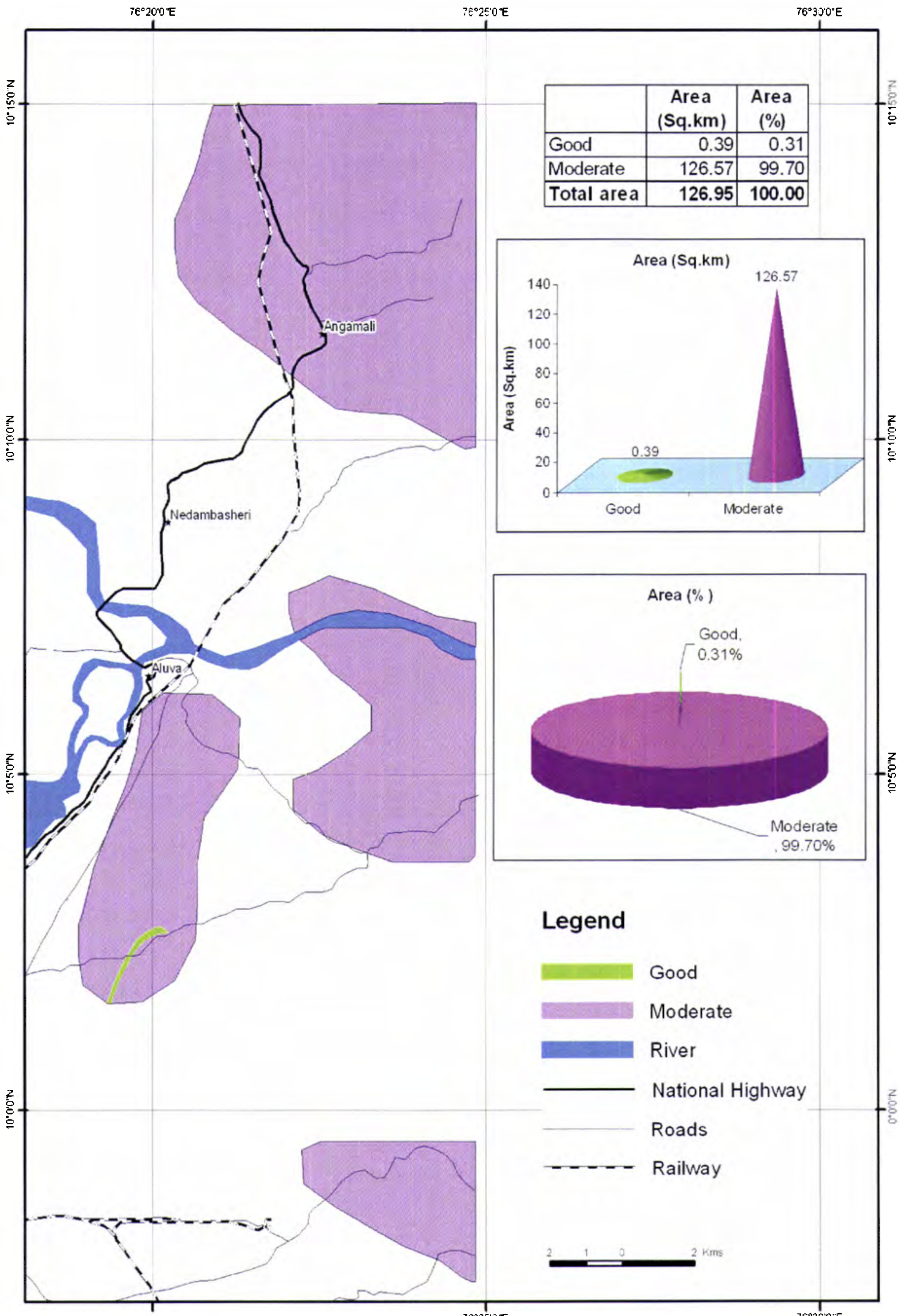



fig.6.23a SPATIAL OVERLAY OF GROUNDWATER PROSPECT AND DRINKING WATER SUITABLE ZONES (TDS) - LATERITE(2003)
ERNAKULAM - ALAPPUZHA STRETCH

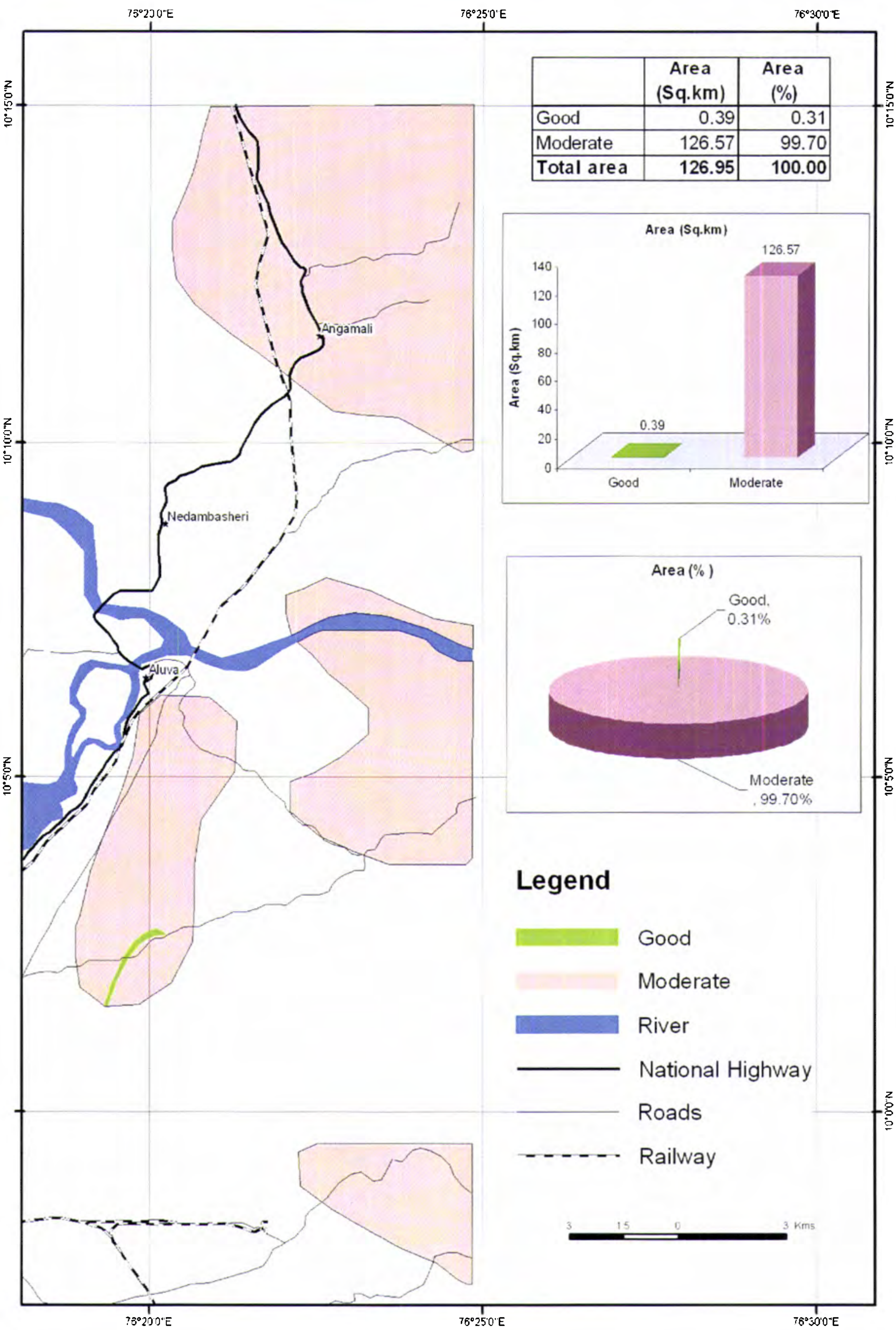
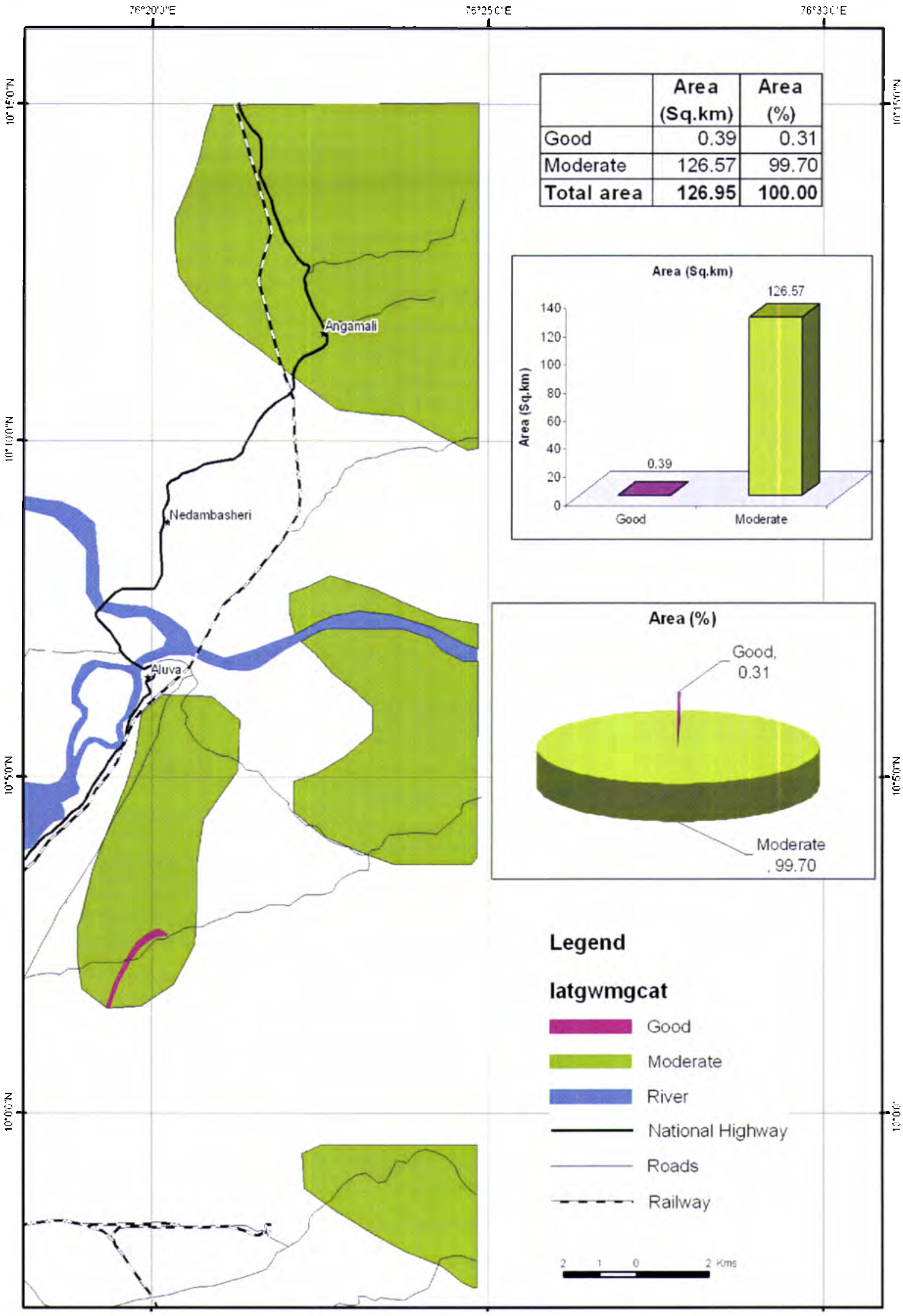
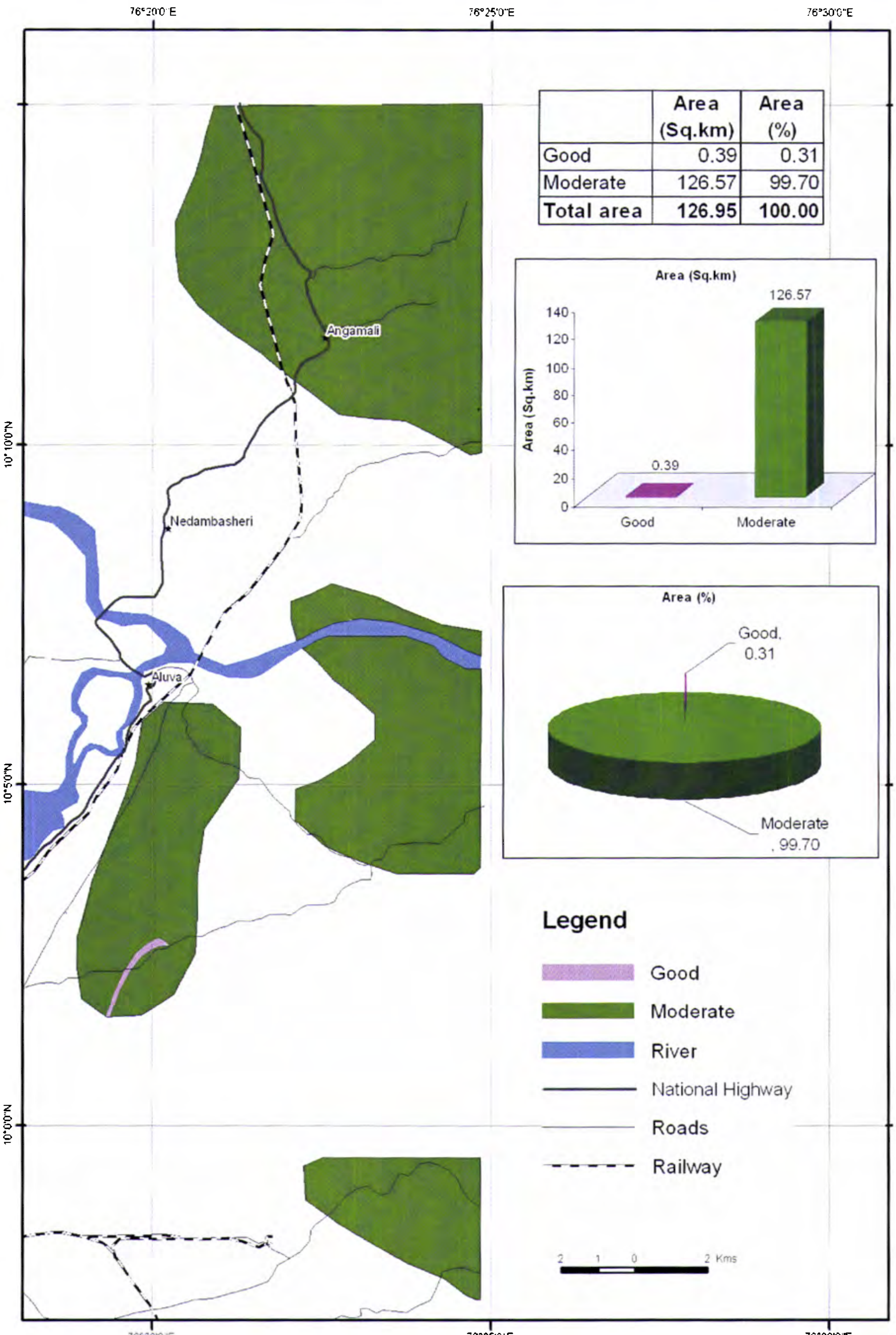



fig.6.23b SPATIAL OVERLAY OF GROUNDWATER PROSPECT AND DRINKING WATER SUITABLE ZONES (Ca) - LATERITE(2003)
ERNAKULAM - ALAPPUZHA STRETCH



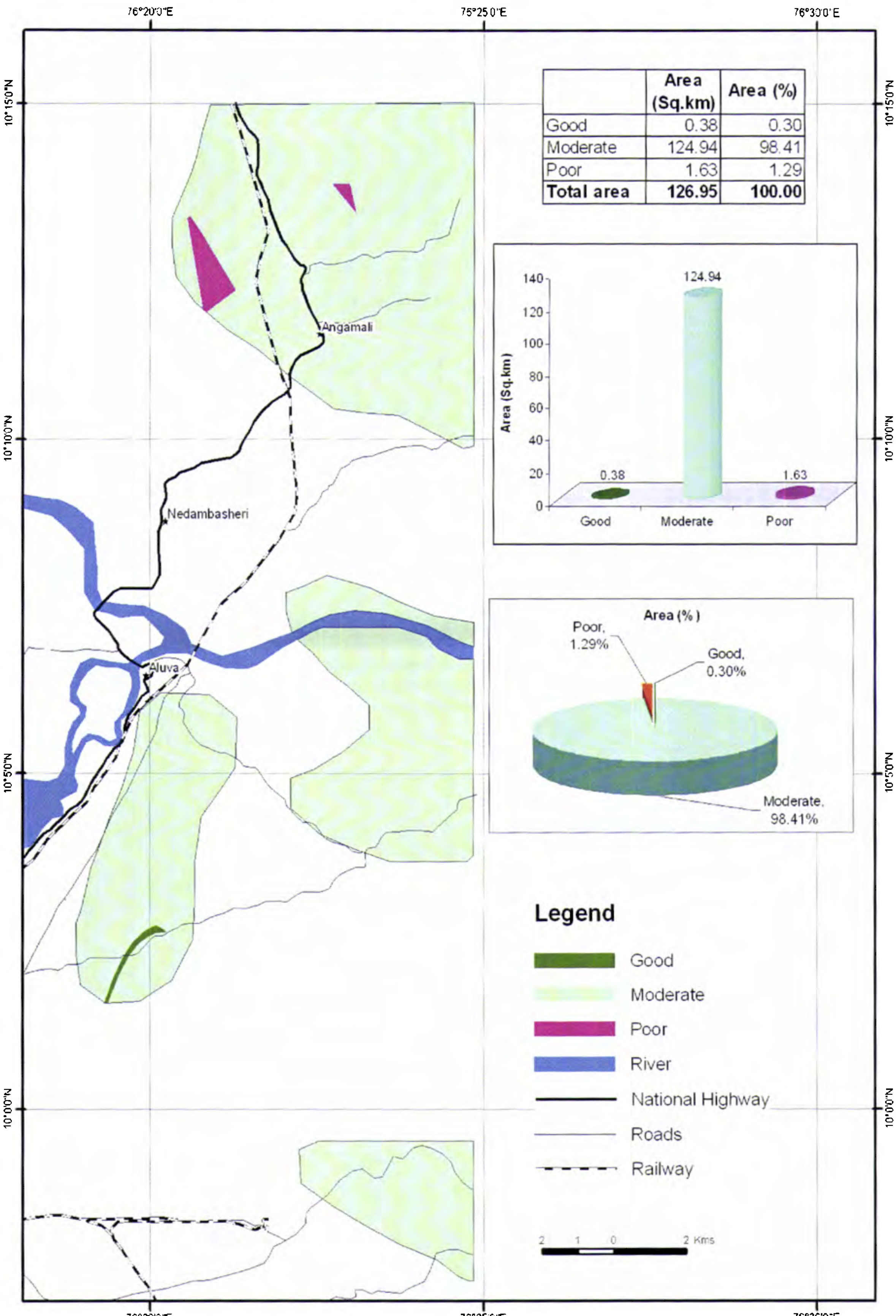

| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 0.39 | 0.31 |
| Moderate | 126.57 | 99.70 |
| **Total area** | **126.95** | **100.00** |

fig.6.23c SPATIAL OVERLAY OF GROUNDWATER PROSPECT AND DRINKING WATER SUITABLE ZONES (Mg) - LATERITE(2003)
ERNAKULAM - ALAPPUZHA STRETCH



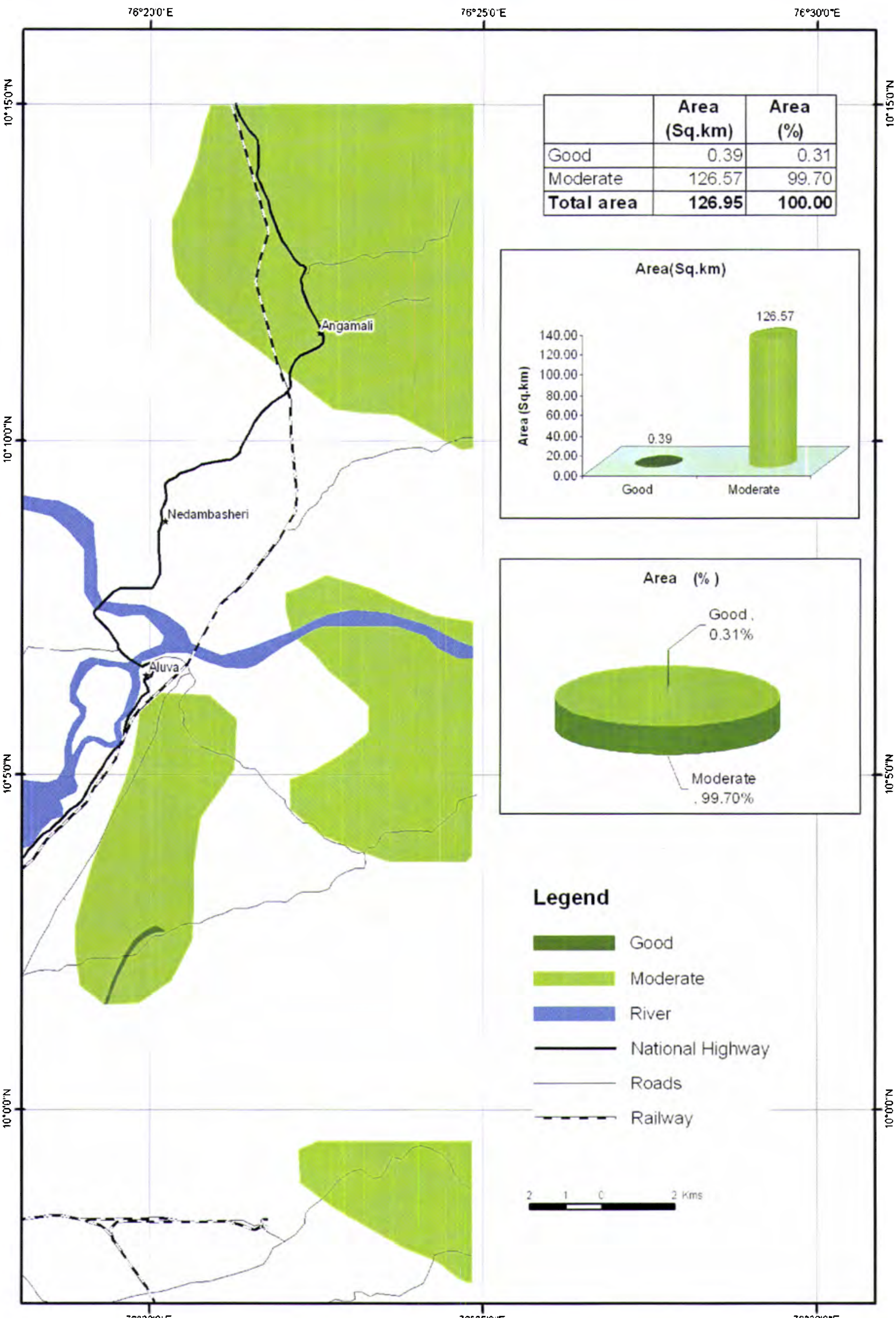

| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 0.39 | 0.31 |
| Moderate | 126.57 | 99.70 |
| **Total area** | **126.95** | **100.00** |

fig.6.23d SPATIAL OVERLAY OF GROUNDWATER PROSPECT AND DRINKING WATER SUITABLE ZONES (Na) - LATERITE(2003)
ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 0.38 | 0.30 |
| Moderate | 124.94 | 98.41 |
| Poor | 1.63 | 1.29 |
| **Total area** | **126.95** | **100.00** |

fig.6.23e SPATIAL OVERLAY OF GROUNDWATER PROSPECT AND DRINKING WATER SUITABLE ZONES (pH) - LATERITE(2003) ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 0.39 | 0.31 |
| Moderate | 126.57 | 99.70 |
| **Total area** | **126.95** | **100.00** |

fig.6.23f SPATIAL OVERLAY OF GROUNDWATER PROSPECT AND DRINKING WATER SUITABLE ZONES (TDS) - LATERITE ERNAKULAM - ALAPPUZHA STRETCH

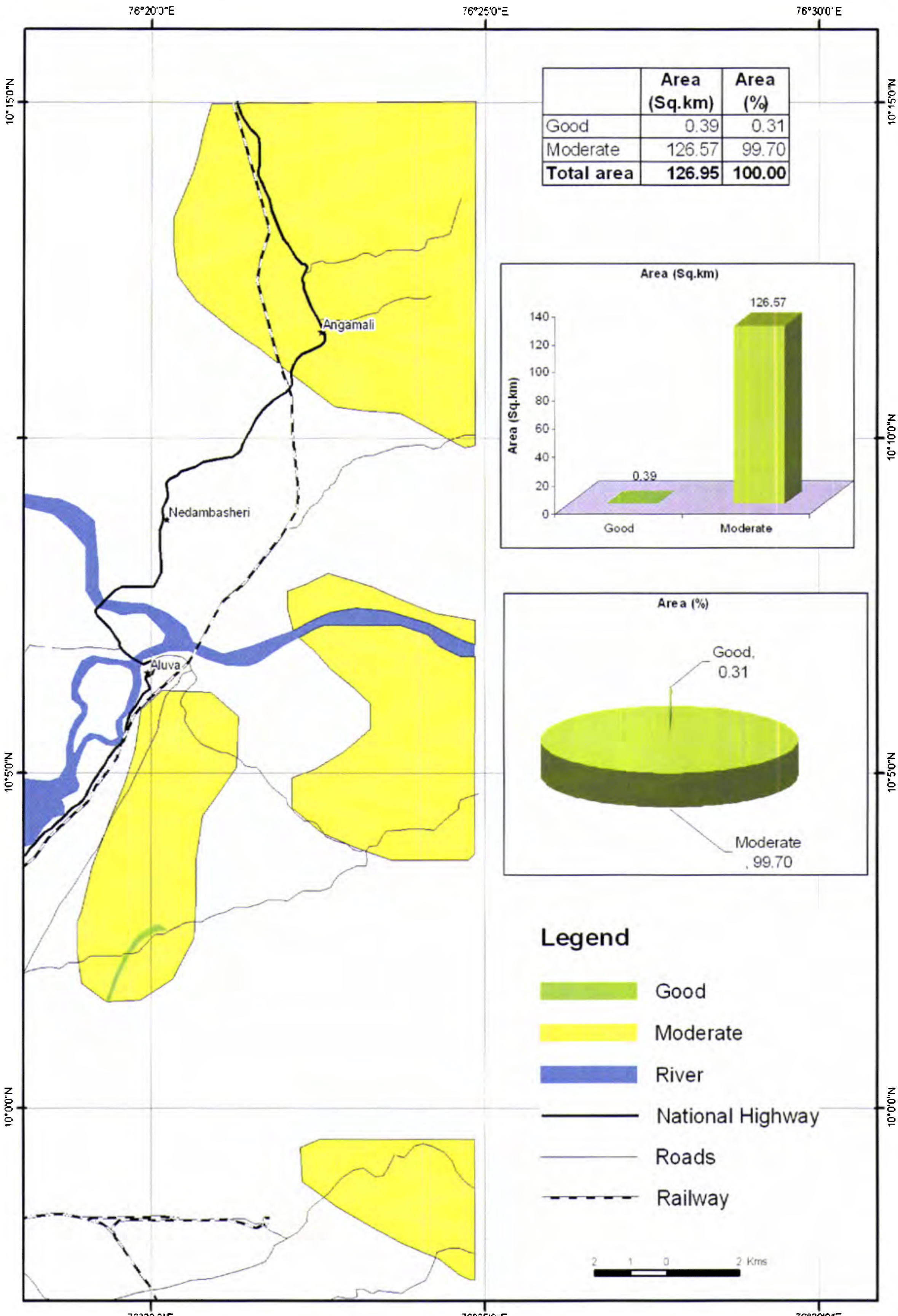
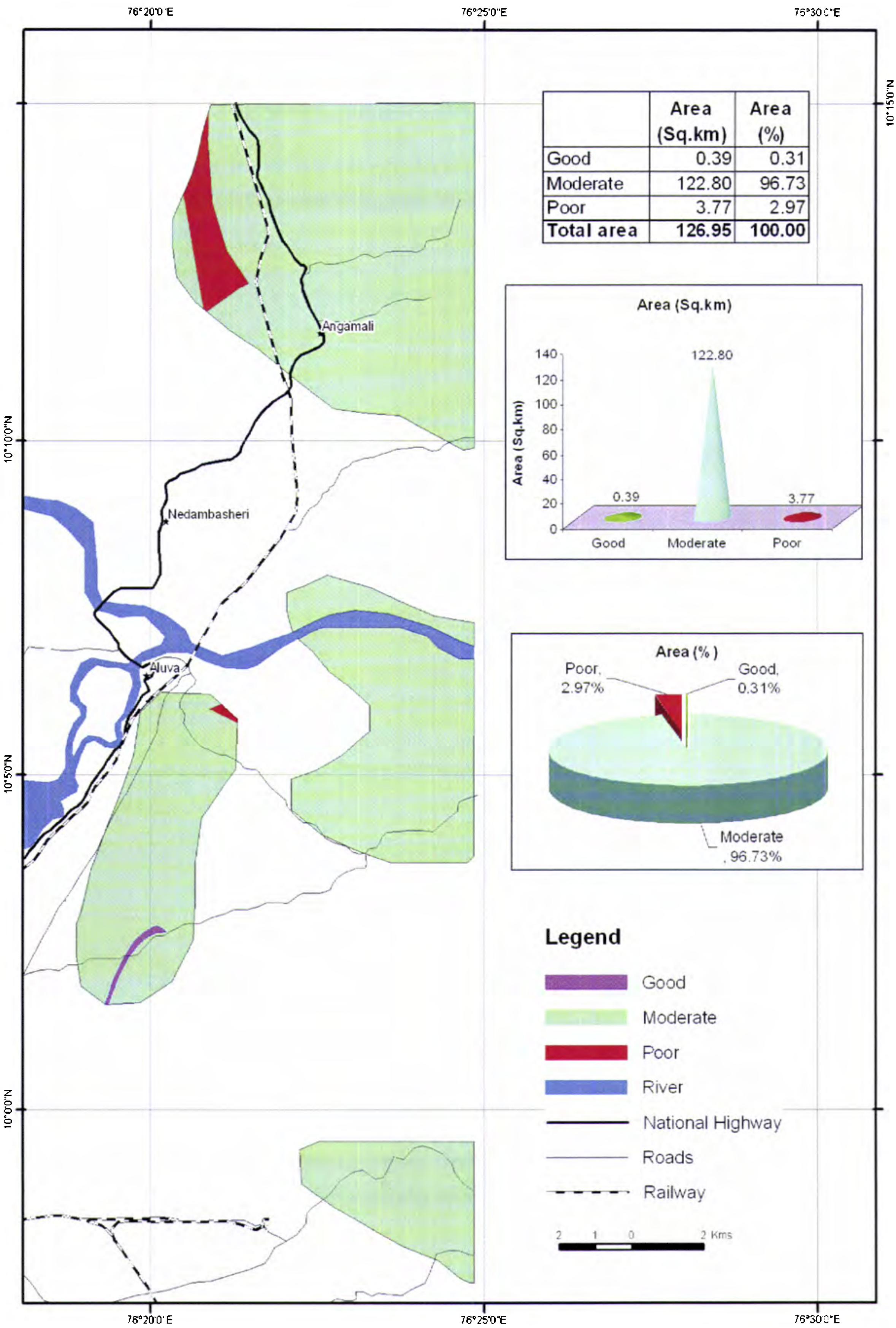



fig.6.23g SPATIAL OVERLAY OF GROUNDWATER PROSPECT AND DRINKING WATER SUITABLE ZONES (Cl) - LATERITE (2003) ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 0.39 | 0.31 |
| Moderate | 122.80 | 96.73 |
| Poor | 3.77 | 2.97 |
| **Total area** | **126.95** | **100.00** |

fig.6.23h SPATIAL OVERLAY OF GROUNDWATER PROSPECT AND DRINKING WATER SUITABLE ZONES (Ecoli) - LATERITE ERNAKULAM - ALAPPUZHA STRETCH

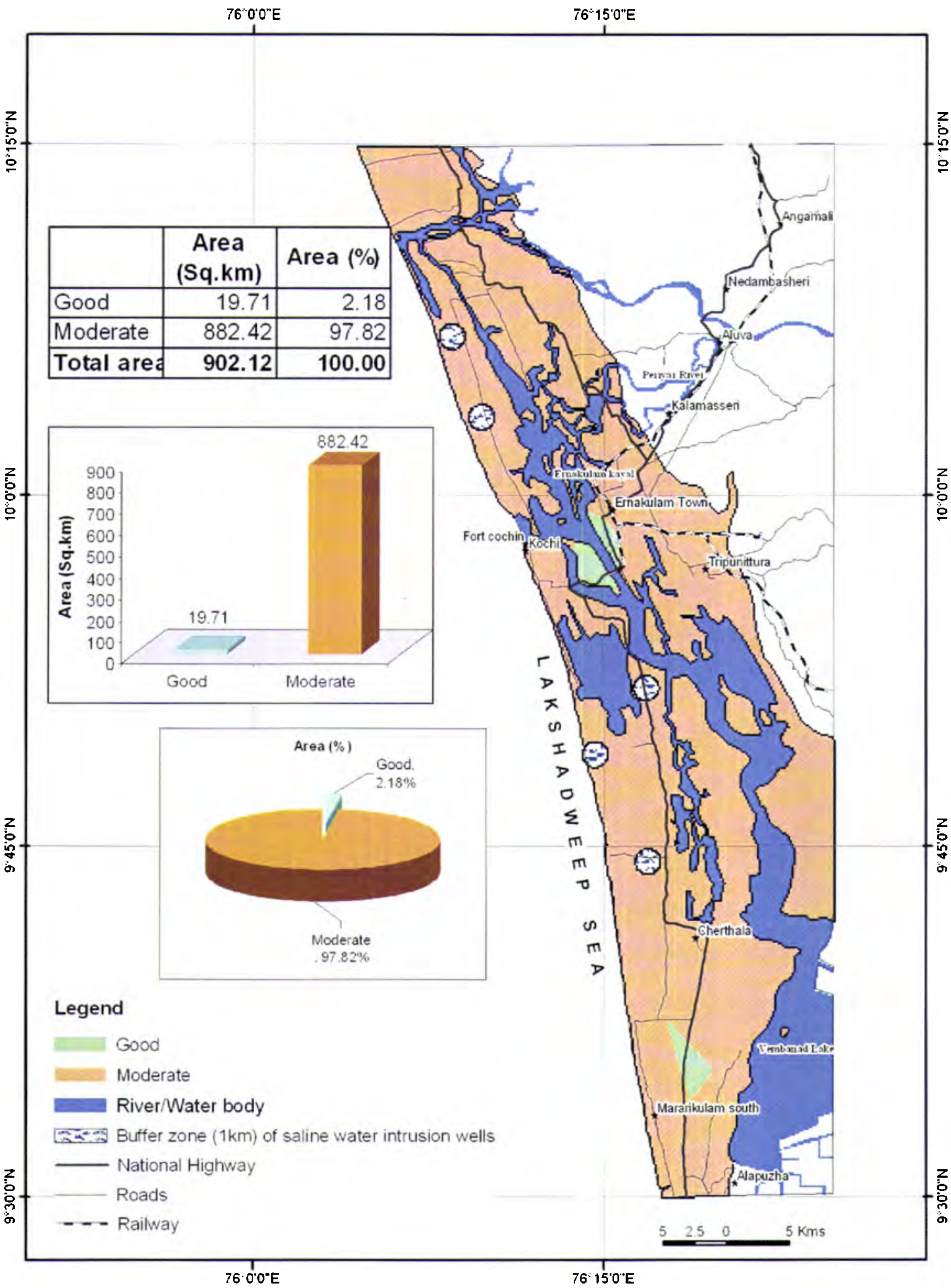
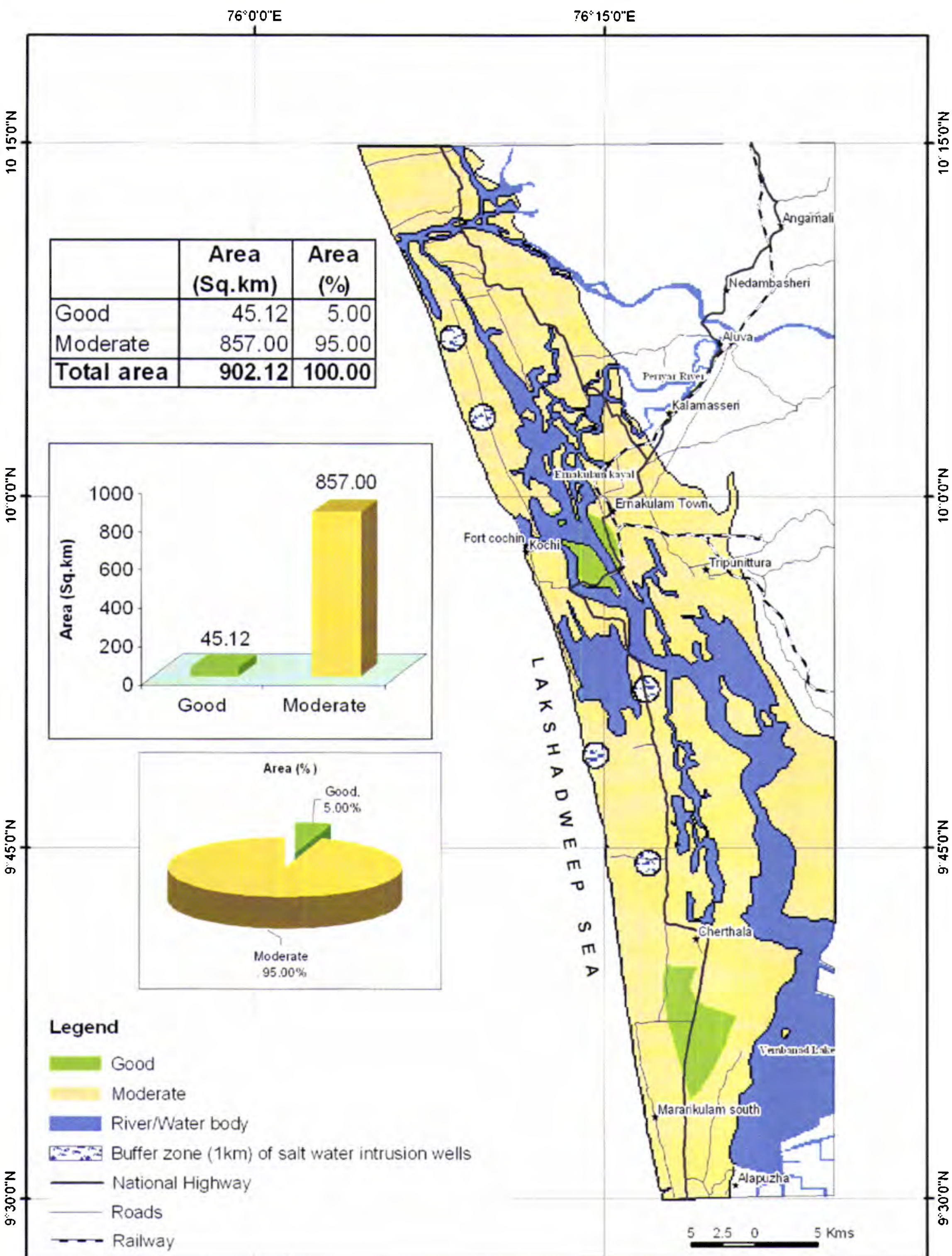


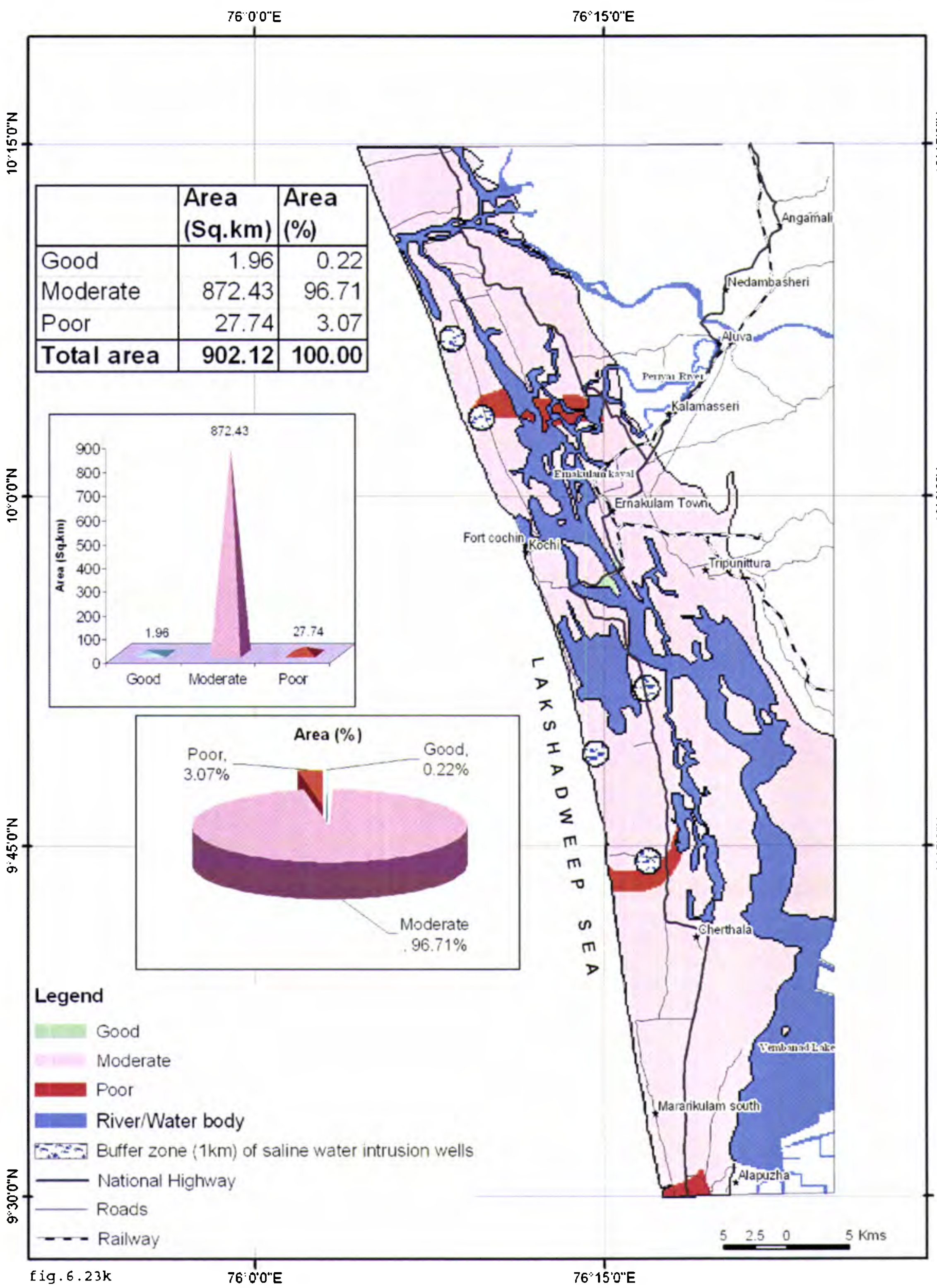

fig.6.23i HIGH GROUNDWATER PROSPECT AND HIGH DRINKING WATER SUITABLE ZONE (TDS) - ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 45.12 | 5.00 |
| Moderate | 857.00 | 95.00 |
| **Total area** | **902.12** | **100.00** |

fig 6.23j

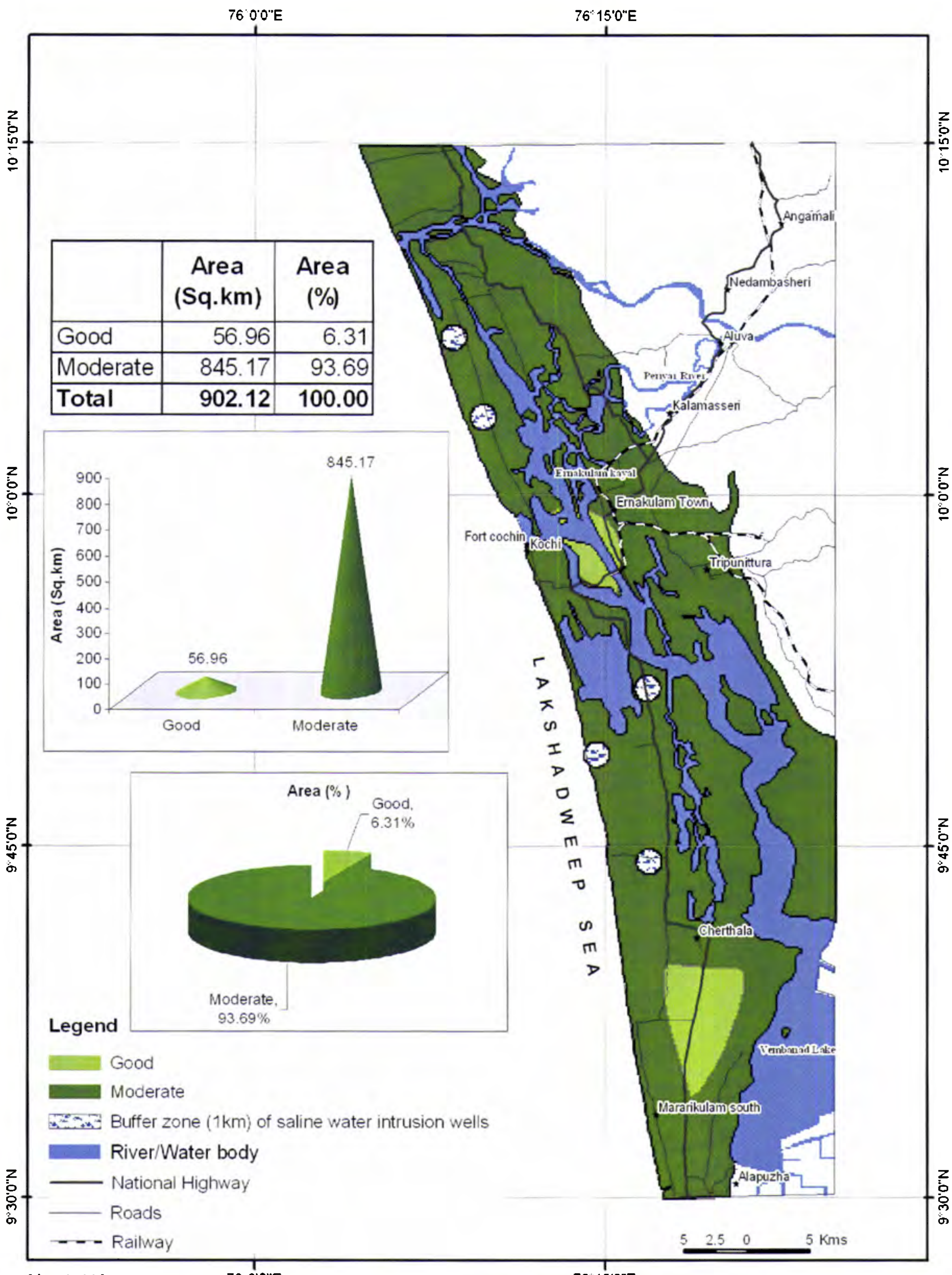
HIGH GROUNDWATER PROSPECT AND HIGH DRINKING WATER SUITABLE ZONE (Ca) - ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 1.96 | 0.22 |
| Moderate | 872.43 | 96.71 |
| Poor | 27.74 | 3.07 |
| **Total area** | **902.12** | **100.00** |

fig.6.23k

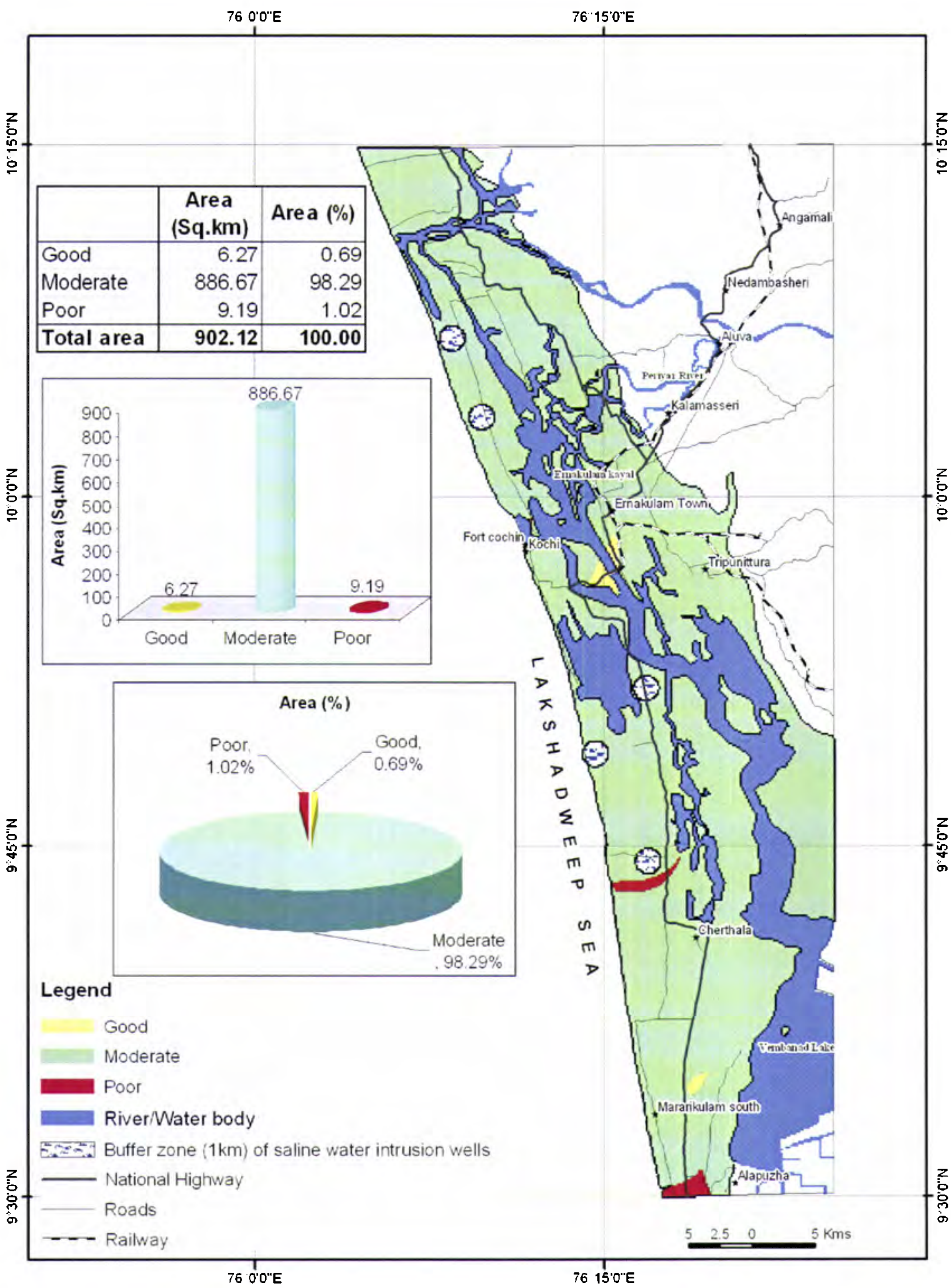
HIGH GROUNDWATER PROSPECT AND HIGH DRINKING WATER SUITABLE ZONE (C1) - ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 56.96 | 6.31 |
| Moderate | 845.17 | 93.69 |
| **Total** | **902.12** | **100.00** |

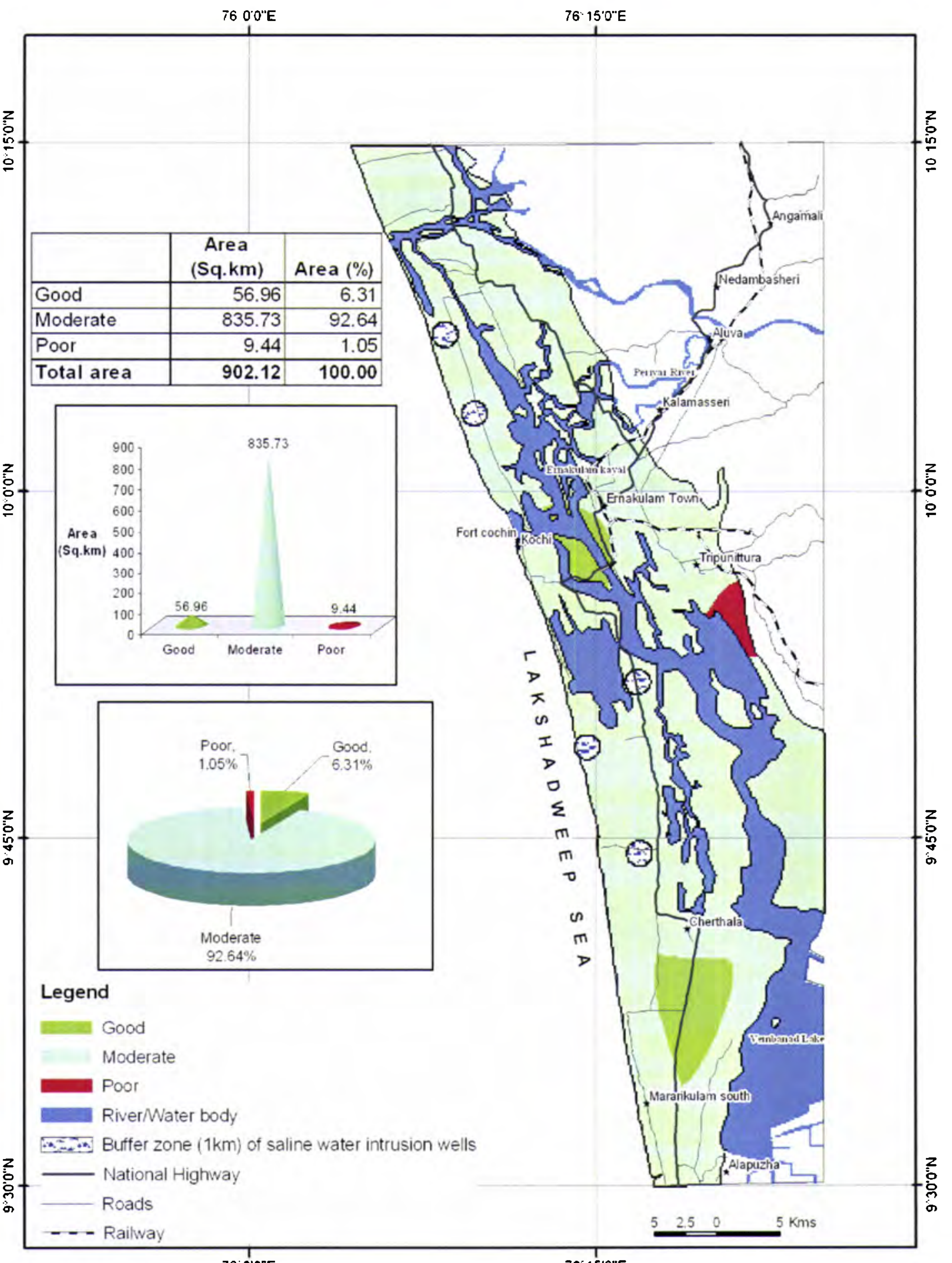
fig.6.231

HIGH GROUNDWATER PROSPECT AND HIGH DRINKING WATER SUITABLE ZONE (Mg) - ALLUVIUM (2003) ERNAKULAM - ALAPPUZHA STRETCH



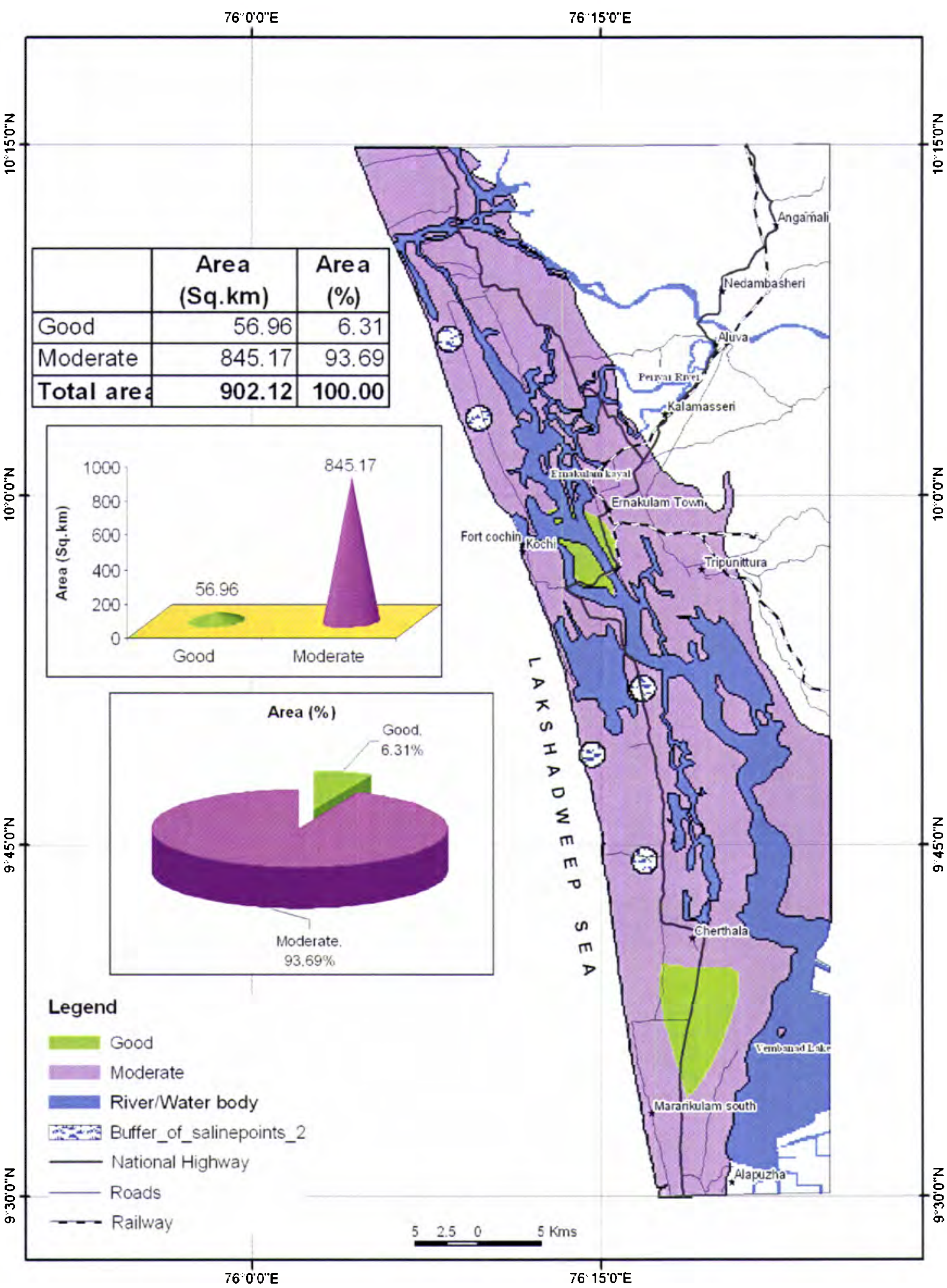

| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 6.27 | 0.69 |
| Moderate | 886.67 | 98.29 |
| Poor | 9.19 | 1.02 |
| **Total area** | **902.12** | **100.00** |

fig.6.23m HIGH GROUNDWATER PROSPECT AND HIGH DRINKING WATER SUITABLE ZONE (Na) - ALLUVIUM (2003) ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 56.96 | 6.31 |
| Moderate | 835.73 | 92.64 |
| Poor | 9.44 | 1.05 |
| **Total area** | **902.12** | **100.00** |

fig.6.23n
HIGH GROUNDWATER PROSPECT AND HIGH DRINKING WATER SUITABLE ZONE (pH) - ALLUVIUM(2003) - ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km) | Area (%) |
|---|---|---|
| Good | 56.96 | 6.31 |
| Moderate | 845.17 | 93.69 |
| **Total area** | **902.12** | **100.00** |

fig.6.23c HIGH GROUNDWATER PROSPECT AND HIGH DRINKING WATER SUITABLE ZONE (S04) - ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH

terrain. The final groundwater prospect map for laterite and alluvium are shown in figs.6.24 and 6.25.

In the alluvium, the overlay operation gave interesting results. 2.12 % (19.13 sq.km) of the area were found to come under high drinking water suitability zone. 6.31 % (56.96 sq.km) of the area were found to be high prospect zone based on resistivity and aquifer thickness. It is interesting to note that in the coastal belt, no area fulfilling all the criteria for good prospect and drinking water suitability together could be delineated. This again reiterates the inferior quality of the groundwater in the coastal belt revealed through geochemical study.

In the case of the lateritic terrain a good zone fulfilling all the criteria of resistivity, aquifer thickness and all drinking water suitability standards could be delineated in 0.30 % (0.38 sq.km) of the prospect zone. 87.03 % (110.48 sq.km) of the area fall in the moderate zone and only 12.67 % (16.09 sq.km) falls in the poor zone.

Thus the integrated approach using GIS helps in delineating potential potable groundwater zones in the area. The present study reveals the inferior quality of groundwater in the coastal alluvium of the study area compared to the hard rock terrain. In the study area, as discussed earlier the flow is from east to west and thus increase in heavy precipitation events are likely to flush more contaminants and sediments into the coastal areas, degrading water quality. Where uptake of agricultural chemicals and other non-point sources could be exacerbated, steps to limit water pollution are

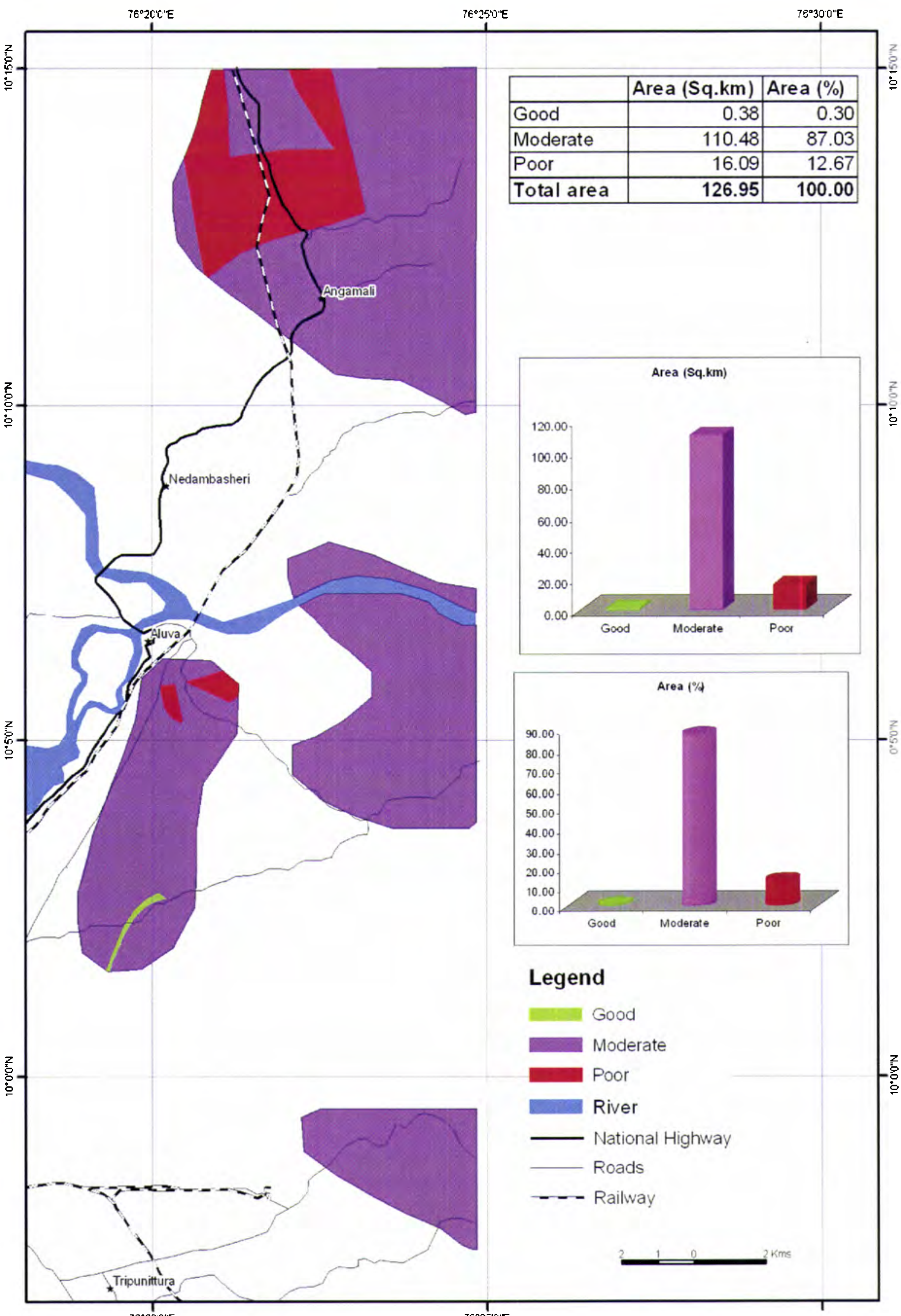
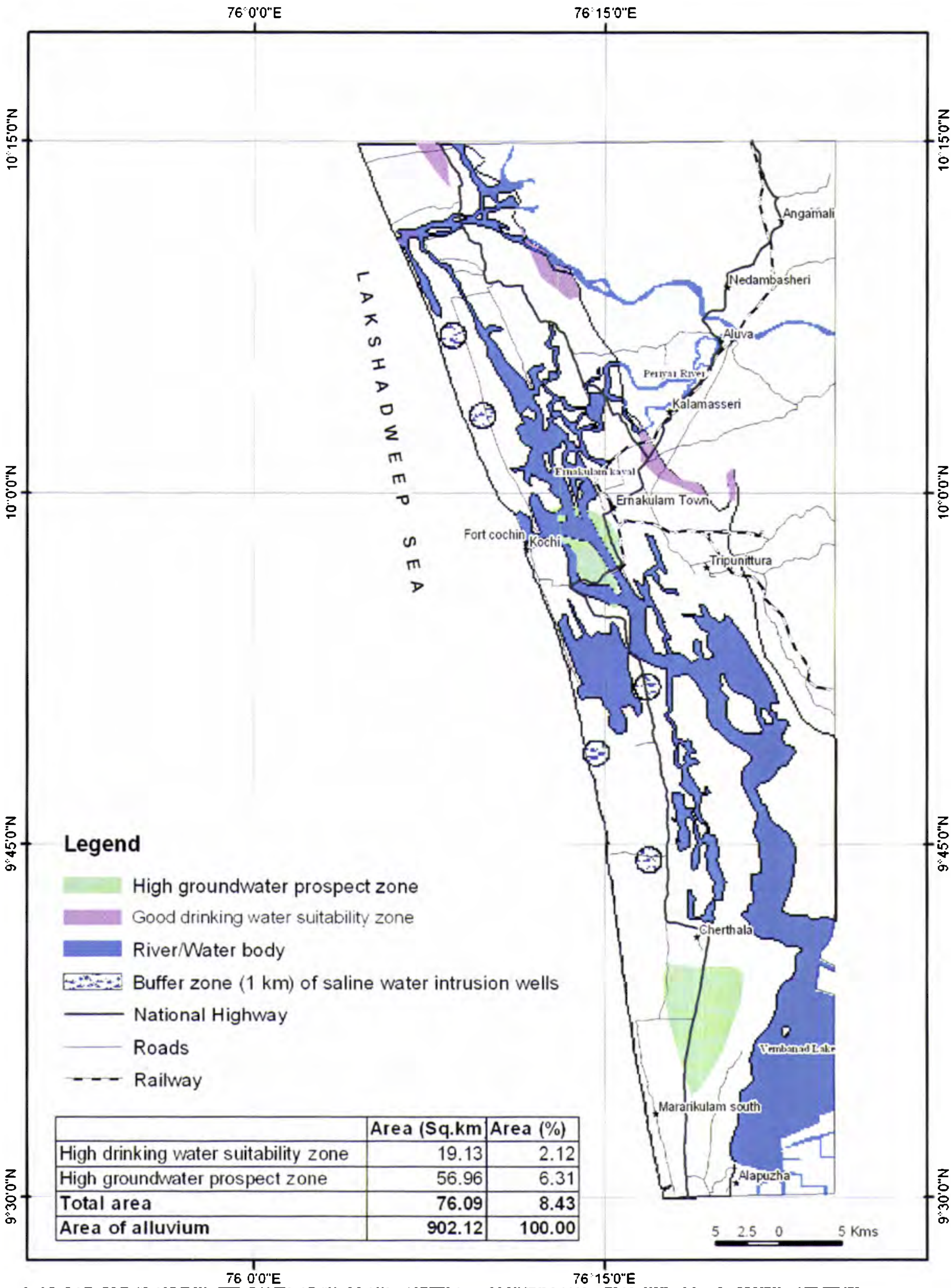



fig.6.24 POTABLE GROUNDWATER ZONES - LATERITE(2003) ERNAKULAM - ALAPPUZHA STRETCH




| | Area (Sq.km | Area (%) |
|---|---|---|
| High drinking water suitability zone | 19.13 | 2.12 |
| High groundwater prospect zone | 56.96 | 6.31 |
| **Total area** | **76.09** | **8.43** |
| **Area of alluvium** | **902.12** | **100.00** |

fig.6.25 POTABLE GROUNDWATER ZONES OF SHALLOW AQUIFERS - ALLUVIUM(2003) ERNAKULAM - ALAPPUZHA STRETCH

likely to be needed. In some regions, however, higher average flows may dilute pollutants and, thus, improve water quality. In the coastal regions where river flows are reduced, and could result in increased salinity. The quality of ground water in the coastal belt is being diminished by a variety of factors, including chemical contamination. Salt-water intrusion is another key ground-water quality concern in the coastal belt where changes in fresh-water flows and increases in sea level occur. Illegal sand mining in many river beds of the study area, especially Periyar leads to stagnation of tidal water which can lead to increased salinity in many parts of the study area.

Chapter 7

# Summary and Conclusion

Water resources are a major cause of concern for all the countries in the world and efforts for the sustainable development of this important resource is high in the agenda. Hence prospecting and scientific management of groundwater resources assumes paramount importance. India also faces severe water shortage along with other third world nations. Water quality is as important as the quantity and this aspect needs special attention in any groundwater study.

The present study has been undertaken with the above aspects in mind, in parts of Central Kerala. The study area has been selected in such a manner that a comparative account of all the hydrogeological, geochemical and geophysical aspects of the coastal belt and the crystalline terrain could be analysed. The present study area falls in the Alleppey, Ernakulam and Trichur districts of Kerala. The satellite data of IRS-ID LISS III (2002), geocoded FCC for visual interpretation and digital data for digital classification were used. Digital data were processed in the laboratory using ERDAS Imagine 8.6 DIP software. Geographical Information Systems provide an efficient and accurate tool for the integration of enormous volumes of spatial and non-spatial data. In the present study GIS has been utilized in all steps right from water level analysis, geochemical zonation and water quality mapping to the final integration of all the data presented as the potential potable groundwater zone map.

The study area may be broadly divided into the coastal belt and the crystalline terrain. The coastal zone of Kerala faces a lot of problems due to its high density of population and peculiar geological settings. Kerala has a unique hydrogeological and climatic condition. The hydrogeological environment along the coast with its backwater, lagoons, estuaries and barrier islands is complex in nature. Deterioration of groundwater quality due to anthropogenic and natural causes (saltwater intrusion) are of major concern. The groundwater development along the coast has been increased many fold during the last four decades to meet the rising requirements due to population growth, industrial development and change in lifestyle.

**Summary**

The salient findings drawn on the study are enumerated below.

Water levels in the 26 observation wells of the State Ground Water Board were analysed in detail for a period of ten years. The average water levels show values of 5.92 mbgl for laterite, 5.71mbgl for charnockites and 1.07mbgl for alluvium. The maximum water levels are 14.45mbgl for laterite, 10.77mbgl for charnokite and 4.32mbgl for alluvium and their minimum values are 0.42mbgl, 2.31mbgl and 0.07 mbgl respectively. Inspection of hydrographs shows the water table to be sensitive to changes in the hydrologic regimen of the study area. Water levels in aquifers in the study area typically follow a cyclic pattern of seasonal fluctuation with rising water levels during post-monsoon due to greater recharge from precipitation and declining water levels during summer and fall due to less recharge, greater evapo-transpiration, and pumping. Correlation of rainfall and water level was done by superimposing the rainfall data and water level data and it was noticed that the water levels follow rainfall pattern of the area. Hence it can be concluded that rainfall is the major controlling factor of water level in the study area. Hydrograph analysis of the coastal belt shows that most of the wells show a declining trend varying from – 0.2 to – 0.027

Water balance studies indicate the tremendous water surplus in this region from the heavy monsoons. As per the estimate during the southwest monsoon season, 5Million $M^3$ water is recharged into groundwater in the selected area. A part of this may be lost due to groundwater flow but the lowering of water table is by overdraft. The study reveals that in the coming decades there will be considerable reduction in water yield if the temperature increases and considerable reduction in per capita water availability if the present rate of growth of population continues in the study region. To meet the requirements of the huge population in the domestic, agricultural and industrial sectors, utilization of more groundwater will become essential, which may lead to lowering of water table and salinity intrusion along the coasts.

Analysis of the Vertical Electrical Sounding (VES) curves showed that most of the sounding curves are of H, QH and KH-types. The occurrence of a significant typical H type curve indicates the presence of a highly resistive top lateritic soil followed by a saturated zone and then the basement topography in the hardrock terrain of the study area. VES studies in the coastal belt were restricted only for the shallow aquifers and mainly to correlate the geochemical findings on groundwater quality and also delineate saline water zones. The VES studies in the coastal belt reiterated the finding through geochemical analysis that saline water intrusion in the study area is localized as shown by some wells close to tidal inlets.

Groundwater samples collected from 41 dug wells during pre-monsoon and post-monsoon periods were analysed for physical parameters and major cations and anions. Groundwater types were deciphered using other important diagrams like Hill Piper diagram and Durov's diagram. Groundwater has been categorized for various uses like drinking, domestic, irrigation, livestock etc by analysing the data using various geochemical diagrams like Wilcox diagram, and U.S.S.L diagram. The spatial and temporal variation of each element (pre-monsoon and post-monsoon) has been analysed using Geographic Information System (GIS) for accurate representation of data in maps. GIS has been used to analyse the geochemical data and also to bring out water quality maps, which are then linked, with the groundwater potential maps created using resistivity data and GIS to decipher potable groundwater maps.

The pH in general shows higher values for the coastal area than the eastern crystallines for both pre-monsoon and post-monsoon periods. In the eastern crystallines of the study area pH value as low as 6.2 is recorded in a considerable part of the study area. In the present study the EC values are found to vary from 124 microseimens/cm to 5300 microseimens/cm during pre-monsoon season for the samples taken from the coastal belt where as the crystalline terrain shows values between 41 and 349 microseimens/cm. In the post-monsoon period the values for the coastal belt ranges from 110 microseimens/cm to 2792 microseimens/cm whereas the crystallines show values ranging from 30-260. The comparative study clearly reveals that in both pre-monsoon and post-monsoon periods wells in the crystalline terrain shows low EC values and hence these are suitable for drinking and other domestic purposes. In the coastal belt higher values are noticed and the quality of water ranges from excellent to saline. Wells in the crystalline terrain show Chloride values ranging from 5 mg/l to 39 mg/l during pre-monsoon and 9 mg/l to 22.9 mg/l for post-monsoon which are well within the permissible limits prescribed by WHO (1984), EEC (Lloyd and Heathcote, 1985) and ISI (1983). But the coastal belt presents an entirely different scenario with seven wells showing values above the permissible limit in both pre-monsoon and post-monsoon periods.

A comparison of the Wilcox diagrams for the crystalline terrain and coastal belt shows that the wells in the crystalline terrain of the study area fall in the excellent to good category during both pre-monsoon and post-monsoon seasons. In the coastal belt a majority of wells fall in the excellent to good category, one well in the good to permissible category and three wells fall in the permissible to doubtful category. In the study area the Residual Sodium Carbonate (RSC) falls in the suitable range for irrigation in both pre-monsoon and post-monsoon periods. The RSC for both the crystalline terrain and coastal belt is well below 1.25meq/l (suitable range in Lloyd and Heathcote's classification). From the U.S.S.L diagrams it is evident that in the crystalline terrain all the wells fall in the Low salinity hazard area during the post-monsoon period. Only one well falls in the medium salinity hazard category in the pre-monsoon. Hence it can be inferred that the water in the crystalline terrain of the study area is very good for irrigation.

According to the standards prescribed by the U.S National Academy of science (1972) the groundwater in the study area can be classified as follows. All the wells except four samples from the coastal belt fall in the excellent range (category 1) for livestock and poultry. Of these three wells fall in the very satisfactory category. Only one well falls in the fourth category, which cannot be used for poultry but can be used for livestock with reasonable safety. The groundwater of the study area has also been classified for suitability for various industries.

From the Piper diagram it is evident that in the crystalline terrain Calcium Bicarbonate (temporary hardness) type dominates in the pre-monsoon period. In the post-monsoon also Calcium Bicarbonate is the dominant type but some samples move towards the mixed type category. From this shift it can be inferred that rainfall is the main controlling element in the area rather than geology. The Piper diagrams of the coastal belt show that the dominant type is the saline or Sodium Chloride type with some samples in the mixed type and a few samples in the Calcium Bicarbonate type.

Drinking water quality maps of each element as per drinking water standards prescribed by WHO and the overlay showing variations between the two seasons were prepared using GIS. An overlay operation of all the drinking water suitability maps resulted in the final water quality maps for alluvium and the lateritic terrain. The study area has been divided into good, moderate and poor categories based on the drinking water suitability. The maps indicate the inferior quality of the coastal belt in comparison to the lateritic terrain.

GIS has been used to integrate the thematic maps of aquifer thickness and resistivity to delineate groundwater prospect zones in the alluvium and laterite terrains of the study area. Drinking water suitability map of the area has been overlain on the groundwater prospect map so as to arrive at potential potable groundwater zones. Thus the study has helped in generating a comprehensive and scientific database of the study area using GIS, which can be helpful in groundwater prospecting and management.

**Conclusions**

The long-term well hydrographs indicate a general decline in groundwater level while maintaining a steady level in localized pockets. Correlation of rainfall and water level revealed that the water levels follow rainfall pattern. Hence it can be concluded that rainfall is the major controlling factor of water level in the study area.The resistivity analysis in crystalline terrain generally reveals a high resistivity zone as upper layer followed by low resistivity zone and a high resistive zone in the bottom. (H-Type). Geochemical analysis shows that the groundwater in the crystalline terrain is good for all domestic, irrigational and industrial purposes because of low EC, TDS, total hardness, major cations ($Na^+$, $K^+$, $Ca^{++}$ and $Mg^{++}$) and anions ($HCO_3^-$, $CO_3^{--}$, $SO_4^{--}$ and $Cl^-$). The salinity and Sodium alkali hazards are also low in the crystalline terrain. The groundwater of the coastal belt is far inferior in quality in comparison to the crystalline terrain of the study area.

Saline water intrusion in the study area is only localized near tidal inlets. Indiscriminate sand mining leading to deepening of the bed of the streams can lead to accumulation of stagnating salt water during high tide that may remain as pools even after the tide has withdrawn.

Groundwater suitability mapping and integration of various thematic maps for potential potable map using GIS also indicate the inferior quality of the coastal groundwater in comparison to the crystalline terrain.

**Future Outlook**

The integrated study using GIS is proved to be an efficient and scientific method for groundwater management. Hence it is recommended that integrated study using GIS may be taken up in the Cadastral scale so as to generate an accurate database.

Further study is needed for the geochemical aspects of groundwater in some localized areas of the coastal plain.

The effects of indiscriminate sand mining on water quality of the study area need to be studied in detail.

More data is needed to suggest remedial measures to gauge the causative factors of saline water intrusion.

In areas of poor groundwater quality, harvesting of groundwater during high monsoon time should be programmed so that it leads to improvement of groundwater quality in specific areas of high population.

Regional studies have been carried out and keeping this regional database, influence of pollutants from industrial units may be monitored.

# References

Agrawal, G.U. (1999). Diffuse agricultural water pollution in India, Water Science & technology, v.39, pp. 33-47

Ahmed, S., Marsily, G.D. and Talbot, A. (1988). Combined use of hydraulic and electrical properties of an aquifer in a geostatistical estimation of transmissivity. Ground Water, v.26, pp. 78-86.

Aller, L., Bennet, T., Lehr, J.H. and Pety, R.J. (1987). DRASTICP: A standardized system for evaluating ground water pollution using hydrogeological settings. United States Environmental Protection Agency, Washington. Report 600/2-85/018.

Anon. (1998). Standard Analytical Procedures for Water Analysis, Laboratory Manuel, Hydrology Project, CSMRS Building, 4th floor, Olof Palme Marg, New Delhi-16.

Anon. (1992). SIDA Assisted Coastal Kerala Groundwater Project (1983-88), Final Technical Report. Ministry of Water Resources Gov. of India, 218p.

APHA. (1985). Standard Methods for the Analysis of Water and Waste Water (16th edn.), American Public Health Association, Washington. D.C.

Aravindan, S. (1999). Integrated hydrogeological studies in hard rocks aquifer system of Gadilam river basin, Tamil Nadu, India, (Ph.D thesis, Bharathidasan University), p.110.

Archie, G.E. (1942). "The electrical resistivity log as an aid in determining some reservoirs characteristics", Journal of Petroleum Technology, v. 5, pp 1-8.

Arora, C.L. and Bose, R.N. (1981). Demarcation of fresh and saline-water zones, using electrical methods (Abohar area, Ferozepur dist. Punjab). Journal of Hydrology, v. 19, pp. 75-85.

Baban, S.M.J. (1997). Potential applications of satellite remote sensing and GIS in maximising the use of water resources in the Middle East: Examining Iraq as a case study. IASH Publication, v. 242. pp. 23-32.

Back, W. and Hanshaw, B.B. (1965). Chemical Geohydrology, Adv. Hydro Science, v.1, pp.49-109.

Bajjali, W. (1999). Evaluation of Groundwater Salinity throughout Sultanate of Oman Using GIS. Internal Report, Ministry of Water Resources, Oman, 14p.

Bajjali, W. (2002). The effect of Hilti/Salahi Recharge Dam in Batineh Area, Sultanate of Oman on the Quality of Groundwater Using GIS: Twenty-Second Annual ESRI International User Conference, July 8–12, San Diego, CA, 19 pp.

Balakrishna, S., Ramanujachary, K.R. and Sastry, T.S. (1978). Resistivity surveys in limestone regions. Geophysical Research Bull., v.16, pp. 97-103.

Balasubramanian, A., Sharma, K.K. and Sastri, J.C.V. (1985). Geoelectrical and hydrogeochemical evaluation of coastal aquifiers of Tambraparni basin, Tamil Nadu, Geophys. Res. Bull. v. 23 (4), pp. 203-209.

Barker, R.D. (1980). Application of geophysics in groundwater investigations. Water. Surv., v. 84, pp. 489-492.

Beeson, S. and Jones, C.R.C. (1988). The combined EM/VES geophysical method for sitting boreholes. Ground Water, v. 26 (1), pp 54-63.

Bernard, J. and Valla, P. (1991). Groundwater exploration in fissured media with electric and VLF methods. Geoexploration, v. 27, pp. 81-91.

Bhimashankaram, V.L.S. and Gaur, V.K. (1977). Lectures on Exploration geophysics for Geologists and Engineers, AEG Publi., Osmania Uni. Hyderabad, 449p.

Biggs. R.B. (1978) Coastal Bays. In: Coastal Sedimentary Environments. (ed) R.A. Davis Jr., Springer-Verlag., New York, pp.69-100.

Bowder, L.W. and Pruit, E.L. (1975). Manual of remote sensing v. II, Interpretation and application, Amer. Soc. of Photogrammetric Engineering, v. 30, pp.630-635.

Boyer, R.E. and Mague, J.E. (1964). Comparison of mapped rock fractures and air photo linear features. Photogrammetric Engg., v. 30, pp. 630-.635.

Broeker, M.E. and Fischel, V.C. (1961). Groundwater levels in observation wells in Kansas, 1960. Kansas Geol. Survey Bull. v. 153, pp. 1-183.

Burger, H.R. (1992). Exploration Geophysics of the Shallow Subsurface: Prentice Hall, Inc.

Carter, H.J. (1857). On the Geology of South Travancore. Rec. Geol. Surv. of India., v. 16(1), pp. 20-35.

CESS, (1984). Resource atlas of Kerala, Centre for Earth Science Studies, Thiruvananthapuram, Kerala.

Chandrasekharan, D. (1989). Anomalous $SO_4$- Cl groundwater in coastal aquifer, Kerala, Proc. Ind. Acad. Sci., v. 98 (3), pp. 287-295.

Chaterjee, R.S. and Bhattacharya, A.K. (1995). Delineation of the drainage pattern of a coal basin related inference using satellite remote sensing techniques. Asia Pacific Rem. Sen. J., v. Fr1, pp. 107-114.

Chebotarev, I. (1950). Metamorphism of natural waters in the crust of weathering. Geochim. Cosmochim. Acta, v. 8, pp 22-48.

Chen, Z., Grasby, S.E. and Osadetz, K.G. (2002). Predicting average annual groundwater levels from climatic variables: an empirical model. J. Hydrol. 260: pp. 102-117

Choudhury, K., Saha, D.K., and Chakraborty, P. (2001). Geophysical study for saline water intrusion in a coastal alluvial terrain. Journal of Applied Geophysics 46: 189-200.

Collins, W.D. (1923). Graphic representation of water analysis, Ind. Eng chem. v.15, 394p.

Colwell, R.N. (1983). Manual of Remote Sensing. American Society of Photogrammetery, 2143p.

Crimnisi, A. and Tucciarelli, T (2003). Water Level Measurement Locations for Coastal Aquifer Management J. Water Resour. Plng. and Mgmt., Volume 129, Issue 1, pp. 49-58.

Cuneyt Guler Geiffrey, Thyne, D., John E. McCray and Keith Turner, A. (2002). Evaluation of graphical and multivariate statistical methods for classification of water chemistry data, Hydrogeology Journal, v. 10, pp. 455-474.

Dahlin, T. (2001). The development of DC resistivity imaging techniques, Computers Geosciences, v. 27: 1019-1029.

Damodaran, A. (1955). Geology of Warkalli formation in parts of Trivandrum district, Kerala. Unpublished, GSI report.

Das, S., Behera, S.C., Kar, A., Narendra, P. and Guha, S. (1997). Hydrogeomorphological mapping in ground water exploration using remotely sensed data – A case study in Keonjhar district in Orissa. Jour. Ind. Soc. Rem. Sens., v. 25 (4), pp. 247-259.

Davis, S.N. and DeWiest, (1960). Hydrogeology, John Wiley Inc., New York, 463p.

Davis, S.N. and DeWiest, R.J.M. (1966). Hydrogeology. John Wiley and Sons.

DeMarsily, G. (1986). Quantitative hydrogeology: Groundwater hydrology for engineers. London: Academic Press.

Desikachar, S.V. (1980). Geology and hydrocarbon prospects of the Kerala West Coast Basin. Bull. ONGC, v. 17, no.1, pp. 25-34.

Dey, A. and Morrison, H.F (1979). Resistivity modeling for arbitrarily shaped three-dimensional structures. Geophysics v. 44, pp. 753-780.

Dey, A.K. (1962). The Miocene mollusca from Quilon, Kerala (India). Mem. Geol. Survey of India, New Series, n.36, 26p.

Domenico, P.A. and Schwartz F.W. (1997). Physical and chemical hydrogeology, 2nd edn. Wiley, New York.

Doser, D.I., Dena-Ornelas, O.S., Langford, R.P. and Baker, M.R. (2004). Monitoring yearly changes and their influence on electrical properties of the shallow subsurface at two sites near the Rio Grande, West Texas. Journal of Environmental and Engineering Geophysics, v. 9, pp. 179-190.

Drury, S.A. (1987). Image interpretation in geology. Allen and Unwin, London, 243p.

Drury, S.A., Harris, N.B.W., Holt, R.W., Reeves Smith, G.J. and Wightman, R.T (1984). Precambrian tectonics and crustal evolution in south India. Jour. Geol., v. 92, pp.3-20.

Eaton, E.M. (1950). Significance of Carbonate in Irrigation Water Soil Sci., v. 69, pp.123-133.

Edet, A.E. and Okereke, C.S. (1997). Assessment of hydrogeological conditions in basement aquifers of the Precambrian Oban massif, southeastern Nigeria, Journal of Applied Geophysics, v. 36, pp. 195-204.

Edmunds, W.M. (1994). Groundwater chemistry and development. Groundwater quality. eds. Nash, H. and McCall, G.J.H. Chapman and Hall.

El-Waheidi, M.M., Merlanti, F. and Pavan, M. (1992). Geoelectrical resistivity survey of the central part of Azraq basin (Jordan) for identifying saltwater/freshwater interface. J. Applied Geophysics v. 29, pp. 125-133.

Emenike, E.A. (2001). Geophysical Exploration for Groundwater in a Sedimentary Environment: A Case Study from Nanka over Nanka formation in Anambra basin, Southeastern Nigeria Department of Physics, University of Abuja, Abuja, Nigeria Global Journal of Pure and Applied Sciences, v. 7 (1).

Firoz Verjee and Alain Gachet. (2006). Mapping water potential GIS Development Asia Pacific v.10, Issue.4.

Fischel and Mason, B.J. (1957). Groundwater levels in observation wells in Kansas, 1956: Kansas Geol. Survey Bull, v. 125, pp. 1-158.

Fischel and Mason. (1958). Groundwater levels in observation wells in Kansas. (1957), Kansas Geol. Survey Bull, v. 131, pp. 1-152.

Fishel, V.C. and Broeker, M.E. (1960). Groundwater levels in observation wells in Kansas, 1959: Kansas Geol. Survey Bull. v. 146, pp. 1-174.

Foote, R.B. (1883). On the geology of south Travancore. Rec. Geol. Survey of India., v.16 (1), pp. 20-35.

Freeze, R.A. and Cherry, J.A. (1979). Groundwater, Prentice Hall, Englewood Cliffs, New Jersey, 604p.

Frohlich, R.K. and Kelly, W.E. (1987). Estimates of specific yield with the geoelectric resistivity method in glacial aquifers. Journal of Hydrology v. 97, pp. 33-44.

Frohlich, R.K. and Urish, D. (2002). The use of geoelectrics and test wells for the assessment of groundwater quality of a coastal industrial site, J. Appl. Geophys., v. 50, pp. 261-278.

Gish, O.H., and Rooney, W.J. (1925). Measurement of resistivity of large masses of undisturbed earth, Terrestrial Magnetism and Atmospheric Electricity v. 30, pp. 161-188.

Gnanasundar, G. and Elango, L. (1999). Groundwater quality assessment of a coastal aquifer using geoelectrical techniques. Journal of Environmental Hydrology. v. 7, 2p.

Goodchild, M.E. (1993). Environmental modeling with GIS. Oxford Univ. Press, New York. pp. 8-15.

Gopinath, G. (2003). An integrated hydrogeological study of the Muvattupuzha river basin, Kerala, India. PhD thesis submitted to the Cochin University of S&T, Kerala.

Grimaldi, V. Viaud, Massa, F., Carteaux, L., Derosch, S., Regeard A., Fauvel, Y., Gilliet, N. and Rouault, F. (2004). Stream Nitrate Variation Explained by groundwater head fluctuations in a pyrite bearing aquifer J. Environ Qual. v. 33: 994-1001(2004).

Groundwater Year Book, (2003). Ernakulam District, State Groundwater Department, Kerala.

Gupta, R.P (1991). Remote Sensing Geology. Springer-Verlag, Berlin, 356p.

Halliday, S.L. and Wolfe, M.L. (1991). Assessing the groundwater pollution potential from nitrogen fertilizer using geographic information system. Water Resources Bull., v. 27 (2), pp 237-245.

Handa, B.K. (1964). Modified classification procedure for rating irrigation waters. Soil Sci., v. 98, pp. 264 -269.

Handa, B.K. (1984). Water quality and water pollution prolems on the Indian subcontinent. IAHS-AISH Publication v.150, pp. 313-322.

Hearst, J.R., Nelson, P.H. and Paillet, F. (2000). Well logging for physical properties: A handbook for geophysicists, geologists, and engineers, John Wiley, New York, 483p.

Heigold, P.C., Gilkeson, R.H., Cartwright, K. and Reed, P.C. (1979). Aquifer transmissivity from surficial electrical methods. Ground Water, v. 17, pp. 338-345.

Hem, J.D. (1959). Study and interpretation of the chemical characteristics of natural water. USGS, water supply paper, 1935-C, p17

Hem, J.D. (1970). Study and interpretation of the chemical characteristics of natural water, U.S. Geological Survey Water-Supply Paper 1473.

Hill, R.A. (1940). Geochemical patterns in Coachella valley, California, Am. Geophy. Union. Trans., v. 21, pp. 46-53.

Holland, T.H. (1900). The Chamockite series, a group of Archaean Hypersthene rocks in Peninsular India. Mem. Geol. Surv. India, v. 28, pp.117-249.

Horton, R.E. (1945). Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull., v. 56: pp.275-370.

Howe, R.H. (1956). Application of air photo interpretation in the locating of groundwater, Jour. Am. Water Works Assoc., v .48, pp.1380-1390.

Hubbard, S.S. and Rubin, Y. (2000). Hyrdogeological parameter estimation using geophysical data. A review of selected techniques. Journal of Contaminant Hydrology, v. 45, pp. 3-34.

ISI. (1983). Indian standard methods of sampling and test (Physical and Chemical) methods for water used in industry, 122p.

Jackson, P.N., Taylor, S.D. and Stanford, P.N. (1978). Resistivity- porosity-particle shape relationships for marine sands, Geophysics, v.43.

Jacob, K and Sasthry, V.V. (1952). Miocene foraminifera from Chavara near Quilon, Travancore. Rec. Geol. Surv. Ind., v. 82 (2), pp 342-353.

Jensen, J.R. (1986). Introductory Digital Image Processing. A Remote Sensing Perspective. Prentice-Hall, New Jersey, 379 p.

John W. Koster and Dennis L. Harry. (2005). Effects of water saturation on a resistivity survey of an unconfined fluvial aquifer in Columbus, MS AGU Hydrology Days conference proceedings.

Johnston, C.D. (1987). Distribution of environmental chloride in relation to subsurface hydrology. J. Hydrology, v. 94, pp. 67-88.

Junge, C.E. and Wrby, R.T. (1958). The concentration of chloride, sodium, potassium, calcium and sulphate in rainwater over the United States. Jour. Meteorol., v. 15, pp.417-25.

Kalinski, R.J., Kelly, W.E. and Bogardi, S. (1993). Combined use of geoelectrical sounding and profiling to quantify aquifer protection properties, Ground Water, v. 31, pp. 538-544.

Karanth, K.R. (1987). Groundwater assessment development and management. Tata Mc Graw-Hill, New Delhi, 720p.

Kaya, G.K. (2001). Investigation of groundwater contamination using electric and electromagnetic methods at an open waste-disposal site: a case study from Isparta, Turkey, Environmental Geology, v. 40, pp. 725-731.

Keller, G.V. and Frisehknecht, F.C. (1966). Electrical methods in geophysical prospecting. Pergamon Press, New York.

Kelley, W.P. (1940). Permissible Composition and concentration of irrigation waters, Proc. A.S.C.E., v. 66, 607p.

Kelly, E.W. (1976). Geoelectric sounding for delineating ground water contamination. Ground Water v. 14, pp.6-11.

Kelly, W.E. and Frohlich, R.K. (1985). Relations between aquifer electrical and hydraulic properties. Ground Water, v. 23, pp. 182-189.

Kelly, W.R. and Wilson, S.D. (2003). Temporal changes in shallow groundwater quality in Northeastern Illinois. Proceedings of the 12th Annual Illinois Groundwater Consortium Conference, Makanda, IL.

Khan, M.A. and Moharana, P.C. (2002). Use of remote sensing and Geographical Information System in the delineation and characterization of groundwater prospect zone. J. Indian Soc. Remote Sensing, v. 31 (3), pp. 131-141.

King, W. (1882). General sketch of the geology of Travancore state. The Warkalli beds and associated deposits at Quilon in Travancore. Rec. Geol. Surv. Ind., v. 15 (2), pp. 93-102.

Kiran, K. and Anji Reddy. M. (2006). Mapping saline water affected villages, Geospatial Today 2006, v. 4., Issue 10, pp 38-42.

Koefoed, O. (1979). Geosounding Principles, (1) Resistivity sounding measurements, Elsevier, Amsterdam, 276p.

Kossinski, W.K. and Kelly, W.E. (1981). Geoelectric sounding for predicting Aquifer Properties, Groundwater, v.19, pp. 163-171.

Krishnamurthy, J. and Srinivas, G. (1995). Role of geological and geomorphological factors in ground water exploration. A study using IRS LISS-II data. International Journal of Remote Sensing, v. 16.

Krishnamurthy, J., Kumar Venkatesa Kumar, N., Jayaraman, V. and Manivel, M. (1996). An approach to demarcate ground water potential zones through remote sensing and Geographic Information System, International Journal of Remote Sensing, v. 17 (10).

Krumbein, W.C., and Sloss, L.L. (1963). Stratigraphy and Sedimentation.

Kumar, C.P. and Pitchamuthu, C.S. (1953). The Tertiary limestone of Travancore. Quart. Jour. Geol. Min Met. Soc. India, v. 5, pp. 85-98.

Kumar, W., Ashok, and Srivastava, S.K. (1991). Geomorphological unit, their geohydrological characteristics and vertical electrical sounding response near Munger, Bihar. J. Indian Soc. Remote Sensing, v. 19 (4), pp. 205-215.

Lal Thompson. (2004). Hydrogeology of Alleppey Districyt, Kerala – An approach through remote sensing and GIS applications. PhD thesis submitted to the Tamil Yniversity, Tanjavur.

Laluraj, C.M., Gopinath, G. and Dinesh Kumar, P.K. (2005). Groundwater chemistry of shallow aquifers in the coastal zone of Cochin, India. Applied Ecology and Environmental Research v. 3 (1), pp. 133-139.

Lampman. (1995). Susceptibility of groundwater to pesticides and nitrate contamination in predisposed areas of southwestern Ontario,Water Quality Res.J.Canada, v.30 (3), pp. 443-468.

Langmuir, D. (1997). Aqueous environmental chemistry, Prentice-Hall, Inc, New Jersey, 600p.

Lashkaripour, G.R. (2005). An investigation of groundwater by geoelectrical method: A case study in southeast Iran, Journal of spatial hydrology, v.3, n.1 fall 2003.

Lattman, L.H. and Parizek, R.R. (1964). Relationship between fracture traces and occurrence of ground water in carbonate rocks. Jour. Hydrol., v. 2, pp. 73-91.

Lenores, E., Arnold, E., Greenberg, R. and Trussell (ed)., (1989). Standard Methods for the Examination of Water and Waster Water, 17th Ed. Pub., American Public Health Association, Washington, D.C.2005.

Lillesand, T.M. and Keifer, R.W. (1994). Remote sensing and image interpretation. John. Wiley and Sons, Inc., New York, USA, 724p.

Lloyd, J.W. and Heathcote, J.A. (1985). Natural inorganic hydrochemistry in relation to ground water–An Introduction, Clarendon Press Oxford, 296p.

Loke, M.H. (1997). Dr. Electrical imaging surveys for environmental and engineering studies a practical guide to 2-D and 3-D surveys.

Manivasakam, N. (1996). Physico-chemical examination of water, sewage and industrial effluents. 3rd edition.

Manivel, M. and Aravindan, S. (1997). Groundwater pollution in and around Sempattu area, Tiruchirappalli, Tamil Nadu. The geography teachers, India, v. 4(2), pp. 22-23.

Matias, M.J.S. (2002). Squary array anisotropy measurements and resistivity sounding interpretation, Journal of Applied Geophysics v. 49, pp. 185-194.

Matson, K.C. and Fels, J.E. (1996). Approaches to automated water table mapping, in Proceeding of the Third International Conference on Integrating GIS and Environmental Modeling, Santa Barbara, Calif.: National Center for Geographic Information and Analysis, 12p.

Matthess, G. (1982). The properties of Groundwater, John Wiley, New York, 406p.

Matthess, G. and Pekdeger, A. (1981). Concepts of a survival and transport model of pathogenic bacteria and virus in groundwater. Proc. Intl. Sympo. on quality of groundwater, Amsterdam.

Mazac, O., Cislerova, M. and Vogel, T (1988). Application of geophysical methods in describing spatial variability of saturated hydraulic conductivity in the zone of aeration, J. Hydrology, v. 103, pp. 117-126.

Md. Munir Hussain, Choudhury, J.T.A., Md. Nunul Osman and Marina Rahman. (2005). Hydro-chemical analysis of groundwater of Hajiganj Upazila, Chandpur District, Bangladesh, Bangladesh Arsenic Mitigation Water Supply Project.

Melanchthon, V.J., Raju, V.N., Ramakrishna, A. and Bhowmick, A.N. (1988). Resistivity survey for mapping fresh water pockets. J. Assoc. of Expl. Geophys. v. IX (2), pp. 71-78.

Mohammed Abdullah Al-Saleh. (1992). Declining Groundwater Level of the Minjur Aquifer, Tebrak Area, SaudiArabia Geographical Journal, v. 158, n. 2, pp. 215-222.

Mollard, J.D. (1988). The role of photo-interpretation in finding groundwater resources in Western Canada, Proceedings 2nd seminar on Air-photo interpretation in the development of Canada, pp, 57-75.

Moony, H.L. (1980). Handbook of Engineering Geophysics, v. 2, Electrical Resistivity, bison Instrument, Minneapolis, Minn.

Moore, G.K. and Duestsch, M. (1975). ERTS- Earth Resource Technology Satellite imagery for groundwater investigations, Groundwater, v. 13 (2), pp. 214-226.

Morgan, C.O. and Winner, M.D. Jr. (1962). Hydrochemical facies in the 400 foot and 600 foot sands of the Baton Rouge Area, Louisiana; United States Geological Survey, Professional Paper 450-B, p 120-121.

Mukherjee, A.L. and Das, D. (1980). Morphometrical analysis for watershed management plan with special reference to aquifer recharge: A case study. Seminar volume. Seminar on "Aquifer characteristics and ground water management in Eastern India": March 1996 pp. 36-42.

Nag, S.K. (1998). Morphometric analysis using remote sensing techniques in the Chaka sub-basin, Purulia district, West Bengal. Journal of the Indian Society of Remote Sensing v. 26 (1&2), pp 69-76.

Nag, S.K. (2005). Application of lineamanet density and hydrogeomorphology to delineate groundwater potential zones of Baghmundi block in Purulia district, West Bengal. Journal of the Indian Society of Remote Sensing 33(4).

Nag, S.K. and Chakraborty, S. (2003). Influence of rock types and structures in the development of drainage network in hard rock area. Journal of the Indian Society of Remote Sensing v.26 (1&2), pp. 69-76.

Nair, N.J.K., Reghunathan Pillai, K. and Nalinakumar, S. (1987). Environmental Geomorphic Atlas, Kerala Coastal Zone. Final Report submitted to the Department of Environment, Govt. of India, 113p.

Nair, N.M. (1990). Structural trend line patterns and lineaments of the Western Ghats, South of 13° latitude. Jour. Geol. Soc. of India, v.35, pp.99-105.

Nayak Purna Rao, Y and Sudheer, K. (2006). Groundwater Level Forecasting in a Shallow Aquifer Using Artificial Neural Network Approach Water Resources Management, v. 20, n. 1, pp. 77-90 (14).

Oreelana, E. and Mooney, H.M. (1966). Master curves and tables for vertical electrical soundings overlayered structures. Interciencia, Madrid.

Ottle, C. Maggar, D.V. and Griward, G. (1989). Remote sensing application to hydrological modelling, Jour. Hydrol., v. 105, pp. 369-384.

Paliwal, B.S. and Khilnani, M. (2001). Electrical resistivity data to assess aquifer parameters for better interpretations of hydrogeology: A study of the Nagaur region Rajasthan, eds. Bhu. H and Agrawal. Proc. of the National Seminar on ground water resources, Dept. of geology, MLS University, Udayapur, pp. 48-67

Patangay, N.S. (1977). Application of surface geophysical methods for groundwater prospecting, in lectures on Exploration Geophysics for geologists and engineers (eds. Bhimashankaram, V.L.S. and Gaur, V.K., pub. AEG, Hyderabad), pp. 375-404.

Patra, H.P., Bagchi, T.C., Chakraborty, A. and Roy, K.K. (1972). Geophysical cum-geological investigation for ground water around Kharagpur railway station complex.

Paulose, K.V. and Narayanaswamy, S. (1968). The Tertiaries of Kerala Coast. Mem. Geol. Soc. of India, v.2, pp.300-308.

Perry, J.J., Amyard W.H. and Taranik, J.V. (1988). A lineament analysis of Yucaa Mountain. Nevada. The proposed high level nuclear waste repository (Abs.), Thematic Conference on Exploration Geology organized by ERIM, U.S.A. Summary v. 43.

Peter, C.Trescott. (1969). Groundwater resources and hydrogeology of the western annapolis valley, Nova Scotia by province of nova scotia department of mines groundwater section report 69- 1.

Philip, G. and Singhal, B.B. (1991). Importance of geomorphology for hydrogeological study in hard rock terrain – An example from Bihar plateau through remote sensing. Indian Jour. Earth Sci., v. 19 (4), pp. 177–188.

Piper, A.M. (1944). A graphic procedure in the geochemical interpretation of water analyses, Trans. Am. Geophy. Union, v. 25, pp. 914–928.

Prabhakar Rao, G. (1968). Age of the Warkalli Formation and the emergence of the present Kerala coast. Bull. Nat. Inst. Sci. v.38 (1), pp.449-456.

Pratap, K., Ravindran, K.V. and Prabakaran, B. (2000). Groundwater prospect zoning using remote sensing and geographical information system: A case study in Dala- Renukoot area, Sonbhadra district, Uttarpradesh, Jour. Ind. Soc. Rem. Sens., v. 28 (4), pp. 249-263.

Raghava Rao, K.V. (1975). Groundwater Exploration, Development and long term aquifer management in Kerala. Proc. Symp. Mineral Resources of Kerala and their utilization, Trivandrum, pp.30-36.

Raghunath, H.M. (1987). Geochemical surveys and water quality. Groundwater, Wiley Eastern Limited, New Delhi, pp. 343- 347

Raha, P.K., Sinha Roy, S. and Rajendran., C.P. (1983). A new approach to the lithostratigraphy of the Cenozoic sequence of Kerala. Jour. Geol. Soc. of India, v. 24, n. 7, pp.325-342.

Rajendran, C.P. (1987). Occurrence of fossil remains in Warkalli sediments (type area) and its Stratigraphic significance. Curr. Sci., v. 56., pp. 534-536.

Rajiv Chopra, Raman Deep Dhiman and Sharma, P.K. (2005). Morphometric Analysis of sub-watersheds in Gurdaspur District, Punjab using remote sensing and GIS techniques. Journal of the Indian Society of Remote Sensing, v. 33, n. 4, pp. 531-539.

Rajmohan, N and Elango, L. (2006). Hydrogeochemistry and its relation to groundwater level fluctuation in the Palar and Cheyyar river basins, southern India. Hydrological Processes v. 20, issue 11.

Ramakrishnan, M. (1988). Tectonic evolution of the Archaean high-grade terrain of south India. Jour. Geo. Soc. of India, v.31, pp.118-120.

Ramalingam, M. and Venugopal, K. (2004). Remote sensing and GIS applications in water resources. Indian Society of Geomatics News letter, special issue on Water Resources, v.10, n. 1, pp. 24-33.

Ramanujachary, K.R and Balakrishna, S. (1985). Resistivity investigations in different geological terrains, Groundwater news, NGRI, pp. 1-14.

Rao, B.R.J. and Datta, A.K. (1976). Foraminiferal and Ostracod fauna of the early Miocene beds of Kerala coast and their stratigraphic significance. General Proc. Of workshop on coastal sedimentaries of India south of 180N latitude, ONGC, Madras, pp. 33-34.

Ravindran, K.V. (1997). Drainage morphometry analysis and its correlation with geology, geomorphology and groundwater prospects in Zuavari basin, Couth Goa. Using remote sensing and GIS, Proc. Nal Sym- remote sensing fir natural resource with special emphasis on water management, held at Pune during Dec. 4-6. 1996, pp. 270-296.

Ravindran, K.V., and Jayaram, A., (1997). Ground water prospect of Shahbad Tehsin, Baran District, Eastern Rajasthan A Remote Sensing Approach, J. Indian Soc. Remote Sensing v. 25(4), pp. 239-246.

Ray, R.G. (1960). Aerial photographs in geologic interpretation and mapping. U.S. Geol. Surv. Professional Paper, v.373, pp. 227

Richard Whittecar, G., Ali A., Nowroozi and James R. Hall. (2005). Delineation of Saltwater Intrusion through a coastal borrow pit by resistivity survey. Environmental and Engineering Geoscience, v.11, n.3, pp. 209-219.

Richards, C.J., Roaza, H.P. and Pratt, T.R. (1996). Applying geographic information systems to ground water assessments. Proceedings of AWRA symposium on GIS and Water Resources held in Ft. Lauderdale, Florida, USA, 1996. Florida: Ft. Lauderdale.

Roy, A. and Niyogi, D. (1961). Geological and Geophysical investigations for ground water around Hijli, District Midnapore. Unpublished Report submitted to Department of Geology & Geophysics, Indian Institute of Technology, Kharagpur, India, 62 p.

Ruhi Ferdowsian, David J. Pannell, Clare McCarron, Arjen Ryder and Lisa Crossing Explaining groundwater hydrographs: separating atypical rainfall events from time trends Sustainability and Economics in Agriculture GRDC ProjectUWA251 SEA Working Paper 00/12.

Sabins, Jr. F.F (1987). Remote Sensing Principle and Interpretation, 2nd edn, Freeman, San Francisco, 449p.

Sakthimurugan, S. (1995). Hydrogeological studies and simulation of contaminant migration in and around Dindigul, Anna district, Tamil Nadu, Ph.D Thesis (unpublished), M.S. University, Tirunelveli, 214p.

Sakthimurugan, S. and Balasubramanian, A. (1991). Resistivity measurement over granular porous media saturate with fresh and salt water, Regional Sem. Groundwater Development problems in Southern Kerala, pp. 43-53.

Sameena, M., Ranganna, G., Krishnamurthy, Mukund Rao and Jayaraman, V. (2000). Targeting Groundwater Zones And Artificial Recharge sets using Remote Sensing and GIS techniques. Abs. 12th Convention IGC. pp. 113-114. M.L. Sukhadia University, Udaipur, India.

Sander, P. (1997). Water well siting in Hard rock areas: Identifying promising targets using a probabilistic approach, Hydrogeology Journal, v. 5 (3), pp. 32-43.

Sanjay K. Jain, Rathore, D.S. and Sharma, K.D. (2004). Remote sensing and GIS applications in the management of water resources development. Indian Society of Geomatics News letter, special issue on Water Resources, v.10, n. 1, pp. 15-23.

Sankar, K. (2002). Evaluation of groundwater potential zones using remote sensing data in upper Vaigai River basin, Tamilnadu, India, J. Indian Soc. Remote Sensing, v. 30 (3), pp. 119-129.

Santasmita Das and Dr. Paul, P.K. (2006). Selection of Site for Small Hydels Using GIS in the Himalayan Region of India Journal of spatial Hydrology, v. 6, n.1.

Santhosh, M. and Drury, S.A. (1988). Alkali granites with Pan African affinities from Kerala, South India. Jour. Geol., v. 96, pp. 616-626.

Saraf A.K. and Choudhury P. R. (1998). Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites International Journal of Remote Sensing, v. 19, n. 10, pp. 1825-1841(17).

Sarkar, B.C., Deota, B.S., Raju, P.L.N. and Jugran, D.K. (2001). A Geographical Information System Approach to evaluation of groundwater potentiality of Shamri Micro-Watershed in the Shimla Taluk Himachal Pradesh. J. Indian Soc. Remote Sensing, v. 29 (3), pp. 151-164.

Sarma, J.V.V. and Sarma, N.K. (1982). Geomorphometric studies of Upper Sarada river basin, Proc. Sem. hydrological investigations during the last 25 years in India, pp. 217-224.

Sarma, R.K. and Sharma, T.K. (1987). Groundwater and tube well irrigation, A text book on - Hydrology and water resources, Dhanpet Rai and Sons, New Delhi.

Sathiyamoorthy, K. and Banerjee, B. (1985). Resistivity surveys locating brine pockets in the Little Rann of Kutch, Gujarat, Jour. Assoc. Exploration Geologists, v. 5 (3), pp. 8-14.

Sawyer, C.N. and McCarty, P.L. (1967). Chemistry for sanitary engineers. 2nd ed., McGraw-Hill, New York, 518p.

Schneider, R. (1961). Correlation of groundwater levels and air-temperatures in the Winter and Springs in Minnesotta, U.S.Geological Water Supply, Paper 1539-D, 14p.

Setzer, J. (1966). Hydrologic significance of tectonic fractures detectable on air photos, Groundwater, v .4, pp. 526-534.

Shahid, S., Nath S.K., and Patra, H.P (2000). Ground water assessment and management within typical laterites around Salboni, District Midnapur (W.B.), Journal of Indian Water Works, v. XXXII (2), pp. 101-106.

Shahid, S., Nath, S.K., Sircar, A. and Patra, H.P. (1999). Estimation of model parameters from one-dimensional vertical electrical sounding data using evolutionary programming technique, Acta Geophysical Polonica, v. XLVII (3), pp. 335-348.

Shamsuddin Shahid and Sankar Kumar Nath. (2003). GIS Integration of Remote Sensing and Electrical Sounding Data for Hydrogeological exploration J. of Spatial Hydrology v.2, n.1.

Shao Q, Campbell N.A., Ferdowsian R, O'Connell D. (1999). Analysing Trends in Groundwater Levels, A report prepared for Agriculture Western Australia as Part of a National Land and Water Resources Audit Project. Report Number: CMIS 99/37

Sharma, D. and Jugran, D.K. (1992). Hydronorphological studies around Pinjaur-Kal Amb area, Ambala distrivt (haryana), and Sirmour distrivt (Himachal Pradesh). J.Indian Soc. Remote Sensing, v. 29(4), pp. 281-286.

Singhal, B.B.S. and Gupta R.P (1999). Applied Hydrogeology of fractured rocks, Kulwer Academic Publishers, The Netherlands, 400p.

Singhal, D.C. (1984). An integrated approach for groundwater investigation in hard rock areas. A case study; International workshop on rural hydrogeology and hydraulics in fissured basement area, pp. 87-93.

Sinha Roy, S. (1981). Tectonic control of coastal lagoon formation in passive continental margin: example from Kerala. In: Institut. Symposium in coastal Lagoon, UNESCO, Bordeanre, (Abstract) Full Paper in Oceanologia Acta.

Sinha Roy, S. and Mathai, T., (1980). Development of Western continental margin of India and Plateau uplift as related to geology and tectonics of Kerala. In: Status Problems and programme in Indian Peninsular shield, 1979. Institute of India Peninsular Geology., pp. 235-271.

Smith, D.G., and Jol, H.M. (1995). Ground penetrating radar, antenna frequencies and maximum probable depths of penetration in Quatenary sediments. Journal of Applied Geophysics, v. 33, pp. 93-100.

Soman, K. (1997). Geology of Kerala. Geological Society of India. Pub., Bangalore, India. 277p.

Soman, K., Nair, N.G.K., Golabyev, V. N. and Arakelyan, M.M. (1982). Age date on prematities of South Kerala and their tectonic significance. Hour. Geol. Soc. Of India, v.23, pp. 458-462.

Srinivasa Vittala, S., Govindaiah, S. and Homme Gowda, H. (2004). Morphometric Analysis of Subwater sheds in the Pavagada Area of Tumkur District, south India Using Remote Sensing and GIS techniques, j. Indian Soc Remote Sensing, v. 32 (4), pp. 351-362.

Srinivasa Vittala, S., Govindaiah, S. and Homme Gowda, H. (2005). Evaluation of groundwater potential zones in the sub-watersheds of North Pennar river basin around Pavagada, Karnataka, India using Remote sensing and GIS techniques. Journal of the Indian Society of Remote Sensing v. 33, n. 4, pp 482-493.

Srivastava, P.K. and Bhattacharya. A.K. (2000). Delineation of groundwater potential zones in a hard rock terrain of Bargarh District, Orissa using IRS Data. J. India Soc. Remote Sensing, v. 28 (2&3), pp.129-140.

Srivastava, V.K. (1997). Study of drainage pattern of Jharia coal field (Bihar), India, through remote sensing technology. Journal of the Indian Society of Remote Sensing v. 32(4), pp. 351-362.

Stiff, H.A. Jr. (1951). The interpretation of chemical water analysis by means of patterns, Jour. Petrol. Tech., v. 3 (10), Tech., Note 84, pp. 15-16.

Stube, M.M and Johnston, D.M. (1990). Runoff volume estimation using GIS Techniques, Water Resource Bulletin, v. 26(4), 1990.

Subramaniam, M.R. (1964). The Teritiary sedimentation of Kerala coast. Int. Geol. Congress, 24th secession.

Sumanovac, F., and Weisser, M. (2001). Evaluation of resistivity and seismic methods for hydrogeological mapping in Karst terrains, Journal of Applied of Geophysics, v. 47, pp. 13-28.

Taylor, C.J., and Alley, W.M., (2001). Ground-water-level monitoring and the importance of long-term water-level data: U.S. Geological Survey Circular 1217, 68p.

Teeuw, R.M. (1999). Groundwater Exploration Using Remote Sensing and A Low-Cost Geographical Information System, Hydrogeology Journal, v. 3 (3), pp. 21-30.

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A. (1990). Applied Geophysics. Cambridge University press, 770p.

Thiagarajan, R. (1980). Geology and geomorphology of Kerala. Geo. Surv. India, Sp. Pub n.5, pp. 55-60.Thornthwaite, C.J. An Approach Towards the Rational Classification of Climate. Geogr. Rev. v 38, n.1 (1948).

Thornthwaite, C.J. (1948). An Approach Towards the Rational Classification of Climate. Geogr. Rev. v .38, n.1.

Thornthwaite, C.J. and Mather J.R. (1955). The Water Balance. Publ. in Climat. Lab. of Climate. v. 8, n.1.

Tickell, S.J. (1994). Dry land salinity hazard map – The northern territory of Australia, Darwin, Power and Water Authority, Report 54/94D, 43p.

Tiwari, A. and Rai, B. (1996). Hydrogeomorphological mapping for groundwater prospecting using Landsat MSS images- A case study of part of Dhanbad district. J. Indian soc. Remote Sensing, v. 24 (4), pp. 281-285.

Todd, D.K. (1980). Groundwater Hydrology, 2nd edn. John Wiley New York, 535p.

Trivedi, R.K. and Goel, P.K. (1986). Chemical and biological methods for water pollution studies. Environmental publication, Karad.

Troisi, S., Fallicos, C., Straface, S., and Migliari, E. (2000). Application of kriging with external drift to estimate hydraulic conductivity from electrical resistively data in unconsolidated deposits near Montato Uffugo, Italy. Hydrogeology Journal, v. 8, pp. 356-367.

Twart, A.C., Hoather, R.C. and Law, F.M. (1974). Water Supply, Edward Arnold Ltd., London.

Van Overmeeren, R. (1989). Aquifer boundaries explored by geoelectrical measurements in the coastal plain of Yemen, A case of equivalence. Geophysics, v. 54, pp.38-48.

Varadarajan, K. and Balakrishnan, M.K. (1980) Kerala coast – a Landsat's view. Geo. Sur. of India, Sp. Pub.no.5, pp. 67-69.

Varadarajan, K. and Nair, K.M. (1978). Stratigraphy and Structure of Kerala Tertiary basin. Jour. Geol. Soc. of India, v.19 (5), pp. 217-220.

Venkateswara Rao, B. and Briz-Kishore, B.H. (1991). A methodology for locating potential aquifers in a typical semi-arid region in India using resistivity and hydrogeologic parameters, Geoexploration, v. 27, pp. 55-64.

Venugopal, T.N. (1998). Hydrogeological investigation in the Arkavathi river basin – A tributary of Cauvery river, Karnataka, Ph.D Thesis, Mysore University, p. 224.

Walsh, S.J. 1988. Geographic information systems: An instructional tool for earth science educators. J. Geogr. v. 87 (1), pp.17-25.

WHO. (1984). Guidelines for drinking water quality, V.I. Recommendations, Geneva.

Wilcox, L.V. (1955). Classification and use of Irrigation waters, U.S. Department of Agriculture circle, Washington, 969p.

Wolfe, P.J., and B.H. Richard. (1996). Integrated goephysical studies of buried valley aquifers. Journal of Environmental & Engineering Geophysics, v. 1, pp. 75-84.

Yadav, G.S., and Abolfazli, H. (1998). Geoelectric soundings and their relationship to hydraulic parameters in semiarid regions of Jalore, northwestern India. Journal of Applied Geophysics v. 39, pp. 35-51.

Young, M.E., de Bruijin, R.G.M., and Salim Al-Ismaily, A. (1998). Reports: Exploration of an alluvial aquifer in Oman by time-domain electromagnetic sounding, Hydrogeology Journal, v. 6, pp. 383-393.

Zaporozec, A. (1972). Graphical interpretation of water quality data. Ground Water, v. 10(2), pp. 32-43.

Zohdy, A. A. R., (1989). A New Method for The Automatic Interpretation of Schlumberger and Wenner Sounding Curves, Geophysics, v. 54 (2), 245p.

Zohdy, A.A.R., and Bisdorf, R.J. (1989). Programs for the automatic processing and interpretation of Schlumberger sounding curves in Quick Basic. U.S. Geological Survey Open File Report 89-137-2, 64p.

Zohdy, A.A.R., Eaton, G.P. and Mabey, D.R. (1974). Application of surface Geophysics to groundwater investigations, USGS, chapter 1, 116 pp.