GEOHYDROLOGICAL STUDIES OF MULKI RIVER BASIN KARNATAKA, INDIA

THESIS

SUBMITTED FOR THE AWARD OF DEGREE OF

DOCTOR OF PHILOSOPHY

IN

CIVIL ENGINEERING

BY

RADHAKRISHNAN K.

Register No: 03221103A

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL, P.O. SRINIVASNAGAR – 575 025, MANGALORE

INDIA

AUGUST 2013

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA SURATHKAL

D E C L A R A T I O N

by the Ph.D. Research Scholar

I hereby **declare** that the Research Thesis entitled

GEOHYDROLOGICAL STUDIES OF MULKI RIVER BASIN KARNATAKA, INDIA

which is being submitted to the

National Institute of Technology Karnataka, Surathkal

for the award of the Degree of

Doctor of Philosophy

in

CIVIL ENGINEERING

is a bonafide report of the research work carried out by me.
The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

RADHAKRISHNAN K.
Reg. No. 03221103A
Department of Civil Engineering

Place: NITK-Surathkal
Date : 08-08-2013

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
SURATHKAL

C E R T I F I C A T E

This is to certify that the Research Thesis entitled

GEOHYDROLOGICAL STUDIES OF MULKI RIVER BASIN KARNATAKA, INDIA

Submitted by

RADHAKRISHNAN K.
(03221103A)

as the record of the research work carried out by him,

is accepted as the Research Thesis

in partial fulfillment of the requirements for the award of Degree of

Doctor of Philosophy

Dr. K.N. Lokesh
Research Guide & Chairman, RPAC

Dr. Katta Venkataramana
Chairman – DRPC & Head
Department of Civil Engineering

Dedicated

To

my mentor Guru

Sri. B.R. Jagannatha Rao

Retired Deputy Director General, Geological Survey of India

&

Those

Who inspired Me

lifting my spirits

to

Move Ahead

ACKNOWLEDGEMENTS

The outcome of this thesis, like any other research is not the single handed job, but is a culmination of the support and motivation of many people who contributed their time and spirit to the achievement of the same. Knowing the limitation of wordily expression of my gratitude to all who inspired and supported me throughout, still I ink it down since it is from the bottom of my heart.

I express my deep sense of gratitude and indebtedness to Dr. K.N. Lokesh, Professor, Department of Civil Engineering, National Institute of Technology Karnataka (NITK) for his understanding, constant support and guidance throughout the work. I profusely thank him for his genuine warmth of a friendly supervisor who offered constructive criticism and pains taking patience instilling inspiring motivation during my studies.

My thanks are due to the Director Dr. Sandeep Sanchethi and the former directors of NITK who extended all the facilities in the Institution and department.

I sincerely thank Dr. Katta Venkataramana, Head of the Civil Engineering Department and Chairman, DRPC; Dr. Ravishankar A.U., Dr. A. Narasimhan and Dr. R. Shivashankar former Heads of Civil Engineering Department at NITK who encouraged and supported me throughout my association with the department providing moral and technical facilities.

I am highly indebted to Dr. Gopal Mugeraya, Professor of Chemical Engineering Department and Dr. S.M. Hegde, Professor of Mathematical and Computational Department who offered their critical comments and invaluable suggestions to improve my research work as the members of my Research Progress Assessment Committee. My special thanks to Dr. Gopal Mugeraya for boosting my morale and facilitating me to submit my research work instilling positive spirits in me.

I acknowledge the constant encouragement and support of all the friendly teaching and non-teaching faculty of Civil Engineering Department and Applied Mechanics and Hydraulics Department at NITK who made me to rise to the occasion supporting me throughout my research work which found fruition in this thesis. I place on records with gratitude the help rendered by Mr. Manohar Shanbogue, Environmental Engineering Laboratory of NITK Surathkal for his ever smiling patience and experienced assistance during my laboratory analysis of water samples. My thanks are also due to Dr. Srihari, Professor of Environmental Engineering for permitting me to utilise the Environmental Engineering Laboratory facilities at NITK.

I extend my thanks to Dr. Narayana Shenoy, Professor and Head of the Department of Civil Engineering, Manipal Institute of Technology (MIT), Manipal for going through the initial drafts and reviewing it, Dr. Venkata Reddy, Professor of Geology, NITK Surathkal, Dr. Naveen Chandra, BSNL, Udupi, Dr. G.S. Dwarakish, Professor of Applied Mechanics, NITK, Surathkal and Dr. Mohandas Chadaga, Professor, Department of Civil Engineering, MIT, Manipal for their moral support and encouragement. I express my gratitude to Dr. Umesh Chandra, Assistant Professor of Geology, Vivekananda College of Engineering and Technology, Puttur for sparing some relevant software and literature. His thanks are also due to Mr. Sanath Kumar, Lecturer, Department of Civil Engineering, Nagarjuna College of Engineering and Technology, Bangalore and Mr. Vipin Joseph Markose, Senior Research Scholar, Mangalore University for helping him during the GIS analysis. I express my deep gratitude to Ms. Thangamani, Assistant Professor, Prince Shri Venkateshwara Padmavathy Engineering College, Chennai for her help rendered during the Land Use/ Land cover map preparation. I express my thanks to Dr. Udaya Kumar G. and Dr. Suresh Y.R., Professors of Civil Engineering, N.M.A.M.I.T, Nitte for some fruitful discussion during the preparation of hydrometeorology chapter. I thank my students especially Chethan, Guruprasad, Prijesha, Vaishali, Nithesh, Sunitha, Dechamma, Ganesh Kamath, Mahesh Kamath, Shreyas, Sirisha, Sooraj, Pallavi, Mamatha, Austin and Mr. Ramesh Rao who assisted me during my field and laboratory works.

I express my gratefulness to Mr. M.K. Rao, Senior Geologist and to Mr. Krishnappa, Director, Karnataka circle, Geological Survey of India, Bangalore for allowing me to refer the unpublished Geological Maps of Dakshina Kannada. I also extend my thanks to Mr. Kannan, Senior Director and HOD, Map Division, Geological Survey of India, Bangalore for facilitating to procure the resource map of Dakshina Kannada and Udupi districts. The helps rendered by the presidents and officials of various Panchayats in the study area through sparing the Panchayat resource data are sincerely acknowledged.

I express my gratitude to Mr. Srinivas Adiga, former director, NNRMS, ISRO and Mr. Anil, Engineer, RSI software for their help extended during the procurement of satellite imageries and training offered in ERDAS imagine software. I express my gratitude to Directors/Officers of the Natural Resource Data Management Systems (NRDMS) and Dakshina Kannada Zilla Panchayat, Mangalore, the Karnataka Agricultural and Forest department officials at Karkala and Moodbidri for sparing the historical and current rainfall and meteorological data of the study area. I also express my sincere thanks to Dr. B.M. Ravindra, Deputy Director, Department of Mines and Geology (DMG), Dakshina Kannada district, Karnataka state for sparing the water level fluctuation data of the DMG owned observation wells in the study area. I express my deep sense of gratitude to all the researchers and scientists who permitted to access their scientific papers and analysis software which they published or developed. I express my sincere gratitude to Mr. A.C. Dinesh, Senior Geologist, Geological Survey of India for providing the bAd Calculator software developed by him for preparation of rose diagrams and analysing the geomorphological parameters and validating the results.

I acknowledge with deep gratitude the constant encouragement and help rendered by Dr. Niranjan N. Chiplunkar, principal, NMAMIT, and management of Nitte Education Trust for permitting me to register for the part time Ph.D. programme and making available the facilities with the Institution. I express my sincere gratitude to all the teaching and non-teaching faculty of Civil Engineering Department, NMAMIT, Nitte for their support and encouragement extended during the period of my research work.

I place on records my deep sense of gratitude to my mother Janaki for her blessings, unstinting support and understanding. I don't have words to appreciate my friends and well-wishers for boosting my morale and enthusing me not to give up in life. Finally I wish to thank all those who have directly or indirectly helped and encouraged me during my doctoral programme to successfully complete the thesis.

RADHAKRISHNAN K.

ABSTRACT

Water being the vital natural resource of concern, the sustainable development of the same is of much importance at present. A river basin or a watershed is a clearly defined basic unit to understand the water resources considering groundwater and surface water as a single resource for integrated development in a given terrain. The complex relationship that exists among soils, geology, land forms, rainfall, vegetation, land use practices and the condition of water resources is better understood and managed in a river basin or watershed. Characterizing and deriving the sustainable developmental plan for watershed, demands accurate information pertaining to its land use, soil, geology, geomorphology, meteorology, hydrogeology, quality of water, etc., in spatial domain. The erstwhile Dakshina Kannada district being blessed with many watersheds and heavy rainfall needs special attention in this regard thanks to its fast development in the coastal part of India. Mulki, a typical midland draining river basin in this coastal part of Karnataka in India has been studied and analyzed in order to understand the various aspects of its groundwater resources for the sustainable development and management. To attain this, an integration of various field and laboratory data of current and historical interest have been carried out in a spatial domain with different thematic maps derived from Survey of India (SOI) Toposheets and imageries of Indian Remote Sensing (IRS) Satellites. They have been visually and digitally processed and analyzed using geoinformatic technologies and statistical analysis.

The geomorphologic studies and morphometric analysis revealed that the Mulki river having a drainage area of about 350 sq. km. is a 6^{th} order, very coarse textured, rectilinear, dendritic, midland draining basin of matured topography with high discharge capacity and meager groundwater potential. Mulki River Basin has elbow bends in its midland area other than an offset of the NE-SW trending land mark structural ridge and WNW-ESE trending lineaments indicating structural deformation into its major course. Morphometric analysis and geomorphologic evidences such as pediplain, structural ridge, lateritic plateaus (mesas) of varying geological origin and time, waterfall, high sinuosity, cross bedding, meandering course and elbow bends in the middle stretches, river terraces, water pooling, etc., suggest neotectonic activity in this area which may be responsible for the groundwater storage and movement.

The geology of the study area depicts rocks of Archaean to the Recent age, exposing fifteen lithological units representing Sargur group and Peninsular Gneissic complex of Archaean age, South Kanara Granite batholith, younger intrusive basic dykes and acid veins of Palaeoproterozoic age, laterites of Cenozoic age and coastal sands of Quaternary period and the Recent sediments of the alluvial deposits. But predominantly the rocks like Granite/Granitic gneisses with occasional laterite capping and unconsolidated river and marine sediments, occupy the area. Basic intrusives like dolerite and gabbro, and acidic intrusives like pegmatite and quartz veins are found at many places shaping the hillocks, ridges and mounds in the terrain. Many sets of joints are parallel to the river course in the ENE-WSW directions other than NE-SW, N-S, E-W and NW-SE which influence or guide the groundwater potential of the area. The NNW-SSE trending dolerite dykes are numerous and relatively abundant in granite. Foliations and joints in rocks dip either north or northeast directions favouring groundwater storage and movement in the upstream directions. Geology of the area and lineament studies confirm the earlier report of three active faults in the area which are responsible for the offset of the river and recent neotectonic activity in this area. There are some lineaments in the basin extending up to the Western Ghats which will be highly potential for groundwater explorations. NE-SW trending structural ridge of intrusive rock (mainly gabbroic) forms a major lineament in the eastern part of the basin. There are about seven genetic types of soils spread over the basin, broadly divided into four types depending on geohydrological condition as alluvial soils, loamy soils, gravelly clayey skeletal soil and lateritic soils of different encrustations. The soils and geological structures such as lineaments and joints in the otherwise hard and impervious rocks have an influence on the geohydrological conditions of this study area.

Water quality, being an important criteria for deciding the suitability for drinking and irrigation purposes, about 21 important physico-chemical water quality parameters (of groundwater and surface water) have been analyzed and seven irrigation water quality parameters have been computed for 154 randomly selected water samples collected during pre-monsoon seasons of 2008 and 2009; and 95 samples collected during post-monsoon period of 2009 to understand the utility values of the same and its spatial variation. Statistical analysis of the above parameters and a comparison with acceptable drinking water quality standards revealed that most of the water samples collected during pre- and post-monsoon periods found to have quality parameters well within permissible limits. However, the spatial variation maps of vulnerable parameters and vulnerability map of water quality has been prepared, and it has been found that certain parameters like Fe, Ca, Chloride, pH, TDS, Total Hardness and Turbidity were beyond permissible limit of potable water during pre-monsoon period especially near to the coast. Salt water intrusion has taken place up to about 7 km. from the coast along the river course. The majority of the post-monsoon water samples are found to be acidic in nature influenced by the geology of the area. The drinking water qualities of surface water sources during pre-monsoon have been affected more compared to groundwater sources in the study area. There is a significant difference between the bore well water chemistry and open well water chemistry, as well as the pre-monsoon water quality and post-monsoon water quality. Bore well waters, except near the coast, are influenced by the silicate weathering of the igneous rocks, whereas the open well waters are influenced by the clay mineral reaction except those near the coast, influenced by the chloride dissolution from the salt water ingression in the study area. The total hydrochemistry in the study area is dominated by alkaline earth (64%) and strong acids (55%) with carbonate hardness (33%) (secondary alkalinity) and primary salinity (26%) influenced by the weathered granitic gneisses and leached laterite besides the influence of saline water. During pre-monsoon season Rock interaction Domain is having a dominating influence on the groundwater whereas in post-monsoon season Precipitation domain influences open well water. The difference in the hydrochemistry during pre-monsoon and post-monsoon periods indicates the influence of weathering, infiltration, mixing and leaching in the study area. A great variation is noticed in irrigation water suitability based on different characteristics and is found to be 95% (pre-monsoon) and 100% (post-monsoon) based on EC, 100% (pre-monsoon) and 98% (post-monsoon) based on SAR, 84% (pre-monsoon) and 33% (post-monsoon) based on % Na, and 60% (pre-monsoon) and 03% (post-monsoon) based on RSC. All groundwater samples fall under no problem category of sodium water type irrigation quality with low to medium salinity. Therefore, they can be used for irrigation on all types of soil with little danger of exchangeable sodium. An analysis of the Water Quality Indices (WQI) and its mapping in spatial and temporal domain in the study area found to be a faster and better tool in assessing and rating the suitability of groundwater for drinking water based on quality weightage. The very high WQI at the coastal front near the mouth of the river and its extension along the river course upstream up to a certain distance during pre-monsoon indicates the influence of saline water and its migration along tidal water in this area. The temporal variation in distribution pattern and density of WQI points to the significant role of precipitation and infiltration playing in the determination of water quality.

As a part of systematic identification, quantification and management of regional hydrologic regime, geophysical investigations especially Vertical Electrical Soundings (VES) have been carried out at about 129 selected stations representing different terrains in the basin to understand the subsurface lithology, groundwater quality and aquifer characteristics at different depths. The data has been interpreted using resistivity cross sections and correlated with a few available drilled data/geology of the area in order to understand the aquifer characteristics and resource potential. Saline water ingression studies also have been carried out using these data along the coastal stretch.

From the hydrometeorological analysis, the study area is found to be falling under tropical humid climatic zone where hot humid climate prevails throughout the year. The rainfall of the study area falling in the wet climatic zone is uneven and shows an overall decreasing trend for the last four decades. From the last four decade's rainfall data analysis, the average annual rainfall is found to be about 4264.09 mm falling in the wet climatic zone giving rise to an average volume of about $1496.70 x 10^6$ m^3 storm water per annum in the basin. The rainfall spread for about five to six months in the study area shows spatial and temporal variation in its distribution with a minimum of 66 days at Mulki during 1973 to 161days at Karkala during 1978. The average daily rainfall also found to be varied from 12.3mm during 1973 to 53.2mm during 1997. A balance in distribution of rainfall found to be characteristic of this area where deficient years or dry years almost equaled the wet years in all three point stations during the 30 years observations period. Temporal and spatial variations in rainfall have been noticed in the study area, where 87% of rainfall is contributed from southwest monsoon spread over a period of four months and the decrease in trend is from Karkala to Mulki in a northeast to southwest direction. However, the moving average curve of rainfall denotes a nine year trend of continuous variation in its pattern and periodicity. The frequency probability analysis of magnitude and return period of rainfall in the basin demonstrate that rainfall above 3176.9mm have a chance of returning every year with 67% to 98% dependence. The computed water budget of the area shows an actual evapotranspiration of 30% of rainfall against the maximum potential evapotranspiration of 46.6% and a runoff about 771.16 x 10^6 cubic meters per annum from the study area.

Groundwater assessment and management studies revealed that there is a surplus availability of storm water and groundwater balance in the 43 villages of the 17 Panchayats falling in the Mulki River basin, but not managed properly underutilizing its huge potential. Estimation of groundwater recharge and potential has been carried out using water table fluctuation data obtained from three observation wells other than 36 observation wells periodically monitored for a period of one year. The average annual decline in the water table of the study area is found to be about 6.85m during last one decade giving rise to a draft of 2,404.35x10^6 cubic meters per annum. Approximate water demand and utilization has been estimated based on Village Panchayat resource data. Even with a net annual recharge of 24,302 ha.m. of groundwater available for development in the study area, the annual net draft for utilisation from the aquifer is estimated to be 993.93 ha.m. only and a balance potential of 23,308 ha.m. is available for future utilization, but unevenly distributed in the area and lost as groundwater flow. Cultivated area of about 27% in the basin has been found in clustered strips irrigated by a good practice of rain fed traditional structures like tanks, ponds, etc. About 73 such structures ideally located with a concentration of one in 4.8 sq. km. spread over an area of 13.5 hectares with a maximum storage capacity of 0.23 MCM have been identified, delineated and mapped from the study area. Rehabilitating old Rainwater Harvesting Structures (RWHS) and increasing the density of tanks at the rate of at least one in one sq km. area can use more than 50 per cent of the runoff water considering the future needs of development. Case studies carried out to understand the viability of these resources proved these to be very effective. About 56 microwatersheds, significant in the sustainable development, spread over an area of about 46.14 sq. kms. comprising 13% of the Mulki River basin have been identified and delineated. Development of microwatersheds along with rehabilitation of abandoned and silted traditional rainwater harvesting structures found to be an efficient management practise to improve the water resource of this area for drinking and irrigational purposes.

Geoinfomatic application found to be a very useful tool in the preparation of various thematic maps and integration of data for efficient planning and management of the water resources in the study area for sustainable development.

TABLE OF CONTENTS

	CONTENTS	PAGE NO.

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

CHAPTER 1

INTRODUCTION

1.1 GENERAL: Water, the vital resource for the sustenance of life on earth is becoming a rare commodity due to various reasons and the sustainable development of the same is of much importance at present. The ever growing demand for water due to the rapid growth in population, increasing agricultural activities, vagaries of monsoon coupled with fast urbanization and industrialization created an acute scarcity for water. The indiscriminate exploitation and improper management worsened the situation, where much of the surface water and groundwater is being polluted due to disposal of human sewage and industrial effluents. As the concern over water resources and the environment increases, the importance of considering groundwater and surface water as a single resource has become increasingly evident.

All the civilizations of the world, ancient and modern were developed and thrived on the banks of the rivers, and the water played a vital role in the existence and sustenance of the same. A river basin is a topographically delineated area drained by a stream system, i.e., the total land area that is drained to some point by a stream or river. This is the basic natural hydrologic unit for integrated development of all resources in a given terrain. The complex relationship that exists among soils, geology, land forms, rainfall, vegetation, land use practices and the condition of water resources is better understood and managed in a river basin or watershed. The management of such a unit is a multi-phase integrated approach involving rational utilization of land and water resources for optimum production with minimum hazard to natural resources. Characterizing and deriving the developmental plan for watershed demands accurate information pertaining to its geomorphology, geology, soil, land use/land cover, meteorology, hydrogeology, quality and quantity of water, etc., in spatial domain.

Dakshina Kannada and Udupi, the coastal districts of Karnataka being bestowed with the highest rainfall next to Cherrapunji in India is threatened by the vagaries of nature even when a number of watersheds of varying scale exist. The spurt of developmental activities in the industrial, power, mining and agricultural sectors during recent years also has put tremendous strain on the land and fresh water resources of coastal Dakshina Kannada districts. The economy and sustenance of people in this part being controlled by the agricultural sector depends purely on the availability of water. The groundwater availability and its quality controlled by the geology, soil, topography and land use/land cover of this area play vital roles in the crop yield and sustenance of agriculture in this part of the country. The river basins or watersheds of various scales (Khan *et al*. 2001) spread in this area thanks to its undulating topography, may reveal the potentials for the sustainable development and management of this natural resource.

1.2 RIVER BASIN OR WATERSHED: In the glossary of geographical terms, a basin is the whole tract of a country drained by a river and its tributaries (Stamp and Clark 1981). A watershed is a hydrological unit that has been described and used as a physical-biological unit and also on many occasions, as a socio-economic-political unit for planning and management of natural resources (Sheng 1990). The dictionary of Ecology (Hanson 1954) defines a watershed as the total area of land above a given point on a waterway that contributes runoff to the flow at that point. A watershed is also considered as a subdivision of a drainage basin (Hanson 1954). The terms watershed, catchment area or drainage basins are used synonymously (Dutta *et al*. 2002). Drainage basin or watershed, a hydrologic entity forms a convenient, clearly defined and an unambiguous natural topographic unit available on the basis of stream network. The size of watershed is dependent on the size of the stream or a river, the point of interception of stream or river, the drainage density and its distribution. The concept of watershed as planning unit for development of land and water resources is widely accepted. In India, since 1974, various developmental projects such as Drought Prone Area Program (DPAP), Desert Development Program (DDP), Hill Area Development Program (HADP), etc., adopt watershed as basic unit for development. The All India Soil and Land Use Survey (1990) has identified six regions, 35 basins, 112 catchments, 500 sub-catchments and 3,237 watersheds over the entire country with specific spatial dimensions and prepared a Watershed Atlas of

India at 1:1 million scales. As per Central Groundwater Board (CGWB), Government of India records the southwestern coastal part of India has been designated as Periyar River basin, the 24th Indian River Basin in the Watershed Atlas of India. National Remote Sensing Agency (NRSA), Government of India during 1988 prepared district wise hydrogeomorphological map of the country using satellite data under National Drinking Water Technology Mission. Further these watersheds have been subdivided into subwatersheds, miniwatersheds and microwatersheds at various levels of hierarchy based on drainage network and areal dimension (NRSA 1995).

The Coastal belt of Karnataka, blessed with many river basins and watersheds of various levels (Khan *et al.* 2001), receives a heavy rainfall for about 4 to 5 months in a year with temporal and spatial variations. Yet the area experiences scarcity of fresh water during summer. Even the groundwater is prone to adverse effect of salt water intrusion which affects the crop yield in the coastal areas. The ultimate goal of watershed development and management is to achieve and maintain a balance between resource development to increase the welfare of the population and resource conservation, to safeguard resources for future exploitation and to maintain ecological diversity, both for ethical reasons and as an assumed pre-requisite for the survival of mankind. For this, a thorough understanding of this vital resource in its quantitative and qualitative form, and the influence of various physical and geological parameters on it at a natural hydrologic entity level such as a river basin or watershed is required.

Mulki, a typical midland draining river basin falling in this coastal part of Karnataka in India is of significance in order to understand the various aspects of its groundwater resources in temporal and spatial domains for the sustainable development and management. Mulki River basin falling in the Dakshina Kannada Districts of south west coast of India is codified as NTRV014, which is a sub basin of Netravati (NTRV) which again is a sub basin (No.1) of Periyar Basin (Fig. 1.1).

1.3 STUDY AREA: Mulki river basin (Fig. 1.2) bounded by North latitudes 13º02´28´´ to 13º12´12´´ and East longitudes 74º46´14´´ to 75º02´47´´ encloses an area of about 350.67 sq. km. spreads in 43 villages of 17 Panchayats sprawling in Karkala Taluk of Udupi district and Mangalore Taluk of Dakshina Kannada district.

It supports a huge population of about 0.2 million people with many commercial, educational and industrial establishments along with stretches of agricultural fields.

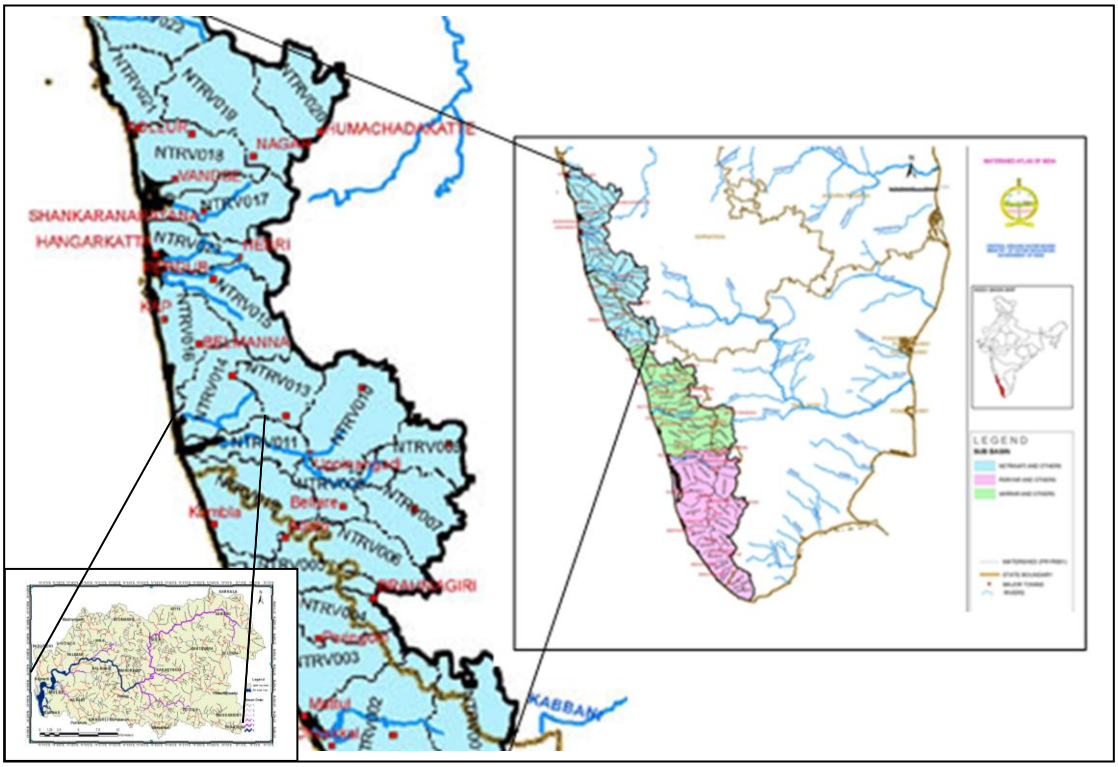

Fig.1.1 Mulki sub-sub basin (NTRV014) in the Netravati sub-basin of Periyar Basin in the Watershed Atlas of India (*after* CGWB, B'lore)

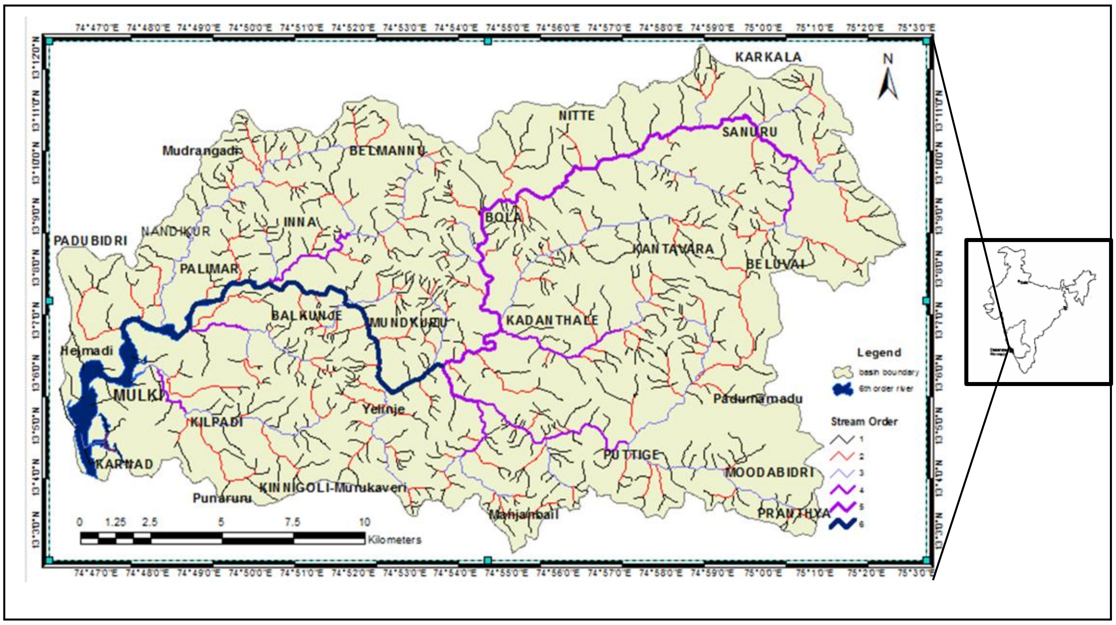

Fig.1.2 Location Map of the study area - Mulki River Basin

The Mulki river originates in the midland area at the foot hills of Western Ghats, flows through the hillocks and plains and takes a right angled turn near the coast before joining the Arabian sea near Mulki. The major Panchayats falling in this basin are Nitte, Sanoor, Bola, Kanthavara, Beluvai, Moodbidri, Puttige, Kallamundkur, Kinnigoli, Mundkoor, Belman, Inna, Palimar, Padubidri, Balkunje, Mulki and Kilpadi.

Agriculture is the major occupation of the people with a huge number of cattle and livestock supporting them. Paddy is the main cultivation. Other than paddy, coconut and arecanut farms are also present in the area. Cash crops like cashew, rubber, pine apple, sugar cane, jack fruit, mango, pepper, etc., are also grown in this area in addition to medicinal plants. Other occupations of the people include education, hotelier, beedi preparation, apparel making, quarrying, horticulture, poultry, wood works, fishing, trade and commerce. Small scale industrial establishments such as cashew factories, cashew nut and cake industries, coconut oils and rice mills, hollow blocks and building materials manufacturing, granite quarries and mechanized stone crusher units, etc., are found in the basin area. Other than small scale industrial belt in the Mulki area, giant industrial establishments in power generating sector like Suzlon and Nandikur Thermal Power Plant are also present in this area. The major portion of the basin area is bounded by Mangalore-Goa National Highway NH-66 (old NH-17) on the west and Mangalore-Pune National Highway NH-13 on the east; and Surathkal-Kinnigoli-Moodbidri State Highway on the south and Padubidri-Karkala State Highway on the north as its approximate boundaries. Well knitted rural and village roads of metaled and non-metaled nature built up by government and private agencies criss-cross the basin area connecting the people all over the basin. Konkan Railway also passes through the western part of the area parallel to the coast having Mulki and Padubidri Railway stations within the basin.

Since groundwater contributes about 80% of the drinking water requirements in the rural areas, 50% of the urban water requirements and more than 50% of the irrigation requirements of the basin, the booming urbanization, modern agricultural practices and fast industrial development apply stress on the water resources. The sustainable development and management of the water resources of this matured, midland rectilinear river basin with its peculiar geological, structural and morphological features flowing through many villages blessed with heavy rainfall and a balanced natural forest ecosystem, dotted with high density of traditional rain water harvesting structures is significant. The main land use/land cover in the area is rain fed agriculture, wasteland with/without scrubs in the plains, and undulating land and scrub forests with forest blanks on the hills. Due to paucity of groundwater for irrigation, the rain fed agriculture area lacks sufficient soil moisture to support good agriculture. The agriculture areas along the streams are constantly washed away and undergo sheet erosion, thus converting valuable agricultural land into unproductive wastelands. The degraded ecosystem has affected the life of the residents within the micro watersheds. There is always a scarcity of water for drinking and domestic use. The depleting vegetative cover has resulted in excessive soil erosion exposing barren rocky wastes. The steep hill slopes, barren cultivable land, depleting vegetative cover, ever increasing human and livestock population increased the problem of soil erosion, silting of tanks and ponds resulting in scarcity of drinking and irrigation water. In the light of all these, an integrated approach using geomorphologic, geological, hydrometeorological, geophysical, geochemical and geoinformatic studies have been carried out in Mulki River basin to understand the geohydrological conditions of this typical midland draining river basin for sustainable development.

1.4 RATIONALE BEHIND THE WORK: A lot of studies have been conducted in various river basins along the length and breadth of the country and the world. Water, being the elixir of life and an essential resource for any developmental activities is facing threats from various sectors due to its non-judicious exploitation and pollution due to population explosion and enhanced developmental anthropogenic activities. Integrated approach in understanding the phenomena and establishing the relationship between various influencing parameters such as geomorphology, geology, tectonics, meteorology, hydrogeochemistry etc., are required for the optimum utilization of this resource for sustainable development. Mulki, being a typical rectilinear coastal river basin in the west coast of India is in the flux of many developmental activities and is drastically draining out its essential water resources. Being the second highest rainfall area next to Cherrapunji in India, Mulki River basin is having its own problems of water scarcity due to the hard rock geology of the region. Despite having many watersheds of varying scale and high density of traditional rainwater harvesting structures, the area suffers from acute shortage of water during summer. Moreover, the area is having an interesting tectonic history evidenced from the course of river and basin shape interspersed with many lineaments, some even spreading across the basin and reaching up to the Western Ghats. But there are no systematic studies conducted, or exhaustive and reliable data available related to its water resources, especially the groundwater potential except the rainfall data at three stations and the water table fluctuation data from two observation wells set up by the government agencies. No runoff data is available for this basin since there is no stream gauging station set up in this river. No relationship has been established between the observed phenomena and the various parameters related to water resources in this area. Even though many groundwater extraction structures have been established in this area, the reliable data is not available. This requires generation of primary and secondary data and utilization of historical data of various parameters available to establish the relationship among them to address the geohydrological problems of this fast developing region. For a realistic understanding of the water resource potential for its judicial utilization through proper planning and management, generation of various maps and its integration is required. An integration of these maps and data in a GIS platform pertaining to its geomorphology, tectonic history, geology, lineaments, hydrogeochemistry, hydrometeorology, potential aquifer zones, hydrogeophysical data, potential zones for recharge, microwatersheds, traditional rainwater harvesting structures, land use/land cover map, etc., will definitely give an idea about the potential aquifers to be tapped and exploited for optimum utilization and sustainable development. This study will also help in understanding many of the phenomena around us related to the geohydrology of such river basins. Integrated approach of modern and advanced computing methods besides integrating traditional methodology with geophysics, remote sensing and Geomatics may help in exploring many unexplained and unexplored phenomena related to this domain.

1.5 OBJECTIVES: The main objective of the study is to understand and evaluate the geohydrological conditions of a typical midland draining coastal river basin through an integrated approach for the sustainable development and management of its water resources. The following are the objectives:

- Generation of base map, various thematic maps, geospatial databases and Digital Elevation Model (DEM) of the basin from SOI Topo sheets and satellite imagery using Geoinformatics.
- Geomorphologic studies and Morphometric analysis of the river basin to understand its influence on the geohydrological conditions of the area generating a detailed hydrogeomorphic map and Land Use/Land Cover (LU/LC) map.
- Analysis of the influence of geology and structure on the groundwater potential of the area by updating the geological map of the basin.
- Groundwater quality evaluation for drinking and irrigation purposes and understanding its spatial and temporal variation within the basin**.**
- Identification of groundwater potential zones and its spatial variation along with the influence of saline water ingression in the basin using Electrical Resistivity method.
- Analysis of the historical hydrometeorological data and understanding the relation of it with the groundwater recharge, potential and balance.
- Groundwater recharge assessment and management study through historical data, well inventories and water level fluctuation monitoring of a network of observation wells within the basin.
- Delineation of Microwatersheds and Traditional Rainwater Harvesting Structures (TRWHS) from Satellite imageries, and analysis of the same for sustainable development and management of water resources.
- Application of Geoinformatics with an integrated approach to understand the spatial and temporal distribution of groundwater potential and its variation in a quantitative and qualitative geo-environmental zone for sustainable development and management.

1.6 METHODOLOGY: In order to understand the groundwater potential and its quality in spatial and temporal domain, a river basin or watershed is ideal due to its natural physical boundary and typical characteristics. The various methods adopted to understand this invaluable natural resource have been detailed below (Fig. 1.3).

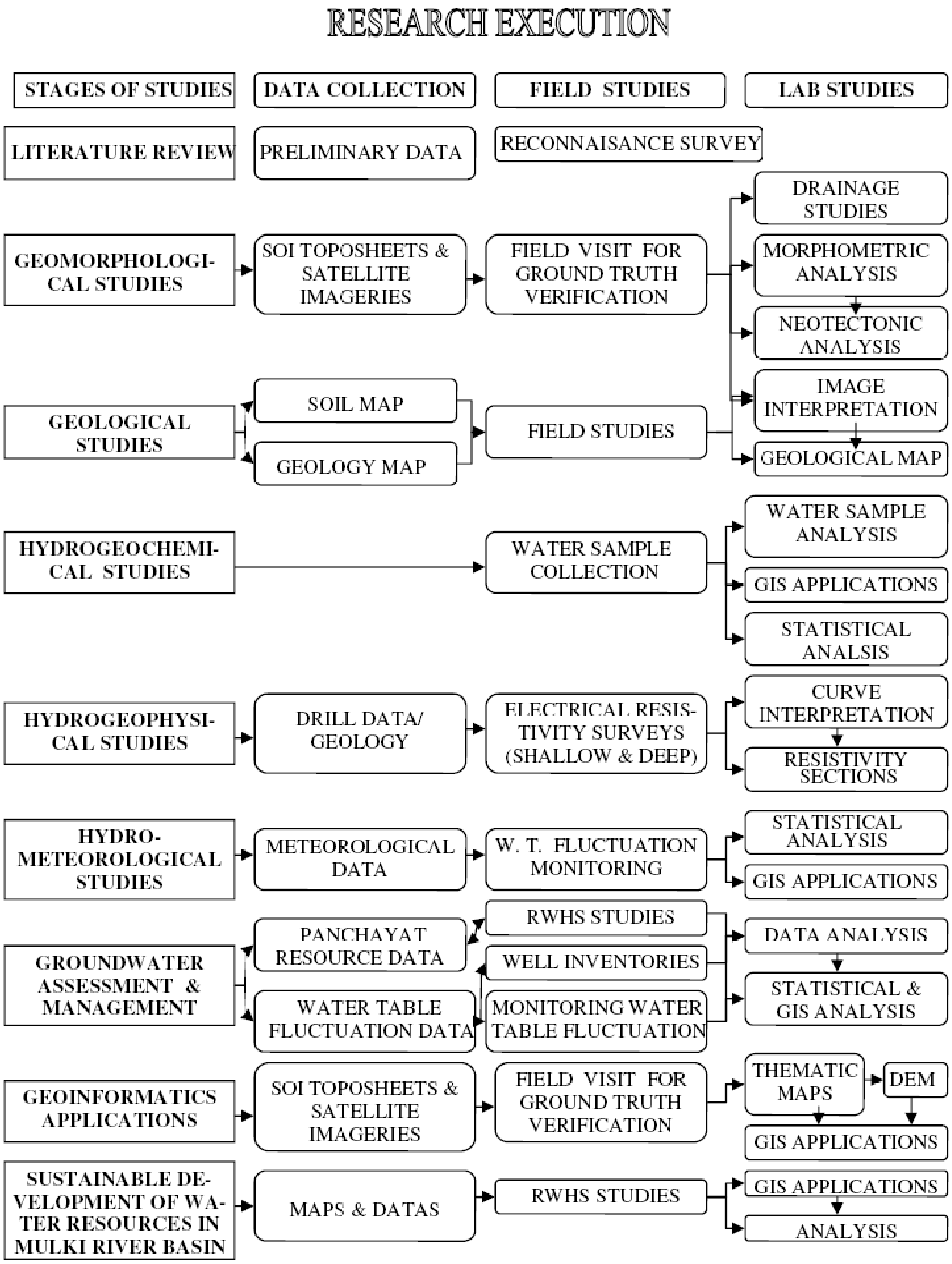

Fig. 1.3 Flow Chart showing methodology of Research carried out

i) The base map of the study area has been prepared from a mosaic of Survey Of India (SOI) Toposheets 48K/16NE, 48K/16NW, 48K/16SW & 48K/16SE (1:25,000 scale; SOI 1991) & 48 O/4 (1:50,000 scale; SOI 1996). And this has been updated using Indian Remote sensing Satellite (IRS) Resourcesat-1 LISS III imagery (IRS_P6_L3_05012005) of 23.5m resolution and LISS IV imageries of 5.8m resolution (IRS_P6_L4_MX_05012006). Image enhancement techniques and different band combinations were applied for better visualization, interpretation and creation of geospatial database and thematic maps using ERDAS Imagine 9.1 and ArcGIS 9.x & 10 versions software. Various thematic maps viz: Road network, Drainage network, Drainage Density, Contours, Slope, Digital Elevation Model (DEM), Lineaments, Geology, Soil, Hydrogeomorphology, Microwatersheds, Tanks, Land Use/Land Cover (LU/LC), etc., have been prepared, delineated and analyzed through manual and computer aided geoinformatic methods using the above.

ii) Morphometric analysis for various linear and areal basin characteristics has been carried out along with geomorphological studies. Basin and Drainage (bAd) program developed by Dinesh A.C. (2011) of Geological Survey of India and CalHypso ArcGIS extension program developed by Jose Vicente Pérez-Peña *et al.* (2009) of Universidad de Granada have been utilized for the morphometric analyses in addition to ArcGIS and ERDAS Imagine 9.x softwares.

iii) Geological map of the study area has been updated using satellite imageries and field observations, and 1:50,000 scale geological map of the area has been prepared. Lineament map of the study area has been prepared from the satellite imageries.

iv) Groundwater samples from randomly selected stations, mostly from public utility open wells and a few bore wells covering the entire basin along with limited surface water samples have been collected during pre-monsoon (154 samples during 2008 and 2009) and post- monsoon (95 samples during 2009) period and analyzed for about 21 physico-chemical parameters to understand their suitability for drinking water through a comparison with the drinking water standards. Moreover another seven irrigational water quality parameters have been derived out of these data to understand their irrigational suitability. The data has been analyzed for its temporal and spatial distribution and variation in the basin using standard statistical methods using Sigma Plot 11 software and GIS methods.

v) Geophysical studies viz: Vertical Electrical Soundings (VES) with Schlumberger array have been carried out extensively in 129 stations using IGIS made Signal Stacking Resistivity Meter (SSR-MP-AT) in different terrains of the Mulki River basin in order to locate the potential aquifers and understand the characteristics of them. Computerized Curve interpretation technique using IPI2 Win (Lite) program (Moscow State University 2002) has been utilized for the analysis of the VES values using inversion techniques, and the resistivity sections have been prepared. Five stations were selected exclusively near to the coastal stretch in the alluvial planes in order to understand the ingression of saline water in these shallow aquifers. Other stations were located in the plain land and plateau of laterite and hard rock terrain where the granite or granitic gneisses are exposed with a thin cover of soil. A maximum electrode spacing of 240metres has been taken in majority of the cases except at few stations where the possibility of spreading was not possible. In order to understand the deep fractures in this basin a maximum electrode spacing of 600m have been carried out at few selected places. Using Surfer 10 software, the data has been plotted to understand the three dimensional spatial variation in the study area.

vi) Rainfall data of about 40 years from the rain gauge stations in the study area has been collected and analyzed. Well density map has been prepared from the Survey of India (SOI) topographic sheets.

vii) Water table fluctuation data of last one decade for 3 open wells and 2 bore wells set up by the Karnataka State Mines and Geology Department has been analyzed for understanding the groundwater fluctuation in this basin along with the 36 observation wells periodically monitored for every month during the one year period in 2010. Assessment of groundwater recharge potential and management of the basin has been carried out using the data such as the population, livestock, forest area, cultivable area, etc., obtained from the Panchayats falling in the study area.

viii) High resolution satellite imageries have been used to delineate and map the Microwatersheds and Traditional Rainwater Harvesting Structures such as ponds, tanks, lakes, etc., to understand their significance in the rural water irrigation and possibilities of sustainable development and management.

ix) An overlaying of various thematic maps prepared and collateral data has been carried out using ArcGIS 10 and an integrated geohydrological analysis has been carried out for sustainable development and management of its water resources.

1.7 LOCATION AND COMMUNICATION: A network of roads connecting all townships and villages' criss-cross the area with the State and National Highways bordering the basin. The river basin is bounded by Cochin-Mumbai National Highway NH-66 (earlier NH-17) on west, Mangalore-Sholapur National Highway (NH-13) on the east, Surathkal-Kinnigoli-Moodbidri state highway (SH– 64A) on the south and Padubidri-Karkala state highway (SH-66) on the north as its boundaries. The Kinnigoli-Belman State highway (SH-66A) and Konkan Railway passes through the mid of the basin.

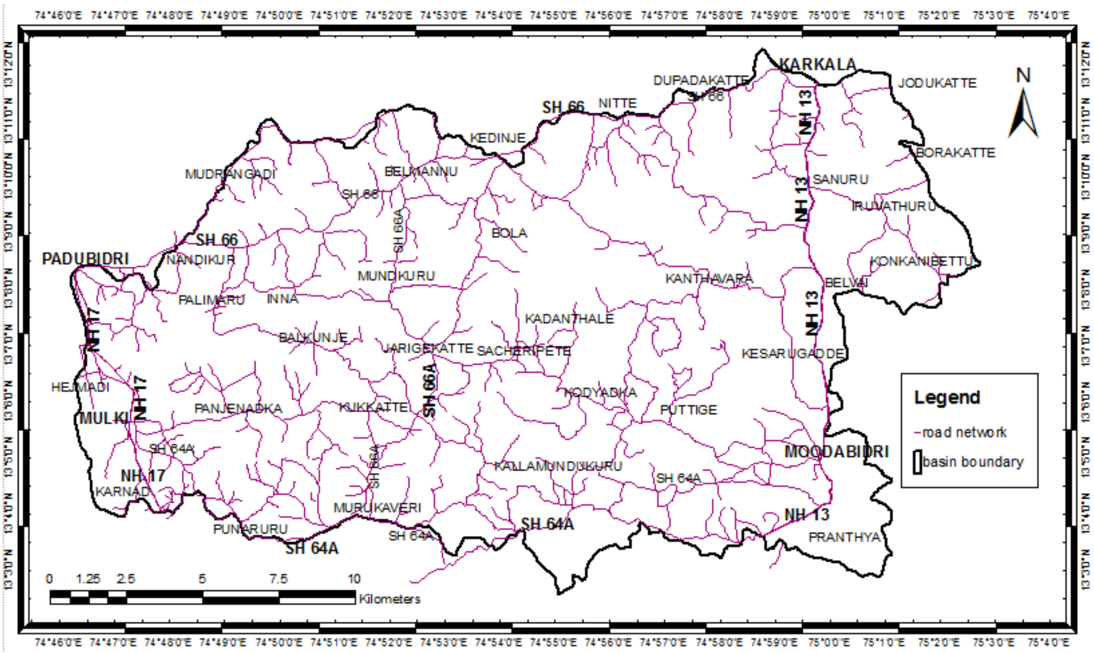

Fig. 1.4 Map showing Road networks in the Study Area

1.8 SOURCES OF INFORMATION: Data related to the basin was collected from various organizations as follows:

i. Base map: Base map of the basin was prepared from the toposheets (1:25,000 & 1:50,000 scale) published by Survey of India (SOI) during 1991 and 1996.
ii. Geological Map of the area based on resource map of Dakshina Kannada and Udupi districts (GSI 2005) has been prepared and updated with the field work in comparison with the map available with Geological Survey of India (GSI), Karnataka circle, Bangalore.
iii. Rainfall data: Precipitation data from the rain gauge stations in the basin has been collected from Agricultural and Meteorological departments, and Zilla Panchayat office, Government of Karnataka.
iv. Collateral data: Collateral data such as population, livestock, forest area, irrigation land, etc., has been obtained from Panchayats of the corresponding areas.
v. Meteorological data: The temperature, humidity and wind speed data were collected from meteorological departments.
vi. The water table fluctuation data of observation wells has been collected from Department of Mines and Geology, Government of Karnataka and Zilla Panchayat Office, Dakshina Kannada, Mangalore other than 36 observation wells set up in the entire basin for a period of one year.
vii. Aerial view of the study area has been obtained and studied using satellite imageries supplied by National Remote Sensing Centre (NRSC), Hyderabad, India and Google Earth.

1.9 ORGANIZATION OF THE CHAPTERS: The thesis has been organized under ten chapters, which are as follows:

Chapter 1 introduces the research topic with a general introduction, river basin details, study area details like geographical location and road networks, facts and figures about the basin collected from available sources, rationale behind the work and scope of the research, specific objectives and methodology of the present research with a brief structure of the thesis and organization of its chapters.

Chapter 2 deals with Morphometric analyses and Hydrogeomorphological features of the Mulki River basin.

Chapter 3 deals with the geology of the Dakshina Kannada districts in general and of the study area in particular.

Chapter 4 deals with the hydrogeochemical studies of groundwater in the study area and its suitability for drinking and irrigation purposes.

Chapter 5 deals with the measurement and applications of geophysical properties such as electrical resistivity of materials and rocks on earth surface, and its evaluation for the assessment of groundwater potential with the quality, and scope for its exploration.

Chapter 6 deals with the analysis of the available hydrometeorological data and describes the meteorological elements and their variations with time and space over the catchment. It also quantitatively evaluates the hydrometeorological data and prepares the water budget of the study area for the rational use, control and distribution of groundwater resources in the study area.

Chapter 7 deals with the geohydrological assessment of the basin and discusses the various management plans. It also deals with the water management studies of the basin with special reference to the microwatersheds and traditional rainwater harvesting structures.

Chapter 8 deals with the application of geoinformatics in the integration, extraction and analysis of various data obtained through different processes of studies and sources in the geohydrolgical studies of the basin.

Chapter 9 deals with the sustainable development of the water resources in Mulki River Basin through case studies on the rehabilitation of Traditional Rainwater Harvesting Structures (TRWHS) and Rooftop Rainwater Harvesting Structures.

Chapter 10 deals with conclusions and interpretations derived from the relevant studies carried out. It also explains the scope for the implementation of the findings and further scope for studies in the basin.

Chapter 2

Geomorphology

CHAPTER 2

GEOMORPHOLOGY

2.1 INTRODUCTION: Geomorphology is the study of landform, distribution of land and geologic interpretations thereof. The classification and identification of different landforms based on geological processes that are responsible for their origin is known as qualitative or descriptive geomorphology. And the study of quantitative aspects of geometry of the landforms is known as quantitative geomorphology. This analysis will help us in interpreting the geohydrological conditions of an area or a drainage basin.

Drainage basin is a catchment unit drained by a river system such that all flow originating in the unit is discharged through a single outlet. There may be many number of small basins within a bigger basin, and a surface water divide separates each one from its adjacent basin dividing the major watersheds into sub, mini and micro watersheds of various scales (Khan *et al.* 2001). Since the basin morphology controls the basin hydrology, it is necessary to understand the evolutionary development of the surface streams with in the basin. These studies will throw light on the lithology, structure, infiltration, runoff, erosional aspects, tectonic history and the stage of maturity of the basin itself. During the past, Morphometric studies were concentrated only on the qualitative aspects such as Consequent, Subsequent, Insequent (Davis 1889, 1895, 1899), Adventitious, Perennial, Intermittent, Ephemeral Streams, etc., (Horton 1945). In spite of the general renaissance of science in recent years, geomorphic studies as related in particular to the development of land forms by erosional and gradational processes still remains largely qualitative. Stream basins and their drainage basins are described as ‘youthful’, ‘mature’, and ‘old’, ‘poorly drained’ or ‘well drained’.

For a detailed groundwater investigation of a river basin, a thorough knowledge of the nature and behaviour of the surface streams in qualitative and quantitative terms are important pre-requisites. The drainage basin analysis is important in any hydrological investigation like assessment of groundwater potential, groundwater management, pedology and environmental assessment. Hydrologists and geomorphologists have recognized that certain relations are most important between runoff characteristics, and geographic and geomorphic characteristics of drainage basin systems. Morphometric analysis of drainage basins, which requires measurement of linear, areal and relief aspects is of great importance in understanding their hydrologic behaviour (Horton 1945, Strahler 1964, Schumm 1956, Melton 1957, Morisawa 1962).

2.2 GEOMORPHOLOGY OF KARNATAKA: Karnataka state is having a spectacular land form with high mountains, plateaus, residual hills and coastal plains derived from the oldest Precambrian to the youngest Recent marine sediments. The two prominent geomorphic zones i.e., the Coastal Landform Terrain in the west and the Elevated Interior Plateaus (Karnataka and Mysore Plateaus) in the east are separated by Western Ghats in the middle (Radhakrishna and Vaidyanadhan 1994).

The Elevated Interior Plateaus, being a prominent geomorphic zone is a mosaic of different lithological units viz: Mysore Plateau in the south and Karnataka Plateau in the north. The Mysore Plateau constituted mainly of igneous rocks, metasediments and metavolcanics is at an altitude of 900m. to 1200m. range. The Karnataka Plateau consists of Pre-Cambrians with Proterozoic (Kaladgi), lower Paleozoic (Bhima) and Eocene volcanics (Deccan Basalts).

The Western Ghats Scarp, separating the other two prominent landforms is an undulating landscape with numerous ridges and scarps of 900 to 1900 m. elevation. This NNW-SSE trending terrain constituted of Deccan Basalts in the north and pre-Cambrian metasediments, granites and gneisses in the south forms the major water divide between the East and West flowing rivers in the southern peninsular India.

The Coastal Landform Terrain, in which the study area falls, is further divided into two major physiographic units viz: coastal low land terrain and Kanara Pediplain surfaces. The Coastal Low Land Terrain, stretched in three districts of coastal Karnataka i.e. Dakshina Kannada, Udupi and Uttara Kannada covers an area of about 15,000 square kilometers with a low relief up to 20m. elevation from mean sea level and is having a coastline of about 320 km. length. Beaches in this zone oriented in the NNW-SSE is often broken by estuaries and lagoons with mangroves, beach ridges, sand dunes, tidal creeks, offshore rocky islands, etc. Kanara Pediplain with an average width of 50km. stretch lying between the coastal low land terrain and western flanks of Western Ghats is carved mainly out of lateritic mesas extending from Maharashtra in the north to Kerala in the south. Imprints of dendritic drainage pattern of west flowing rivers, gneissic inselbergs, meandering lobes and points are common features of Kanara Pediplain. Being a part of Coastal Landform terrain major portion of the Mulki river basin is covered by Kanara Pediplain with a small stretch of coastal lowland terrain.

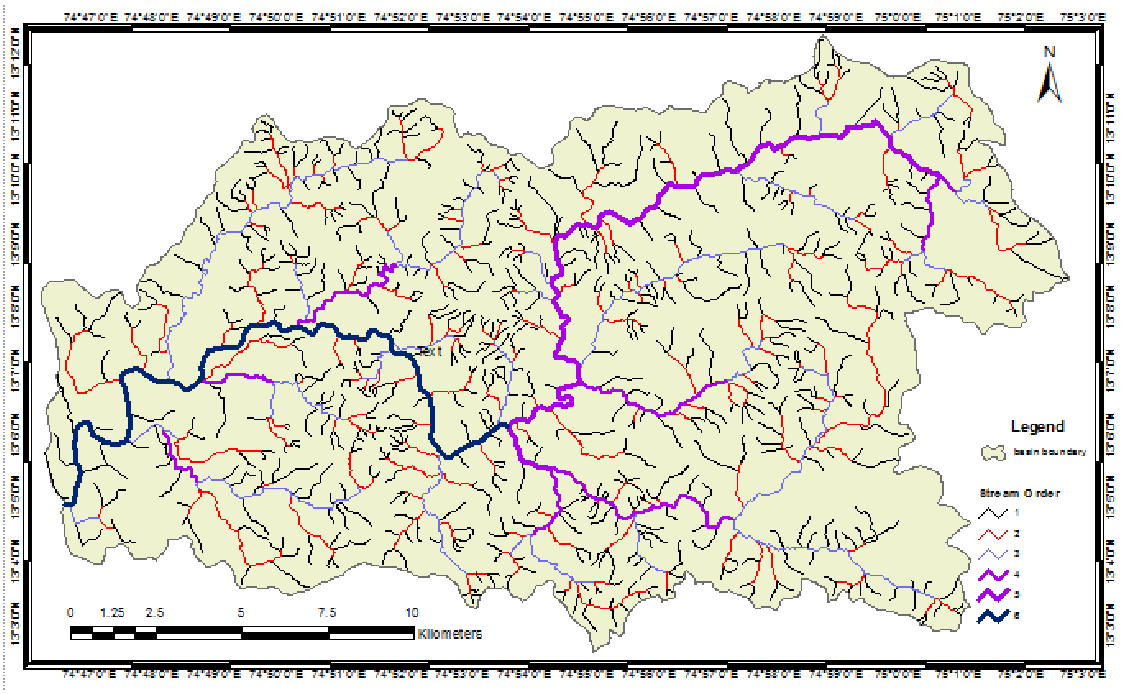

Fig. 2.1 Showing the Drainage network of Mulki River Basin

2.3 GEOMORPHOLOGY OF MULKI RIVER BASIN: Mulki is a closed rectilinear midland draining coastal river basin (Srivastava and Prasad 1982) falling in the Mulki-Pulikat lake axis (Subrahmanya 1994) in the South Indian Peninsular shield exhibiting dendritic pattern of drainage in general with rectangular drainage pattern. The river drains from East to West direction along a gentle slope trending in East of North East (E.NE) to West of South West (W.SW) direction (Fig. 2.1). The higher order streams show a parallel drainage pattern controlled by the N72ºE-S72ºW aligned lineament, the middle of the basin shows radial drainage pattern of lower order streams demonstrating a later originated structural control, and the western portion in alluvial terrain and eastern portion of the area in the lateritic plateau show again the dendritic pattern. The rectilinear watershed with its two prominent sharp elbow bends at two places (Fig. 2.1) in its main course, which deviate the river towards south in its middle reaches along with the water pools in the basin indicates neogenic tectonic activities in this area (Valdia 2001, Kale and Shejwalker 2008). Inland beach ridges at about 1.5 km from the present beach and twinning of this river basin (Bhat 1995) with Pavanje river at its mouth, aligned water divides and drainages with planation surfaces at different elevations in the basin point towards a tectonic influence and neogene uplift in the area (Subrahmanya 1994). These peculiar behaviour patterns of this river along with the abrupt deflections of streams, the formation of conspicuous loops with high sinuosity and stream ponding in the channels indicate neotectonic activity in this area (Valdia 2001). The formation of pediplain, river terraces, lateritic plateaus (mesas) of varying geological origin and time (Sankaran 1997), dissected flood plain deposits at its middle reaches at Sachcharepete, waterfall (knick points) at Nitte and steep meandering course, again stress for a morphometric analysis for understanding the neogene activities (Subrahmanya 1994,1996) in this area (Radhakrishnan and Lokesh 2011). An attempt is made in this chapter to quantify geomorphological characters of Mulki River basin along with its major geomorphic units.

The basin is composed of two major sub-basins of 5th order, eight sub-basins of 4th order and about 29 sub-basins of 3rd order streams (Fig. 2.2). Geomorphology of the area consists of coastal landforms such as beach, spit, estuary and lagoon; fluvial landforms such as Channel Islands, tidal creeks; denudation landforms such as inselbergs, lateritic mesas and isolated hillocks; and structurally controlled landforms like sharp elbow bends, entrenched meandering and sinuosity in river course other than steep ridges with displacement in alignment (Fig. 2.3). A huge residual resistive massive hill range trending N32°E-S32°W is exposed to great lengths along eastern side of the basin area forming a land mark feature giving steep slopes to the western side of the terrain and a lateritic plateau region on its eastern side. The Geomorphic features are largely governed by lithology like Granite, Granitic Gneiss, Laterite, basic intrusive like Dolerite and Gabbro, and their structures. These are generally jointed and river pattern normally follows the joint pattern. Tectonic activities also played an important role in the carving of these features.

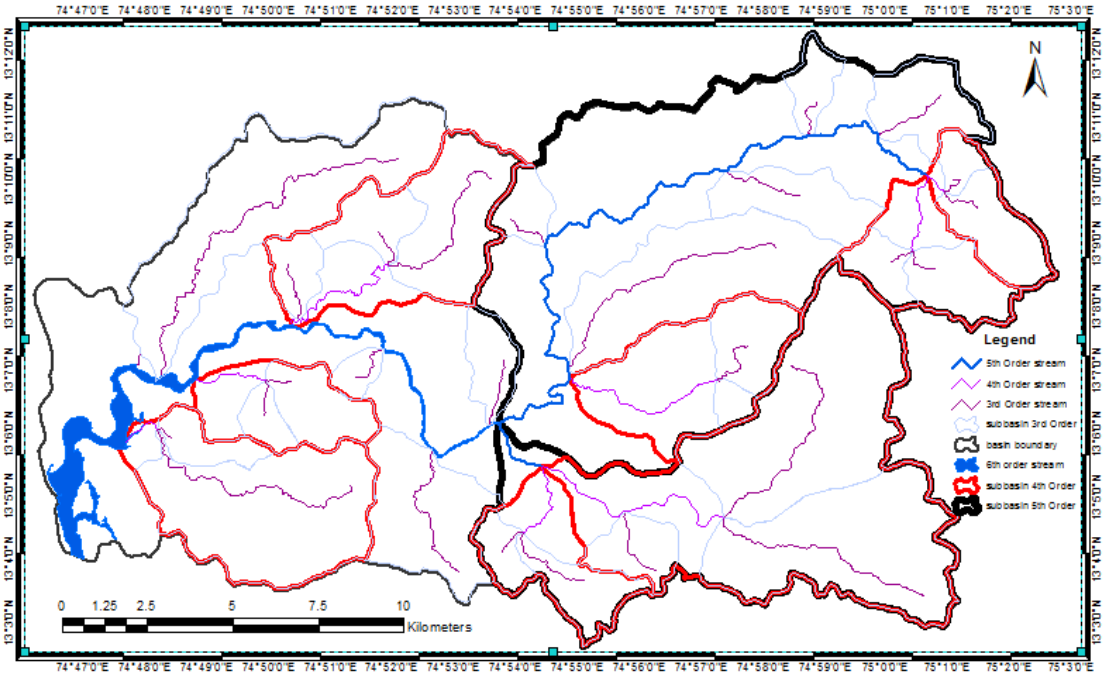

Fig. 2.2 Showing the Sub-basins of Mulki River Basin

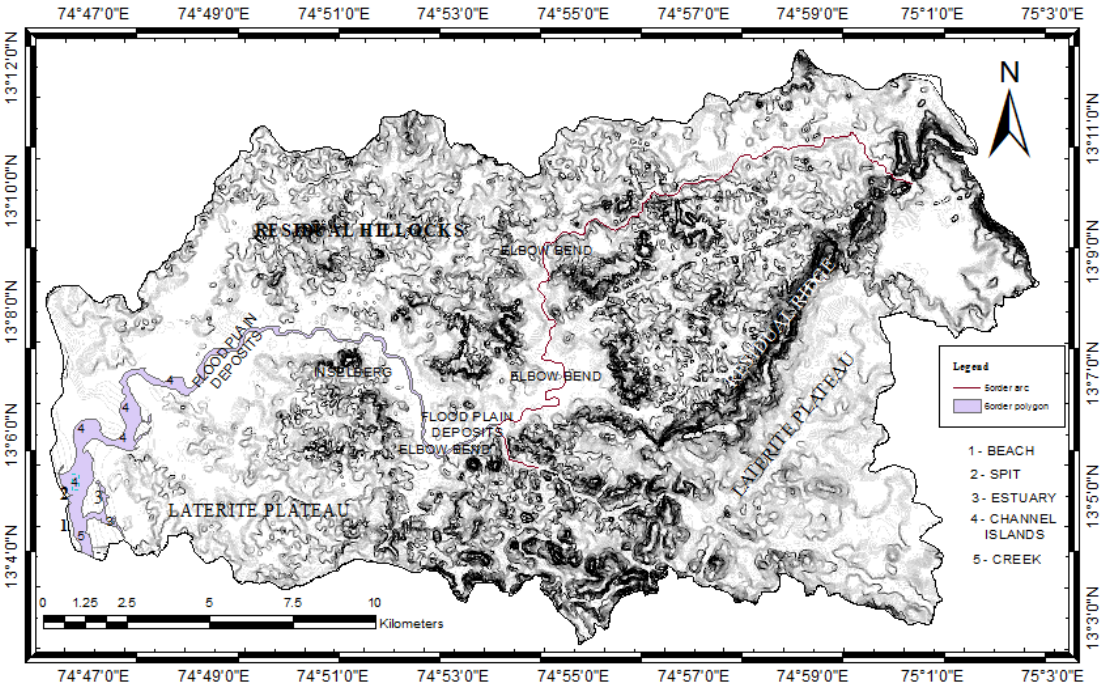

Fig. 2.3 Showing the Geomorphological features of Mulki River Basin

2.3.1 Rose Diagrams of Streams: Streams are the pathway for the circulation of surface water and the natural channels for recharging groundwater. Rivers are the most active and sensitive elements of the fluvial landscape and the tectonic activities will be amply reflected in the morphometry and geomorphology of the drainage basin, valley and network properties (Kale and Shejwalkar 2008). The trends of stream channels give an indication of the development of the morphology as well as the structural and tectonic activity in an area. The drainage networks are usually controlled by the slope and lineament pattern in an area. The first and second order streams trend may indicate the natural slope of the area since it follows the easiest path. The trend and flow of higher order streams usually is controlled by the lineaments such as joints, faults, dykes, etc., since it follows the naturally weak zones on the earth surface. This may be highly useful for deciphering the geohydrological conditions of an area. Since the rose diagrams can give the visual picture of the trend and its population, the same is utilized here to delineate the trend of the drainage pattern in this study area. The rose diagrams for the bearing and azimuth of streams of different orders as well as for the entire drainage network in the basin have been prepared using the visual basic software 'bearing and drainage (bAd) calculator' developed (Dinesh 2011) at Geological Survey of India, Mangalore.

The bearing and azimuth of the first order streams mainly indicate the natural slope of the terrain. Fig. 2.4 (a) indicates that more than 50% of the first order streams are running in the N10°W-S10°E to N10°E-S10°W directions. This may be due to the structural control over them. About 24% of the second order streams also fall in the N-S to N10°E-S10°W directions possibly indicating a structural control over them. Other major directions of them are in the NW-SE and NE-SW directions (Fig 2.5). More than 50% of the 3rd order streams trend in the NW-SE direction whereas about 21% of its trend each in the NE-SW and N-S directions (Fig. 2.6). This shows an influence of lineaments over them (Valdia 2001, Kale and Shejwalkar 2008). The major trends of the 4th order streams are in the N10°W-S10°E to N20°E-S20°W other than the E-W direction reflecting the slope and the trend of the structural features (Fig. 2.7).

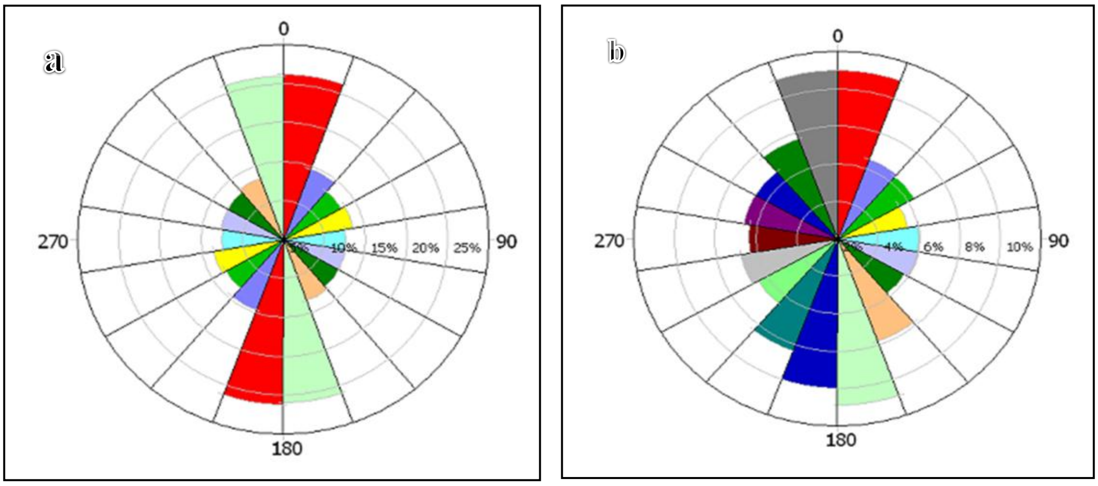

Fig. 2.4 a. & b. Rose diagrams of the 1st order streams (a. bearing & b. azimuth) in Mulki river basin

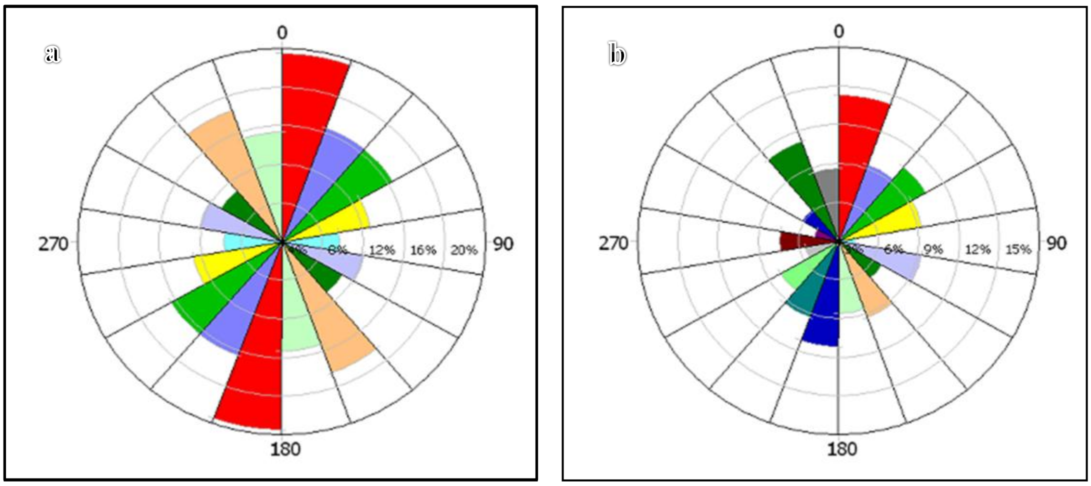

Fig. 2.5 a. & b. Rose diagrams of the 2nd order streams (bearing & azimuth) in Mulki river basin

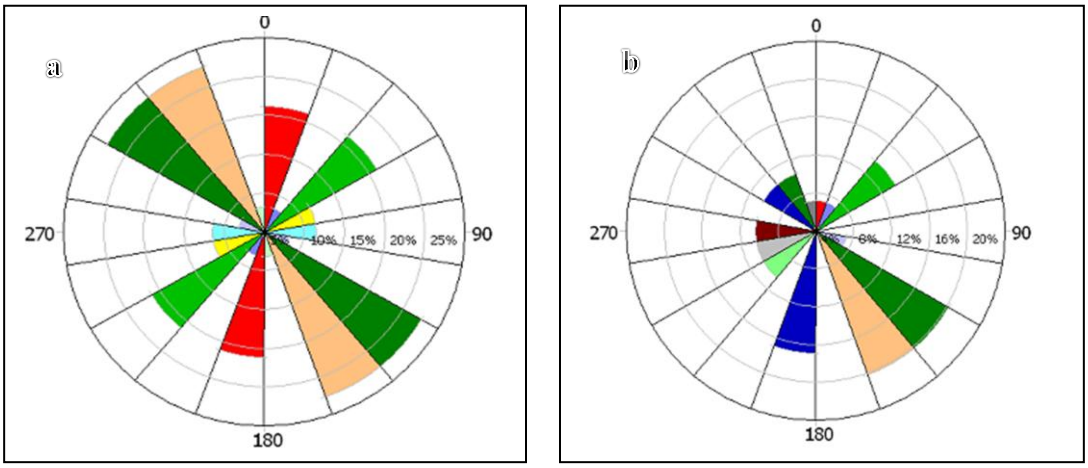

Fig. 2.6 a. & b. Rose diagram of the 3rd order streams (bearing & azimuth) in Mulki river basin

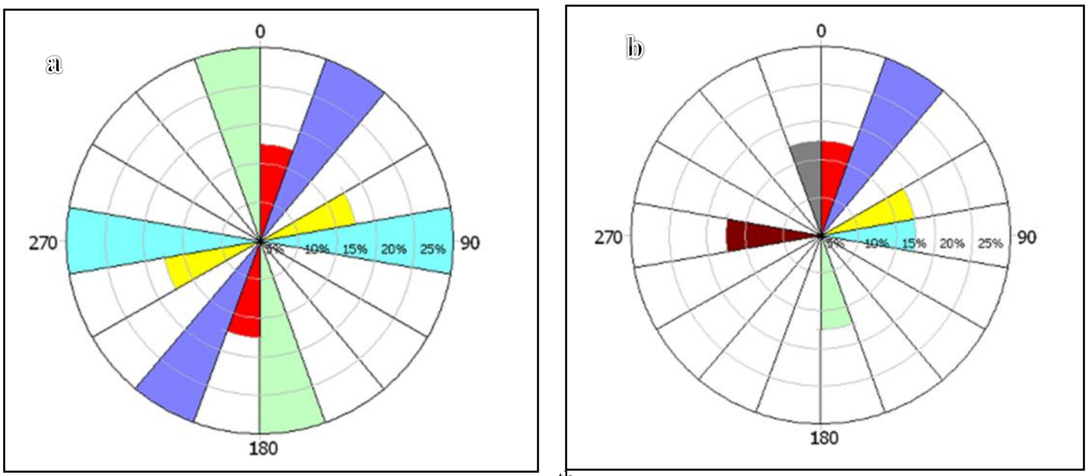

Fig. 2.7 a. & b. Rose diagram of the 4th order streams (bearing & azimuth) in Mulki river basin

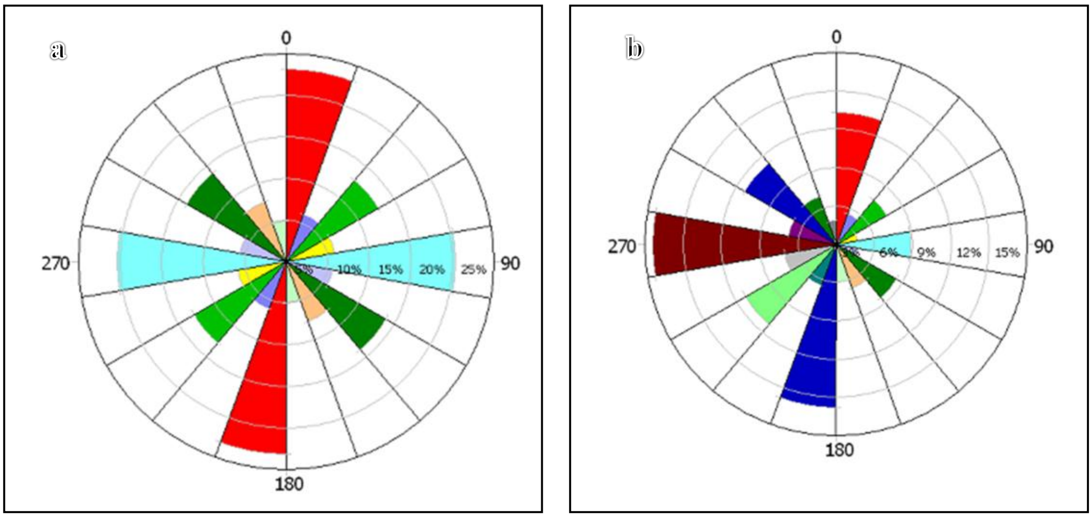

Fig. 2.8 a. & b. Rose diagram of the net drainage (bearing & azimuth) in Mulki river basin (SRTM data)

The rose diagram of entire drainage network in the Mulki River basin extracted from the SRTM 90m resolution DEM (http://srtm.usgs.gov/data/obtaining.html) shows four major directions of alignments (Fig. 2.8). About 58% of the streams alignments are in the N-S to N10°E-S10°W direction governed by lineament fabric and structural features (Powar 1993, Kale and Shejwalker 2008, Valdia 2001). Another major trend is in the E-W direction where the natural slope of the terrain controls the flow of streams and about 1/5th of the streams are directed towards the west. Other two major directions are in the NE-SW and NW-SE directions which are the trends of the lineament fabric. According to Powar and Patil (1980) the lineament patterns reflect the combined role of compression (resulting from the collision of the Indian plate and its subsequent subduction, beginning middle Eocene, below the Eurasion Plate) and vertical uplift due to isostatic adjustment.

The rose diagrams confirm the influence of lineament fabric in the drainage pattern of the Mulki River basin. This is significant in the geohydrological studies of this area since it will give clues about the occurrence and movement of surface water and groundwater.

2.4 QUANTITATIVE GEOMORPHOLOGY: Various important hydrologic phenomena can be correlated with the physiographic characteristics of drainage basins such as size, shape, slope of drainage area, drainage density, stream order, size, length of the contributories, etc. (Rastogi *et al.* 1976).

2.5 MORPHOMETRIC ANALYSIS: Morphometry is the measurement and mathematical analysis of the configuration of the earth surfaces, shape and dimensions of its landforms or geometry of natural geomorphological features (Clarke 1966). It is the systematic description of the geometry of the drainage basin and its stream channel system which requires measurement of linear, areal and relief aspects of the basin and slope contribution (Nag and Chakraborthy 2003). Horton (1945), Strahler (1950, 1952, 1956, 1957, 1958, 1964), Schumm (1956, 1963), Melton (1957) and Morisawa (1962) have given various linear, areal and relief parameters which could be determined. The development of drainage networks depends on geology and precipitation apart from exogenic and endogenic forces of the area. While the linear aspects and areal aspects of the drainage basin are plannimetric, the relief aspects of channel network and contributing ground slopes treat the vertical inequalities of the drainage basin forms. An attempt is made in this chapter to quantify geomorphological characters of Mulki River basin along with its major geomorphic units.

2.5.1 Methodology: In order to study the linear, areal and relief aspects of the Mulki river basin, the toposheets of 1:25,000 scale published by Survey of India (SOI) are used. The Chartometer has been used to carry out linear measurements while digital plannimeter has been used for area measurements of the basin. After digitizing the map using the ERDAS IMAGINE 9.1 version the drainage network has been updated using the Resourcesat-1 LISS III satellite imagery (IRS_P6_L3_05012005) of 23.5m resolution and the attribute data has been analyzed for the various above said parameters. Digitization errors such as reversing streams have been rectified and calculation of bearing, azimuth, drainage density, stream frequency, bifurcation ratio, etc., per sq.km grid have been carried out using the Bearing and Drainage (bAd) Calculator (Dinesh *et al.* 2012). Variation Maps of the above parameters have been prepared using ArcGIS 10 version. Analysis of Basin characteristics, geomorphology and morphometry is given in Tables 2.1 and 2.2. Rose diagrams for bearing and azimuth of different stream orders have been prepared using bAd calculator and analyzed for its hydrogeomorphological and tectonic significance. Hypsometric analysis of the basin and its sub-basins up to 3rd order has been derived using the CalHypso ArcGIS extension program developed by Vicente Pérez-Pena *et al.* (2009) of Universidad de Granada.

2.5.2 Linear Aspects of Basin: The first step in drainage basin analysis is to delineate the outline of a river basin, showing the drainage area and also every stream channel in it. Strahler's (1964) method for numbering the segment is used for designating stream channel segments. The linear measurements of the basin include the stream order, stream number, bifurcation ratio, stream length, length ratio, etc.

2.5.2.1 Stream Order: The first and foremost step in the drainage basin analysis is designating the stream order or fixing the hierarchy of the stream order segments. Designating the Stream Order is important to index the size, scale of the basin and this forms an approximate index of the amount of stream flow. The method advocated by Horton (1945) is widely adopted for stream ordering. In this system, the smallest fingertip stream without any tributaries is designated as first order. The second order channel is produced from the point where two first order channels meet, and continues down to the next point where two second order channels meet to produce the third order channel, and so on. After this initial ordering is completed, the highest order stream is projected back to the headwaters along the stream which involved least deviation from the main stream direction. Since two stages are involved in this system, Strahler (1952) proposed a modification assuming that in a channel net-work map, all intermittent and prominent flow lines are located in clearly defined valleys.

No	Characteristics	Formula	Author	Mulki	Remarks
1	Area of the Basin (A_u)		Horton (1932)	350.237 sq.km.	
2	Maximum Length of the Basin (L_b)		Horton (1945)	30.089 km.	
3	Width of the Basin (W_b)		Horton (1945)	17.698 km.	Rectilinear basin
4	Basin Perimeter (P)		Horton (1945)	110.582 km.	
5	Diameter of the circle having same perimeter (D_c)			35.217 km.	
6	Area of the circle having same perimeter (A_c)			973.597 km^2	
7	Form factor (R_f)	(Rf) $=A_u/L_b^2$	Horton (1932)	0.387	
8	Shape factor (S_f)	(S_f) $=L_b^2/A_u$	Strahler (1957)	2.585	
9	Elongation Ratio (R_e)	(R_e) $=D_c/L_b$	Schumm (1956)	1.170	
10	Circularity Ratio (R_c)	(R_c) $=A_u/A_c$	Miller (1953)	0.360	
11	Total Stream Length ($\sum L_u$)	($\sum L_u$) $=\sum L_u$	Horton (1932)	657.290 km	
12	Total Number of Streams within the basin ($\sum N_u$)	($\sum N_u$)	Strahler (1964)	867	
13	Drainage Density (D_d)	(D_d) $=\sum L_u/A_u$	Horton (1932)	1.877 km/km^2	Very coarse textured River basin
14	Constant of channel maintenance (C)	(C) $=A_u/\sum L_u$	Schumm (1956)	0.533 km^2/km	
15	Stream frequency (F_s)	(F_s) $=\sum N_u/A_u$	Horton (1932)	2.476	Melton(1958), $F=.694D^2=2.445$
16	Length of Overland flow (L_g)	(L_g) $=1/2D_d$	Horton (1945)	0.266 km	
17	Main Channel Length (L)		Horton (1945)	50.764 km	Main channel distance along it
18	Height of the basin mouth (H_m)		Horton (1932)	0 m	Since it is the sea face
19	Basin Relief (H)			251 m	
20	Maximum Basin Relief (R_b)			220 m	Highest point of the basin perimeter measured along the longest dimension parallel to the principal drainage line of the basin
21	Relief Ratio (R_G)	(R_G) $=R_b/L_b$	Schumm (1956)	.007	.008, When H/L_b is taken
22	Relative Relief (R_{GP})	(R_{GP})$=R_b/P$		.002	.002, when H/P is taken
23	Drainage Texture (R_t)	(Rt) $=\sum N_u/P$	Horton (1945)	7.84	
24	Ruggedness Number (R_n)	(Rn)$=D_d.R_b/1000$		0.41	0.47, when $D_d.H/1000$ is taken

Table 2.1 Basin Characteristics of Mulki River

Stream Order	Number of streams	Stream Length	Mean Stream Length	Stream Length Ratio	Bifurcation ratio	Drainage Area	Stream Basin Area Ratio	Mean Basin area	Cumulative Stream Length	Drainage Density
	N_u	L_u	L_{sm}	R_L	R_b	A_u	R_a	$\bar{A}_u$	$\sum Lu$	D_d
		Km	Km			(Sq. km)	Km/Km2			
			$=L_u/N_u$	$= L_u/L_{u-1}$	$=N_u/N_{u+1}$		$=L_u/A$	$= A_u/N_u$		$=L_u/A_u$
Strahler (1964)	Strahler (1964)	Horton (1932)	Strahler (1964)	Horton (1945)	Schumm (1956)	Horton (1932)	Horton (1945)		Horton (1932)	Horton (1932)
1	683	365.35	0.53		4.35	115.80	3.16	0.17	365.35	3.16
2	157	134.15	0.85	0.37	5.41	143.10	0.94	0.91	499.50	3.49
3	29	83.01	2.86	0.62	3.63	221.00	0.38	7.62	582.51	2.64
4	8	26.95	3.37	0.32	4.00	169.38	0.16	21.17	609.46	3.60
5	2	25.44	12.72	0.94	2.00	200.00	0.13	100.00	634.90	3.17
6	1	22.38	22.38	0.88		350.24	0.06	350.24	657.29	1.88
Total	880	657.29				350.24			657.29	
Mean			7.12	0.63	3.88		0.80	80.02		2.99

Table 2.2 Geomorphological Analysis of Mulki River Basin

Strahler (1964) designated the smallest fingertip tributaries as first order, two first orders to produce a second order segment, two second orders to produce a third order and so on and the trunk stream through which discharge of water and sediment takes place is designated as the highest order (Fig. 2.9).

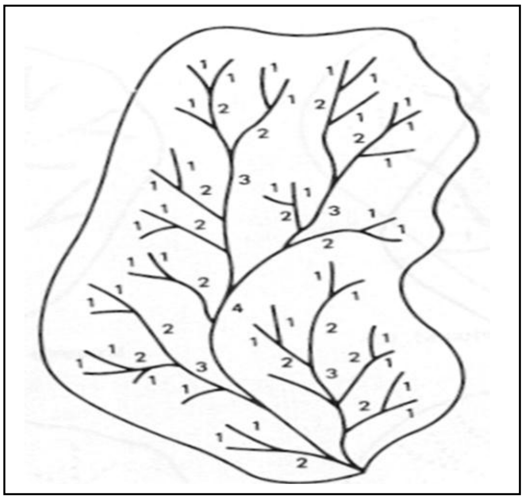

Fig. 2.9 Determination of Stream Order by Strahler's (1964) Method

2.5.2.2 Number of Streams (N_u): Stream order number is directly proportional to size of the contributing watershed, channel dimensions and stream discharge at that place. Because order number is dimensionless, two drainage networks differing greatly in linear scale can be compared with respect to their geometry through use of order number. After the discharge network elements have been assigned their order number, the segments of each order are counted. The symbol of order is 'U' and the number of segments is given the symbol 'N'.

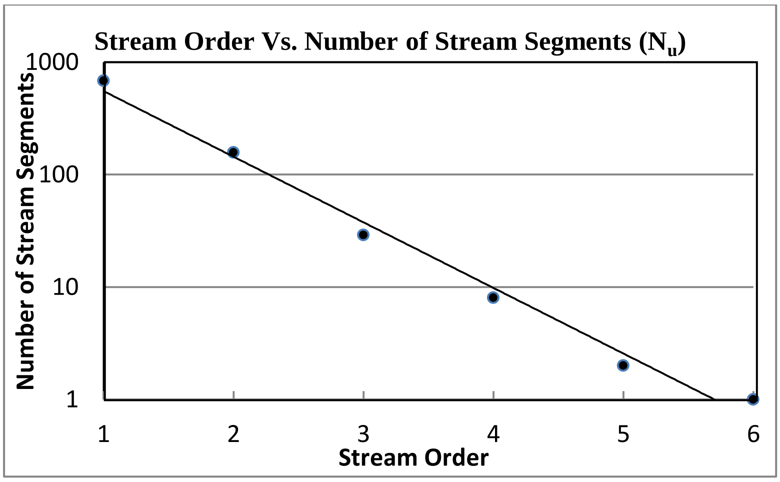

Fig. 2.10 Graph showing Relation of Stream Order to Number of Stream Segments in Mulki River Basin

The Mulki River basin is a sixth order basin with 683, 157, 29, 08 and 2 segments in first, second, third, fourth and fifth order respectively (Figs. 2.1 & 2.2). The details of stream characteristics (Fig. 2.10) confirm Horton's first law (1945) "Law of stream numbers" which states that the number of streams of different orders in a given drainage basin tends closely to approximate an inverse geometric ratio.

<u>2.5.2.3 Bifurcation Ratio (R_b):</u> The term was introduced by Horton (1932) to express the ratio of the number of streams of any given order to the number in the next lower order. It is further observed that there is a decrease in the number of channels with increase in stream order. According to Strahler (1964), the ratio of number of streams of a given order (N_u) to the number of segments of the next higher order ($N_{(u+1)}$) is termed as the bifurcation ratio. Mathematically it is represented as $R_b = N_u / N_{(u+1)}$. The bifurcation ratio will not be exactly the same from one order to the next, because of chance variation in watershed geometry, but will tend to be a constant throughout the series. Horton (1945) considered the bifurcation ratio as an index of relief and dissections. Strahler (1957) demonstrated that Rb shows only a small variation for different regions on different environment except where powerful geological control dominates. Lower Rb values are the characteristics of structurally less disturbed watersheds without any distortion in drainage pattern (Nag 1998).

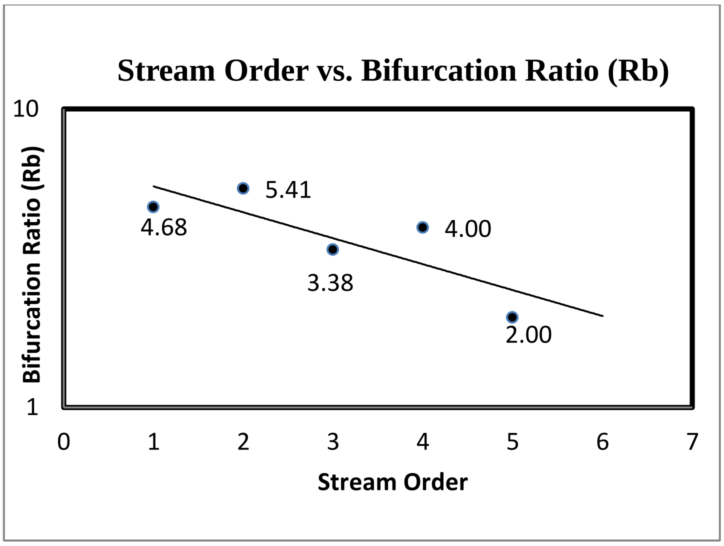

Fig. 2.11 Graph showing relation of Stream Order to Bifurcation Ratio in Mulki River Basin

The bifurcation ratio for Mulki river basin ranges between 2 and 5.41 and the mean bifurcation ratio is 3.9 (Table 2.2). Chow (1964) stated that the Bifurcation ratio ranging between 3 and 5 indicate the mature surfaces where the geologic structures may not have dominant influence on the drainage pattern. But the bifurcation ratio of 5.41 for the 2nd to 3rd order streams and 4 for the 4th to 5th order streams indicates a variation from the general trend (Fig. 2.11) which has to be investigated for a better understanding of the basin characteristics. These irregularities are dependent on geological and lithological development of drainage basin (Strahler 1964). The higher value may be the result of large variation in frequencies between successive orders and indicates the mature topography (Sreedevi *et al.* 2009). But in the case of Mulki River basin it may be due to the structural control of the lineaments over it.

The grid (1 Sq.Km) wise bifurcation ratio map (Fig. 2.12) prepared shows a variation of 0 to 9 values indicating the environmental variation in structure and topography. This map indicates the significance of geology and topography of the area in the distribution of bifurcation ratios.

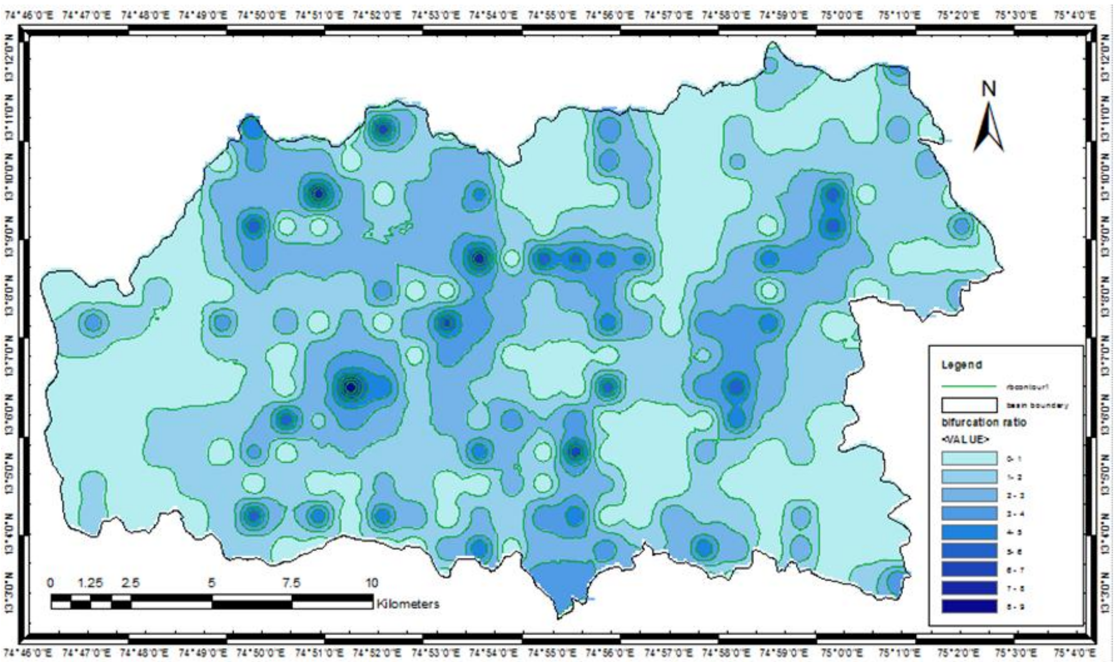

Fig. 2.12 Showing grid wise variation in Bifurcation Ratios of Mulki River Basin

Though the bifurcation ratio (R_b) will not be precisely the same for different orders, on account of variation in watershed geometry, is tend to be constant throughout the series. This observation formed the basis for Horton's law of 'stream numbers' which states that the number of stream segments of successively lower order in a given basin tend to form a geometric series, beginning with a single segment of highest order and increasing with a constant bifurcation ratio.

2.5.2.4 Stream Length (Lu): The length of each individual stream is measured order wise using GIS tools and recorded as attributes. Other geological, climatological factors remaining the same, stream length has an important relationship with the surface flow discharge. Surface runoff is directly proportional to the stream length. Longer the length, slower is the appearance of flood and larger the surface flow. Leopold and Miller (1956) have derived the following relations:

$$L \propto A^k \quad ; \quad Q \propto A^k \quad \text{therefore} \quad Q \propto L$$

where A^k is basin area, L is stream length, Q is surface runoff. This clearly indicates that surface runoff is directly proportional to stream length.

The lengths of the first, second, third, fourth, fifth and sixth order streams of Mulki river basin are 365.352 km, 134.153 km, 83.011 km, 26.947 km, 25.444 km and 22.383 km respectively (Table 2.2). Total Length of the Mulki river is 657.29 km. Generally, the total length of stream segments decreases with stream order and obey Horton's (1932) "Law of stream length". In general logarithms of the length of stream segments of a given order, when plotted against it, the points lie on a straight line (Horton 1945). Deviation from its general behavior indicate that the terrain is characterized by high relief and/or moderately steep slopes, underlain by varying lithology and probable uplift across the basin (Singh and Singh 1997). The deviation of lower order streams (1, 2 & 3) from the higher order streams (4, 5 & 6) of Mulki river basin from this conceptual line indicates (Fig. 2.13) a recent regional uplift. This neogene uplift has an effect on the hydrogeological condition of the area due to the change in runoff characteristics and recharging. The cumulative stream length shows (Fig. 2.14) a uniform linear gradation from 1st order to 6th order. The variation in order and size of the tributary basins are largely due to physiographic and structural conditions of the region.

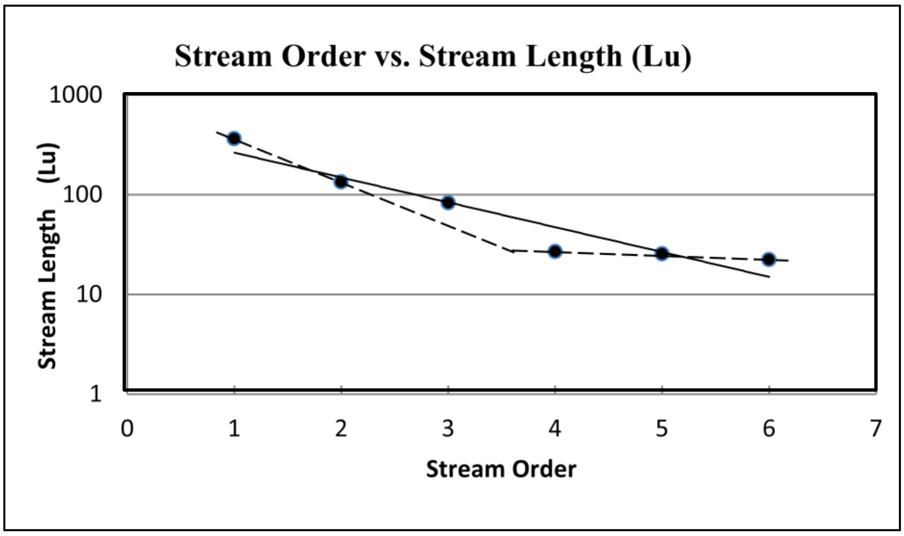

Fig. 2.13 Graph showing Relation of Stream Order to Stream Length in Mulki River Basin

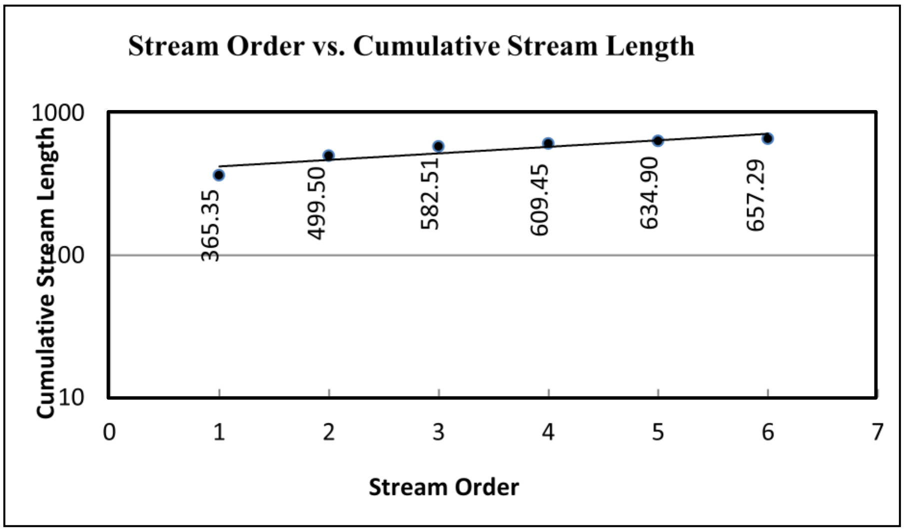

Fig. 2.14 Graph showing Relation of Stream Order to Cumulative Stream Length in Mulki River Basin

2.5.2.5 Length of the Basin (L_b): It is the Maximum Length of the basin from the head to the mouth perpendicular to the coast and is measured with the help of GIS software. It is measured as 30.1 KM.

2.5.2.6 Mean Stream Length (Lsm): It is a characteristic dimensional property of a channel and is related to the drainage network components and its associated basin surfaces. It reveals the characteristic size of drainage network components and its contributing basin surfaces (Strahler 1964). This has been calculated by dividing the total stream length of a particular order (u) by the number of stream segments belonging to that order which is as follows:

1st Order : 365.352/683 = 0.535 KM; 2nd Order : 134.153 /157 = 0.854 KM

3rd Order : 83.011 /29 = 2.862 KM; 4th Order : 26.95/08 = 3.369 KM

5th Order : 25.444./02 = 12.72 KM; 6th Order : 22.383/01 = 22.383 KM

The mean stream length is presented in Table 2.2 which is varying from 0.53 to 22.38. It is observed that the Lsm value of a given order is greater than that of the lower order and less than that of its next order. It also confirms to Horton's (1932) "Law of stream length" which states that the average length of streams of each of the different orders in a drainage basin tends closely, to approximate a direct geometric ratio. But the values disobey to fall in a progressive straight line (Fig. 2.15). The variation in order and size of the tributary basins are largely due to physiographic and structural conditions of the region.

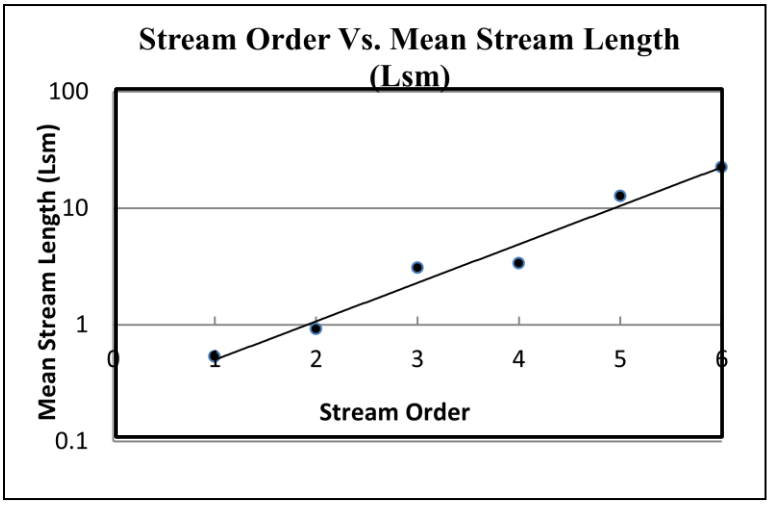

Fig. 2.15 Graph showing relation of Stream Order to Mean Stream Length in Mulki River Basin

<u>2.5.2.7 Stream Length Ratio (R_L):</u> It is the ratio of the mean length of one order to the next lower order of the stream segments. It is apparent from drainage network map (Fig. 2.1) that the first order channel segments have, on an average, the shortest length and that segments become longer as stream order increases. It is observed that mean stream length increases as the stream order increases and as such mean stream length of any given order is greater than that of the lower order and less than that of

the next higher order. This proportion of length increase is known as the stream length ratio **R_L**, and tends to be approximately constant for a given drainage system. The length ratio **'R_L'** is expressed as the ratio of mean stream length (L_u) of stream order (U) to mean stream length of segments, of next order (L_{u-1}) which is mathematically given as follows:

$$\text{Stream Length Ratio} \quad (R_L) = \bar{L}_u / \bar{L}_{u-1}$$

$$\text{Stream Length Ratio} = \frac{\text{Mean Length of segments of order U}}{\text{Mean Length of segments of order U-1}}$$

Stream length ratios (R_L) are changing haphazardly in the basin (Fig. 2.16) and its values vary from 0.367 to 0.944 (Table 2.2). It is noticed that the R_L between successive stream orders of the basin vary due to differences in slope and topographic conditions (Rakesh Kumar *et al.* 2001, Sreedevi *et al.* 2005, 2009) and may be attributed to a late youth stage of geomorphic development in the streams (Rudraiah *et al.* 2008) of the study area. The R_L has an important relationship with the surface flow discharge and erosional stage of the basin.

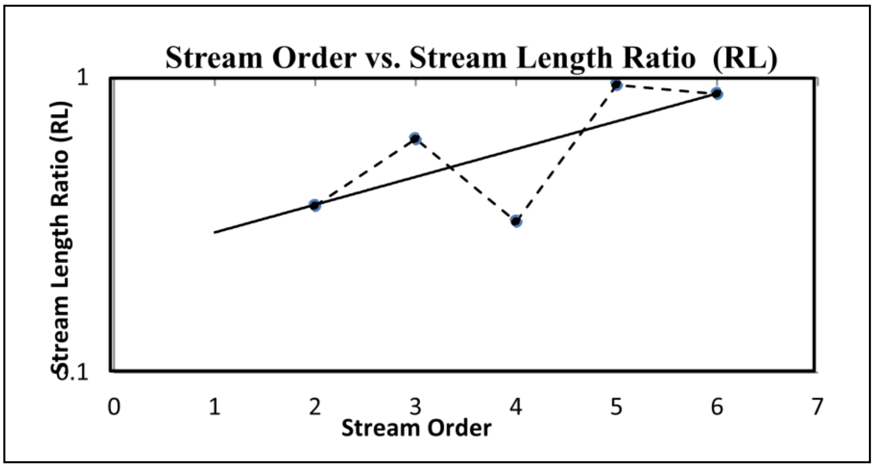

Fig. 2.16 Graph showing Relation of Stream Order to Stream Length Ratio in Mulki River Basin

<u>2.5.2.8 Width of the Basin:</u> It is the maximum width of the basin measured perpendicular to the length of the basin. The Mulki river basin has a maximum width of about 17.698 KM.

<u>2.5.2.9 Basin Perimeter:</u> It is the circumference of the basin measured along the basin water divide and is 110.582 KM for Mulki River basin.

2.5.2.10 Diameter of the circle having same perimeter: It is the length of the basin in its circular shape and reflects the sphericity of the basin. It is found to be 35.217 KM (Table 2.1) in the study area.

2.5.2.11 Area of the circle having same Perimeter: It is found to be 973.597 Sq. KM for the Mulki River basin which shows the much compressed nature of the basin.

2.5.3 Areal Aspects: The areal aspects of a basin include different morphometric parameters like basin area, drainage density, textural ratio, stream frequency, form factor, circularity ratio, elongation ratio and length of overland flow. All these parameters have been computed using the GIS measuring tools (Tables 2.1 & 2.2).

2.5.3.1 Basin Area: The area of a basin of a given order 'U' is the total area projected upon a horizontal plane, contributing overland flow to the channel segment of the given order and including all tributaries of lower order (Horton 1945). The area of the $\mathbf{n}^{th}$ order basin is the cumulative area of all first, second, third and **n-1** order basins plus all inter basin areas, contributing directly to a channel of order higher than the first (Schumm 1956). Area of the Basin has been measured initially using Digital Plannimeter, and attribute data of GIS has been used to verify the same and found to be 350. 237 Sq. KM. Mean area of the basin A_u is the ratio between the areas of a given order to the number of segments of the same order (Horton 1945). Based on Horton's (1945) observation the mean drainage basin areas of progressively higher orders should increase in a geometric sequence (Fig. 2.17).

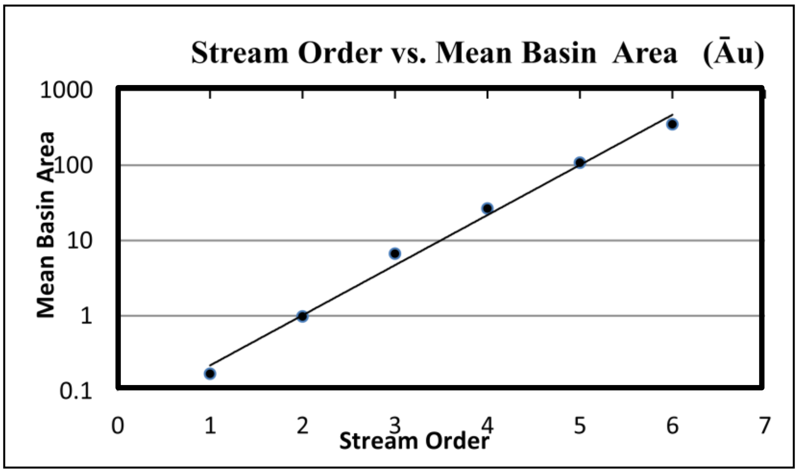

Fig. 2.17 Graph showing relation of Stream Order to Mean Basin Area in Mulki River Basin

The "law of stream areas" (Schumm 1956) says that the mean basin areas of streams of each order tend closely to approximate a direct geometric sequence in which the first term is the mean area of the first order basin. Mulki river basin agrees with the law of stream areas and a regular exponential geometrical relationship of the stream orders to drainage area is established in the Mulki River basin (Fig. 2.18).

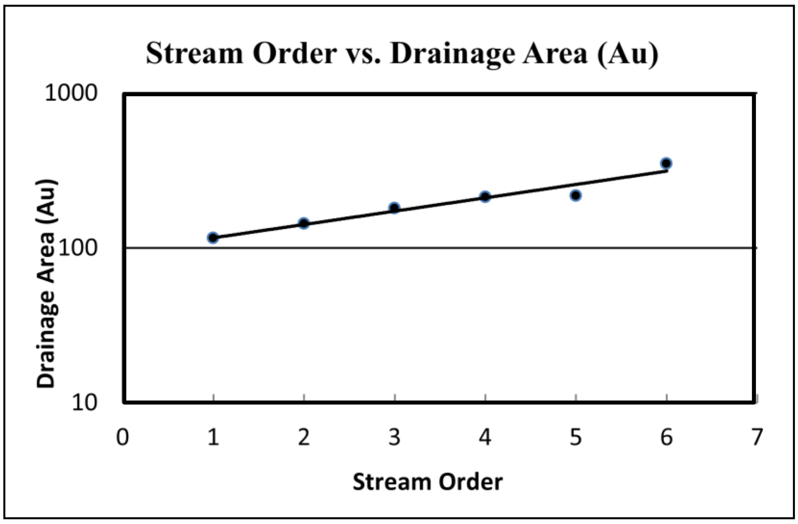

Fig. 2.18 Graph showing relation of Stream Order to Drainage Area in Mulki River Basin

<u>2.5.3.2 Basin Shape</u>: The shape of a basin, as it is projected upon a horizontal plane of a map, may have effect on the discharge characteristics of the basin. In order to explain the shape of the drainage basin various parameters such as basin area (A_u), basin length (L_b) measured along the longest dimension parallel to the principal drainage line and perimeter of the basin (P) are important. Quantitative expression of drainage basin outline or shape of the basin has been worked out by different authors in different ways. They are Form factor (R_f), Shape factor (S_f), Circularity ratio (R_c) and Elongation ratio (R_e).

<u>*2.5.3.2.1 Form Factor (R_f):*</u> It is defined as the dimensionless ratio of the basin area (A_u) to the square of the basin length (L_b). $\mathbf{R_f}$ = Basin Area (A_u)/ Basin Length (L_b^2). Horton (1932) proposed this parameter to predict the flow intensity of a basin of a defined area. The value of the form factor will be always greater than 0.78 for a perfectly circular basin. Smaller the value of form factor, more elongated will be the basin (Rudraiah *et al.* 2008). The basins with high form factors have high peak flows

of shorter duration, whereas, elongated sub-watershed with low form factors have lower peak flow of longer duration (Chopra *et al.* 2005). The index of $\mathbf{R_f}$ shows the inverse relationship with the square of the axial length and a direct relationship with the peak discharge (Gregory and Walling 1973). The form factor of Mulki river basin is 0.387**.** This indicates that the river basin is sub-circular and elongated (Fig. 2.1) suggesting flatter peak flow for longer duration. Flood flows of such elongated basins are easier to manage than those of the circular basin. Fig. 2.19 shows the relation of mean basin area to mean stream length for different orders. Here the mean basin areas values range from 0.17 to 350.24 indicating the shape variation of the different order streams, but all elongated, compressed, flattened and sub-circular (Fig. 2.2).

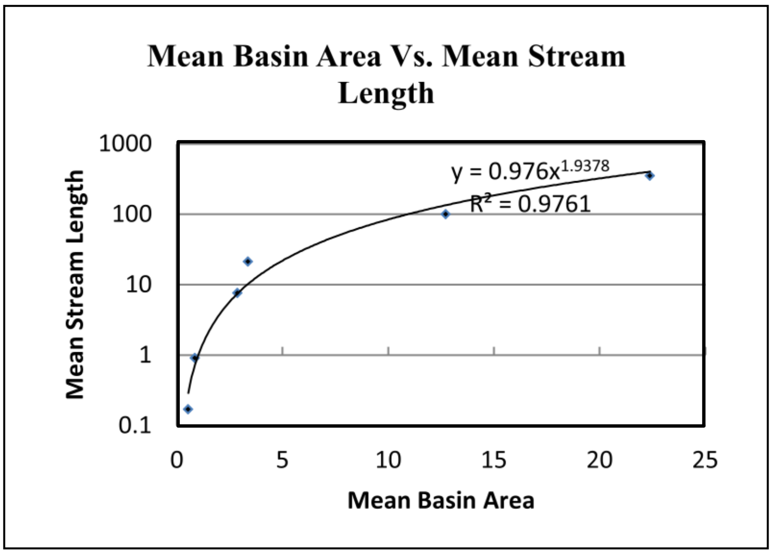

Fig. 2.19 Graph showing relation of Mean Stream Length to Mean Basin Area in Mulki River Basin

<u>*2.5.3.2.2 Shape Factor (S_f):*</u> It is the reciprocal of the Form factor (R_f) (Strahler 1957). i.e., Reciprocal of Form Factor $(L_b)^2/A_u$

Or it can be calculated as equal to Catchment's Perimeter/Perimeter of equivalent circle area. In the Mulki River basin it is found to be 2.59.

<u>*2.5.3.2.3 Circularity Ratio (R_c):*</u> It is the ratio of the area of the basin to the area of circle having the same circumference as the perimeter of the basin (Miller 1953). It is influenced by the length and frequency of streams, geological structures, land use/land cover, climate, relief and slope of the basin. The circularity ratio has been used as an areal aspect and is expressed as the ratio of the basin area (A_u) to the area of a circle

(A_c) having the same circumference as the perimeter of the basin (Strahler 1964). It is affected by the lithological character of the basin. Circularity ratio (R_c) values approaching 1 indicates that the basin shapes are like circular and as a result, it gets scope for uniform infiltration and takes long time to reach excess water at basin outlet, which further depends on the prevalent geology, slope and land cover. The ratio is more influenced by length, frequency (Fs) and gradient of various orders rather than slope conditions and drainage pattern of the basin. Circularity ratio (R_c) of the Mulki river basin is 0.36 (Table 2.1), which is significant and indicates that the area is characterized by an elongated basin with high relief and the drainage system is of structurally controlled dendritic stage (Sreedevi *et al.* 2009).

2.5.3.2.4 Elongation Ratio (R_e): Elongation ratio is defined as the ratio between the diameter of the circle with the same area as that of the basin (A_u) and the maximum length (L_b) of the basin (Schumm 1956). A circular basin is more efficient in runoff discharge than an elongated basin (Singh and Singh 1997). The value of elongation ratio (Re) generally varies from 0.6 to 1.0 associated with a wide variety of climate and geology. Values close to 1.0 are typical of regions of very low relief whereas that of 0.6 to 0.8 are associated with high relief and steep ground slope (Strahler 1964). These values can be grouped into three categories, namely circular (>0.9), oval (09-0.8) and less elongated (<0.7). Bull and McFadden (1977) have shown that basins draining tectonically active areas are more elongated and become more circular with the cessation of uplift. Elongated basin shapes are also associated with high local relief and steep valley slopes (Molin *et al.* 2004). Elongation ratio for the Mulki river basin is estimated as 1.17 (Table 2.1) indicating a very low relief for the basin. The low value of the elongation ratio shows that the area is having low infiltration capacity and high runoff. This also indicates high relief and steep slopes (Rudraiah *et al.* 2008). This shows recent tectonic activity for the origin of the ridge and spurs in the study area (Fig. 2.3). The area is also susceptible to high erosion and sedimentation load. The variation of the elongated shapes of the basin is due to the guiding effect of thrusting and faulting in the basin (Sreedevi *et al.* 2009, Kale and Shejwalkar 2008). Due to this characteristic, the units will tend to have smaller flood peaks but longer lasting flood flows compared to a round basin (Mesa 2006).

2.5.3.3 Drainage Density (D_d): The term drainage density was introduced by Horton (1932), considering it as an important factor affecting the flow of stream. Drainage density is defined as the total length of streams of all orders per unit drainage area. The drainage density indicates the closeness of spacing of channels (Horton 1932). Horton (1945) considered drainage density as an important indicator in stream eroded topography. Drainage density is a measure of the degree of fluvial dissection and is influenced by numerous factors such as lithology, resistance to weathering, climate, permeability of rock formation, vegetation, relief, runoff intensity index, etc., among which the resistance to erosion of rocks, infiltration capacity of the land and climatic conditions rank high (Verstappen 1983).

The amount and type of precipitation influence directly the quantity and characters of surface runoff. Several studies indicate the influence of climate on drainage density. Gregory and Gardiner (1975) and Gregory (1976) showed that drainage density broadly increases with precipitation intensity index, defined as the ratio between the maximum reported 24 hour rainfall and average rainfall. Generally it is a positive correlation between D_d and rainfall parameters (Montgomery and Dietrich 1989, Tucker and Bras 1998). Abrahams (1984) showed that several climatic factors simultaneously affect drainage density in a complex way. An area with high precipitation such as thundershowers loses greater percentage of rainfall in runoff resulting in more surface drainage lines. Field observations generally show that high drainage density is favoured in arid regions with sparse vegetation cover, as also in temperate and tropical regions subjected to frequent heavy rains (Melton 1957, Strahler 1964, Toy 1977, Morisawa 1985).

Amount of vegetation and rainfall absorption capacity of soils, which influences the rate of surface runoff, affects the drainage texture of an area. The similar condition of lithology and geologic structures, semi-arid regions have finer drainage density texture than humid regions. Low drainage density generally results in the areas of highly resistant or permeable sub-soil material, dense vegetation and low relief. High drainage density is the result of weak or impermeable sub-surface material, sparse vegetation and mountainous relief. Low drainage density leads to coarse drainage texture while high drainage density leads to fine drainage texture.

Slope gradient and relative relief are the main morphological factors controlling drainage density. Strahler (1964) noted that low drainage density is favoured where basin relief is low, while high drainage density is favoured where basin relief is high. The combined role of relief and climate on drainage density has also been investigated by Kirkby (1987), suggesting that the relationship between drainage density and relief depends on the dominant hill slope processes. He predicts a positive relationship for semi-arid environments and an inverse one for humid climate. Gardiner (1995) showed that greater drainage densities are generally associated with impermeable rocks.

Drainage density is generally inversely related to hydraulic conductivity of the underlying soil. For steep slopes, an inverse correlation has been modeled by Montgomery and Dietrich (1992). Generally, drainage density increases with decreasing infiltration capacity of the underlying rocks and/or decreasing transmissivity of the soil.

Horton (1945) defined Drainage density (D_d) as the ratio of total channel stream lengths (L_u) cumulated for all orders within a basin to basin area (A_u) of the catchment, expressed in terms of kilometer per sq. kilometer. Where Lu = the total length of channel segments of all orders in km; Au = area of the basin in sq. km; Drainage Density = Total Stream Length/ Total Basin Area. i.e. $D_d = \sum L_u/A_u$. The Drainage density for the Mulki river basin is calculated as 1.88 KM/ KM^2 (Table 2.1). Langbein (1947) recognized the significance of 'D_d' as a factor determining the time of travel by water within the basin and suggested that it varies between 0.55 and 2.09 km/km^2 in humid region.

Grid (1 Sq. Km.) wise Drainage density variation map (Fig. 2.20) gives a better idea about the physical properties of the underlying rocks in the study area. Generally low drainage density occurs in the regions of highly resistant or highly permeable subsoil material with dense vegetative cover and low relief. High drainage density is favoured in the regions of weak impermeable subsurface materials which are sparsely vegetated and show high relief in the study area (Fig. 2.20).

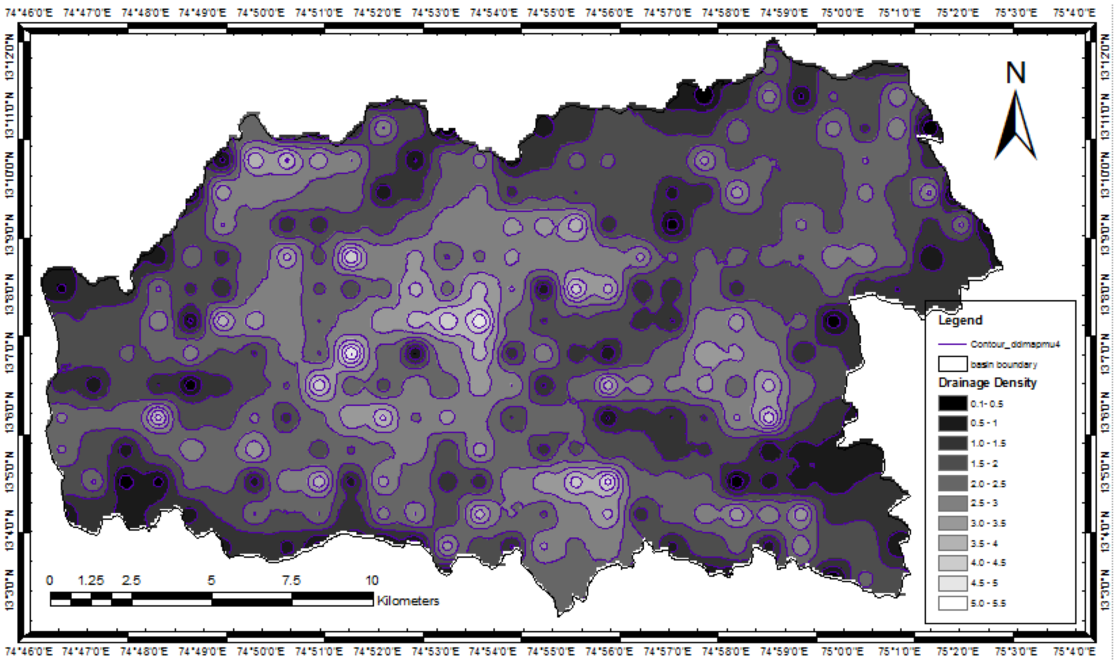

Fig. 2.20 Showing the Drainage Density variation in the Mulki River Basin

The drainage density in the study area (Table 2.2) varies from 1.88 km/km^{2} for the sixth order stream to 3.16 for the 1st order streams (Fig. 2.21). The highest drainage density is 3.60 created by the 4th order streams. The mean drainage density of the study area is 2.99 km/km^{2}. The low drainage density values of the sub basins in the study area can be attributed to resistance of rocks like gneisses and granites to stream erosion, basic intrusive of dolerite and gabbroic masses forming resistive hillocks and ridges, thick vegetation cover and low relief. The percentage contribution of drainage densities to the basin plotted in Fig. 2.22 shows a uniform increase in contribution of drainage density to the basin indicating a matured river.

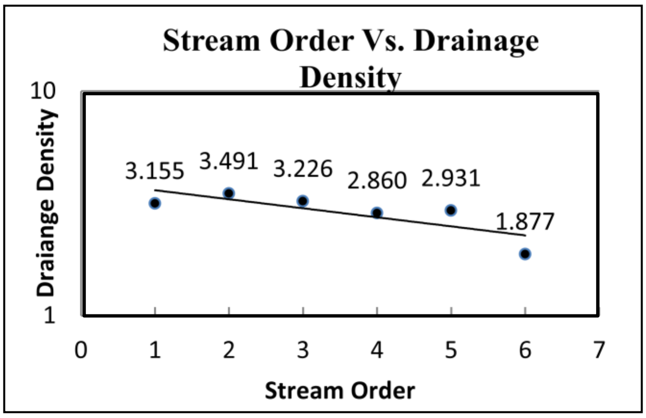

Fig. 2.21 showing the relation of Drainage Density to the Stream Order in Mulki basin

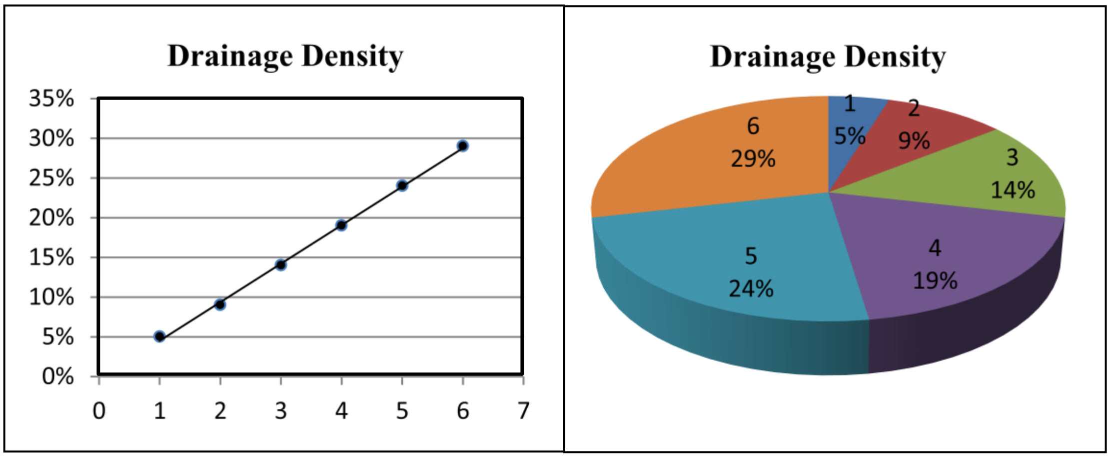

Fig. 2.22 Showing the Drainage Density Variation in Mulki River Basin

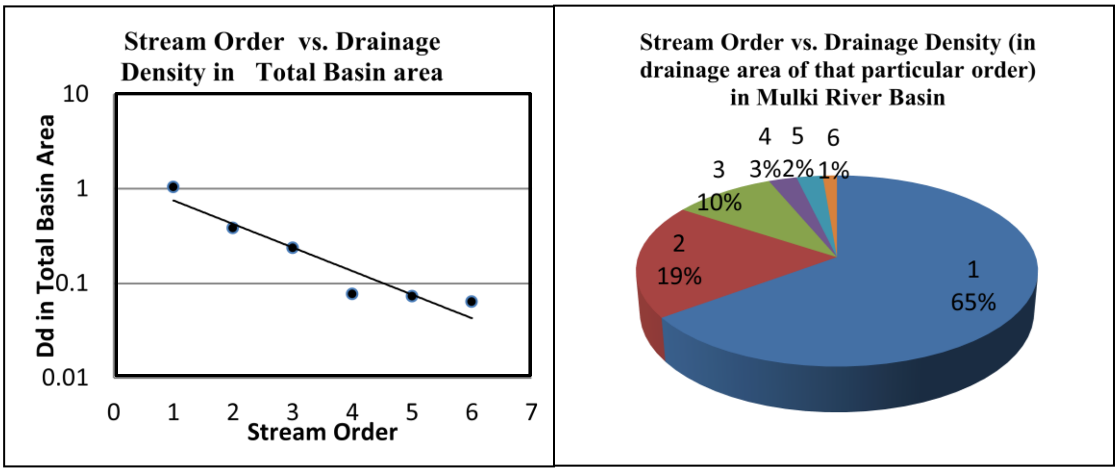

Fig. 2.23 Showing the Drainage Density of each Order in the whole basin area

Strahler (1964) noted that low drainage density is favoured where basin relief is low, while high drainage density is favoured where basin relief is high. The Mulki river basin is having highest drainage density of first order streams with 65% in its own drainage area indicating natural slope of the terrain and the control of structural features (Fig. 2.23). The low drainage density of the higher order streams are mainly due to the low relief in these drainage area. The drainage density indicates the closeness of channel spacing (Horton 1932).

The drainage density can be used for categorizing the texture of the basin. Smith (1950) has classified drainage density into five different textures i.e. very coarse (<2), Coarse (2-4), moderate (4-6), fine (6-8) and very fine (>8). In the study area, the drainage density of all the streams falls in the range of coarse to very coarse type of drainage texture. From this, it may be concluded that the basin has a coarse graded drainage texture over a hard resistant rock and impermeable subsoil with vegetative cover and low relief. There is a variation in drainage density in the basin depending on the geology, topography and vegetative cover. The major part of the basin is covered with highly meandering river with sinuous curves and bends in almost plain land with coastal and alluvial deposits, other than the highly porous lateritic terrains and granitic rocks at the river channels. Horton (1945) recognized infiltration capacity as the single important factor which influences the drainage texture. So the infiltration capacity also varies depending on the above factors but it is usually low understood from the above inferences.

2.5.3.4 Length of Overland Flow (L_g): It is the length of water over the ground, before it gets concentrated into definite stream channels (Horton 1945). This factor basically relates inversely to the average slope of the channel and is quite synonymous with the length of the sheet flow to the large degree. It is approximately equal to half of reciprocal of drainage density (Horton 1945). For Mulki river basin, it is 0.266 KM indicating sheet flow is much in this area on the smooth soil of paddy fields and granitic outcrops of high relief (Table 2.1).

2.5.3.5 Constant of Channel Maintenance (C): Schumm (1956) has used the inverse of drainage density as a property termed constant of channel maintenance, which can be defined as the area of watershed per unit length of stream channel.

$C = A_u / \sum L$ =Area of the Basin/ Total Stream Length of all Orders

In Mulki river basin it is found to be 0.53 KM^2/KM (Table 2.1). This constant explains the area of watershed surface in square kilometers required to sustain one kilometer of stream length. The values of C as 0.5329 KM^2/KM mean that on an average 0.5329 sq.km. surface is needed to support each linear kilometer of the channel.

2.5.3.6 Stream Frequency (Fs): Stream frequency of (Fs) of a basin may be defined as the total number of stream segments of all orders per unit area (Horton 1932). That is $Fs = \sum N_u / A_u$, where $\sum N_u$ is the total number of streams segments of all orders and A_u, the total area of the basin. According to this formula the Stream frequency for the Mulki river basin is found to be 2.476 KM/KM^2 (Table 2.1).

The relationship of the drainage density (D_d) to stream frequency (F_s) tends to be a constant, with a small variation. Melton (1958) found a relation of $F_s=0.694\ D_d^2$ for a large number of basins covering a vast range in scale, climate, relief, surface cover and geologic types. This relationship is applicable to measures of intensity of dissection of the Mulki River basin with a very small variation. The value obtained as 2.444 KM/KM^2 (Table 2.1) is almost same as the one obtained by Horton's (1932) method.

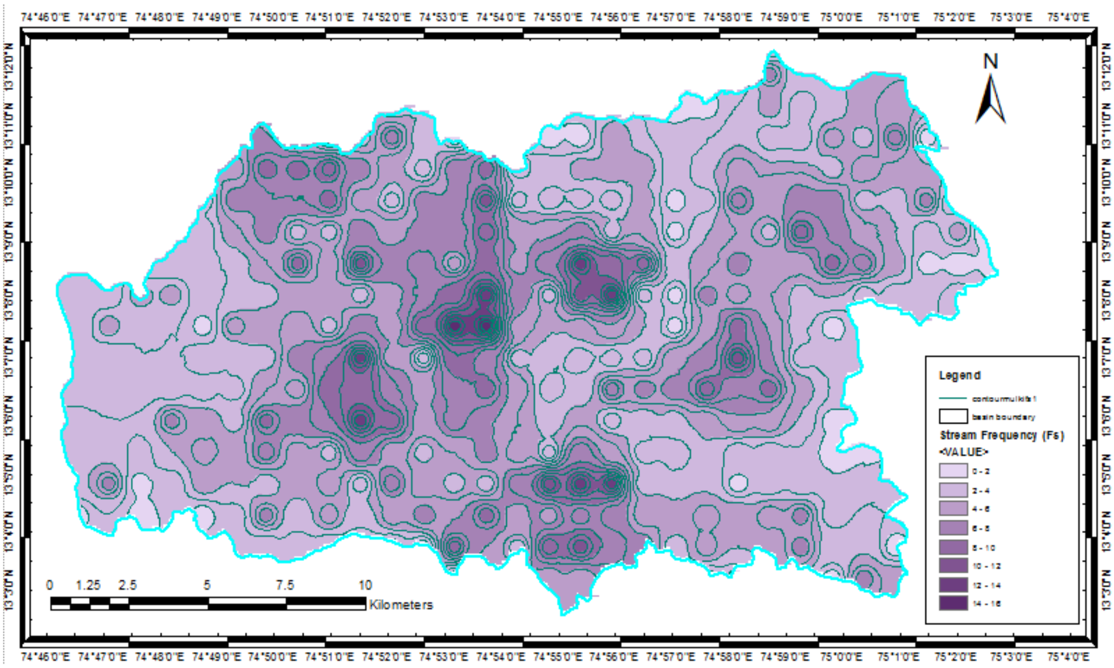

Fig. 2.24 Showing the Stream Frequency Variation in the Mulki river basin

There are always possibility to have basins of same drainage density with differing stream frequency and basins of the same stream frequency with differing drainage density. The variation of stream frequency in each square kilometer grid for Mulki River Basin has been calculated using basin and drainage calculator program (Dinesh *et al.* 2012) and plotted in Arc map (Fig. 2.24). It mainly depends on the lithology of the basin and reflects the texture of the drainage network. This map shows that the stream frequency is related to the geology of the area and infiltration capacity. Middle stretches of the basin is having an increased stream frequency suggesting rejuvenation.

The high value of stream frequency contour shows that they are all around the residual hillocks and impermeable terrains of ridges and hard rocks. When the Dd, Fs and Rb overlaid (Fig. 2.25), it could be seen that they are all related very closely indicating the infiltration capacity and geohydrological condition of the study area.

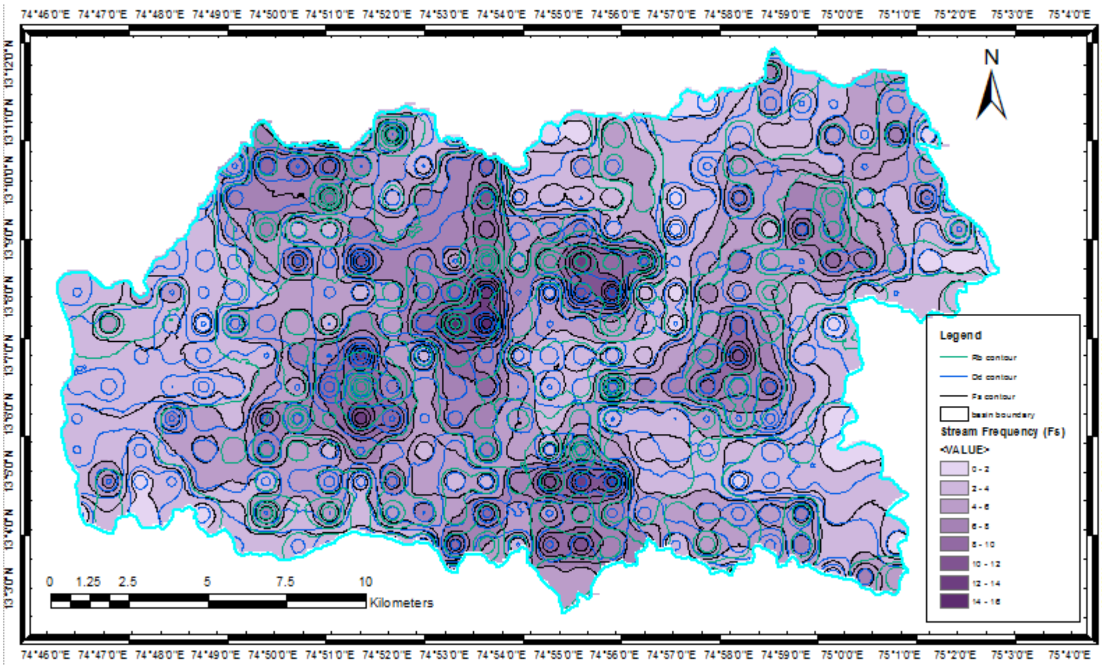

Fig. 2.25 Showing the overlay of Dd and Rb contour values over Fs variation

<u>2.5.3.7 Drainage Texture (T):</u> It is the total number of streams of all orders per perimeter of that area (Horton 1945). It is one of the important concepts of geomorphology which indicates the relative spacing of drainage lines. Drainage lines are numerous over impermeable areas than permeable areas. The drainage texture depends upon a number of natural factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development (Smith 1950). According to Horton (1945), infiltration capacity is the single important factor which influences drainage texture. This has got a considerable influence of drainage density and stream frequency. The soft or weak rocks unprotected by vegetation produce a fine texture, whereas massive and resistant rocks cause coarse texture. Sparse vegetation of arid climate causes finer textures than those developed on similar rocks in a humid climate. The texture of a rock is commonly dependent upon vegetation type and climate (Dornkamp and King 1971). In simple terms Drainage Texture (T) is

the product of drainage density and Stream frequency (Fs).

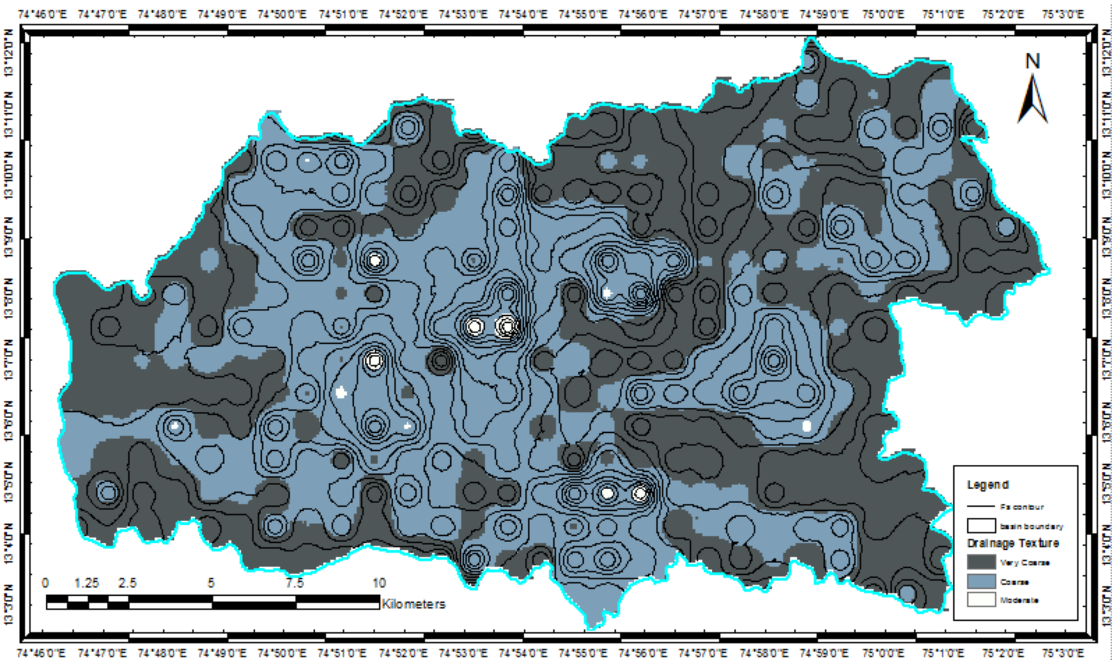

Fig. 2.26 Showing the overlay of Fs contours values over Drainage texture

For the Mulki river basin Drainage Texture (T) is found to be 4.59 (Table 2.1) and according to Smith's (1950) classification the basin comes under coarse textured drainage basin as the values are above 4.0. This indicates a hard and resistant bed rock dominating the basin area which reduces the infiltration. But the drainage density values range from 0.1 to 5 in the basin when it is plotted in each one square kilometers grid (Fig. 2.20). And the basin shows a coarse to very coarse drainage texture (Fig. 2.26).

2.5.4 Relief Aspects of Basin: Basin relief refers to the relative heights of points on the surface with respect to the horizontal base of reference. Vertical inequalities of an area plays an important role in controlling the distribution of precipitation through movement of surface water, formation of features like stream, tank, etc., besides occurrence and movement of groundwater. Evaluation of some of the relief aspects such as relief, relief ratio, relative relief, ruggedness number, slope, etc., of the basin are discussed below which are significant in the geohydrological conditions of the study area.

2.5.4.1 Relief: It is the maximum vertical distance between the lowest and the highest points of the basin. Basin relief is an important factor in understanding the denudational characteristics of the basin. The maximum basin relief (H) is the difference in elevation between basin mouth and the highest point on the basin perimeter measured along the longest dimension parallel to the principal drainage line of the basin (Schumm 1956). According to this concept, the maximum basin relief is 220 meters. However, the maximum height of the whole basin or highest basin relief is 251 meters above mean sea level due to the higher elevational ridge within the basin not bounded along the perimeter of the basin. Since the river mouth is in the sea face, the lowest height is considered to be zero meters at mean sea level. Therefore the relief of the basin is 251 meters.

2.5.4.2 Relief Ratio (R_h): According to Schumm (1963) the relief ratio is the dimensionless height-length ratio equal to the tangent of the angle formed by two planes intersecting at the mouth of the basin, one representing the horizontal, and the other passing through the highest point of the basin. Or it is the ratio of the maximum basin relief (H) to horizontal distance along the longest dimension (L) of the basin parallel to the principal drainage line (Schumm 1963).

The relief ratio of the Mulki River basin is 0.008, which indicates the characteristic value for almost a plain land with a gentle slope formed by the erosional stage. But the high altitude ridge along the eastern side of the basin (Fig. 2.3) form a steep slope in otherwise almost plain channel area indicating a later uplift in the upstream side of the basin. In relation to stream slope, the relief ratio or the inclinations of the ground surfaces are closely tied with its channel gradients and relief. It measures the overall steepness of a drainage basin and is an indicator of intensity of erosion processes operating on the slopes of the basin. The relief ratio normally increases with decreasing drainage area and size of the watersheds of a given drainage basin (Gottschalk 1964). In field, it has been observed that there is a high degree of correlation between high relief and high drainage frequency, high stream frequency and high stream channel slopes which bring out high discharges in short duration (Gopalakrishna *et al.* 2004). This indicates that the discharge capacity of the Mulki river basin is very high and the groundwater potential is meager.

2.5.4.3 Relative Relief (R_{hp}): According to Melton (1957) the relative relief (**R_{hp}**) is the ratio of maximum basin relief (H) to the basin perimeter (P). For Mulki River basin it is found to be 1.99 (Table 2.1).

2.5.4.4 Ruggedness Number (R_n): It is the product of maximum basin relief (H) and drainage density (D_d). Ruggedness number shows the qualities of slope steepness and length. A high value of ruggedness number occurs when slopes are very steep and long. Low values of ruggedness number can be attributed to gentle slope of the land. Mulki river basin shows a ruggedness number of 0.413 indicating an average sloping terrain (Table 2.1).

2.5.5 Slope: Slope Analysis is an important aspect of geomorphological studies. The slope elements, in turn are controlled by the climatomorphogenic processes in the area having the rock of varying resistance. An understanding of the slope distribution is essential as a slope map provides data for planning, settlement, mechanization of agriculture, deforestation, planning of engineering structures, morphoconservation practices, etc. (Sreedevi *et al.* 2005).

Various methods of slope analysis are in practice. The slope map (Fig. 2.27) of the Mulki river basin has been prepared using the contour map (10 meter contour interval) and Digital Elevation Map (DEM) of the Mulki river basin prepared out of SOI Toposheets (1:25,000 scale) using the ERDAS imagine 9.1 software. The slope of the area varies from plain land of 0 degrees to a maximum of 33.5 degrees steepness. The values of 0° to 33.5° have been stretched in between 0° to 90° to understand the variation in slope using ArcGIS 10 version software. The slope map of the area shows that majority of the area is plain having very less slope except the steep slopes developed along the steep ridges and the mounts formed in the basin. This map also reveals the geomorphological units of residual hillocks, structural hillocks, major lineaments, major river courses and flood plain areas formed in the area. The slope analysis shows that western part of the basin is having an almost gentle slope and is a plain area up to 7KM stretch from the mouth of the river. The area is almost plain without much slope difference in its river course extending almost up to 16.5KM from the coast in its middle reaches forming a wide valley about 1 to 1.5KM stretch. Then the streams enter the river through steep slopes. The basin is having steep slopes in its middle reaches showing a very rugged topography. Again the slope becomes low to medium in lateritic plateaus on eastern side of the basin with steep slopes along the massive ridge trending NE-SW direction.

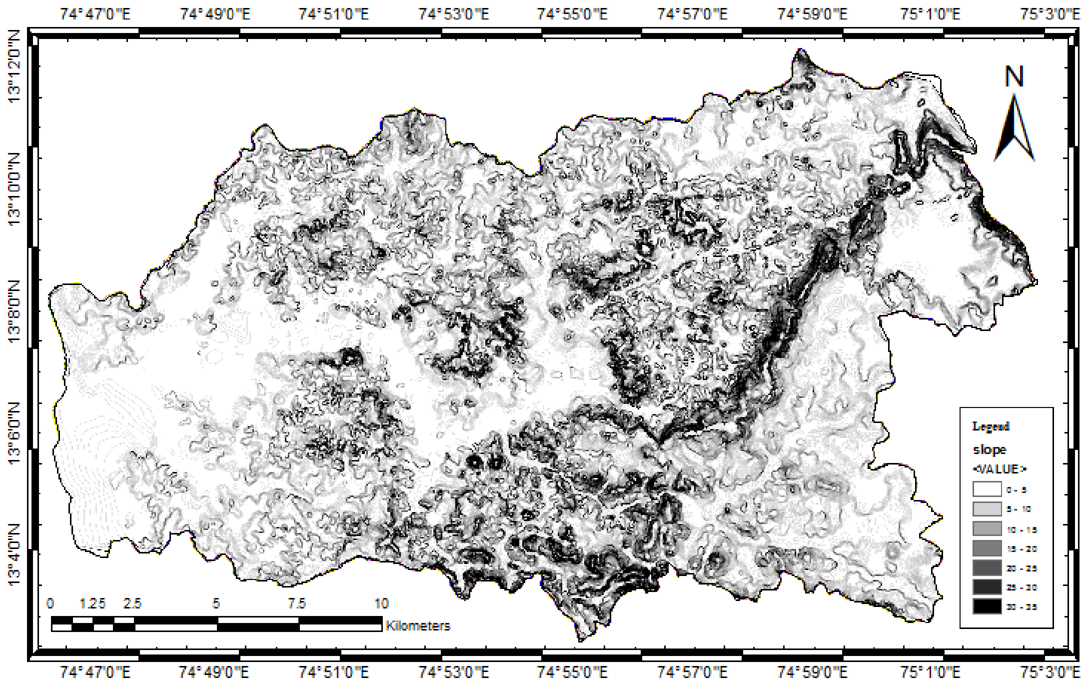

Fig. 2.27 Slope Map of the Mulki River Basin

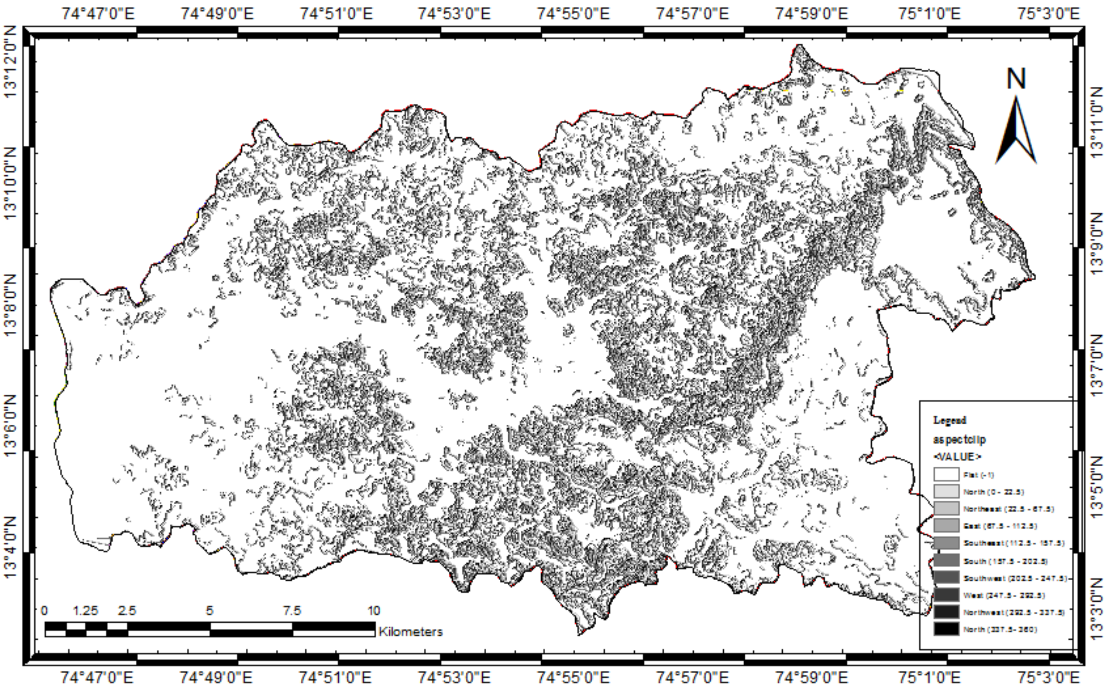

Fig. 2.28 Aspect Map of the Mulki River Basin

Aspect grid is identified as "the downslope direction of the maximum rate of change in value from each cell to its neighbours" (Gorokhovich and Voustianiouk 2006). The aspect map of Mulki river basin (Fig. 2.28) will give an idea about the surface water flow direction. The prevailing high gradient in the hilly terrain and heavy rainfall brings great volume of water during monsoon. The river is prone to tidal effects to considerable lengths in the inland area. The longitudinal slope is measured by overlapping the drainage map with the slope map. First, the area is divided in to three portions viz: Head ward region i.e. from the originating point of the river near Belvai extending up to Sanur where the river takes a turn; then the midland region, from Sanur to Bola; and Mouth portion near the sea. The general slope along the headword portion is 1 in 2.03; that of midland region is 1 in 4.25. The last portion extends from Bola to the mouth of the river. That was calculated to be 1 in 14.18. Drainage pattern of an area is very important in terms of its groundwater potentiality. It is the source of surface water and is affected by structural, lithological and geomorphological set up of an area (Schumm 1956). The drainage pattern in the study area is mainly dendritic in nature. This may be due to more or less homogeneous lithology and structural controls. In the study area high drainage density is observed in the hilly terrain with impermeable hard rock substratum, and low drainage density over the highly permeable sub-soils and low relief area. Low drainage density areas are favourable for identification of groundwater potential zones. Slope plays a very significant role in determining infiltration vs. runoff relation. Infiltration is inversely related to slope i.e. gentler the slope, higher is infiltration and less the runoff and vice versa.

2.6 HYPSOMETRIC CURVE ANALYSIS: Hypsometric curve analysis or the relation of horizontal cross-sectional drainage basin area to elevation was developed in its dimensionless form by Langbein (1947), who applied it, to large watersheds. Strahler (1952), Miller (1953), Schumm (1956) and Coates (1958) applied this area-altitude relation to small drainage basins of lower orders. This analysis is useful to find out the relationship between the horizontal area and height of the drainage basin (Langbein 1947, Strahler 1952). The drainage area and corresponding heights can be determined from Digital Elevation Model (DEM). Hypsometric curve is a plot of the continuous function of relative height (h/H) to relative area (a/A). The relative height is the ratio of height of given contour (h) to total basin height or relief (H). Relative area is the ratio of horizontal cross sectional area (a) to the entire basin area (A).

The hypsometric curve for a drainage basin (Fig. 2.29) represents the relative proportion of the watershed area below (or above) a given height (Strahler 1952, Schumm 1956). This surface elevation curve is a useful tool for characterizing the topographic relief within a drainage basin. The shape of the hypsometric curve is related with the stage of geomorphic development of the basin. Convex hypsometric curves are typical of a youthful stage; S-shaped curves are related to a maturity stage, and concave curves are indicative of a peneplain stage (Strahler 1952). The hypsometric integral is defined as the area below the hypsometric curve (Strahler 1952, Schumm 1956), and it has been used, as well as the hypsometric curve, to infer the stage of development of a basin.

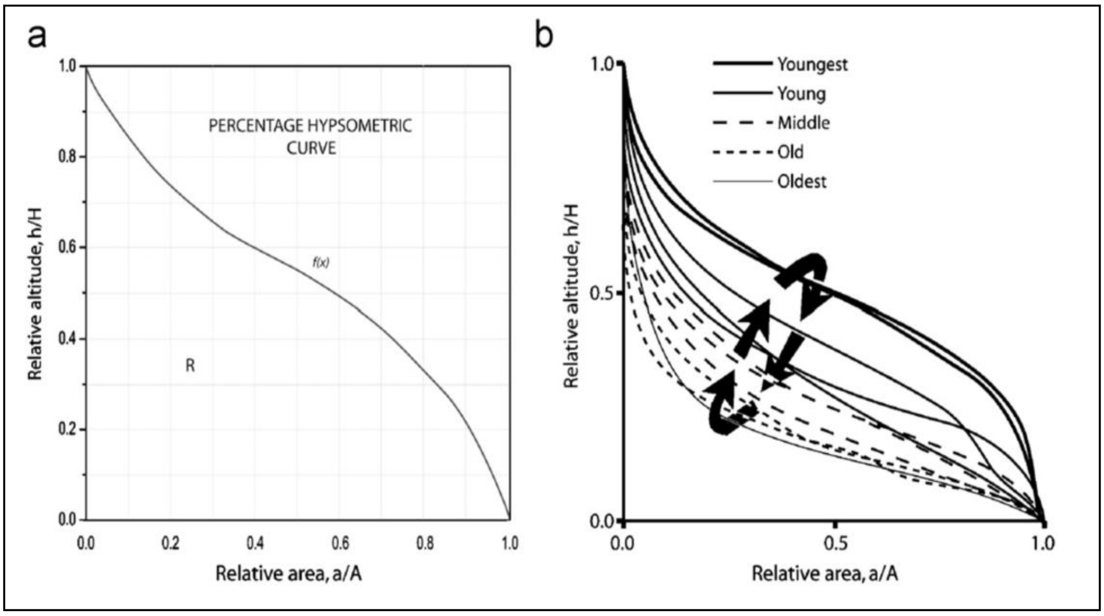

Fig. 2.29 a. Hypsometric curve after Strahler (1952) b. Changes in Hypsometric curves (*modified* after Ohmori 1993)

For instance, values near 1 indicate a state of youth and are typical of convex curves. Nevertheless, mature S-shaped hypsometric curves can present a great variety of shapes, but the same hypsometric integral value (Hurtrez *et al.* 1999, Ohmori 1993). The shape of hypsometric curve varies in early geologic stage of development of the drainage basin, but once the mature stage is attained, it tends to vary little thereafter, despite lowering relief (Strahler 1952). Isolated bodies of resistant rocks may form prominent hillocks rising above a generally subdued surface. The result is distorted hypsometric curves termed as monadnock phase. Hypsometric analysis has been widely used in geomorphology, hydrology, and active tectonics (Lifton and Chase 1992, Ciccacci *et al.* 1992, Ohmori 1993, Willgoose 1994, Willgoose and Hancock 1998, D'Alessandro *et al.* 1999, Chen *et al.* 2003). Howard (1990) studied the relations between hypsometry and hydrology, and found that hypsometric curve parameters have a pronounced relation with basin hydrology and particularly with its flood response. Various authors (Lifton and Chase 1992, Chen *et al.* 2003) established a relation between the hypsometric curves and morphotectonics.

With the current development of geographical information systems (GIS), the calculation of hypsometric curves has become easier. The spreading of digital elevation models (DEMs) offers good raw material to analyze hypsometry. It is not necessary to count on a very detailed DEM, since the hypsometric curve is robust against variations in DEM resolution (Hurtrez *et al.* 1999, Keller and Pinter 2002). The CalHypso (Perez-Pena *et al*. 2009), an ArcGIS extension (for ArcMap) proposed the use of zonal statistical functions integrated in GIS to obtain binned elevation frequencies from digital elevation models. This method automatically extracts multiple hypsometric curves at once from the relative areas and relative elevations of DEM based on the raster data model using ArcGIS.

Hypsometric analysis for the Mulki river basin has been carried out for its main basin and its sub-basins up to 3rd order. For this, the basin boundaries of different order of streams were overlaid on DEM of the basin and the hypsometric curves were prepared using the CalHypso extension of ArcGIS 9 version (Perez-Pena *et al*. 2009). The hypsometric curve for the Mulki River Basin (Fig. 2.30) shows that the river reached the mature stage of its development with monadnock phase. The hypsometric curves for the sub-basins (5th order basins) of Mulki river (Fig. 2.31) show the mature stage of the river development with equilibrium phase. The hypsometric curves for the 4th order basins of Mulki river (Fig. 2.32) show the mature stage of the river development with equilibrium phase to that of monadnock phase. And the aberrancy in the last phase of the curve indicates the recent disturbance or upliftment of the basins indicating a probability of neotectonic activity in the area (Perez-Pena *et al*. 2009).

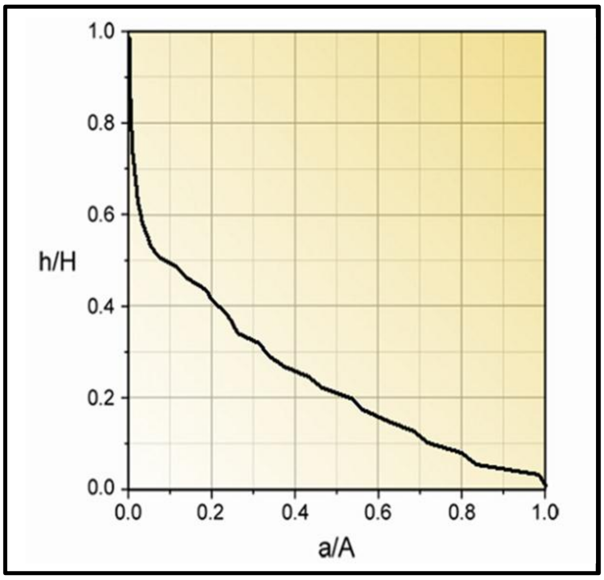

Fig. 2.30 Hypsometric curve of the Mulki River Basin (6th order)

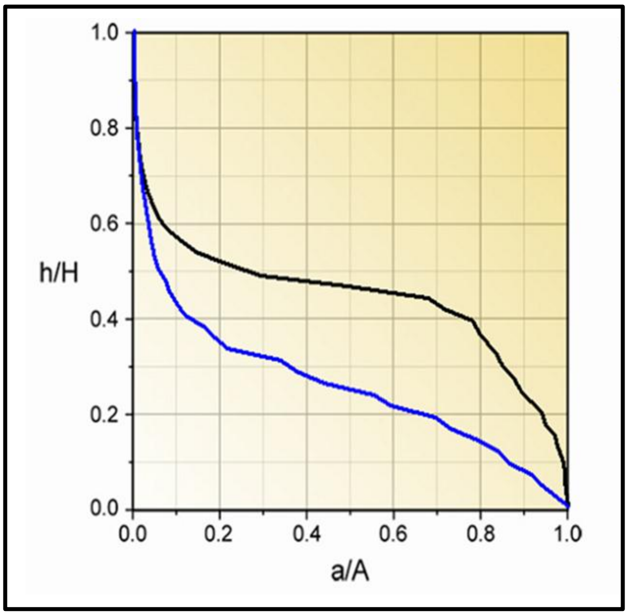

Fig. 2.31 Hypsometric curves of the sub-basins (5th order streams) in Mulki River Basin

The hypsometric curves for the 3rd order basins of Mulki river (Fig. 2.33) show the mature stage of the river development with equilibrium phase to that of monadnock phase. A few of these curves show the inequilibrium stage representing the young phase of the river development pointing towards the recent development of the streams or a revival of the streams pointing towards a neogene uplift or neotectonic activity in the area (Perez-Pena *et al.* 2009).

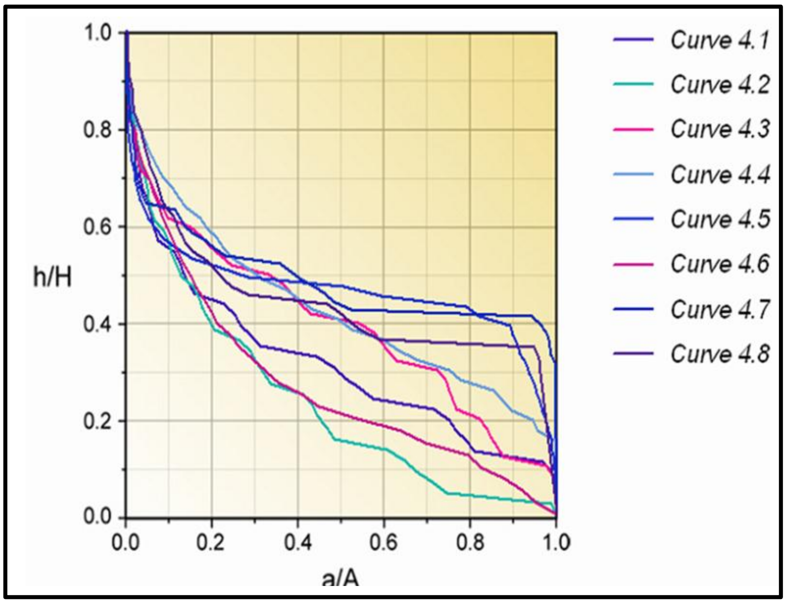

Fig. 2.32 Hypsometric curves of the sub-basins (4th order streams) in Mulki River Basin

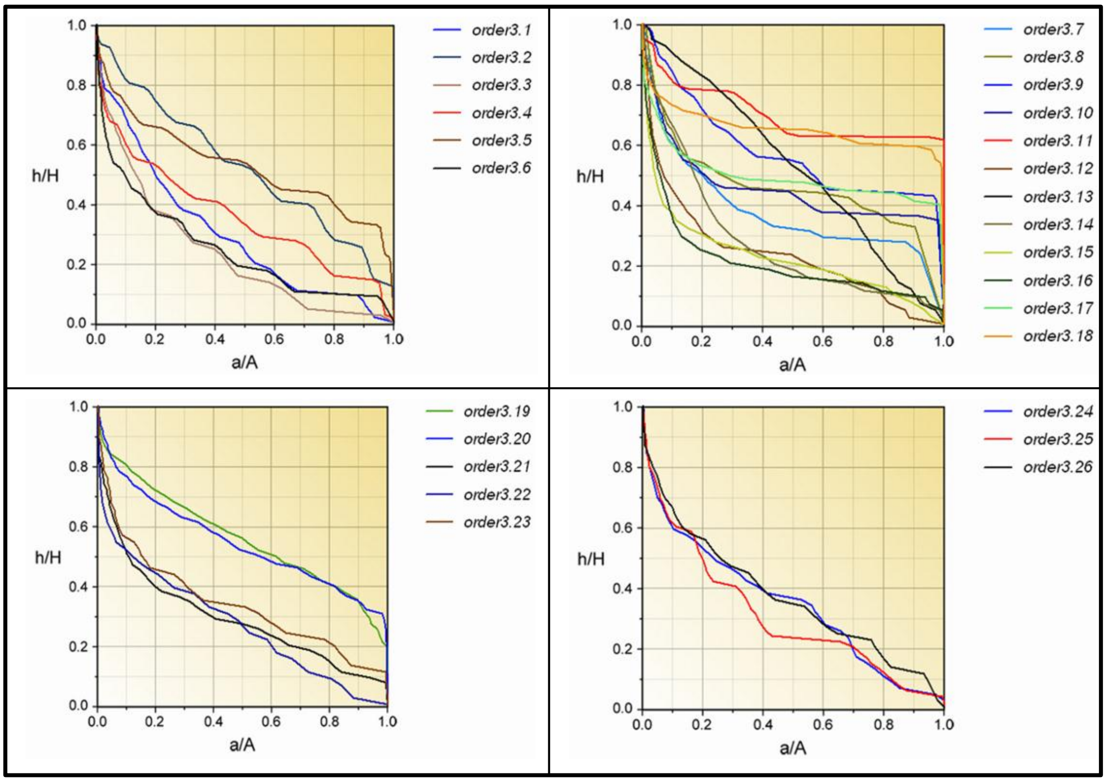

Fig. 2.33 Hypsometric curves of the sub-basins (3rd order streams) in Mulki River Basin

2.7 CONCLUSIONS: Mulki is a 6th order closed rectilinear midland draining coastal river basin exhibiting dendritic pattern of drainage in general with parallel, rectangular and radial drainage patterns in its different sub-basins. Mulki river basin being a part of Coastal Landform terrain is dominantly covered by Kanara Pediplain with a small stretch of coastal lowland terrain. Major structural disturbance affected the river dissecting in into three parts pulling down the middle part towards south. The major lineaments trending almost in the E.NE-W.SW control the higher order streams and the lineament fabric aligned in N-S, NW-SE, NE-SW control the lower order streams in this area. Geomorphic evidences and morphometric relations strongly indicate neotectonic activities and regional uplift in this matured river basin area. This has been supported by the rose diagrams of streams and hypsometric curves of the sub-basins. The basin is having a very coarse graded drainage texture with predominant sheet flow and erosion in this area. Even though the undulating topography with monadnocks, inselbergs, residual hillocks and ridges, flood plain deposits, meandering course and drainage network controlled by lineament fabric favours the groundwater accumulation, the drainage texture and drainage density indicate a poor recharge in this area due to the impervious rocks and steep slopes. So, proper control of surface water movement through an effective topographic terrain management will favour the geohydrological conditions of this study area.

Fig. 2.34 Photograph showing the Butte formed in the Mulki river Basin near Bola

Fig. 2.35 Photograph showing deep entrenched meandering valley near Sachcharepete

Fig. 2.36 Photograph showing deep entrenched meandering valley near Sachcharepete with a highly crushed breccia formation (?) at the bottom of riverine deposits

Fig. 2.37 Photograph showing stratified deposits above the present valley near Sachcharepete indicating neogene uplift

Fig. 2.38 Photograph showing stratified deposits and cross beddings in recent alluvium near Sachcharepete indicating neogene uplift

Fig. 2.39 Photograph showing Waterfall in the Mulki River at Parappady, Nitte

Chapter 3

Geology

CHAPTER 3

GEOLOGY

3.1 INTRODUCTION: The occurrence and movement of groundwater, being a subsurface phenomenon, the same is controlled by the geology of the area along with its structural features and their hydrological characteristics. In the hard rock terrain, availability of groundwater is limited and its occurrence is essentially confined to fractures and weathered zones. Satellite remote sensing provides synoptic view, which is helpful in identification and delineation of various landforms, linear features, structural elements, and terrain characteristics which are indicators of groundwater potentials.

3.2 GEOLOGY OF KARNATAKA: Karnataka Craton being one of the oldest Pre-Cambrian terrains of the world, its geological history (Radhakrishna and Vaidyanadhan 1994, Ravindra 2007) is largely confined to the Archaean and the Proterozoic eras (Fig. 3.1).

Archaean era is represented by a series of volcanic and sedimentary activities. The oldest group of rocks 'Ancient Supracrustals', the highly metamorphosed remnants found in grey gneisses (3400m.y) belonging to Sargur Schists of Archaean era are thought to be the oldest rocks in Karnataka. The next in order of age are Auriferrous Schist belt (Kolar type) constituted mainly of basic igneous rocks with associated intrusives. During 3400 to 3000m.y due to tectono-thermal events, an extensive formation of grey gneisses developed and named as Older Gneissic Complex. Later during 2700m.y to 2000m.y. Younger Gneissic Complex of granodioritic and granitic composition formed in the eastern parts of the State. Together they are named as Peninsular Gneiss. Then the formation of Younger Schist Belts (Dharwar type) comprised of older Bababudan group (igneous origin with iron formations) and younger Chitradurga group (metasedimentary) formed. The end of Dharwar cycle is marked by a fresh outburst of granitic activity around 2600m.y. ago and is called as Younger (Closepet) Granite. Emplacement of Charnockite and layered ultramafics occurred coeval to this period. The close of Archaean is marked by a period of N-S and E-W trending dolerite dyke formation which are of younger age of less than 2400m.y. Then a long Great Eparchaean Interval of more than 1000m.y. succeeded without any major formation.

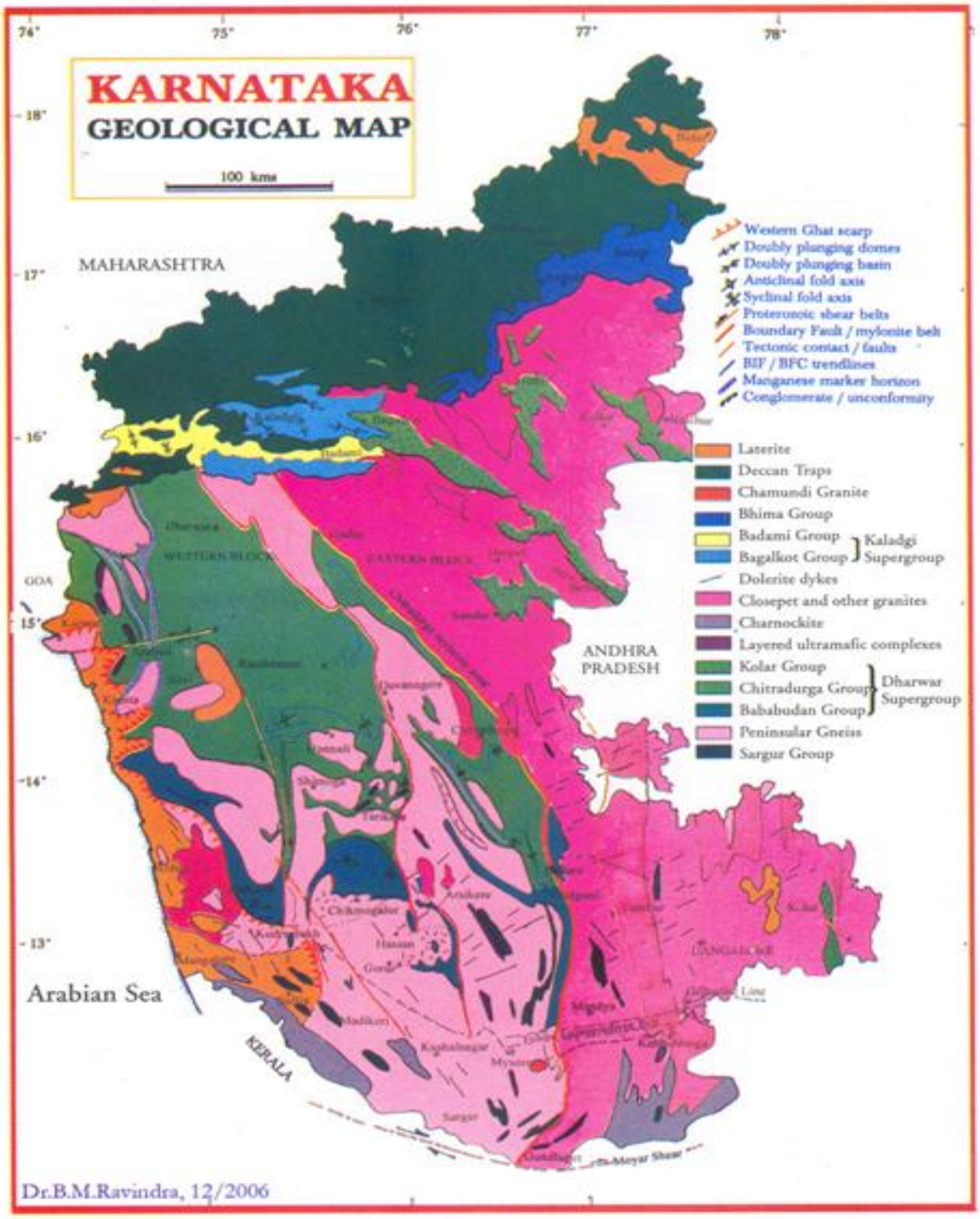

Fig. 3.1 Geological Map of Karnataka (*after* B.M. Ravindra 2007)

The Proterozoic era of Karnataka is marked by the submergence of northern parts of Karnataka below sea level and the development of Kaladgi and Bhima sedimentary formations. The elevation of these landmasses and the formation of Peninsular Indian Shield as a part of Gondwana land marked the end of Proterozoic era.

The rocks belonging to Phanerozoic era (600m.y. to present) are less abundant and restricted only to certain parts of Karnataka. Deccan Traps in the northern Karnataka represent a phenomenal outburst of volcanic activity at the end of Cretaceous and the dawn of Tertiary era (65m.y. ago). The dykes assigned an age around 65m.y. formed along the west coast are mainly associated with this event. It was during the Tertiary period, major changes in Physiography took place. But there is no representation of this period in Karnataka. Over the Deccan Traps are found capping of laterite which probably started forming at cessation of Deccan volcanic activity in early tertiary and are continuing to form even to this day. The narrow coastal belt, between the coastline and precipitous edge of the Western Ghats is a plain of marine denudation and is covered by extensive capping of detrital and residual laterite. Minor sedimentary deposits of quaternary age are exposed along the West Coast.

3.3 GEOLOGY OF DAKSHINA KANNADA AND UDUPI DISTRICTS: The geology of Dakshina Kannada and Udupi districts are similar to the rest of the state except for its occasional laterite capping and unconsolidated river and marine sediments. The granitic gneiss, which is wide spread in the districts outcrops at varying magnitude especially along river courses. Basic intrusives like dolerites and gabbros, and acidic intrusives like pegmatite and quartz veins, and pink porphyritic granites and grey granite are found all over the district. The recent alluvium and colluvial deposits occur along the riverbanks and seacoast. The exposures of crystalline rocks found as isolated spurs, inselbergs and mounds along the shore and off shore. The black clayey marine sediments of 0.3m to >1m thickness occur as lenses at a depth range of 5 to 6 m below ground level along the coast and in the deltaic islands (CGWB 2008).

The rock types in the districts could be classified into (i) high grade schist of Sargur group (ii) migmatites, granites and gneisses of Peninsular Gneissic Complex and (iii) meta volcano-sedimentary sequence of Bababudan group (Fig. 3.2). Vast expanse of irregular patches of laterite is formed mainly in the western sector; in situ type being derived from the alteration of the underlying rocks confined above 600m. elevation whereas transported gravelly type occupy the coastal plains and the adjoining areas. Garnetiferous-Sillimanite gneiss/schist, Kayanite-Sillimanite Schist and Charnockite/

Pyroxene granulite that are exposed in the southeastern part of the districts are high grade metamorphic variants of Sargur Group lithoassemblage (GSI 2005).

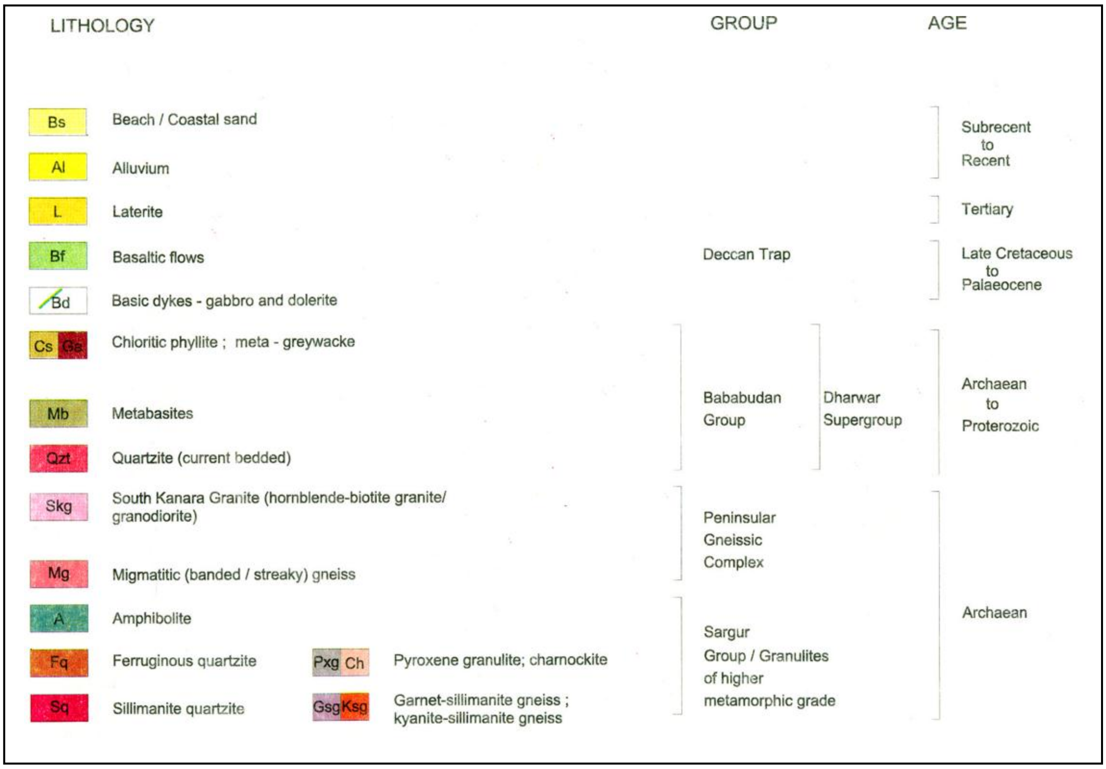

Fig. 3.2 Geological Succession of Dakshina Kannada districts (*after* GSI 2005)

Amphibolite, belonging to Sargur Group occurs as enclaves within the Peninsular Gneissic Complex. Banded quartzites mostly occur as N-S trending linear bands in the area north and northeast of Sulliya. Peninsular Gneissic Complex comprising quartzo-feldspathic gneiss, biotite gneiss, and South Kanara granite occupies major part of the districts except the northern and the eastern fringes. Migmatisation on a large scale seem to have resulted in the formation of varied rock types like homblende-biotite gneiss, quartzo-feldspathic gneiss, migmatitic gneiss and granite gneiss. These rocks show a trend of North-South strike direction. They have developed joints parallel to the strike direction and store groundwater forming deeper aquifers. These rocks when exposed to atmosphere for a long time form large spheroidal masses of dark grey or black colour.

Rocks of Bababudan Group of Dharwar Super group are represented by conglomerate, amphibolite, quartzites, banded iron formation, chloritic phyllite/schist, metabasalt and meta–greywacke/argillite. They are exposed all along the eastern fringe and also in the northernmost part of the districts. Gabbro and granite are the major intrusives, whereas dolerite dykes also intruded mostly along NW-SE directions. Proterozoic younger dykes are scattered throughout the districts.

Phanerozoic formations like Laterite, acid volcanics and recent alluvium found along beaches and river channels are other geologic formations. Extensive lateritization during the Tertiary-Quaternary period had given rise to 15-20 m thick capping of laterite on all the litho units in the districts. Coastal sands and “Teri” sands are seen in the coastal plains as parallel sand flats consisting of coarse sands mainly of quartz with limonite coating.

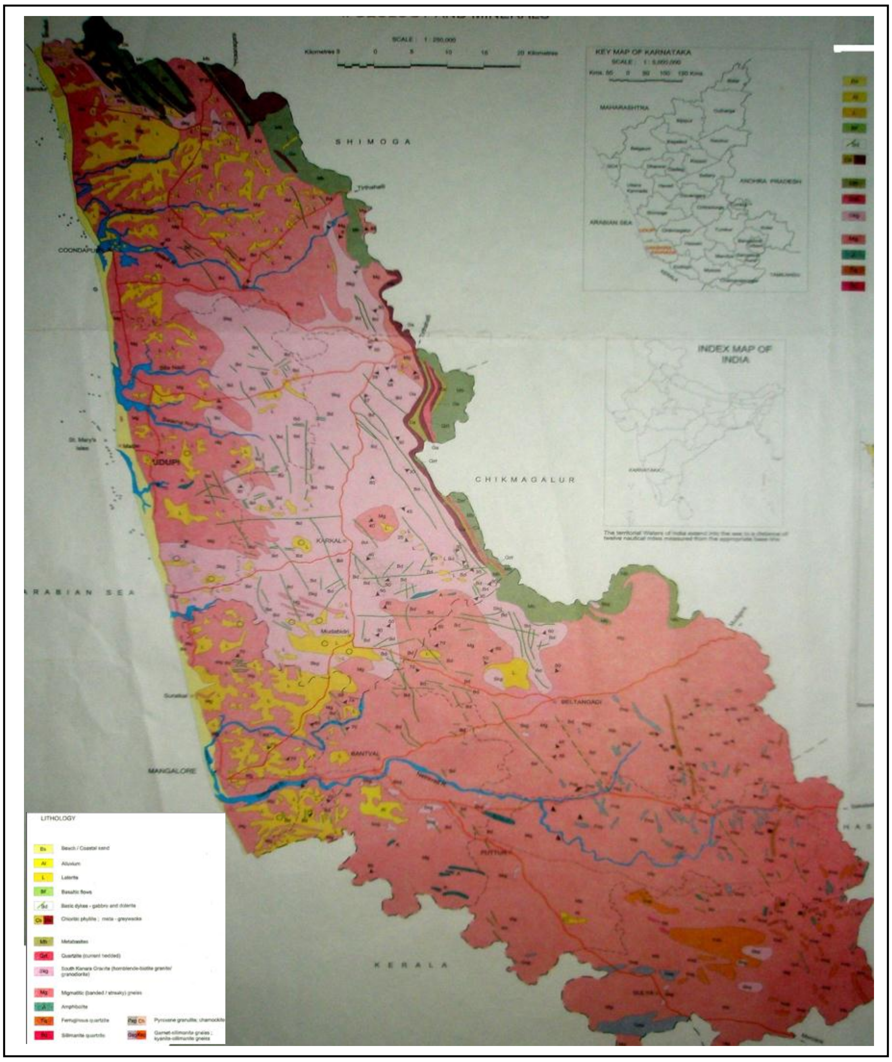

Fig. 3.3 Geological Map of Udupi and Dakshina Kannada districts (*after* GSI 2005)

Systematic studies on geology, geomorphology and geochronology of different parts of erstwhile Dakshina Kannada District were carried out by earlier workers such as

Balasubrahmanyan (1967, 1975, 1978), Radhakrishna (1965), Naganna (1966), Nagaraja (1967), Rao, R.M.G. (1968), Krishnamurthy (1972), Rajashekhariah (1973), Viswanathiah *et al.* (1974), Srivastava (1976), Awasthy and Krishnamurthy (1979), Valsangkar *et al.* (1981), Ravindra and Janardhan (1981), Ramakrishnan and Harinadhababu (1981), Balsubrahmanyan *et al.* (1982), Srivastava and Prasad (1982), Devaraju and Khanadhali (1983), Aurora (1985), Ranganna *et al.* (1986), Laratine *et al*. (1990), Ranganna *et al.* (1994), Saivasan (1998), Shenoy (1999) and Bijumol Jose (2008). The updated geological map of erstwhile Dakshina Kannada District is given above (Fig. 3.3).

3.4 GEOLOGY OF THE STUDY AREA: A systematic study of the Mulki river basin has been carried out based on the resource map of Udupi and Dakshina Kannada district available (GSI 2005), actual field work, utilizing satellite imageries, and comparing it with available geological maps (Geological Survey of India maps) and also based on the work of earlier workers. The geological succession (Fig. 3.4) and the geological map (Fig. 3.5) of the study area have been prepared based on the earlier published woks and the data availed at the Geological Survey of India Karnataka section, Bangalore.

LITHOLOGY		GROUP	AGE
Bs	Beach/Costal Sand		Quaternary
Al	Alluvium		
L/Bl	Laterite/Bauxitic Laterite		Cenozoic
Q	Quartz Veins	Intrusive	Palaeoproterozoic
D/G	Dolerite/Gabbro		
N	Norite		
Pbg	Porphyritic Biotite Granite (South Kanara Granite)	Peninsular Gneissic Complex	Archaean
Hbg	Hornblende Biotite Granite (South Kanara Granite)		
Gg	Granite Gneiss		
Sbg	Streaky Biotite Gneiss		
Bbg	Banded Biotite Gneiss		
C	Charnockite	Sargur Group	
A	Amphibolite		

Fig. 3.4 Geological Succession of the Study Area (Mulki River Basin)

The Mulki river basin exposes the rocks of Sargur group, Peninsular Gneissic complex of Archaean age, South Kanara Granite batholith, younger intrusive of basic dykes and acid veins of Palaeoproterozoic age, laterites of Cenozoic age, coastal sands of Quaternary period and Recent alluvium. The details of the geology of the area have been discussed below.

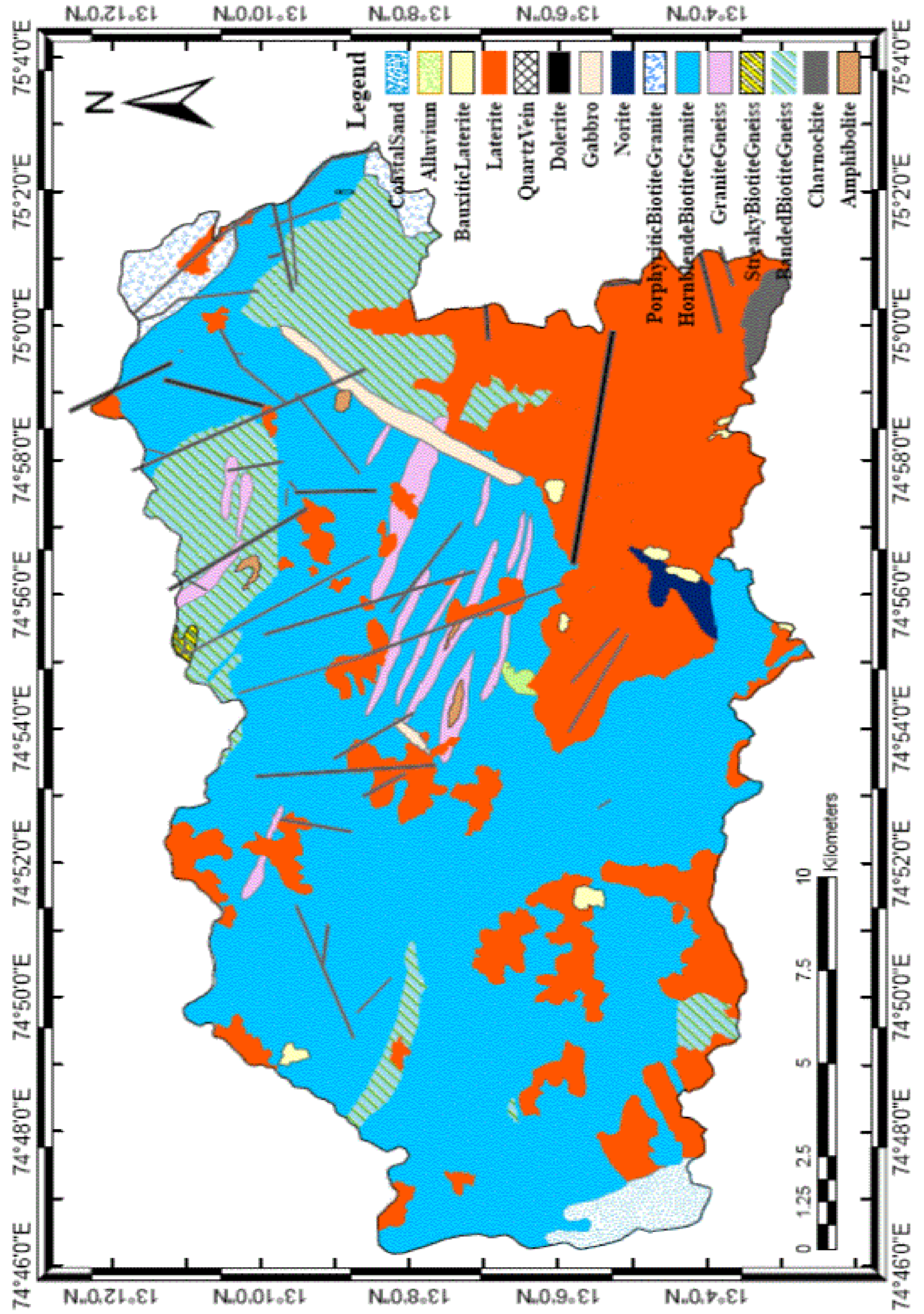

Fig. 3.5 Geological Map of the Mulki River Basin

3.4.1 Sargur Group: This group of rocks is represented by Amphibolite and Charnockite exposed in the area.

3.4.1.1 Amphibolite: Small lenses of Amphibolite are exposed in the eastern part as enclaves of Peninsular Gneissic Complex. It has been exposed at north of Sachcharapete at two places within banded biotite gneiss with a trend of NW-SE and at east of Kemmannu with a folded structure. It can be distinguished by its dark grey colour which is massive and medium grained, constituted of hornblende and plagioclase feldspar.

3.4.1.2 Charnockite: A patch of Charnockite enclave is exposed within Peninsular Gneissic Complex in the south eastern corner of the area near Prantya, north of Hosabettu which is a large patch extending beyond the basin. It shows joints dipping with 65° to 80° striking in almost three directions of E-W, N10°W-S10°E and NW-SE.

3.4.2 Peninsular Gneissic Complex: This is represented by a variety of gneisses and granites with variation in texture, varying from quartz diorite to granite in composition. Based on these criteria they are classified as banded biotite gneiss, streaky biotite gneiss, granitic gneiss and South Kanara granite (Granodiorite/Biotite Hornblende granite and porphyritic biotite granite) which are well exposed in the area.

3.4.2.1 Banded Biotite Gneiss: These are exposed as linear stretches with a general NW-SE trend with foliations of 40° average dipping towards NE. They are well exposed in a stretch between Belman-Bola-Sachcharepete-Kadanthale-Paladka-Kemar in the west to Kalya-Parapadi-Kanthavara in the east. They are also exposed around south of Bola, Kadanthale and Paladka and are intruded by South Kanara biotite granite at a number of places. They are characterized by banded structure formed by biotite rich layers alternating with the light coloured quartz and feldspar rich layers (Fig. 3.6). This formation has been trapped in between the granitoid mass and the boundary is almost marked by the major river lineament trend in the north and west, and by steep granitoid ridge in the south and east forming into a NE-SW trending obloidal mass. Migmatisation is also observed in this rock mass.

Fig. 3.6 Photograph showing the gneissosity and migmatisation in Peninsular Gneiss

3.4.2.2 Streaky Biotite Gneiss: These rocks are exposed around Kalya and Nitte. It is represented by granodiorite gneiss with nebulous folia having biotite and feldspar streaks (Fig. 3.7). They occur along with South Kanara granite batholiths.

Fig. 3.7 Photograph showing the streaky Biotite Gneiss with nebulous folia of feldspar streaks in a well at Kedinje near Kallya

<u>3.4.2.3 Granite Gneiss:</u> These banded grey granitic gneissose rocks are exposed over large parts of the area as small hillocks and isolated outcrops of spurs and inselbergs in valley portions. It is having almost homogenous gneissic pattern resulting from granitisation. But the thickness of banding varies from place to place. In some cases the bands are very thick, as seen in a quarry near Dupadakatte. In some other cases it is only a millimeter thick gneissic banding. These are grey to pink coloured, medium to coarse grained rock. Migmatisation along with intrusions of quartz and pegmatite veins are other common features. According to chronological studies carried out by Balasubrahmanyan (1978) the archaean tonolitic gneisses of South Kanara district shows a minimum age of 3200m.y. Granite gneiss is well exposed around Nitte in the north eastern part of the area. Other places where the rocks exposed are near Atikaribettu alongside of the Mulki river, Nandikur to Inna in a NW-SE trend with a foliation dip of 50°, Puttige, Padumarnad, Belvai, Kariyangadi, Kukkude, Konkanibettu and Iravattur.

Highly foliated gneisses have been found near Sachcharepete in the river valley (Fig. 3.8). Folded and foliated gneisses have been found in Keplaje as inselbergs (Fig. 3.9).

Fig. 3.8 Photograph showing steep foliations in granite gneiss near Sachcharepete

Fig. 3.9 Photograph showing folded foliations in granite gneiss inselberg at Keplaje

Fig. 3.10 Photograph showing the contact of two genetically different gneissic formations with different attitude and foliations overlaid at Sachcharepete

The foliation trend in gneisses varies from N.NW-S.SE to W.NW-E.SE with dips ranging between 15°-70° towards North. Foliation joints, terminal joints and shear joints are common. At places, they are intruded by pegmatite and quartz veins. Near Sachcharepete in the river valley, where the river takes a meandering diversion both banded biotite gneiss and granite gneiss are found (Fig. 3.10).

Under normal conditions gneissic rocks are having less than 1% porosity hence do not hold much water. An experimental work (Mithanthaya 1990) shows that porosity of gneisses in this part varies from 0.388% to 2.61% and highest is near Mudrangadi region in the northern part of the area. The occurrence, movement and distribution of groundwater in Gneisses are complicated and depend on secondary porosity, intensity of weathering, structural pattern and topography.

3.4.2.4 South Kanara Granite: Older granitoid (South Kanara granite pluton) varies in composition from hornblende biotite granite, porphyritic biotite granite to quartz diorite or granodiorite. The rock is medium to coarse grained, grey coloured often with phenocrysts of microcline and plagioclase embedded in quartzo feldspathic and micacious matrix. Granite forms the major rock unit of Peninsular Gneissic Complex and widely exposed in the area. Porphyritic biotite granite is the variant of South Kanara granite. This unit is well exposed in the north eastern part of the basin area near Karkala, Sanuru and Dupadakatte (Fig. 3.11). South Kanara granite Batholith (granodiorite) with highly variable grain size and mineral composition is intrusive into the gneissic rocks (Fig. 3.12) along the axis of the anticlinal fold (Srivastava and Prasad 1982). Rb-Sr isochronal dating gives an age of 2669±60m.y. for non-porphyritic phase and 2681±236m.y for porphyritic phase (Balsubrahmanyan 1978, Balasubrahmnayan *et al.* 1982).

3.4.2.5 Hornblende Biotite Granite: It is exposed at Nitte and passing along side of NET campus, Nitte in a NW-SE trend. In between Palimaru and Karnire, and around Talipadi, Punaruru, Sinappaiyakodi and Padmannur these rocks are exposed on the surface. These South Kanara Granites (Fig. 3.13) generally show three types of joints viz: (i) strike joints along N80°W-S80°E with steep dips of 70°-80° towards north and south, (ii) flat lying strike joint along N80°W-S80°E with dips of 10°-30° towards north, (iii) cross joints (dip joints) striking N10°E-S10°W with vertical dips. The trend of drainage pattern also follows the same trend indicating an influence of joints on the same.

Fig. 3.11 Massive South Kanara Granite with joints exposed on the river channel

Fig. 3.12 Photograph showing highly foliated Granite gneiss with massive South Kanara Granite (near Sachcharepete)

Fig. 3.13 Photograph showing the South Kanara Granite in a quarry where the highly fractured and weathered aquifer zone is sandwiched in between

3.4.3 Intrusives: Younger intrusives represented by Norite and Dolerite dykes are seen penetrated into the Peninsular Gneissic Complex in the area. Quartz vein intrusions are also found in the study area in addition to pegmatite veins.

3.4.3.1 Norite: It is a coarse grained plutonic rock containing labradorite as the chief constituent and differing from Gabbro by presence of hypersthene as the dominant mineral. In between Gundiyadka in the north and Todangai in the south, on the south bank of the Mulki river lying east of Kallamundkuru, an elongated ridge has been formed out of this basic intrusive rock.

3.4.3.2 Dolerite: A vast majority of dykes in Karnataka are of Proterozoic (2100$\pm$600m.y.) in age (Radhakrishna and Vaidyanadhan 1994). Dolerite dyke emplacement is believed to be younger event in Dharwar craton (Pichamuthu 1967). The orientations of Proterozoic basic dyke swarms imply that the Archaean crust of South India is thermally warped into an elliptical dome with a roughly E-W axis under varying regional tectonic conditions (Drury 1984).

A dolerite dyke trending ENE-WSW exposed south of Karkala (Kuntalpadi) on Karkala-Padubidri state highway in the study area reveals an age of 2193$\pm$45 by K-Ar dating (Balasubrahmanyan 1975). N-S or E-W trending dykes are common in this area. The reddish yellow coloured dyke remnants exposed at Nitte-Kemmannu road indicates the lateritization of the NNE-SSW trending intrusive body. Dykes normally act as subsurface barriers for groundwater movement and act as a boon or bane in groundwater locations. Occasionally, dykes also act as good aquifers especially when they are highly weathered and extensively fractured (Kukkillaya *et al.* 1992). The dykes in this area have been developed joints which are significant in groundwater prospecting.

They occur around Nagundihole near Kallamundkuru, Katil (along Kollur Hole), NW of Talipadi, west of Suntipadigudde near Elinje, north of Shimanturu, Atikaribetta and SE of Surinje. They are trending NNW-SSE, NNE-SSW, ENE-WSW, N-S, and E-W directions. The NNW-SSE trending dolerite dykes are numerous and relatively abundant in granite. They are seen cutting across the gneisses and granite. Often these dykes show branching which can be seen near Karkala and it extends up to Kolake on one side and to Kotalkyar on the other side along the north eastern boundary of the basin.

Two generations of dolerite dykes have been found in this area. The older one being coarse grained and younger one fine grained. In some places the younger dykes (E-W) cut across the older dykes (N-S) as found in Kalya and Dupadakatte (Balasubrahmanyan 1975, Ananthapadmanabha 1990).

3.4.3.3 Gabbro: Massive Gabbroic intrusions are found near Bola and Chilme gudde (Pupmel gudde) which are trending in NE-SW direction (Ananthapadmanabha 1990). The steep land mark feature found in the study area as an elongated ridge extending for a long distance is mainly constituted of this gabbroic intrusive. The petrological examination revealed that this gabbroic mass is slightly metamorphosed (Ananthapadmanabha 1990). Three generation of joints (vertical, inclined and horizontal) are found in the grabbroic hillock intruded in the peninsular gneiss at Bola (Fig. 3.14). This may be of the results of stresses induced depicting later tectonic activity in this area (Valdiya 2001). Spheroidal weathering is found in these dyke rocks and the capping of hard ferruginous laterite is found at the top of it (Fig. 3.15).

Fig. 3.14 Photograph showing the multiple sets Joints in the gabbroic mass at Bola gudde

Fig. 3.15 Photograph showing the jointing and spheroidal weathering of Gabbroic mass at Bola

3.4.3.4 Other Intrusives: A large number of quartz veins and pegmatite veins are noticed intruding into gneissic rocks. Generally it has followed the trend of foliation of gneisses and joint patterns in the study area. In some instances these veins are believed to be favourable places for the accumulation of groundwater and hence are immensely important in groundwater investigation. Prominent N-S trending Quartz vein intrusion is found near eastern part of the study area near Iravattur. Some of these Quartz veins are seen even in lateritised area as relict structures. They are very significant in the occurrence and movement of groundwater in this area. Sometimes they act as a conduit or as a barrier to groundwater flow.

3.4.4 Cenozoic: Cenozoic time is represented by the Laterite and bauxitised Lateritic capping.

3.4.4.1 Laterite: Laterites are the product of intense sub aerial rock weathering whose iron and aluminium contents are higher, leaching out the other minerals where silica content is lower than in merely kaolinite parent rocks (Prescott and Pendleton 1947). Two major types of laterites are identified in the Study area. They are primary laterites and detrital laterites. Primary laterites are in situ in nature, and were developed over the crystalline rocks viz: gneisses, gabbro, dolerite, etc. Detrital laterites were developed from reworking of primary laterites and contain sands and rounded pebbles of quartz (Fig. 3.18). Good exposures of laterite are seen in many parts of the area other than granite or granitic gneiss. Some of these laterites show relic foliation of gneisses. In some places dark red laterite showing lateritisation of dolerite dykes/or gabbro has been observed (Fig. 3.16). Laterite covers the rock formations in the coastal region and forms the caps in the flat topped hills. They are in situ in origin passing into weathered bedrock through a zone of “terra rosa” or kaolinitic clays. Three types of laterites are noticed in the area viz: ferruginous, aluminous and pisolitic type (Figs. 3.16, 3.17 & 3.18).

Most of the open wells in this area are dug in laterite rocks and the depth of these wells varies depending upon its thickness. They form productive aquifers in the area close to valley portions or in the areas where the plateau merges in the valley. The high porosity and hydraulic conductivity of the laterite favours the upward and lateral movement of groundwater. But the ruggedness of the topography and the good hydrologic properties induce the infiltrated water to escape as base flow resulting in the drying up of wells during summer seasons. Laterites are underlain by a layer of lithomarge clay which is sandy silt in composition. Caving in of lithomarge clay in dug wells is common where in the depth of a dug well is more than the top diameter of dug wells. The dug wells tapping laterites in general have large diameter ranging from 9-13m. The thickness of the aquifer tapped ranges from 1m.- 6.21m. Laterite and lateritic soil of this area are highly porous and possess high to medium permeability. The water absorption property of laterites of this area varies from 10.5% to 23% (Srinath 1993) and the porosity varies from 29.92% to 38.17% (Udayakumar 2008). The hydraulic conductivity of the ferruginous laterite is found to be very high and around 10^{-04} cm/s. (Udayakumar 2008).

Fig. 3.16 Photograph showing the hard ferruginous laterite (Primary) capping on the Gabbroic mass at Bola gudde

Prominent laterite formations are found as plateaus at different elevations of planation surfaces. They are mainly found as capping on peninsular gneissic complex. Places such as Mulki, Nadisal, Padubidri, Kenchanakere, Nekkara, Nandikur, Mudrangadi, Belman, Nandalike, Atikaribettu, Kinnigoli, Pompei, Damaskatte, Elinje, Jarigakate,

Fig. 3.17 Primary laterite (in situ) aluminous formation through spheroidal weathering of granitic gneiss at Karnire (Munkur- Inna Road)

Fig. 3.18 Detrital laterite formation near Sachcharepete

Mundkuru, Bola, Guddeangadi, Kukkatte, Balkunje, Manjabail, Kolattaru, Gundyadka, Barangala, Paladka, Beladi, Onjarakatte, Kadanthale, Sanuru, Banterpadu gudde, Mugligudde, Parapadi gudde, Sunkada padavu, Piliyur gudde, Parpale gudde, Kolluru gudde, Kollurpadu gudde, Sunketi gudde, Manjalgudde and Moodbidri-Belvai plateau exposes laterite on a widespread area. “Padavu” and “gudde” mean plateau and hillock respectively in local terms and indicate the lateritisation on the highly elevated areas where the bare hill top is exposed to intense sub aerial weathering and leaching.

Relict structures depicting the foliations of the granitic gneiss could be observed in some of the laterite formations. Different levels of planation surfaces formed by the laterite plateaus at different level from the coastal area to the perimeter of the basin indicate probable uplift of the terrain due to neogenic activity.

3.4.4.2 Bauxitic Laterite: Vermicular, massive bauxite and clay bauxite occur at places as pockets associated with laterite. Laterite with pisolitic and spherulitic textures are more greyish in colour and are found to be exposed at Prantya, east of Puttigepadavu, at Kencha and Kanchivayal northeast of Kallamundkuru, Paladka gudde, Paladka, Kukkatte and Santur.

3.4.5 Quaternary or Recent Sediments: They are represented by the silica sands on the beach and sand bars, clayey marine sediments and recent alluvial deposits**.**

3.4.5.1 Coastal Sands: The coastal strip reveals silica rich sands of recent to sub recent origin. This fine to coarse, even textured grains of pure silica is in greyish white to white in colour. They occur in the beach sands as isolated lensed pockets and often preserved under sand dunes. Red to Maroon coloured ‘teri’ sand deposits occur in patches parallel to the National Highway NH-66. Occurrence of a thin layer of good quality silica (average silica 96.9%) of about 20 cm to 100 cm. thick is reported from Hejmady (Narayana *et al.* 1991).

3.4.5.2 Clayey Marine Sediments: Lagoonal clays with alternating layers of clays, silt and clayey sands are present in Kolachikambla.

3.4.5.3 Alluvial Sediments: In the middle reaches of the river basin fairly thick deposits of alluvial sediments with stratification have been formed (Fig. 3.19) other than flood plain deposits. Sand mining is carried out in a few places such as Elinje, Sachcharepete and near Palimaru from the river channel indicating the high quality of silica percentage in it. Even cross beddings in the alluvial deposits could be seen near Sachcharepete (Fig. 3.20). Except clay, other quaternary sediments are favourable zones for groundwater development.

Fig. 3.19 Stratified alluvial deposits near Sachcharapete

Fig. 3.20 Photograph showing the stratification and cross bedding (recent uplift and tilting?) in the recent alluvial deposits near Sachcharepete

3.5 STRUCTURAL FEATURES: Under lying geological structures play an important role in the occurrence and movement of surface and groundwater**.** The trends of the streams and the flow direction of the surface water and its accumulation are controlled by the structural features. Lineaments or Linear structures such as joint planes, fracture zones, foliations, faults and ridges other than folds have deciding role in the geohydrology of the area since they form weaker planes through which groundwater can enter the aquifers. The major structural features observed in the study area are joints/fractures, foliations, intrusions, folds and faults. Since these structures control groundwater storage and movement in hard rock areas (Radhakrishna 1968), study of these features are very much essential for the groundwater exploration. An understanding of them will give a clue to the tectonic movements and the origin of the present topography and geology of the area (Subrahmanya 1994, 1996; Valdiya 2001). Due to the synoptic view and multispectral information, satellite images can provide invaluable data on the topography and tectonic history of the area. The lineaments such as the alignment of natural vegetation, morphological features, alignment of streams and surface water bodies indicate the control of structures on the land forms and help in the extraction of information related to geological structures.

3.5.1 Lineaments: Mappable linear features on the earth surface, which are simple or composite, aligned in a rectilinear or slightly curvilinear nature and distinctly different from the patterns of adjacent structures reflecting a subsurface phenomenon can be called as lineaments (O'Leary *et al.* 1976). Several geologists recognized the importance of lineaments as a zone of weakness or structural displacement (Hobbs 1904, O'Leary *et al.* 1976). Drury and Holt (1980) and Drury *et al.* (1984) combined remote sensing with geological, geochemical and geophysical data and brought out a detailed tectonic interpretation of the South Indian Peninsular Shield. Mega lineaments of Karnataka have been studied by Ganeshraj (1994) and they are associated with major rivers in Karnataka. Dykes and ridges also are lineaments but with a positive relief.

From LISS-III image, band-3 was extracted using image processing software which clearly distinguishes the man-made features from the natural lineaments in the study

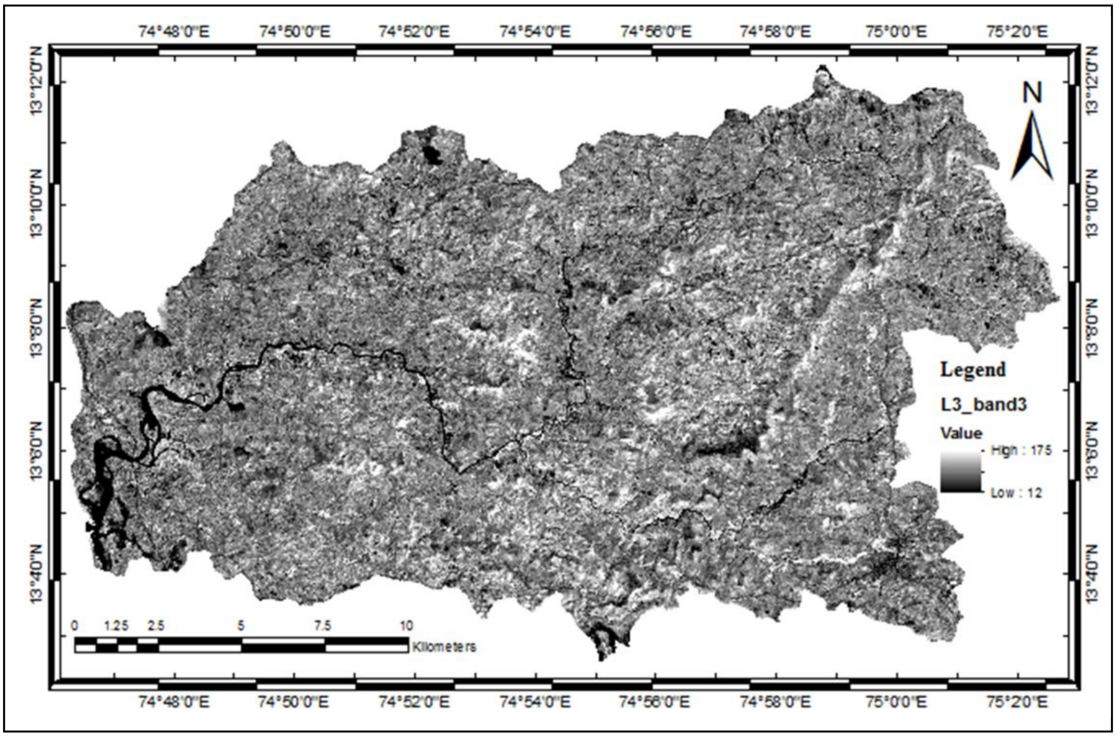

Fig. 3.21 showing the LISS-III band-3 image indicating the differentiation of man-made structures and lineaments of nature

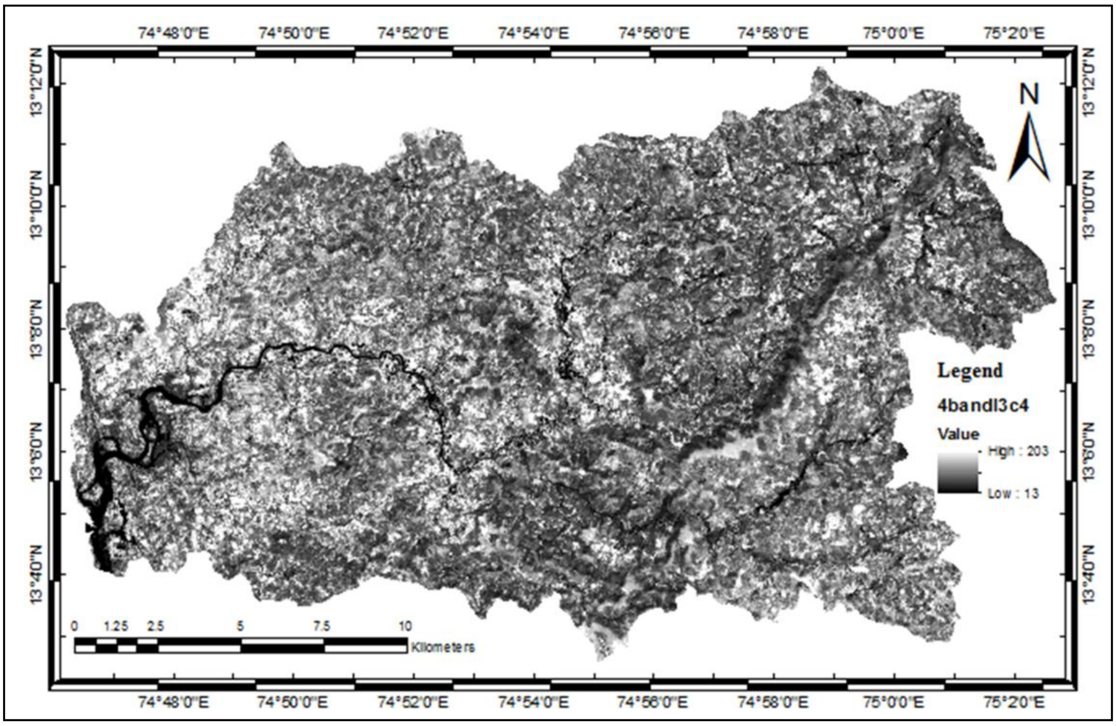

Fig. 3.22 showing the LISS-III band-4 image indicating the prominence of linear features in the study area

area (Fig. 3.21). In LISS-III band 4, the lineaments especially the joints along drainages, ridges, faults, etc., are more clear (Fig. 3.22). Other than visual image interpretation, different methods of image processing such as high pass filtering, edge enhancement, edge detection, band ratioing, principal component analysis, etc., were employed to identify and distinguish the lineament features of the study area. The major structural features like fractures, master joints, faults, structural ridges, etc., were being extracted and delineated (Fig. 3.23) from the LISS-III and LISS-IV MX Satellite imageries using ERDAS Imagine 9.1 software. From this, it could be inferred that the parallel and rectangular drainage pattern noticed in the study area (Figs. 2.1 & 2.8) is controlled by the lineament fabric. The major trends of the lineaments are in E-W, W.NW-E.SE, NE-SW, N-S, N.NE-S.SW, N.NW-S.SE and NW-SE directions (Fig. 3.24). The average length of the lineaments within the basin is 2.32 km having a minimum and maximum length of 0.213 km and 27.56 km respectively (Appendix II). The original trend of the river could be delineated from the lineament stretched along the Mulki-Munkur-Bola-Sanuru alignment (Fig. 3.23). There are some lineaments extending up to the Western Ghats from the basin which will be highly potential for groundwater explorations. A few of the lineaments extend across the water divide to other river basins and may be potential zones for groundwater prospecting.

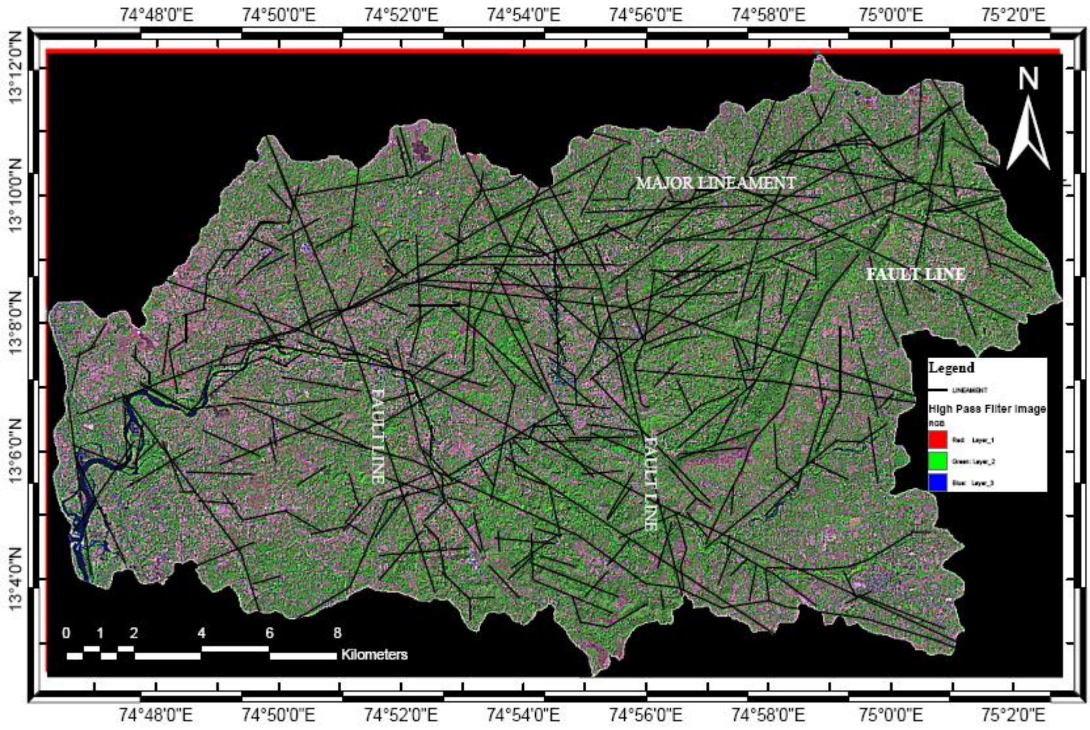

Fig. 3.23 Lineament Map of Mulki River basin

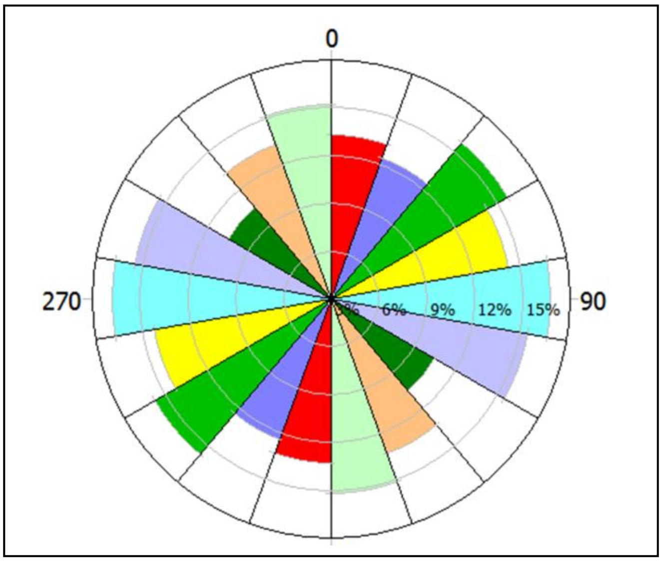

Fig. 3.24 Rose diagram showing the trend of lineaments in the study area

<u>3.5.1.1 Faults:</u> The Western Ghats Scarps, which lie parallel to the straight line boundary coast of the western peninsular India, is attributed to the NW-SE to NNW-SSE trending en echelon faults (Valdiya 2001). Knick points or waterfalls, displacement in the alignment of vegetation, topography and drainage patterns are indications of the faults occurring in an area (Widdowson and Mitchell 1999).

The main channel of the Mulki River takes a "U" turn with knee bends in between Bola and Mundkur and stretches up to Sachcharapete and Elinje down south in the basin. The bending of streams and its arm bend offsets indicate control of faults on the drainage. There is no denying that the deflection of streams was guided by erodible rocks of the fault zone. However, the development of conspicuous loops implies strike slip movements concurrent with the flow in the valleys of the meandering streams (Valdiya 2001). Other than three major active faults in this area (Valdiya 2001), there are other fault planes in the upstream demarcated by the offsetting of river channels (Fig. 3.23). A NW-SE strike slip fault trending along Sanuru-Nitte visibly separate the gabbroic ridge, which is a steep landmark feature in this area moving the NE block towards east. A waterfall (Fig. 2.39) occurs along this line at Parapady, Nitte creating a knick point. The other two active fault lines are passing through Sachcharapete and Elinje near Damaskatte. According to Valdiya (2001) these faults are active and are responsible for the neogene uplift in this area

(Fig. 3.25). The stream ponding found at Elinje is a supporting evidence for the same (Valdiya 2001). The asymmetry of the river basin with wider left bank along with the offset of the river in the middle stretch also is an evidence for the fault and neogene uplift (Molin *et al.* 2004, Rachna Raj *et al.* 2004). It can therefore be surmised that the abrupt deflections of streams and the formation of conspicuous loops in the channels were due to the activeness of the faults (Valdiya 2001). The faults are very significant in the geohydrological studies since they are the weak zones through which water can penetrate, store and migrate through across the basin.

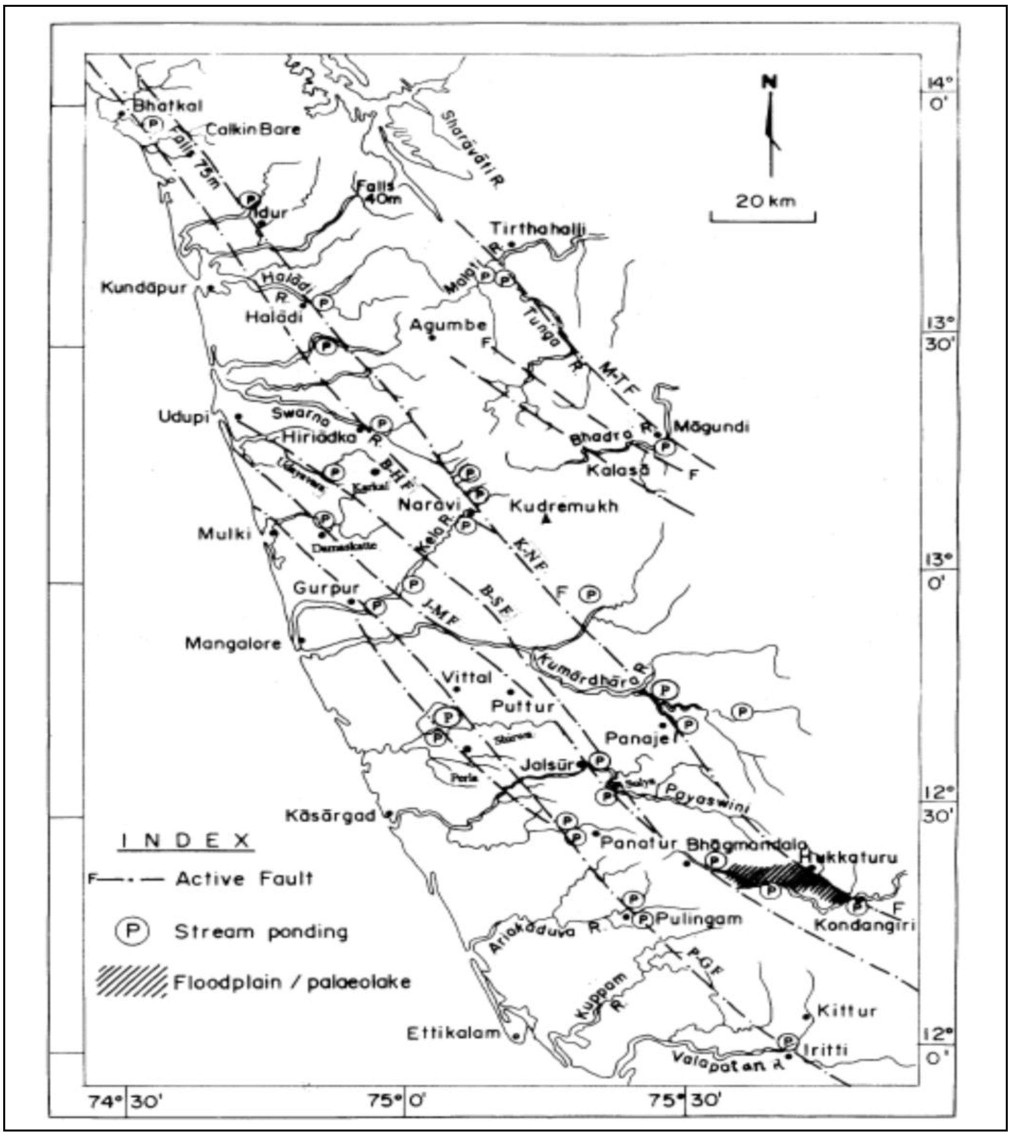

Fig. 3.25 Showing the three active faults (Mulki-Gurpur-Pulingome, Udupi-Damaskatte-Jalsoor, Hiriyadka-Sullia-Bagamandala) in the Mulki river basin (*after* Valdiya 2001)

3.5.1.2 Dykes and Ridges: Dykes and Ridges are the two other types of lineaments which are of significance in the geohydrological studies. Both will act as natural barriers in the movement and storage of surface water and groundwater. Some of the dykes are conductive in nature and are proved to be good aquifer zones (Kukkillaya *et al*. 1992). The upstream sides of the dykes and ridges found to be good aquifer zones provided that the geological conditions are feasible.

There are many dykes formed of basic rocks such as dolerite and gabbro found in this area other than norites, quartz and pegmatite veins in the study area. Sometimes the massive, impervious South Kanara granite batholiths also act as natural barriers for groundwater in gneissic and lateritic terrains. The majority of the Dolerite and gabbroic dykes found to be in the N.NE-S.SW direction barring a few in other directions (Fig. 3.22). They are highly jointed in some areas making it feasible for groundwater storage. Sometimes the sub-basin boundaries are decided by the hard and resistant dykes.

A major ridge extending from Sanoor to Paladka, a land mark feature with a maximum elevation of 251 metres above mean sea level is constituted mainly of highly impervious gabbroic mass. They are bounded by highly folded migmatitic gneiss and laterite capping. This ridge makes the area into two different geohydrological land mass where the eastern side of it is lateritic plateau and the west the granitic and gneissic terrain.

3.5.1.3 Joints: Joints are planes of weaknesses developed in the hard rocks due to cooling or fracturing of beds. Joints are very significant in understanding the geological characteristics of the terrain. The confluence or crossing points of joints emerging from the west would be better prospective zones for high yielding bore wells. A master joint running in the E.NE-W.SW direction controls the trend of the main river channel and many sets of joints are also in the same directions. The gabbroic hillock found in the middle of the Munkur-Bola stretch shows many generation of joints (Fig. 3.26) indicating the stress induced in this area. Foliation joints, terminal joints and shear joints are common in gneissic rocks. Granites show northerly dipping strike joints of 30°-40° and 70°-80° trending in the N80°W-S80°E direction other than vertical dip joints.

Fig. 3.26 Photograph showing the different sets of joints in the gabbroic mass

3.5.1.4 Foliations/Lineations: Parallel planar elements give rise to foliation. In metamorphic rocks they are of secondary origin. The Indian Peninsular gneissic complex of the area shows foliations or lineations/gneissocity, which could be mapped in the field. Majority of the foliations found in the rocks are oriented in the W.NW-E.SE to NW-SE directions. The foliations are dipping towards N to NE and the dips vary between 20° to 80° where majority of the foliations found to be within 40°-50° dipping category. Even the laterite capping shows the relict foliation showing its origin from the gneissose rocks.

3.5.1.5 Folds: River tributaries in the upstream side of the rivers in Western Ghats show meandering pattern due to folding. River channel in the Kadanthale-Sachcharapete area shows steep meandering trenches in the river channel either indicating a folded structure or down cutting streams due to the slow uplift of the area.

Ptygmatic folds in gneisses are another type of folded structures found in the rocks of the area.

3.6 SOILS: Soil influences the infiltration, water availability, water quality, crop pattern, irrigation, etc., and plays an important role in geohydrological conditions in an area. The knowledge on the type of soil and their spatial distribution is a pre-requisite for the rational land use planning for irrigation, agriculture, forestry, drainage, cropping patterns, etc. Karnataka state has been divided into ten agro-climatic zones based on climate, soil, crops and topography. These zones are further divided into six major regions (Badrinath *et al.* 1984). The study area falls under coastal zone and region VI. Five major types of soils viz: Alluvial soils, lateritic soils, red loamy soils, laterite gravelly soils and mountain soils are encountered in the region VI.

3.6.1 Soils of Dakshina Kannada and Udupi Districts: Dakshina Kannada and Udupi Districts have five distinct types of soils (GSI 2005) viz: i) Hilly area soil ii) Red loamy soil iii) Lateritic soil iv) Coastal alluvial (Sandy) soil and v) Laterite gravelly soil (Fig. 3.27). These soils are the result of weathering of Peninsular Gneissic complex (granites and granitic gneiss rocks) mainly.

3.6.1.1 Hilly Area Soil: The eastern boundary of the Dakshina Kannada districts is bounded by the bastion of Western Ghats. And the undulating topography of its terrain is covered by the hilly area soil protected by a thick forest in many parts and in some areas with a barren top.

3.6.1.2 Red Loamy Soil: They are transported from upstream origin and are found often deposited on either side of the banks of the river and lower reaches of valleys. They consist of fine sand with clay. They are usually formed during rainy season. They are mostly used for tile industries. This soil type is very well suited for irrigation and shows good response to irrigation practices.

3.6.1.3 Lateritic Soil: Red lateritic soil is the most dominant soil type in the area and is formed on the crest of the lateritic hills. The hard lateritic crust is broken in to smaller fragments forming pellets. Plenty of fine clayey soil is leached out by the surface water as well as the percolating water. Torrential rain washes down these soils leaving behind the pellets on the slopes and carrying down the fine clay to the downstream. It is normally found in the topographic lows or valley regions or swampy portions. Usually clayey soil is brownish in colour with iron richness. It also forms fertile soils on the banks. The texture of these soils varies from fine to coarse. The soil in the valleys and immediate slopes are rich in loam, where as in upper slopes and pediplains are much coarser in nature. The degree of leaching undergone by this soil type is also variable. It is often associated with a certain percentage of sand and silt which is more suitable for irrigation of paddy and banana plantation. Fine clay is available in paddy fields and swarms.

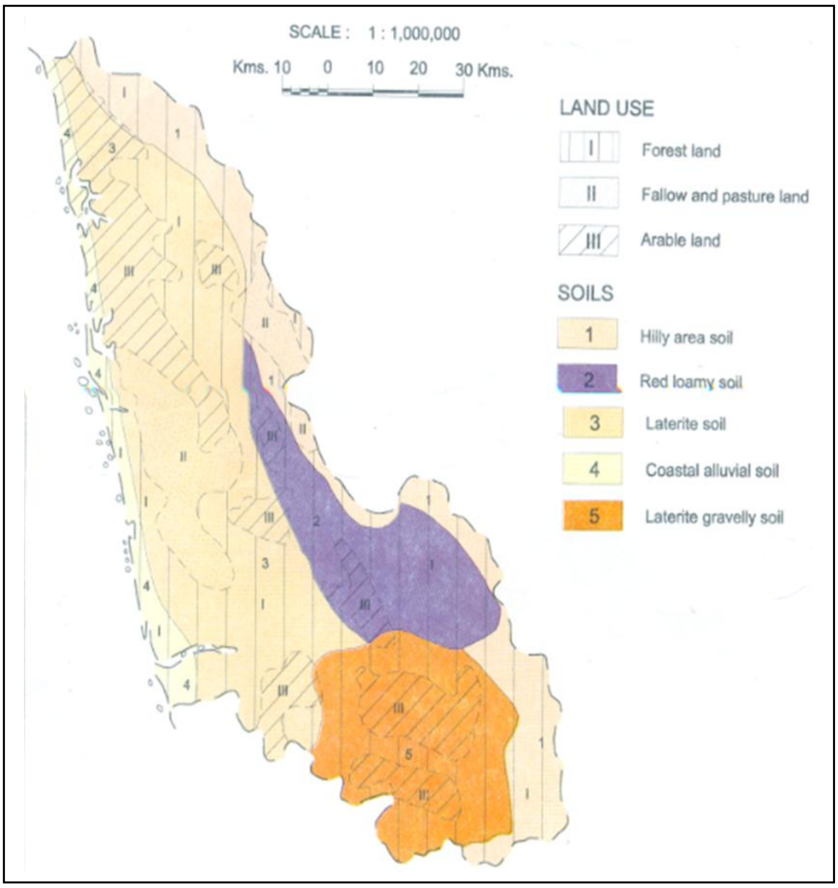

Fig. 3.27 Soil and Land Use Map of Dakshina Kannada districts
(*after* Central Groundwater Board and National Bureau of Soil Survey 1993)

<u>3.6.1.4 Coastal Alluvial Soil</u>: The west flowing rivers of the district becomes active during south west monsoon. The water becomes reddish or brownish due to dispersion of soil matter in the river water. The velocity is checked in the low region and at their

mouths. The transported materials are deposited on either side of the banks of the river and form coastal alluvium. Among these rivers, the largest river Netravati deposits a large quantity of alluvial material nearer its mouth. In other rivers the coastal alluvium is not very significant.

These soils are found in a narrow strip along the coast as well as on either side of the river course. They consist of deposition of sediments carried by the rivers from the upstream side and its adjoining area, as well as by the action of wind and waves. The colour varies from light grey to pale or brown, and darkens with depth. Coastal alluvium consists of river sand of assorted size, fine clay and silt. Usually, the texture varies from loamy sand to sandy loam in the surface and gradually changes to gravelly sandy loam to clay loam in the sub-surface horizon. The sandy soils are confined to a narrow strip of the coast having width ranging from less than 100 m to as much as a kilometre. Along the coastal tract we have beach sands of uniform size. It is honey yellow or light brown and at some places sugar white sand is deposited along the beaches. This has 99.8% silica and it is used in the manufacture of glass and used as foundry sand. The river sand is coarser and available near the mouth. It is used as finer aggregate for cement concrete. These fines to medium textured sands are characterized by their extremely high rate of infiltration, and act as a good recharge media for groundwater. These deposits form very fertile lands for growing paddy and vegetables.

3.6.1.5 Laterite Gravelly Soil: The ferruginous laterite develops a hard crust of dark grey or black cover up to a depth of 15-20m. The hard lateritic crust is broken to smaller fragments and they form pellets. The texture of these variously shaded brownish red or yellowish red soils also varies in between clay loam to gravelly sandy loam on the surface to gravel sandy clay or clay in subsurface horizon. These soils mainly occur in gently undulating plains, foots hills, and at the top of the hilly regions. According to a study (Ranganna *et al.* 1994) rainwater infiltrates at the rate of 7.5 cm./hr. in lateritic soil.

3.6.2 Soils of the Mulki River Basin: An understanding of the soils in the study area is very important in geohydrological studies since the percolation of water in this hard rock terrain is mainly determined by the texture and thickness of the soils present. The soils in the study area can be classified into seven textural types based on its texture and mineral properties (Fig. 3.28). The seven types of soils fall in to four broad family as Sandy soil, Sandy over loamy, Loamy over sandy and a variety of Clayey skeletal with gravely nature having iron or surface encrustation depending on the place of deposition (Table 3.1). They belong to five subgroups of three orders viz: Entisols, Alfisols and Ultisols, where the Entisols are mainly constituted of sand and loam, the Alfisols and Ultisols with gravely clayey skeletal soils having iron or surface encrustations.

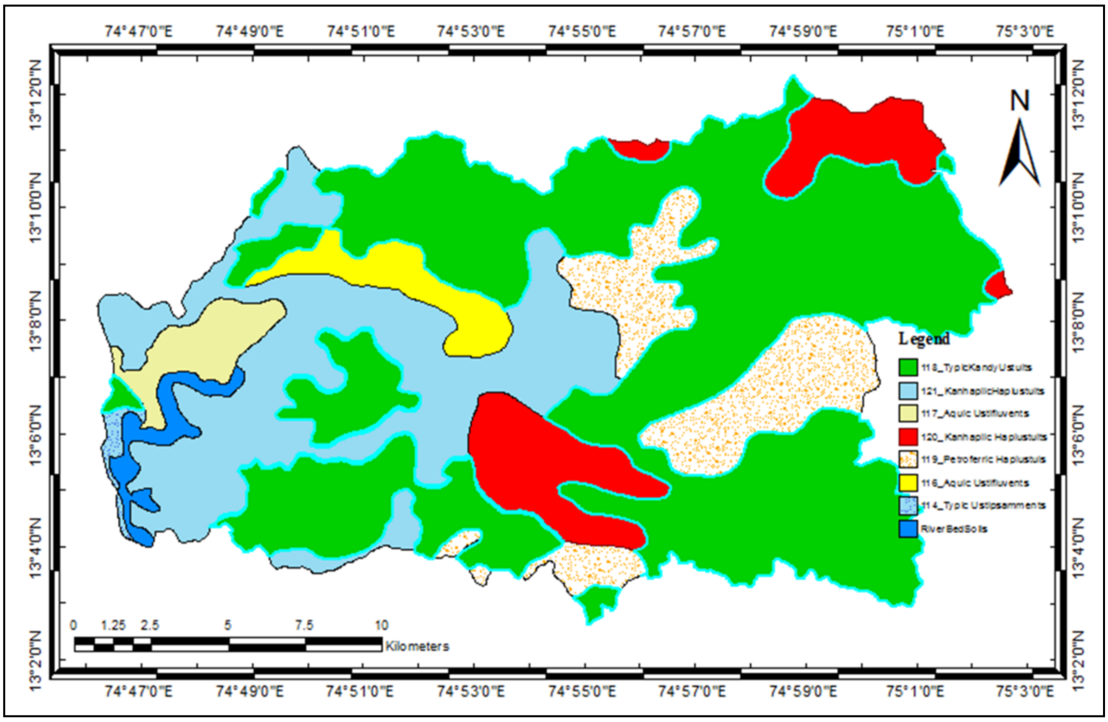

Fig. 3.28 Soil Map of the Mulki River Basin

Based on their origin and textural characteristics the soils of the study area can be classified (National Bureau of Soil Survey and Land use Planning 1996) in to four broad categories viz: i) Coastal alluvial soils ii) Red loamy soil iii) Gravelly clayey soil and iv) Laterite soils which are being discussed below.

<u>3.6.2.1 Coastal Alluvial Soil</u>: These soils comprised of alluvial deposits formed on the river channel and beach front. They are predominantly sandy in nature. The Sandy soils form the ridges and bars on the coastal belt forming costal alluvial soil. They

form the spits and bars and the narrow beach front in the study area. They are very deep, moderately well drained with very low available water capacity. They can be categorised in the Typic Ustipsamments subgroup of the textural classification. The sandy loamy soil of river valleys also belongs to the alluvial soil. They are imperfectly drained soils with shallow water table and can be included in the Aquic Ustifluvents. They are found on the middle stretch of the study area indicating a paleaochannel in the northern side of the present channel.

Soil ID	Order	Sub order	Great group	Sub group	Family Taxonomy	Family Mineral	Characteristic of
114	Entisols	Psamments	Ustipsamments	Typic Ustipsamments	Sandy soil	mixed	ridges/bars
116	Entisols	Fluvents	Ustifluvents	Aquic Ustifluvents	Sandy Loamy	mixed	valleys
117	Entisols	Fluvents	Ustifluvents	Aquic Ustifluvents	Loamy sandy	Fine, mixed	marshes
118	Alfisols	Ustults	Kandiustults	Typic Kandiustults	Clayey skeletal	Kaolinite	undulating uplands (gravelly with surface crusting)
119	Ultisols	Ustults	Haplustults	Petroferric Haplustults	Clayey skeletal	Kaolinite	Coastal plateau summits (gravelly with iron)
120	Ultisols	Ustults	Haplustults	Kanhaplic Haplustults	Clayey skeletal	Kaolinite	Laterite mounds (gravelly)
121	Ultisols	Ustults	Haplustults	Kanhaplic Haplustults	Clayey skeletal	Kaolinite	undulating uplands (gravelly with surface crusting)

Table: 3.1 Classification of Soils in the Mulki river basin

(*after* All India Soil and Land Use Survey 1996)

3.6.2.2 Red Loamy Soil: They are poorly drained loamy over sandy soils found in marshes or downstream side of the river with very shallow water table. It belongs to the Aquic Ustifluvents of Entisols order. They are found in the Channel Islands and marshes formed in the downstream side of the river channel. Some of these islands have been aggraded and degraded due to the channel erosion.

3.6.2.3 Gravely Clay Soil: They are clayey skeletal with Kaolinite minerals. They are well drained compacted gravelly clay soil with surface encrustations and subjected to moderate erosion. It belongs to the Typic Kandiustults of Alfisols order. A major portion of the study area with undulating topography is covered with this soil type.

3.6.2.3 Laterite Soil: The predominant lateritic soil in this area is of three different categories belonging to Ultisols order. They are i) Lateritic gravelly soils (Petroferric Haplustults), which are gravelly clay soils with hard iron rich lateritic capping found on the summit of the lateritic plateau or mesas in the study area. They are deposited as shallow pellets or gravels of laterites after excessive draining with moderate erosion. They are found in the lateritic Mesas ("Padavu" in local terms) of the study area. ii) Well drained gravelly clay soils (Kanhaplic Haplustults), with low available water capacity found on laterite mounds (buttes) with slight erosion. They are found on a few laterite mounds especially in the periphery of the study area. iii) Gravelly clay soils with surface crusting (Kanhaplic Haplustults), found in the middle to lower reaches of the area is having low available water capacity. They are found on the undulating uplands of the basin with moderate erosion.

3.7 CONCLUSIONS: The geology of the study area depicts rocks of Archaean to the Recent age, exposing the rocks of Sargur group and Peninsular Gneissic complex of Archaean age, South Kanara Granite batholith, younger intrusive basic dykes and acid veins of Palaeoproterozoic age, laterites of Cenozoic age and coastal sands of Quaternary period and the Recent sediments of the alluvial deposits. Granitic gneisses intruded with South Kanara granite batholiths dominate the area with laterite capping on the top of the mounds and plateaus. Basic intrusives of Dolerite, Gabbro and Norite are found criss-crossing the area shaping the hillocks, ridges and mounds in the terrain. They are trending NNW-SSE, NNE-SSW, ENE-WSW, N-S, and E-W directions. The NNW-SSE trending dolerite dykes are numerous and relatively abundant in granite. Two generation of coarse grained (N-S) and fine grained dolerites (E-W) are found in the area. Dolerite and gabbroic dykes show multiple joints related to the stresses. Acidic intrusives of Quartz and pegmatite veins are also found in the study area. Thick elevated stratified sediments, cross beddings and steep entrenched meandering (folds?) rivers in the middle reaches of the river channel along with the multiple joints found in the gabbroic mass near Sachcharepete-Bola point towards the neogenic tectonic activity in the area. Lineament studies confirm the earlier report of three active faults in the area which are responsible for the offset of the river and recent upliftment of the terrain. The major trend of the river course is determined by the master joint extended in the northern side of the basin giving an asymmetry to the drainage basin. The parallel drainage pattern of the higher order streams are determined by the lineaments in the study area. The major trends of the lineaments are in E-W, W.NW-E.SE, NE-SW, N-S, N.NE-S.SW, N.NW-S.SE and NW-SE directions according to their population. A few of the lineaments extend across the water divide to other river basins and even to the Western Ghats. These may be highly potential zones for groundwater prospecting. NE-SW trending structural ridge of intrusive rock (mainly gabbroic) forms a major lineament in the eastern part of the basin. Majority of the foliations found in the rocks are oriented in the W.NW-E.SE to NW-SE directions. The foliations are dipping towards N to NE and the dips vary between 20° to 80° degrees where majority of the foliations found to be within 40°-50° dipping category. Granites show northerly dipping strike joints of 30°-40° and 70°-80° trending in the N80°W-S80°E direction other than vertical dip joints. These are very important clues in the prospecting of groundwater in these hard rock terrains. The soil study of the area reveals that there are about seven genetic types of soils spread over the basin. And they can be broadly divided into four types depending on their origin and geohydrological condition such as alluvial soils, loamy soils, gravelly clayey skeletal soil and lateritic soils of different encrustations. The soils and geological structures such as lineaments and joints in the otherwise hard and impervious rocks have an influence on the geohydrological conditions of this study area.

Chapter 4

Hydrogeochemical Studies

CHAPTER 4

HYDROGEOCHEMICAL STUDIES

4.1 INTRODUCTION: Groundwater has long been regarded as the pure form of water compared to surface water, since purification of the groundwater takes place in the soil column through anaerobic decomposition, filtration and ion exchange. This is one of the reasons for the excessive consumption of well water in rural and semi-urban areas. Many natural processes and human activities affect the interaction of groundwater and surface water degrading the quality (Winter *et al.* 1998, CPCB 2008, Singh *et al.* 2011). Rapid urbanization, industrialization and modern agricultural practices along with geological set up and climatic conditions demand geochemical assessment of groundwater quality and its variation in temporal and spatial domain, since standard of human health and hygiene as well as the agricultural development depends on this vital resource.

Groundwater contributes to about eighty percent of the drinking water requirements in the rural areas, fifty percent of the urban water requirements and more than fifty percent of the irrigation requirements of the nation (CGWB 2008). Groundwater being the major source of drinking water and irrigation water supply, its quality variation gets utmost importance in an area. The water quality may yield information about the environments through which the water has circulated (Drever 1982) since the meteoritic water charged with atmospheric gases react with soil and earth's materials, and prevails certain characteristics before entering the aquifer (Back 1966). The chemical alteration of the rainwater depends on several factors such as soil-water interaction, dissolution of minerals and anthropogenic activities (Hem 1985, Bartarya 1993, Subba Rao 2001, Umar and Ahmaed 2007, Subrahmani *et al.* 2010). Most of the inland areas of Indian sub-continent have Ca-Mg-HCO_3 type of groundwater (Bartarya 1993, Datta and Tyagi 1996). According to the Water Aid works of British Geological Survey (2000) 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. Handa (1984) discussed the water quality and water pollution problem in India and attributed it to the natural and anthropogenic activities. The intake of cationic concentration is related to both soil-water interaction and anthropogenic factors (Bartarya 1993, Subba Rao 2001). Such direct relationship between lithology and the relative abundances of cations has been established in hard rock area (Faure 1998, Subramani *et al.* 2005). Agriculture being the means of food production is intimately related to water (Aldwell 1997) and requires huge quantity of water. But, the modern agricultural practices are affecting its availability and quality (Lowrance *et al.* 1997, Agrawal 1999, Fakir *et al.* 2002, Cardona *et al.* 2004, Jeere *et al*. 2008, Sivakumar and Elango 2008).

To decide the suitability of water for domestic, irrigation and industrial needs knowledge on hydrogeochemistry is important. Various researchers carried out the hydrochemical characteristics and quality of groundwater in different basins as well as in urban areas (Rao *et al.* 1997, Jeen *et al.* 2001, Elango *et al.* 2003, Subramani *et al.* 2005, Umar *et al.* 2006, Pandian and Sankar 2007, Raju 2007, Sivakumar and Elango 2008, Gupta *et al.* 2009, Haque 2009, Manjushree *et al.* 2009, Raju *et al.* 2009a, 2009b, Ramakrishnaiah *et al.* 2009, Shaji *et al.* 2009, Singh *et al*. 2011, Srinivasamoorthy *et al.* 2011). Geographic Information System (GIS) has been used for the groundwater vulnerability assessment and has become a highly useful tool for planning and decision making of groundwater management and protection (Vias *et al.* 2005, Umar *et al.* 2009).

The study of a relatively large number of groundwater samples from a given area offers clues to various chemical alterations which the meteoric water to groundwater undergoes, before acquiring distinct chemical characteristics. The physical properties of an aquifer, such as thickness, rock or sediment type, and location, play a large part in determining whether contaminants from the land surface will reach the groundwater. The risk of contamination is greater for unconfined aquifers than for confined aquifers because they usually are nearer to land surface and lack an overlying confining layer to impede the movement of contaminants. Because groundwater moves slowly in the subsurface and many contaminants seep in to the sediments, restoration of a contaminated aquifer is difficult and may require years, decades, centuries, or even millennia. This chapter analyses the hydrogeochemistry of the water samples collected from the study area and evaluate its suitability for domestic and irrigation purposes in a spatial and temporal domain using statistical and Geographic Information System (GIS) applications.

4.2 GROUNDWATER QUALITY IN MULKI RIVER BASIN: Groundwater being the major source of drinking and irrigation water requirements provided through a network of open wells and bore wells, its quality and variation in the area gets utmost importance.

The study area falls under two coastal districts, Dakshina Kannada and Udupi, where more than 80% of the population depends on agriculture for their livelihood. But due to its peculiar undulating topography with South Kanara granite and granitic gneiss outcrops with laterite capping, only 40% - 45% of the available land is used for agriculture, and the rest is either forest or land unsuitable for agriculture. Paddy being the main crop cultivated both in ‘Kharif’ and “Rabi” seasons consumes a lot of surface water and groundwater deteriorating its quantity and quality (CGWB 2008). Crops during the first season are raised under rain fed conditions due to the highest rainfall available, while during the subsequent seasons, they are raised under irrigation (CGWB 1998). The thick coastal alluvial plain and flood plain comprising of sandy silt materials and lateritic soils allow the saline water intrusion and contamination of the groundwater easily. The highly porous lateritic cover on the top of the underlying granitic gneiss also encourages the contamination of groundwater quality.

In general, the quality of groundwater at certain depths in the sandy aquifer is found to be good and potable whereas in the adjoining areas covered by lateritic/weathered gneissic rocks, it is slightly acidic. The dug wells in the alluvial area generally yield saline water during summer months and get fresh water during monsoon periods, thanks to the heavy rainfall. Some groundwater in the area is contaminated with salinity due to tidal effects. This contamination is more pronounced in wells along the stream courses up to a distance of seven kilometers from the coast where tidal effect extends. Further, groundwater in proximity to stream course is contaminated with seepage of domestic waste besides waste from agricultural fields.

4.3 METHODOLOGY: The water sampling has been carried out randomly in two pre-monsoon and a post-monsoon seasons of two successive years 2008 and 2009 in order to understand the spatial and temporal variations in hydrogeochemistry of water in the study area. Standard methods of water sampling (NEERI 1988) and analysis (APHA 1995) have been adopted and the locations have been marked using the hand held GPS with an accuracy of eight meters.

4.3.1 Sampling Locations: The area has been divided into 2 km × 2 km grids and the sampling stations were fixed randomly within these grids depending up on the accessibility, availability of groundwater structures and population of the area. The traversing routes and sampling locations were pre-fixed using the base map (SOI Toposheets 48K/16 & 48O/4) and road map of the area. The public open wells or multiple user wells in populated areas have been given importance. During the pre-monsoon (April-May) period of 2008, more importance has been given to the coastal stretch other than a few public wells, lakes, ponds, springs, etc., randomly spread across the study area. During other seasons the sampling locations were spread out to represent the entire study area.

4.3.2. Water Sampling: In order to understand the regional, temporal and seasonal hydrochemical variations of the groundwater and surface water, the influence on them by the geology, environment and anthropogenic activities, and their suitability for drinking and irrigation purposes, a total of 249 water samples representing dug wells and bore wells in addition to representative samples from few springs, lakes, tanks/ponds have been collected during the pre-monsoon (April-May) period of two consecutive years 2008 and 2009, and the post-monsoon (December-January) period of 2009. Out of the 249 water samples analyzed, 154 samples represented the groundwater and surface water sources of pre-monsoon season (comprising 79 collected during 2008 and 75 during 2009) and 95 groundwater samples of post-monsoon.

The pre-monsoon sampling has been carried out from 131 groundwater sources represented by 101 dug wells, 3 springs and 27 bore wells, whereas 21 ponds and 2 lakes represented surface water samples of the study area (Fig. 4.1). Out of the 79 samples collected during pre-monsoon 2008, about 43 samples representing 35 dug wells, six ponds and two lakes were from the alluvial plains and lateritic terrains stretched in between Padumarnad-Padubidri coast. The remaining 36 samples were collected randomly from other parts of the study area represented by groundwater from 21 open wells other than one bore well and one spring each, whereas of surface water from 13 ponds depending upon the accessibility. During 2009 pre-monsoon, for a better understanding of the spatial distribution of water quality parameters, about 75 water samples have been collected randomly from the dug wells and bore wells covering the whole basin area (Fig. 4.1). These were represented by groundwater samples from 45 open wells, 2 springs and 26 bore wells comprising 10 public tanks supply other than surface water samples represented from a pond and a lake.

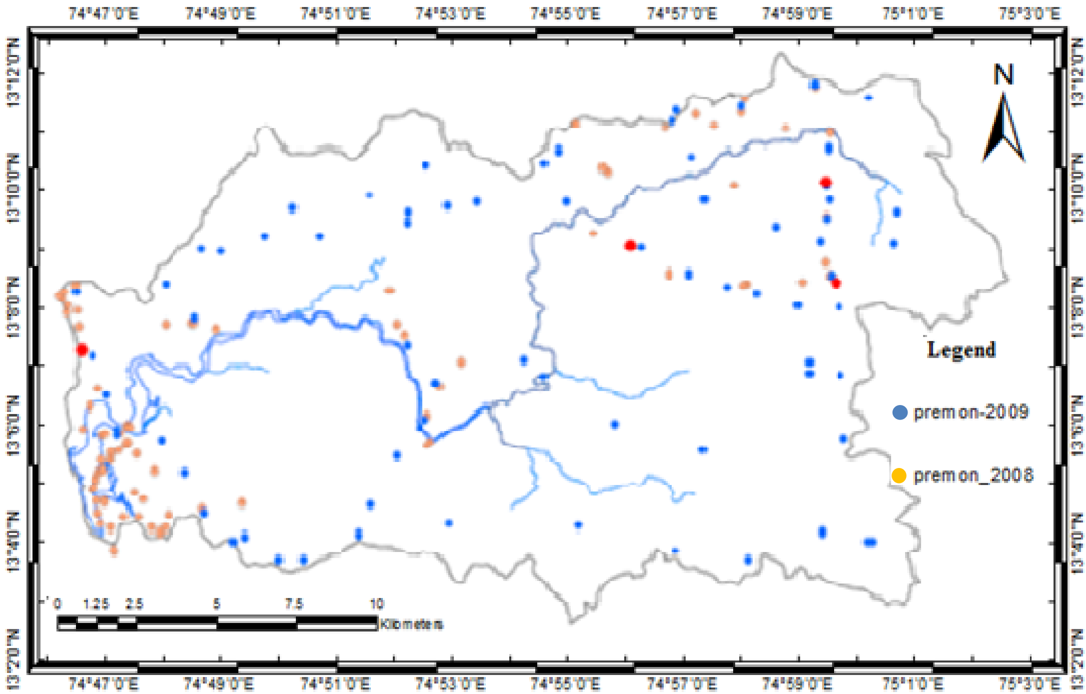

Fig. 4.1 Water sampling stations in Mulki River basin during the Pre-Monsoon periods of 2008 & 2009

In order to understand the temporal and seasonal variation in the hydrogeochemical characteristics of the groundwater, about 95 groundwater samples comprising 85 open wells and 10 bore wells have been collected in the pre-determined 2 km x 2 km grids covering the whole study area during the post-monsoon period (November-December) of 2009 (Fig. 4.2). Due to the absence of groundwater structures and accessibility problem of certain area in the basin, some of the grids have been missed during this sampling occasion.

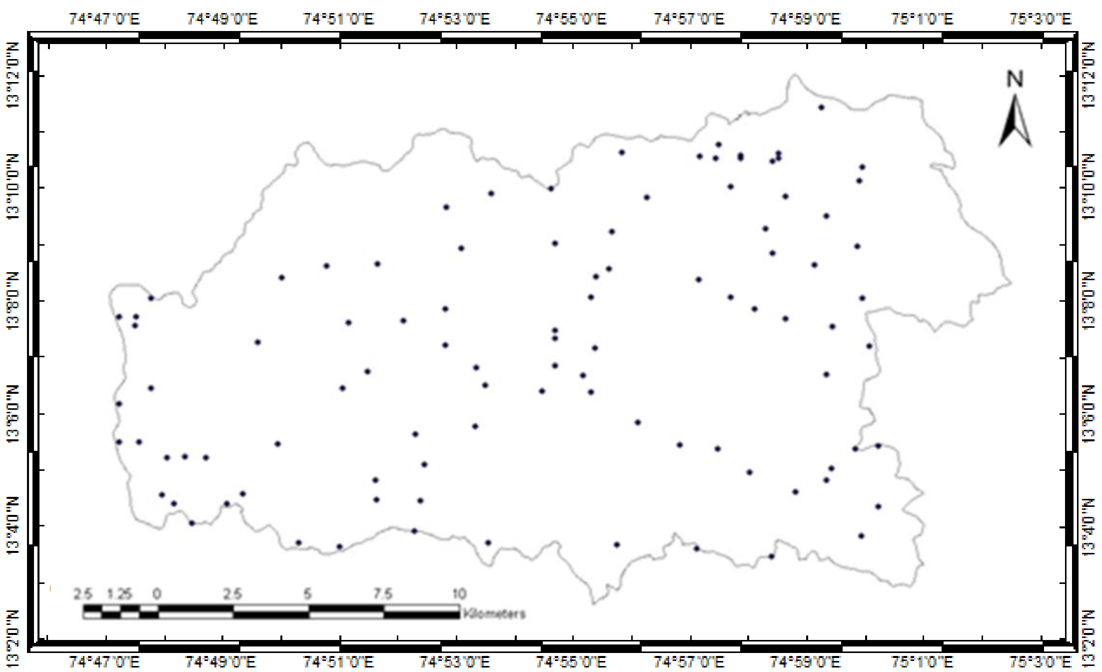

Fig. 4.2 Water sampling stations in Mulki River basin during the Post-Monsoon period of 2009

The water samples have been collected in high quality pre-cleaned polyethylene containers of five liters capacity each and transported during the same day itself to the laboratory under air tight condition to avoid oxidation. Thoroughly cleaned and washed cans were rinsed with the water from the sampling stations in order to avoid any contaminations. The physical parameter like pH has been recorded in the spot using Litmus paper and Universal Indicator, along with temperature using field thermometer. The cans were properly numbered and marked as OW, BW and SW to differentiate the water samples collected from open wells, bore wells and surface water respectively.

4.3.3 Hydrogeochemical Analysis: A total of about twenty one various physico-chemical characteristics of groundwater samples such as pH, temperature, electrical conductivity (EC), Turbidity, Total dissolved solids (TDS), Ca hardness, Mg hardness, Total Hardness (TH), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), Potassium (K^{+}), Iron (Fe), Carbonate (CO_3^{2-}), Bicarbonate (HCO_3^{-}), Chlorides (Cl^{-}), Sulphates (SO_4^{2-}), Nitrates (NO_3^{-}), Dissolved Oxygen (DO), Biochemical Oxygen

Demand (BOD) and Fluorides were determined using the standard analytical methods (APHA, AWWA, WEF 1995).

4.4 ANALYTICAL RESULTS: In the planning and development of water resources management, and its suitability for domestic, industrial and agricultural purposes, the quality and distribution of the water is as important as its quantity. The analytical results of various physico-chemical parameters of the water samples collected from different sources in the study area during the pre-monsoons 2008 and 2009 in addition to post-monsoon 2009 are presented below.

4.4.1 Hydrogeochemistry of Pre-Monsoon Water Samples: Pre-monsoon water samples represent a cross section of the surface water and groundwater bodies used for the irrigation and potable purposes in the study area. Mainly they can be classified in to groundwater sources from dug wells, springs and bore wells other than surface water sources of lakes and ponds.

4.4.1.1 Hydrogeochemistry (Pre-Monsoon) of the Open wells: The analytical results of various physico-chemical parameters in the pre-monsoon open well water samples of 2008 and 2009 collected from Mulki river basin are given in Table 4.1 and Table 4.2 respectively. About twenty physico-chemical parameters have been analyzed using the experimental methods and another five significant parameters of irrigation quality have been calculated using appropriate formulae.

4.4.1.2 Hydrogeochemistry (Pre-Monsoon) of the Bore wells: The analytical results of about twenty one various physico-chemical parameters in bore well water samples collected from Mulki river basin during 2008 and 2009 pre-monsoon seasons were presented (Table 4.3) along with the five significant irrigation quality parameters derived.

4.4.1.3 Hydrogeochemistry (Pre-Monsoon) of the Surface Water Bodies: The analytical results of the various physico-chemical parameters in pre-monsoon surface water samples of 2008 and 2009 collected from the study area is given in the Table 4.4.

Source No.	Sample No.	Latitude	Longitud	Tem (°C)	pH	DO	Turb (NTU)	EC (µS/cm)	TDS (ppm)	Na+ (ppm)	K+ (ppm)	Alkali (ppm)	Ca++ (ppm)	Mg++ (ppm)	Iron (ppm)	CO3 (ppm)	HCO3 (ppm)	Cl- (ppm)	SO4 (ppm)	NO3 (ppm)	Ca_H (ppm)	Mg_H (ppm)	TH (ppm)	%Na	SAR	RSC (ppm)	PI	Cl/ HCO3
OW 01	6	13.15670	74.99290	26	5.88	6.40	1	118	73	0.48	0.20	0.68	4.80	13.85	0.00	0.00	14.00	2.94	0.20	0.09	12.00	57.00	69.00	3.52	0.1572	-4.65	22.07	0.21
OW 02	14	13.17110	74.92860	30	4.79	4.90	2	256	159	4.13	2.31	6.44	8.00	1.85	0.00	0.00	14.00	2.94	0.10	3.19	20.00	7.60	27.60	39.54	1.8613	4.15	56.32	0.21
OW 03	15	13.18970	74.95020	28	5.87	6.72	1	353	219	3.92	4.12	8.04	8.00	5.20	0.00	0.00	16.00	1.46	0.40	2.57	20.00	21.40	41.40	37.85	1.5258	2.80	46.26	0.09
OW 04	16	13.19217	74.94908	29	5.15	5.12	2	228	142	4.68	0.24	4.92	25.60	15.45	0.00	0.00	8.00	4.40	1.50	9.04	64.00	63.60	127.60	10.70	1.0329	-33.05	16.42	0.55
OW 05	17	13.19018	74.94795	29	6.00	7.00	1	127	79	1.95	0.20	2.15	4.80	0.44	0.10	0.00	14.00	1.46	4.20	2.13	12.00	1.80	13.80	29.10	1.205	8.76	79.19	0.10
OW 06	19	13.18190	74.98185	28	5.24	7.20	1	213	132	5.91	1.10	7.01	3.20	0.29	0.00	0.00	10.00	5.87	0.05	0.62	8.00	1.20	9.20	66.75	4.4729	6.51	96.50	0.59
OW 07	20	13.16666	74.96666	27	4.85	4.00	2	488	303	2.99	0.97	3.96	4.80	1.56	0.00	0.00	10.00	1.46	0.10	3.81	12.00	6.40	18.40	38.39	1.6773	3.64	65.83	0.15
OW 08	21	13.14037	74.99433	29	6.42	6.72	2	641	398	7.83	3.27	11.10	8.00	7.78	0.00	0.00	30.00	146.00	0.05	0.00	20.00	32.00	52.00	41.30	2.7879	14.22	56.37	4.87
OW 09	22	13.14035	74.99400	29	6.14	5.92	2	621	386	4.20	1.19	5.39	9.60	1.46	0.00	0.00	26.00	1.46	0.00	6.20	24.00	6.00	30.00	32.77	1.7862	14.94	60.95	0.06
OW 10	23	13.11630	74.88718	29	5.93	7.00	1	174	108	5.76	0.43	6.19	3.20	10.28	0.00	0.00	18.00	30.80	0.10	7.44	8.00	42.30	50.30	31.47	2.2188	4.52	51.99	1.71
OW 11	24	13.10870	74.88096	28	5.17	6.40	3	76	47	3.74	0.09	3.83	9.60	0.87	0.00	0.00	10.00	3.26	0.05	8.68	24.00	3.60	27.60	26.77	1.6342	-0.47	48.56	0.33
OW 12	25	13.09213	74.87748	28	6.62	6.40	5	577	358	10.39	0.85	11.24	4.80	2.67	0.00	0.00	22.00	10.27	0.40	4.16	12.00	11.00	23.00	60.07	5.3751	14.53	84.42	0.47
OW 13	26	13.08503	74.79800	28	5.65	4.50	2	914	568	19.80	1.41	21.21	4.80	7.14	0.00	0.00	14.00	26.17	0.40	4.52	12.00	29.40	41.40	63.97	8.1022	2.06	74.16	1.87
OW 14	27	13.09230	74.72268	28	5.09	6.80	2	269	167	8.28	2.44	10.72	4.80	3.79	0.00	0.00	20.00	117.41	0.30	6.29	12.00	15.60	27.60	55.51	3.9951	11.41	75.59	5.87
OW 15	28	13.09232	74.72270	30	5.93	5.76	1	592	368	7.87	2.57	10.44	16.00	2.50	0.00	0.00	18.00	4.40	0.80	4.52	40.00	10.30	50.30	36.07	2.5874	-0.50	45.93	0.24
OW 16	29	13.08787	74.78530	29	6.10	7.00	2	856	532	57.77	20.05	77.82	11.20	7.73	0.00	0.00	28.00	43.29	12.00	11.52	28.00	31.80	59.80	80.44	18.779	9.07	82.22	1.55
OW 17	32	13.14100	74.94766	26	5.20	7.20	2	1490	925	1.69	0.65	2.34	17.60	0.49	0.00	0.00	12.00	3.36	0.10	5.58	44.00	2.00	46.00	11.46	0.562	-6.09	26.06	0.28
OW 18	33	13.13790	74.97055	27	6.03	6.72	1	1480	919	2.54	0.03	2.57	10.40	1.82	0.00	0.00	10.00	1.45	0.05	5.85	26.00	7.50	33.50	17.37	1.0275	-2.22	38.63	0.15
OW 19	35	13.13860	74.98648	27	6.32	7.36	1	1453	902	3.17	1.68	4.85	12.94	1.84	0.00	0.00	14.00	2.88	0.20	7.97	32.34	7.56	39.90	24.72	1.1664	-0.77	38.52	0.21
OW 20	36	13.12617	74.80880	26	6.41	6.40	1	1560	969	12.30	1.91	14.21	10.12	3.13	0.00	0.00	12.00	2.34	0.10	0.89	25.30	12.87	38.18	51.75	4.7792	-1.25	61.71	0.20
OW 21	37	13.12618	74.80956	27	6.10	7.00	1	1345	835	5.44	1.32	6.76	8.16	3.30	0.00	0.00	28.00	15.75	0.05	2.84	20.40	13.60	34.00	37.09	2.2721	16.54	63.48	0.56
OW 22	38	13.19018	74.91890	27	6.60	6.88	2	1456	904	7.32	2.17	9.49	5.46	1.38	0.00	0.00	12.00	13.45	0.20	7.97	13.65	5.67	19.32	58.12	3.9588	5.16	76.17	1.12
OW 23	41	13.05628	74.79870	28	6.73	6.20	1	942	585	12.14	0.76	12.90	3.20	17.50	0.00	0.00	22.00	28.36	0.05	0.00	8.00	72.00	80.00	38.40	3.7739	1.30	51.26	1.29
OW 24	43	13.05592	74.79335	29	6.41	6.72	1.5	670	416	7.57	0.87	8.44	2.40	100.60	0.00	0.00	22.00	12.06	0.80	5.14	6.00	414.00	420.00	7.57	1.0548	-81.00	11.09	0.55
OW 25	44	13.05915	74.79258	28	6.83	5.92	1	989	614	7.45	9.05	16.50	3.20	18.95	0.00	0.00	52.00	6.89	3.00	1.42	8.00	78.00	86.00	42.69	2.2384	29.85	49.52	0.13
OW 26	46	13.06178	74.78660	32	6.10	6.34	2	4550	2826	72.20	9.48	81.68	8.80	56.86	0.07	0.00	110.00	141.24	11.70	0.00	22.00	234.00	256.00	55.44	12.601	44.34	59.98	1.28
OW 27	48	13.05120	74.78608	31	7.32	6.45	2.5	859	533	4.88	3.53	8.41	3.20	13.61	0.08	0.00	34.00	10.33	2.80	0.00	8.00	56.00	64.00	33.35	1.6834	17.19	49.39	0.30
OW 28	49	13.06818	74.78545	28	6.48	6.35	2	608	378	41.26	12.08	53.34	4.00	8.26	0.07	0.00	26.00	6.89	0.20	1.95	10.00	34.00	44.00	81.31	16.663	13.74	86.62	0.27
OW 29	50	13.06880	74.78240	29	7.15	6.62	3	2170	1348	58.56	17.81	76.37	5.60	21.38	0.04	0.00	66.00	60.28	6.80	0.97	14.00	88.00	102.00	73.89	15.943	39.02	77.95	0.91
OW 30	52	13.07563	74.78115	35	7.49	6.90	2	30300	18816	105.74	75.63	181.37	240.00	388.80	0.02	0.00	148.00	4118.49	29.80	3.10	600.00	1600.00	2200.00	22.39	5.9635	-480.80	16.05	27.83
OW 31	53	13.07542	74.78370	28	7.33	6.67	1	4390	2726	104.06	76.29	180.35	32.00	43.74	0.08	0.00	60.00	179.14	1.40	0.89	80.00	180.00	260.00	70.42	16.91	-15.74	62.18	2.99
OW 32	55	13.07147	74.78926	32	6.75	6.89	1	1180	733	27.43	9.78	37.21	5.60	17.98	0.07	0.00	30.00	4.82	0.80	0.62	14.00	74.00	88.00	61.21	7.9882	6.42	64.51	0.16
OW 33	56	13.07818	74.79200	28	5.94	5.88	1	1440	894	38.12	3.57	41.69	4.80	8.75	0.10	0.00	16.00	60.28	0.10	0.89	12.00	36.00	48.00	75.47	14.646	2.45	81.52	3.77
OW 34	57	13.07910	74.77990	29	7.18	6.12	2	3000	1863	31.19	6.45	37.64	32.00	38.88	0.08	0.00	98.00	51.67	0.05	0.62	80.00	160.00	240.00	34.68	5.2392	27.12	40.26	0.53
OW 35	58	13.07913	74.77975	28	7.47	6.36	1	1447	899	60.96	5.43	66.39	51.20	30.13	0.08	0.00	118.00	40.76	9.40	0.53	128.00	124.00	252.00	44.94	9.5594	36.67	50.48	0.35
OW 36	59	13.07967	74.78030	30	7.88	6.87	1	1500	932	90.97	56.60	147.57	51.20	47.63	0.08	0.00	118.00	113.44	3.00	0.89	128.00	196.00	324.00	59.89	12.941	19.17	53.65	0.96
OW 37	61	13.08282	74.78080	29	7.23	5.90	2	1455	904	9.20	3.92	13.12	720.00	121.50	0.09	0.00	158.00	1579.30	8.50	0.00	1800.00	500.00	2300.00	1.54	0.4485	-683.50	2.56	10.00
OW 38	62	13.08470	74.78170	29	6.78	6.64	3	1447	899	15.89	4.04	19.93	2.40	11.66	0.08	0.00	30.00	1402.05	0.00	2.04	6.00	48.00	54.00	58.63	5.9922	15.94	71.33	46.73
OW 39	63	13.05735	74.74157	29	6.90	6.56	2	1464	909	41.60	6.43	48.03	20.00	36.84	0.11	0.00	66.00	19.49	0.10	0.27	50.00	151.60	201.60	45.80	7.8034	9.16	50.51	0.30
OW 40	64	13.08523	74.78292	28	6.32	6.40	2	1470	913	58.92	5.13	64.05	12.80	12.78	0.08	0.00	32.00	44.31	1.30	0.89	32.00	52.60	84.60	71.46	16.474	6.42	76.42	1.38
OW 41	65	13.08515	74.78328	29	6.62	6.72	1.2	1530	950	91.54	58.93	150.47	12.00	27.70	0.07	0.00	22.00	161.29	12.00	0.00	30.00	114.00	144.00	79.12	20.546	-17.70	73.32	7.33
OW 42	67	13.08925	74.78560	29	6.77	6.34	0.8	4100	2546	7.90	2.87	10.77	10.40	27.80	0.09	0.00	68.00	26.58	3.60	0.53	26.00	114.40	140.40	21.99	1.8077	29.80	35.02	0.39
OW 43	68	13.09023	74.78553	29	6.48	6.32	0.7	1870	1161	67.75	22.14	89.89	9.60	12.10	0.07	0.00	30.00	1.77	4.00	0.00	24.00	49.80	73.80	80.55	20.567	8.30	81.86	0.06
OW 44	69	13.09055	74.78800	29	6.16	6.84	0.3	1530	950	18.95	4.19	23.14	14.40	36.74	0.03	0.00	32.00	303.09	11.70	0.00	36.00	151.20	187.20	31.15	3.7475	-19.14	35.11	9.47
OW 45	70	13.09227	74.78987	28	5.61	6.23	1	1550	963	13.36	4.04	17.40	4.80	4.96	0.04	0.00	12.00	10.63	1.30	0.89	12.00	20.40	32.40	64.07	6.0487	2.24	72.78	0.89
OW 46	71	13.09318	74.79015	29	5.96	5.99	2	1490	925	3.67	0.90	4.57	8.80	3.40	0.03	0.00	14.00	10.63	1.70	0.00	22.00	14.00	36.00	27.25	1.4858	1.80	46.70	0.76
OW 47	73	13.09777	74.79040	29	6.09	6.20	1.2	1560	969	42.96	8.55	51.51	6.40	8.36	0.07	0.00	20.00	19.49	3.50	0.00	16.00	34.40	50.40	77.73	15.814	5.24	82.18	0.97
OW 48	74	13.09737	74.79065	27	6.85	6.59	0.5	1570	975	38.57	10.18	48.75	10.40	24.30	0.05	0.00	36.00	28.36	5.80	1.15	26.00	100.00	126.00	58.42	9.2598	1.30	60.83	0.79
OW 49	76	13.09572	74.78398	30	6.97	6.81	4	1565	972	15.43	28.16	43.59	8.80	7.34	0.03	0.00	16.00	46.08	5.70	1.15	22.00	30.20	52.20	72.98	5.4319	-0.14	61.55	2.88
OW 50	77	13.09605	74.78837	31	9.66	6.23	0.6	1580	981	15.87	28.45	44.32	16.00	12.59	0.07	16.00	38.00	10.63	1.40	0.35	40.00	51.80	91.80	60.79	4.1976	25.41	49.56	0.28
OW 51	78	13.12882	74.77252	30	5.91	6.77	0	602	374	5.66	0.33	5.99	4.80	1.46	0.00	0.00	14.00	3.54	2.50	4.52	12.00	6.00	18.00	48.91	3.1997	7.74	78.89	0.25
OW 52	79	13.13330	74.77117	29	5.42	6.56	0	1370	851	14.23	6.31	20.54	1.60	4.71	0.00	0.00	24.00	15.95	2.50	0.00	4.00	19.40	23.40	76.49	8.0087	17.69	93.11	0.66
OW 53	80	13.13328	74.76728	29	6.64	6.89	0	1570	975	16.03	1.41	17.44	7.20	21.00	0.00	0.00	60.00	7.09	5.60	0.00	18.00	86.40	104.40	38.22	4.2693	31.80	53.76	0.12
OW 54	81	13.13327	74.76290	28	7.59	6.39	0.6	1580	981	106.97	12.73	119.70	1680.00	204.12	0.08	0.00	126.00	1933.79	11.90	0.89	4200.00	840.00	5040.00	5.97	3.4852	-1758.12	5.94	15.35
OW 55	82	13.13398	74.76850	30	5.95	6.33	0.5	1570	975	12.27	3.25	15.52	6.40	3.55	0.07	0.00	16.00	12.40	2.00	0.00	16.00	14.60	30.60	60.94	5.5017	6.05	73.23	0.78
OW 56	83	13.13315	74.76890	30	5.57	5.78	0.3	1570	975	12.26	3.15	15.41	4.00	1.51	0.06	0.00	22.00	8.86	4.00	0.09	10.00	6.20	16.20	73.67	7.3886	16.49	95.41	0.40
OW 57	85	13.13980	74.77072	29	5.40	5.55	0.5	1410	876	41.37	7.91	49.28	8.00	6.51	0.08	0.00	38.00	49.63	0.10	0.00	20.00	26.80	46.80	77.25	15.358	23.49	85.06	1.31

Table 4.1 Physico-Chemical parameters of Pre-Monsoon (2008) Open Well Water samples from Mulki river basin

Source No.	Sample No.	Latitude	Longitude	Temp (°C)	pH	DO	BOD	Turbid (NTU)	EC (µmS/cm)	TDS (ppm)	Na+ (ppm)	K+ (ppm)	Alkali (ppm)	Ca++ (ppm)	Mg++ (ppm)	Iron (ppm)	CO3 (ppm)	HCO3 (ppm)	Cl- (ppm)	SO4 (ppm)	NO3 (ppm)	Ca_H (ppm)	Mg_H (ppm)	TH (ppm)	%Na	SAR	RSC (ppm)	PI	Cl/ HCO3
OW 58	86	13.18390	74.94863	28.5	6.6	4.2	0.20	0.30	341.00	211.76	3.54	2.52	6.06	25.60	16.09	0.40	0	20	16.60	0.10	0.35	64	66.20	130.20	12.69	0.78	-21.687	17.72	0.83
OW 59	87	13.17432	74.95463	28	7.2	7.0	1.20	0.00	87.90	54.59	2.20	0.57	2.77	6.40	25.49	0.00	0	18	16.06	0.20	0.97	16	104.90	120.90	7.99	0.55	-13.891	18.90	0.89
OW 60	88	13.16137	74.95828	24.5	7.1	7.1	1.10	0.10	46.40	28.81	3.06	0.84	3.90	8.00	10.96	0.12	0	18	8.57	0.40	3.28	20	45.10	65.10	17.06	0.99	-0.959	33.16	0.48
OW 61	89	13.15423	74.97912	28	6.0	6.5	0.40	1.90	81.20	50.43	5.19	0.82	6.01	5.60	19.20	0.10	0	6	16.60	0.00	3.54	14	79.00	93.00	19.51	1.47	-18.797	25.48	2.77
OW 62	90	13.14867	75.01291	26.5	7.1	7.4	1.40	0.20	95.00	59.00	2.17	0.75	2.92	44.80	4.42	0.14	0	26	7.50	0.00	7.09	112	18.20	130.20	5.60	0.44	-23.223	14.14	0.29
OW 63	92	13.15818	75.01382	24.5	6.7	7.0	1.20	0.20	75.50	46.89	2.93	0.40	3.33	13.60	12.08	0.00	0	12	11.24	44.00	5.14	34	49.70	83.70	11.48	0.82	-13.677	22.35	0.94
OW 64	94	13.16579	74.99296	28.5	6.5	7.1	0.40	0.50	63.60	39.50	5.10	1.30	6.40	7.20	18.23	0.00	0	14	10.71	0.30	16.13	18	75.00	93.00	20.11	1.43	-11.425	28.97	0.76
OW 65	95	13.17646	74.99364	28	5.9	7.2	0.80	0.00	80.30	49.87	3.27	3.92	7.19	8.80	12.73	0.00	0	14	13.92	3.00	7.80	22	52.40	74.40	25.03	1.00	-7.533	28.27	0.99
OW 66	96	13.18681	74.95008	31	5.6	6.3	1.80	0.00	82.50	51.23	10.61	0.61	11.22	8.80	12.73	0.00	0	18	14.46	4.00	6.91	22	52.40	74.40	34.26	3.23	-3.533	46.21	0.80
OW 67	99	13.19463	74.98954	27	7.0	4.3	2.90	0.20	1810.00	1124.01	109.13	74.37	183.50	27.20	35.45	0.00	0	44	147.78	0.00	4.61	68	145.90	213.90	74.55	19.50	-18.654	67.39	3.36
OW 68	100	13.19535	75.00231	29	6.4	4.6	1.90	0.00	288.00	178.85	19.82	6.72	26.54	4.00	24.69	0.00	0	26	39.09	1.10	3.81	10	101.60	111.60	48.05	5.23	-2.689	51.37	1.50
OW 69	101	13.15651	74.99303	27	6.9	5.7	0.80	0.10	42.70	26.52	4.56	1.14	5.70	6.40	30.01	0.10	0	22	10.17	0.90	3.28	16	123.50	139.50	13.54	1.07	-14.411	22.58	0.46
OW 70	102	13.14954	74.99117	29	6.9	6.3	0.20	3.10	79.60	49.43	10.42	1.45	11.87	11.20	20.31	0.80	0	36	5.89	0.80	1.95	28	83.60	111.60	27.36	2.62	4.485	39.16	0.16
OW 71	103	13.14030	74.99454	28	6.9	7.2	3.30	0.20	124.00	77.00	7.00	1.51	8.51	4.80	24.20	0.02	0	30	12.32	0.30	1.77	12	99.60	111.60	22.69	1.84	0.997	34.66	0.41
OW 72	104	13.13076	74.99688	28	6.7	6.0	1.00	0.10	178.00	110.54	14.18	4.78	18.96	9.60	16.77	0.10	0	24	17.13	0.00	4.25	24	69.00	93.00	41.83	3.91	-2.367	47.05	0.71
OW 73	105	13.11224	74.99737	27	5.5	7.1	2.40	0.10	83.50	51.85	8.89	2.54	11.43	11.20	29.35	0.02	0	16	12.85	0.30	1.59	28	120.80	148.80	21.99	1.97	-24.554	26.07	0.80
OW 74	106	13.09438	74.99862	27	5.8	7.0	0.10	0.50	101.00	62.72	6.38	2.00	8.38	5.60	32.76	0.00	0	28	9.64	0.00	3.90	14	134.80	148.80	17.93	1.46	-10.356	26.09	0.34
OW 75	107	13.06689	74.99166	28	5.9	5.5	0.20	0.10	61.30	38.07	6.14	0.11	6.25	8.00	22.26	0.10	0	14	11.24	0.30	7.00	20	91.60	111.60	17.12	1.58	-16.259	27.15	0.80
OW 76	108	13.06487	75.00506	27	6.6	6.8	1.10	0.10	65.40	40.61	4.65	1.22	5.87	3.20	38.73	0.18	0	16	22.49	0.00	1.77	8	159.40	167.40	12.28	1.02	-25.934	18.57	1.41
OW 77	109	13.06474	75.00653	22	6.8	6.0	0.10	0.00	176.00	109.30	17.76	2.27	20.03	1.60	44.23	0.00	0	20	27.31	0.10	12.58	4	182.00	186.00	30.41	3.71	-25.826	34.96	1.37
OW 78	110	13.05955	74.97092	28	7.6	7.2	1.80	0.50	40.00	24.84	2.83	0.40	3.23	6.40	14.19	0.00	0	14	9.10	0.00	4.61	16	58.40	74.40	13.56	0.88	-6.591	28.06	0.65
OW 79	112	13.06864	74.92113	22	6.7	6.4	0.60	0.20	92.00	57.13	3.56	1.72	5.28	4.00	51.81	0.00	0	24	8.57	0.00	1.24	10	213.20	223.20	8.64	0.67	-31.808	14.25	0.36
OW 80	113	13.06891	74.88331	29	6.7	6.2	0.30	0.10	56.00	34.78	6.09	0.38	6.47	9.60	25.81	0.20	0	20	6.96	1.70	2.92	24	106.20	130.20	15.45	1.45	-15.407	25.45	0.35
OW 81	114	13.06644	74.85738	26	7.0	7.1	0.80	0.10	160.00	99.36	14.23	5.96	20.19	12.80	48.72	0.14	0	48	19.81	0.30	3.37	32	200.50	232.50	24.71	2.57	-13.522	27.93	0.41
OW 82	116	13.07427	74.86072	29	7.7	6.7	0.50	0.20	155.00	96.26	8.22	4.31	12.53	4.80	40.02	0.00	0	36	13.39	0.10	3.72	12	164.70	176.70	21.85	1.74	-8.822	26.81	0.37
OW 83	117	13.09765	74.87489	28	7.5	6.8	0.10	1.30	190.00	117.99	16.17	4.53	20.70	25.60	25.13	0.12	0	34	22.49	3.20	2.92	64	103.40	167.40	28.98	3.21	-16.726	32.89	0.66
OW 84	118	13.09956	74.87664	30	7.7	7.1	0.50	18.40	238.00	147.80	12.04	6.25	18.29	24.00	84.86	3.90	0	74	18.21	0.90	3.37	60	349.20	409.20	14.39	1.63	-34.856	17.07	0.25
OW 85	121	13.11643	74.90564	27	6.6	5.8	0.10	0.30	216.00	134.14	23.98	4.86	28.84	17.60	20.95	0.20	0	16	32.66	3.90	0.97	44	86.20	130.20	42.80	5.46	-22.547	44.75	2.04
OW 86	122	13.11204	74.91124	29	6.6	6.5	0.10	0.60	99.00	61.48	9.36	2.93	12.29	6.40	16.45	0.18	0	20	16.60	0.20	4.52	16	67.70	83.70	34.97	2.77	-2.851	42.94	0.83
OW 87	123	13.09835	74.93196	31	6.8	6.0	0.50	0.10	103.00	63.96	2.44	0.55	2.99	11.20	29.35	0.00	0	36	13.92	3.30	4.25	28	120.80	148.80	6.87	0.54	-4.554	19.63	0.39
OW 88	124	13.09048	74.95781	28	6.3	6.2	0.70	0.20	44.10	27.39	2.16	0.39	2.55	4.00	31.47	0.03	0	22	8.57	2.90	2.92	10	129.50	139.50	6.71	0.51	-13.469	18.21	0.39
OW 89	125	13.11271	74.98830	27	6.4	7.4	0.50	0.50	103.00	63.96	2.45	3.28	5.73	8.80	55.67	0.00	0	36	9.10	0.00	5.05	22	229.10	251.10	8.16	0.43	-28.471	12.63	0.25
OW 90	133	13.16068	74.89177	27	7.3	6.3	2.10	1.10	269.00	167.05	13.48	11.61	25.09	17.60	102.30	0.20	0	132	8.57	75.00	11.34	44	421.00	465.00	17.30	1.74	12.097	18.72	0.06
OW 91	134	13.15965	74.88299	28	6.2	6.5	0.50	0.10	110.00	68.31	7.38	5.59	12.97	16.00	28.70	0.02	0	38	10.17	76.00	0.00	40	118.10	158.10	22.49	1.56	-6.698	26.01	0.27
OW 92	138	13.15080	74.83063	28	6.9	6.5	1.50	3.40	289.00	179.47	21.78	9.87	31.65	4.80	92.00	0.30	0	102	13.92	59.00	3.19	12	378.60	390.60	24.64	3.13	5.200	26.88	0.14
OW 93	139	13.12740	74.80970	26	6.6	6.3	0.30	0.40	87.70	54.46	5.95	2.53	8.48	16.00	103.28	0.70	0	64	33.73	62.00	1.15	40	425.00	465.00	6.64	0.77	-55.275	11.14	0.53
OW 94	140	13.14678	74.81773	29	6.5	6.3	1.00	2.20	284.00	176.36	21.27	6.80	28.07	14.40	59.05	0.30	0	32	9.64	63.00	2.66	36	243.00	279.00	27.65	3.51	-41.449	28.43	0.30
OW 95	142	13.14126	74.79145	26	6.6	6.1	0.20	0.40	48.20	29.93	13.75	4.92	18.67	6.40	138.49	0.30	0	52	12.32	65.00	6.38	16	569.90	585.90	11.42	1.62	-92.886	13.21	0.24
OW 96	145	13.13247	74.76299	29	7.6	6.1	4.50	0.40	924.00	573.80	63.38	12.48	75.86	32.00	70.96	0.00	0	260	31.59	54.00	0.71	80	292.00	372.00	42.42	8.83	157.044	47.80	0.12
OW 97	147	13.10618	74.78419	28	4.6	6.4	2.20	0.90	1060.00	658.26	9.54	3.84	13.38	5.60	25.98	0.00	0	28	497.48	53.00	0.00	14	106.90	120.90	29.76	2.40	-3.577	36.07	17.77
OW 98	149	13.09529	74.78738	31	5.1	4.7	0.40	0.40	104.00	64.58	38.05	29.25	67.30	31.20	161.84	0.00	0	78	15.53	98.00	2.13	78	666.00	744.00	25.85	3.87	-115.038	20.29	0.20
OW 99	150	13.09382	74.80010	26	5.8	5.6	2.10	0.30	110.00	68.31	12.83	10.89	23.72	5.60	41.80	0.05	0	38	11.24	78.00	0.00	14	172.00	186.00	33.35	2.64	-9.396	31.54	0.30
OW 100	152	13.07199	74.81259	29	5.9	5.3	0.20	2.30	156.00	96.88	14.79	2.80	17.59	16.00	35.48	0.30	0	36	8.57	73.00	2.13	40	146.00	186.00	25.47	2.92	-15.478	31.37	0.24
OW 101	153	13.06567	74.82414	27	5.7	7.0	0.30	0.50	155.00	96.26	14.90	2.76	17.66	14.40	70.35	0.00	0	20	11.24	75.00	0.71	36	289.50	325.50	17.24	2.29	-64.749	19.44	0.56
OW 102	155	13.05939	74.83463	30	5.3	6.5	1.50	0.30	707.00	439.05	29.04	7.19	36.23	7.20	63.42	0.30	0	20	20.35	63.00	0.18	18	261.00	279.00	33.91	4.89	-50.623	33.63	1.02
OW 103	161	13.17214	74.87703	28	5.9	6.5	1.00	0.30	182.00	113.02	5.73	5.84	11.57	4.80	42.28	0.40	0	36	11.24	64.00	2.48	12	174.00	186.00	19.73	1.18	-11.082	22.21	0.31
OW 104	162	13.17556	74.90603	29	7.0	6.5	0.20	0.20	137.00	85.08	17.00	2.65	19.65	3.20	29.69	0.10	0	34	20.35	58.00	3.72	8	122.20	130.20	37.40	4.19	1.105	45.76	0.60

Table 4.2 Physico-Chemical parameters of Pre-Monsoon (2009) Open Well Water samples from Mulki river basin

Source No.	Sample No.	Latitude	Longitude	Temp (°C)	pH	DO	BOD	Turbid (NTU)	EC (µmS/cm)	TDS (ppm)	Na+ (ppm)	K+ (ppm)	Alkali (ppm)	Ca++ (ppm)	Mg++ (ppm)	Iron (ppm)	CO3 (ppm)	HCO3 (ppm)	Cl- (ppm)	SO4 (ppm)	NO3 (ppm)	Ca_H (ppm)	Mg_H (ppm)	TH (ppm)	%Na	SAR	RSC (ppm)	PI	Cl/HCO3
BW 01	30	13.1006	74.8774	28	7.1	7.2	1.56	2.0	1590	987.39	26.68	4.35	31.03	16.0	29.40	0.25	0	52	41.09	2.0	9.66	40	121.00	161.00	40.60	5.60	6.597	47.02	0.79
BW 02	93	13.1614	74.9939	26.5	7.6	8.1	0.50	0.5	236	146.56	2.90	0.65	3.55	11.2	94.89	0.20	0	16	5.89	2.0	2.48	28	390.50	418.50	3.24	0.40	-90.092	6.33	0.37
BW 03	97	13.1930	74.9673	30	6.8	5.7	0.60	0.1	171	106.19	15.39	4.14	19.53	9.6	39.37	0.20	0	46	9.64	0.9	7.09	24	162.00	186.00	28.51	3.11	-2.966	34.45	0.21
BW 04	111	13.0622	74.9498	25	8.3	5.4	0.40	0.2	292	181.33	11.34	6.97	18.31	4.8	60.36	1.20	0	90	3.21	0.1	4.16	12	248.40	260.40	21.94	1.99	24.839	27.22	0.04
BW 05	115	13.0596	74.8409	29	7.6	6.4	1.90	1.8	262	162.70	11.76	6.27	18.03	6.4	88.77	1.17	0	70	9.64	0.0	8.06	16	365.30	381.30	15.93	1.70	-25.168	18.82	0.14
BW 06	119	13.1098	74.8799	30	8.1	7.0	1.00	0.5	669	415.45	112.71	5.34	118.05	34.4	46.90	0.20	0	80	81.92	3.1	2.84	86	193.00	279.00	59.22	17.68	-1.299	62.71	1.02
BW 07	120	13.1099	74.8799	30	7.9	6.4	0.90	0.5	455	282.56	43.48	6.23	49.71	24.0	116.49	0.60	0	90	30.52	0.7	0.97	60	479.40	539.40	26.14	5.19	-50.494	28.79	0.34
BW 08	126	13.1159	74.9883	29	7.5	6.1	0.10	5.1	142	88.18	9.13	10.43	19.56	3.2	61.33	1.94	0	42	6.96	0.0	1.77	8	252.40	260.40	23.26	1.61	-22.533	21.19	0.17
BW 09	127	13.1314	74.9852	30	7.8	5.9	1.90	24.1	309	191.89	14.78	7.90	22.68	11.2	110.71	3.60	0	98	10.17	0.0	2.04	28	455.60	483.60	15.69	1.89	-23.911	18.05	0.10
BW 10	128	13.1350	74.9737	30	8.1	6.8	2.60	1.0	297	184.44	10.44	6.08	16.52	12.8	132.34	0.30	0	110	6.96	0.0	2.75	32	544.60	576.60	10.22	1.23	-35.138	13.45	0.06
BW 11	129	13.1372	74.9646	31	7.1	6.2	2.00	0.5	140	86.94	11.63	6.40	18.03	4.8	42.28	0.70	0	30	12.85	0.3	1.24	12	174.00	186.00	27.69	2.40	-17.082	29.14	0.43
BW 12	130	13.1406	74.9539	29	7.6	5.7	0.90	0.8	194	120.47	13.74	7.37	21.11	7.2	58.90	0.28	0	54	9.10	0.1	6.38	18	242.40	260.40	24.21	2.39	-12.103	26.41	0.17
BW 13	131	13.1476	74.9398	31	7.6	5.3	0.20	1.8	278	172.64	16.88	8.81	25.69	5.6	109.59	1.10	0	86	6.96	3.1	4.78	14	451.00	465.00	18.23	2.22	-29.193	19.80	0.08
BW 14	132	13.1604	74.9176	30	7.1	5.4	0.70	40.1	148	91.91	10.66	4.81	15.47	3.2	92.97	5.22	0	40	10.17	0.5	7.09	8	382.60	390.60	13.86	1.54	-56.172	15.90	0.25
BW 15	135	13.1627	74.8605	26	6.9	4.6	0.40	1.5	267	165.81	12.95	6.47	19.42	8.0	51.64	0.32	0	74	6.43	75.0	8.86	20	212.50	232.50	24.56	2.37	14.363	29.69	0.09
BW 16	136	13.1512	74.8457	29	7.1	6.4	2.10	0.5	322	199.96	11.75	9.46	21.21	9.6	107.16	0.25	0	116	6.96	55.0	2.04	24	441.00	465.00	15.37	1.54	-0.763	17.52	0.06
BW 17	141	13.1533	74.8066	27	6.8	5.4	1.20	11.3	139	86.32	14.59	11.60	26.19	11.2	115.23	1.20	0	120	6.96	0.8	2.30	28	474.20	502.20	17.16	1.84	-6.431	18.11	0.06
BW 18	143	13.1395	74.7712	31	6.2	7.6	3.90	1.0	1710	1061.91	16.64	4.10	20.74	5.6	129.93	0.28	0	20	24.63	2.0	1.33	14	534.70	548.70	13.27	2.02	-115.532	13.87	1.23
BW 19	146	13.1176	74.7742	28	7.1	7.6	2.30	1.1	374	232.25	58.93	14.97	73.90	16.8	75.67	3.20	0	112	37.48	52.0	0.71	42	311.40	353.40	44.42	8.67	19.530	45.91	0.33
BW 20	151	13.0848	74.8070	27	6.6	6.7	0.20	0.5	92	57.13	14.79	5.56	20.35	4.0	31.47	0.22	0	44	14.99	64.0	1.15	10	129.50	139.50	36.46	3.51	8.531	42.63	0.34
BW 21	154	13.0649	74.8210	32	6.3	7.5	3.00	0.2	356	221.08	9.77	1.78	11.55	5.6	170.61	0.30	0	60	11.24	71.0	0.00	14	702.10	716.10	6.15	1.04	-116.210	9.42	0.19
BW 22	156	13.0887	74.8681	30	7.3	6.6	0.80	0.3	218	135.38	11.18	10.45	21.63	10.4	68.26	0.29	0	150	11.78	25.0	5.85	26	280.90	306.90	21.57	1.78	71.341	26.08	0.08
BW 23	157	13.1098	74.8799	29	7.3	6.5	0.50	0.3	325	201.83	155.30	7.50	162.80	16.0	80.68	0.25	0	114	106.02	33.0	1.15	40	332.00	372.00	62.74	22.34	17.324	65.87	0.93
BW 24	158	13.1206	74.8712	30	7.3	7.5	1.80	0.3	215	133.52	109.00	9.70	118.70	19.2	33.53	0.27	0	124	76.57	0.6	3.90	48	138.00	186.00	69.24	21.23	71.266	74.28	0.62
BW 25	159	13.1552	74.8713	31	7.4	8.7	1.70	0.6	590	366.39	9.73	9.58	19.31	4.8	87.48	0.30	0	80	5.89	22.0	3.90	12	360.00	372.00	17.30	1.43	-12.280	18.31	0.07
BW 26	160	13.1581	74.8714	31	6.9	6.6	0.10	0.8	182	113.02	9.60	9.33	18.93	6.4	52.61	0.30	0	84	7.50	29.0	1.15	16	216.50	232.50	24.29	1.77	24.991	27.35	0.09
BW 27	163	13.1785	74.9103	31	7.4	6.3	0.20	0.4	208	129.17	12.12	10.14	22.26	4.0	81.19	0.23	0	92	11.24	33.0	1.77	10	334.10	344.10	20.72	1.86	6.814	22.31	0.12

Table 4.3 Physico-Chemical parameters of Pre-Monsoon (2008 & 2009) Bore Well Water samples from Mulki river basin

Source No.	Sample No.	Latitude	Longitude	Temp. (°C)	pH	DO	Turbid (NTU)	EC µmS/cm	TDS (ppm)	Na+ (ppm)	K+ (ppm)	Alkali (ppm)	Ca++ (ppm)	Mg++ (ppm)	Iron (ppm)	CO3 ppm	HCO3 (ppm)	Cl- (ppm)	SO4 (ppm)	NO3 (ppm)	Ca_H (ppm)	Mg_H (ppm)	TH (ppm)	%Na	SAR	RSC (ppm)	PI	Cl/HCO3
SW 01	1	13.17000	74.93000	32	6.3	6.40	1	246	152.77	3.69	0.75	4.44	9.6	1.069	0	0	18	4.56	0.40	1.77	24	4.40	28.40	29.39	1.60	7.331	55.24	0.25
SW 02	3	13.19375	74.98965	32	6.3	5.10	1	237	147.18	3.85	0.61	4.46	3.2	1.409	0	0	8	2.94	0.30	0.35	8	5.80	13.80	49.18	2.54	3.391	78.95	0.37
SW 03	4	13.14345	74.99260	30	5.7	6.08	1	155	96.26	2.32	0.26	2.58	3.2	5.881	0	0	8	1.46	0.50	0.00	8	24.20	32.20	22.13	1.09	-1.081	45.16	0.18
SW 04	5	13.18055	74.99400	30	6.1	6.72	1	234	145.31	2.02	0.45	2.47	1.2	4.86	0	0	12	2.94	0.10	4.52	3	20.00	23.00	28.96	1.16	5.940	67.87	0.24
SW 05	7	13.13590	74.86610	30	5.9	5.60	2	391	242.81	3.10	0.38	3.48	8	0.729	0	0	18	5.87	0.05	1.33	20	3.00	23.00	28.50	1.48	9.271	62.07	0.33
SW 06	8	13.12580	74.86800	32	5.8	5.28	2	706	438.43	6.87	3.93	10.80	6.4	5.054	0.4	0	46	2.94	5.80	5.14	16	20.80	36.80	48.53	2.87	34.546	74.50	0.06
SW 07	9	13.12292	74.87025	32	5.4	7.32	3	380	235.98	9.08	5.27	14.35	3.2	17.06	0	0	24	2.94	0.10	4.52	8	70.20	78.20	41.46	2.85	3.741	47.65	0.12
SW 08	10	13.09300	74.87830	31	5.7	5.12	2	326	202.45	4.57	0.79	5.36	8	7.363	0	0	14	1.46	3.00	2.04	20	30.30	50.30	25.87	1.65	-1.363	41.70	0.10
SW 09	11	13.07332	74.81200	31	6.2	7.32	4	345	214.25	7.15	1.36	8.51	8	8.554	0	0	12	2.94	0.10	4.25	20	35.20	55.20	33.95	2.49	-4.554	44.78	0.24
SW 10	12	13.08957	74.79270	30	7.1	7.68	1	766	475.69	8.74	4.03	12.77	6.4	9.526	0.1	0	32	11.74	3.10	5.85	16	39.20	55.20	44.50	3.10	16.074	58.37	0.37
SW 11	13	13.07480	74.82330	30	6.3	5.40	1	386	239.71	6.61	1.95	8.56	19.2	16.28	0.08	0	22	17.61	0.10	4.52	48	67.00	115.00	19.44	1.57	-13.481	26.85	0.80
SW 12	31	13.15210	74.92617	29	6.2	5.60	9	1460	906.66	12.14	1.87	14.01	4	2.43	0	0	18	23.70	0.05	8.33	10	10.00	20.00	68.54	6.77	11.570	88.22	1.32
SW 13	34	13.13758	74.96940	28	6.6	6.72	2	1460	906.66	5.44	0.54	5.98	8.936	1.58	0	0	14	43.24	0.05	7.09	22.3	6.50	28.84	36.25	2.37	3.485	57.55	3.09
SW 14	42	13.05585	74.79576	29	6.9	5.20	1	257	159.60	8.05	2.05	10.10	2.4	52	0	0	24	9.50	0.30	3.81	6	214.00	220.00	15.66	1.54	-30.402	20.73	0.40
SW 15	45	13.06050	74.79262	28	5.4	5.60	4	995	617.90	12.32	4.22	16.54	5.6	10.94	0	0	42	15.95	2.80	0.00	14	45.00	59.00	50.01	4.28	25.465	65.16	0.38
SW 16	47	13.06257	74.78640	29	7.3	5.80	3	4190	2601.99	8.58	1.16	9.74	4.8	27.7	0	0	56	184.30	4.60	1.77	12	114.00	126.00	23.06	2.13	23.498	39.10	3.29
SW 17	51	13.07225	74.78162	29	8.0	5.20	2.5	43600	27075.60	105.51	76.98	182.49	240	2090	0.07	0	68	20998.99	2.70	1.51	600	8600.00	9200.00	7.26	3.09	-2261.800	4.67	308.81
SW 18	54	13.07497	74.78360	29	8.2	5.50	2.5	43800	27199.80	14.25	1.04	15.29	240	63.18	0.06	0	56	25132.99	2.30	1.42	600	260.00	860.00	4.80	1.16	-247.180	6.85	448.80
SW 19	60	13.08217	74.78075	34	9.1	5.40	6	1460	906.66	388.70	65.80	454.50	1280	972	0.08	0	84	25330.79	2.00	3.10	3200	4000.00	7200.00	16.79	11.58	-2168.000	15.07	301.56
SW 20	66	13.08775	74.78277	34	9.8	5.84	3	1460	906.66	29.19	12.15	41.34	1920	230.9	0.06	0	70	34193.29	2.00	0.00	4800	950.00	5750.00	1.89	0.89	-2080.850	1.72	488.48
SW 21	84	13.13430	74.77022	31	5.8	6.20	0.5	1050	652.05	10.25	2.92	13.17	4.8	1.021	0.09	0	12	7.09	2.80	0.09	12	4.20	16.20	69.35	6.01	6.179	85.34	0.59
SW 22	98	13.19462	74.98955	34	6.2	5.20	16.8	889	552.07	10.32	3.04	13.36	7.2	40.82	1.1	0	20	13.92	0.80	7.71	18	168.00	186.00	21.76	2.11	-28.024	25.35	0.70
SW 23	137	13.15888	74.83825	30	6.9	6.10	1.3	248	154.01	21.57	9.63	31.20	8	117.2	0.07	0	120	18.74	64.00	3.54	20	482.20	502.20	19.95	2.73	-5.175	22.16	0.16

Table 4.4 Physico-Chemical parameters of Pre-Monsoon (2008 & 2009) Surface Water samples from Mulki river basin

Sample	Source	Latitude	Longitude	Temp.	pH	DO	BOD	Turbidity	EC	TDS	Na+	K+	Alkali	Ca++	Mg++	Iron	HCO3	CO3	Cl	NO3	SO4	Ca_H	Mg_H	TH	Flouride	Cl/HCO3	%Na	SAR	RSC	PI	MH	CAI
No.	No.	Deci.Deg	Deci.Deg.	°C		ppm	ppm	NTU	(µS/cm)	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm		%					
1	OW1	13.2714	74.9174	33	5.2	4.80	1.30	6.0	48	31	14.50	9.90	24.40	2.80	0.24	0.07	34	0	11.0	0.51	0.72	7	1	8	0.343	0.323	88.9	11.8	31.0	116	8.0	-1.22
4	OW2	13.2567	74.9206	31	4.9	4.20	0.60	4.4	30	19	13.20	9.90	23.10	0.80	1.22	ND	13	0	8.5	1.09	2.08	2	5	7	0.228	0.653	92.0	13.2	11.0	110	60.3	-1.72
5	OW3	13.1200	74.9147	31	5.5	5.90	0.40	2.7	161	103	21.00	12.70	33.70	7.00	2.31	ND	41	0	31.5	6.87	3.23	18	10	27	0.418	0.768	78.4	9.7	31.7	90	24.8	-0.07
6	OW4	13.3492	74.9091	31	5.8	5.60	0.40	2.6	55	35	13.20	10.20	23.40	7.00	0.97	ND	35	0	5.5	1.25	0.79	18	4	22	0.631	0.157	74.6	6.6	27.0	90	12.2	-3.26
7	OW5	13.3108	74.9138	31	5.5	5.10	0.20	3.6	69	44	14.10	10.10	24.20	6.80	0.97	ND	35	0	10.0	3.71	1.15	17	4	21	0.314	0.287	75.7	7.2	27.2	92	12.5	-1.41
8	OW6	13.1204	74.9049	31	5.5	6.80	0.60	0.9	22	14	13.20	10.00	23.20	1.60	0.49	ND	15	0	10.5	1.49	0.29	4	2	6	0.326	0.699	93.5	14.8	13.4	115	23.4	-1.21
9	OW7	13.1232	74.8872	31	5.2	5.90	1.10	1.5	34	22	14.30	10.10	24.40	1.00	0.24	ND	23	0	15.9	1.69	4.17	3	1	4	0.354	0.691	95.2	18.1	21.8	123	19.5	-0.53
11	OW8	13.1326	74.8702	31	5.6	4.50	0.80	0.4	53	34	14.50	10.10	24.60	3.00	0.85	ND	16	0	10.5	3.94	1.94	8	4	11	0.648	0.656	86.5	10.5	12.1	101	22.1	-1.35
12	OW9	13.1337	74.8566	30	6.3	5.10	1.00	0.3	95	61	16.40	10.50	26.90	6.60	1.46	ND	46	0	19.1	0.92	1.22	17	6	23	0.595	0.415	76.9	8.2	37.9	95	18.1	-0.41
13	OW10	13.1439	74.8396	30	6.0	5.80	0.80	0.4	66	42	14.70	11.10	25.80	3.12	0.78	ND	21	0	10.6	6.71	1.87	8	3	11	0.759	0.502	86.9	10.5	17.1	104	20.0	-1.45
14	OW11	13.1341	74.8153	31	5.7	6.70	1.50	0.6	89	57	16.60	10.30	26.90	5.40	0.85	ND	33	0	19.5	3.04	1.44	14	4	17	0.255	0.591	81.1	9.4	26.7	98	13.6	-0.38
15	OW12	13.1187	74.8333	29	5.4	5.20	0.10	0.3	59	38	14.80	10.00	24.80	2.60	1.09	ND	21	0	12.0	3.66	2.01	7	5	11	0.602	0.571	87.0	10.9	17.3	105	29.6	-1.07
16	OW13	13.0940	74.8672	29	6.2	6.00	ND	0.2	53	34	14.10	9.90	24.00	5.60	0.36	ND	42	0	4.9	2.21	1.65	14	2	16	0.631	0.117	80.1	8.2	36.0	103	6.1	-3.90
17	OW14	13.0862	74.8653	29	5.2	4.90	0.60	0.3	117	75	19.50	11.40	30.90	10.00	8.26	ND	17	0	21.9	21.62	0.79	25	34	59	0.641	1.288	62.9	6.5	-1.3	63	45.2	-0.41
18	OW15	13.0670	74.8620	28	5.6	4.70	0.20	0.3	45	29	14.50	9.80	24.30	3.00	0.49	ND	23	0	10.9	3.07	1.08	8	2	10	0.608	0.474	87.5	11.0	19.5	107	13.9	-1.23
19	OW16	13.1847	74.9521	28	6.1	5.97	2.06	4.2	33	21	4.60	3.60	8.20	2.00	0.97	0.16	13	0	18.5	ND	6.68	5	4	9	0.069	1.423	73.4	3.8	10.0	108	32.7	0.56
20	OW17	13.1851	74.9600	31.5	6.2	4.85	1.31	0.3	100	64	12.80	6.10	18.90	2.80	2.67	0.01	16	0	22.5	ND	19.79	7	11	18	0.067	1.406	77.5	7.7	10.5	92	48.8	0.16
21	OW18	13.1849	74.9621	31.5	7.4	5.97	0.97	0.3	134	86	4.20	3.60	7.80	14.80	5.10	0.10	60	0	11.0	ND	7.02	37	21	58	0.068	0.183	28.2	1.3	40.1	50	25.6	0.29
22	OW19	13.1886	74.9702	31.5	6.3	7.08	0.56	0.1	33	21	3.40	3.40	6.80	2.80	0.49	0.02	10	0	8.0	ND	5.58	7	2	9	0.049	0.800	67.4	2.7	6.7	98	14.8	0.15
23	OW20	13.4472	74.9921	31.5	6.0	3.73	0.37	1.5	30	19	2.50	3.30	5.80	1.60	2.31	0.15	17	0	15.0	ND	5.58	4	10	14	0.048	0.882	59.7	1.8	13.1	103	59.1	0.61
24	OW21	13.1929	74.9923	31.5	6.0	5.03	0.74	0.1	45	29	6.50	3.40	9.90	1.60	0.49	ND	10	0	17.0	0.97	5.67	4	2	6	0.045	1.700	82.6	6.4	7.9	113	23.3	0.42
25	OW22	13.1751	74.9737	31.5	7.3	5.03	0.37	0.1	158	101	3.40	3.60	7.00	2.40	0.49	ND	77	0	8.5	ND	12.60	6	2	8	0.055	0.110	70.8	2.8	74.1	194	16.8	0.18
26	OW23	13.1831	75.0003	31.5	6.3	7.08	0.56	0.2	69	44	7.10	6.00	13.10	2.00	1.22	ND	9	0	5.0	ND	11.37	5	5	10	0.043	0.555	80.3	5.6	5.8	98	37.8	-1.62
27	OW24	13.1763	74.9994	31.5	6.0	6.34	0.37	1.1	50	32	5.10	3.60	8.70	2.40	0.73	ND	13	0	19.0	ND	5.85	6	3	9	0.046	1.461	73.5	4.1	9.9	106	23.3	0.54
28	OW25	13.1900	75.0015	31.5	6.6	6.15	2.79	1.9	83	53	6.20	3.70	9.90	9.20	1.46	ND	30	0	12.5	0.50	4.74	23	6	29	0.043	0.417	48.2	2.7	19.3	69	13.7	0.21
29	OW26	13.1930	75.0040	31.5	7.8	0.56	102.00	1.6	1703	1090	79.20	33.10	112.30	1.60	0.73	ND	3	0	52.5	63.14	5.25	4	3	7	0.099	17.499	98.0	73.4	0.7	99	31.3	-1.14
30	OW27	13.1610	74.9996	31.5	7.7	6.89	2.23	3.6	34	22	2.50	3.20	5.70	2.40	0.49	ND	12	0	12.0	ND	6.99	6	2	8	0.057	1.000	66.4	2.1	9.1	111	16.8	0.52
31	OW28	13.1510	74.9884	31.5	5.6	6.34	2.61	1.3	31	20	2.90	3.40	6.30	2.00	1.70	ND	14	0	5.0	ND	6.86	5	7	12	0.051	0.357	63.0	2.1	10.3	101	46.0	-0.26
32	OW29	13.1570	74.9847	31.5	6.9	4.66	0.93	1.5	73	47	3.00	3.50	6.50	10.40	1.94	ND	34	0	9.5	ND	5.52	26	8	34	0.054	0.279	34.5	1.2	21.7	58	15.7	0.32
33	OW30	13.1697	74.9745	31.5	6.4	5.22	2.61	0.9	64	41	6.30	3.50	9.80	6.40	0.49	ND	28	0	13.5	ND	6.64	16	2	18	0.051	0.482	58.7	3.4	21.1	88	7.1	0.27
34	OW31	13.1798	74.9568	31.5	6.5	5.03	0.81	1.8	113	72	11.50	7.30	18.80	5.20	1.94	ND	17	0	13.0	ND	4.58	13	8	21	0.047	0.765	72.5	6.1	9.9	84	27.2	-0.45
35	OW32	13.1744	74.9363	27	4.9	6.90	2.00	3.0	48	31	5.80	3.70	9.50	2.80	3.16	ND	25	0	12.5	ND	6.63	7	13	20	0.046	0.500	61.5	3.4	19.0	92	53.0	0.24
36	OW33	13.1865	74.9236	28	4.6	6.00	0.60	4.1	45	29	6.40	3.50	9.90	2.80	0.97	ND	19	0	13.5	ND	5.95	7	4	11	0.048	0.710	72.4	4.7	15.2	106	25.8	0.27
37	OW34	13.1789	74.9096	27.5	4.9	6.60	0.80	1.8	94	60	8.20	7.20	15.40	6.00	1.46	ND	24	0	20.0	0.80	6.99	15	6	21	0.049	0.833	67.4	4.2	16.5	84	19.5	0.23
39	OW35	13.1683	74.9184	27	4.8	6.10	0.40	0.1	89	57	10.70	3.40	14.10	4.80	1.46	ND	24	0	18.5	ND	10.89	12	6	18	0.104	0.771	69.3	6.0	17.7	92	23.3	0.24
41	OW36	13.1549	74.9515	27	5.2	5.00	0.50	2.2	95	61	7.40	6.20	13.60	4.40	4.86	ND	39	0	14.0	ND	8.00	11	20	31	0.106	0.359	59.5	3.4	29.7	82	52.5	0.03
42	OW37	13.1456	74.9568	28	4.2	6.90	2.00	0.5	28	18	2.80	3.40	6.20	1.20	1.70	ND	11	0	8.5	ND	6.78	3	7	10	0.087	0.773	68.1	2.3	8.1	107	58.6	0.27
43	OW38	13.1396	74.9688	27.5	4.6	5.40	0.90	1.2	28	18	5.20	3.50	8.70	2.00	0.49	ND	20	0	8.5	ND	8.91	5	2	5	0.077	0.425	81.3	5.2	18.0	134	19.7	-0.02
45	OW39	13.1420	74.9870	27	5.7	6.30	1.50	10.9	72	46	3.80	3.50	7.30	10.00	0.97	ND	38	0	11.0	ND	10.05	25	4	29	0.110	0.289	40.0	1.6	27.0	67	8.9	0.34
46	OW40	13.1451	75.0020	27.5	4.9	5.90	0.80	2.0	67	43	6.80	3.70	10.50	5.20	2.19	ND	16	0	12.5	7.07	4.85	13	9	22	0.084	0.781	58.7	3.5	8.6	76	29.6	0.16
47	OW41	13.1318	75.0055	28	5.0	5.60	0.40	0.9	58	37	5.60	4.00	9.60	3.60	2.43	ND	18	0	13.0	2.30	5.42	9	10	19	0.074	0.722	61.4	3.2	12.0	85	40.3	0.26
48	OW42	13.1173	75.0025	28	4.2	5.90	0.10	2.1	28	18	3.60	3.30	6.90	2.00	0.24	ND	14	0	9.0	1.01	5.77	5	1	6	0.068	0.643	75.5	3.4	11.8	126	10.8	0.23
49	OW43	13.1075	75.0094	28	5.0	6.80	1.20	0.9	41	26	5.50	3.40	8.90	4.00	1.22	ND	20	0	12.5	ND	6.13	10	5	15	0.067	0.625	63.1	3.4	14.8	93	23.3	0.29
51	OW44	13.0920	74.9861	27	5.4	6.50	0.70	3.1	89	57	9.20	7.20	16.40	2.80	3.16	ND	17	0	18.0	2.91	11.52	7	13	20	0.095	1.059	73.3	5.3	11.0	88	53.0	0.09

Table 4.5 Physico-Chemical parameters of Post-Monsoon (2009) Open Well Water samples from Mulki river basin (contd…)

Sample No.	Source No.	Latitude Deci.Deg	Longitude Deci.Deg.	Temp. °C	pH	DO ppm	BOD ppm	Turbidity NTU	EC (µS/cm)	TDS ppm	Na+ ppm	K+ ppm	Alkali ppm	Ca++ ppm	Mg++ ppm	Iron ppm	HCO3 ppm	CO3 ppm	Cl ppm	NO3 ppm	SO4 ppm	Ca_H ppm	Mg_H ppm	TH ppm	Flouride ppm	Cl/HCO3	%Na	SAR	RSC	PI	MH	CAI
52	OW45	13.0860	75.0042	28	5.0	6.70	0.80	1.2	61	39	8.50	3.40	11.90	3.60	0.73	ND	16	0	18.0	5.23	4.48	9	3	12	0.080	1.125	73.3	5.8	11.7	97	16.8	0.34
53	OW46	13.0912	74.9784	28	4.8	5.00	0.20	1.0	50	32	5.00	3.40	8.40	3.60	1.46	ND	18	0	14.5	ND	8.96	9	6	15	0.069	0.806	62.4	3.1	12.9	92	28.8	0.42
54	OW47	13.0895	74.9668	28	4.5	5.20	0.30	2.2	38	24	5.00	3.70	8.70	2.40	1.46	ND	15	0	12.0	ND	5.79	6	6	12	0.065	0.800	69.3	3.6	11.1	100	37.8	0.27
55	OW48	13.1017	74.9523	27	5.6	4.20	0.30	3.2	125	80	5.20	3.80	9.00	20.40	2.43	ND	68	0	13.0	ND	6.54	51	10	61	0.068	0.191	28.3	1.5	45.2	48	10.6	0.31
56	OW49	13.1039	74.9419	28	4.2	4.90	0.40	1.9	23	15	2.90	3.30	6.20	2.80	0.49	ND	9	0	10.0	ND	6.47	7	2	7	0.061	1.111	68.9	2.5	6.2	104	14.9	0.38
57	OW50	13.1042	74.9319	28	4.9	4.70	0.60	0.6	119	76	9.00	4.50	13.50	9.20	3.16	ND	20	0	18.5	22.96	9.21	23	13	36	0.060	0.925	52.2	3.6	7.6	63	25.6	0.27
58	OW51	13.1195	74.9187	28.5	4.6	5.40	0.70	3.8	70	45	7.30	4.50	11.80	4.80	1.94	ND	16	0	13.0	ND	5.49	12	8	20	0.068	0.812	63.6	4.0	9.3	80	28.8	0.09
59	OW52	13.1769	74.8902	29	4.0	6.52	0.55	1.0	38	24	8.10	5.30	13.40	8.80	0.49	ND	36	0	9.0	ND	4.63	22	2	24	0.020	0.250	59.1	3.8	26.7	81	5.2	-0.49
60	OW53	13.1695	74.8764	28	6.0	7.08	1.11	1.5	52	33	12.10	8.40	20.50	4.80	0.49	0.19	30	0	9.5	ND	5.47	12	2	14	ND	0.317	79.5	7.4	24.7	101	9.2	-1.16
61	OW54	13.1517	74.8545	28.5	5.0	9.13	2.42	1.4	64	41	12.90	7.90	20.80	2.40	0.49	0.14	12	0	19.5	0.19	8.63	6	2	8	0.023	1.625	87.8	10.7	9.1	104	16.8	-0.07
62	OW55	13.1509	74.8398	28	5.0	5.22	0.56	1.8	33	21	16.60	8.30	24.90	2.80	1.22	0.11	16	0	22.0	4.52	4.17	7	5	12	0.022	1.375	86.1	11.7	12.0	100	30.3	-0.13
63	OW56	13.1560	74.8195	28	6.0	7.08	0.37	1.6	91	58	17.00	8.70	25.70	6.40	2.92	0.02	44	0	12.0	2.22	7.36	16	12	28	0.034	0.273	73.4	7.9	34.7	90	31.3	-1.14
64	OW57	15.8363	74.5912	29	6.0	6.71	0.74	2.9	95	61	17.20	9.30	26.50	6.40	3.40	0.07	65	0	10.5	ND	6.65	16	14	30	0.071	0.162	73.0	7.8	55.2	94	34.7	-1.52
65	OW58	13.1453	74.7834	28	6.5	6.34	0.19	1.5	77	49	17.10	10.90	28.00	3.60	2.19	0.04	23	0	22.0	4.07	6.32	9	9	18	0.023	0.957	82.9	10.1	17.2	96	37.8	-0.27
66	OW59	13.1426	74.7751	28	6.0	5.41	0.56	1.7	100	64	18.20	9.00	27.20	6.40	2.19	0.06	29	0	22.5	2.68	12.23	16	9	25	0.038	0.776	76.0	8.8	20.4	88	25.5	-0.21
67	OW60	13.1359	74.7754	29	6.0	6.52	0.37	1.6	91	58	16.80	8.80	25.60	8.80	1.94	0.05	39	0	17.5	1.16	6.97	22	8	30	0.041	0.449	70.4	7.2	28.3	84	18.1	-0.46
68	OW61	13.1217	74.7831	29	7.0	5.22	ND	1.4	375	240	25.70	12.20	37.90	63.60	3.65	0.07	11	0	32.0	20.15	24.93	159	15	174	0.056	2.909	36.0	4.4	-56.2	31	5.4	-0.18
69	OW62	13.1050	74.7769	30	7.0	4.47	0.18	1.4	438	280	50.60	18.50	69.10	20.40	11.18	ND	93	0	28.5	54.06	30.62	51	46	97	0.057	0.306	68.6	12.7	61.4	73	35.4	-1.42
71	OW63	13.1647	75.3203	29	6.0	5.03	0.37	0.9	188	120	20.60	15.50	36.10	20.40	3.40	ND	68	0	45.0	5.74	14.45	51	14	65	0.075	0.662	60.3	6.0	44.2	65	14.3	0.20
72	OW64	13.0974	74.7896	29	6.2	5.41	0.56	0.8	278	178	69.70	17.70	87.40	70.40	14.09	ND	136	0	27.0	2.89	56.64	176	58	234	0.094	0.199	50.8	10.7	51.5	53	16.7	-2.24
73	OW65	13.1594	74.8748	29	6.3	5.41	0.19	1.2	36	23	1.60	2.70	4.30	2.00	0.97	ND	21	0	9.0	ND	6.22	5	4	9	0.127	0.429	59.1	1.3	18.0	135	32.7	0.52
74	OW66	13.1396	74.8695	26	6.6	6.71	0.19	2.3	52	33	4.70	3.60	8.30	4.40	1.94	0.12	31	0	12.0	ND	7.49	11	8	19	0.109	0.387	56.7	2.6	24.7	93	30.6	0.31
76	OW67	13.3403	74.8627	29	6.9	6.52	0.37	0.6	67	43	2.70	2.70	5.40	10.80	0.24	0.02	30	0	11.5	2.94	4.93	27	1	28	0.082	0.383	32.8	1.1	19.0	60	2.2	0.53
77	OW68	13.1217	74.8366	29	6.3	6.71	ND	3.9	44	28	2.70	3.60	6.30	4.80	0.49	ND	20	0	13.0	ND	7.42	12	2	14	0.050	0.650	54.4	1.7	14.7	90	9.2	0.52
78	OW69	13.1044	74.8258	30	5.8	4.47	0.19	1.2	52	33	5.40	2.70	8.10	6.00	0.49	0.03	27	0	16.5	ND	5.86	15	2	17	0.050	0.611	55.5	3.0	20.5	89	7.5	0.51
79	OW70	13.0971	74.8003	29	6.3	4.29	0.37	5.5	153	98	19.90	16.20	36.10	8.80	2.43	0.11	31	0	45.0	3.02	9.01	22	10	32	0.054	1.452	76.3	8.4	19.8	82	21.6	0.20
80	OW71	13.0893	74.7889	31	7.6	5.78	1.30	3.2	242	155	98.30	5.40	103.70	51.20	6.80	ND	284	0	41.5	4.26	6.14	128	28	156	0.721	0.146	64.1	18.3	226.0	74	11.7	-1.50
81	OW72	13.0848	74.7916	30	6.9	6.71	1.30	1.7	248	159	69.70	9.80	79.50	57.60	1.22	ND	81	0	149.5	0.01	32.34	144	5	149	0.150	1.846	57.5	12.9	22.2	61	2.1	0.47
82	OW73	13.0748	74.7931	29.5	6.5	5.41	0.19	0.9	148	95	12.70	3.30	16.00	16.80	4.62	0.24	42	0	31.0	6.00	15.83	42	19	61	0.130	0.738	42.8	3.9	20.6	56	21.6	0.48
83	OW74	13.0856	74.7407	29	7.3	4.85	0.19	1.7	656	420	71.60	17.40	89.00	10.00	0.24	ND	293	0	98.0	8.92	34.23	25	1	26	0.230	0.334	89.7	31.6	282.8	108	2.4	0.09
84	OW75	13.0850	74.7975	29.5	7.4	5.59	ND	6.9	250	160	39.90	8.80	48.70	13.20	4.13	ND	25	0	78.0	3.28	5.87	33	17	50	0.100	3.120	73.8	13.6	7.7	78	23.8	0.38
85	OW76	13.0896	74.8076	29.5	6.4	3.91	1.49	7.9	266	170	55.90	8.20	64.10	13.60	2.67	ND	45	0	90.0	5.03	6.68	34	11	45	0.100	2.000	79.8	19.6	28.7	87	16.4	0.29
86	OW77	13.0764	74.8209	29.5	5.5	5.78	0.37	0.8	50	32	6.70	3.50	10.20	3.60	0.97	0.02	16	0	13.0	0.02	6.28	9	4	13	0.072	0.813	69.0	4.4	11.4	95	21.3	0.22
87	OW78	13.0761	74.8252	30	6.1	5.41	0.37	6.7	69	44	9.50	4.20	13.70	5.20	1.46	ND	33	0	13.5	2.96	7.01	13	6	19	0.091	0.409	67.3	5.2	26.3	94	21.9	-0.01
88	OW79	13.0658	74.8564	29.5	5.2	5.22	0.19	0.8	88	56	12.40	5.50	17.90	4.80	1.22	ND	13	0	23.0	17.24	6.55	12	5	17	0.683	1.769	74.8	7.2	7.0	87	20.2	0.22
89	OW80	13.0868	74.8554	30	5.0	5.41	0.75	1.3	36	23	4.30	2.70	7.00	2.00	1.22	ND	12	0	10.0	ND	5.96	5	5	10	0.076	0.833	68.5	3.4	8.8	103	37.8	0.30
90	OW81	13.0658	74.8799	28.5	5.5	4.66	0.56	2.4	44	28	2.00	4.30	6.30	4.00	0.24	ND	15	0	10.5	ND	5.86	10	1	11	0.065	0.700	59.8	1.4	10.8	94	5.7	0.40
91	OW82	13.0652	74.9193	27.5	5.6	4.29	0.37	9.3	56	36	2.10	4.50	6.60	7.60	0.97	ND	30	0	10.5	0.11	5.26	19	4	23	0.230	0.350	43.5	1.0	21.4	71	11.3	0.37
92	OW83	13.0639	74.9437	27	5.2	3.36	0.56	20.2	27	17	3.40	4.40	7.80	3.20	1.70	0.85	16	0	8.5	0.56	9.61	8	7	15	0.120	0.531	61.4	2.2	11.1	89	34.7	0.08
94	OW84	13.0677	74.9942	28.5	5.8	4.29	1.02	0.6	27	17	1.20	3.40	4.60	3.20	0.97	0.07	28	0	10.5	ND	6.75	8	4	12	0.663	0.375	52.4	0.8	23.8	121	23.3	0.56
95	OW85	13.0670	74.9980	28.5	6.1	3.91	0.69	0.8	27	17	2.80	2.70	5.50	2.40	0.49	0.03	12	0	11.0	0.68	4.63	6	2	8	0.415	0.917	69.6	2.6	9.6	120	17.0	0.50

Table 4.5 Physico-Chemical parameters of Post-Monsoon (2009) Open Well Water samples from Mulki river basin

4.4.2 Hydrogeochemistry of Post-Monsoon Water Samples: The post-monsoon water samples represent mainly the dug wells and a few bore wells spread across the basin used for drinking water and irrigation purposes.

4.4.2.1 Hydrogeochemistry (Post-Monsoon) of the Open Wells: The analytical results of various physico-chemical parameters in the post-monsoon open well water samples of 2009 collected from Mulki river basin is given in Table 4.5. About twenty two physico-chemical parameters have been analyzed using the experimental methods and another five significant parameters of irrigation quality have been calculated along with Magnesium Hazard (MH) and Chloro-Aalkaline Indices (CAI) using appropriate formulae.

4.4.2.2 Hydrogeochemistry (Post-Monsoon) of the Bore Wells: The analytical results of about twenty two various physico-chemical parameters in the bore well water samples collected from Mulki river basin during 2009 post-monsoon seasons were presented (Table 4.6) along with the five significant irrigation water quality parameters derived other than Magnesium Hazard (MH) and Chloro-Aalkaline Indices (CAI) using appropriate formulae.

Sample	Source	Latitude	Longitude	Temp.	pH	DO	BOD	Turbidity	EC	TDS	Na+	K+	Alkali	Ca++	Mg++	Iron	HCO3	CO3	Cl	NO3	SO4	Ca_H	Mg_H	TH	Flouride	Cl/HCO3	%Na	SAR	RSC	PI	MH	CAI
No.	No.	Deci.Deg.	Deci.Deg.	°C		ppm	ppm	NTU	(µS/cm)	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm		%					
2	BW1	13.1530	74.9120	31	7.9	5.20	0.90	3.8	264	169	19.40	11.50	30.90	2.00	1.84	0.81	65	0	8.2	1.29	0.72	5	8	13	0.457	0.126	88.9	14.0	61.2	118	47.9	-2.76
3	BW2	13.3642	74.9218	32	6.4	5.50	0.80	49.0	158	101	15.40	10.80	26.20	11.20	7.29	1.24	90	0	11.0	2.26	9.13	28	30	58	0.938	0.122	58.6	5.1	71.5	73	39.4	-1.38
10	BW3	13.1213	74.8827	31	6.6	3.30	0.40	11.0	194	124	18.00	11.60	29.60	12.40	7.78	0.91	112	0	6.5	2.03	9.06	31	32	63	1.129	0.058	59.5	5.7	91.8	75	38.5	-3.56
38	BW4	13.1789	74.9096	31	7.3	7.20	1.00	2.1	344	220	13.60	7.20	20.80	39.20	11.42	ND	167	0	12.5	ND	5.80	98	47	145	0.214	0.075	29.1	2.7	116.4	41	22.6	-0.66
40	BW5	13.1604	74.9427	30	6.3	6.90	0.90	80.1	241	154	9.90	5.30	15.20	31.60	7.29	2.92	128	0	9.5	ND	20.44	79	30	109	0.312	0.074	28.1	2.2	89.1	43	18.7	-0.60
44	BW6	13.1349	74.9734	29	6.2	4.40	0.20	80.5	238	152	6.00	6.00	12.00	16.40	19.44	2.00	125	0	8.5	ND	19.33	41	80	121	0.121	0.068	25.1	1.4	89.2	41	54.2	-0.41
50	BW7	13.1018	74.9979	31	6.0	5.90	0.20	3.0	153	98	8.80	6.60	15.40	12.80	3.65	ND	87	0	8.5	ND	8.38	32	15	47	0.150	0.098	48.4	3.1	70.6	72	22.2	-0.81
70	BW8	13.1135	74.7884	30	7.0	6.34	0.19	3.6	166	106	30.90	9.40	40.30	4.00	4.13	0.21	43	0	124.5	0.48	14.09	10	17	27	0.081	2.895	83.2	15.3	34.9	96	50.8	0.68
75	BW9	13.1023	74.8819	30	7.8	6.90	0.75	7.5	234	150	37.40	5.50	42.90	21.60	10.94	0.28	130	0	31.0	ND	10.55	54	45	99	0.030	0.238	56.9	9.3	97.5	70	33.6	-0.38
93	BW10	13.0597	74.9670	29	7.1	4.85	0.56	55.0	103	66	5.90	3.90	9.80	10.80	7.05	1.53	60	0	8.0	2.74	8.54	27	29	56	0.130	0.133	35.4	2.0	42.2	57	39.5	-0.23

Table 4.6 Physico-Chemical parameters of Post-Monsoon (2009) Bore Well Water samples from Mulki river basin

4.5 HYDROGEOCHEMICAL EVOLUTION, FACIES AND CLASSIFICATION OF GROUNDWATER: Knowledge on hydrogeochemical processes that control the chemical composition of groundwater will lead to the improved understanding of hydrochemical system. And this can contribute to effective management and utilization of the groundwater resource by clarifying relations among many hydrogeological parameters. Various hydrogeochemical parameters have been computed and analysed using suitable computer programs and software developed by various authors. HYCHEM program developed by Balasubramanian (1986) has been found to be a good tool in enhanced analysis of individual samples.

4.5.1 Weathering and Solute Acquisition Processes: Weathering and ion exchange processes besides inputs from the anthropogenic sources, are the major solute acquisition mechanism controlling concentration of chemical constituents in the groundwater. The dissolved ions can reveal the origin of solutes and the processes that generated the observed water compositions. The relative proportion of the various dissolved ions in the water depends on their abundance in the host rocks/aquifer and its solubility (Sarin *et al.* 1989, Singh and Hasnain 1999, Singh *et al.* 2011).

4.5.1.1 Chloro-Aalkaline Indices: The ion exchange between the groundwater and its host environment during residence or in movement processes can be understood by Chloro-Aalkaline Indices (CAI), also known as Schoeller Index (Schoeller 1977) and expressed as:

$$CAI = \frac{Cl - (Na+K)}{Cl}$$

The Chloro-Alkaline Indices (CAI) can be either positive or negative depending on whether exchange of Na and K is from water with Mg and Ca in rocks/soil or vice versa. If Na and K are exchanged in water with Mg and Ca, the value of the ratio will be positive, indicating a Base Exchange phenomenon. The negative values of the ratio will indicate chloro-alkaline disequilibrium, and the reaction as a cation–anion exchange reaction (Singh *et al.* 2011). Chloro-Alkaline Indices (CAI) can also be used for demarcating recharge and discharge areas based on the positive and negative values respectively (Sathyamoorthy *et al.* 1993).

In the Mulki river basin area, an average of 42% of the open well samples and majority (89%) of the bore well water samples show negative Schoeller Index indicating cation-anion exchange reactions. And about 58% of the open well and 11% of the bore well groundwater samples show positive values indicating Base Exchange reaction. This also point towards the significant difference in the bore well water chemistry where the chloro-alkaline disequilibrium dominates with a cation-anion exchange whereas in the open well water chemistry, Base Exchange reaction slightly predominates or both Base Exchange and cation-anion exchange almost balance. Majority of the bore well samples show negative chloro-alkaline ratio indicating the discharge zone whereas in the case of the open wells 58% wells show positive chloro-alkaline ratio indicating the recharging zone (Sathyamoorthy *et al.* 1993).

The plot (Fig. 4.3) of $Na^{+}+K^{+}$ (alkali ions) vs. Cl^{-} (Chlorides) in the pre-monsoon (Fig. 4.3a) and post-monsoon (Fig. 4.3b) show that most of the values fall on and above the equi-line suggesting the alkali is balanced by the chloride ions in majority of samples.

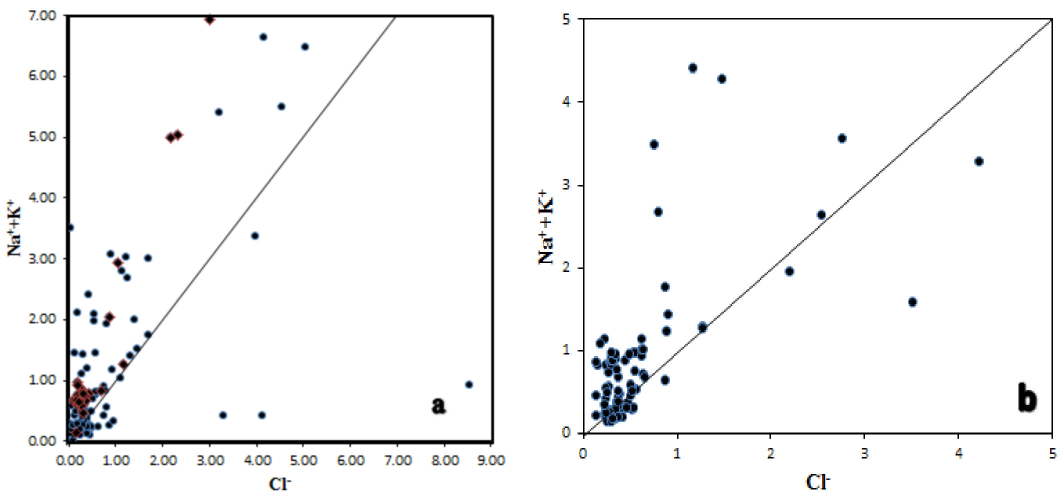

Fig. 4.3 Plots showing the inter-relationship between Chloride and Alkali ions in the Study Area during Pre-Monsoon (a) and Post-Monsoon (b)

<u>4.5.1.2 Sodium-Chloride Ratio</u>: This has been frequently used to identify saline water intrusion (Sami 1992, Manjushree *et al.* 2009). Based on the Na^{+}/Cl^{-} molar ratio, Maybeck (1987) interpreted the source of Na^{+} in water as silicate weathering if the value is greater than 1. All the pre-monsoon bore well samples except BW2 at Pre-University College, Sanoor show a value of more than 1.0 implying the source of Na^{+} from the silicate weathering of the rocks in deeper source of the study area. But at the same instance, 56% of the pre-monsoon open well water samples only show silicate weathering of the rocks in the study area implying either an influence of dissolution of

chloride salts or reaction with clay minerals (Manjushree *et al.* 2009). The lower Na^{+}: Cl^{-} ratio might be due to reaction with clay minerals exchanging Na^{+} for Ca^{2+} or Mg^{2+} ions (Mercado 1985, Manjushree *et al.* 2009). All bore well water samples of post-monsoon show silicate weathering except BW8 from Hejamadi Kodi having less value of Na^{+}/Cl^{-} ratio indicating chloride dissolution which is evidenced from its closeness to the beach. Among the open well water samples 45% samples only show silicate weathering. From these it can be inferred that the bore well waters except near the coast are influenced by the silicate weathering of the igneous rocks, whereas the open well waters are influenced by the clay mineral reaction except those near the coast influenced by the chloride dissolution from the salt water ingression in the study area.

<u>4.5.1.3 Bicarbonate Leaching</u>: The plot of HCO_3^{-} vs. $(Ca^{2+}+Mg^{2+})$ marks the upper limit of contribution from carbonate weathering. The plot for the present study shows that the plotted points fall on or above the equi-line during the pre-monsoon (Fig. 4.4a) and falls below the equi-line during the post-monsoon (Fig. 4.4b) suggesting that the bicarbonate chemistry is almost reverse during pre-monsoon and post-monsoon seasons. This implies that during pre-monsoon season a large fraction of $(Ca^{2+}+Mg^{2+})$ are derived from non-carbonate source and to be balanced by some other anions like SO_4^{2-} and Cl^{-} suggesting multiple sources (Manjushree *et al.* 2009). Whereas, during post-monsoon season sufficient dissolution of the percolating water with bicarbonate leaching happens with Ca+Mg fractions (Singh *et al.* 2011) in the study area.

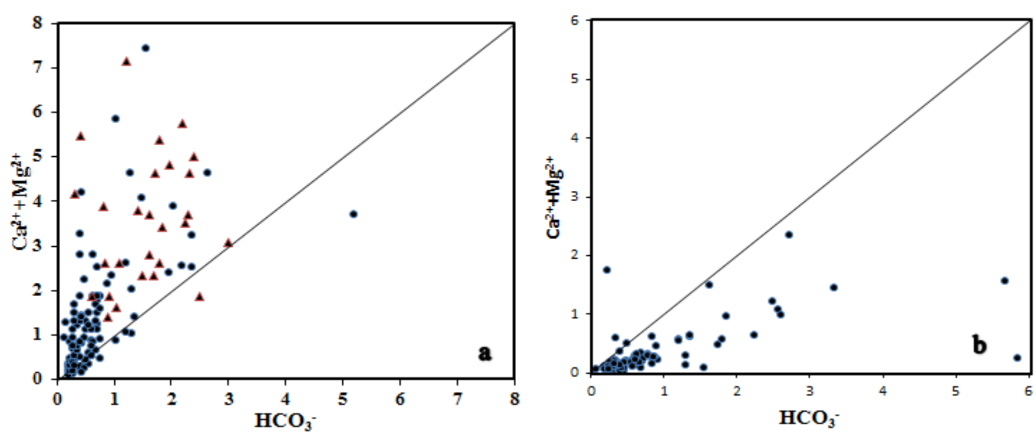

Fig. 4.4 Plots showing the inter-relationship between bicarbonate and lime-magnesia ions in the Study Area during Pre-Monsoon (a) and Post-Monsoon (b)

Bicarbonate dominance can also be related to dissolution and leaching processes and can be understood from sulphate-chloride relationship (Llyod and Heathcote 1985, Gupta *et al.* 2009). The plot (Fig. 4.5) of sulphate-chloride relations in the study area explains the multiple origins of carbonates of calcium and magnesium during pre-monsoon period (Fig. 4.5a) whereas the dissolution in carbonates leaching as the only source during post-monsoon (Fig. 4.5b). But, in both the cases the origin of bicarbonate can be predominantly attributed to the dissolution in carbonates.

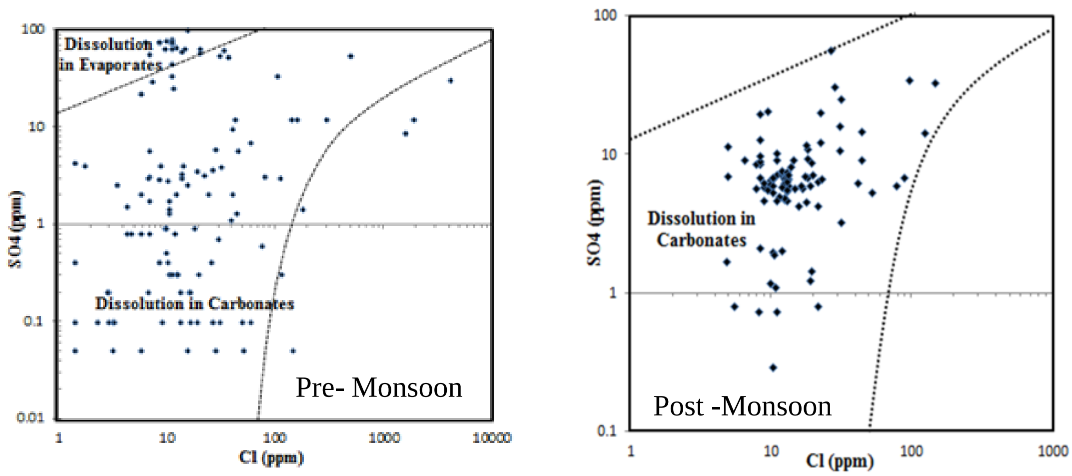

Fig. 4.5 Sulphate-Chloride relationship plots for Pre-Monsoon & Post-Monsoon groundwater samples from the study area (*after* Lloyd and Heathcote 1985)

4.5.1.4 Ion Exchange Process: The dominance of ion exchange process can be understood by plotting the (Ca^{2+}+Mg^{2+}) against (HCO_3^-+SO_4^{2-}). The plot will be close to 1:1 line in case of dissolution of calcite, dolomite and gypsum. Ion exchange tends to shift the plotted points towards right due to a large excess of (HCO_3^-+SO_4^{2-}) and towards the left in case of reverse ion exchange and dominance of (Ca^{2+}+Mg^{2+}) over (HCO_3^-+SO_4^{2-}) (Cerling *et al.* 1989, Fisher and Mullican 1997).

The plot of (Ca^{2+}+Mg^{2+}) vs. (HCO_3^-+SO_4^{2-}) for pre-monsoon shows that majority of the groundwater samples fall above the 1:1 equiline indicating reverse ion exchange (Fig. 4.6a), whereas during post-monsoon they fall below the equiline suggesting the dominance of ion exchange process (Fig. 4.6b). The deviation from the 1:1 equiline plot of (Ca^{2+}+Mg^{2+}) vs. (HCO_3^-+SO_4^{2-}) during post-monsoon suggests that dissolution reactions of calcite, dolomite and gypsum are not dominant in the system (Singh *et al.* 2011).

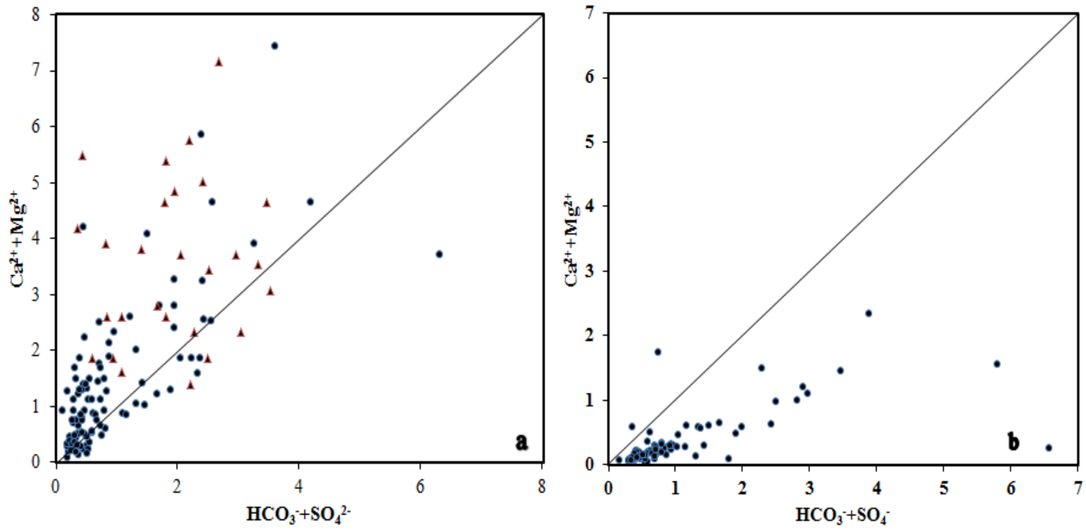

Fig. 4.6 Plots showing the inter relationship of ($HCO_3^-+SO_4^{2-}$) vs. ($Ca^{2+}+Mg^{2+}$) ions in the groundwater samples of the study area during Pre-Monsoon (a) and Post-Monsoon (b)

The groundwater data of the study area along with the above analysis suggests that weathering of alumina-silicate minerals like plagioclase, mica, amphiboles and pyroxenes are major contributors for Na, K, Ca, Mg and HCO_3 along with minor addition of Ca, Mg and HCO_3 from dissolution of carbonates.

4.5.2 Mechanisms Controlling Groundwater Chemistry: Since the groundwater used to undergo a phenomenal change in its chemistry due to its movement and collection from the atmosphere to the aquifer, the origin of the same will be interesting.

4.5.2.1 Gibb's Variation Diagram: Gibbs' variation diagram (Gibbs 1970) is very useful to find out the mechanism of controlling groundwater chemistry. It was prepared by using Gibbs' ratios (Gibbs 1970) of major cations (Na+K/Na+K+Ca) and major anions ($Cl/Cl+HCO_3$) of the water samples plotted separately against respective values of total dissolved solids (TDS). Gibb's variation diagram shows that the chemistry of water is controlled by three major factors viz: chemistry of the rocks, evaporation and precipitation. The mechanism controlling the chemistry of pre-monsoon and post-monsoon groundwater samples (*after* Gibbs 1970) is detailed in the Table 4.7.

Mechanism controlling the Chemistry	Post Monsoon Samples (2009)			Pre-Monsoon samples (2008&2009)		
	Sample Numbers	Total Number of Samples		Sample Numbers	Total Number of Samples	
		OW (85)	BW (10)		OW (104)	BW (27)
Rock Interaction Domain	OW22,OW61-64, OW71-72 &74-76	10	7	BW1, 3-7, 9, 10, 12, 15, 16, 19, 21, 22-27;	71	23
Precipitation Domain	BW4, BW8, BW10	75	3	BW17, 20	30	2
Evaporation Domain	NIL	NIL	NIL	OW26,30,34	3	2

Table 4.7 Mechanism controlling chemistry of groundwater in Mulki River basin

In the pre-monsoon groundwater samples, 23 out of 27 bore well water samples (85%) fall in the Rock Water Interaction Domain whereas two samples (7.5%) each fall in the Precipitation Domain and Evaporation Domain (Fig. 4.7). In the pre-monsoon open well water samples, 71 out of 104 samples (68%) fall in the Rock water Interaction Domain whereas 30 samples (29%) fall in the Precipitation Domain and OW26, OW30 and OW34 (3%) fall in the Evaporation Domain (Fig. 4.7). The specific area dominance of the distribution points in the central portion of the diagram point towards the interaction between the rock chemistry and the percolating precipitated waters from the surface.

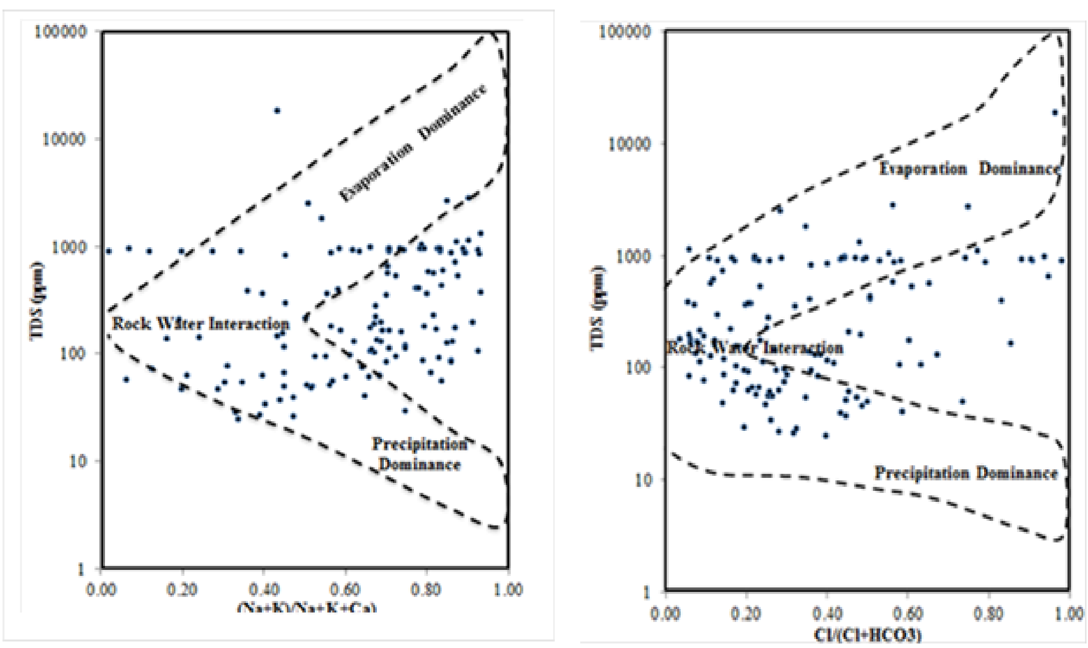

Fig. 4.7 Mechanism controlling chemistry of Pre-Monsoon Groundwater in Mulki River Basin (*after* Gibbs 1970)

In the post-monsoon, seven out of ten bore well samples (10%) fall in Rock Water Interaction Domain whereas samples BW4, BW8 and BW10 fall in Precipitation domain. In the post-monsoon open well water samples, 10 (OW22, OW61, 62, 63, 64, OW71, 72, 74, 75 & OW76) out of 85 samples (12%) fall in the Rock water Interaction Domain whereas the remaining 75 samples (88%) fall in the Precipitation Domain (Fig. 4.8). From this, it can be inferred that during pre-monsoon season Rock interaction Domain is having a dominating influence on the groundwater whereas in post-monsoon season Precipitation domain influences open well water.

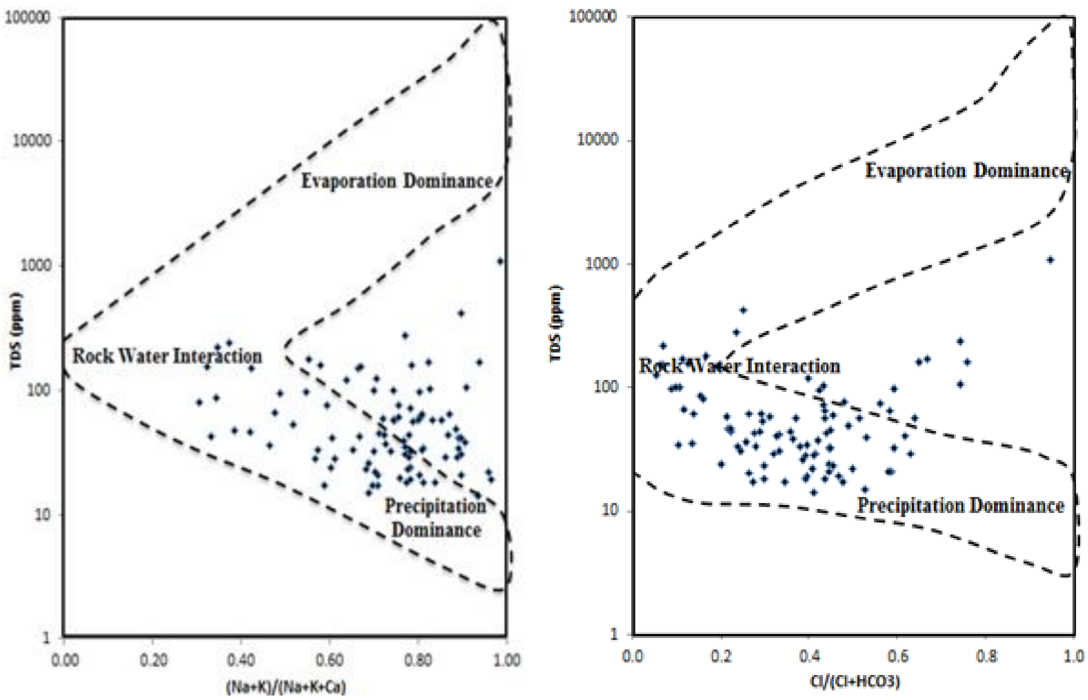

Fig. 4.8 Mechanism controlling chemistry of Post-Monsoon groundwater in Mulki River Basin (*after* Gibbs 1970)

4.5.3 Hydrochemical Characters and Type of Groundwater: As water flows through an aquifer it assumes a characteristic chemical composition as a result of interaction with the lithological framework. The hydrochemical facies, a function of the lithology, solution kinetics and flow pattern of the aquifer is used to describe the bodies of groundwater in an aquifer, that differ in their chemical composition and evolution. It can be classified on the basis of dominant ions using different methods such as the Piper's Trilinear diagram, Multi-Rectangular Diagram, Handa's method, Schoeller's method, Stuyfzand method, etc.

<u>4.5.3.1 Piper Tri-linear Classification</u>**:** Piper (1944) has developed a form of tri-linear diagram, which is an effective tool in segregating data with respect to sources of the dissolved constituents in groundwater, modifications in the character of water as it passes through an area and related geochemical problems. The diagram is useful in presenting graphically a group of analysis on the same plot. Piper Tri-linear diagram is used to express similarity and dissimilarity in the chemistry of water based on major cat-ions and anions (Todd 1980). The geochemical evolution of groundwater and chemical relationship between dissolved ions may also be evaluated by Piper Tri-linear diagram.

The concentrations of major ionic constituents of groundwater samples were plotted in the Piper Trilinear diagram (Piper 1953) using graphical user interface for MODFLOW version.4 software (Winston 2000) to determine the water type (Figs. 4.9 & 4.10). The classification for cation and anion facies, in terms of major-ion percentages and water types, is according to the domain in which they occur on the diagram segments (Back 1966). The diagrams combine three distinct fields by plotting two triangular fields at the lower left and lower right respectively and an intervening diamond-shaped field. The diamond shaped field between the two triangles is used to represent the composition of water with respect to both cations and anions. All three fields have scales reading in 100 parts. The points for both the cations and anions are plotted on the appropriate triangle diagrams. In the triangular fields at the lower left, the percentage reacting values of the three cation groups (Ca, Mg, Na+K) are plotted as a single point according to conventional trilinear coordinates. The three anion groups (HCO_3, SO_4, Cl) are plotted likewise in the triangular field at the lower right. Thus, two points on the diagram, one in each of the two triangular fields, indicate the relative concentrations of the several dissolved constituents of a groundwater. The central diamond-shaped field is used to show the overall chemical character of the groundwater by a third single point plotting, which is at the intersection of rays projected from the plotting of cations and anions. The position of this plotting indicates the relative composition of a groundwater in terms of cation-anion pairs that correspond to the four vertices of the field. The three areas of plotting show the essential chemical character of groundwater according to the relative concentrations of its constituents. This will bring out the chemical relationship among groundwater in more definite terms (Walton 1970). The geochemical evolution can be understood from the Piper plot, which has been divided into six sub categories viz: I (Ca-Mg-HCO_3 type), II (Na-Cl type), III (Mixed Ca-Mg-Na-HCO_3 type), IV (Mixed Ca-Mg-HCO_3-SO_4 type), V (Ca-Mg-SO_4 type) and VI (Na-HCO_3 type).

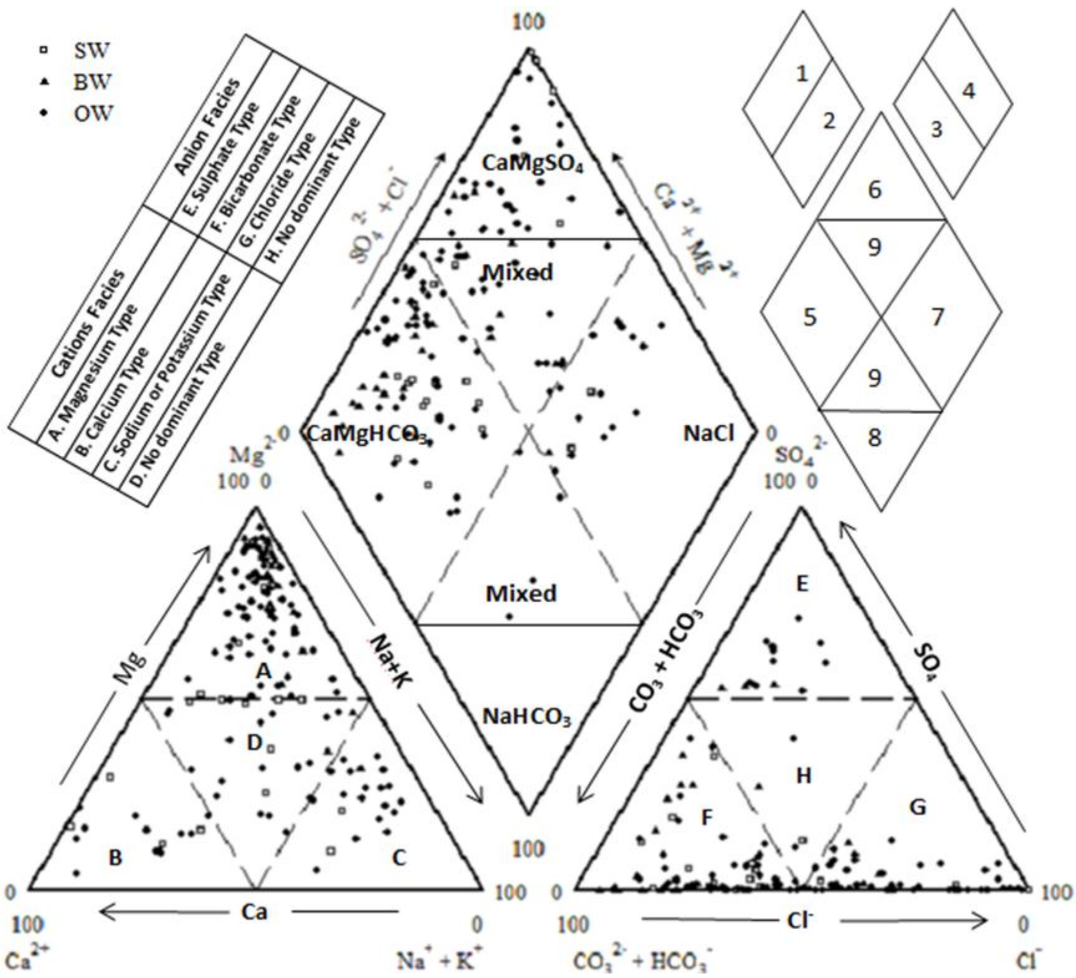

Fig. 4.9 Trilinear diagram showing the relative cation and anion composition of Pre-Monsoon groundwater samples (*after* Piper 1953)

From the cationic-anionic triangular fields of Piper diagram (Figs. 4.9 & 4.10) it is observed that majority of the samples fall in the magnesium and chloride types in cation and anion facies respectively during pre-monsoon period (Fig. 4.9); whereas during post-monsoon period, it is Sodium or Potassium and No Dominant types dominating (Fig. 4.10). During the post-monsoon, total absence of Magnesium type and Sulphate type of water has been observed in the open well samples. But a good number of (48% of open well) samples falling in the Na-Cl field indicates strong sea water influence (Srinivasamoorthy *et al.* 2011) in these wells during post-monsoon period.

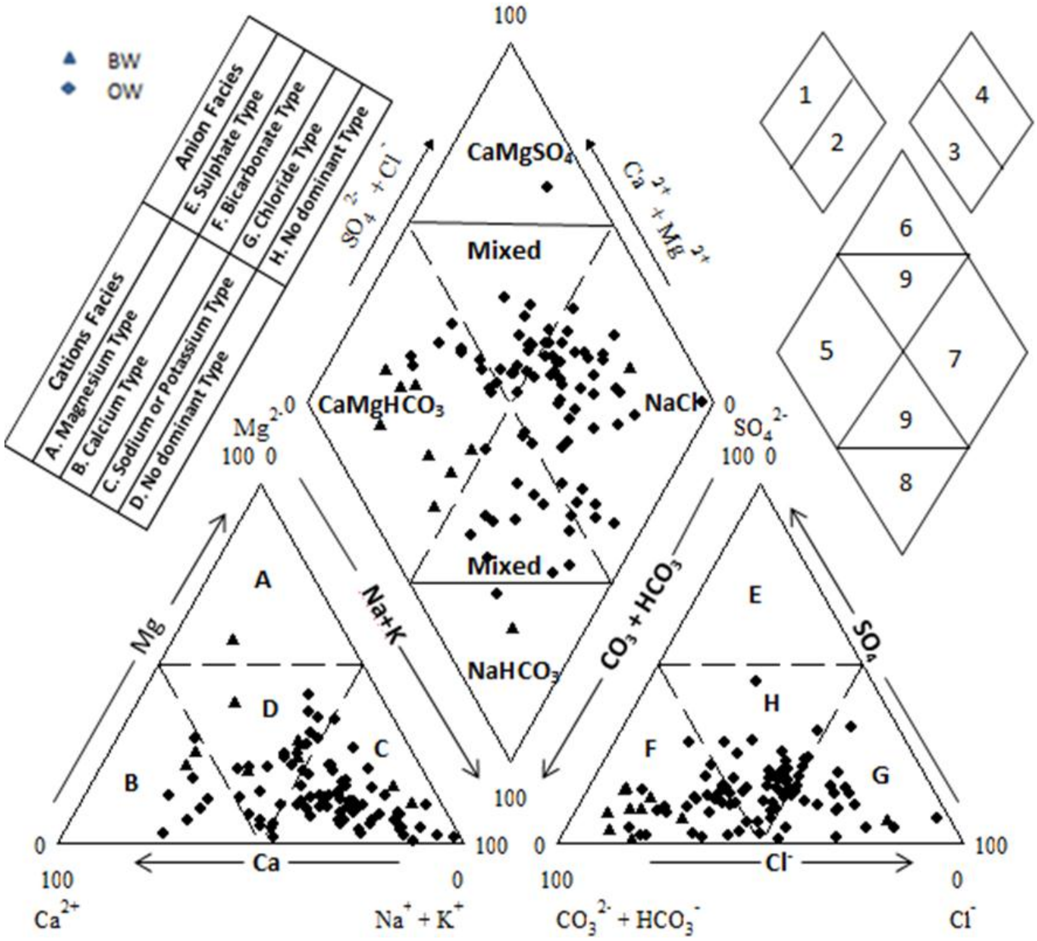

Fig. 4.10 Trilinear diagram showing the relative cation and anion composition of Post-Monsoon groundwater samples (*after* Piper 1953)

The percentage of groundwater of the study area falling in different types (Table 4.8) clearly explains the variation of cation and anion concentrations during pre-monsoon and post-monsoon seasons. During pre-monsoon, 56% of open well water, 85% of bore well water and 43% of surface water samples fall in Magnesium type making it as the dominant water type (59%) of cation facies in the study area. Magnesium is a common ion in most of the rock forming minerals and its dominance indicates the weathering and leaching of these ferromagnesian minerals bearing rocks. Out of the remaining samples, No Dominant type predominates (18%) followed by Sodium or Potassium (14%) and Calcium (10%) types in the decreasing order of predominance in the study area. Conversely among anion facies, Chloride type (47%) predominates with 56% of open wells, 37% of bore wells and 17% of surface water sources over others. The Bicarbonate type (42%), Sulphate type (8%) and No Dominant type (3%) are in the order of decreasing predominance among anion facies during pre-monsoon season. During post-monsoon, Sodium or Potassium type (59%) among cations and Bicarbonate type (39%) among anion facies predominates over others in the whole study area. But the noticeable predominance of the Bicarbonate type (90%) in the bore well samples during post-monsoon shows the distinct facies of bore well sources in the study area. The predominance among others during post-monsoon in the decreasing order is No Dominant type (31%), Calcium type (9%) and Magnesium type (1%) among cation facies and No Dominant type (37%), Chloride type (24%) and Sulphate type (NIL) among anion facies.

Water Type	Post Monsoon Samples (2009)			Pre Monsoon samples (2008&2009)			
	Sample Numbers	Total Number of Samples		Sample Numbers (%)	Total Number of Samples		
		OW (85)	BW (10)		OW (104)	BW (27)	SW (23)
Cation Facies							
A. Magnesium Type	BW6	NIL	1	56% OW; 85% BW; 43% SW	58	23	10
B. Calcium Type	OW48, 61, 62, 63, 64, 71,72; BW4 & 5	7	2	10% OW; 4% BW; 17% SW	10	1	4
C. Sodium or Potassium Type	BW3 & BW8	54	2	17% OW; 4% BW; 9% SW	18	1	2
D. No Dominant Type	BW1, 2, 7, 9, 10	24	5	17% OW; 7% BW; 30% SW	18	2	7
Anion Facies							
E. Sulphate type	NIL	NIL	NIL	9% OW; 15% BW	9	4	NIL
F. Bicarbonate Type	BW1-7, 9 &10	28	9	34% OW; 44% BW; 78% SW	35	12	18
G. Chloride Type	BW8	22	1	56% OW; 37% BW; 17% SW	58	10	4
H. No Dominant Type	41% OW samples	35	NIL	2% OW; 4% BW; 4% SW	2	1	1

Table 4.8 Geochemical classification of groundwater samples based on Cation-Anion abundance in the Piper Triangle fields (*after* Piper 1953)

Most of the inland areas of Indian sub-continent have Ca-Mg-HCO_3 type of groundwater (Bartarya 1993, Datta and Tyagi 1996). In the groundwater chemistry of the study area, the order of cations abundance is Mg>Na>K>Ca and of anions Cl>HCO_3>SO_4>NO_3 during pre-monsoon, and it is Na>K>Ca>Mg for cations and

HCO_3>Cl>NO_3>F for post-monsoon respectively. The water chemistry and mixing up of the ionic facies in the study area indicates a coastal area environment.

Distribution of the groundwater samples in different subdivisions of the piper diagram reveals the analogies and dissimilarities (Table 4.9). From the data plots (Figs. 4.9 & 4.10), it is apparent that the total hydrochemistry in the study area is dominated by Alkaline Earth (64%) and Strong Acids (55%) with Carbonate hardness (33%)(Secondary alkalinity) and primary salinity (26%) influenced by the weathered granitic gneisses and leached laterite other than the influence of saline water. More than one fourth of the samples (27%) also fall in the mixed zones indicating balance on anion-cation pair.

Subdivision of the diamond shaped field	Characteristics of corresponding subdivision of diamond shaped field	Post Monsoon 2009		Pre Monsoon (2008 & 2009)		
		Number of Samples in different fields		Number of Samples in different fields		
		OW (85)	BW (10)	OW (104)	BW (27)	SW(23)
1	Alkaline Earths (Ca+Mg) exceed Alkalies (Na+K)	28	8	85	24	21
2	Alkalies exceed Alkaline earths	57	2	19	3	2
3	Weak acids (CO_3+HCO_3) exceed Strong acids (SO_4+Cl+F)	28	9	46	19	13
4	Strong Acids (SO_4+Cl+F) exceed Weak acids (CO_3+HCO_3)	57	1	58	8	10
5	Carbonate Hardness (Secondary alkalinity) exceeds 50%	12	8	39	16	13
6	Non-carbonate Hardness (secondary salinity) exceeds 50%	1	NIL	27	3	6
7	Non-carbonate alkali (Primary Salinity) exceeds 50%	41	1	13	3	3
8	Carbonate Alkali (Primary alkalinity) exceeds 50%	1	1	-	-	-
9	None of the Cat ion and Anion pairs exceeds 50%	30	NIL	25	5	1

Table 4.9 Hydrochemical Characterisation of groundwater samples on the basis of Piper Trilinear Diagram in the study area (*after* Piper 1953)

The difference in the hydrochemistry during pre-monsoon and post-monsoon periods indicates the influence of weathering, infiltration, mixing and leaching in the study area. During pre-monsoon if the Alkaline Earth (83%) exceeds the Alkalis, it is Alkalis (62%) which exceed Alkaline Earth during post-monsoon period indicating the possibility of different origin. During both the pre- and post-monsoon periods, the

Strong Acids (51% and 61% respectively) exceeds Weak Acids with Carbonate Hardness (42% and 21% respectively) and Primary Salinity (12% and 44% respectively) (Table 4.9). Again this shows the variation in the origin and mixing of the water types in the study area during two different seasons indicating the influence of weathering and heavy rainfall in this area.

<u>4.5.3.2 Handa's Classification</u>**:** Handa (1964) suggested a modified classification to the SAR classification for assessing salinity and alkalinity hazards of irrigation water and use of gypsum in effected soils. Handa's classification (Table 4.10) is based on Total Dissolved Solids (TDS) and Sodium instead of electrical conductivity and SAR.

HANDA'S CLASSIFICATION			Post Monsoon Samples (2009)			Pre Monsoon samples (2009)		
			Sample Numbers	Total Number of Samples		Sample Numbers	Total Number of Samples	
				OW (85)	BW (10)		OW (41)	BW (20)
Hardness	Permanent	A_1	OW 18, 25, 29, 39, 48, 64, 67 & 82; BW 5, 6 & 10	8	3	OW60, 62, 68-71 ,74, 80- 82, 84, 87, 89, 90, 92, 96; BW 3, 5, 7, 9, 10, 12, 16, 17, 22, 25, 26, 27	16	12
		A_2	OW 50, 61 &73	3	-	OW59, 63- 66, 68, 72, 73, 75, 78, 83, 85, 86, 91, 94, 95, 97-104; BW6, 15, 19-21, 23	24	6
		A_3	26 OW samples; BW 8	26	1	OW67	1	-
	Temporary	B_1	BW 2, 4, 7 & 9	-	4	BW 4	-	1
		B_2	17 OW samples; BW1 & BW3	17	2	-	-	-
		B_3	26 OW samples	26	-	BW 24	-	1
Salinity	Very Low	C_1	74 OW samples; BW1, 2, 7 & 10	74	4	OW59, 60, 62- 65, 66, 68- 75, 78, 80-87, 89, 91, 94, 99-104; BW 3, 4, 5, 7, 9, 10, 12, 17, 20, 25, 26, 27	33	12
	Low	C_2	OW 63, 64, 71, 72, 75 & 76; BW 3, 4, 5, 6, 8 & 9	6	6	OW67, 90, 92, 93, 95,96, 98; BW6,15,16,19, 21,22, 23, 24;	7	8
	Moderate	C_3	OW 74	1	-	OW 97	1	-
Sodium Hazard	Low	S_1	OW 1- 73 & OW 75- 85; BW 1-10	84	10	All samples	41	20
	Moderate	S_2	-	-	-	-	-	-
	High	S_3	OW 74	1	-	-	-	-

Table 4.10 Hydrochemical Characterisation of groundwater samples on the basis of Handa's classification in the study area (*after* Handa 1964)

According to this classification, major part of the study area (64% of the total samples) is characterised by waters of permanent hardness where the pre-monsoon (97% of pre- monsoon) samples contribute much towards this (Table 4.10). But during post-monsoon period the temporary hardness predominates (52%) over permanent hardness. When majority of the pre-monsoon samples fall in A_1 and A_2 category of permanent hardness it is in the A_3 category the post-monsoon samples fall. This information could be conveniently used for developing groundwater for domestic, agricultural and industrial purposes. Almost all the samples (99%) during both the seasons show very low to low salinity except one open well sample each in both seasons divulge from this trend with moderate salinity. Except one open well water sample (OW74) at Mundegudi, Chitrapu collected during post-monsoon 2009 all the groundwater samples of both the seasons show low sodium hazard satisfying the irrigational water quality requirements. OW74 (during post-monsoon) which falls in S_3 (high sodium hazard) category is suitable only for well drained soils.

SCHOELLER'S WATER TYPE		Post Monsoon Samples (2009)			Pre Monsoon samples (2009)		
		Sample Numbers	Total Number of Samples		Sample Numbers	Total Number of Samples	
			OW (85)	BW (10)		OW (41)	BW (20)
I	Since $rCO_3 > rCl$ OR $rCO_3 > rSO_4$	-	-	-	OW 62, 67, 72, 74, 78, 89; BW 5, 9, 10	6	3
II	Since $rSO_4 > rCl$	OW 22, 23, 28 & 64; BW 3, 5 & 6	4	3	OW63, 90-96, 98-104; BW15,16,19-22, 25-27	15	9
III	Since $rCl > rSO_4 > rCO_3$	69 OW samples; BW 4, 7, 9 & 10	69	4	OW59, 60, 64-66, 68-71, 73, 75, 80- 87, 97; BW3, 4, 7, 12, 17	20	5
IV	Since $rCl > rSO_4 > rCO_3$ and $rNa > rMg > rCa$	OW14, 17, 20, 32, 36, 37, 41 & 44; BW 1, 2 & 8	8	3	BW 6, 23 & 24	-	3

Table 4.11 Hydrochemical Characterisation of groundwater samples on the basis of Schoeller's classification in the study area (*after* Schoeller 1967)

<u>4.5.3.3 Schoeller's Classification</u>**:** Schoeller (1967) has given a classification of groundwater based on the prominent anions and their dominance. The Schoeller's concept of water types is related to the evolution of groundwater with respect to chemistry. A perusal of the table (Table 4.11) shows that Types III and IV contribute to seventy two percent (112 out of 156) of the groundwater samples analyzed during both the seasons of 2009. The predominance of chloride dominated water is a reflection on the greater residence time of groundwater in the aquifers (Sathyamoorthy *et al.*1993). The carbonate dominated water (Type I) is totally absent during post-monsoon period showing the Base Exchange and fluxing of the same with chloride or

sulphate during this season. The sulphate dominated over chloride water (Type II) is represented by 39% of the samples during pre-monsoon and by 7% during post-monsoon periods.

4.5.3.4 Stuyfzand's Classification**:** Stuyfzand (1989) classification methods, which aim at defining natural types of water, only use a subset of the available parameters (Ca, Mg, Na, K, Cl, SO_4, HCO_3, and NO_3). In this method, groundwater has been classified on the basis of major cation and anion. Units of all chemical components have been converted into milli equivalent, and then which parameter is the highest in cation and anion for each sample is observed. About 156 groundwater samples collected during pre- and post- monsoon periods of year 2009 have been analysed using HYCHEM program developed by Balasubramanian (1986) and the results are given in the table below (Table 4.12).

Based on Chloride concentrations, four water types viz: Brackish (B), Fresh (F), Oligohaline (g), and Very Oligohaline (G) have been identified in the study area. Majority of the pre- and post-monsoon samples (82% & 86% respectively) belongs to Oligohaline (g) water type indicating the presence of chloride ions in the samples showing the long residence time of the water in the aquifer. Open well water located at Hejmadi Kodi (OW97) near the estuarine river mouth during pre-monsoon is found to show brackish (B) water type. About 11% of the open wells and 23% of the bore wells are found to be of fresh water type. A bore well at Sampige near Moodbidri and an open well at Kilpadi belong to Very Oligohaline water type.

The sub-water type classification based on alkalinity shows five sub-types ranging from very low to moderately high alkaline waters. The very low alkaline sub-type water (51%) predominates over others being low alkaline water (24%), moderately low alkaline water (17%), moderate alkaline water (5%) and moderately high alkaline water (2%) following the decreasing order.

Based on Stuyfzand method nine water facies (Na+K) HCO_3, (Na+K) Cl, (Na+K) mixed, $CaHCO_3$, Ca mixed, $MgHCO_3$, $MgSO_4$, $MgCl_2$ and Mg mixed have been identified in the study area (Table 4.12). The clear distinction between the pre- and post-monsoon facies could be evolved at a glance of the above table. During pre-monsoon, the most predominant water type in the study area is found to be $MgHCO_3$ facies (41%) and the predominant cation the Mg (95%) and anion the HCO_3 (41%);

STUYFZAND'S CLASSIFICATION			Post Monsoon Samples (2009)			Pre Monsoon Samples (2009)		
			Sample Numbers	Total Samples		Sample Numbers	Total Samples	
				OW (85)	BW (10)		OW (41)	BW (20)
WATER TYPE (Based on Chloride)	B	BRACKISH	-	-	-	OW97	1	-
	F	FRESH	OW 3, 61, 63 & 70-76 ; BW 8 & 9	10	2	OW67, 68, 85, 96; BW 6, 7, 19, 23, 24	4	5
	g	OLIGOHALINE	All other samples	74	8	OW59, 60, 62-66, 69-75, 78, 80-84, 86, 87, 89-95,98-104; BW 3, 5 , 9, 10, 12, 15, 16, 17, 20, 21, 22, 25, 26, 27	36	14
	G	V.OLIGOHALINE	OW 13	1	-	BW 4	-	1
SUB-TYPE (Based on Alkali)	ALKALINE	VERY LOW	OW 8, 10, 12, 14-17, 19-21, 23-25, 27, 28, 30-35, 37, 38, 40-47, 49-51, 53-55, 58, 59, 61, 65, 67-69, 75, 77, 79-85	58	-	OW59, 60, 62-66, 68, 69, 71-75, 78, 80, 85, 86, 97, 101,102; BW 6	21	1
		LOW	OW 1, 3, 5, 9, 11, 13, 18, 29, 36, 39, 52, 56, 60, 66, 70, 73,76& 78; BW 8 & 10;	18	2	OW67, 70, 81, 82, 83, 87, 89, 91, 94, 95, 99, 100, 103,104; BW3, 12, 20, 21	14	4
		MODERATELY LOW	OW22, 48, 57, 62, 63& 72 ; BW 1, 2, 3 & 7;	6	4	OW84, 92, 93, 98; BW 4, 5 , 7, 9, 10, 15, 16, 17, 19, 23, 25, 26, 27	4	13
		MODERATE	OW 64; BW 4, 5, 6 & 9	1	4	OW90; BW 22, 24	1	2
		MOD-HIGH	OW 71 & 74	2	-	OW 96	1	-
FACIES		(NA+K) HCO_3	OW 1, 4, 5, 9, 13, 22, 36, 52, 53, 56, 57, 66, 71, 74 & 84; BW 1 & 3	15	2	-	-	-
		(NA+K) Cl	OW 3, 16, 20, 21, 24, 34, 45, 54, 55, 58, 70, 72, 75, 76, 79 & 85; BW 8	16	1	OW67; BW 24	1	1
		NA+K Mixed	43 OW samples	43	-	-	-	-
		Ca HCO_3	BW 4, 5, 7, 9 & 10; OW 18, 25, 29, 39, 48, 64, 67 & 82	8	5	OW62	1	-
		Ca Mixed	OW 50, 61 & 73	3	-	-	-	-
		Mg HCO_3	BW 2 & 6	-	2	OW69-71, 74, 80-82, 84, 87, 89-90, 96; BW3-5,7,9,10,12,16, 17, 22, 25-27	12	13
		Mg SO_4	-	-	-	OW 63,91,94,95,98-104; BW15,20,21	11	3
		Mg Cl	-	-	-	OW59, 68,72, 73,85, 86, 97; BW6, 23	7	2
		Mg Mixed	-	-	-	OW60,64-66,75,78,83,92,93; BW19	9	1
SIGNIFICANT ENVIRON-MENT	surplus (+) Na+Mg	Indicates FRESHWATER INTRUSION- Any time any where	BW 1-7 & 9-10; OW 1, 3, 4, 13, 22, 36, 56, 57, 62, 64, 71 & 74	12	9	OW63,70,81,82,84,87,89,90-96, 98-104 ; BW 3, 4, 5, 7, 9, 10, 12,15, 16, 17, 19, 20, 21, 22, 23, 24, 25, 26, 27	21	19
	Na&Mg EQBM	Indicates ADEQUATE FLUSHING WITH WATER of const. Composition	BW 8; OW 8, 11, 14, 16, 17, 19,20, 21, 24, 25, 27, 29-35, 37, 39-52, 54-55, 58-59, 61, 63, 67-70, 72, 73, 75-77, 79-82, 84-85	55	1	OW59,60, 62, 65, 66, 67, 68, 72, 73, 75, 78, 83, 85, 86, 97; BW6	15	1
		No Significant Environment	-	-	-	OW64, 69, 71,74, 80	5	-

Table 4.12 Hydrochemical Characterisation of groundwater samples on the basis of Stuyfzand classification in the study area (*after* Stuyfzand 1989)

whereas during post-monsoon Alkali (Na+K) mixed facies (45%) found to be predominant being alkali (Na+K) (81%) the cations and HCO_3 (34%) the anions respectively predominating. A mixed type of water indicates that in these water samples, no single anion is predominant. In the bore well waters, $MgHCO_3$ facies (65%) predominates during pre-monsoon whereas $CaHCO_3$ facies (50%) predominates in the post-monsoon period. No sulphate anions represent during the post-monsoon season where alkalis (Na+K) and Ca predominates the cations. Except two bore well water samples none of the post-monsoon water samples represent Mg cations, whereas except two open well samples and one bore well sample all pre-monsoon water samples represent only Mg as cations. This will probably explains the extensive leaching actions of the groundwater over the laterite or highly weathered calc-alkali feldspars and clay minerals of overlying granitic rocks in this area during heavy monsoon.

According to the Stuyfzand classification three significant environments have been identified in the study area as (i) with surplus sodium and magnesium indicating fresh water intrusion at anytime and anywhere, (ii) with sodium and magnesium in equilibrium indicating adequate flushing with water of constant temperature and (iii) no significant environment with any particular indication. In the pre-monsoon samples the first category with surplus sodium and magnesium predominates (66%) indicating fresh water intrusion at anytime and anywhere, whereas during post-monsoon the second category with sodium and magnesium in equilibrium predominates (59%) indicating adequate flushing with water of constant temperature. Majority of the bore wells (93%) shows the freshwater intrusion with sodium and magnesium in surplus whereas majority of the open wells (56%) shows the adequate flushing with water of constant temperature with sodium and magnesium in equilibrium. About 12% of the pre-monsoon open well samples belong to the no significant environment category also.

4.5.4 Interrelationship between Chemical Parameters: Correlation coefficient is commonly used as a measure to establish the relation between two variables. It is simply a measure to exhibit how well one variable predict the other (Kurumbein and Graybill 1965). The different physico-chemical water quality parameters have been correlated with each other to establish the relationship of them in different seasons and different sources (Tables 4.13 to 4.18). Three sets of strong relationships (Douglas and Leo 1977) have been established between major cations and anions of groundwater in the study area (Table 4.18).

<u>4.5.4.1 Correlation Coefficient of Pre-Monsoon Open Well Water Samples:</u> In the pre-monsoon (2008) open well waters (Table 4.13), the highest significant correlation is established by the magnesium (0.836), chlorides (0.812), sulphates (0.739) and potassium (0.586) with TDS in the reducing order indicating the relative contributions from these constituents towards the contamination of the water. The highest correlation of anions viz: chlorides (0.918), sulphates (0.782) and bicarbonates (0.706) with the cation magnesium, indicate its proportions and the probable cause for the hardness of the water from the anthropogenic and natural processes.

	Temp.	*pH*	*DO*	*Turbidity*	*EC*	*TDS*	*Na+*	*K+*	*Alkali*	*Ca++*	*Mg++*	*Iron*	*CO3*	*HCO3*	*Cl*	*SO4*	*NO3*	*Ca_Hard*	*Mg_Hard*	*TH*
Temp.	1.000																			
pH	0.313	1.000																		
DO	0.020	0.284	1.000																	
Turbidity	0.041	0.008	-0.093	1.000																
EC(µmS/cm)	**0.568**	0.266	0.131	0.048	1.000															
TDS	**0.568**	0.266	0.131	0.048	**1.000**	1.000														
Sodium	0.314	0.445	0.133	-0.061	0.460	0.460	1.000													
Potassium	0.417	0.493	0.200	0.001	**0.586**	**0.586**	**0.771**	1.000												
Na+K(alkali)	0.372	0.489	0.166	-0.041	**0.535**	**0.535**	**0.969**	**0.904**	1.000											
Calcium	0.016	0.276	-0.023	-0.075	0.114	0.114	0.369	0.085	0.280	1.000										
Magnesium	0.496	0.379	0.107	0.012	**0.836**	**0.836**	**0.550**	**0.515**	**0.568**	**0.566**	1.000									
Iron	0.280	0.463	0.009	-0.091	0.061	0.061	0.496	0.280	0.441	0.221	0.146	1.000								
CO3	0.196	**0.525**	-0.032	-0.122	-0.008	-0.008	-0.047	0.145	0.025	-0.023	-0.031	0.118	1.000							
HCO3	0.402	**0.580**	0.073	-0.007	0.500	0.500	**0.606**	0.426	**0.571**	**0.541**	**0.706**	0.458	0.001	1.000						
Chlorides	0.455	0.306	0.092	0.098	**0.812**	**0.812**	0.442	0.448	0.470	**0.552**	**0.918**	0.132	-0.038	**0.617**	1.000					
Sulphates	**0.547**	0.325	0.187	-0.028	**0.739**	**0.739**	**0.615**	**0.553**	**0.626**	0.362	**0.782**	0.172	-0.047	**0.624**	**0.730**	1.000				
Nitrates	-0.190	-0.352	0.040	0.277	-0.061	-0.061	-0.260	-0.169	-0.239	-0.105	-0.090	-0.573	-0.094	-0.321	-0.058	-0.115	1.000			
Ca_Hardness	0.016	0.276	-0.023	-0.075	0.114	0.114	0.369	0.085	0.280	**1.000**	**0.566**	0.221	-0.023	**0.541**	**0.552**	0.362	-0.105	1.000		
Mg_Hardness	0.496	0.379	0.107	0.012	**0.836**	**0.836**	**0.550**	**0.515**	**0.568**	**0.566**	**1.000**	0.146	-0.031	**0.706**	**0.918**	**0.782**	-0.090	**0.566**	1.000	
Total_Hardness	0.170	0.337	0.016	-0.055	0.356	0.356	0.465	0.231	0.401	**0.965**	**0.763**	0.220	-0.028	**0.650**	**0.726**	0.534	-0.111	**0.965**	**0.763**	1.000

Table 4.13 Correlation coefficient of physico-chemical water quality parameters in the Pre-Monsoon (2008) Open Well (OW) water samples from the study area

In the pre-monsoon (2009) open well waters (Table 4.14), the highest significant correlation is established by the sodium (0.834), potassium (0.764) and chlorides (0.609) with TDS in the reducing order indicating the proportionately lesser contributions from these constituents towards the contamination of the water. The highest correlation of anions viz: sulphates (0.627) and HCO_3 (0.527) with the cation magnesium, indicates its proportions and the probable cause for the hardness of the water from the anthropogenic and natural processes. The very high correlation (0.957) of iron with turbidity indicates the extent of contamination in the physical property of water. The correlation of total hardness with the Mg shows the highest significant value (0.988) with a decreasing trend towards sulphate (0.623) and bicarbonate (0.571).

	Temp.	pH	DO	BOD	Turbidity	EC	TDS	Na+	K+	Alkali	Ca++	Mg++	Iron	HCO3-	Cl	SO4	NO3	Ca_Hard	Mg_Hard	TH
Temp.	1.000																			
pH	-0.152	1.000																		
DO	-0.179	0.178	1.000																	
BOD	0.053	0.070	-0.016	1.000																
Turbidity	0.226	0.253	0.135	-0.104	1.000															
EC(µmS/cm)	0.088	-0.050	-0.389	**0.544**	0.019	1.000														
TDS	0.088	-0.050	-0.389	**0.544**	0.019	**1.000**	1.000													
Sodium	0.111	0.075	-0.492	0.464	0.001	**0.834**	**0.834**	1.000												
Potassium	0.061	0.020	-0.505	0.352	0.006	**0.764**	**0.764**	**0.897**	1.000											
Na+K(alkali)	0.094	0.055	-0.509	0.431	0.003	**0.828**	**0.828**	**0.985**	**0.961**	1.000										
Calcium	0.170	0.198	-0.193	0.162	0.200	0.307	0.307	0.415	0.386	0.414	1.000									
Magnesium	0.038	-0.064	-0.172	-0.017	0.232	0.064	0.064	0.266	0.278	0.277	0.193	1.000								
Iron	0.195	0.265	0.095	-0.159	**0.957**	-0.016	-0.016	-0.039	-0.026	-0.035	0.216	0.246	1.000							
HCO3	0.143	0.298	-0.110	**0.504**	0.181	0.343	0.343	0.464	0.259	0.394	0.418	**0.527**	0.146	1.000						
Chlorides	0.011	-0.364	-0.122	0.272	-0.012	**0.609**	**0.609**	0.209	0.225	0.221	-0.021	-0.062	-0.059	-0.001	1.000					
Sulphates	0.111	-0.358	-0.179	0.095	-0.026	0.123	0.123	0.192	0.163	0.186	0.149	**0.627**	-0.034	0.401	0.103	1.000				
Nitrates	-0.151	0.186	0.144	-0.137	-0.039	-0.153	-0.153	-0.077	-0.021	-0.057	-0.073	-0.054	-0.077	-0.062	-0.165	-0.241	1.000			
Ca_Hardness	0.170	0.198	-0.193	0.162	0.200	0.307	0.307	0.415	0.386	0.414	**1.000**	0.193	0.216	0.418	-0.021	0.149	-0.073	1.000		
Mg_Hardness	0.038	-0.064	-0.172	-0.017	0.232	0.064	0.064	0.266	0.278	0.277	0.193	**1.000**	0.246	**0.527**	-0.062	**0.627**	-0.054	0.193	1.000	
Total_Hardness	0.063	-0.030	-0.195	0.010	0.254	0.110	0.110	0.320	0.328	0.331	0.344	**0.988**	0.270	**0.571**	-0.063	**0.623**	-0.063	0.344	**0.988**	1.000

Table 4.14 Correlation coefficient of physico-chemical water quality parameters in the Pre-Monsoon (2009) Open Well (OW) water samples from the study area

<u>4.5.4.2 Correlation Coefficient of Post-Monsoon Open Well Water Samples:</u> In the post-monsoon (2009) open well waters (Table 4.15), the highest significant correlation is established by the nitrates (0.780), potassium (0.755) and sodium (0.680) with TDS in the reducing order indicating the proportionately lesser contributions from these constituents towards the contamination of the water. Nitrates might have introduced through the fertilizers and anthropogenic activities, whereas potassium and sodium through the weathering of feldspars and pyroxenes of igneous rocks. The high correlation of BOD with TDS also probably indicates the anthropogenic contamination and influence of fertilizers in the groundwater which again stressed by the significant correlation of nitrates with BOD. A significant correlation (0.608) of iron with turbidity indicates the probability of contamination from the iron rich lateritic formation and from the organic enrichment. The significant correlation of anions viz: chloride (0.732), bicarbonate (0.703), sulphates (0.516) and nitrates

(0.487) with the cation sodium, indicates the significant dissociation of sodium minerals especially feldspars from the host rocks. At the same time, the high correlation of sodium and chlorides also indicates the contamination through anthropogenic activities and saline water influence in the open well sources of the area.

	Temp.	*pH*	*DO*	*BOD*	*Turbidity*	*EC*	*TDS*	*Na+*	*K+*	*Ca++*	*Mg++*	*Iron*	*HCO3*	*CO3*	*Cl*	*NO3*	*SO4*	*Ca_Hard*	*Mg_Hard*	*TH*	*Flouride*
Temp.	1.000																				
pH	0.445	1.000																			
DO	-0.134	-0.147	1.000																		
BOD	0.164	0.252	-0.469	1.000																	
Turbidity	-0.211	-0.028	-0.220	-0.023	1.000																
EC(µS/cm)	0.161	0.458	-0.495	**0.866**	-0.024	1.000															
TDS	0.161	0.458	-0.495	**0.866**	-0.024	**1.000**	1.000														
Na+	0.173	0.469	-0.235	0.379	0.015	**0.680**	**0.680**	1.000													
K+	0.192	0.324	-0.356	**0.579**	-0.054	**0.755**	**0.755**	**0.675**	1.000												
Ca++	0.026	0.365	-0.008	-0.060	-0.012	0.241	0.241	**0.633**	0.272	1.000											
Mg++	-0.053	0.210	-0.092	-0.064	-0.026	0.188	0.188	0.468	0.309	**0.608**	1.000										
Iron	-0.186	0.007	-0.135	-0.035	**0.608**	-0.071	-0.071	-0.102	-0.069	-0.033	0.007	1.000									
HCO3	0.069	0.406	-0.032	-0.080	0.001	0.287	0.287	**0.703**	0.265	**0.514**	0.379	-0.067	1.000								
CO3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000							
Cl	0.057	0.395	-0.137	0.164	0.090	0.475	0.475	**0.732**	0.414	0.493	0.158	-0.058	0.452	0.000	1.000						
NO3	0.102	0.268	-0.460	**0.660**	-0.091	**0.780**	**0.780**	0.487	**0.674**	0.157	0.356	-0.068	0.075	0.000	0.232	1.000					
SO4	-0.081	0.287	-0.021	-0.041	-0.041	0.306	0.306	**0.516**	0.307	**0.696**	**0.586**	0.034	0.491	0.000	0.472	0.204	1.000				
Ca_Hardness	0.026	0.365	-0.008	-0.060	-0.012	0.241	0.241	**0.633**	0.272	**1.000**	**0.608**	-0.033	**0.514**	0.000	0.493	0.157	**0.696**	1.000			
Mg_Hardness	-0.053	0.210	-0.092	-0.064	-0.026	0.188	0.188	0.468	0.309	**0.608**	**1.000**	0.007	0.379	0.000	0.159	0.356	**0.586**	**0.608**	1.000		
TH	0.011	0.357	-0.028	-0.066	-0.016	0.247	0.247	**0.642**	0.303	**0.981**	**0.749**	-0.026	**0.521**	0.000	0.450	0.218	**0.722**	**0.981**	**0.749**	1.000	
Flouride	0.169	0.030	-0.177	-0.045	-0.112	-0.038	-0.038	0.191	0.214	0.027	-0.008	-0.108	0.187	0.000	-0.023	0.080	-0.259	0.027	-0.008	0.021	1.000

Table 4.15 Correlation coefficient of Physico-chemical water quality parameters in the Post-Monsoon (2009) Open Well (OW) water samples from the study area

<u>4.5.4.3 Correlation Coefficient of Pre-Monsoon Bore Well Water Samples:</u> In the pre-monsoon (2008-2009) bore well waters (Table 4.16), no significant correlation is made between the TDS and any of the cations or anions indicating the negligible influence of the contamination of the bore well water from the natural weathering and leaching of the aquifer rocks in the area. The highest significant correlation is established between the sodium and chloride (0.977) indicating the contamination from the external sources. Among the alkalies sodium predominates (0.997), and magnesium establish very significant correlation (0.992) with total hardness. The hardness is of temporary introduced by the HCO_3. Bicarbonates are negatively correlated with the TDS at higher ionic concentration, indicating decreasing lithogenic and increasing anthropogenic contribution at higher concentration. Chlorides and calcium show a significant positive correlation (0.713) as well as calcium and sodium (0.704). The very high correlation (0.860) of iron with turbidity indicates the extent

of contamination in the physical property of water and its introduction due to the rusting of the casing pipes.

	Temp.	*pH*	*DO*	*BOD*	*Turbidity*	*EC*	*TDS*	*Na+*	*K+*	*Alkali*	*Ca++*	*Mg++*	*Iron*	*HCO3*	*Cl*	*SO4*	*NO3*	*Ca_Hard*	*Mg_Hard*	*TH*
Temp.	1.000																			
pH	-0.177	1.000																		
DO	0.272	-0.126	1.000																	
BOD	0.343	-0.303	0.471	1.000																
Turbidity	0.043	-0.001	-0.336	-0.043	1.000															
EC	0.110	-0.209	0.405	**0.509**	-0.136	1.000														
TDS	0.110	-0.209	0.405	**0.509**	-0.136	**1.000**	1.000													
Sodium	0.037	0.171	0.189	-0.024	-0.153	0.084	0.084	1.000												
Potassium	-0.003	0.128	-0.110	-0.121	-0.030	-0.273	-0.273	0.134	1.000											
Alkali	0.036	0.179	0.177	-0.033	-0.154	0.061	0.061	**0.997**	0.213	1.000										
Calcium	-0.022	0.371	0.231	0.076	-0.170	0.218	0.218	0.704	0.008	**0.694**	1.000									
Magnesium	0.321	-0.088	0.129	0.506	0.182	0.087	0.087	-0.223	-0.144	-0.232	-0.119	1.000								
Iron	-0.034	0.108	-0.274	0.003	**0.860**	-0.185	-0.185	-0.110	0.219	-0.091	-0.152	0.147	1.000							
HCO3	0.004	0.290	-0.076	-0.015	-0.097	-0.255	-0.255	0.353	**0.667**	0.402	0.345	0.103	-0.030	1.000						
Chlorides	0.068	0.099	0.271	0.045	-0.159	0.243	0.243	**0.977**	0.036	**0.966**	**0.713**	-0.250	-0.150	0.257	1.000					
Sulphates	-0.108	-0.483	0.067	0.008	-0.239	-0.152	-0.152	-0.004	0.112	0.005	-0.160	0.062	-0.175	0.166	-0.029	1.000				
Nitrates	-0.258	0.102	-0.351	-0.208	0.164	0.132	0.132	-0.177	-0.174	-0.188	-0.078	-0.382	0.048	-0.096	-0.136	-0.204	1.000			
Ca_Hardness	-0.022	0.371	0.231	0.076	-0.170	0.218	0.218	**0.704**	0.008	**0.694**	**1.000**	-0.119	-0.152	0.345	**0.713**	-0.160	-0.078	1.000		
Mg_Hardness	0.321	-0.088	0.129	**0.506**	0.182	0.087	0.087	-0.223	-0.144	-0.232	-0.119	**1.000**	0.147	0.103	-0.250	0.062	-0.382	-0.119	1.000	
Total_Hardness	0.321	-0.043	0.159	**0.519**	0.163	0.115	0.115	-0.138	-0.144	-0.148	0.004	**0.992**	0.129	0.146	-0.164	0.042	-0.394	0.004	**0.992**	1.000

Table 4.16 Correlation coefficient of Physico-chemical water quality parameters in the Pre-Monsoon (2008-2009) Bore Well (BW) water samples from the study area

4.5.4.4 Correlation Coefficient of Post-Monsoon Bore Well Water Samples: In the post-monsoon (2009) bore well waters (Table 4.17), the highest significant correlation is established by the HCO_3 (0.723) and calcium (0.629) whereas magnesium (0.339) in a low positive order with TDS indicating the relative contributions from these constituents towards the contamination of the water. No significant correlation is made between the TDS and any of the cations or anions indicating the negligible influence of the contamination of the bore well water from the natural weathering and leaching of the aquifer rocks in the area. The highest significant correlation is established between the calcium and bicarbonate (0.891) indicating the temporary hardness introduced in the water. The significant correlation of anion sulphate with cations iron (0.635) and magnesium (0.510) indicates the influence of external systems and rock weathering. The very high significant correlation of turbidity with iron (0.927) and sulphate (0.704) indicates the extent of contamination in the physical property of water introduced due to the rusting of the casing pipes forming its sulphates. The significant correlation of fluoride with potassium (0.738) indicates the probable source from orthoclase feldspars of the granitic rock.

	Temp.	*pH*	*DO*	*BOD*	*Turbidity*	*EC*	*TDS*	*Na+*	*K+*	*Ca++*	*Mg++*	*Iron*	*HCO3*	*CO3*	*Cl*	*NO3*	*SO4*	*Ca_Hard*	*Mg_Hard*	*TH*	*Flouride*
Temp.	1.000																				
pH	-0.035	1.000																			
DO	0.070	0.260	1.000																		
BOD	0.352	0.495	0.452	1.000																	
Turbidity	-0.473	-0.506	-0.171	0.007	1.000																
EC(µS/cm)	0.154	0.362	0.393	**0.550**	-0.167	1.000															
TDS	0.154	0.362	0.393	**0.549**	-0.167	**1.000**	1.000														
Na+	0.138	**0.601**	0.325	0.068	-0.582	0.116	0.116	1.000													
K+	**0.713**	0.104	-0.372	0.040	-0.439	0.076	0.076	0.285	1.000												
Ca++	-0.032	-0.072	**0.553**	0.492	0.187	**0.629**	**0.629**	-0.174	-0.478	1.000											
Mg++	-0.450	-0.209	-0.104	-0.108	0.491	0.339	0.339	-0.198	-0.399	0.466	1.000										
Iron	-0.397	-0.387	-0.211	0.138	**0.927**	-0.085	-0.085	-0.505	-0.281	0.149	0.292	1.000									
HCO3	0.069	-0.073	0.287	0.404	0.130	**0.723**	**0.723**	-0.106	-0.264	**0.891**	**0.647**	0.093	1.000								
CO3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000							
Cl	-0.158	0.171	0.295	-0.380	-0.322	-0.177	-0.177	**0.616**	0.144	-0.310	-0.232	-0.346	-0.457	0.000	1.000						
NO3	0.165	0.059	-0.611	0.068	0.093	-0.572	-0.572	-0.174	0.341	-0.502	-0.307	0.133	-0.491	0.000	-0.196	1.000					
SO4	-0.542	-0.574	0.085	-0.341	**0.704**	-0.093	-0.093	-0.149	-0.449	0.275	**0.510**	**0.635**	0.206	0.000	0.203	-0.393	1.000				
Ca_Hardness	-0.032	-0.072	**0.553**	0.491	0.187	**0.628**	**0.629**	-0.174	-0.478	**1.000**	0.467	0.149	**0.891**	0.000	-0.309	-0.502	0.275	1.000			
Mg_Hardness	-0.450	-0.209	-0.104	-0.108	0.491	0.339	0.339	-0.198	-0.399	0.466	**1.000**	0.292	**0.647**	0.000	-0.232	-0.307	**0.510**	0.467	1.000		
TH	-0.238	-0.150	0.327	0.283	0.363	**0.591**	**0.591**	-0.213	-0.517	**0.905**	**0.798**	0.242	**0.918**	0.000	-0.322	-0.489	0.432	**0.905**	**0.798**	1.000	
Flouride	**0.651**	-0.223	-0.562	0.157	-0.017	-0.103	-0.103	-0.079	**0.738**	-0.194	-0.183	0.125	0.007	0.000	-0.321	**0.602**	-0.239	-0.194	-0.183	-0.220	1.000

Table 4.17 Correlation coefficient of physico-chemical water quality parameters in the Post-Monsoon Bore Well (BW) water samples from the study area

<u>4.5.4.5 Correlation Coefficient of Pre-Monsoon Surface Water Samples:</u> In the surface water (Table 4.18), the highest correlation between the total dissolved solids can be found with magnesium (0.622), then chloride (0.570) and potassium (0.481) in the decreasing order. This indicates relative contribution of these constituents towards polluting the groundwater. Low positive correlation of bicarbonate (0.316) indicates less lithogenic influence in its contribution (Singh *et al.* 2011). The chloride in the surface water might have been contributed from the sea water. The high correlation of pH with chlorides (0.894) and calcium (0.827) indicates contamination of surface water with anthropogenic pollution. There is a very high significant correlation between the magnesium and potassium (0.957) indicating the weathering and leaching influence of magnesium and potassium rich rocks on the surface waters of the study area. A significant correlation of iron and turbidity (0.763) and iron and nitrate (0.501) indicates the anthropogenic pollution in the surface water.

	Temp.	*pH*	*DO*	*Turbidity*	*EC*	*TDS*	*Na+*	*K+*	*Alkali*	*Ca++*	*Mg++*	*Iron*	*HCO3*	*Cl*	*SO4*	*NO3*	*Ca_Hard*	*Mg_Hard*	*TH*
Temp.	1.000																		
pH	0.262	1.000																	
DO	-0.077	-0.160	1.000																
Turbidity	0.359	0.038	-0.234	1.000															
EC(µmS/cm)	-0.289	0.419	-0.243	-0.036	1.000														
TDS	-0.289	0.419	-0.243	-0.036	**1.000**	1.000													
Sodium	0.368	**0.565**	-0.203	0.180	0.129	0.129	1.000												
Potassium	0.170	**0.563**	-0.246	0.098	0.481	0.481	**0.800**	1.000											
Alkali	0.339	**0.584**	-0.218	0.169	0.205	0.205	**0.992**	**0.868**	1.000										
Calcium	0.542	**0.827**	-0.142	0.091	0.066	0.066	**0.564**	0.452	**0.560**	1.000									
Magnesium	0.029	**0.504**	-0.266	0.049	**0.622**	**0.622**	**0.601**	**0.957**	**0.694**	0.332	1.000								
Iron	0.474	-0.054	-0.255	**0.763**	-0.035	-0.035	-0.009	-0.006	-0.009	-0.036	-0.016	1.000							
HCO3	0.093	**0.645**	-0.182	-0.001	0.316	0.316	0.477	**0.534**	**0.505**	0.481	0.455	0.004	1.000						
Chlorides	0.307	**0.894**	-0.242	0.056	**0.570**	0.570	**0.552**	**0.608**	**0.582**	**0.853**	**0.569**	-0.049	**0.556**	1.000					
Sulphates	-0.071	0.075	0.021	-0.120	-0.049	-0.049	-0.008	0.033	0.001	-0.059	0.002	-0.002	**0.690**	-0.072	1.000				
Nitrates	-0.020	-0.166	0.238	**0.501**	-0.209	-0.209	-0.048	-0.124	-0.065	-0.263	-0.156	0.417	-0.144	-0.321	0.006	1.000			
Ca_Hardness	**0.542**	**0.827**	-0.142	0.091	0.066	0.066	**0.564**	0.452	**0.560**	**1.000**	0.332	-0.036	0.481	**0.853**	-0.059	-0.263	1.000		
Mg_Hardness	0.029	**0.504**	-0.266	0.049	**0.622**	**0.622**	**0.601**	**0.957**	**0.694**	0.332	**1.000**	-0.016	0.455	**0.569**	0.002	-0.156	0.332	1.000	
Total_Hardness	0.269	**0.756**	-0.265	0.078	0.497	0.497	**0.709**	**0.925**	**0.777**	**0.706**	**0.902**	-0.028	**0.562**	**0.817**	-0.025	-0.237	**0.706**	**0.902**	1.000

Table 4.18 Correlation coefficient of physico-chemical water quality parameters in the Pre-Monsoon (2008-2009) Surface Water (SW) samples from the study area

<u>4.5.4.6 Relationship of Cations-Anions Groundwater Chemistry:</u> Based on groundwater chemistry, three sets of strong relationships existing between major cations and anions (Douglas and Leo 1977) were established in the study area (Table 4.19). They are:

(i) The highly competitive relationship between ions having same charge but different valence number. For e.g. Ca^{2+} and Na^{+}

(ii) The affinity ions relationship between ions having different charges but the same valence number. For e.g. Na^{+} and Cl^{-}

(iii) The non-competitive relationship between ions having the same charge and same valence number. For e.g. Ca^{2+} and Mg^{2+}

Among these relationship groups, a high significant positive relationship of competitive ions have been established between SO_4^{2-} & Cl^{-} in the pre-monsoon open well samples and Na^{+} & Ca^{2+} in the pre-monsoon bore well samples indicating the contamination of sources through anthropogenic and natural processes of saline water intrusion.

In the affinity ions relationship, a high significant positive relationship of ions have been established between SO_4^{2-} & Mg^{2+} in the pre-monsoon open well samples and Na^{+} & Cl^{-} in the pre-monsoon bore well samples indicating the contamination of sources through anthropogenic and natural processes of saline water intrusion generating hard water. In the post-monsoon open well water samples also this high significant positive relationship is established between the Na^+ & Cl^- and Na^+ & HCO_3^-.

Relationship		Pre monsoon				Post monsoon	
		OW (2008)	OW (2009)	BW	SW	OW	BW
Highly competitive relationship	High significant +ve correlation	SO4 & Cl (0.730)		Ca & Na (0.704)			
	Significant +ve correlation	Fe & Na (0.496) SO_4 & HCO_3 (0.624)			Ca & Na (0.564) Ca & K (0.452) SO4 & HCO3 (0.690)	Ca & Na (0.633) SO4 & Cl (0.472) SO4 & HCO3 (0.491)	
	Low +ve correlation	Ca & Na (0.369) Ca & K (0.085) Fe & K (0.280)	Ca & Na (0.415) Ca & K (0.386) SO4 & Cl (0.103) SO4&HCO3 (0.401)	Ca & K (0.008) Fe & K (0.219) SO4 & HCO3 (0.166)		Ca & K (0.272)	SO4 & Cl (0.203) SO4 & HCO3 (0.206)
	-ve correlation		Fe & K (-0.026) Fe & Na (-0.039)	Fe & Na (-0.110) SO4 & Cl (-0.029)	Fe & K (-0.006) Fe & Na (-0.009) SO4 & Cl (-0.072)	Fe & Na (-0.102) Fe & K (-0.069)	Ca & Na (-0.174) Ca & K (-0.478) Fe & K (-0.281) Fe & Na (-0.505)
Affinity Ions relationship	High significant +ve correlation	SO_4 & Mg (0.782)		Cl & Na (0.977)		Cl & Na (0.732) HCO3 & Na (0.703)	
	Significant +ve correlation	HCO_3& Na (0.606)	HCO3 & Na (0.464) SO4 & Mg (0.627)	HCO3 &K (0.667)	HCO3 & Na (0.477) HCO3 & K (0.534) Cl & K (0.608) Cl & Na (0.552)	SO4 & Ca (0.696) SO4 & Mg (0.586)	SO4 & Mg (0.510) Cl & Na (0.616)
	Low +ve correlation	Cl & K (0.448) HCO_3&K (0.426) Cl & Na (0.442) SO_4 & Ca (0.362)	Cl & K (0.225) HCO3 &K (0.259) Cl & Na (0.209) SO4 & Ca (0.149)	Cl & K (0.036) HCO3 & Na (0.353) SO4 & Mg (0.062)	SO4 & Mg (0.002)	Cl & K (0.414) HCO3 &K (0.265)	Cl & K (0.144) SO4 & Ca (0.275)
	-ve correlation			SO4 & Ca (-0.160)	SO4 & Ca (-0.059)		HCO3 &K (-0.264) HCO3 &Na (-0.106)
Non-competitive relationship	High significant +ve correlation	Na & K (0.771)	Na & K (0.897)		Na & K (0.800)		
	Significant +ve correlation	Ca & Mg (0.566) HCO_3& Cl (0.617)			HCO3 & Cl (0.556)	Ca & Mg (0.608) HCO3 & Cl (0.452) Na & K (0.675)	Ca & Mg (0.466)
	Low +ve correlation		Ca & Mg (0.193)	HCO3 & Cl (0.257) Na & K (0.134)	Ca & Mg (0.332)		Na & K (0.285)
	-ve correlation		HCO3 & Cl (-0.001)	Ca & Mg (-0.119)			HCO3 & Cl (-0.457)

Table 4.19 Summary table showing the relationship of major cations and anions of Pre- and Post-Monsoon water samples in the study area
(*after* Douglas and Leo 1977)
(OW- Open Well, BW-Bore Well, SW-Surface Water)

Among noncompetitive ions relationship, a high significant positive relationship of ions has been established between Na^+& K^+ in the pre-monsoon open well water and surface water samples indicating the influence of weathering and leaching. Significant positive correlation has been established by Fe & Na, SO_4^{2-}& HCO_3^-, Na^+ & HCO_3^-,

SO_4^{2-} & Mg^{2+}, Ca^{2+} & Mg^{2+} and Cl^- & HCO_3^- in the open well water samples during pre-monsoon, whereas during post-monsoon it is among Ca^{2+} & Na^+, SO_4^{2-}& Cl^-, SO_4^{2-}& HCO_3^-, SO_4^{2-} & Mg^{2+}, SO_4^{2-} & Ca^{2+} , Ca^{2+} & Mg^{2+}, Na^+& K^+ and HCO_3^-& Cl^- . The correlation of ions in the pre-monsoon and post-monsoon samples are almost similar except among Fe & Na, Na^+ & HCO_3^- relations present in pre-monsoon and Ca^{2+} & Na^+, SO_4^{2-}& Cl^-, SO_4^{2-} & Ca^{2+} and Na^+& K^+ established in the post-monsoon open well water samples. In the bore well samples, significant positive correlation has been established only by HCO_3^-& K^+ during pre-monsoon, whereas during post-monsoon it is among SO_4^{2-}& Mg^{2+}, Na^+ & Cl^- and Ca^{2+} & Mg^{2+} indicating the influence of rock weathering and leaching.

The high positive relationship established among various ions of competitive, non-competitive and affinity ions in the pre-monsoon open well water samples suggests the influence of the natural and anthropogenic contaminations in these water sources. But there is no such strong relationships established in the cases of post-monsoon bore well water indicating the absence of such influence in those water resources.

4.6 DRINKING WATER CLASSIFICATION OF GROUNDWATER: The water used for drinking purpose should be free from colour, turbidity and microorganisms (Karanth 1987). Physically and chemically the water should be soft with less dissolved solids and free from harmful chemical constituents. Range of various hydrogeochemical parameters and their statistical analysis in the water samples of Mulki River basin with their compliance with national (BIS 1991) and international (WHO 1993) drinking water standards are presented in Tables 4.20 to 4.25. This shows that the important physical and chemical water quality parameters in the area are generally well within the permissible limit of drinking water standards prescribed except at a few places.

4.6.1 Hydrogeochemistry of Pre-Monsoon Water Samples: Pre-monsoon water samples represent a cross section of the surface and groundwater bodies used for the irrigation and potable purposes in the study area. Mainly they can be classified in to groundwater sources from dug wells, springs and bore wells besides surface water sources like lakes and ponds.

<u>4.6.1.1 Pre-Monsoon Hydrogeochemistry of Dug wells and Springs:</u> Statistical analysis of the pre-monsoon groundwater samples collected from the dug wells and springs within the basin for two consecutive years 2008 (Table 4.20) and 2009 (Table 4.21) were carried out to understand the variation trend and the influence of other parameters on it. They were correlated with the drinking water standards prescribed by Bureau of Indian Standards (BIS: 10500, 1993) and World Health Organization (WHO 1993). Except the pH value, other parameters are in compliance with the prescribed standards but for a few samples. Samples collected during pre-monsoon 2009 show more compliance compared to the samples of 2008, where influence of the coastal aquifer is more prominent. The acidity in water samples may be mainly due to the influence of laterites in the area.

Parameters	Unit	Maximum	Mini-mum	Median	Mean (57 samples)	Std. Dev.	Skew-ness	Kurto-sis	BIS:10500 (1993)	%age Compli-ance	WHO (1993)	%age Compli-ance	Samples Beyond Permissible Limit	
													Source Nos. OW	Sample Numbers & Remarks
Temperature	°C	35.00	26.00	29.00	28.77	1.54	1.23	4.09	-	-	-	-		
pH		9.66	4.79	6.32	6.34	0.85	0.94	2.85	6.5-8.5	37%	7.0-8.5	16%	all samples Except OW27, 29-31,34-37,54	All samples except 48,50,52, 53,57,58,59, 61 & 81. All acidic except no.77
DO	ppm	7.36	4.00	6.40	6.38	0.63	-1.67	3.78	-	-	-	-	-	-
Turbidity	NTU	5.00	ND	1.00	1.46	0.95	1.22	2.66	5.0-10.0	100%	5	100%	-	-
EC	mµS/cm	30300.00	76.00	1447.00	1810.26	3952.62	6.93	50.50	2000	89%	-	-	OW26,29,30, 31,34,42	46,50,52,53, 57,67
TDS	ppm	18816.30	47.20	898.59	1124.17	2454.58	6.93	50.50	500-2000	93%	1000	88%	OW26,30,31,42	46,52,53,67
Sodium	ppm	106.97	0.48	12.27	26.23	29.86	1.47	1.16	200-600	100%	200	100%	-	-
Potassium	ppm	76.29	0.03	3.53	9.82	17.28	2.86	7.84	200-600	100%	-	-	-	-
Alkali	ppm	181.37	0.68	15.52	36.05	44.56	1.94	3.36	200-600	100%	-	-	-	-
Calcium	ppm	1680.00	1.60	8.00	56.35	240.13	6.11	39.55	75-200	96%	500	95%	OW30,37,54	52,61,81
Magnesium	ppm	388.80	0.29	8.36	26.30	59.29	4.81	26.42	30-100	93%	-	-	OW24,30,37,54	43,52,61,81
Iron	ppm	0.11	0.00	0.03	0.04	0.04	0.33	-1.61	0.3-1.0	100%	2	100%	-	-
Carbonate	ppm	16.00	0.00	0.00	0.28	2.12	7.55	57.00	-	-	-	-	-	-
HCO_3	ppm	158.00	8.00	22.00	37.79	36.82	1.90	2.80	200	100%	-	-	-	-
Chloride	ppm	4118.49	1.45	13.45	192.50	644.95	4.83	25.86	250-1000	93%	250	91%	OW30,37,38, 44,54	52,61,62,69,81
Sulphate	ppm	29.80	ND	1.30	3.17	5.10	3.06	12.60	200-400	100%	500	100%	-	-
Nitrate	ppm	11.52	ND	0.89	2.38	2.90	1.32	0.91	45-100	100%	50	100%	-	-
Ca-Hardness	ppm	4200.00	4.00	20.00	140.87	600.33	6.11	39.55	-	-	-	-	-	-
Mg-Hardness	ppm	1600.00	1.20	34.40	108.21	243.98	4.81	26.42	-	-	-	-	-	-
Tot. Hardness	ppm	5040.00	9.20	52.00	249.08	765.29	5.19	29.23	300-600	95%	-	-	OW30,37,54	52,61,81

Table 4.20 Statistical details of the Hydrogeochemistry of Pre-Monsoon (2008) Open Well water samples from the study area with their compliance of drinking water standards

Parameters	Unit	Maxi-mum	Mini-mum	Median	Mean (47 samples)	Std. Dev.	Skew-ness	Kurto-sis	BIS:10500 (1993)	%age Compli-ance	WHO (1993)	%age Compli-ance	Samples Beyond Permissible Limit	
													Source Nos. OW	Sample Numbers & Remarks
Temperature	ºC	31.00	22.00	28.00	27.69	1.89	-1.02	2.24	-	-	-	-	-	-
pH		7.74	4.56	6.63	6.52	0.70	-0.52	0.31	6.5-8.5	60%	7.0-8.5	23%	All except OW59,60,62, 67, 78, 81, 82, 83, 84, 90, 96	All acidic except 87, 88, 90, 99, 110, 114, 116, 117, 118, 133,145
DO	ppm	7.40	4.20	6.50	6.35	0.78	-1.13	1.14	-	-	-	-	-	-
BOD	ppm	4.50	0.10	0.70	1.00	0.95	1.62	3.03	-	-	-	-	-	-
Turbidity	NTU	18.40	ND	0.30	0.92	2.72	6.04	39.07	5.0-10.0	98%	5	98%	OW 84	118
EC	mµS/cm	1810.00	40.00	104.00	214.51	315.09	3.68	15.18	2000	100%	-	-	-	-
TDS	ppm	1124.01	24.84	64.58	133.21	195.67	3.68	15.18	500-2000	100%	1000	98%	OW 67	99
Sodium	ppm	109.13	2.16	8.89	13.60	17.95	3.91	18.28	200-600	100%	200	100%	-	-
Potassium	ppm	74.37	0.11	2.76	5.63	11.34	5.24	30.75	200-600	100%	-	-	-	-
Alkali	ppm	183.50	2.55	11.87	19.23	28.57	4.55	24.50	200-600	100%	-	-	-	-
Calcium	ppm	44.80	1.60	8.80	11.75	9.11	1.69	2.96	75-200	100%	500	100%	-	-
Magnesium	ppm	161.84	4.42	29.70	41.72	33.30	1.88	3.72	30-100	91%	-	-	OW 90, 93,95,98	133, 139, 142, 149
Iron	ppm	3.90	ND	0.10	0.21	0.58	5.93	38.05	0.3-1.0	98%	2	98%	OW 84	118
Carbonate	ppm	ND	ND	-	-	-	-	-	-	-	-	-	-	-
HCO_3	ppm	260.00	6.00	26.00	37.70	40.72	4.04	19.75	200	98%	-	-	OW 96	145
Chloride	ppm	497.48	5.89	13.39	28.23	72.95	6.13	39.39	250-1000	100%	250	100%	-	-
Sulphate	ppm	98.00	ND	1.10	23.16	32.14	0.87	-1.01	200-400	100%	500	100%	-	-
Nitrate	ppm	16.13	ND	3.28	3.71	3.27	1.86	4.50	45-100	100%	50	100%	-	-
Ca-Hardness	ppm	112.00	4.00	22.00	29.36	22.77	1.69	2.96	-	-	-	-	-	-
Mg-Hardness	ppm	666.00	18.20	122.20	171.68	137.04	1.88	3.72	-	-	-	-	-	-
Tot. Hardness	ppm	744.00	65.10	148.80	201.04	143.18	1.98	4.18	300-600	98%	-	-	OW 98	149

Table 4.21 Statistical details of the Hydrogeochemistry of Pre-Monsoon (2009) Open Well water samples from the study area with their compliance of drinking water standards

4.6.1.2 Pre-Monsoon Hydrogeochemistry of Bore Wells: The analysis details (Table 4.22) show that the bore well samples compliance with the drinking water standards is high. Except a few samples and a few parameters most of the samples are not much affected by contamination.

4.6.1.3 Pre-Monsoon Hydrogeochemistry of Surface water: Statistical analysis of surface water samples shows the influence of contamination in these bodies along the coastal tracts. Water samples SW17, SW18, SW19 and SW20 show contamination with chloride, cations and total hardness, indicating the influence of saline water.

Parameters	Unit	Maxi-mum	Mini-mum	Medi-an	Mean (27 samples)	Std. Dev.	Skew ness	Kurto-sis	BIS:10500 (1993)	%age Compli-ance	WHO (1993)	%age Compli-ance	Samples Beyond Permissible Limit	
													Source Nos. BW	Sample Numbers & Remarks
Temperature	◦C	32.00	25.00	30.00	29.28	1.76	-0.84	0.08	-	-	-	-	-	-
pH		8.30	6.15	7.28	7.28	0.53	-0.20	0.00	6.5-8.5	93%	7.0-8.5	81%	BW03, 15, 17, 18, 20, 21& 26	Acidic : 97, 135, 141, 143, 151, 154 & 160
DO	ppm	8.70	4.60	6.40	6.50	0.95	0.28	-0.04	-	-	-	-	-	-
BOD	ppm	3.90	0.10	0.90	1.24	0.99	0.90	0.38	-	-	-	-	-	-
Turbidity	NTU	40.10	0.10	0.60	3.62	8.79	3.49	12.48	5.0-10.0	89%	5	85%	BW8, 9, 14, 17	126, 127, 132, 141
EC	mµS/ cm	1710.00	92.00	267.00	377.07	390.27	2.84	7.81	2000	100%	-	-	-	-
TDS	ppm	1061.91	57.13	165.81	234.16	242.36	2.84	7.81	500-2000	100%	1000	96%	BW18	143
Sodium	ppm	155.30	2.90	12.95	28.07	37.58	2.45	5.34	200-600	100%	200	100%	-	-
Potassium	ppm	14.97	0.65	6.97	7.27	3.10	0.14	0.52	200-600	100%	-	-	-	-
Alkali	ppm	162.80	3.55	20.74	35.34	38.12	2.37	4.97	200-600	100%	-	-	-	-
Calcium	ppm	34.40	3.20	8.00	10.22	7.20	1.79	3.86	75-200	100%	500	100%	-	-
Magnesium	ppm	170.61	29.40	80.68	80.36	35.75	0.53	-0.11	30-100	70%	-	-	BW7, 9, 10, 13, 14, 17, 18, 21	120, 127, 128, 131, 136, 141, 143, 154
Iron	ppm	5.22	0.20	0.30	0.90	1.24	2.40	5.60	0.3-1.0	70%	2	89%	BW4,5,8,13,17, BW9, 14, 19	>1.0- 111, 115, 126, 131, 141; >2.0- 127, 132, 146
Carbonate	ppm	ND	ND	-	-	-	-	-	-	-	-	-	-	-
HCO_3	ppm	150.00	16.00	80.00	77.56	34.56	0.02	-0.69	200	100%	-	-	-	-
Chloride	ppm	106.02	3.21	10.17	21.21	26.29	2.22	4.28	250-1000	100%	250	100%	-	-
Sulphate	ppm	75.00	ND	2.00	17.60	25.03	1.23	0.13	200-400	100%	500	100%	-	-
Nitrate	ppm	9.66	ND	2.48	3.53	2.75	0.87	-0.40	45-100	100%	50	100%	-	-
Ca-Hardness	ppm	86.00	8.00	20.00	25.56	17.99	1.79	3.86	-		-		-	-
Mg-Hardness	ppm	702.10	121.00	332.00	330.71	147.12	0.53	-0.11	-	-	-	-	-	-
Tot. Hardness	ppm	716.10	139.50	353.40	356.26	146.08	0.52	-0.23	300-600	96%	-	-	BW21	154

Table 4.22 Statistical details of the Hydrogeochemistry of Pre-Monsoon Bore Well water samples from the study area with their compliance of drinking water standards

Parameters	Unit	Maximum	Mini-mum	Medi-an	Mean (23 samples)	Std. Dev.	Skew ness	Kurto-sis	BIS:10500 (1993)	%age Compli-ance	WHO (1993)	%age Compli-ance	Samples Beyond Permissible Limit	
													Source Nos. SW	Sample Numbers & Remarks
Temperature	◦C	34.00	28.00	30.00	30.61	1.80	0.60	-0.41	-	-	-	-	-	-
pH		9.75	5.38	6.29	6.66	1.14	1.43	1.64	6.5-8.5	30%	7.0-8.5	17%	SW 1-9, 11-12, 15, 19-22, 13, 14, 23	Acidic: 1, 3, 4, 5, 7, 8, 9,10, 11,13, 31, 45, 84, 98, 34, 42, 137; Basic: 60, 66
DO	ppm	7.68	5.10	5.60	5.93	0.77	0.97	-0.05	-	-	-	-	-	-
Turbidity	NTU	16.80	0.50	2.00	3.07	3.56	3.01	10.31	5.0-10.0	96%	5	87%	SW 12, 19, 22	31, 60, 98
EC	mµS/ cm	43800.00	155.00	706.00	4567.00	12377.99	3.11	8.49	2000	87%	-	-	SW 16, 17, 18	47, 51, 54
TDS	ppm	27199.80	96.26	438.43	2836.11	7686.73	3.11	8.49	500-2000	87%	1000	87%	SW 16, 17, 18	47, 51, 54
Sodium	ppm	388.70	2.02	8.58	29.75	81.02	4.35	19.61	200-600	100%	200	96%	SW 19	60
Potassium	ppm	76.98	0.26	1.95	8.75	20.06	3.06	8.48	200-600	100%	-	-	-	-
Alkali	ppm	454.50	2.47	10.80	38.50	97.81	3.96	16.38	200-600	100%	-	-	-	-
Calcium	ppm	1920.00	1.20	7.20	165.31	467.71	3.27	10.32	75-200	83%	500	91%	SW 17, 18, 19, 20	>200: 51, 54 ; >500: 60, 66
Magnesium	ppm	2089.80	0.73	9.53	160.32	467.01	3.74	14.51	30-100	83%	-	-	SW17,19,20,23	51, 60, 66, 137
Iron	ppm	1.10	0.00	0.00	0.09	0.24	3.96	16.67	0.3-1.0	96%	2	100%	SW 22	>1.0: 98
Carbonate	ppm	ND	ND	-	-	-	-	-	-	-	-	-	-	-
HCO_3	ppm	120.00	8.00	22.00	34.70	28.94	1.50	2.04	200	100%	-	-	-	-
Chloride	ppm	34193.29	1.46	11.74	4610.00	10433.11	2.02	2.64	250-1000	83%	250	83%	SW 17, 18, 19, 20	51, 54, 60, 66
Sulphate	ppm	64.00	0.05	0.80	4.26	13.13	4.68	22.19	200-400	100%	500	100%	-	-
Nitrate	ppm	8.33	ND	3.10	3.16	2.55	0.49	-0.70	45-100	100%	50	100%	-	-
Ca-Hardness	ppm	4800.00	3.00	18.00	413.28	1169.27	3.27	10.32	-	-	-	-	-	-
Mg-Hardness	ppm	8600.00	3.00	39.20	659.74	1921.83	3.74	14.51	-	-	-	-	-	-
Tot.Hardness	ppm	9200.00	13.80	55.20	1073.02	2560.09	2.52	5.26	300-600	83%	-	-	SW 17, 18, 19, 20	51, 54, 60, 66

Table 4.23 Statistical details of the Hydrogeochemistry of Pre-Monsoon Surface Water samples from the study area with their compliance of drinking water standards

4.6.2 Hydrogeochemistry of Post-Monsoon Water Samples: Post-monsoon (November –December 2009) water samples represent only groundwater from different lithology in the study area. Various statistical analyses of different constituents have been carried out separately for the open well sources (Table 4.24) and bore well sources (Table 4.25) in addition to drinking water and irrigation water quality suitability analysis.

4.6.2.1 Post-Monsoon Hydrogeochemistry of Dug wells: Except pH and turbidity all other parameters are well within the permissible drinking water standards. Only four samples show a variation from this fact regarding the drinking water standards. OW26 and OW62 show nitrate contamination probably influenced from the leach pit nearby. OW26 also shows higher levels of Total Dissolved Solids (TDS) indicating the influence of contamination (Table 4.24). HCO_3 in two drinking water samples (OW71 & OW74) is beyond the permissible limit indicating the hard water other than affected by its pH also.

Parameters	Unit	Maxi-mum	Mini-mum	Median	Mean (85 samples)	Std. Dev.	Skew-ness	Kurto-sis	BIS:10500 (1993)	%age Compli-ance	WHO (1993)	%age Compli-ance	Samples Beyond Permissible Limit	
													Source Nos. OW	Sample Numbers & Remarks
Temperature	◦C	33.00	26.00	29.00	29.31	1.58	0.20	-1.02	-	-	-	-	-	-
pH		7.77	4.00	5.83	5.80	0.86	0.21	-0.35	6.5-8.5	20%	7.0-8.5	11%	All except OW18, 22, 26, 27, 61, 62, 71, 74 & 75	All acidic except 21, 25, 29, 30, 68, 69, 80, 83 & 84.
DO	ppm	9.13	0.56	5.41	5.55	1.13	-0.70	4.10	-	-	-	-	-	-
BOD	ppm	102.00	ND	0.56	1.94	11.00	9.17	84.41	-	-	-	-	-	-
Turbidity	NTU	20.20	0.10	1.50	2.25	2.84	3.77	19.37	5.0-10.0	98%	5	91%	OW1, 39,70,75, 76, 78, 82 & 83	1, 45,79, 84, 85, 87, 91 & 92
EC	mµS/cm	1703.13	21.87	64.06	112.61	200.09	6.45	48.79	2000	100%	-	-	-	-
TDS	ppm	1090.00	14.00	41.00	72.07	128.06	6.45	48.79	500-2000	100%	1000	99%	OW 26	29
Sodium	ppm	98.30	1.20	8.50	14.66	18.58	2.77	7.70	200-600	100%	200	100%	-	-
Potassium	ppm	33.10	2.70	4.50	6.98	4.86	2.36	9.07	200-600	100%	-	-	-	-
Alkali	ppm	112.3	4.30	13.60	21.63	22.148	2.46	6.14	200-600	100%	-	-	-	-
Calcium	ppm	70.40	0.80	4.40	8.17	12.61	3.71	14.04	75-200	100%	500	100%	-	-
Magnesium	ppm	14.09	0.24	1.22	1.92	2.23	3.30	13.54	30-100	100%	-	-	-	-
Iron	ppm	0.85	ND	0.00	0.03	0.10	6.46	49.82	0.3-1.0	100%	2	100%	-	-
Carbonate	ppm	ND	ND	-	-	-	-	-	-	-	-	-	-	-
HCO_3	ppm	293.00	3.00	23.00	34.49	44.83	4.60	23.74	200	98%	-	-	OW 71, 74	80, 83
Chloride	ppm	149.50	4.90	13.00	19.97	21.62	3.89	17.78	250-1000	100%	250	100%	-	-
Sulphate	ppm	56.64	0.29	6.22	7.99	8.18	3.61	16.40	200-400	100%	500	100%	-	-
Nitrate	ppm	63.14	ND	0.56	3.78	9.72	4.69	24.29	45-100	100%	50	98%	OW 26, 62	29, 69
Ca-Hardness	ppm	176.00	2.00	11.00	20.43	31.53	3.71	14.04	-	-	-	-	-	-
Mg-Hardness	ppm	58.00	1.00	5.00	7.89	9.16	3.30	13.54	-	-	-	-	-	-
Tot. Hardness	ppm	234.00	3.50	18.00	28.27	37.83	3.58	14.08	300-600	100%	-	-	-	-
Fluoride	ppm	0.76	ND	0.07	0.17	0.21	1.71	1.49	1.0-1.5	100%	0.6-1.2	100%	-	87% samples <0.6

Table 4.24 Statistical analysis for the Hydrogeochemistry of Post-Monsoon (2009) Open well water samples from the study area with their compliance of drinking water standards

4.6.2.2 Post-Monsoon Hydrogeochemistry of the Bore wells: Iron content and turbidity have affected a good percentage of bore wells in the study area (Table 4.25). This may be attributed to the poor quality iron casing, and the improper well designing and construction.

Even though the hydrochemistry of groundwater is attained by the geochemistry of the aquifer or overlying rocks, it has not been greatly influenced except very limited parameters. Majority of the open well waters in the lateritic aquifers of the study area demonstrate low pH value indicating the acidic nature influenced by the laterites. The acidic nature of bore well waters which increased during the post-monsoon season might have been imparted due to the improper casing in the lateritic overburden. The turbidity and iron contents in the bore wells can also be attributed to the low quality and improper casing being adopted. A very few groundwater and surface water samples near to the coast and river have shown the influence of saline water intrusion.

Parameters	Unit	Maxi-mum	Mini-mum	Median	Mean (10 samples)	Std. Dev.	Skew-ness	Kurto-sis	BIS:10500 (1993)	%age Compli-ance	WHO (1993)	%age Compli-ance	Samples Beyond Permissible Limit	
													Source Nos. BW	Sample Numbers & Remarks
Temperature	°C	32	29	30.5	30.4	0.97	-0.12	-0.62	-	-	-	-	-	-
pH		7.93	6.02	6.79	6.86	0.67	0.44	-1.15	6.5-8.5	60%	7.0-8.5	50%	BW 2, 3, 5, 6 &7	3, 10, 40, 44, 50. All Acidic
DO	ppm	7.20	3.30	5.70	5.65	1.25	-0.54	-0.36	-	-	-	-	-	-
BOD	ppm	1.00	0.19	0.65	0.59	0.32	-0.20	-1.84	-	-	-	-	-	-
Turbidity	NTU	80.50	2.10	9.25	29.56	33.00	0.75	-1.37	5.0-10.0	50%	5	40%	BW2, 3, 5, 6, 9,10	3, 10, 40, 44, 75, 93
EC	mμS/cm	343.75	103.13	214.06	209.38	68.89	0.45	0.36	2000	100%	-	-	-	-
TDS	ppm	220.00	66.00	137.00	134.00	44.09	0.45	0.36	500-2000	100%	1000	100%	-	-
Sodium	ppm	37.40	5.90	14.50	16.53	10.49	1.08	0.41	200-600	100%	200	100%	-	-
Potassium	ppm	11.60	3.90	6.90	7.78	2.82	0.29	-1.58	200-600	100%	-	-	-	-
Alkali	ppm	42.90	9.80	23.50	24.31	11.61	0.40	-1.12	200-600	100%	-	-	-	-
Calcium	ppm	39.20	2.00	12.60	16.20	11.67	0.95	0.38	75-200	100%	500	100%	-	-
Magnesium	ppm	19.44	1.84	7.29	8.08	5.00	1.26	2.29	30-100	100%	-			
Iron	ppm	2.92	ND	0.86	0.99	0.95	0.90	0.26	0.3-1.0	60%	2	90%	BW 2, 5, 6, 10	3, 40, 44, 93
Carbonate	ppm	ND	ND	-	-	-	-	-	-	-	-	-	-	-
HCO_3	ppm	167.00	43.00	101.00	100.70	38.41	0.11	-0.68	200	100%	-	-	-	-
Chloride	ppm	124.50	6.49	9.00	22.82	36.42	2.96	8.96	250-1000	100%	250	100%	-	-
Sulphate	ppm	20.44	0.72	9.09	10.60	5.96	0.37	0.06	200-400	100%	500	100%	-	-
Nitrate	ppm	2.74	ND	0.24	0.88	1.10	0.75	-1.30	45-100	100%	50	100%	-	-
Ca-Hardness	ppm	98.00	4.92	31.50	40.49	29.19	0.95	0.38	-	-	-	-	-	-
Mg-Hardness	ppm	80.00	7.58	30.00	33.26	20.57	1.26	2.29	-	-	-	-	-	-
Tot. Hardness	ppm	145.00	12.50	60.50	73.75	42.84	0.29	-0.96	300-600	100%	-	-	-	-
Fluoride	ppm	1.13	0.03	0.18	0.36	0.38	1.44	0.86	1.0-1.5	100%	0.6-1.2	100%	BW 1, 4, 5, 6, 7, 8, 9 & 10	80% samples <0.6ppm

Table 4.25 Statistical analysis for the Hydrogeochemistry of Post-Monsoon (2009) Bore well water samples from the study area with their compliance of drinking water standards

4.6.3 Physical Parameters: The appearance, taste, odour, and 'feel' of water determine its quality; other physical characteristics can suggest whether corrosion and encrustation are likely to be significant problems in pipes or fittings. Colour and turbidity influence the appearance of water. Taste can be influenced by temperature, Total Dissolved Solids (TDS) and pH. The 'feel' of water can be affected by pH, temperature and hardness. Rates of corrosion and encrustation (scale build-up) of pipes and fittings are affected by pH, temperature, hardness, TDS and dissolved oxygen. Electrical Conductance (EC) depends on the dissolved salts which in turn influence the taste of the water.

4.6.3.1 Temperature: Temperature to a great extent determines the trends and tendencies of changes in water quality. Seasonal pattern and climatic condition influence the temperature of the water. The source and processes the water has undergone also influence the temperature of the water. Generally groundwater is cooler than surface water. Temperature affects the ion and phase equilibrium and influences rates of biological activity and biochemical processes. As a result, changes may occur in the concentration and content of organic and mineral substances in water. High temperature stimulates the growth of plankton and accelerates the biodegradation of organic materials and may increase taste, odour, colour and corrosion problems. The desirable temperature of water for domestic uses, particularly for drinking has no standards and is highly subjective with local influences. Cool water is generally more potable than warm water and contains more dissolved oxygen. High water temperature enhances the growth of microorganisms

The mean temperature of the open wells in the study area during pre-monsoon seasons found to be around 28°C with a varying range of 22°C to 35°C (Tables 4.20 & 4.21, Figs. 4.11 & 4.12), whereas during post-monsoon it is around 29°C with a range varying between 26°C to 33°C (Table 4.24, Fig. 4.13). The bore well waters found to have a mean temperature of around 29°C during both seasons with a range varying between 25°C to 32°C during pre-monsoon (Table 4.22, Fig. 4.18) and 26°C to 33°C during post-monsoon periods (Table 4.25, Fig. 4.14). The surface water sources show a mean temperature of around 31°C with a varying range of 28°C to 34°C during the pre-monsoon period (Table 4.23, Fig. 4.20). There is not much variation in temperature during the different seasons and the sources, even though a higher temperature is recorded for surface water sources compared to groundwater sources in the study area. The range of variation in temperature may be due to the influence of weather conditions during collection time. No relationship is established between other parameters.

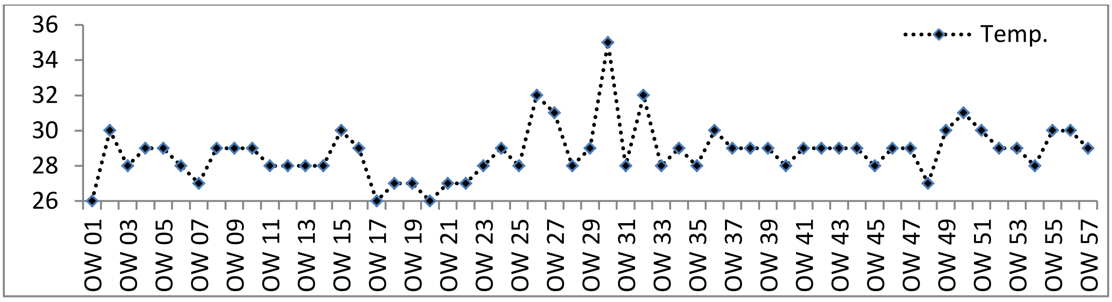

Fig. 4.11 Showing Temperature variation in Pre-Monsoon (2008) Open well water samples of the study area

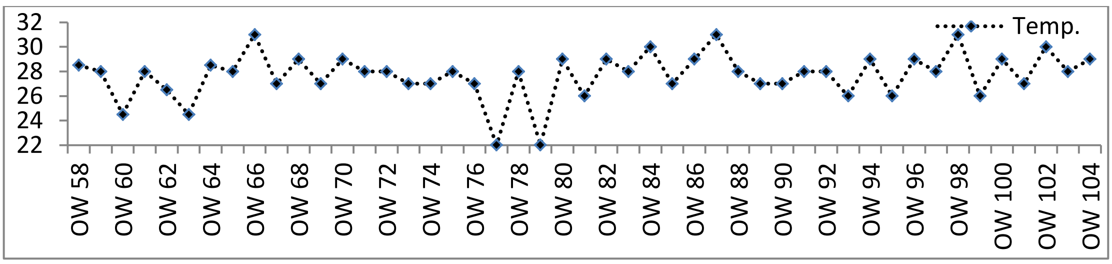

Fig. 4.12 Showing Temperature variation in Pre-Monsoon (2009) Open well water samples of the study area

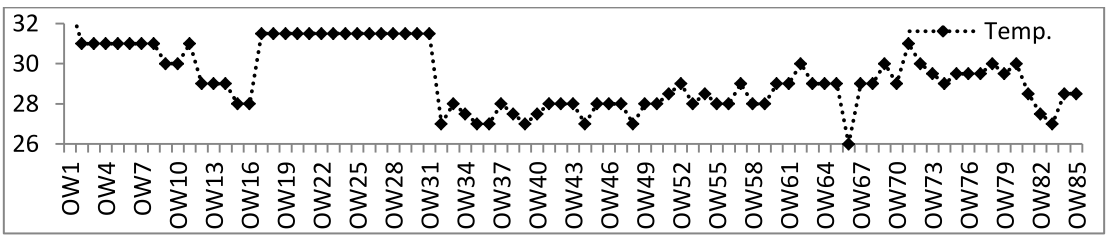

Fig. 4.13 Showing the temperature variation in the Post-Monsoon Open Well water samples of Mulki River basin during 2009

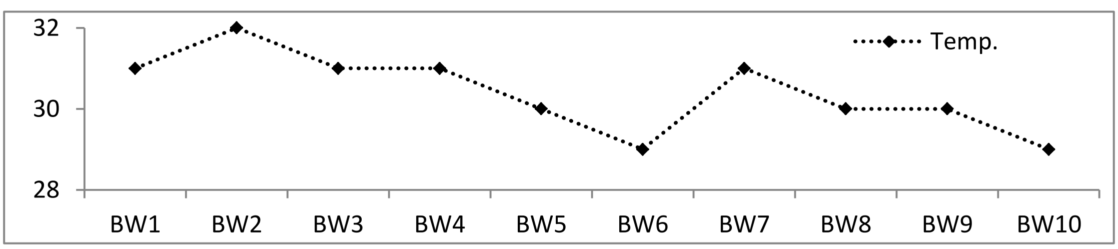

Fig. 4.14 Showing the Temperature variation in the Post-Monsoon Bore Well water samples of Mulki River basin during 2009

4.6.3.2 pH: It is the measure of the acidic or alkaline nature of water. It is technically defined as the negative logarithm, of the hydrogen ion activity or concentration expressed in moles per liter. It ranges from 0 to 14 where a pH of 7 is neutral. Pure water has a pH of 7.0, and other solutions are usually described with reference to this value. Variations in pH value from 7 are mainly due to hydrolysis of salts of strong bases and weak acids or vice versa in water. Water with a pH below 7 means there are more H^+ ions than OH^- ions in solution and the solution is regarded as acidic; while that with pH above 7 is regarded as alkaline or basic since there is an excess of OH^- ions. The pH influences the corrosiveness of the water, the amount of chemicals needed for proper disinfection, and ability of an analyst to detect contaminants.

pH of groundwater depends on several factors. The most important of which is regulated by the carbonate system (Stumm and Morgan 1970), which comprises carbon dioxide (CO_2), Carbonic acids (H_2CO_3), bicarbonate ions (HCO_3) and carbonate ions (CO_3). Dissolved gases such as hydrogen sulphide and ammonia also affect the pH of water. The overall pH range of natural water is generally between 6 and 8. Industrial wastes may be strongly acidic or basic and their effect on pH value of receiving water depends on the buffering capacity of water. pH lower than 4 will produce sour taste and higher value above 8.5 bitter taste. pH below 6.5 starts corrosion in pipes, thereby releasing toxic metals such as Zn, Pb, Cd, Cu, etc. Low-pH water will corrode or dissolve metals and other substances affecting the pumps and casing pipes of bore wells. The permissible limit is between 6.5 and 8.5 as per BIS:10500 (1993).

The mean pH of the open wells in the study area during pre-monsoon seasons found to be 6.43 with a range varying from 4.56 to 9.66 (Tables 4.20 & 4.21), whereas during post-monsoon it is around 5.80 with a range varying between 4.00 to 7.77 (Table 4.24). The bore well waters found to have a mean pH of 7.28 during pre-monsoon with a range varying from 6.15 to 8.30 (Table 4.22), whereas during post-monsoon it was around 6.86 average with a range varying from 6.02 to 7.93 (Table 4.25). The surface water sources show a mean pH of 6.66 with a range varying from 5.38 to 9.75 during the pre-monsoon period (Table 4.23).

During 2008 pre-monsoon, only 37% of the open well samples found to be in compliance with the BIS (Bureau of Indian Standards) drinking water standards whereas as per WHO guidelines the percentage of compliance is only 16%. Except an open well near Bappanadu temple (OW 50) which shows a pH of 9.66, all other contaminated sources are acidic in nature (Fig. 4.15). High pH causes a bitter taste; water pipes and water-using appliances become encrusted; depresses the effectiveness of the disinfection of chlorine, thereby causing the need for additional chlorine when pH is high.

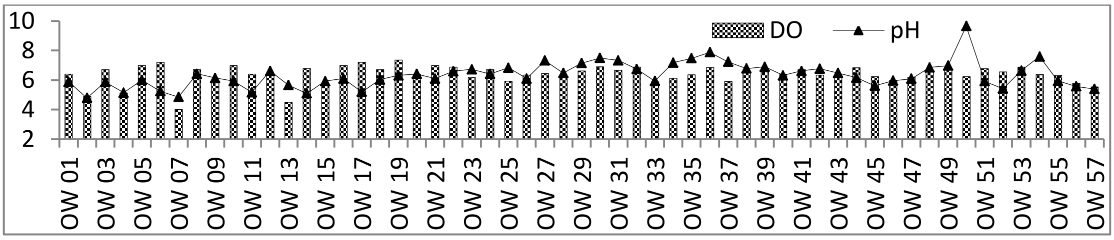

Fig. 4.15 showing the variation of pH and DO in the Pre-Monsoon (2008) Open Well water samples from the study area

During 2009 pre-monsoon, 60% of the open well samples found to be within BIS drinking water standards whereas only 23% samples found to be within the specifications of WHO standards. All the contaminated samples are of acidic in nature (Fig. 4.16).

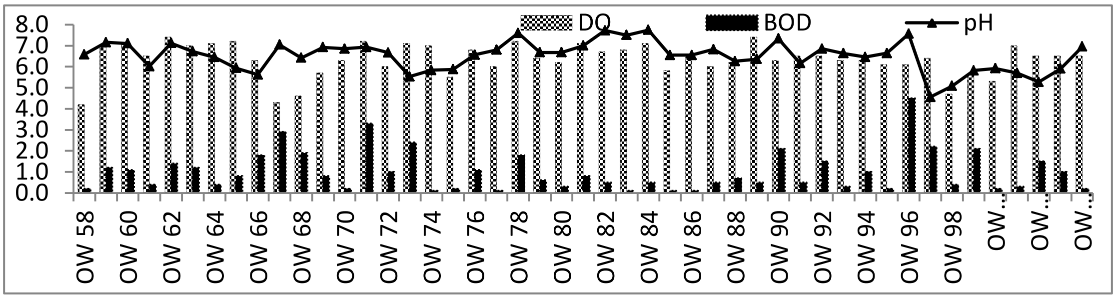

Fig. 4.16 showing the variation of pH, DO and BOD in the Pre-Monsoon (2009) Open Well Water samples from the study area

During 2009 post-monsoon, only 20% of the open well samples found to be within BIS drinking water standards whereas only 11% samples found to be within the specifications of WHO standards. All other samples are of acidic in nature (Fig. 4.17). The high acidic content of the water may cause corrosion of the pipes and duodenal problems in humans.

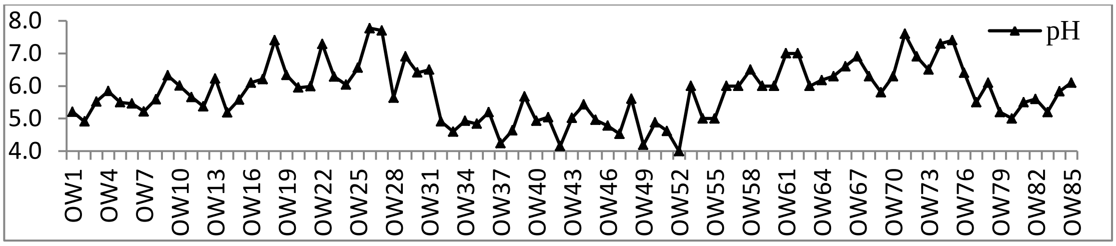

Fig. 4.17 showing pH variations in Post-Monsoon (2009) Open Well Groundwater Samples of the study area

During pre-monsoon, 93% of the bore well samples found to be within BIS drinking water standards whereas 81% samples comply with the specifications of WHO standards. All other samples are of acidic in nature (Table 4.22, Fig. 4.18).

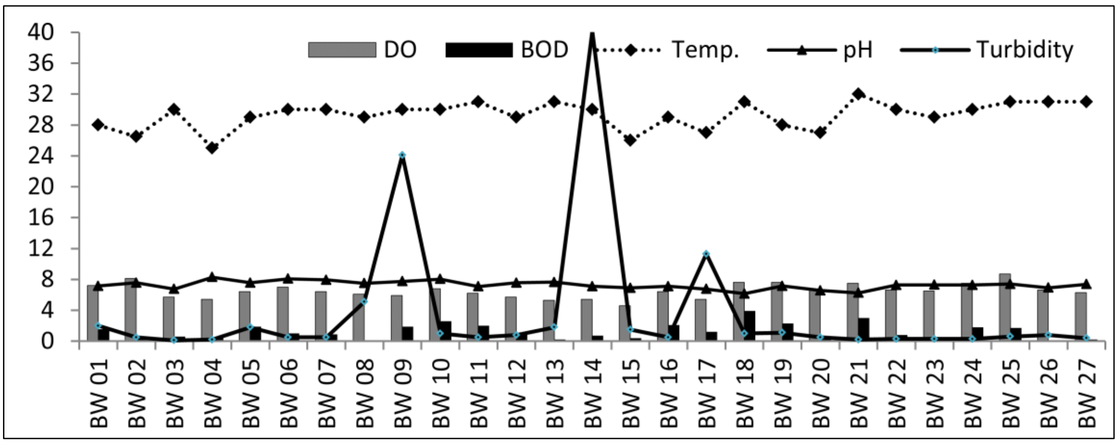

Fig. 4.18 showing the variation of pH, temperature, DO, BOD and turbidity in the Pre-Monsoon (2008 & 2009) Bore Well water samples from the study area

During post-monsoon, only 60% of the bore well samples found to be within BIS drinking water standards, whereas 50% samples comply with the specifications of WHO standards. All other samples are of acidic in nature (Table 4.25, Fig. 4.19).

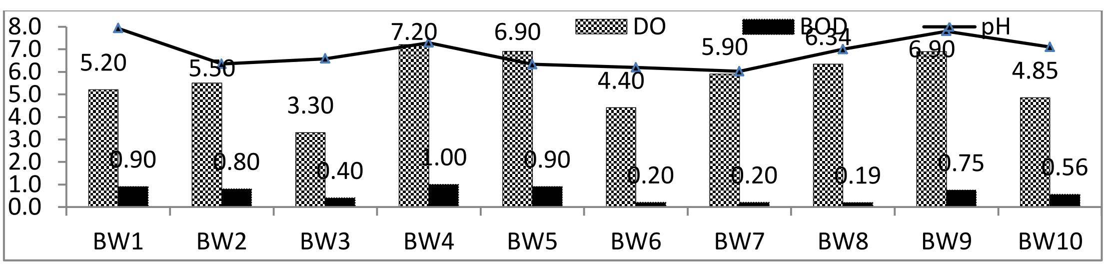

Fig. 4.19 showing pH, DO and BOD variations in Post-Monsoon (2009) Bore Well groundwater samples of the study area

During pre-monsoon, 30% of the surface water samples mainly from ponds and lakes found to be within BIS drinking water standards whereas 17% samples comply with the specifications of WHO standards. High pH above 8.5 has been noticed in two samples which are in near shore ponds in Kolachikambla and Mulki masjid where the influence of saltwater is existing (Fig. 4.5). Low pH below 6.5 has been noticed in fourteen surface water samples showing contamination and influence of lateritic terrain (Table 4.22, Fig. 4.20).

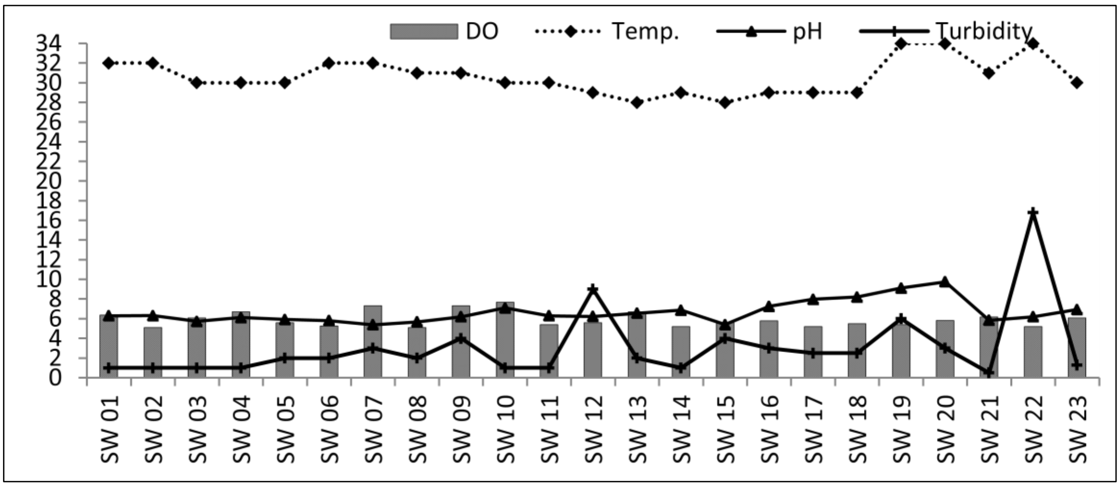

Fig.4.20 showing the pH variation in the 2008 & 2009 Pre-Monsoon surface water samples of Mulki river basin

It can be clearly seen that the study area is having waters of low pH value which is acidic in nature and in many cases it is below the prescribed limit for potable water. This can be attributed to the porous character of the laterite and acidic nature of lateritic soil through which the pollution causing solids and liquids enter the groundwater causing contamination (Sunil and Shrihari 2002). The study area is dominant with highly porous lateritic soil except the coast where the area is sandy. Most of the samples along the coastal stretch are having pH value less than 6.5. The clays present below the laterite cover captures and exchanges some elements and compounds that may be suspended in water. Other than this, the rainwater which is naturally acidic due to dissolution of atmospheric gases carries the pollutants when it falls on land and drained through the sewerage systems percolating them to groundwater.

<u>4.6.3.3 Turbidity</u>: Clarity of water is important in producing products destined for human consumption and in many manufacturing operations. Turbidity in water is the reduction of transparency caused by the presence of suspended matter such as clay, silt, finely divided organic and inorganic matter and other microscopic organisms.

These causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. The colloidal material exerts turbidity, provides adsorption sites for chemicals that may be harmful or cause undesirable tastes and odours. High levels of turbidity can protect micro-organisms from the effects of disinfection and can stimulate bacterial growth. In natural water bodies, turbidity may impart a brown or other colour to water and may interfere with light penetration and photosynthetic reaction in streams and lakes. The appearance of water with a turbidity of less than 5 Nephelometric Turbidity Units (NTU) is usually acceptable to consumers, although this may vary with local circumstances. The maximum permissible limit of Turbidity is 10 NTU (WHO 1993).

The mean turbidity of the open wells in the study area during pre-monsoon seasons is found to be about 1.92 NTU (Tables 4.20 & 4.21), whereas during post-monsoon it is around 2.25 NTU (Table 4.24). The bore well waters found to have a mean turbidity of around 3.62 NTU during pre-monsoon (Table 4.22) and 29.56 NTU during post-monsoon periods (Table 4.25). The surface water sources show a mean turbidity of around 3.07 NTU during the pre-monsoon period (Table 4.23).

4.6.3.3.1 Dug Wells and Springs (Pre-Monsoon): During 2008 pre-monsoon, all the 57 open well samples found to be in compliance with the BIS (Bureau of Indian Standards) and WHO drinking water standards; whereas during 2009 pre-monsoon it is about 98% samples which showed compliance with the drinking water standards (Tables 4.20 & 4.21). Only one open well sample at Sankalkaria (OW84) showed a high turbidity of 18.4 NTU which is beyond permissible limit (Table 4.21, Fig. 4.22)

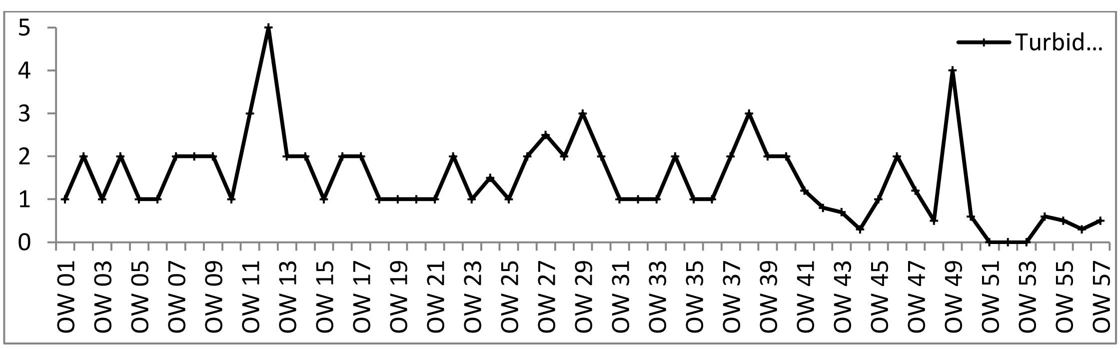

Fig. 4.21 showing Turbidity variations in Pre-Monsoon (2008) Open Well groundwater samples of the study area

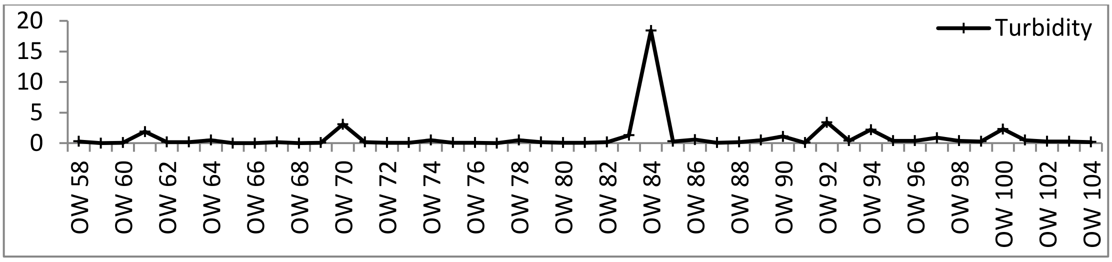

Fig. 4.22 showing Turbidity variations in Pre-Monsoon (2009) Open Well groundwater samples of the study area

4.6.3.3.2 Dug Wells and Springs (Post-Monsoon): During post-monsoon, 98% of the open well samples found to be in compliance with the BIS (Bureau of Indian Standards) drinking water standards whereas as per WHO guidelines the percentage of compliance is only 91% (Table 4.24). Except the wells at Kariangadi and Sampige all other sources are acceptable as per BIS (Fig. 2.23).

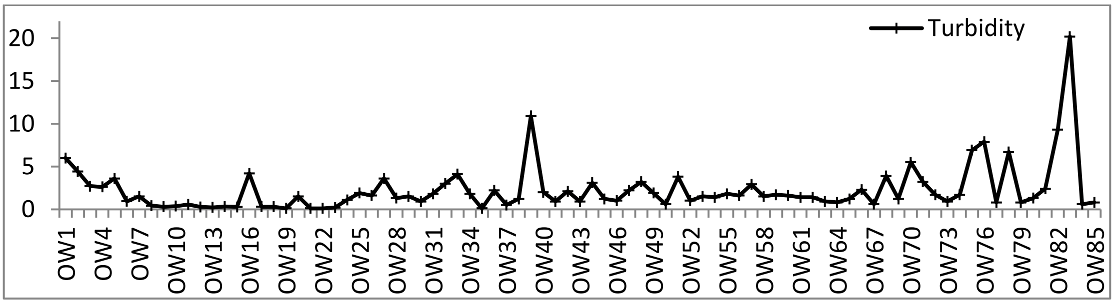

Fig. 4.23 showing Turbidity variation in Post-Monsoon Open well groundwater samples of the study area

4.6.3.3.3 Bore Wells (Pre-Monsoon): About 89% of the open well samples found to be in compliance with the BIS (Bureau of Indian Standards) drinking water standards whereas as per WHO guidelines the percentage of compliance is only 85% (Table 4.22). Bore wells BW09, BW14 & BW17 have very high turbidity (Fig. 4.18) indicating the improper casing of the bore wells and its contamination due to agitation of samples and iron contamination from the casing pipes.

4.6.3.3.4 Bore Wells (Post-Monsoon): About 50% of the open well samples found to be in compliance with the BIS (Bureau of Indian Standards) drinking water standards whereas as per WHO guidelines the percentage of compliance is only 40% (Table 4.22). Bore wells BW2, BW3, BW5, BW6 & BW10 have very high turbidity (Fig. 4.24) indicating the improper casing of the bore wells and its contamination due to iron and agitation of samples.

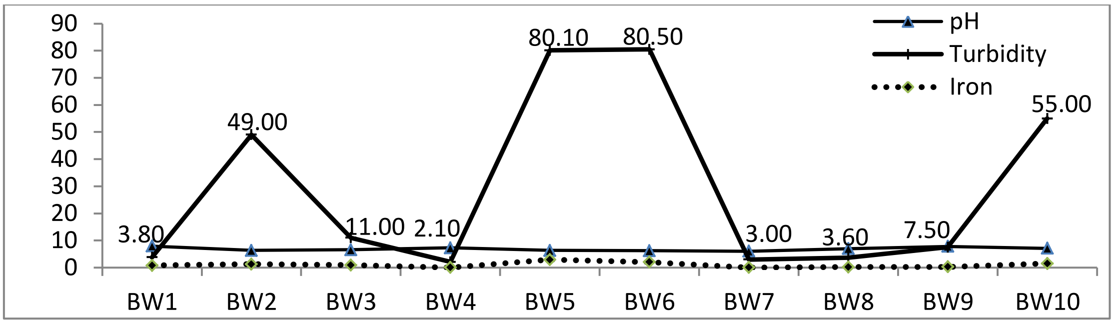

Fig. 4.24 showing Turbidity variation in Post-Monsoon Bore well groundwater samples of the study area and its relation to the Iron content and pH

4.6.3.3.5 Surface Water (Pre-Monsoon): About 96% of the surface water samples found to be in compliance with the BIS (Bureau of Indian Standards) drinking water standards whereas as per WHO guidelines the percentage of compliance is only 85% (Table 4.23). Madathakere near Karkala (SW22) found to have high turbidity (Fig. 4.25) indicating the presence of suspended matter such as clay, silt, finely divided organic and inorganic matter and other microscopic organisms in it. Turbid waters are non-aesthetic and are not accepted by consumers. Turbidity will also interfere in several treatment processes and will increase the consumption of chemicals.

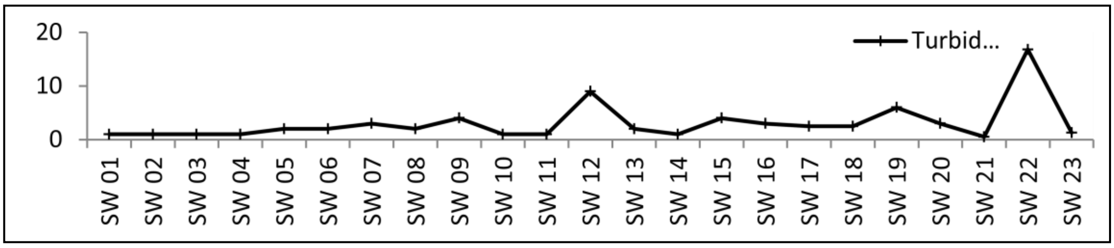

Fig. 4.25 showing Turbidity variations in Pre-Monsoon (2008 & 2009) Surface water samples of the study area

<u>4.6.3.4 Electrical Conductivity (EC):</u> Specific conductance or electrical conductance yields a measure of water's capacity to convey an electric current. This property is related to the total concentration of the ionized substances in water and the temperature at which the measurement is made. Usually the EC is reported at 25°C and expressed in the unit of µmhos/cm or µsiemens/cm. The nature of the various dissolved substances, their actual and relative concentrations, and the ionic strength of the water sample vitally affects the specific conductance.

The mean EC of the open wells in the study area during pre-monsoon seasons is found to be about 1012µmhos/cm (Tables 4.20 & 4.21), whereas during post-monsoon it is about 114μmhos/cm (Table 4.24). The bore well waters found to have a mean EC of about 377μmhos/cm during pre-monsoon (Table 4.22) and 209μmhos/cm during post-monsoon periods (Table 4.25). The surface water sources show a mean EC of about 4567 μmhos/cm during the pre-monsoon period (Table 4.23).

4.6.3.4.1 Dug Wells and Springs (Pre-Monsoon): During 2008 pre-monsoon, 89% of the open well water samples found to be in compliance with the BIS drinking water standards; whereas during 2009 all the samples are well within the acceptable limit of drinking water standards (Tables 4.20 & 4.21). The samples which showed EC beyond permissible limit (2000μmhos/cm) are all located near the coastal area such as Padupanambur, Karnad, Kolachikambla and Mulki which are influenced by the marine water (Fig. 4.26).

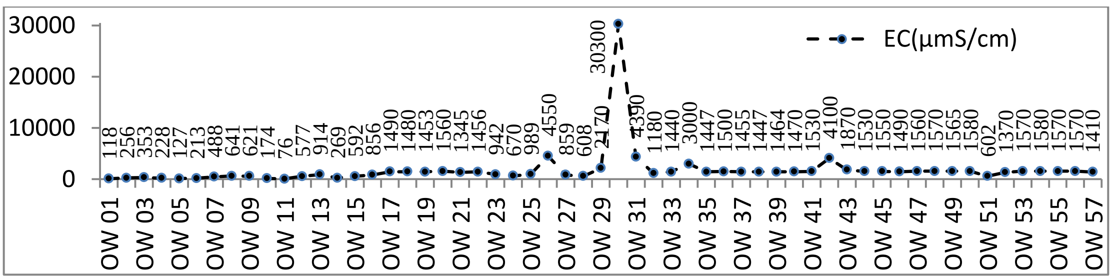

Fig. 4.26 showing the Electrical Conductance variation in the Pre-Monsoon (2008) Open Well water samples of Mulki River basin

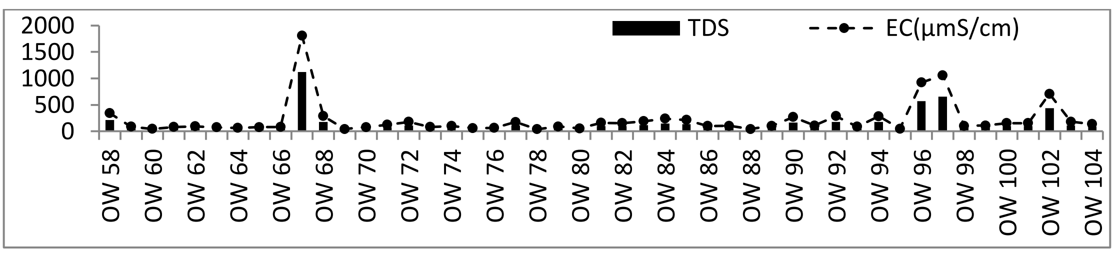

Fig. 4.27 showing the variation of Electrical Conductance and TDS in the Pre-Monsoon (2009) Open Well water samples of Mulki River basin

4.6.3.4.2 Dug Wells and Springs (Post-Monsoon): During 2009 post-monsoon, all the open well water samples were well within the permissible limit of BIS drinking water standards (Table 4.24, Fig. 4.28).

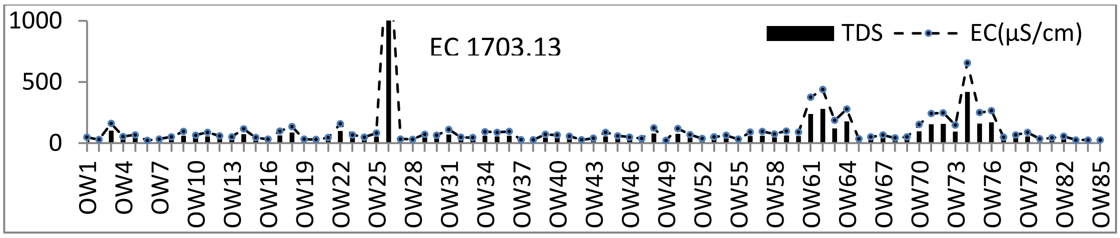

Fig. 4.28 showing the variation of Electrical Conductance and TDS in the Post-Monsoon (2009) Open Well water samples of Mulki River basin

4.6.3.4.3 Bore Wells: During the pre- and post-monsoon periods, all the bore well waters were well within the permissible limit of BIS drinking water standards (Tables 4.22 & 4.25, Figs. 4.29 & 4.30).

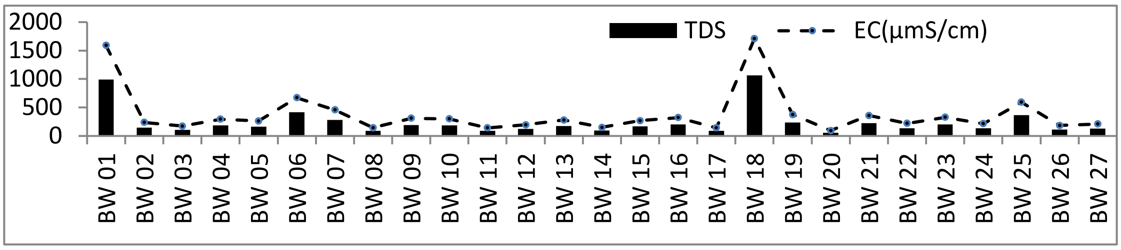

Fig. 4.29 showing the variation of Electrical Conductance and TDS in the Pre-Monsoon (2008 & 2009) Bore Well water samples of Mulki River basin

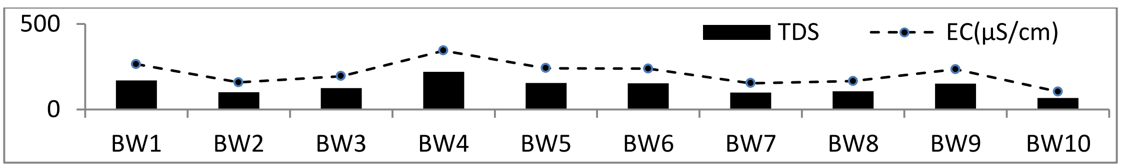

Fig. 4.30 showing the variation of Electrical Conductance and TDS in the Post-Monsoon (2009) Bore Well water samples of Mulki River basin

4.6.3.4.4 Surface Water (Pre-Monsoon): During 2008 pre-monsoon, 87% of the surface water sources found to be in compliance with the BIS drinking water standards; whereas three surface water bodies located at Padupanambur and Karnad found to have a high value of EC depicting the influence of the saline water in these stations (Fig. 4.32).

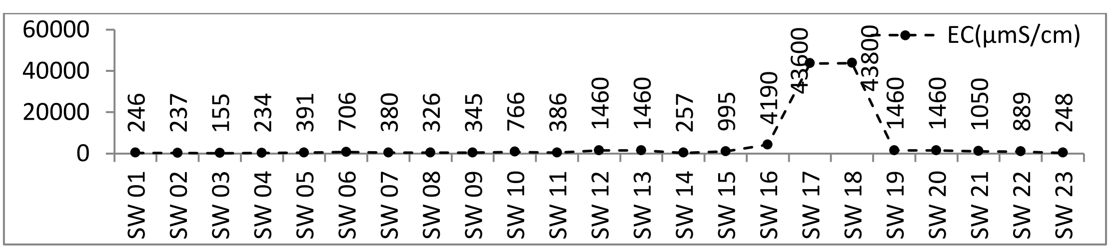

Fig. 4.32 showing EC variation in Pre-Monsoon Surface Water samples of the study area

4.6.3.5 Hardness: Hardness is a measure of the ability of water to cause precipitation of insoluble calcium and magnesium salts of higher fatty acids from soap solutions. Hardness of water is caused largely due to calcium and magnesium ions. Other cations may include iron, manganese, copper, strontium, aluminium, lead and zinc. Substances contributing to hardness may leach from soils or rocks naturally or the return flow from irrigation fields. Hardness can be classified in to two types- temporary hardness and permanent hardness. The temporary hardness is due to the presence of bicarbonates of calcium and magnesium. Permanent hardness is non-carbonate hardness and is caused due to the presence of sulphates, chlorides and nitrates of calcium and magnesium. Hardness is commonly expressed as equivalent concentration of calcium carbonate and is reported in terms of mg/l or ppm of $CaCO_3$.

The low and high value of Hardness has advantages and disadvantages. Absolutely soft water is tasteless. On the other hand, hardness up to 600 mg/l can be relished if got acclimatized to. Moderately hard water is preferred to soft water for irrigation purposes. Absolutely soft water is corrosive and dissolves the metals. Depending on pH and alkalinity, hardness above 200 mg/litre can result in scale deposition, particularly on heating. Soft waters with a hardness of less than about 100 mg/litre have a low buffering capacity and may be more corrosive to water pipes (WHO 1993). The mean hardness of the open wells in the study area during pre-monsoon seasons is found to be about 225 ppm (Tables 4.20 & 4.21), whereas during post-monsoon it is about 28ppm (Table 4.24). The bore well waters found to have a mean hardness of about 356ppm during pre-monsoon (Table 4.22) and 74ppm during post-monsoon periods (Table 4.25). The surface water sources show a mean hardness of about 1073ppm during the pre-monsoon period (Table 4.23).

4.6.3.5.1 Dug Wells and Springs (Pre-Monsoon): During 2008 pre-monsoon, 95% of the open well samples found to be in compliance with the BIS drinking water standards; whereas during 2009, it is 98% of the samples that are well within the acceptable limit of drinking water standards (Tables 4.20 & 4.21). The samples which showed hardness beyond permissible limit (600ppm) are all located near the coastal area such as Karnad (OW30), Kolachikambla (OW37), Padubidri (OW54) and Bappanadu (OW98) which are influenced by the marine water (Fig. 4.33 & Fig. 4.34).

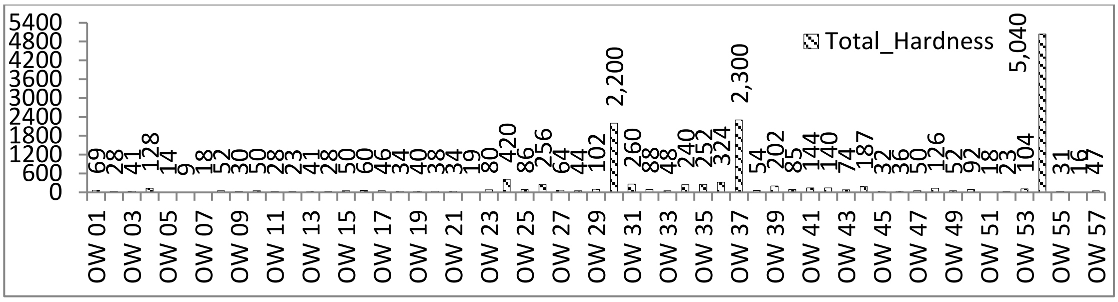

Fig. 4.33 showing the variation of Total Hardness in the Pre-Monsoon (2008) Open Well water samples of Mulki River basin

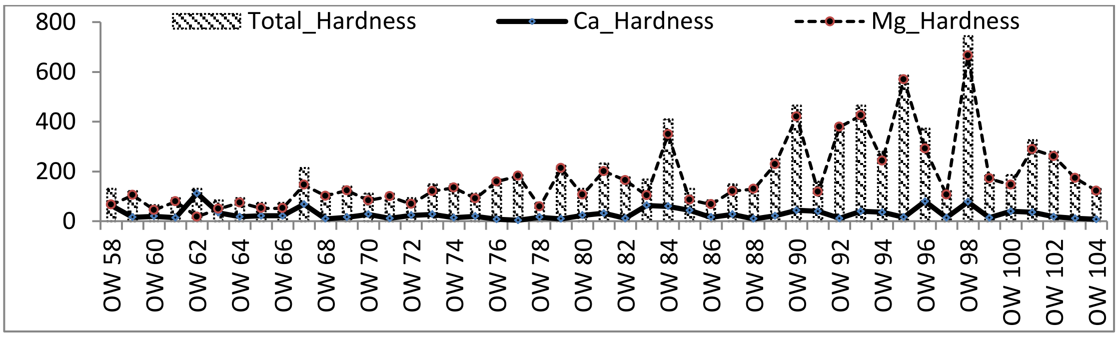

Fig. 4.34 showing the variation of Hardness in the Pre-Monsoon (2009) Open Well water samples of Mulki River basin

4.6.3.5.2 Dug Wells and Springs (Post-Monsoon): During 2009 post-monsoon, all the open well water samples were well within the permissible limit of BIS drinking water standards (Table 4.24, Fig. 4.35). In majority of the cases Calcium hardness is more than Magnesium hardness in these samples.

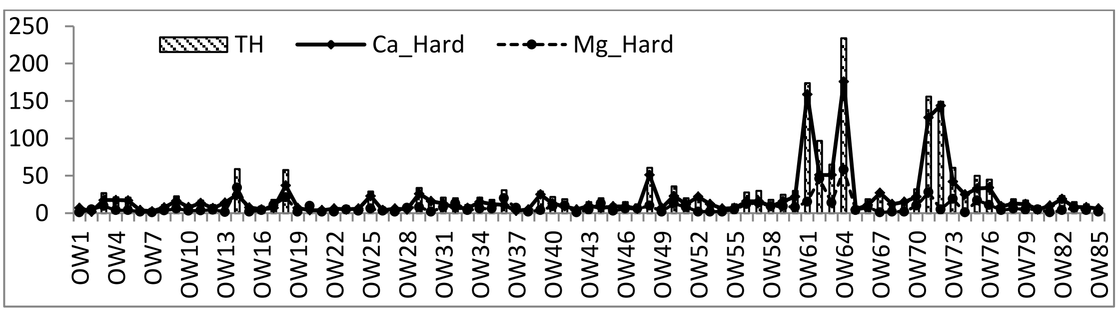

Fig. 4.35 showing the variation of Hardness in the Post-Monsoon (2009) Open Well water samples of Mulki River basin

4.6.3.5.3 Bore Wells: During the pre- and post-monsoon periods, all the bore well waters were well within the permissible limit of BIS drinking water standards except a pre-monsoon sample at Punaroor (BW21) (Tables 4.22 & 4.25, Figs. 4.36 & 4.37).

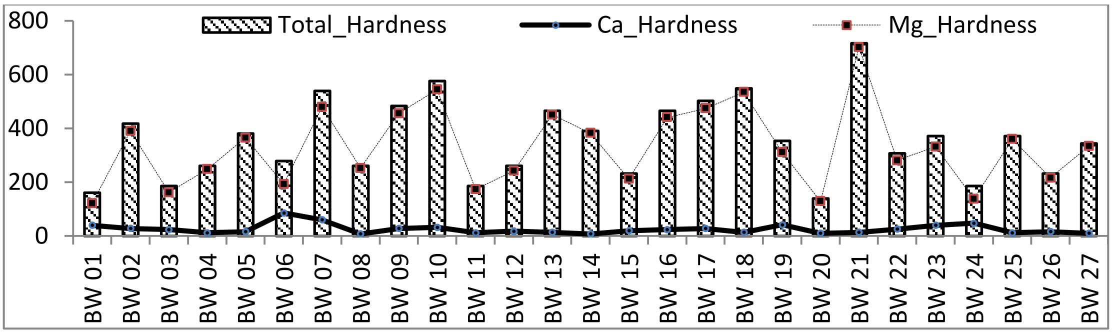

Fig. 4.36 showing the variation of Hardness in the Pre-Monsoon (2008 & 2009) Bore Well water samples of Mulki River basin

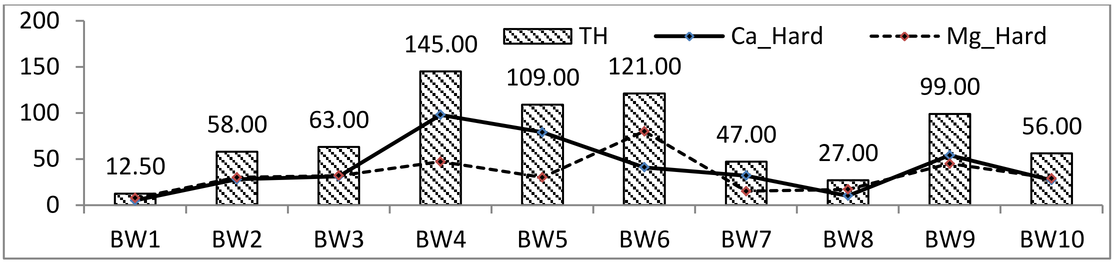

Fig. 4.37 showing the variation of Hardness in the Post-Monsoon (2009) Bore Well water samples of Mulki River basin

4.6.3.5.4 Surface Water (Pre-Monsoon): During 2008 pre-monsoon, 83% of the surface water sources found to be in compliance with the BIS drinking water standards; whereas four surface water bodies located at Karnad (OW17 & OW18), Kolachikambla (OW19) and Mulki mosque (OW20) found to have a high value of EC depicting the high influence of the coastal saline water intrusion in these stations (Fig. 4.32).

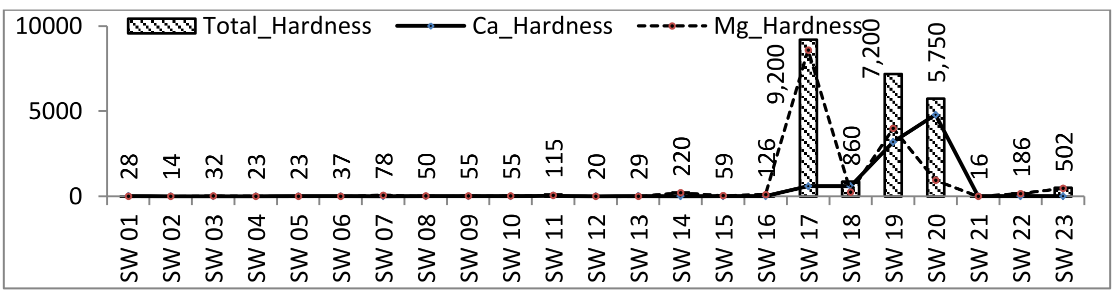

Fig. 4.38 showing the variation of Hardness in the Pre-Monsoon (2008 & 2009) Surface water samples of Mulki River basin

4.6.4 Chemical Parameters: The chemical processes involved during the interaction of water with soil and rocks of the area introduce major ions in the water changing the water quality with respect to space and time. The quality of groundwater depends upon the characteristics and type of the subsurface soil and nature of recharge water.

Groundwater being the major component of water systems in domestic, industrial and agricultural sectors, its quality is having a direct impact on the quality of human health and the agricultural yield. A number of chemicals, both organic and inorganic, including some pesticides, are of concern in drinking water from the health perspective because they are toxic to humans and can also affect the aesthetic quality of water (CPCB 2008). Inorganic chemicals in drinking water usually occur as dissolved salts. Organic compounds are usually present in drinking water in very low concentrations which might have been introduced either naturally or as a result of human activities. Important chemical parameters are discussed below:

4.6.4.1 Dissolved Oxygen (DO): The dissolved oxygen content of water is influenced by the raw water temperature, composition, treatment, and any chemical or biological processes taking place in the distribution system. The major inputs of dissolved oxygen to natural water are from atmosphere and photosynthetic reaction. Where the algae and phytoplankton production is high, the saturation of oxygen can occur during day time. Depletion of dissolved oxygen in water supplies can encourage the microbial reduction of nitrate to nitrite and sulphate to sulphide, giving rise to odour problems. It can also cause an increase in the concentration of ferrous iron in solution. However, the dissolved oxygen content substantially lower than the saturation concentration may be indicative of poor water quality. A minimum DO of 4 to 5 mg/l is desirable for the survival of aquatic life; higher values of DO may cause corrosion of iron and steel. Drinking water should be rich in DO concentration for good taste.

The mean Dissolved Oxygen content of the open wells in the study area during pre-monsoon seasons is found to be about 6.37ppm with a range varying from 4ppm to 7.4ppm (Tables 4.20 & 4.21, Figs. 4.15 & 4.16), whereas during post-monsoon it is about 5.55ppm with a range varying between 0.56 to 9.13ppm (Table 4.24, Fig. 4.39). The bore well waters found to have a mean DO of about 6.50ppm during pre-monsoon with a range varying between 4.60 to 8.70ppm (Table 4.22, Fig. 4.18) and 5.65ppm with 3.30ppm to 7.20ppm during post-monsoon periods (Table 4.25, Fig. 4.19). The surface water sources show a mean DO of about 5.93ppm with a varying range of about 5.10 to 7.68ppm during the pre-monsoon period (Table 4.23, Fig. 4.20). This shows that the water in the study area is rich in dissolved oxygen content and is all within the desirable range for survival of aquatic life as well as for drinking water needs.

<u>4.6.4.2 Biochemical Oxygen Demand (BOD)</u>: The dissolved oxygen present in water is mainly used for dissociating the organic materials present in it, especially when it is charged with sewage or organic pollutants. All of the oxygen demand in water is used mainly for the carbonaceous organic material usable as a source of food by aerobic organisms and is determined by biochemical oxygen demand test. It is determined by the variation in DO concentration during and after the incubation period of 5 days with a specific temperature of 20°C. The BOD will give idea about the potability of water and level of organic or nitrogenous pollution.

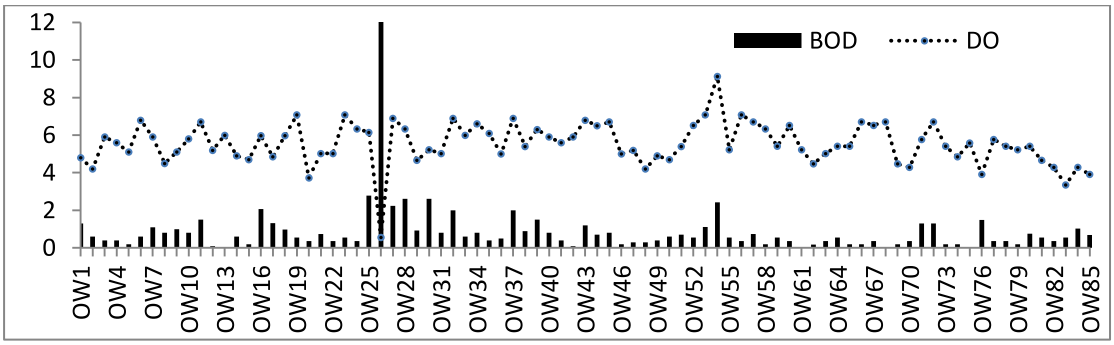

Fig. 4.39 showing the variation of DO and BOD in the Post-Monsoon (2009) Open Well water samples of Mulki River basin

The mean BOD content of the open wells in the study area during pre-monsoon seasons is found to be about 1ppm with a range varying from 0.10ppm to 4.50ppm (Table 4.21, Fig. 4.16), whereas during post-monsoon it is about 1.94ppm with a range varying between non detectable to 102ppm (Table 4.24, Fig. 4.39). The bore well waters found to have a mean DO of about 1.24ppm during pre-monsoon with a range varying between 0.10 to 3.90ppm (Table 4.22, Fig. 4.18) and 0.59ppm with 0.19ppm to 1.00ppm during post-monsoon periods (Table 4.25, Fig. 4.19). The very low DO of about 0.56ppm and the very high biochemical oxygen demand (BOD) of about 102ppm detected at an open well at Kariakkal (OW26) near Karkala during post-monsoon indicate the leach pit contamination of the well from the nearby hostel indicating the poor sanitary precaution in the study area. Most of the leach pits in the study area with the highly porous laterite bedrock overlying the granite are constructed without much leak proof facilities making them to the worst situation of contamination.

4.6.4.3 Total Dissolved Solids (TDS)**:** In natural waters, dissolved solids consists mainly of inorganic salts such as carbonates, bicarbonates, chlorides, sulphates and nitrates of cations such as calcium, magnesium, sodium, potassium, iron etc. and small amount of organic matter and dissolved gases. Many dissolved substances are undesirable in water. Dissolved minerals, gases and organic constituents may produce aesthetically displeasing colour, taste and odour. Some dissolved organic chemicals may deplete the dissolved oxygen in the receiving waters and some may be inert to biological oxidation. Water with higher solids content often has a laxative and sometimes the reverse effect upon people whose bodies are not adjusted to them. High dissolved solids concentration of about 3000 mg/l may produce distress in livestock.

Total dissolved solids (TDS) can have an important effect on the taste of drinking water. The palatability of water with a TDS level of less than 600 mg/litre is generally considered to be good; drinking water becomes increasingly unpalatable at TDS levels greater than 1200 mg/litre. Water with extremely low concentrations of TDS may be unacceptable because of its flat, insipid taste. The presence of high levels of TDS may also be objectionable to consumers owing to excessive scaling in water pipes, heaters, boilers, and household appliances. Water with concentrations of TDS below 1000 mg/litre is usually acceptable to consumers, although acceptability may vary according to local circumstances.

The mean TDS content of the open wells in the study area during pre-monsoon seasons found to be about 629ppm (Tables 4.20 & 4.21, Figs. 4.40 & 4.27), whereas during post-monsoon it is about 72ppm (Table 4.24, Fig. 4.28). The bore well waters found to have a mean TDS of about 234ppm during pre-monsoon (Table 4.22, Fig. 4.29) and 134ppm during post-monsoon periods (Table 4.25, Fig. 4.30). The surface water sources show a mean TDS of about 2,836ppm during the pre-monsoon period (Table 4.23, Fig. 4.41).

4.6.4.3.1 Dug Wells and Springs (Pre-Monsoon): Majority of the pre-monsoon dug well water samples are found to be well within the permissible limit of BIS drinking water standards except those samples collected from Padupanambur, Karnad and Mulki Bus stand during 2008 (Fig. 4.40).

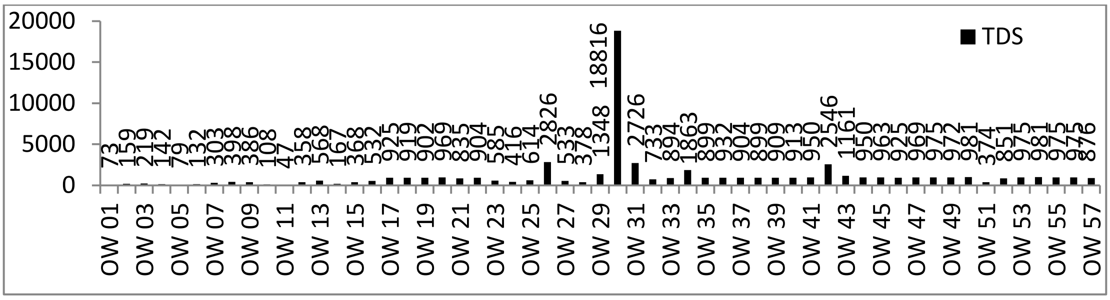

Fig. 4.40 showing TDS variation in the Pre-Monsoon (2008) Open Well water samples of the study area

4.6.4.3.2 Dug Wells and Springs (Post-Monsoon): All the samples found to be well within the permissible limit of BIS drinking water standards whereas only one sample from Kariyakal (OW26) near Karkala found to be beyond the specification of WHO standards (Table 4.24, Fig. 4.28).

4.6.4.3.3 Bore Wells (Pre- & Post-Monsoon): All the bore well water samples found to be in compliance with the BIS drinking water standards whereas only one sample from Padubidri (BW18) during pre-monsoon found to be beyond the maximum permissible limit of the WHO standard (Table 4.22, Fig. 4.29).

4.6.4.3.4 Surface Water samples: Majority of the samples (87%) found to be in compliance with the BIS and WHO drinking water standards except those in a pond at Padupanambur (SW16) and in two lakes (OW17 & OW18) at Karnad (Table 4.23, Fig. 4.41). The influence and interaction of tidal water from the sea can be observed in these lakes.

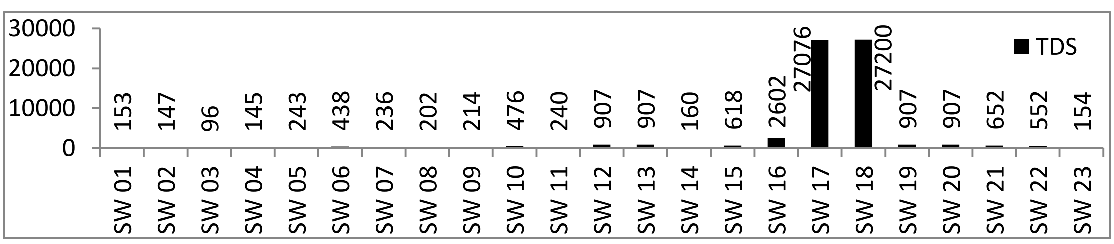

Fig. 4.41 showing TDS variation in the Pre-Monsoon (2008 & 2009) Surface water samples of the study area

A general classification of the groundwater samples collected from the study area during pre- and post-monsoon has been carried out and three categories of water have been identified (*after* Carroll 1962). From this analysis (Table 4.26) it could be understood that, except one sample at Kariyakkal (OW26- brackish) all the groundwater samples of the post-monsoon period are well within the permissible limit of drinking water standards and are of fresh water category. During pre-monsoon, majority of the samples (92%) are of fresh water category whereas 6% of the samples fall in the brackish water category and three samples (2%) collected from Karnad comprising OW30, SW17 and SW18 in the saline category.

Category of water	TDS (mg/L)	Post-Monsoon Samples (2009)			Pre-Monsoon samples (2008 & 2009)			
		(%) Samples	Total Number of Samples		(%) Samples	Total Number of Samples		
			OW (85)	BW (10)		OW (104)	BW (27)	SW (23)
Fresh Water	0-1000	99%	84	10	92%	96	26	20
Brackish	1000-10,000	OW26	1	-	6%; OW26, 29, 31, 34, 42, 43 & OW67 BW18; SW16	7	1	1
Saline	10,000-1,00,000	-	-	-	2%; OW30; SW17, SW18	1	-	2
Brine	>1,00,000	-	-	-		-	-	-

Table 4.26 General Classification of groundwater samples of the study area according to TDS (*after* Carroll 1962)

High values of TDS in groundwater are generally not harmful to human beings but high concentration of these may affect persons, who are suffering from kidney and heart diseases. Water containing high solids may cause laxative or constipation effects.

<u>4.6.4.4 Sodium:</u> The taste threshold concentration of sodium in water depends on the associated anion and the temperature of the solution. At room temperature, the average taste threshold for sodium is about 200 mg/litre. Sodium salts (e.g. sodium chloride) are found in virtually all food (the main source of daily exposure) and drinking water. Although concentrations of sodium in potable water are typically less

than 20 mg/litre, they can greatly exceed this in some countries. The levels of sodium salts in air are normally low in relation to those in food or water. It should be noted that some water softeners can add significantly to the sodium content of drinking water. No firm conclusions can be drawn concerning the possible association between sodium in drinking water and the occurrence of hypertension. Therefore, no health-based guideline value is proposed. However, concentrations in excess of 200 mg/litre may give rise to unacceptable taste.

The mean sodium content of the open wells in the study area during pre-monsoon seasons found to be about 20ppm (Tables 4.20 & 4.21, Figs. 4.42 & 4.43), whereas during post-monsoon it is about 15ppm (Table 4.24, Fig. 4.44). The bore well waters found to have a mean sodium content of about 28ppm during pre-monsoon (Table 4.22, Fig. 4.45) and 16.53ppm during post-monsoon periods (Table 4.25, Fig. 4.46). The surface water sources show mean sodium content of about 29.75ppm during the pre-monsoon period (Table 4.23, Fig. 4.47).

All the groundwater samples were found to be within 200ppm with an average sodium content of about 20ppm well within the drinking water standards without giving any unacceptable salty taste. Only one pre-monsoon surface water sample in a pond (SW19) at Kolachikambla found to have a higher sodium content of about 388.70ppm (Fig. 4.47) which can be attributed to the saline water intrusion since it is near to the coast.

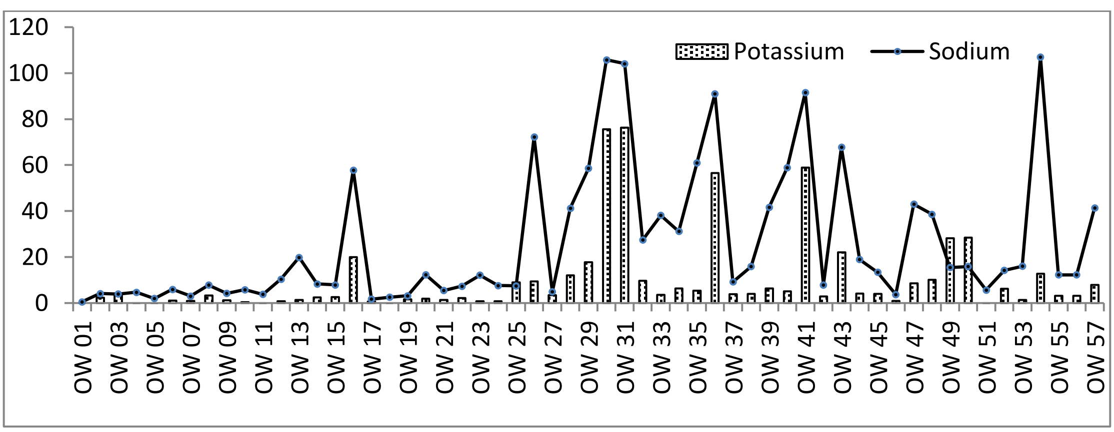

Fig. 4.42 showing Sodium and Potassium variation in the Pre-Monsoon (2008) Open Well water samples of the study area

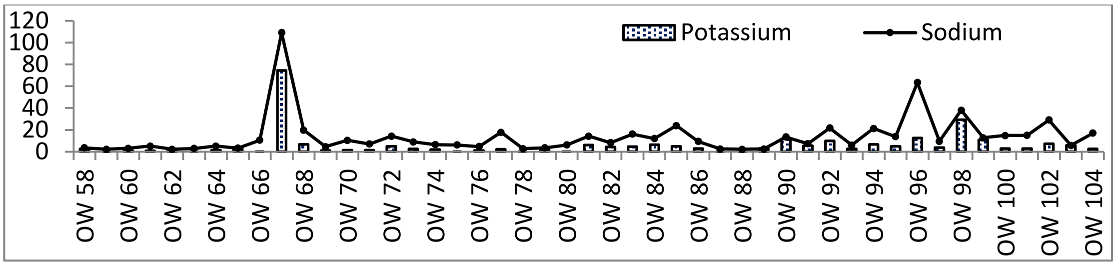

Fig. 4.43 showing Sodium and Potassium variation in the Pre-Monsoon (2009) Open Well water samples of the study area

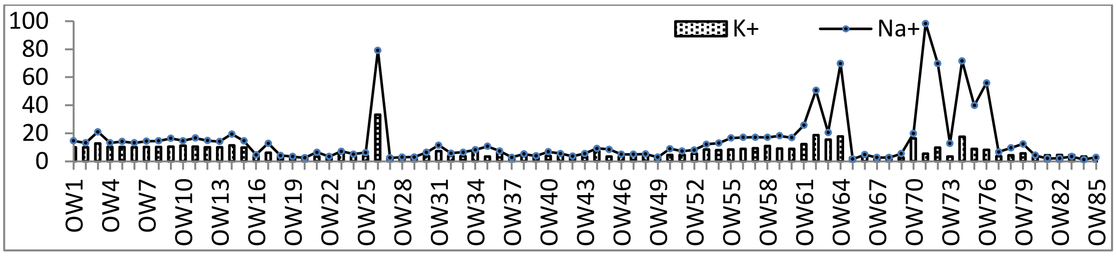

Fig. 4.44 showing Sodium and Potassium variation in the Post-Monsoon (2009) Open Well water samples of the study area

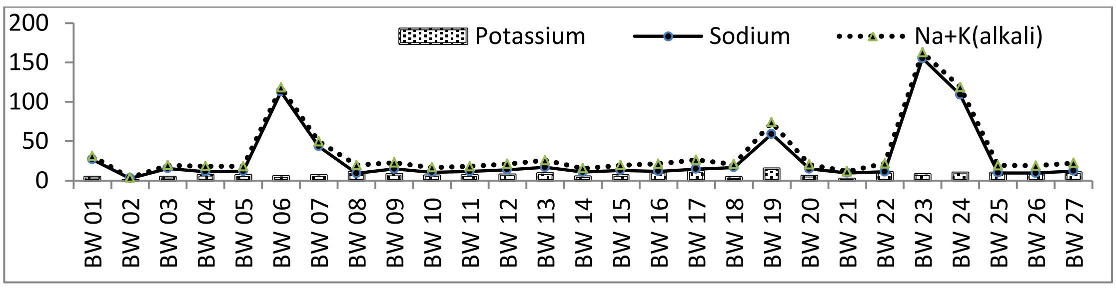

Fig. 4.45 showing Sodium and Potassium (alkali) variation in the Pre-Monsoon (2008 & 2009) Bore Well water samples of the study area

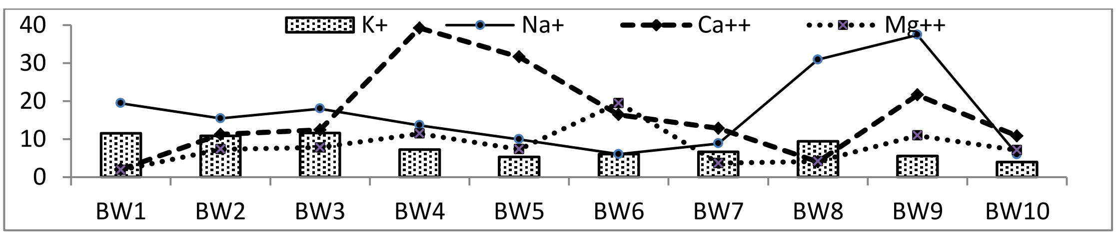

Fig. 4.46 showing Cations variations in the Post-Monsoon (2009) Bore Well water samples of the study area

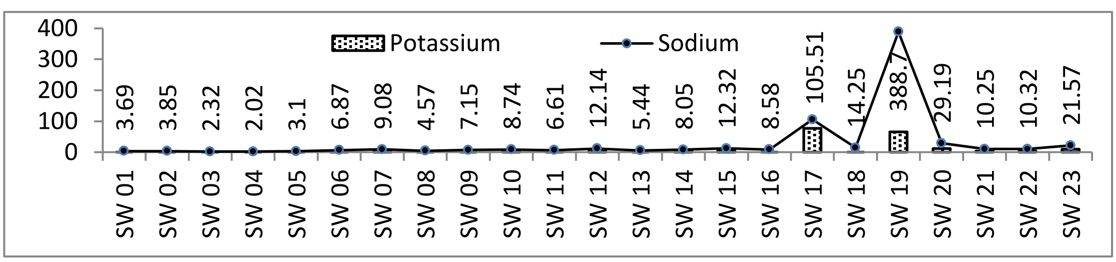

Fig. 4.47 showing Sodium and Potassium variation in the Pre-Monsoon (2008 & 2009) Surface Water samples of the study area

<u>4.6.4.5 Potassium</u>: Potassium is an essential element in plant, animal and human nutrition. It plays a critical role in many vital cell functions such as metabolism, growth, repair and volume regulation, as well as in the electric properties of the cell. It plays a key role in mediating the osmotic balance of the body fluids and is involved in the regulation of the acid-base balance of the body by affecting the kidney's ability to re-absorb bicarbonate the buffer to metabolic acids. Potassium levels generally found in drinking water are not a health concern, and there is no drinking water guideline proposed for potassium.

The mean potassium content of the open wells in the study area during pre-monsoon seasons found to be about 7.72ppm with a range varying from 0.03ppm to 76.29ppm (Tables 4.20 & 4.21, Figs. 4.42 & 4.43), whereas during post-monsoon it is about 6.98ppm with a range varying between 2.70ppm to 33.10ppm (Table 4.24, Fig. 4.44). The bore well waters found to have a mean potassium content of about 7.27ppm during pre-monsoon with a range varying between 0.65 to 14.97ppm (Table 4.22, Fig. 4.45) and 7.78ppm with 3.90ppm to 11.60ppm during post-monsoon periods (Table 4.25, Fig. 4.46). The surface water sources show mean potassium content of about 8.75ppm with a varying range of about 0.26 to 76.98ppm during the pre-monsoon period (Table 4.23, Fig. 4.47). All the groundwater samples were found to be within 80ppm with an average potassium content of about 7.70ppm.

<u>4.6.4.6 Calcium</u>**:** Calcium is a major constituent of various types of rock. It is one of the most common constituents present in natural waters ranging from zero to several hundred milligrams per liter depending on the source and treatment of the water. Calcium is a cause for hardness in water and incrustation in boilers.

The mean calcium content of the open wells in the study area during pre-monsoon seasons is found to be about 34ppm with a range varying from 1.60ppm to 1680ppm (Tables 4.20 & 4.21, Figs. 4.48 & 4.49), whereas during post-monsoon it is about 8.17ppm with a range varying between 0.80ppm to 70.40ppm (Table 4.24, Fig. 4.50). The bore well waters found to have a mean calcium content of about 10.22ppm during pre-monsoon with a range varying between 3.20 to 34.40ppm (Table 4.22, Fig. 4.51) and 16.20ppm with 2ppm to 39.20ppm during post-monsoon periods (Table 4.25,

Fig. 4.46). The surface water sources show mean calcium content of about 165.31ppm with a varying range of about 1.20 to 1920ppm during the pre-monsoon period (Table 4.23, Fig. 4.52). Except three pre-monsoon open well water samples from Karnad (OW30), Kolachikambla (OW37) and Padubidri coast (OW54) all the groundwater samples fall well within the permissible BIS and WHO drinking water standards. Majority of the surface water samples (83%) were found to be within the permissible limit of BIS drinking water standards except samples from Karnad (SW17 & SW18), Kolachikambla (SW19) and Mulki masjid (SW20).

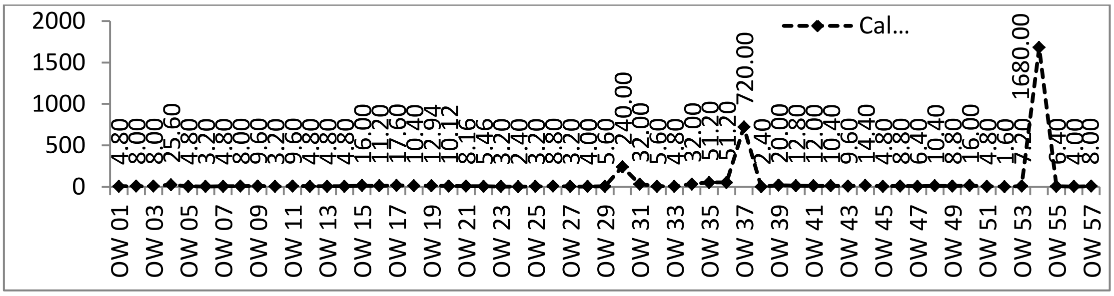

Fig. 4.48 showing Calcium variations in the Pre-Monsoon (2008) Open Well water samples of the study area

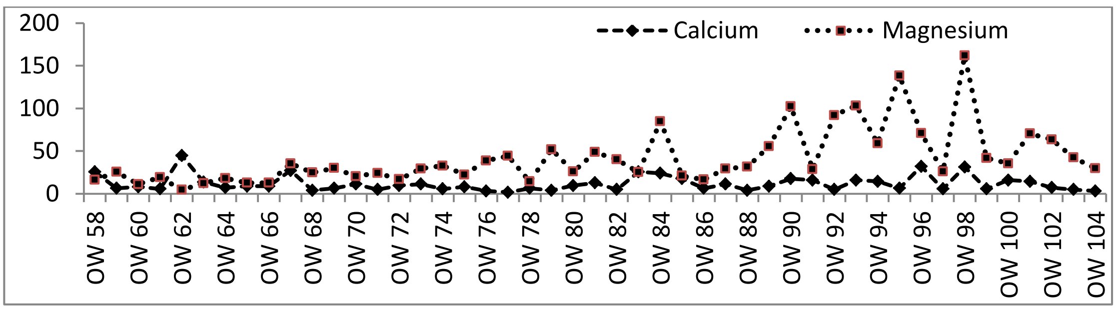

Fig. 4.49 showing Calcium and Magnesium variations in the Pre-Monsoon (2009) Open Well water samples of the study area

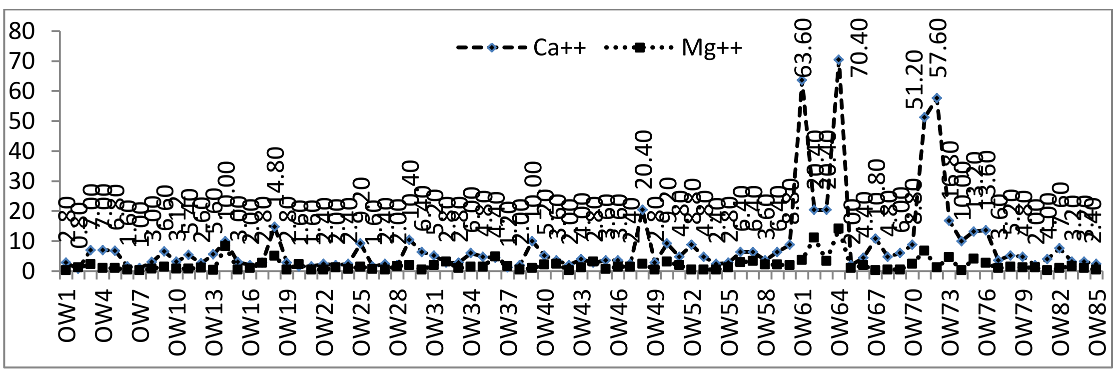

Fig. 4.50 showing Calcium and Magnesium variations in the Post-Monsoon (2009) Open Well water samples of the study area

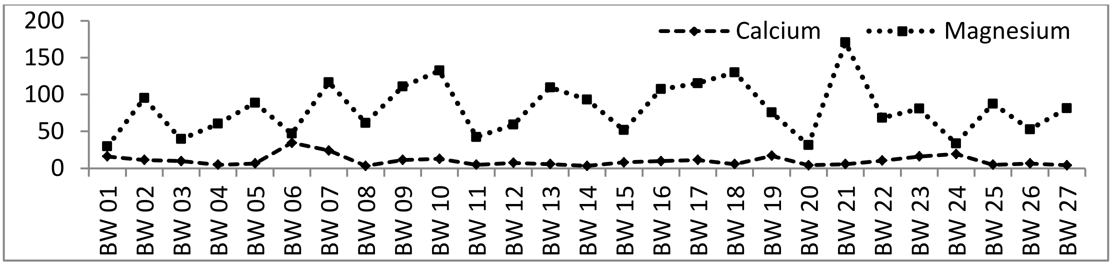

Fig. 4.51 showing Calcium and Magnesium variations in the Pre-Monsoon (2008 & 2009) Bore Well water samples of the study area

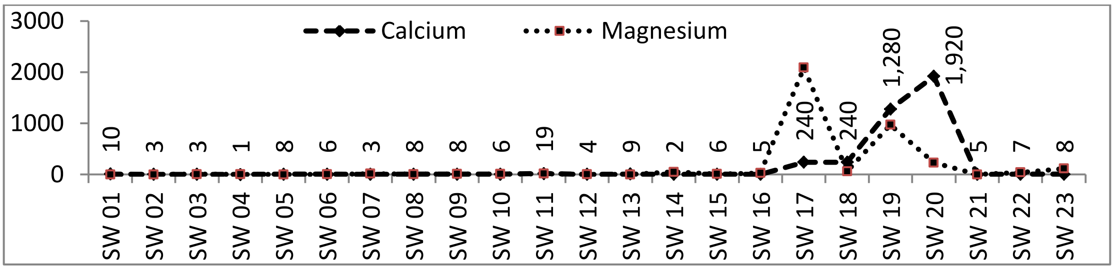

Fig. 4.52 showing Calcium and Magnesium variations in the Pre-Monsoon (2008 & 2009) Surface water samples of the study area

4.6.4.7 Magnesium: Magnesium is a common constituent in natural water. Magnesium salts are important contributors to the hardness of water which break down when heated, forming scale in boilers. The magnesium concentration may vary from zero to several hundred milligrams affecting the taste of water. The daily magnesium requirements are 300ppm to 500ppm and its deficiency may cause cardiac necrosis. It may produce gastrointestinal irritation in the presence of sulphates. Chemical softening, reverse osmosis, electro dialysis, or ion exchange reduces the magnesium and associated hardness to acceptable levels.

The mean magnesium content of the open wells in the study area during pre-monsoon seasons is found to be about 34ppm (equal to average calcium content) with a range varying from 0.29ppm to 388.80ppm (Tables 4.20 & 4.21, Figs. 4.48 & 4.49), whereas during post-monsoon it is about 1.92ppm (less than average calcium) with a range varying between 0.24ppm to 14.09ppm (Table 4.24, Fig. 4.50). The bore well waters found to have a mean magnesium content of about 80.36ppm (higher than mean calcium) during pre-monsoon with a range varying between 29.40 to 170.61ppm (Table 4.22, Fig. 4.51) and 8.08ppm (less than average calcium) with 1.84ppm to 19.44ppm during post-monsoon periods (Table 4.25, Fig. 4.46). The surface water sources show mean magnesium content of about 160.32ppm (less than average calcium) with a varying range of about 0.73 to 2089.80ppm during the pre-monsoon period (Table 4.23, Fig. 4.52). Usually fresh natural waters show less magnesium content than calcium content. The higher values of magnesium content in pre-monsoon bore well water indicate probably contamination of these sources. In all the post-monsoon and majority of the pre-monsoon (92%) open well waters magnesium is found to be well within the BIS drinking water standards. In the case of bore well waters, it is 70% of the pre-monsoon and cent percent of the post-monsoon waters which are in compliance with the BIS drinking water standards. Majority of the surface water samples (83%) were found to be within the permissible limit of BIS drinking water standards except samples from Karnad (SW17 & SW18), Mulki masjid (SW20) and Kanjarakatte Subrahmanya temple pond (OW23).

4.6.4.8 Iron: Iron is one of the most abundant metals in the earth's crust and an essential element in human nutrition. Estimates of the minimum daily requirement for iron is about 10 to 50 mg/day depending on age, sex, physiological status and iron bioavailability. It is found in natural fresh waters at levels ranging from 0.5 to 50 mg/litre. Iron may also be present in drinking water as a result of the use of iron coagulants or the corrosion of steel and cast iron pipes during water distribution. Anaerobic groundwater may contain ferrous iron at concentrations up to several milligrams per liter without discolouration or turbidity in the water when directly pumped from a well. On exposure to the atmosphere, however, the ferrous iron oxidizes to ferric iron, giving an objectionable reddish-brown colour to the water. Iron also promotes the growth of “iron bacteria”, which derive their energy from the oxidation of ferrous iron to ferric iron and in the process deposit a slimy coating on the piping which causes problems in water closets, pipes, pumps and distribution system. There is usually no noticeable taste at iron concentrations below 0.3 mg/litre, although turbidity and colour may develop. At levels above 0.3 mg/litre, iron stains laundry and plumbing fixtures. Although iron has got little concern as a health hazard but is still considered as a nuisance in excessive quantities. Long time consumption of drinking water with a high concentration of iron can lead to liver diseases (hemosiderosis). Due to very high concentration of iron, the common health hazard caused are gastrointestinal disease, respiratory disorders especially asthma and chronic bronchitis, loss of hair and spinal cord system involving arthritis, muscle and joint pains (Jana and Haque 1999, Haque 2009). High concentration of iron in water is not suitable for processing of food, beverages, ice, dyeing, bleaching and many other items.

The mean iron content of the open wells in the study area during pre-monsoon seasons is found to be about 0.13ppm with a range varying from non-detectable level to 3.90ppm (Tables 4.20 & 4.21, Figs. 4.53 & 4.54), whereas during post-monsoon it is about 0.03ppm with a range varying between a non-detectable level to 0.85ppm (Table 4.24, Fig. 4.55). The bore well waters found to have a mean iron content of about 0.90ppm during pre-monsoon with a range varying between 0.20 to 5.22ppm (Table 4.22, Fig. 4.56) and 0.99ppm with a non-detectable level to 2.92ppm during post-monsoon periods (Table 4.25, Fig. 4.57). The surface water sources show mean iron content of about 0.09ppm with a range varying from a non-detectable level to 1.10ppm during the pre-monsoon period (Table 4.23, Fig. 4.58).

All the pre- and post-monsoon open well water samples except one pre-monsoon sample from Sankalkaria (OW84) are within the permissible limit of drinking water standards; whereas only 70% of the pre-monsoon and 60% of the post-monsoon bore well waters show compliance with the BIS drinking water standards. When the contamination in the open well water may be of a local phenomenon, the bore well waters might have been affected mainly due to the rusting of the mild steel casing pipes or from iron bacteria. All the surface water samples are well within the WHO drinking water standards even though one sample from Madathakere near Karkala shows a higher value of about 1.10ppm indicating the external contamination of a local phenomenon.

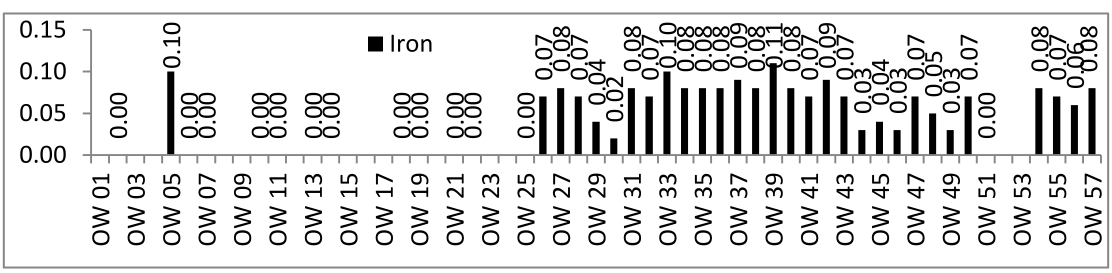

Fig. 4.53 showing Iron variation in the Pre-Monsoon (2008) Open Well water samples of the study area

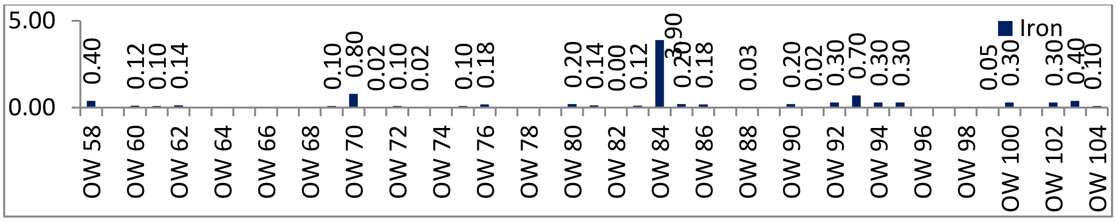

Fig. 4.54 showing Iron variation in the Pre-Monsoon (2009) Open Well water samples of the study area

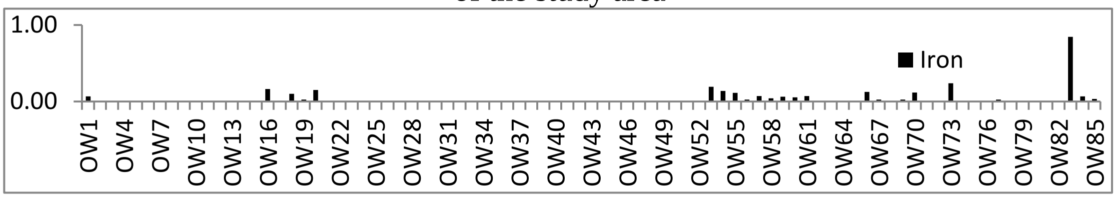

Fig. 4.55 showing Iron variation in the Post-Monsoon (2009) Open Well water samples of the study area

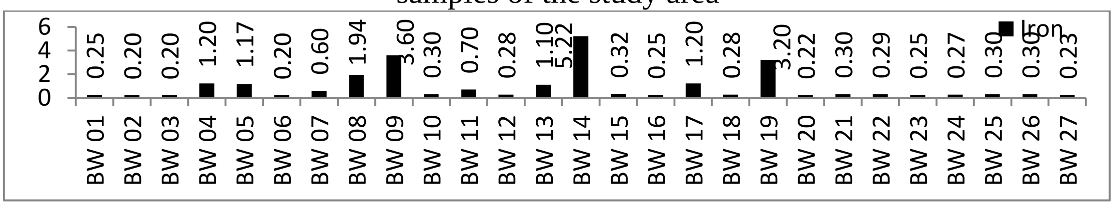

Fig. 4.56 showing Iron variation in the Pre-Monsoon (2008 & 2009) Bore Well water samples of the study area

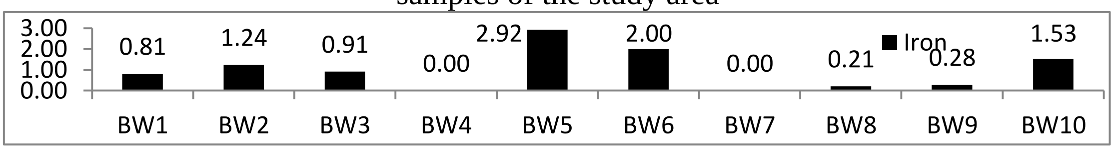

Fig. 4.57 showing Iron variation in the Post-Monsoon (2009) Bore Well water samples of the study area

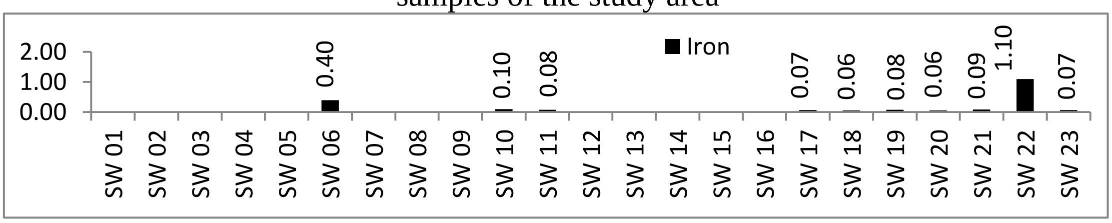

Fig. 4.58 showing Iron variation in the Pre-Monsoon (2008 & 2009) Surface water samples of the study area

4.6.4.9 Carbonates & Bicarbonates: Hardness in water is usually associated with carbonate or bicarbonate concentrations. Where carbonates or bicarbonates are present in concentration equivalent to or greater than the calcium and magnesium, the scale that forms upon evaporation or heating will consist primarily of calcium carbonate and magnesium hydroxide. This hardness in water is usually called as carbonate hardness or temporary hardness since they can be removed with acid. Carbonate is not detected in any of the samples. The concentration of bicarbonate can be compared with the chloride content to understand the contamination in coastal area. Bicarbonate concentration in most of the samples has in situ origin. The reaction involved in organic matter decay generates CO_2 that reacts with H_2O to form carbonic acid in groundwater which may be the source of HCO_3. The bicarbonates might have also derived from the chemical weathering of the feldspars and pyroxenes bearing rocks in the study area.

The mean bicarbonate content of the open wells in the study area during pre-monsoon seasons is found to be about 37.75ppm with a range varying from 6ppm to 260ppm (Tables 4.20 & 4.21, Figs. 4.59 & 4.60), whereas during post-monsoon it is about 34.49ppm with a range varying between 3ppm to 293ppm (Table 4.24, Fig. 4.61). The bore well waters found to have a mean bicarbonate content of about 77.56ppm during pre-monsoon with a range varying between 16 to 150ppm (Table 4.22, Fig. 4.62) and 100.70ppm with a 43 to 167ppm during post-monsoon periods (Table 4.25, Fig. 4.63). The surface water sources show mean bicarbonate content of about 34.70ppm with a range varying from 8ppm to 120ppm during the pre-monsoon period (Table 4.23, Fig. 4.58).

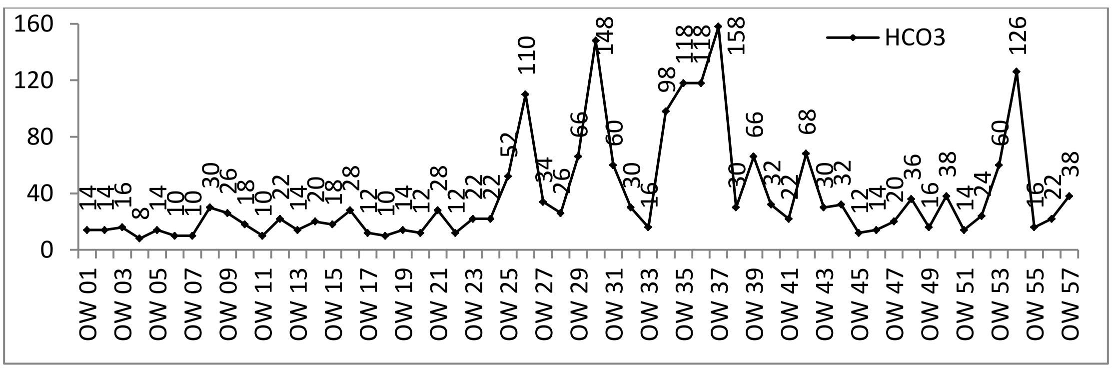

Fig. 4.59 showing Bicarbonate variation in the Pre-Monsoon (2008) Open Well water samples of the study area

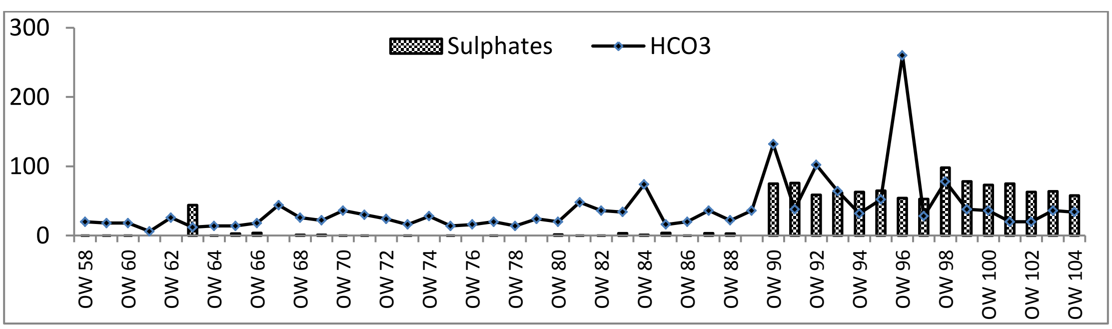

Fig. 4.60 showing variations of Bicarbonates and Sulphates in the Pre-Monsoon (2009) Open Well water samples of the study area

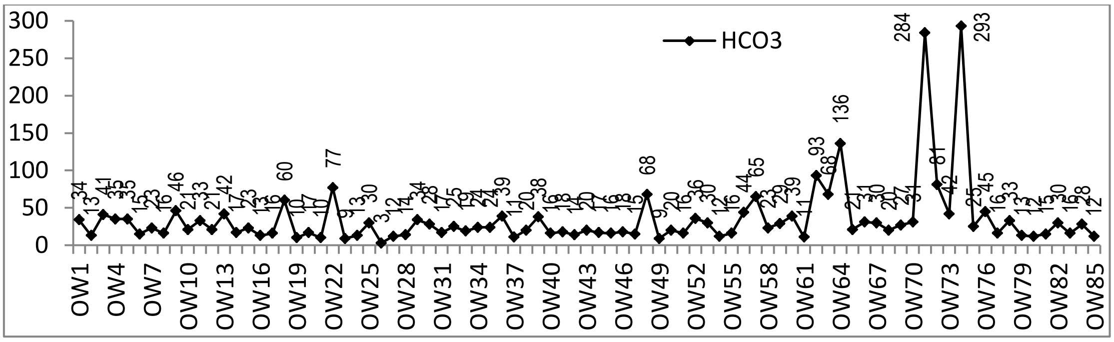

Fig. 4.61 showing Bicarbonate variation in the Post-Monsoon (2009) Open Well water samples of the study area

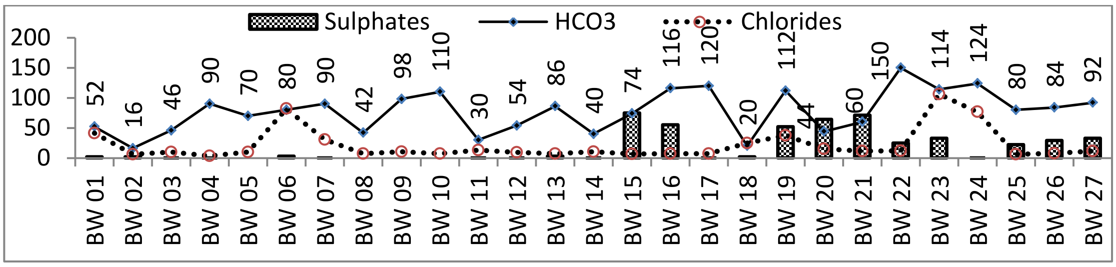

Fig. 4.62 showing variations of Bicarbonates, Sulphates and Chlorides in the Pre-Monsoon (2008 & 2009) Bore Well water samples of the study area

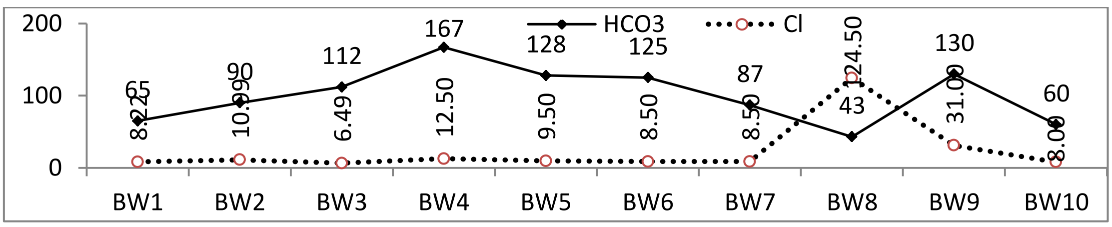

Fig. 4.63 showing variations of Bicarbonate and Chlorides in the Post-Monsoon (2009) Bore Well water samples of the study area

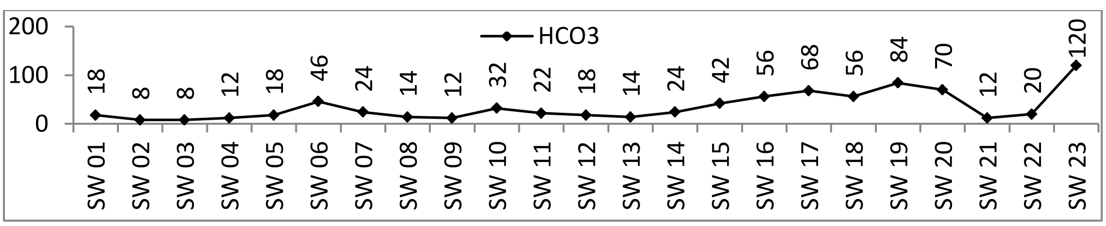

Fig. 4.64 showing Bicarbonate variation in the Pre-Monsoon (2008 & 2009) Surface water samples of the study area

All the groundwater samples, both open wells and bore wells except one pre-monsoon open well sample from Padubidri (OW96), and two post-monsoon open wells from Kolachikambla (OW71) and Chitrapu (OW74) are within the permissible limit of BIS drinking water standards. These may be due to the weathering of calcareous materials and carbonate shells in this coastal tract.

4.6.4.10 Chlorides: Chloride is one of the major inorganic anion in water and gives salty taste to the potable water. Concentration is variable and dependent on the chemical composition. High concentrations of chloride give an undesirable taste to water and beverages. Taste thresholds for the chloride anion depend on the associated cation and are in the range of 200-300 mg/litre for sodium, potassium, and calcium chloride. There is no known evidence that chlorides constitute any human health hazard. For this reason, chlorides are generally limited to 250 mg/l in supplies intended for public use. In many areas of the world where water supplies are scarce, sources containing as much as 2000 mg/l are used for domestic purposes without the development of adverse effect, once the human system becomes adapted to the water. High chloride content may harm metallic pipes and structures as well as growing plants.

Chloride may originate from natural deposits of igneous and sedimentary rocks, or may be derived from contamination of surface and groundwater due to saline water intrusion from the sea, from agricultural fields receiving fertilizers and animal wastes, from municipal sewage and industrial effluents, water softening plants, etc. In coastal areas, rainwater may be a source. Any sudden increase in chloride concentration in surface water or groundwater may indicate faecal pollution, especially when it is accompanied by an increase in nitrate concentration.

The mean chloride content of the open wells in the study area during pre-monsoon seasons is found to be about 110.37ppm (Tables 4.20 & 4.21, Figs. 4.65 & 4.66), whereas during post-monsoon it is about 19.97ppm (Table 4.24, Fig. 4.67). The bore well waters found to have a mean chloride content of about 21.21ppm (Table 4.22, Fig. 4.62) and 22.82ppm during post-monsoon periods (Table 4.25, Fig. 4.63). The surface water sources show mean chloride content of about 4,610ppm during the pre-monsoon period (Table 4.23, Fig. 4.68).

Majority of the groundwater (98%) samples, both open wells and bore wells except five pre-monsoon samples from Karnad (OW30), Kolachikambla (OW37 & OW38), Mulki (OW44) and Padubidri (OW54) are well within the permissible limit of BIS drinking water standards. The high chloride content suggests that the above sources have been contaminated from saline water intrusion along this coastal tract stations. Majority of the surface water samples also (83%) are having less than 250ppm of chloride indicating its compliance with the BIS and WHO drinking water standards except those from Karnad (SW17 & SW18), Kolachikambla (SW19) and Mulki masjid (SW20). The very high level of chloride in these surface water sources suggests the seriousness of the salt water intrusion in these sources.

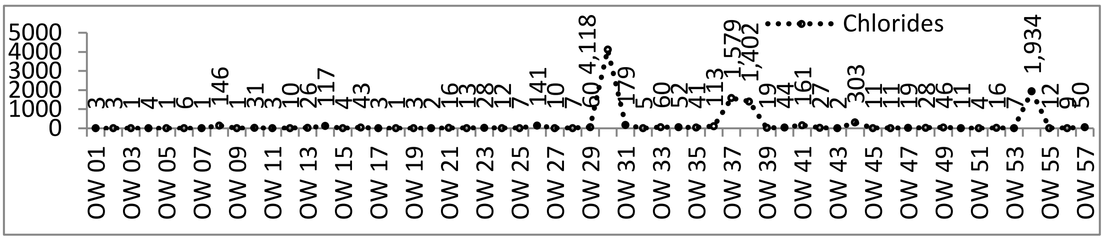

Fig. 4.65 showing Chloride variation in the Pre-Monsoon (2008) Open Well water samples of the study area

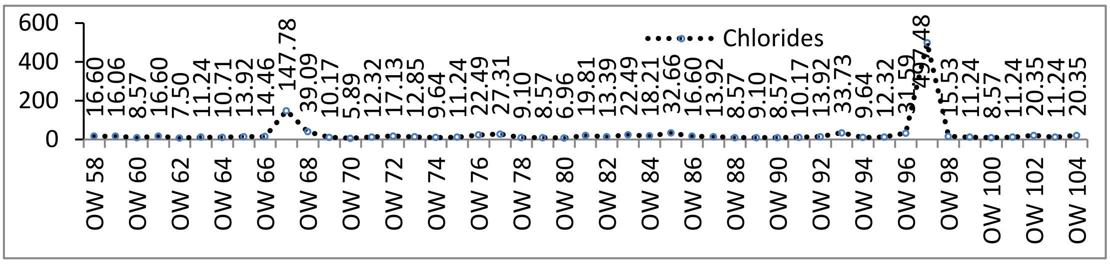

Fig. 4.66 showing variations of Chlorides in the Pre-Monsoon (2009) Open Well water samples of the study area

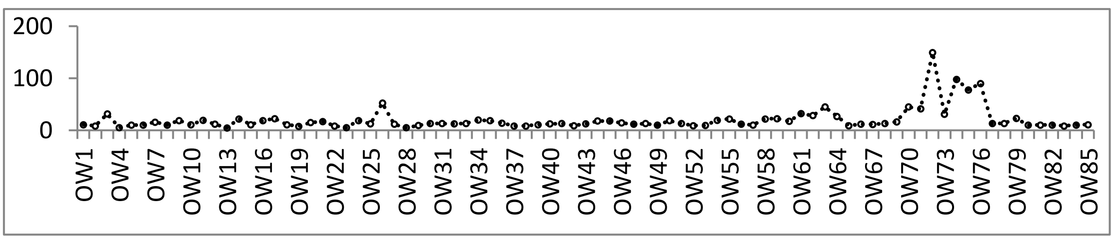

Fig. 4.67 showing Chloride variation in the Post-Monsoon (2009) Open Well water samples of the study area

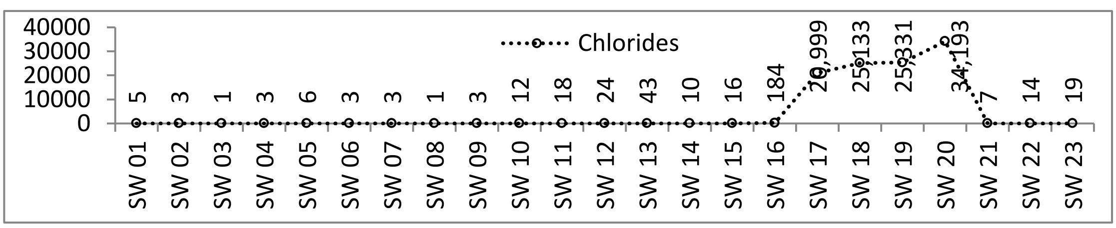

Fig. 4.68 showing Chloride variation in the Pre-Monsoon (2008 & 2009) Surface water samples of the study area

4.6.4.11 Sulphate: Sulphate is one of the least toxic anions which occur naturally in numerous minerals and are used commercially in the chemical industry. One of the important sources of sulphate is evaporate sediment from which magnesium, sodium and calcium sulphate (gypsum) may be leached into surface water and groundwater. Sulphides, sulphites and thiosulphates may be oxidized to sulphate by natural aeration. Domestic sewage, including detergents, also contain sulphate and may be a source of it when discharged into natural water courses. Sulphate once dissolved in water gives permanent hardness to it and may contribute to the corrosion of distribution systems. The major physiological effects resulting from the ingestion of large quantities of sulphate are catharsis, dehydration, and gastrointestinal irritation. Water containing magnesium sulphate at levels above 600 mg/l acts as a purgative in humans. The presence of sulphate in drinking water can also result in a noticeable taste where taste thresholds have been found to range from 250 mg/litre for sodium sulphate to 1000 mg/litre for calcium sulphate.

The mean sulphate content of the open wells in the study area during pre-monsoon seasons is found to be about 13.17ppm with a range varying from non-detectable level to 98ppm (Tables 4.20 & 4.21, Figs. 4.69 & 4.60), whereas during post-monsoon it is about 7.99ppm with a range varying between 0.29ppm to 56.64ppm (Table 4.24, Fig. 4.70). The bore well waters found to have a mean sulphate content of about 17.60ppm during pre-monsoon with a range varying between non detectable level to 75ppm (Table 4.22, Fig. 4.62) and 10.60ppm with a range varying between 0.72 to 20.44ppm during post-monsoon periods (Table 4.25, Fig. 4.71). The surface water sources show mean sulphate content of about 4.26ppm with a range varying from 0.05ppm to 64ppm during the pre-monsoon period (Table 4.23, Fig. 4.72).

All the surface water and groundwater resources in the study area are found to have less than 100ppm of sulphate concentration which is very well within the permissible limit of BIS and WHO drinking water standards. Irrigation return flows and anthropogenic activities may be the causes for the high sulphate contents in the water resources of the study area.

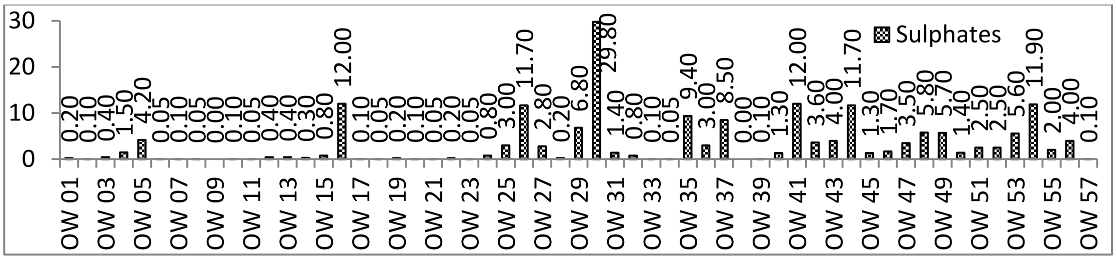

Fig. 4.69 showing Sulphate variation in the Pre-Monsoon (2008) Open Well water samples of the study area

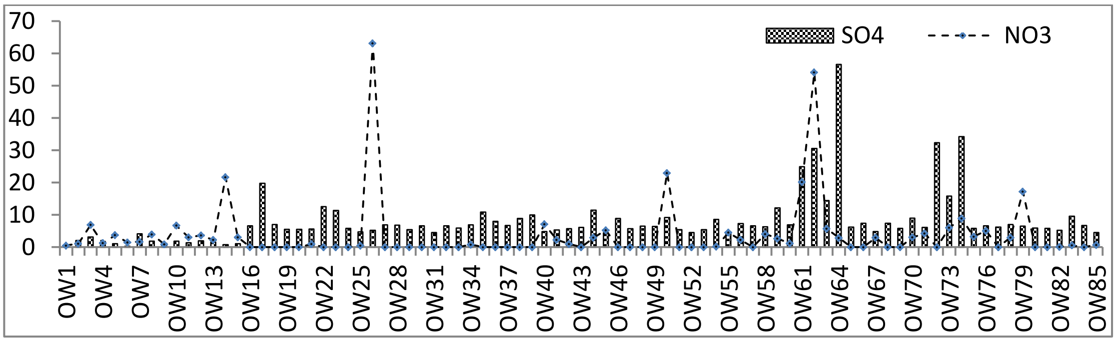

Fig. 4.70 showing Sulphate variation in the Post-Monsoon (2009) Open Well water samples of the study area

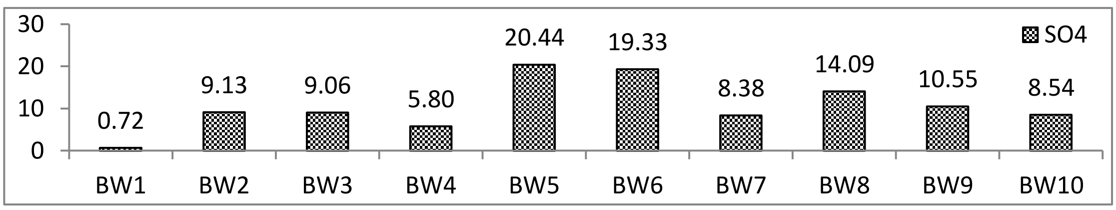

Fig. 4.71 showing Sulphate variation in the Post-Monsoon (2009) Bore Well water samples of the study area

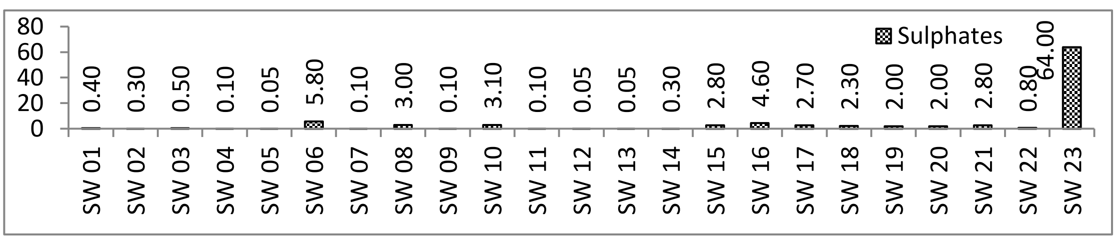

Fig. 4.72 showing Sulphate variation in the Pre-Monsoon (2008 & 2009) Surface water samples of the study area

4.6.4.12 Nitrates: Nitrate and nitrite are naturally occurring ions that are part of the nitrogen cycle. Naturally occurring nitrate levels in surface water and groundwater are generally a few milligrams per litre ranging from trace quantities in surface waters to the high level in some groundwater. It can be toxic to certain aquatic organisms even at concentration of 1ppm, and in excessive limits it contributes to the illness known as methaemoglobianemia in infants. It may also increase risk of cancer (BIS 1991, WaterAid 2007). Nitrate in water resources originates from the atmosphere during lightning other than sewage, industrial effluents and agriculture. Increased use of inorganic fertilizers to enrich the soil for higher crops yield, increase the concentration of nitrates in the groundwater.

The mean nitrate content of the open wells in the study area during pre-monsoon seasons is found to be about 3.05ppm with a range varying from non-detectable level to 16.13ppm (Tables 4.20 & 4.21, Figs. 4.73 & 4.74), whereas during post-monsoon it is about 3.78ppm with a range varying between non-detectable level to 63.14ppm (Table 4.24, Fig. 4.70). The bore well waters found to have a mean nitrate content of about 3.53ppm during pre-monsoon with a range varying between non-detectable level to 9.66ppm (Table 4.22, Fig. 4.75) and 0.88ppm with a range varying between non detectable level to 2.74ppm during post-monsoon periods (Table 4.25, Fig. 4.76). The surface water sources show mean nitrate content of about 3.16ppm with a range varying from non-detectable level to 8.33ppm during the pre-monsoon period (Table 4.23, Fig. 4.77). All the surface water and groundwater samples in the study area are found to have less than 100ppm of nitrate concentration which is very well within the permissible limit of BIS drinking water standards; whereas two post-monsoon open well water samples collected from Kariyakkal (OW26) and Hejmadi Kodi (OW62) showed more than 50ppm nitrate concentration which is beyond the WHO drinking water standards. This high level of nitrate concentration can be attributed to the leach pits close by.

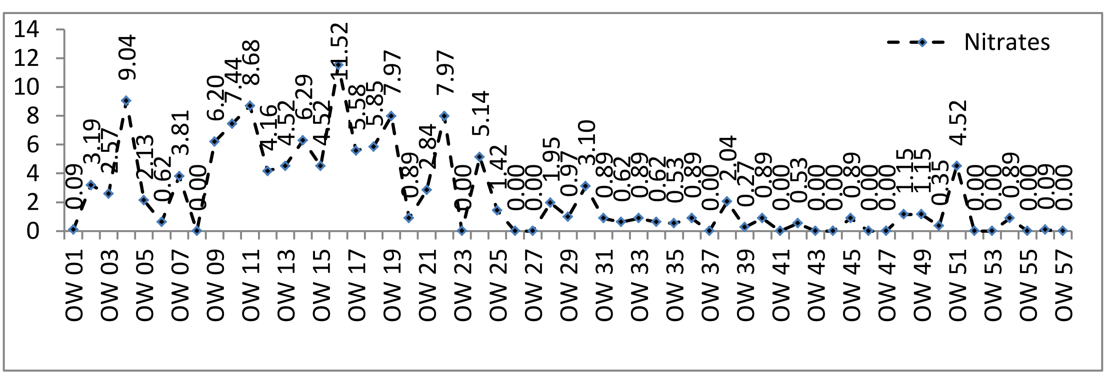

Fig. 4.73 Showing Nitrates variation in the Pre-Monsoon (2008) Open Well water samples of the study area

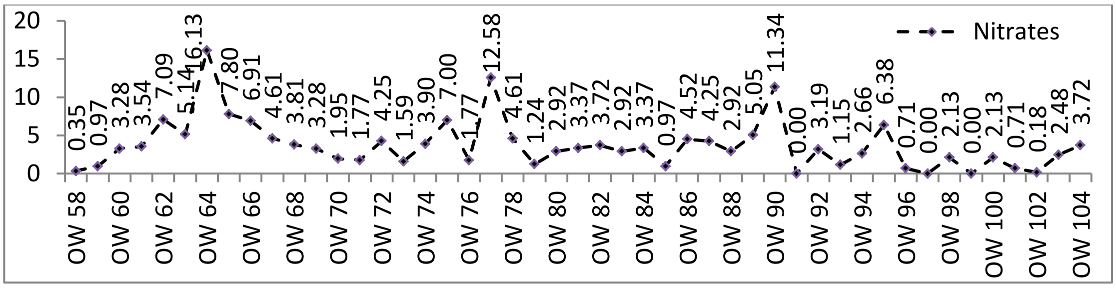

Fig. 4.74 showing Nitrates variation in the Pre-Monsoon (2009) Open Well water samples of the study area

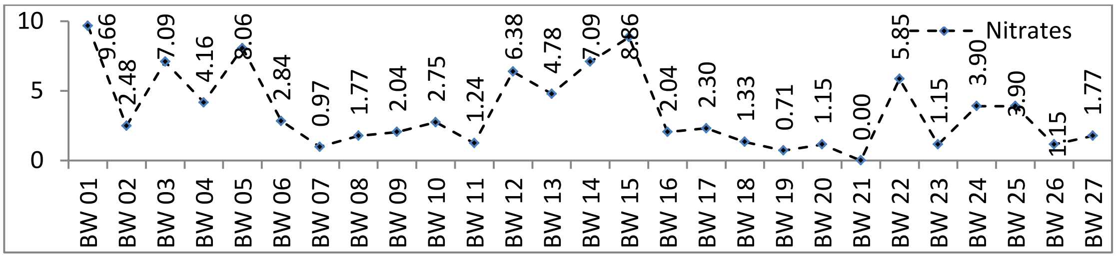

Fig. 4.75 showing Nitrates variation in the Pre-Monsoon (2008 & 2009) Bore Well water samples of the study area

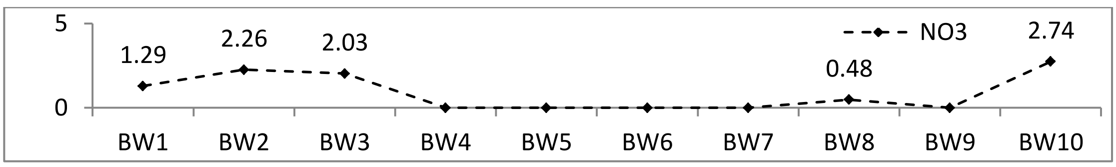

Fig. 4.76 showing Nitrates variation in the Post-Monsoon (2009) Bore Well water samples of the study area

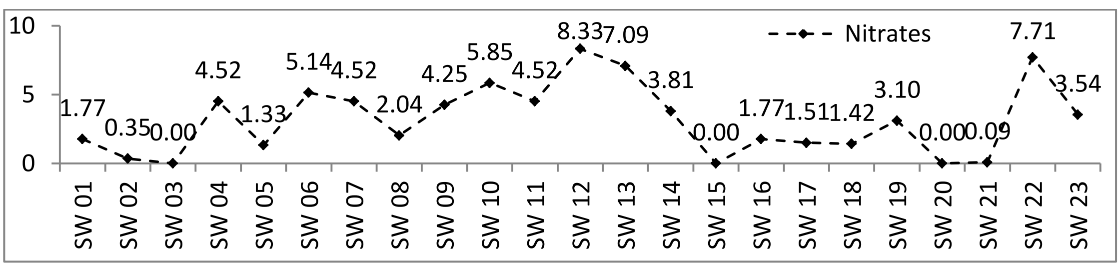

Fig. 4.77 showing Nitrates variation in the Pre-Monsoon (2008 & 2009) Surface water samples of the study area

<u>4.6.4.13 Fluoride:</u> Fluoride is a normal constituent of all diets and it is considered as an essential nutrient. Traces of fluorides are present in many waters. Higher concentrations are often associated with underground sources. Calcium carbonate oversaturation and calcium ion exchange processes are the origin of fluoride in the hard rock areas (Tamta 1994). In groundwater, fluoride concentrations vary with the type of rock that the water flows through but do not usually exceed 10mg/l. Presence of large amounts of fluoride is associated with dental and skeletal fluorosis (>1.5

mg/l) and inadequate amounts with dental caries (<0.5mg/l). A fluoride concentration in the range of 0.8 to 1.0ppm in drinking water effectively reduces dental caries without harmful effect to health. If diets contain fish and tea, exposure to fluoride through food may be particularly high. Immediate symptoms of high fluoride concentration include digestive disorders, skin diseases and dental fluorosis. Fluoride in larger quantities (20-80 mg/day) taken over a period of 10-20 years results in crippling and skeletal fluorosis, which is severe bone damage (WaterAid.org 2007).

The fluoride content in the groundwater samples of the study area has been analyzed during the post-monsoon period and found to have values below the maximum permissible limit of BIS and WHO drinking water standards. The mean fluoride concentration in the open wells was found to be about 0.17ppm with a range varying between non-detectable levels to 0.76ppm (Table 4.24, Fig. 4.78). The bore well waters found to have a mean fluoride content of about 0.36ppm with a range varying between 0.03 to 1.13ppm (Table 4.22, Fig. 4.79). Majority of the open well samples (87%) and bore well samples (80%) were having low fluoride concentration (<0.6ppm) than the minimum desirable limit of WHO drinking water standards. Low concentration of fluoride in groundwater is reported from different parts of India (Handa 1975). According to Handa (1975) this phenomena in west coast is due to the high rainfall and its diluting effect on groundwater. This low fluoride occurrence may also be due to the absence of fluoride bearing magmatic solution or mineral in the strata thorough which groundwater is assimilating. According to Tamta (1994) the low fluoride content in the $CaCO_3$-undersaturated groundwater from this coastal Karnataka region is due to the effect of intensive lateralization in the area while the infiltrating rainwater has a tendency to escape by the shortest trajectory. High fluoride concentrations in the groundwater correlate positively with alkalinity (bicarbonate concentration), pH, sodium and potassium and are present in groundwater with low calcium concentrations (BGS 2000). Even though fluoridation of the drinking water could be suggested for this grave problem of low fluoride concentration, it has not been recommended in India by experts since almost all the food materials contain certain amount of Fluoride. About an average of 1.70ppm is ingested in the body of an adult in Indian condition (Tamta 1994).

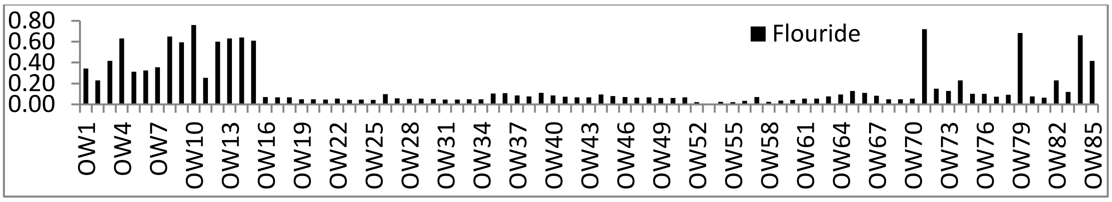

Fig. 4.78 showing Fluoride variation in the Post-Monsoon (2009) Open Well water samples of the study area

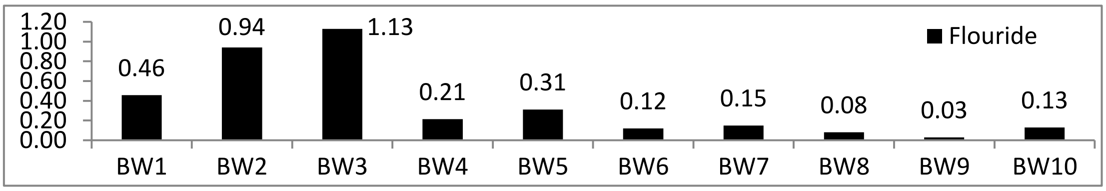

Fig. 4.79 showing Fluoride variation in the Post-Monsoon (2009) Bore Well water samples of the study area

4.6.5 Classification of Groundwater for Domestic Purposes: The analysis of the pre- and post-monsoon water samples from the study area reveals, that a total of about 42 pre-monsoon water samples (27% of total samples) comprising 21 open wells (20% of OWs), 13 bore wells (48% of BWs) and 8 surface water samples (35% of SWs) were contaminated (Table 4.27, Fig. 4.80), whereas about 18 post-monsoon groundwater samples (19% of total samples) comprising 12 open wells (14% of OWs) and 6 bore wells (60% of BWs) were contaminated and are beyond permissible limit of drinking water standards (Table 4.28, Fig. 4.80).

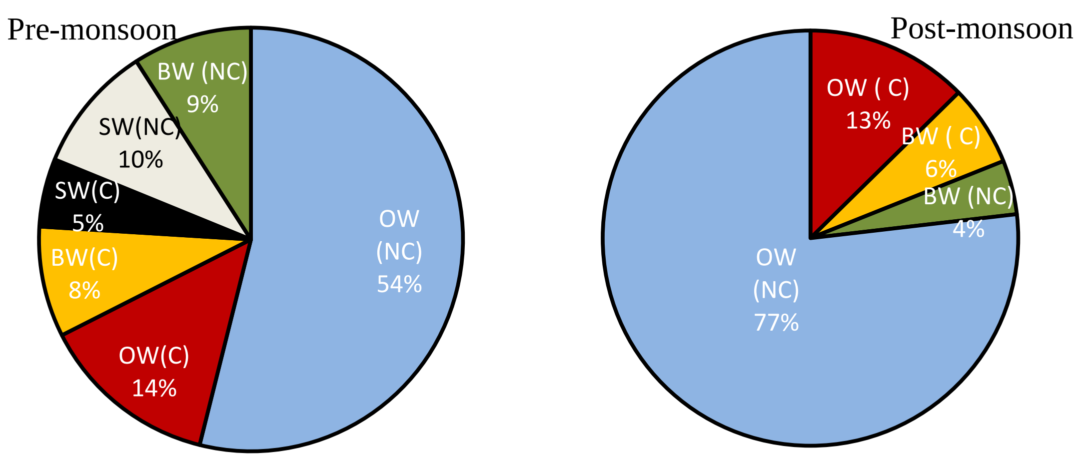

Fig. 4.80 Pie diagrams showing the contmainated (C) and non contaminated (NC) water samples beyond drinking water standards in the Pre- and Post-Monsoon seasons of the study area. (OW-open wells, BW- bore wells, SW-surface water samples)

Other than this, 53% of pre-monsoon and 80% of post-monsoon open well water samples, 7% of pre-monsoon and 10% of post-monsoon bore well water samples, and 85% of the surface water samples have been affected by pH beyond permissible limit of drinking water standards (Table 4.29).

Source	Sample No.	pH	DO	BOD	Turbidity	EC	TDS	Na+	K+	Alkali	Ca++	Mg++	Iron	HCO3	Cl-	SO4	NO3	TH	Cl/ HCO3
BW 04	111	8.30	5.40	0.40	0.20	292	181.33	11.34	6.97	18.31	4.80	60.36	1.20	90.00	3.21	0.10	4.16	260.40	0.04
BW 05	115	7.57	6.40	1.90	1.80	262	162.70	11.76	6.27	18.03	6.40	88.77	1.17	70.00	9.64	0.00	8.06	381.30	0.14
BW 07	120	7.93	6.40	0.90	0.50	455	282.56	43.48	6.23	49.71	24.00	116.49	0.60	90.00	30.52	0.70	0.97	539.40	0.34
BW 08	126	7.50	6.10	0.10	*5.10*	142	88.18	9.13	10.43	19.56	3.20	61.33	1.94	42.00	6.96	0.00	1.77	260.40	0.17
BW 09	127	7.75	5.90	1.90	24.10	309	191.89	14.78	7.90	22.68	11.20	110.71	3.60	98.00	10.17	0.00	2.04	483.60	0.10
BW 10	128	8.05	6.80	2.60	1.00	297	184.44	10.44	6.08	16.52	12.80	132.34	0.30	110.00	6.96	0.00	2.75	576.60	0.06
BW 13	131	7.64	5.30	0.20	1.80	278	172.64	16.88	8.81	25.69	5.60	109.59	1.10	86.00	6.96	3.10	4.78	465.00	0.08
BW 14	132	7.10	5.40	0.70	40.10	148	91.91	10.66	4.81	15.47	3.20	92.97	5.22	40.00	10.17	0.50	7.09	390.60	0.25
BW 16	136	7.11	6.40	2.10	0.50	322	199.96	11.75	9.46	21.21	9.60	107.16	0.25	116.00	6.96	55.00	2.04	465.00	0.06
BW 17	141	6.76	5.40	1.20	11.30	139	86.32	14.59	11.60	26.19	11.20	115.23	1.20	120.00	6.96	0.80	2.30	502.20	0.06
BW 18	143	6.15	7.60	3.90	1.00	1710	*1061.91*	16.64	4.10	20.74	5.60	129.93	0.28	20.00	24.63	2.00	1.33	548.70	1.23
BW 19	146	7.14	7.60	2.30	1.10	374	232.25	58.93	14.97	73.90	16.80	75.67	3.20	112.00	37.48	52.00	0.71	353.40	0.33
BW 21	154	6.25	7.50	3.00	0.20	356	221.08	9.77	1.78	11.55	5.60	170.61	0.30	60.00	11.24	71.00	0.00	716.10	0.19
OW 24	43	6.41	6.72	0.00	1.50	670	416.07	7.57	0.87	8.44	2.40	100.60	0.00	22.00	12.06	0.80	5.14	420.00	0.55
OW 26	46	6.10	6.34	0.00	2.00	4550	2825.55	72.20	9.48	81.68	8.80	56.86	0.07	110.00	141.24	11.70	0.00	256.00	1.28
OW 29	50	7.15	6.62	0.00	3.00	2170	*1347.57*	58.56	17.81	76.37	5.60	21.38	0.04	66.00	60.28	6.80	0.97	102.00	0.91
OW 30	52	7.49	6.90	0.00	2.00	30300	18816.30	105.74	75.63	181.37	240.00	388.80	0.02	148.00	4118.49	29.80	3.10	2200.00	27.83
OW 31	53	7.33	6.67	0.00	1.00	4390	2726.19	104.06	76.29	180.35	32.00	43.74	0.08	60.00	179.14	1.40	0.89	260.00	2.99
OW 34	57	7.18	6.12	0.00	2.00	3000	*1863.00*	31.19	6.45	37.64	32.00	38.88	0.08	98.00	51.67	0.05	0.62	240.00	0.53
OW 37	61	7.23	5.90	0.00	2.00	1455	903.56	9.20	3.92	13.12	720.00	121.50	0.09	158.00	1579.30	8.50	0.00	2300.00	10.00
OW 38	62	6.78	6.64	0.00	3.00	1447	898.59	15.89	4.04	19.93	2.40	11.66	0.08	30.00	1402.05	0.00	2.04	54.00	46.73
OW 42	67	6.77	6.34	0.00	0.80	4100	2546.10	7.90	2.87	10.77	10.40	27.80	0.09	68.00	26.58	3.60	0.53	140.40	0.39
OW 43	68	6.48	6.32	0.00	0.70	1870	*1161.27*	67.75	22.14	89.89	9.60	12.10	0.07	30.00	1.77	4.00	0.00	73.80	0.06
OW 44	69	6.16	6.84	0.00	0.30	1530	950.13	18.95	4.19	23.14	14.40	36.74	0.03	32.00	*303.09*	11.70	0.00	187.20	9.47
OW 54	81	7.59	6.39	0.00	0.60	1580	981.18	106.97	12.73	119.70	1680.00	204.12	0.08	126.00	1933.79	11.90	0.89	5040.00	15.35
OW 64	94	6.45	7.10	0.40	0.50	64	39.50	3.06	0.84	3.90	7.20	18.23	0.00	14.00	10.71	0.30	16.13	93.00	0.76
OW 65	95	5.93	7.20	0.80	0.00	80	49.87	4.56	1.14	5.70	8.80	12.73	0.00	14.00	13.92	3.00	7.80	74.40	0.99
OW 66	96	5.62	6.30	1.80	0.00	83	51.23	5.10	1.30	6.40	8.80	12.73	0.00	18.00	14.46	4.00	6.91	74.40	0.80
OW 84	118	7.74	7.10	0.50	18.40	238	147.80	17.00	2.65	19.65	24.00	84.86	3.90	74.00	18.21	0.90	3.37	409.20	0.25
OW 90	133	7.33	6.30	2.10	1.10	269	167.05	17.76	2.27	20.03	17.60	102.30	0.20	132.00	8.57	75.00	11.34	465.00	0.06
OW 93	139	6.63	6.30	0.30	0.40	88	54.46	5.73	5.84	11.57	16.00	103.28	0.70	64.00	33.73	62.00	1.15	465.00	0.53
OW 95	142	6.64	6.10	0.20	0.40	48	29.93	2.45	3.28	5.73	6.40	138.49	0.30	52.00	12.32	65.00	6.38	585.90	0.24
OW 96	145	7.56	6.10	4.50	0.40	924	573.80	38.05	29.25	67.30	32.00	70.96	0.00	260.00	31.59	54.00	0.71	372.00	0.12
OW 98	149	5.08	4.70	0.40	0.40	104	64.58	8.89	2.54	11.43	31.20	161.84	0.00	78.00	15.53	98.00	2.13	744.00	0.20
SW 12	31	6.23	5.60	0.00	*9.00*	1460	906.66	12.14	1.87	14.01	4.00	2.43	0.00	18.00	23.70	0.05	8.33	20.00	1.32
SW 16	47	7.26	5.80	0.00	3.00	4190	2601.99	8.58	1.16	9.74	4.80	27.70	0.00	56.00	184.30	4.60	1.77	126.00	3.29
SW 17	51	7.97	5.20	0.00	2.50	43600	27075.60	105.51	76.98	182.49	240.00	2089.80	0.07	68.00	20998.99	2.70	1.51	9200.00	308.81
SW 18	54	8.20	5.50	0.00	2.50	43800	27199.80	14.25	1.04	15.29	240.00	63.18	0.06	56.00	25132.99	2.30	1.42	860.00	448.80
SW 19	60	9.11	5.40	0.00	*6.00*	1460	906.66	*388.70*	65.80	*454.50*	1280.00	972.00	0.08	84.00	25330.79	2.00	3.10	7200.00	301.56
SW 20	66	9.75	5.84	0.00	3.00	1460	906.66	29.19	12.15	41.34	1920.00	230.85	0.06	70.00	34193.29	2.00	0.00	5750.00	488.48
SW 22	98	6.20	5.20	0.00	16.80	889	552.07	10.32	3.04	13.36	7.20	40.82	1.10	20.00	13.92	0.80	7.71	186.00	0.70
SW 23	137	6.93	6.10	0.00	1.30	248	154.01	21.57	9.63	31.20	8.00	117.17	0.07	120.00	18.74	64.00	3.54	502.20	0.16

Table 4.27 showing the water samples in which certain water quality parameters are affected beyond permissible limit of drinking water standards in the Pre-Monsoon (2008 & 2009) seasons

In the open wells of the study area, about ten drinking water quality parameters have been affected with a maximum of seven in certain samples (OW30) during pre-monsoon, whereas only about seven parameters with a maximum of three in any sample have been affected during post-monsoon season. In the bore well water samples of the study area, about seven drinking water quality parameters have been affected with a maximum of three in any samples during pre-monsoon, whereas only four parameters with a maximum of three in any sample have been affected during post-monsoon season. In the surface water sources it is about eleven drinking water quality parameters that have been affected with a maximum of nine in certain samples (SW19) during pre-monsoon. A detailed summary of the analysis has been given in the Table 4.29 with the sampling stations and the places in the study area where they have been seriously affected beyond the drinking water quality standards during pre- and post-monsoon seasons (Figs. 4.81 to 4.91).

The study revealed that the drinking water qualities of pre-monsoon groundwater samples especially open wells have been affected more compared to the bore wells in the region. It may be due to the groundwater recharging, flushing and dilution of the open well water during heavy monsoon in the study area. The drinking water qualities of surface water sources during pre-monsoon have been affected more compared to groundwater sources in the study area.

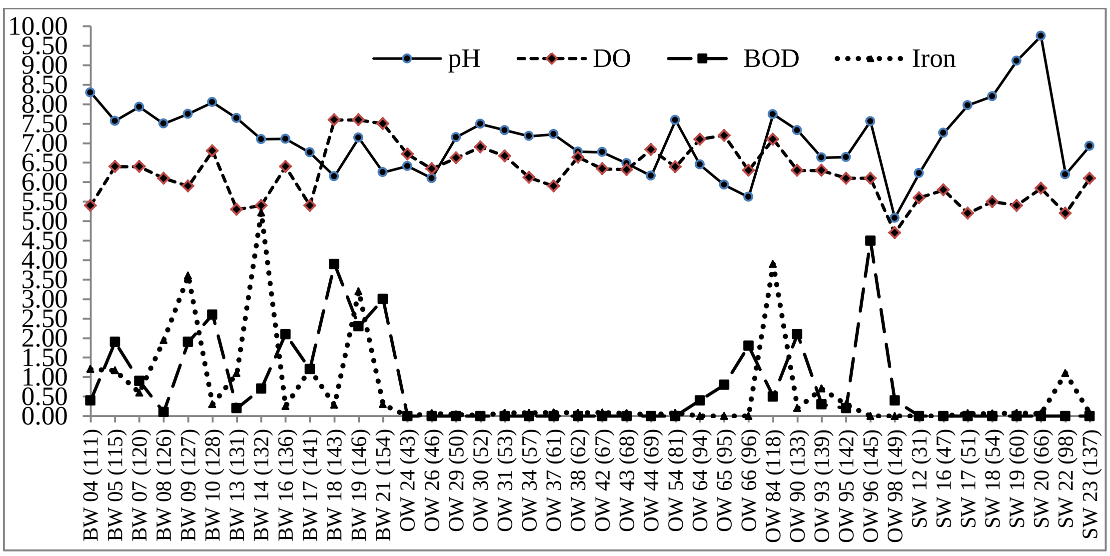

Fig. 4.81 showing variation of pH, DO, BOD and Iron in the Pre-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

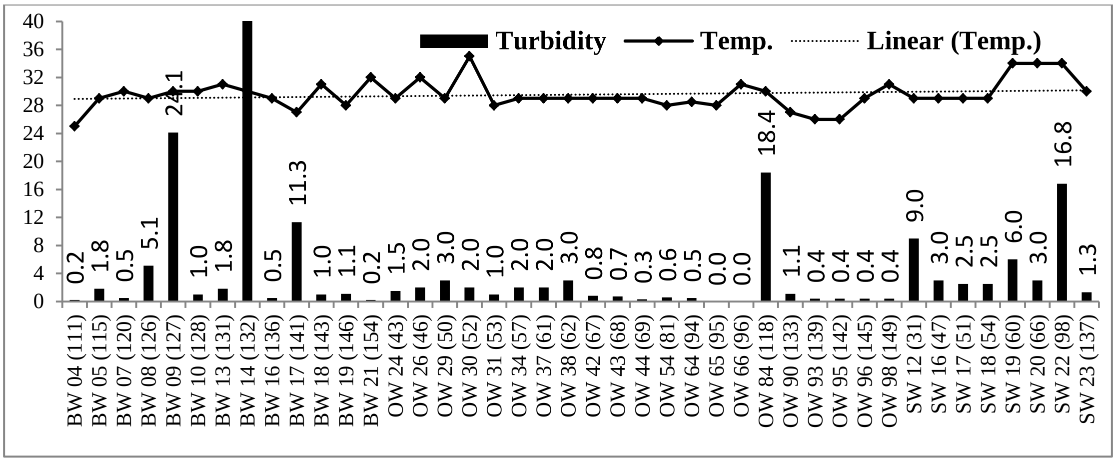

Fig. 4.82 showing Temperature and Turbidity variation in the contaminated Pre-Monsoon samples in the study area

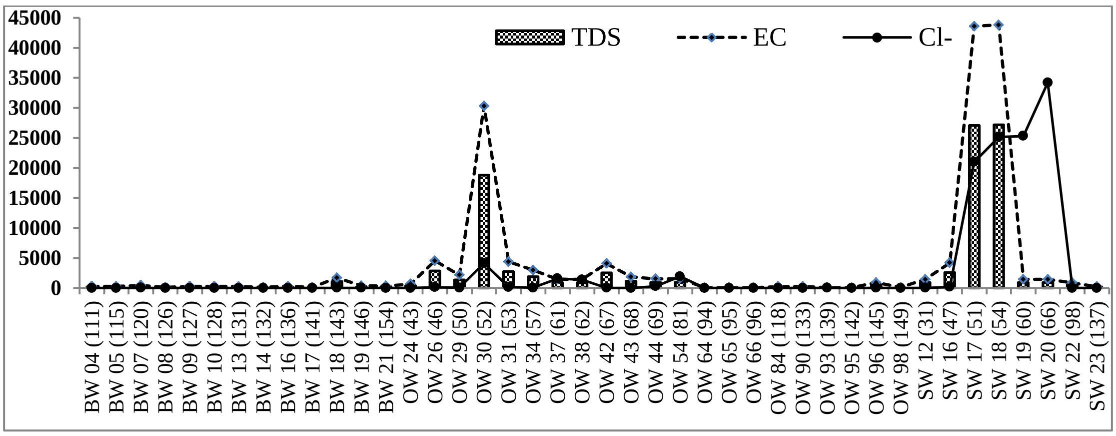

Fig. 4.83 showing variation of TDS, EC and Chloride in the Pre-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

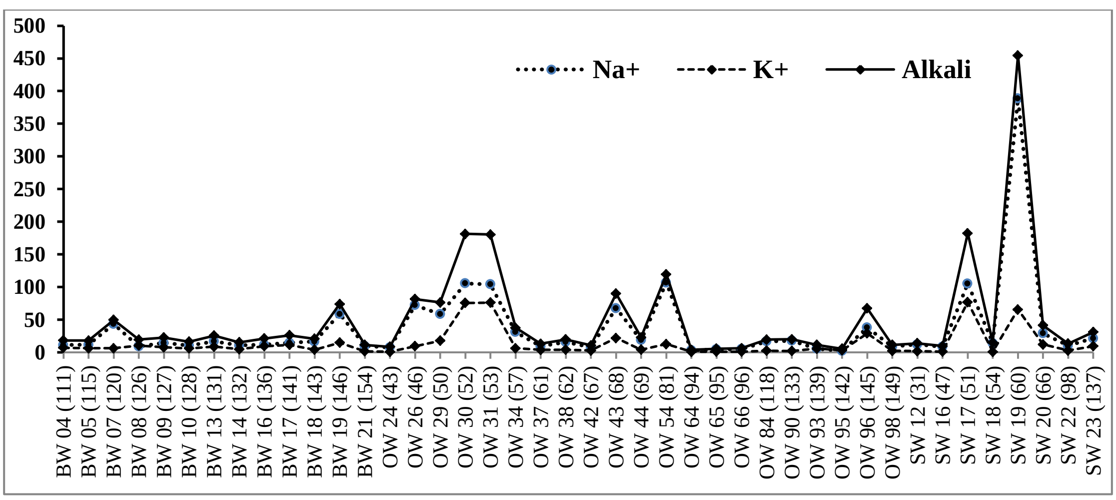

Fig. 4.84 showing variation of Alkali (Na and K) in the Pre-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

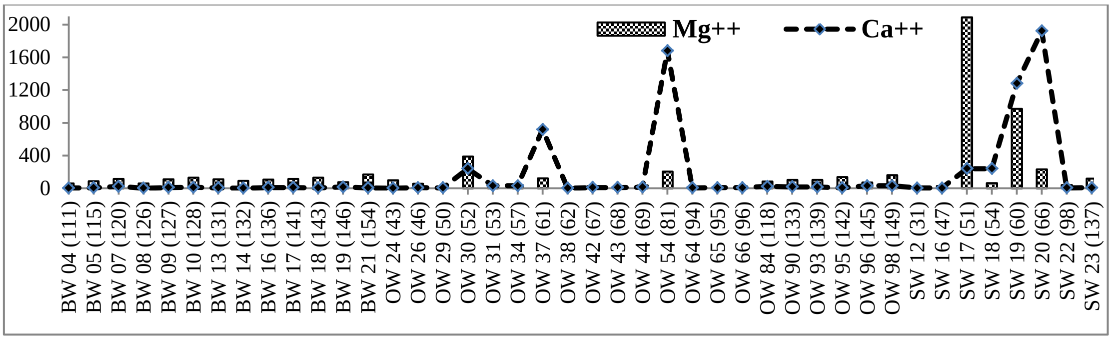

Fig. 4.85 showing Magnesium and Calcium variation in the Pre-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

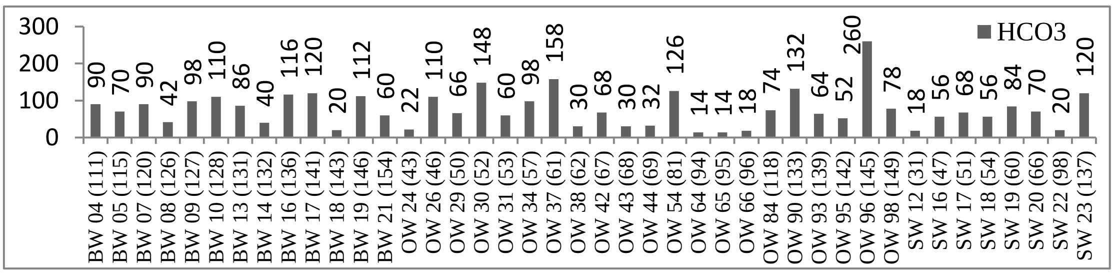

Fig. 4.86 showing variation of Bicarbonate in the Pre-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

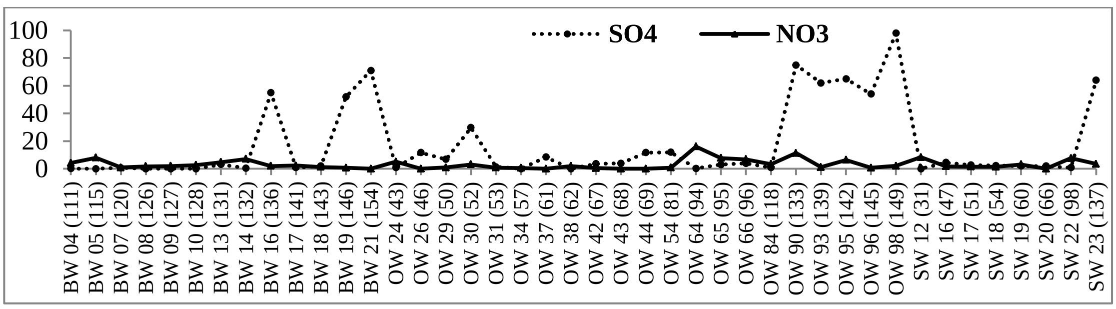

Fig. 4.87 showing variations of Nitrate and Sulphates in the Pre-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

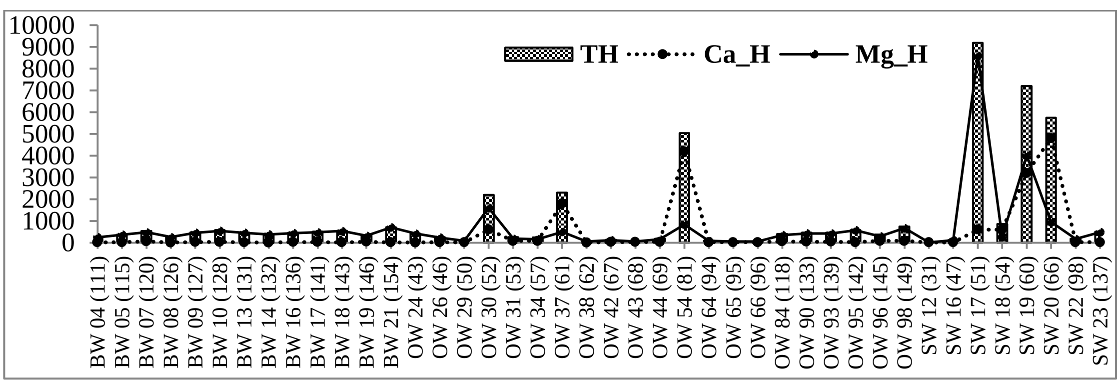

Fig. 4.88 showing variation of Hardness in the Pre-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

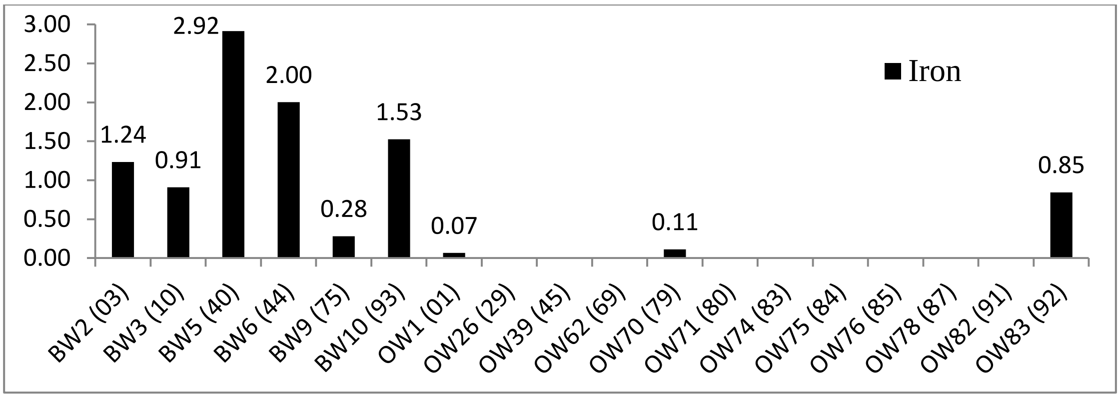

Fig. 4.89 showing variation of Iron content in the Post-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

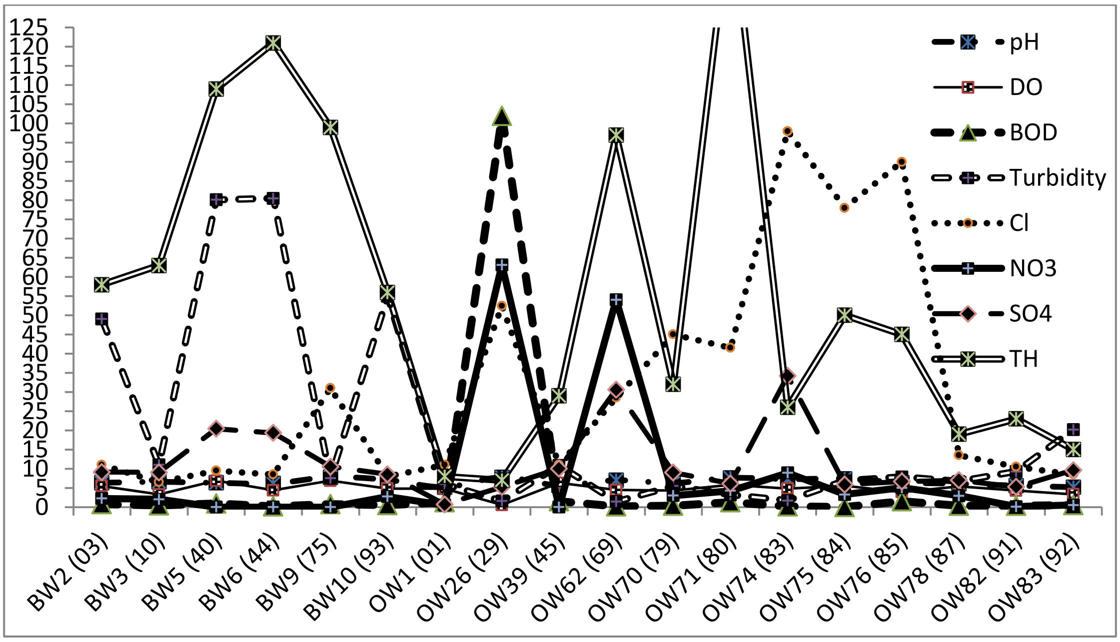

Fig. 4.90 showing variation of pH, DO, BOD, Turbidity, Chloride, NO_3, SO_4 and Total Hardness in the Post-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

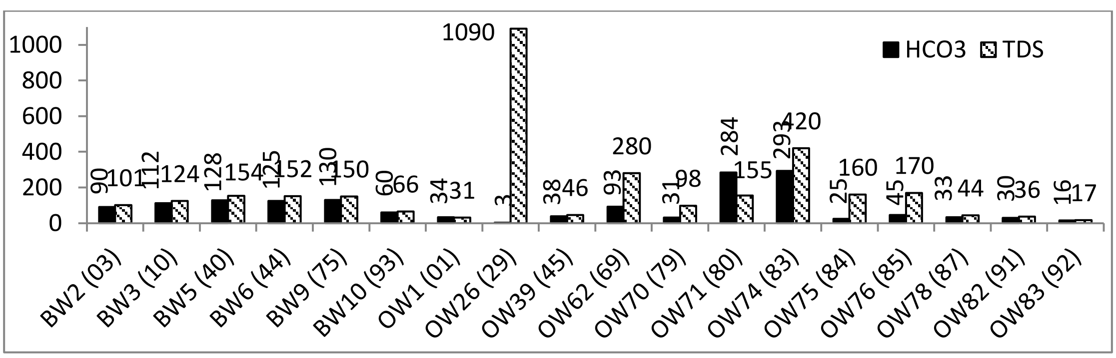

Fig. 4.91 showing variation of TDS and Bicarbonate in the Post-Monsoon samples which were affected beyond the permissible limit of drinking water standards in the study area

Sample No.	Source code	Temp.	pH	DO	BOD	Turbidity	EC	TDS	Na+	K+	Alkali	Ca++	Mg++	Iron	HCO_3	Cl-	NO_3	SO_4	TH
3	BW2	32	**6.35**	5.50	0.80	**49.00**	157.80	101.00	15.40	10.80	26.20	11.20	7.29	**1.24**	90.00	10.99	2.26	9.13	58.00
10	BW3	31	6.58	**3.30**	0.40	**11.00**	193.75	124.00	18.00	11.60	29.60	12.40	7.78	0.91	112.00	6.49	2.03	9.06	63.00
40	BW5	30	**6.33**	6.90	0.90	**80.10**	240.63	154.00	9.90	5.30	15.20	31.60	7.29	**2.92**	128.00	9.50	ND	20.44	109.00
44	BW6	29	**6.19**	4.40	0.20	**80.50**	237.50	152.00	6.00	6.00	12.00	16.40	19.44	**2.00**	125.00	8.50	ND	19.33	121.00
75	BW9	30	7.80	6.90	0.75	***7.50***	234.38	150.00	37.40	5.50	42.90	21.60	10.94	0.28	130.00	31.00	ND	10.55	99.00
93	BW10	29	7.10	4.85	0.56	**55.00**	103.13	66.00	5.90	3.90	9.80	10.80	7.05	**1.53**	60.00	8.00	2.74	8.54	56.00
1	OW1	33	**5.21**	4.80	1.30	***6.00***	48.44	31.00	14.50	9.90	24.40	2.80	0.24	0.07	34.00	10.99	0.51	0.72	8.00
29	OW26	31.5	7.77	**0.56**	**102.00**	1.60	1703.13	***1090.00***	79.20	33.10	112.30	1.60	0.73	ND	3.00	52.50	***63.14***	5.25	7.00
45	OW39	27	**5.68**	6.30	1.50	**10.90**	71.88	46.00	3.80	3.50	7.30	10.00	0.97	ND	38.00	11.00	ND	10.05	29.00
69	OW62	30	7.00	4.47	0.18	1.40	437.50	280.00	50.60	18.50	69.10	20.40	11.18	ND	93.00	28.50	***54.06***	30.62	97.00
79	OW70	29	**6.30**	4.29	0.37	***5.50***	153.13	98.00	19.90	16.20	36.10	8.80	2.43	0.11	31.00	45.00	3.02	9.01	32.00
80	OW71	31	7.60	5.78	1.30	3.20	242.19	155.00	98.30	5.40	103.70	51.20	6.80	ND	**284.00**	41.50	4.26	6.14	156.00
83	OW74	29	7.30	4.85	0.19	1.70	656.25	420.00	71.60	17.40	89.00	10.00	0.24	ND	**293.00**	98.00	8.92	34.23	26.00
84	OW75	29.5	7.40	5.59	ND	***6.90***	250.00	160.00	39.90	8.80	48.70	13.20	4.13	ND	25.00	78.00	3.28	5.87	50.00
85	OW76	29.5	**6.40**	**3.91**	1.49	***7.90***	265.63	170.00	55.90	8.20	64.10	13.60	2.67	ND	45.00	90.00	5.03	6.68	45.00
87	OW78	30	**6.10**	5.41	0.37	***6.70***	68.75	44.00	9.50	4.20	13.70	5.20	1.46	ND	33.00	13.50	2.96	7.01	19.00
91	OW82	27.5	**5.60**	4.29	0.37	***9.30***	56.25	36.00	2.10	4.50	6.60	7.60	0.97	ND	30.00	10.50	0.11	5.26	23.00
92	OW83	27	**5.20**	**3.36**	0.56	**20.20**	26.56	17.00	3.40	4.40	7.80	3.20	1.70	0.85	16.00	8.50	0.56	9.61	15.00

Table 4.28 Groundwater samples in which the water quality is affected beyond permissible limit of drinking water standards in the Post-Monsoon (2009) season

Type of Source	Number & %age of Samples affected		Pre Monsoon Sample Numbers	No. of Para-meters affected	Post Monsoon Sample Numbers	No. of Para-meters affected	Places where water quality beyond permissible limit (BIS & WHO standards 1993)
	Pre Monsoon	Post Monsoon					
Open Well	pH<6.5=54 pH>8.5=1 =53% 21/104 =20%	pH- 68/85 =80% 12/85 =14%	OW 24 (43), OW 26 (46) OW 29 (50), OW 30 (52) OW 31 (53), OW 34 (57) OW 37 (61), OW 38 (62) OW 42 (67), OW 43 (68) OW 44 (69), OW 54 (81) OW 64 (94), OW 65 (95) OW 66 (96), OW 84 (118), OW 90 (133, OW 93 (139) OW 95(142), OW 96 (145), OW 98 (149)	10 with a maxi-mum of 7 in OW30	68 samples pH <6.5 (OW1-OW17,OW19-24,OW28,OW30,OW32-OW57,OW59-60,OW63-65,OW68_70, OW76-OW85) --------------------- OW1, OW26, OW39, OW62, OW70, OW71, OW74, OW75, OW76, OW78, OW82, OW83	7 with a maximum of 3 in any sample	Padupanambur, Kamad, Kolachikambla, around Mulki Bus stop, Near padubidri beach, Sanoor public well, Sanoor school, Opposite to Nitte Panchayath, Sankalkariya, Abbanadka, Palimar Mahalingeshwara temple, Adjacent to Suzlon, Paubidri, Bappanadu, Bola Grama Panchayath Office, Kariyakkal, Kariangadi, Hejmadi Kodi, Akkasaligerekere, Kolachikambla, Chitrapu, Kamad, Kilpadi, Punarooru, Niddodi, Sampige
Bore Well	pH<6.5=2 =7% 13/27=48%	pH - 4/10 =10% 6/10 =60%	BW 04 (111), BW 05 (115) BW 07 (120), BW 08 (126) BW 09 (127), BW 10 (128) BW 13 (131), BW 14 (132) BW 16 (136), BW 17 (141) BW 18 (143), BW 19 (146) BW 21 (154)	7 with a Maxi-mum of 3	pH-(4 BW<6.5) BW2, 5, 6 & 7; 40% BW2, BW3, BW5, BW6, BW9, BW10	4 with maximum of 3 in any sample	Dupadkatte, Nadigudde, Kariyangadi, Beladi, Bola Piliyur Opp. Ramakrishna School, Padubidri, Kanthavara, Nadigudde, Jarigekatte, Masjid cross, Punaroor. Ambaradi, Mundukur, Onjarakatte, Kanthavara, Sankalkaria, Puttigepadavu
Surface Water source	pH<6.5=14 =70% pH>8.5=2 =10% 8/23=35%	-	SW 12 (31), SW 16 (47) SW 17 (51), SW 18 (54) SW 19 (60), SW 20 (66) SW 22 (98), SW 23 (137)	11 with a maxi-mum of 9 in SW19	-	-	Madathakere, Padupanambur, Kamad, Kolachikambla, Mulki Mosque, Santurkople subrahmanya temple

Table 4.29 Places where the water quality (Pre-Monsoon and Post-Monsoon) is affected beyond permissible limit of drinking water standards in the study area

4.7 Classification of Groundwater for Irrigation Purposes: Irrigation water quality refers to its suitability for agricultural use. The concentration and composition of dissolved constituents in water determine its quality for irrigation use. Quality of water is an important consideration in any appraisal of salinity or alkali conditions in an irrigated area. Good quality water has the potential to cause maximum yield under good soil and water management practices. Assessment of the suitability of groundwater for irrigation purpose requires consideration of the total dissolved solids, the concentrations of certain constituents and substances that may be toxic to plants. The important characteristics or properties of groundwater to be considered for irrigation use are Total Salt concentration (Electrical Conductivity), Sodium Adsorption Ratio (SAR) i.e. the relative proportion of Sodium to other Cat-ions, Residual Sodium Carbonate (RSC), Percentage Sodium (%Na), Permeability Index (PI), Magnesium Hazard (MH), Chloride, Sulphate and Chloride/Bicarbonate ratio (Ayers and Wascot 1985). The details of the statistical analysis and the classification based on BIS standards (IS: 2296-1963) revised by Central Groundwater Board and Central Pollution Control Board (CGWB and CPCB 2000) is given in Tables 4.30 to 4.35. Summary of the Irrigation water quality evaluation of the pre-monsoon and post-monsoon water samples of Mulki River basin is given in Table 4.36. U.S. Salinity Laboratory classification (Wilcox 1955) is also used to study the suitability of groundwater for irrigation purposes. In classification of irrigation waters, it is assumed that the water will be used under average conditions with respect to soil texture, infiltration rate, drainage characteristics, quantity of water used, climate and salt tolerance of crop.

Electrical Conductivity (EC) and Sodium concentration are very important parameters in classifying irrigation water. Water used for irrigation always contains measureable quantities of dissolved substances as salts. The salts, besides affecting the growth of the plants directly also affect soil structure, permeability and aeration, which indirectly affect plant growth. Surface samples SW16, SW17 and SW18 were found to be not suitable for irrigation purposes due to its high electrical conductance contributed through the saline water contamination identified through its high chloride content and Chloride/Bicarbonate ratio. Samples SW12, SW13, SW19 and SW20 also show saline water dominance indicating its unsuitability for irrigation. Other than these, SW12 and SW21 show high percentage of Sodium ion and Residual Sodium Carbonate making it unfit for irrigation purposes. About 70% of the surface water samples were found to be unfit for irrigation purposes due to saline water contamination or percentage sodium or RSC. Out of these 30% samples were unfit due to saline water dominance contributed through very high electrical conductance (13%), high chloride influence (17%) and high percentage sodium ion (9%). 52% of the surface water samples are unfit due to the high value of Residual Sodium Carbonate (Table 4.30).

Parameters	Unit	Maximum	Mini-mum	Medi-an	Mean (23 samples)	Std. Dev.	Skewness	Kurto-sis	Quality Classification of irrigation water according to IS 2296-1963 (Revised after CGWB and CPCB 2000)				
									Excellent	Good	Medium	Bad	Very Bad
Electrical Conductance (EC)	mµS/cm	43800.00	155.00	706.00	4567.00	12377.99	3.11	8.49	(<250)	(250-750)	(750-2250)	(2250-4000)	(>4000)
									SW 01- 04 & SW 23	SW 05-09, SW 11 &14	SW10, 12,13,15, 19, 20, 21& 22	-	SW 16, 17 & 18
									(22% samples)	(30%)	(35% samples)	-	(13% samples)
Sodium Adsorption Ratio (SAR)	epm	11.58	0.89	2.37	2.92	2.39	2.55	7.49	(< 10)	(10-18)	(18-26)	(> 26)	-
									SW1-18, 20-23	SW19	NIL	NIL	-
									96% samples	(4%)	-	-	-
Residual Sodium Carbonate (RSC)	epm	34.55	-2261.80	3.39	-290.93	746.67	-2.33	3.83	(<1.25)	(1.25 - 2)	(2 - 2.5)	(2.5 – 3)	(>3)
									SW 03, 08,09, 11, 14, 17, 18, 19, 20, 22 &23	NIL	NIL	NIL	SW01, 02, 04, 05, 06, 07, 10, 12, 13, 15, 16 & 21
									(48% samples)	-	-	-	(52% samples)
% Na	epm	69.35	1.89	28.50	30.75	18.17	0.58	-0.03	< 20%	20% - 40%	40% - 60%	60% - 80%	>80%
									SW 11, SW 14 SW 17-SW 20, SW 23	SW01, 03-05, 08, 09, 13, 16, 22	SW 02, SW 06, SW 07, SW 10, SW 15	SW 12, SW 21	NIL
									(30% samples)	(39%)	(22% samples)	(9% samples)	-
Permeability Index (PI)	epm	88.22	1.72	45.16	45.00	26.03	-0.08	-1.02	(>75)	(75-25)	(<25)	-	-
									SW 2, 12, 21	SW 01, SW 03-11, SW 13, 15, 16 & 22	SW 14, 17, 18, 19, 20 & 23	-	-
									(13% samples)	(61%)	(26% samples)	-	-
Chloride	ppm	34193.29	1.46	11.74	4610.00	10433.11	2.02	2.64	(≤ 600 ppm)			(> 600 ppm)	
									SW 01- SW 16, SW 21- SW 23			SW17, SW18, SW19 & SW20	
									83% SW samples are suitable for irrigation			17% samples unsuitable	
Sulphate	ppm	64.00	0.05	0.80	4.26	13.13	4.68	22.19	(≤ 1000 ppm)			(> 1000 ppm	
									SW 01- SW 23			NIL	
									100% SW samples are suitable for irrigation			-	
Chloride/ Bicarbonate (Cl/HCO_3)		488.48	0.06	0.38	67.85	153.81	2.06	2.85	70% SW samples are suitable for irrigation			SW12, 13, 16, 17, 18, 19 & 20 show values ≥ 1 indicating saline water dominance	

Table 4.30 Irrigation water quality classification of Surface Water Samples of Mulki River basin (*after* CGWB and CPCB 2000)

An analysis of Pre-Monsoon (2008) Open Well water samples (Table 4.31) revealed that majority of the samples are unfit for irrigation purposes due to various reasons.

When 33% were due to saline water dominance due to very high chloride content (7%), high percentage Sodium (35%) and very high electrical conductance (9%), a good number of samples (62%) showed high value of RSC making the water unfit for irrigation.

Parameters	Unit	Maximum	Mini-mum	Medi-an	Mean (57 samples)	Std. Dev.	Skewness	Kurto-sis	Quality Classification of irrigation water according to IS 2296-1963 (Revised after CGWB and CPCB 2000)				
									Excellent	Good	Medium	Bad	Very Bad
Electrical Conductance (EC)	mµS/cm	30300.00	76.00	1447.00	1810.26	3952.62	6.93	50.50	(<250)	(250-750)	(750-2250)	(2250-4000)	(>4000)
									OW 01, 04, 05, 06, 10, 11	OW 02, 03, 07, 08, 09, 12, 14, 15, 24, 28 & 51	OW 13, 16-23, 25, 27, 29, 32, 33, 35-41, 43-50, 52-57	OW 34	OW 26, 30, 31 & OW 42
									(10.5% samples)	(19% samples)	(61.5% samples)	(2% samples)	(7% samples)
Sodium Adsorption Ratio (SAR)	epm	20.57	0.16	4.27	6.44	5.80	1.09	0.00	(< 10)	(10-18)	(18-26)	(> 26)	-
									45 samples	OW 26, 28, 29, 31, 33, 36, 40, 47, 57	OW 16, 41, 43	-	-
									(79% samples)	(16% samples)	(5% samples)	-	-
Residual Sodium Carbonate (RSC)	epm	44.34	-1758.12	6.05	-44.57	256.96	-5.85	37.07	(<1.25)	(1.25 - 2)	(2 - 2.5)	(2.5 – 3)	(>3)
									16 samples	OW 23, OW 46 & OW 48	OW 13, OW 33, OW 45	OW 03	34 samples
									(28% samples)	(5% samples)	(5% samples)	(2% samples)	(60% samples)
% Na	epm	81.31	1.54	45.80	47.18	22.71	-0.24	-0.94	< 20%	20% - 40%	40% - 60%	60% - 80%	>80%
									OW 01, 04, 17, 18, 24, 37, 54	OW 02, 03, 05, 07, 09-11, 15, 19, 21, 23, 27, 30, 34, 42, 44, 46, 53	OW 08, 14, 20, 22, 25, 26, 35, 36, 38, 39, 48, 51	OW 06, 12, 13, 29, 31, 32, 33, 40, 41, 45, 47, 49, 50, 52, 55, 56, 57	OW 16, 28, 43
									(12% samples)	(32% samples)	(21% samples)	(30% samples)	(5% samples)
Permeability Index (PI)	epm	96.50	2.56	60.83	58.02	22.80	-0.57	-0.13	(>75)	(75-25)	(<25)	-	-
									OW 05, 06, 12, 14, 16, 22, 28, 29, 33, 40, 43, 47, 51, 52, 56, 57	35 samples	OW 01, 04, 24, 30, 37 & 54	-	-
									(28% samples)	(61% samples)	(11% samples)	-	-
Chloride	ppm	4118.49	1.45	13.45	192.50	644.95	4.83	25.86	(≤ 600 ppm)			(> 600 ppm)	
									53 samples			OW 30, 37, 38 & 54	
									93% samples are suitable for irrigation			7% samples unsuitable	
Sulphate	ppm	29.80	ND	1.30	3.17	5.10	3.06	12.60	(≤ 1000 ppm)			(> 1000 ppm)	
									OW 01 – OW 57			NIL	
									100% samples are suitable for irrigation			-	
Chloride/ Bicarbonate (Cl/HCO_3)		46.74	0.06	0.56	2.87	7.42	4.62	23.86	67% samples are suitable for irrigation			33% samples show values ≥ 1 indicating saline water dominance	

Table 4.31 Irrigation water quality classification of Pre-Monsoon (2008) Open Well (OW) Water Samples of Mulki River basin (*after* CGWB and CPCB 2000)

An analysis of Pre-Monsoon (2009) Open Well water samples (Table 4.32) revealed that 25% of samples were unfit for irrigation purposes due to various reasons. When 17% were due to saline water dominance only one (2%) sample showed high percentage Sodium whereas another 8% samples showed high value of RSC making the water unfit for irrigation.

Parameters	Unit	Maximum	Mini-mum	Medi-an	Mean (47 samples)	Std. Dev.	Skewness	Kurto-sis	Quality Classification of irrigation water according to IS 2296-1963 (Revised after CGWB and CPCB 2000)				
									Excellent	Good	Medium	Bad	Very Bad
Electrical Conductance (EC)	mµS/cm	1810.00	40.00	104.00	214.51	315.09	3.68	15.18	(<250)	(250-750)	(750-2250)	(2250-4000)	(>4000)
									38 samples	OW 58, 68, 90, 92, 94, 102	OW 67, 96, 97	NIL	NIL
									(81% samples)	(13% samples)	(6% samples)	-	-
Sodium Adsorption Ratio (SAR)	epm	19.50	0.43	1.74	2.60	3.01	4.19	22.02	(< 10)	(10-18)	(18-26)	(> 26)	-
									46 samples	NIL	OW 67	NIL	-
									(98% samples)	(0% samples)	(2% samples)	-	-
Residual Sodium Carbonate (RSC)	epm	157.04	-115.04	-13.68	-15.76	35.04	1.87	13.81	(<1.25)	(1.25 - 2)	(2 - 2.5)	(2.5 – 3)	(>3)
									43 samples	NIL	NIL	NIL	OW 70, 90, 92& 96
									(92% samples)	-	-	-	(8% samples)
% Na	epm	74.55	5.60	21.85	23.06	13.23	1.43	3.65	< 20%	20% - 40%	40% - 60%	60% - 80%	>80%
									OW 58-63, 69,74-76, 78-80, 84, 87-90, 93, 95, 101, 103	OW 64-66, 70, 71, 73, 77, 81-83, 86, 91, 92, 94, 97-100, 102, 104	OW 68, 72, 85, 96	OW 67	NIL
									(47% samples)	(43% samples)	(8% samples)	(2% samples)	-
Permeability Index (PI)	epm	67.39	11.14	26.88	28.80	11.78	0.99	1.21	(>75)	(75-25)	(<25)	-	-
									NIL	30 samples	OW 58, 59, 62, 63, 69, 76, 79, 84, 87, 88, 89, 90, 93, 95, 98, 101, 103	-	-
									(0% samples)	(64% samples)	(36% samples)	-	-
Chloride	ppm	497.48	5.89	13.39	28.23	72.95	6.13	39.39	(≤ 600 ppm)			(> 600 ppm)	
									OW 58- OW 104			NIL	
									100% samples are suitable for irrigation			0% samples unsuitable	
Sulphate	ppm	98.00	ND	1.10	23.16	32.14	0.87	-1.01	(≤ 1000 ppm)			(> 1000 ppm_	
									OW 58- OW 104			-	
									100% samples are suitable for irrigation			-	
Chloride/ Bicarbonate (Cl/HCO_3)		17.77	0.06	0.48	1.06	2.57	6.23	40.86	83% samples are suitable for irrigation			17% samples (OW61, 67, 68, 76, 77, 85, 97 &102) show values ≥ 1 indicating saline water dominance	

Table 4.32 Irrigation water quality classification of Pre-Monsoon (2009) Open Well (OW) Water Samples of Mulki River basin (*after* CGWB and CPCB 2000)

Post-Monsoon (2009) Open Well water samples analysis (Table 4.33) revealed that majority of samples were unfit for irrigation purposes due to various reasons. When 21% were due to saline water dominance and 2% due to Sodium Adsorption Ratio, 73% samples showed more than 60% sodium ion concentration and 96.5% were due to high value of RSC making the water unfit for irrigation.

Parameters	Unit	Maximum	Mini-mum	Medi-an	Mean (85 samples)	Std. Dev.	Skewness	Kurto-sis	Quality Classification of irrigation water according to IS 2296-1963 (Revised after CGWB and CPCB 2000)				
									Excellent	Good	Medium	Bad	Very Bad
Electrical Conductance (EC)	mµS/cm	1703.13	21.87	64.06	112.61	200.09	6.45	48.79	(<250)	(250-750)	(750-2250)	(2250-4000)	(>4000)
									79 samples	OW 61, 62, 64, 74 & 76	OW26	NIL	NIL
									(93% samples)	(6% samples)	(1% sample)	-	-
Sodium Adsorption Ratio (SAR)	epm	73.39	0.83	5.20	7.21	8.86	5.37	37.57	(< 10)	(10-18)	(18-26)	(> 26)	-
									66 samples	14 samples	OW 07, 71, 76	OW26,OW74	-
									(78% samples)	(16.5% samples)	(3.5% samples)	(2% samples)	-
Residual Sodium Carbonate (RSC)	epm	282.76	-56.25	17.31	24.43	39.37	5.00	29.67	(<1.25)	(1.25 - 2)	(2 - 2.5)	(2.5 – 3)	(>3)
									OW 14, 26, 61	NIL	NIL	NIL	82 samples
									(3.5% samples)	NIL	NIL	NIL	(96.5% samples)
% Na	epm	97.97	28.16	69.26	68.05	15.18	-0.58	0.34	< 20%	20% - 40%	40% - 60%	60% - 80%	>80%
									NIL	OW 18, 29, 39, 48, 61, 67	OW20, 25, 30, 36, 40, 50, 52, 64-66, 68-69, 72-73, 81-82, OW 84	44 samples	OW1, 2, 6, 7, 8, 10, 11, 12, 13, 15, 21, 23, 26, 38, 54, 55, 58, OW 74
									(0 % samples)	(7% samples)	(20% samples)	(52% samples)	(21% samples)
Permeability Index (PI)	epm	193.68	31.22	92.97	92.29	22.44	0.69	4.42	(>75)	(75-25)	(<25)	-	-
									69 samples	16 samples	NIL	-	-
									(81% samples)	(19% samples)	-	-	-
Chloride	ppm	149.50	4.90	13.00	19.97	21.62	3.89	17.78	(≤ 600 ppm)			(> 600 ppm)	
									OW 01- OW 85			NIL	
									100% samples are suitable for irrigation			-	
Sulphate	ppm	56.64	0.29	6.22	7.99	8.18	3.61	16.40	(≤ 1000 ppm)			(> 1000 ppm_	
									OW 01- OW 85			NIL	
									100% samples are suitable for irrigation			-	
Chloride/ Bicarbonate (Cl/HCO_3)		17.50	0.11	0.66	0.95	1.90	8.10	70.78	79% samples are suitable for irrigation			21% samples show values ≥ 1 indicating saline water dominance	

Table 4.33 Irrigation water quality classification of Post-Monsoon (2009) Open Well (OW) Water Samples of Mulki River basin (*after* CGWB and CPCB 2000)

Bore Well water sample analysis revealed that 44% of the Pre-Monsoon samples were unfit for irrigation purposes (Table 4.34). When 7% samples each showed saline water dominance and high sodium ion concentration, 37% showed high value of RSC making the water unsuitable for irrigation purposes. But during the 2009 post-monsoon (Table 4.35), 100% bore well samples showed high value of RSC other than high percentage sodium ion concentration in 20% samples and saline water dominance in 10% samples, thus making them unsuitable for irrigation purposes. BW8 found to be the most vulnerable sample for irrigation purposes.

Parameters	Unit	Maximum	Minimum	Median	Mean (27 samples)	Std. Dev.	Skewness	Kurtosis	Quality Classification of irrigation water according to IS 2296-1963 (Revised after CGWB and CPCB 2000)				
									Excellent	Good	Medium	Bad	Very Bad
Electrical Conductance (EC)	mµS/cm	1710.00	92.00	267.00	377.07	390.27	2.84	7.81	(<250)	(250-750)	(750-2250)	(2250-4000)	(>4000)
									BW 02, 03, 08, 11, 12, 14, 17, 20, 22, 24, 26 & 27	BW 04, 05, 06, 07, 09, 10, 13, 15, 16, 19, 21, 23& 25	BW 01 & BW 18	-	-
									44.4% samples	48.2% samples	7.4% samples	-	(% samples)
Sodium Adsorption Ratio (SAR)	epm	22.34	0.40	1.99	4.46	6.02	2.36	4.48	(< 10)	(10-18)	(18-26)	(> 26)	-
										BW 06	BW 23& 24	-	-
									88.9% samples	3.7 % samples	7.4% samples	-	-
Residual Sodium Carbonate (RSC)	epm	71.34	-116.21	-6.43	-13.03	45.15	-0.62	0.97	(<1.25)	(1.25 - 2)	(2 - 2.5)	(2.5 – 3)	(>3)
									BW 02, 03, 05-14, 16-18, 21&25	-	-	-	BW 01, 04, 15, 19, 20, 22, 23, 24, 26, 27
									63% samples	-	-	-	37% samples
% Na	epm	69.24	3.24	21.94	26.00	16.50	1.34	1.39	< 20%	20% - 40%	40% - 60%	60% - 80%	>80%
									BW02, 05, 09, 10, 13, 14, 16, 17, 18, 21 &25	BW 03, 04, 07, 08, 11, 12, 15, 20, 22, 26 & 27	BW 01, 06 & 19	BW 23 & BW 24	-
									41% samples	41% samples	11% samples	7 % samples	-
Permeability Index (PI)	epm	74.28	6.33	26.08	28.91	17.22	1.30	1.17	(>75)	(75-25)	(<25)	-	-
									NIL	BW 01, 03, 04, 06, 07, 11, 12, 15,19, 20, 22, 23, 24 & 26	BW 02, 05, 08, 09, 10, 13, 14, 16, 17, 18, 21, 25 & 27	-	-
									(0% samples)	(52% samples)	(48% samples)	-	-
Chloride	ppm	106.02	3.21	10.17	21.21	26.29	2.22	4.28	(≤ 600 ppm)			(> 600 ppm)	
									BW 01- BW 27			NIL	
									100% samples are suitable for irrigation			0% samples unsuitable	
Sulphate	ppm	75.00	ND	2.00	17.60	25.03	1.23	0.13	(≤ 1000 ppm)			(> 1000 ppm_	
									BW 01- BW 27			NIL	
									100% samples are suitable for irrigation			-	
Chloride/ Bicarbonate (Cl/HCO_3)		1.23	0.04	0.17	0.31	0.33	1.62	1.79	93% BW samples are suitable for irrigation			BW6 & BW18 show values ≥ 1 indicating saline water dominance	

Table 4.34 Irrigation water quality classification of Pre-Monsoon Bore Well (BW) Water Samples of Mulki River basin (*after* CGWB and CPCB 2000)

Parameters	Unit	Maximum	Minimum	Median	Mean (10 samples)	Std. Dev.	Skewness	Kurtosis	Quality Classification of irrigation water according to IS 2296-1963 (Revised after CGWB and CPCB 2000)				
									Excellent	Good	Medium	Bad	Very Bad
Electrical Conductance (EC)	mµS/cm	343.75	103.13	214.06	209.38	68.89	0.45	0.36	(<250)	(250-750)	(750-2250)	(2250-4000)	(>4000)
									BW 02-BW 03, BW 05-BW 10	BW 01& BW 04	NIL	NIL	NIL
									(80% samples)	(20% samples)	-	-	-
Sodium Adsorption Ratio (SAR)	epm	15.33	1.42	4.07	6.07	5.09	1.08	-0.26	(< 10)	(10-18)	(18-26)	(> 26)	-
									BW 02-BW 07, BW 09-BW 10	BW 01&BW08	NIL	NIL	-
									(80% samples)	(20% samples)	-	-	-
Residual Sodium Carbonate (RSC)	epm	116.38	34.87	80.31	76.42	25.37	-0.30	-0.51	(<1.25)	(1.25 - 2)	(2 - 2.5)	(2.5 – 3)	(>3)
									NIL	NIL	NIL	NIL	BW 01-BW 10
									-	-	-	-	(100% samples)
% Na	epm	88.94	25.08	52.62	51.32	22.52	0.50	-0.85	< 20%	20% - 40%	40% - 60%	60% - 80%	>80%
									NIL	BW 04, 05, 06 & BW 10	BW 02, 03, 07 & BW 09	NIL	BW 01 & BW 08
									-	(40% samples)	(40% samples)	-	(20% samples)
Permeability Index (PI)	epm	118.158	41.06	70.79	68.73	24.81	0.75	0.33	(>75)	(75-25)	(<25)	-	-
									BW 01&BW08	BW 02-BW 07, BW 09-BW 10	NIL	-	-
									(20% samples)	(80% samples)	-	-	-
Chloride	ppm	124.50	6.49	9.00	22.82	36.42	2.96	8.96	(≤ 600 ppm)			(> 600 ppm)	
									BW 01 – BW 10			NIL	
									100% samples are suitable for irrigation			NIL	
Sulphate	ppm	20.44	0.72	9.09	10.60	5.96	0.37	0.06	(≤ 1000 ppm)			(> 1000 ppm)	
									BW 01 – BW 10			NIL	
									100% samples are suitable for irrigation			NIL	
Chloride/ Bicarbonate (Cl/HCO_3)		2.895	0.06	0.11	0.39	0.88	3.14	9.90	90% samples are suitable for irrigation			BW 08 show values ≥ 1 indicating saline water dominance	

Table 4.35 Irrigation water quality classification of Post-Monsoon (2009) Bore Well (BW) Water Samples of Mulki River basin (*after* CGWB and CPCB 2000)

From the irrigation water quality evaluation of EC, SAR, % Na and RSC (Table 4.36), a great variation is noticed in irrigation water suitability based on different characteristics and is found to be 95% (pre-monsoon) and 100% (post-monsoon) based on EC, 100% (pre-monsoon) and 98% (post-monsoon) based on SAR, 84% (pre-monsoon) and 33% (post-monsoon) based on % Na, and 60% (pre-monsoon) and 03% (post-monsoon) based on RSC. Based on EC and SAR more than 95% of waters in the study area can be used for irrigation without the fear of salinity hazard. But, almost all the samples (97%) of post-monsoon and majority (60%) of pre-monsoon showed very high value of Residual Sodium Carbonate making the major water resources in the study area unfit for irrigation without proper corrective measures.

IRRIGATION WATER QUALITY CLASSIFICATION *after* **CGWB and CPCB (2000)**												
Water Class	**Electrical Conductivity (mµS/cm)**	Post Monsoon		Pre Monsoon			**Sodium Adsorption Ratio (epm)**	Post Monsoon		Pre Monsoon		
		Number of samples		Number of samples				Number of samples		Number of samples		
		OW (85)	BW (10)	OW (104)	BW (27)	SW (23)		OW (85)	BW (10)	OW (104)	BW (27)	SW (23)
Excellent	< 250	79	8	44	12	5	< 10	66	8	92	24	22
Good	250-750	5	2	17	13	7	10 - 18	14	2	9	1	1
Medium/Fair	750-2250	1	-	38	2	8	18 - 26	3	-	3	2	-
Bad/Poor	2250-4000	-	-	1	-	-	>26	2	-	-	-	-
Very Bad	>4000	-	-	4	-	3	-	-	-	-	-	-
Water Class	**% Na**	OW (85)	BW (10)	OW (104)	BW (27)	SW (23)	**Residual Sodium Carbonate (meq/l)**	OW (85)	BW (10)	OW (104)	BW (27)	SW (23)
Excellent	< 20	-	-	29	11	7	< 1.25	3	-	59	17	11
Good	20-40	6	4	38	11	9	1.25-2.0	-	-	3	-	-
Medium/Fair	40-60	17	4	16	3	5	2.0-2.5	-	-	3	-	-
Bad/Poor	60-80	44	-	18	2	2	2.5-3.0	-	-	1	-	-
Very bad	> 80	18	2	3	-	-	> 3.0	82	10	38	10	12

Table 4.36 Summary of Irrigation water quality suitability (Pre-Monsoon and Post-Monsoon) of water samples from Mulki River basin
(*after* Richards 1954; revised *after* CGWB and CPCB 2000)

<u>4.7.1 Salinity and Alkali Hazards:</u> The quality of water is commonly expressed by classes of relative suitability for irrigation with reference to salinity levels. A high salt content (high EC) in irrigation water leads to formation of saline soil. This affects the salt intake capacity of the plants through their roots. On the basis of electrical

conductivity values, Richards (1954) classified irrigation water in to four groups and CGWB and CPCB (2000) revised it into five groups (Table 4.36). The electrical conductivity values in the study area vary and range from 21.87μS/cm to 43,800μS/cm depending on the source and seasons with an average of 1215.14μS/cm (Tables 4.30 to 4.35). During the pre-monsoon period (2008 & 2009), it has been observed that the value is ranging between 40μS/cm to 30,300μS/cm in the open wells with a mean value of 1012.39μS/cm. The pre-monsoon bore well samples show mean Electrical conductance of 377.07μS/cm ranging between 92μS/cm to 1710μS/cm; whereas in the surface water samples mean EC is about 4567μS/cm with a ranging value of 155μS/cm to 43800μS/cm. This shows the influence of saline water in the open wells and surface water sources of coastal area. The EC value has not been much influenced the bore well samples and open well samples much during the post-monsoon period which ranges between 103.13μS/cm to 343.75μS/cm and 21.87μS/cm to 1703.13μS/cm respectively.

As per CGWB and CPCB (2000) classification a total of 148 samples (59%) comprising 123 Open wells, 20 bore wells and 5 surface water sources found to be excellent; 44 samples (18%) consisting of 22 open wells, 15 bore wells and 7 surface water sources found to be good; 49 samples (20%) comprising 39 open wells, 2 bore wells and 8 surface water sources found to be fair/medium; one pre-monsoon open well sample found to be poor/bad and 7 samples comprising 4 open wells and 3 surface water sources found to be of very bad category with high salinity (Table 4.36). Groundwater samples falling in medium salinity hazard can be used, if a moderate amount of leaching occurs. High salinity waters cannot be used on soil with restricted drainage. Excess salinity reduces the osmotic activity of plants and thus interferes with the absorption of water and nutrients from the soil (Saleh *et al.* 1999).

Comparatively Alkali hazards have not much affected the water resources of the study area (Table 4.36). Only two open well samples found to have a high value of alkalinity hazard (SAR). About 212 samples (85%) comprising 158 open wells, 32 bore wells and 22 surface sources found to be falling in the excellent category. About 27 samples (11%) comprising 23 open wells, 3 bore wells and 1 surface water source found to be in the good category. About eight samples (3%) comprising 6 open wells and 2 bore wells found to be in the fair/medium category of alkalinity hazard.

4.7.2 Sodium Adsorption Ratio (SAR): Sodium concentration is an important criterion in irrigation water classification because sodium reacts with the soil to create sodium hazards by replacing other cations. The relative activity of sodium ion in the exchange reaction with soil is expressed in terms of a ratio known as Sodium Adsorption Ratio (SAR). It is an important parameter for determining the suitability of irrigation water, because it is a measure of alkali/sodium hazard for crops. SAR can be estimated by the formula:

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

There is a significant relationship between sodium adsorption ratio of irrigation water and the extent to which sodium is adsorbed by the soils. If water used for irrigation is high in sodium and low in calcium content, then exchangeable calcium in soil may replace sodium by Base Exchange reaction in water. This can destroy the soil structure owing to dispersion of the clay particles. The SAR values in the study area range from 0.16 to 73.39 with an average of 4.95 (Tables 4.30 to 4.35). The water is of excellent quality in majority of the study area (Table 4.36). Based on the Bower (1978) classification, 64% of the water samples (57% during post-monsoon and 68% during pre-monsoon) from the study area have a SAR value less than 6, falls under no problem category confirming the excellent irrigation water quality. If the SAR value is greater than 6 to 9, the irrigation water will cause permeability problems in shrinking and swelling types of clayey soils (Saleh *et al.* 1999).

The plot of data on U.S. Salinity Laboratory classification diagram (Figs. 4.92 & 4.93), in which the EC is taken as salinity hazard and SAR as alkalinity hazard, shows that most of the water samples fall in the category C1S1 suggesting low salinity and low sodium hazards during both pre-monsoon and post-monsoon.

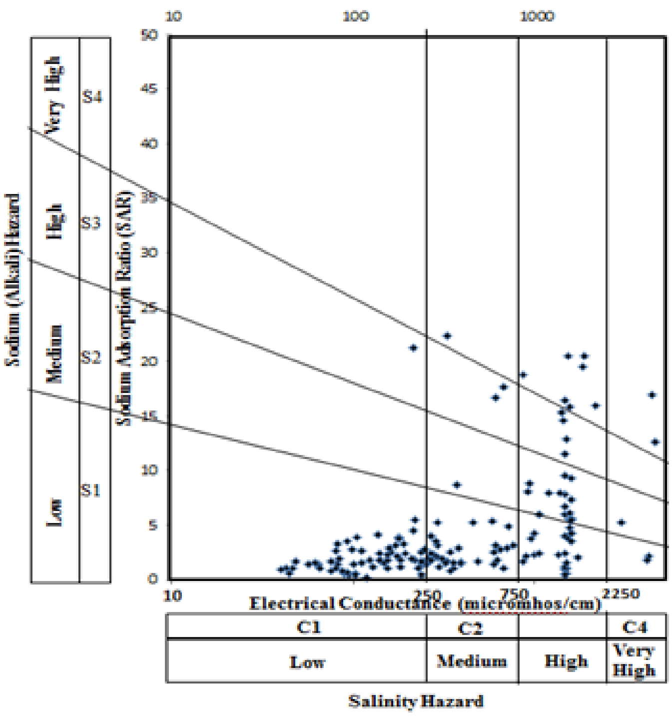

Fig. 4.92 Rating of Pre-Monsoon groundwater samples in relation to salinity hazards and sodium hazard (*after* Richards 1954) in the study area

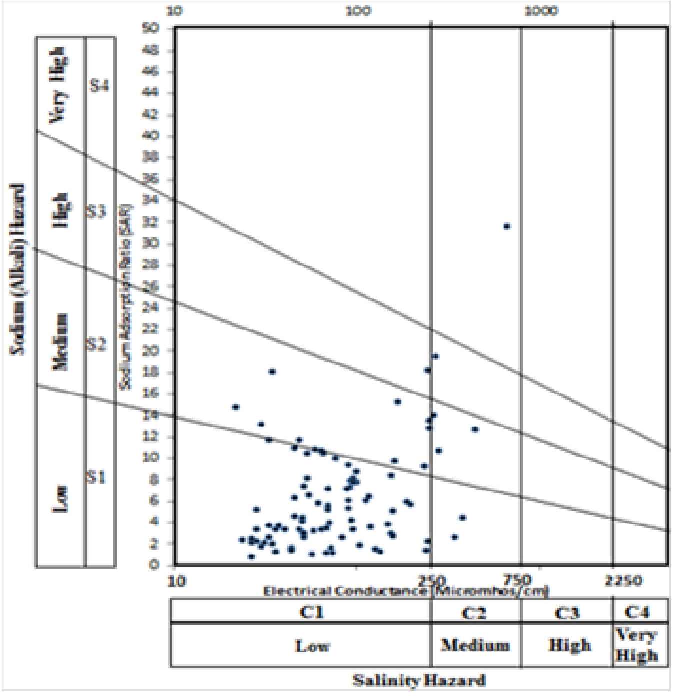

Fig. 4.93 Rating of Post-Monsoon groundwater samples in relation to salinity hazards and sodium hazard (*after* Richards 1954) in the study area

During pre-monsoon 43% open wells, 44% bore wells and 26% surface water sources fall in low salinity water field; whereas it is 69% open wells, 77% bore wells and 87%

surface water sources in the low SAR (S1) field. 95% of post-monsoon water falls in this Low salinity water (C1) category whereas it is 99% in the SAR (S1) field. Low salinity water (C1) can be used for irrigation with most crops on most soils. Low sodium (alkali) water (S1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium.

Medium salinity water (C2) can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control. During pre-monsoon 36% of open wells, 48% bore wells and 26% surface water sources fall in this category other than 4% open wells and 20% bore wells during post-monsoon. Medium sodium water (S2) will present an appreciable sodium hazard in fine textured soils having high cation exchange capacity especially under low leaching conditions. During pre-monsoon, 15% open wells, 11% bore wells and 13% surface water sources fall in this category. This water can be used on coarse textured or organic soils with good permeability (Karanth 1987).

The summary analysis of the plot and data (Table 4.37) shows that almost all samples during the post-monsoon fall in the excellent water category with low sodium hazard (99% samples) and low salinity (95% samples). But during pre-monsoon 41% of samples only falls in the low salinity whereas about 73% falls in the low sodium hazard category (Table 4.37). A few of the samples also fall in the high to severe salinity category, and high to very high sodium hazard category (Table 4.37). A high to very high and severe salinity category may be due to the declining in water table and concentration of salts during the pre-monsoon, other than saline water ingression. High Salinity (C3) cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good tolerance should be selected. Only good salt tolerant plants can use this water for irrigation during summer period. Highly saline water cannot be used on soils with restricted drainage and requires special management for salinity control. The soil must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching and salt tolerant crops/plants should be selected for such region (Karanth 1987). High sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management, good drainage, high leaching and organic matter additions.

Very high salinity water (C4) is not suitable for irrigation water under ordinary conditions, but may be used occasionally under very special circumstances. The soil must be permeable, drainage must be adequate and irrigation water must be applied in excess to provide considerable leaching and very salt tolerant crops should be selected. Severe salinity water (C5) is not at all useful for irrigation. Very high sodium water (S4) is generally unsatisfactory for irrigation purposes. Few samples have been found during pre-monsoon season for these categories (Table 4.37).

Water Type		Post Monsoon Samples (2009)			Pre-Monsoon samples (2008 & 2009)			
		Sample Numbers	Total Number of Samples		Sample Numbers (%)	Total Number of Samples		
			OW (85)	BW (10)		OW (104)	BW (27)	SW (23)
	Salinity							
C_1	Low	95% samples except 3 OW & 2 BW	82	8	43% OW, 44% BW & 26% SW	45	12	6
C_2	Medium	OW74, OW75, OW76 & BW1, BW4	3	2	16% OW, 48% BW & 26% SW	17	13	6
C_3	High	-	-	-	36% OW, 07% BW & 34% SW	37	2	8
C_4	Very High	-	-	-	OW 26, 31, 34 & 42; SW 16	4	-	1
C_5	Severe	-	-	-	OW 30; SW 17 & SW18	1	-	2
	Sodium Hazard		OW (85)	BW (10)		OW (104)	BW (27)	SW (23)
S_1	Low	99% samples	84	10	69% OW, 77% BW & 87% SW	72	21	20
S_2	Medium	OW 74	1	0	15% OW, 11% BW & 13% SW	16	3	3
S_3	High	-	-	-	3% OW	03	-	-
S_4	Very High	-	-	-	13% OW, 11% BW	13	3	-

Table 4.37 Summary of U.S. Salinity Diagram (Pre-Monsoon and Post-Monsoon) of water samples from Mulki River basin (*after* Richards 1954)

<u>4.7.3 Percent Sodium:</u> Since excess sodium in waters produces undesirable effects of changing soil properties and reducing soil permeability (Kelley 1946), its concentration is important in classifying irrigation water. In all natural waters, percentage of sodium content is a parameter to evaluate its suitability for agricultural purposes (Wilcox 1948). Sodium combining with carbonate can lead to the formation of alkaline soils, while sodium combining with chloride form saline soils. Both these soils do not help the growth of plants. Hence, the assessment of sodium concentration is of utmost importance while considering the suitability of irrigation water. The percent sodium is obtained by the following equation:

$$\%Na = \frac{Na^{+}+K^{+}}{Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}} \times 100 \quad \text{(all ionic concentrations are in epm)}$$

Sodium content is usually expressed in terms of percent sodium (%Na) and varies from 1.54 to 97.97 with an average of 41.06 in the study area (Tables 4.30 to 4.35). High percent sodium (%Na) causes deflocculation and impairment of the permeability of soils (Karanth 1987). As per Bureau of Indian Standards (BIS 1991), a maximum of 60% sodium in groundwater is allowed for agricultural purposes (Ramakrishna 1998) and 83% of the water samples from the study area are well within this limit. Plot of analytical data on Wilcox (1955) diagram (Fig. 4.94) relating electrical conductivity to sodium percent shows that 97% of the post-monsoon samples are Excellent for irrigation whereas only 64% of pre-monsoon samples are in this category of Excellent to Good. But all the bore well water samples during pre-monsoon found to be of Excellent to permissible categories. Only 6% of the all water samples found to be of the doubtful to unsuitable categories during pre-monsoon season (Table 4.38). The agricultural crop yields are generally low in lands irrigated with waters belonging to doubtful to unsuitable category. This is probably due to the presence of excess sodium salts, which cause osmotic effects on soil plant system. When the concentration of sodium is high in irrigation water, sodium ions tend to be adsorbed by clay particles, displacing Mg^{2+} and Ca^{2+} ions. This exchange process of Na^{+} in water for Ca^{2+} and Mg^{2+} in soil reduces the permeability and eventually results in soil with poor internal drainage. Hence, air and water circulation is restricted during wet conditions and such soils are usually hard when dry (Collins and Jenkins 1996, Saleh *et al.* 1999).

Water Type	Post Monsoon Samples (2009)			Pre-Monsoon samples (2008 & 2009)			
	Sample Numbers	Total Number of Samples		Sample Numbers (%)	Total Number of Samples		
		OW (85)	BW (10)		OW (104)	BW (27)	SW (23)
Excellent to Good	97% samples	83	9	59% OW; 93% BW; 52% SW	61	25	12
Good to Permissible	NIL	NIL	NIL	16% OW; 07% BW; 26% SW	17	2	6
Permissible to Doubtful	OW74 ; BW1	1	1	18% OW; 9% SW	19	-	2
Doubtful to Unsuitable	NIL	NIL	NIL	OW29 , OW34 & OW43	3	-	-
Unsuitable	OW7	1	NIL	OW26,30,31,42;SW16,17 &18	4	-	3

Table 4.38 Summary of Wilcox Diagram analysis of Mulki river Basin

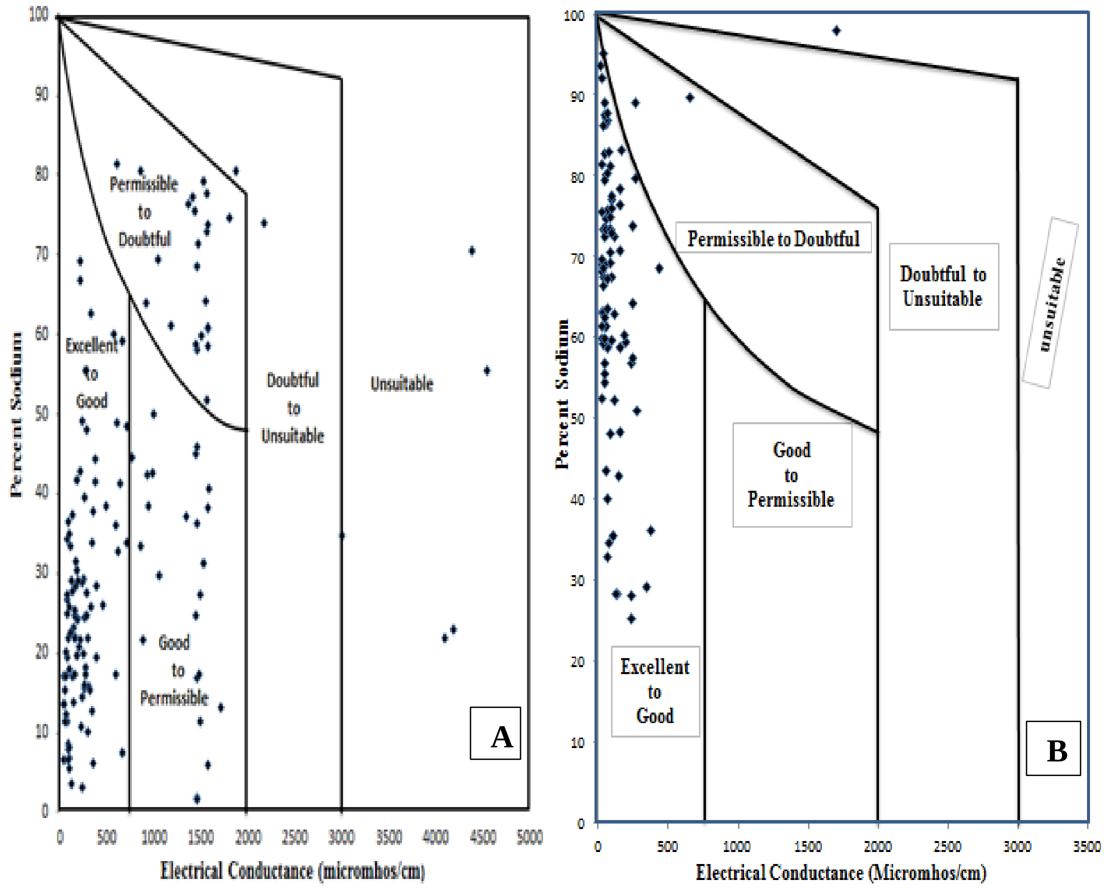

Fig. 4.94 Rating of Post-Monsoon (A) and Pre-Monsoon (B) groundwater samples on the basis of Electrical Conductance and Percent Sodium (*after* Wilcox 1948)

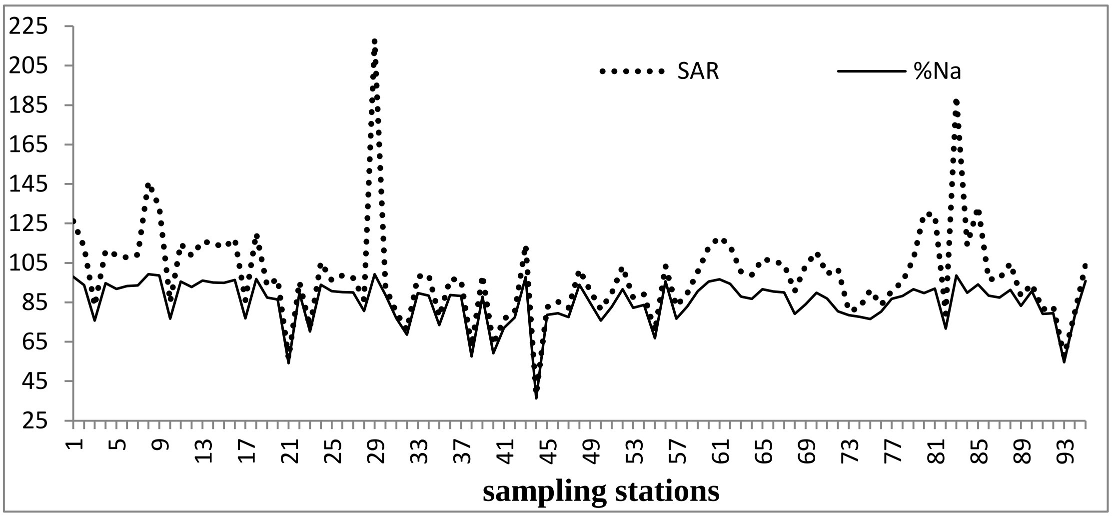

Fig. 4.95 Graph showing the variation and relation of SAR and Percent Sodium in the Post-Monsoon groundwater samples

The analysis revealed that the water in the study area generally is not having a problem caused by the sodium percentage in both seasons.

4.7.4 Residual Sodium Carbonate (RSC): In addition to the SAR and Sodium percent, the excess sum of carbonate and bicarbonate in groundwater over the sum of calcium and magnesium (alkaline earths) also influences the suitability of groundwater for irrigation. When the sum of carbonate and bicarbonates is in excess of calcium and magnesium, there may be possibility of complete precipitation of Ca and Mg (Karanth 1987). As a result water in the soil becomes more concentrated and the relative proportion of sodium in the water is increased in the form of sodium carbonate. To quantify the effects of carbonate and bicarbonate, residual sodium carbonate (RSC) in water has been computed as follows:

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+}) \quad \text{(all ions are expressed in epm)}$$

A high value of RSC in water leads to an increase in the adsorption of sodium in soil (Eaton 1950). Irrigation waters having RSC values greater than 5epm are considered harmful to the growth of plants, while water with RSC values above 2.5epm is not suitable for irrigation purpose. The calculated RSC values of groundwater samples of the study area show a very wide variation in range (Tables 4.30 to 4.35). Only 36% of all the water samples are of safe category (excellent) since their RSC values are less than 1.25epm and 61.45% samples found to be unsuitable for irrigation because of their high RSC values beyond 2.5epm (Table 4.36). During the pre-monsoon period 56.5% of water samples comprising 57% open wells, 63% bore wells and 48% surface water sources found to be of excellent category (RSC<1.25epm); whereas 39% comprising 36.5% of open wells, 37% of bore wells and 52% of surface water sources found to be of very bad (RSC>3 epm) category (Table 4.36). During the post-monsoon season 96.5% open well water samples and 100% bore well water samples found to be of very bad (RSC>3epm) category for irrigation except 3.5% open well water found to be of excellent nature. Continued usage of high residual sodium carbonate water affects the yields of crops.

4.7.5 Permeability Index**:** The soil permeability is affected by long-term use of irrigation water and is influenced by sodium, calcium, magnesium and bicarbonate contents of the soil. The permeability index (PI), as developed by Doneen (1964) indicates the suitability of groundwater for irrigation. It is defined as follows:

$$PI = \frac{(Na^{+} + \sqrt{HCO_3^{-}})}{(Ca^{2+} + Mg^{2+} + Na^{+})} \times 100$$

According to permeability indices the groundwater may be divided into Class I, Class II and Class III types. Class I and Class II water types are suitable for irrigation with 75 percent or more of maximum permeability, and Class III types of water with 25 percent maximum permeability. The PI values of the groundwater samples range from 1.72 to 193.68 with an average of 53.63 (Tables 4.30 to 4.35).

On the basis of Doneen's charts, 27.27% of pre-monsoon water samples comprising 26% surface water, 22% open well water and 48% bore well water found to have less than 25epm permeability index falling in the class III water type. The majority of the water samples (60.39%) fall in Class-II and 12% in Class I in the Doneen's chart, implying that the pre-monsoon water is of good quality for irrigation purposes. All the post-monsoon samples are of good quality for irrigation purposes thanks to its high permeability index falling in the Class-I and Class-II water types only. The majority of about 75% fall in Class-I and the remaining 25% in the Class-II water type making the post-monsoon water excellent for irrigation purposes.

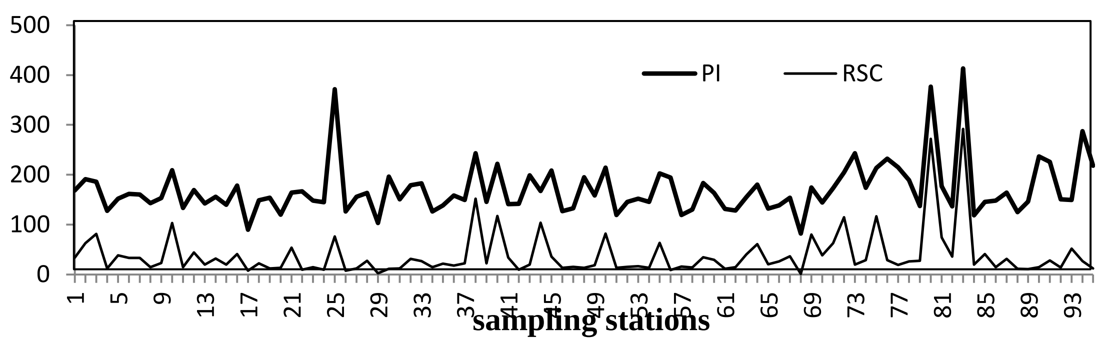

Fig. 4.96 showing the variation in the Permeability Index and Residual Sodium Carbonate of the Post-Monsoon water samples at different sampling stations

<u>4.7.6 Magnesium Hazard (MH)</u>**:** The Magnesium Hazard (MH) or Magnesium Ratio (MR) is the excess amount of Mg^{2+} over Ca^{2+}**.** Normally Mg^{2+} amounts are level with that of Ca^{2+}, and Mg^{2+} will thus be in a state of equilibrium. The excess Mg^{2+} affects the quality of the soil resulting in poor agricultural yields. High Concentration of Magnesium (MH>50) is considered harmful and unsuitable for irrigation purpose (Lloyd and Heathcoat 1985). Magnesium Hazard (MH) values were computed by Szaboles and Darab (1964) equation as given below:

$$MH = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100$$

In the analyzed post-monsoon water samples of the study area, 92% samples are having magnesium hazard below 50, indicating the water is suitable for irrigation purposes. But only 30.52% of the pre-monsoon samples found to have value MH<50 indicating the suitability for irrigation. All the pre-monsoon bore well waters found to have MH>50 making it unsuitable for irrigation purposes. This may be due to the dissolution and concentration of Mg rich minerals in the granitic rocks of the deep aquifer in this area. In the 52% surface water samples, and in 34% open well waters of pre-monsoon period MH found to be <50 indicating its suitability for irrigation purposes.

4.7.7 Chloride: Chloride being the most common constituent in all natural waters including rainwater in coastal region it may affect the crops if exceeds the limit of tolerance level. The contamination can also be from saline water intrusion along the coastal area other than return flow from agricultural fields receiving fertilizers. Irrigation water containing more than 600 ppm chloride is not suitable for the same. The concentration of chloride in the study area varies from 1.45 ppm to 34,193.29 ppm with a mean of 815.79 ppm (Tables 4.30 to 4.35). About 83% of the surface water samples found to be suitable for irrigation, whereas the remaining were contaminated with very high chloride concentration due to the saline water intrusion along the coastal stretch in Mulki, Kolachikambla and Karnad. The chloride concentration in the pre-monsoon open well water samples of the study area found to be varying from 1.45ppm to 4118.49ppm with an average of 110.37ppm, and about 96% of them found to be suitable for irrigation purposes (Tables 4.31 and 4.32). The four open wells which showed very high concentration of chloride belong to the coastal stretch along Karnad, Kolachikambla and Padubidri which are contaminated due to the saline water intrusion. During the post-monsoon, chloride concentration in the open well samples varied from 4.90ppm to 149.90ppm with a mean of 19.97ppm and is well suited for irrigation purposes (Table 4.33). The bore well samples during pre- and post-monsoon are all well suited for irrigation purposes without high concentration of chloride in it (Table 4.34 and 4.35). Thus 97% of the water samples found to be suitable for irrigation purposes, except a few along the coast where the saline water migration might have contaminated the surface and open well water sources.

<u>4.7.8 Sulphate</u>: The sulphate content in groundwater generally occurs as soluble salts of calcium, magnesium and sodium. The sulphate content changes significantly with time during infiltration of rainfall and groundwater recharge, which mostly takes place from stagnant water pools and surface runoff water collected in low lying areas (CPCB 2008). Other than leaching from the soils or rocks it can be from the return flow from irrigation fields. If in excess or equivalent to the calcium or magnesium it may contribute to the permanent hardness of the water and may create impermeable conditions in the soil affecting the agriculture. The concentration of sulphate in the study area varies from zero to 98 ppm with a mean of 11.13 ppm (Tables 4.30 to 4.35) which is excellent for irrigation purposes. The water resources in the study area found to be excellent for irrigation regarding sulphate concentration.

<u>4.7.9 Chloride-Bicarbonate Ratio:</u> The Chloride-Bicarbonate ratio shows the predominance of chloride or saline water over the other anions. The chloride-bicarbonate ratio has been computed for all the samples and analyzed to understand the saline water intrusion in the study area (Tables 4.30 to 4.35). The computed values range from 0.04 to 488.48 with an average of 12.24 showing the aggressiveness of the saline water migration in certain areas along the coast (Figs. 4.97 to 4.102). About 22% of the water resources in the area comprising 30% of the surface water sources, 24% of open well sources and 8% of the bore wells have been contaminated with saline water intrusion.

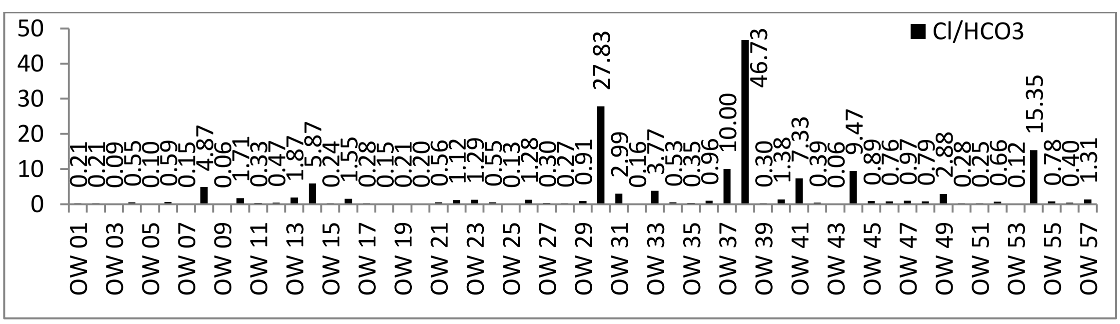

Fig. 4.97 Chloride-Bicarbonate ratio diagram for Pre-Monsoon (2008) Open Well water samples from the study area

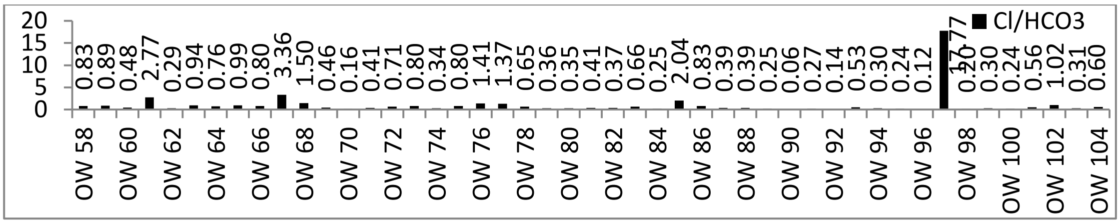

Fig. 4.98 Chloride-Bicarbonate ratio diagram for Pre-Monsoon (2009) Open Well water samples from the study area

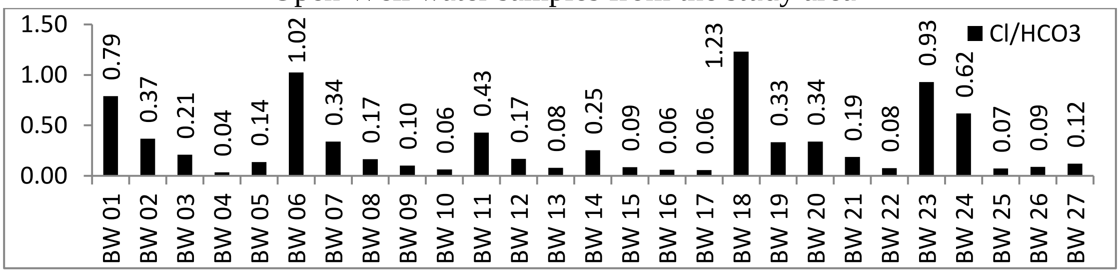

Fig. 4.99 Chloride-Bicarbonate ratio diagram for Pre-Monsoon (2008 & 2009) Bore Well water samples from the study area

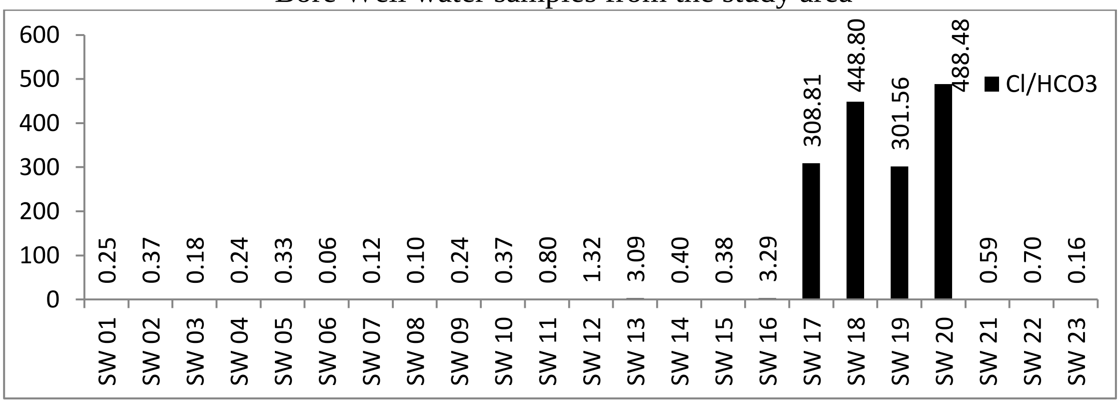

Fig. 4.100 Chloride-Bicarbonate ratio diagram for Pre-Monsoon (2008 & 2009) Surface water samples from the study area

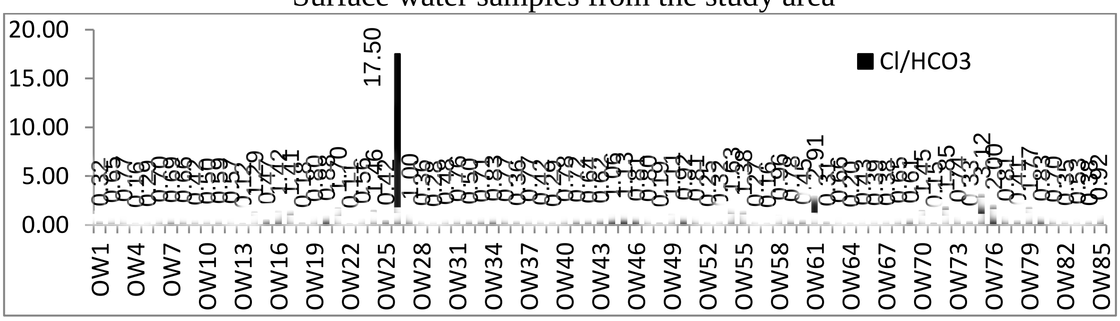

Fig. 4.101 Chloride-Bicarbonate ratio diagram for Post-Monsoon (2009) Open Well water samples from the study area

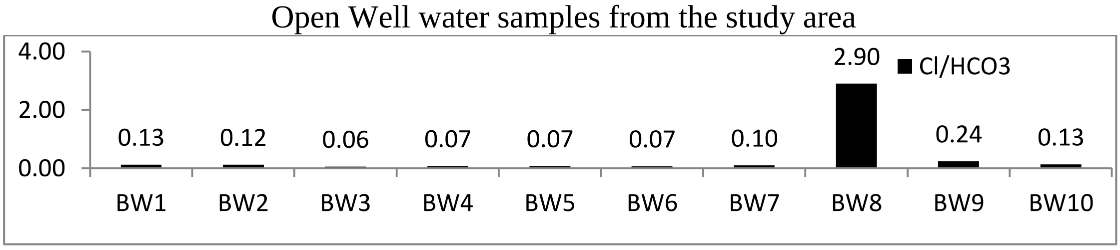

Fig. 4.102 Chloride-Bicarbonate ratio diagram for Post-Monsoon (2009) Bore Well water samples from the study area

4.8 GEOSTATISTICAL ANALYSIS OF SPATIAL VARIABILITY IN HYDRO GEOCHEMISTRY: An integration of various groundwater quality parameters in the Geographical Information System may give better spatial variation of the water quality and will be useful in the sustainable development of groundwater (Ambhazhagan and Archana 2004, Singh and Lawrence 2007, Rao, J. M. *et al.* 2007, Jeere D.S. *et al.* 2008, Vennila *et al.* 2008). Groundwater vulnerability maps are valuable derivative maps that show quantitatively or qualitatively, certain characteristics of the sub-surface environment that determine the vulnerability of groundwater to contamination (Umar R. *et al.* 2009). Water Quality Index (WQI) is one of the most effective tools to understand the suitability of water for drinking purposes (Ramakrishnaiah et al. 2009, Priya et al. 2010). An integrated approach of Geographical Information System with the statistical analysis of the hydrogeochemistry may give a better understanding of the quality variation of groundwater with domain and time (Radhakrishnan, K. et al. 2011).

4.8.1 Preparation of Thematic Maps and GIS Analysis: The geographical co-ordinates of the sampling stations in the study area located by Garmin hand held GPS have been transferred in to the base map of the river basin using ERDAS Imagine 9.1 version software. Thematic maps of important water quality parameters variation were prepared transferring the analytical values of pH, Turbidity, EC, TDS, TH, B.O.D., Cl^-, Na^+, Ca^{2+}, HCO_3^-, Fe, SO_4^{2-} and NO_3^- of two different pre-monsoon seasons (April-May 2008 & 2009) and a post-monsoon season (2009) using ArcGIS 9.x versions to understand the spatial and temporal variation (Figs 4.103 – 4.116). Then data of both years were merged and interpolated using weighted average method (ESRI 2000) to obtain the variation maps of different parameters. Using ArcGIS, vulnerability map of the area has been prepared (Fig. 4.117) overlaying the quality vulnerability of the above parameters.

4.8.2 Quality Variation and Vulnerability: Regional assessment of groundwater quality is gaining importance where pollution is encroaching natural barriers and beyond. In the past few decades groundwater contamination has become one of the most serious problems in the world. Once polluted, remediation of aquifers would be very difficult, and even sometimes it becomes impossible to restore its original quality

(Qinghai et al. 2007). The groundwater utilization has increased manifold due to advancement in agrarian sector together with rapid industrialization. The groundwater abstraction from shallow aquifers is continuously on the rise which could be related to multifarious problems, like overexploitation and quality deterioration, thus posing threats to the sustainability of this precious resource. Spatial variation map of vulnerable parameters in the pre-monsoon groundwater has been plotted and given below (Fig. 4.117).

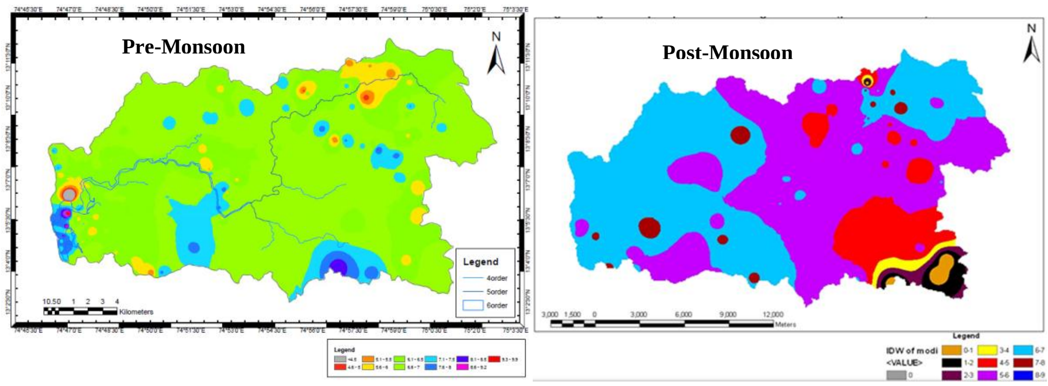

Fig. 4.103 Spatial variation of pH during Pre-Monsoon (a) & Post-Monsoon (b) in Mulki River basin

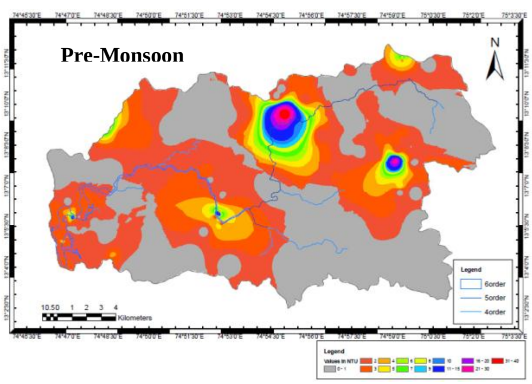

Fig. 4.104 Spatial variation of Turbidity during Pre-Monsoon in Mulki River basin

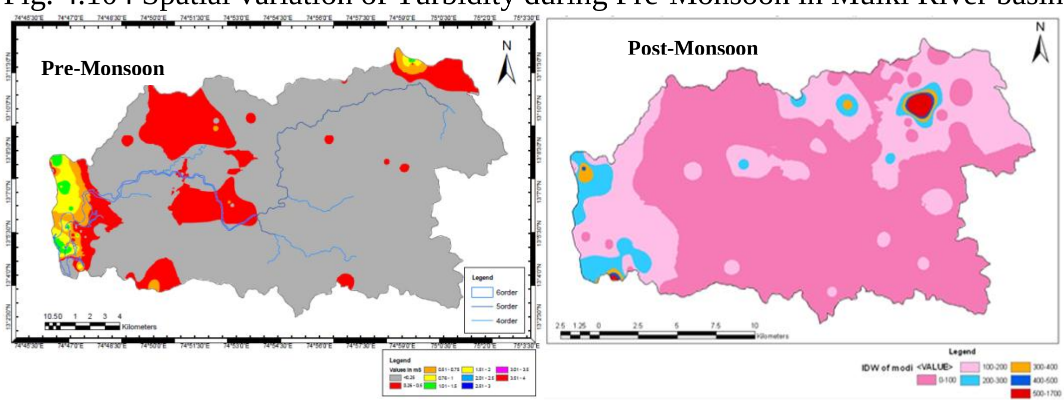

Fig. 4.105 Spatial variation of EC during Pre- & Post-Monsoon in Mulki River basin

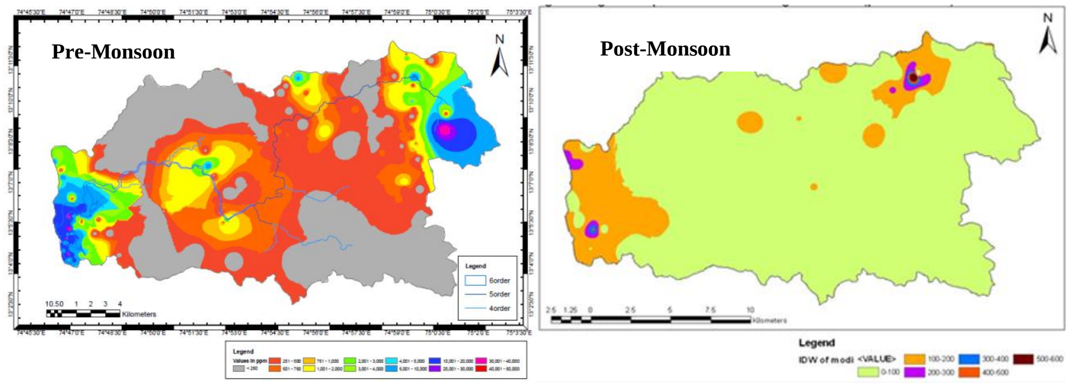

Fig. 4.106 Spatial variation of TDS during Pre- & Post-Monsoon in Mulki River basin

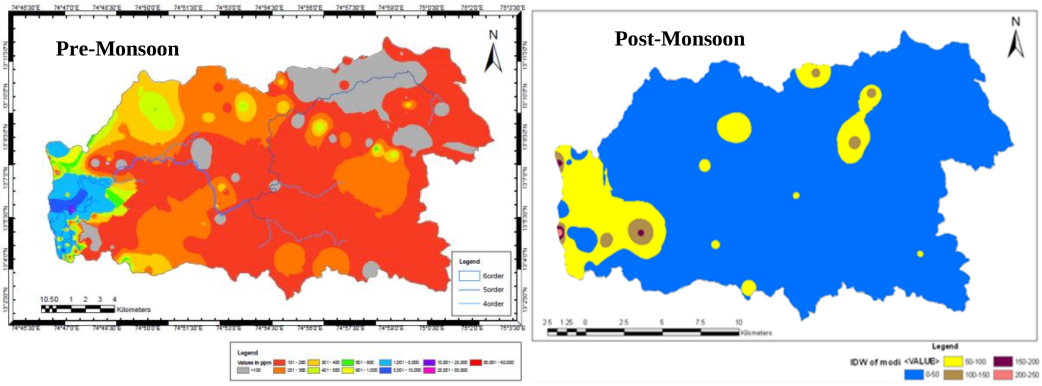

Fig. 4.107 Spatial variation of TH during Pre- & Post-Monsoon in Mulki River basin

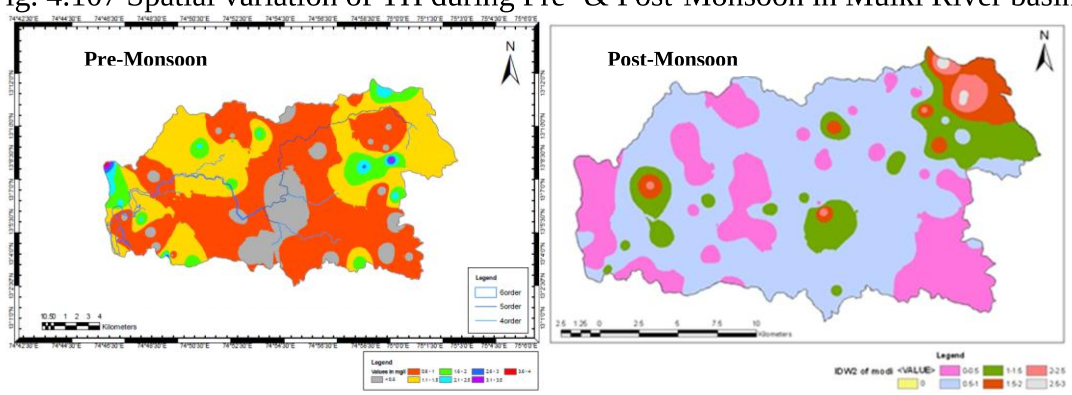

Fig. 4.108 Spatial variation of B.O.D. during Pre-Monsoon (2009) in Mulki River basin

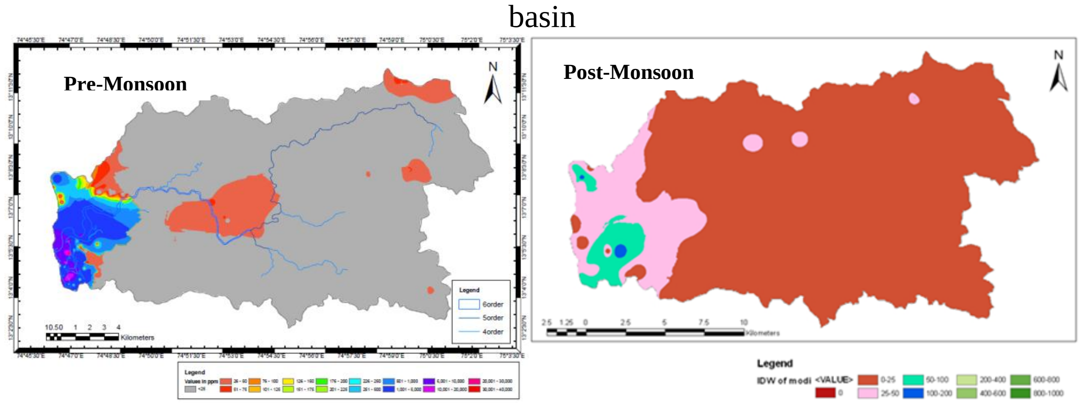

Fig. 4.109 Spatial variation of Chloride during pre- and Post-Monsoon in Mulki River basin

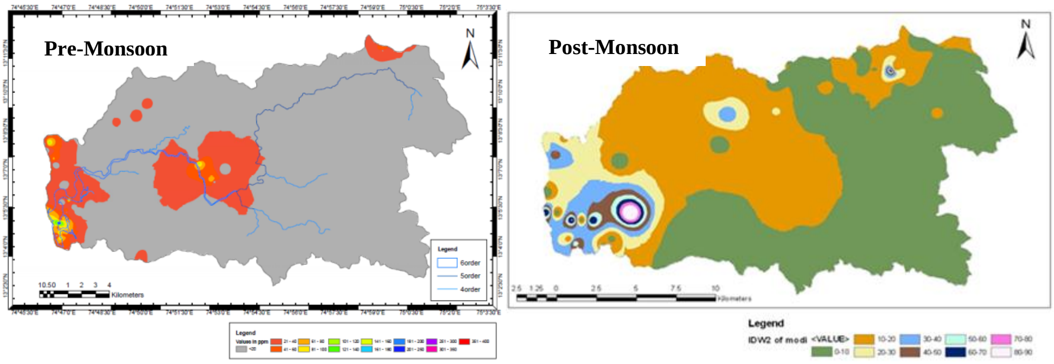

Fig. 4.110 Spatial variation of Sodium during Pre- and Post- monsoon in Mulki River basin

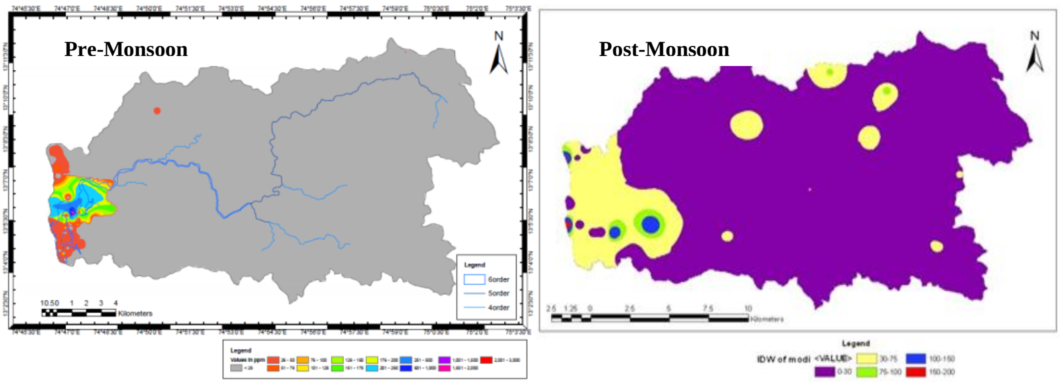

Fig. 4.111 Spatial variation of Calcium during Pre- & Post-Monsoon in Mulki River basin

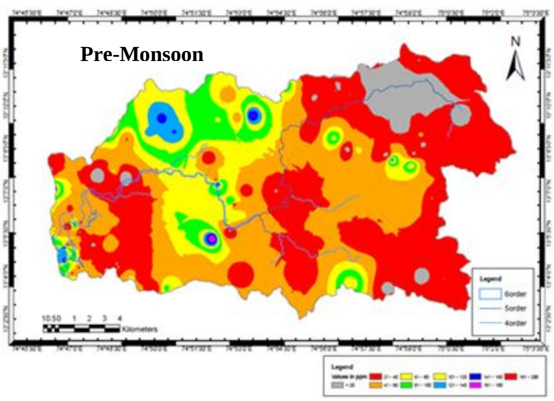

Fig. 4.112 Spatial variation of Bicarbonate during Pre-Monsoon in Mulki River basin

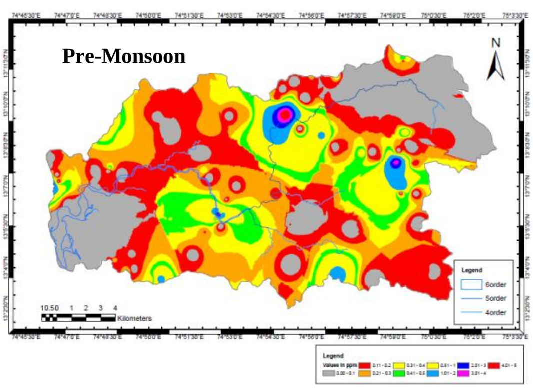

Fig. 4.113 Spatial variation of Iron during Pre-Monsoon in Mulki River basin

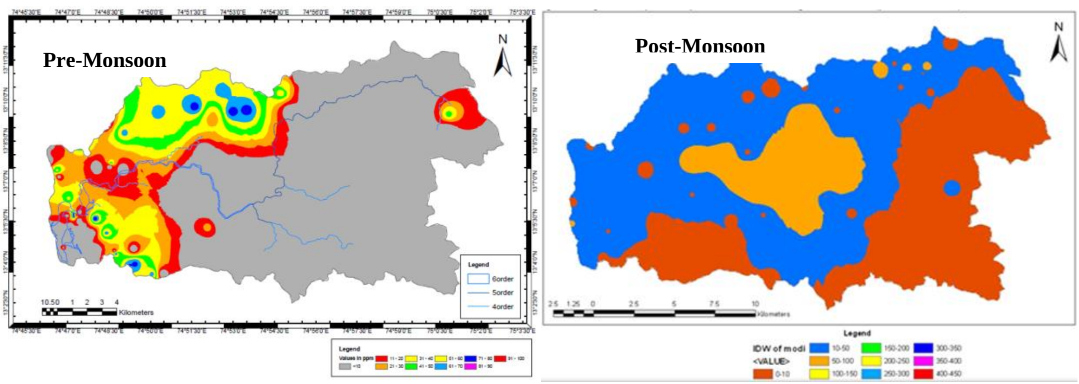

Fig. 4.114 Spatial variation of Sulphate during Pre- & Post-Monsoon in Mulki River basin

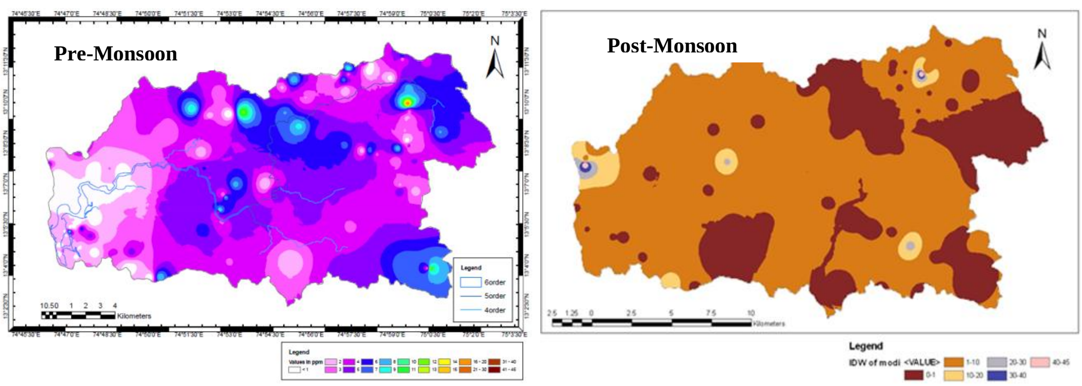

Fig. 4.115 Spatial variation of Nitrate during Pre- & Post-Monsoon in Mulki River basin

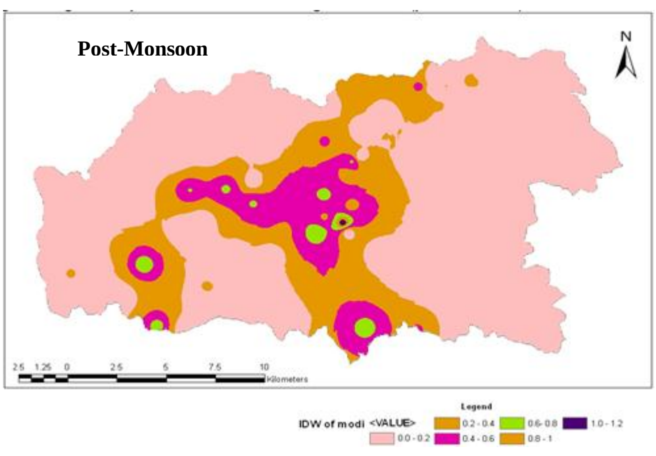

Fig. 4.116 Spatial variation of Fluoride during Post-Monsoon in Mulki River basin

The spatial distribution map of different water quality parameters suggests that the geology of the area also influences the concentration of certain parameters in the groundwater besides the temporal variation observed. The temporal variation could be due to the fluctuation of the groundwater and infiltrating rainwater in addition to outside influence in the natural system. In recent years, groundwater vulnerability assessment has become very useful tool for planning and decision making of groundwater management and protection (Collin and Melloul 2003, Vias *et al*. 2005, Vrba and Zeporozec 1994, Umar *et al.* 2009). From the spatial variation maps of different water quality parameters prepared, the vulnerable area has been mapped based on the permissible limit (BIS 1991) using ArcMap 9.x and overlaid to obtain the water quality vulnerable area in the basin (Fig. 4.117).

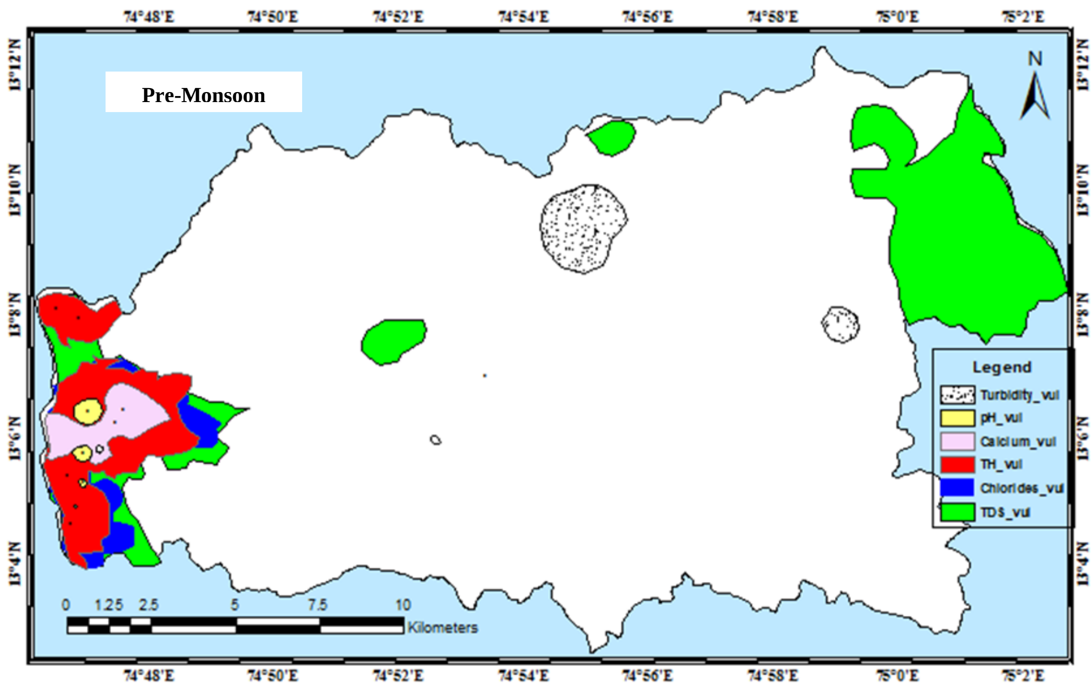

Fig. 4.117 Water Quality Vulnerability Map of Mulki River Basin during Pre-Monsoon

From this, it has been observed that the coastal area is more vulnerable in respect of various quality parameters such as pH, Turbidity, Total Hardness, TDS, Calcium and Chloride which extends up to seven kilometers from the coast especially along the alluvial plain indicating the influence of rapid urbanization and industrialization in water quality deterioration. Field observations revealed that deterioration of quality of groundwater along the coastal region of Mulki was caused by industrial waste, sewage of urban or semi-urban sanitary effluents, intrusion of salt water due to over exploitation of coastal aquifers, and sea water ingression through streams during high tidal times (Lokesh and Shenoy, 1996, 1997a, 1997b, Radhakrishnan and Lokesh

2010, Radhakrishnan *et al.* 2011a, 2011b). Other water quality vulnerable areas are in north eastern side of the basin in terms of Total Hardness, and another near Jarigakatte which may be attributed to the geology of the area and localized anthropogenic interference. The high turbidity, especially in the bore wells of inland area may be attributed to the iron oxides and agitation due to pumping in the poorly developed wells.

4.8.3 Water Quality Index: Water quality index (WQI) gives an idea about the suitability of the source water for drinking purposes based on quality weightage factor (Priya *et al.* 2010). WQI is defined as a rating of the suitability of groundwater for human consumption, reflecting the composite influence of different water quality parameters (Ramakrishnaiah et al. 2009). This becomes an important tool for the assessment and management of groundwater (Asadi *et al.* 2007, Dwivedi and Vandana 2007). The water quality standard for various physico-chemical parameters have been decided based on the BIS or WHO standards for drinking water. The weightages have been calculated based on the BIS standards and ideal values of each parameter. All the samples collected during pre- and post- monsoon seasons were assessed separately and source wise in order to understand the water quality index for the sampling source. The calculations were made as follows:

Water Quality Index $WQI = antilog \sum_{i=1}^{n} \mathrm{Wi}.log10.qi$

Where 'Wi' is the weightage for each parameter and 'qi' is the water quality rating.

Weightage of each parameter is calculated as, $W_i = K/S_i$

where 'K' is the proportionality constant given by

$$K = 1/\sum_{i=1}^{n}(1/Si)$$

'S_i' is the drinking water standard value prescribed by WHO/BIS for each parameter. Then the quality rating is calculated using the equation

$$qi = 100 * [(V_{actual} - V_{ideal}) / (V_{standard} - V_{ideal})$$

where V_{actual} and V_{ideal} are the observed values and the ideal value for each parameter respectively, $V_{standard}$ is the standard value for each parameter as per BIS/WHO standards. V_{ideal} for pH is taken as 7 and that for DO as 14.6ppm, when for all other parameters zero is assumed as the ideal value. The standard value ($V_{standard}$) and the corresponding weightage (W_i) obtained for each parameter during pre-monsoon and post-monsoon seasons are given in Table 4. 39.

Sl. No.	Parameter	Standard Value ($V_{Standard}$)	Weightage (Wi)	
			Pre-Monsoon	Post-Monsoon
1	pH	6.5	0.038166685	0.030580234
2	Dissolved Oxygen	4 ppm	0.062020862	0.049692881
3	Turbidity	5 NTU	0.04961669	0.039754305
4	EC	2000 ppm	0.000124042	9.93858E-05
5	Total Dissolved Solids	500 ppm	0.000496167	0.000397543
6	Alkalinity	200 ppm	0.001240417	0.000993858
7	Calcium	75 ppm	0.003307779	0.002650287
8	Magnesium	30 ppm	0.008269448	0.006625717
9	Iron	0.3 ppm	0.826944831	0.662571747
10	Bicarbonate	200 ppm	0.001240417	0.000993858
11	Chloride	250 ppm	0.000992334	0.000795086
12	Nitrate	45 ppm	0.005512966	0.004417145
13	Sulphate	200 ppm	0.001240417	0.000993858
14	Total Hardness	300 ppm	0.000826945	0.000662572
15	Flouride	1 ppm	-	0.198771524

Table 4.39 Standard values of water quality parameters and their weightages in Mulki River Basin

The water quality indices computed for all the samples collected during pre- and post-monsoon seasons (Table 4.40 & Table 4.41) were plotted using 'Surfer 10' software and analyzed for the spatial variation in distribution pattern during pre- and post-monsoon seasons (Fig. 4.118 & Fig. 4.119).

The very high WQI indices at the coastal front near the mouth of the river and its extension along the river course upstream to certain distance during pre-monsoon indicates the influence of saline water and its migration along tidal water in this area (Fig. 4.118). Other places where very high water quality indices noticed in the inland area suggests the influence of geology in groundwater quality.

Source No.	Sam-ple No.	WQI	Source No.	Sam-ple No.	WQI	Source No.	Sam ple No.	WQI	Source No.	Sam ple No.	WQI
OW 01	6	1.93	**OW 27**	48	25.21	**OW 53**	80	1.63	**OW 79**	112	1.75
OW 02	14	2.08	**OW 28**	49	26.75	**OW 54**	81	25.02	**OW 80**	113	54.72
OW 03	15	1.95	**OW 29**	50	14.57	**OW 55**	82	25.35	**OW 81**	114	34.85
OW 04	16	2.13	**OW 30**	52	8.49	**OW 56**	83	21.72	**OW 82**	116	1.50
OW 05	17	34.44	**OW 31**	53	24.78	**OW 57**	85	29.11	**OW 83**	117	34.87
OW 06	19	1.91	**OW 32**	55	25.11	**OW 58**	86	103.50	**OW 84**	118	713.43
OW 07	20	2.08	**OW 33**	56	35.70	**OW 59**	87	1.38	**OW 85**	121	58.66
OW 08	21	1.97	**OW 34**	57	25.50	**OW 60**	88	30.08	**OW 86**	122	55.20
OW 09	22	2.01	**OW35**	58	24.72	**OW 61**	89	37.03	**OW 87**	123	1.67
OW 10	23	1.96	**OW 36**	59	24.81	**OW 62**	90	35.47	**OW 88**	124	12.16
OW 11	24	2.08	**OW 37**	61	28.96	**OW 63**	92	1.74	**OW 89**	125	1.89
OW 12	25	2.03	**OW 38**	62	29.70	**OW 64**	94	1.87	**OW 90**	133	54.24
OW 13	26	2.09	**OW 39**	63	36.79	**OW 65**	95	1.70	**OW 91**	134	8.43
OW 14	27	2.07	**OW 40**	64	30.43	**OW 66**	96	1.73	**OW 92**	138	90.10
OW 15	28	1.97	**OW 41**	65	26.12	**OW 67**	99	1.55	**OW 93**	139	168.83
OW 16	29	2.05	**OW 42**	67	30.88	**OW 68**	100	1.70	**OW 94**	140	92.44
OW 17	32	2.02	**OW 43**	68	25.45	**OW 69**	101	29.36	**OW 95**	142	84.53
OW 18	33	1.93	**OW 44**	69	12.48	**OW 70**	102	197.56	**OW 96**	145	1.58
OW 19	35	1.90	**OW 45**	70	16.78	**OW 71**	103	7.85	**OW 97**	147	2.04
OW 20	36	1.89	**OW 46**	71	13.49	**OW 72**	104	30.98	**OW 98**	149	2.03
OW 21	37	1.93	**OW 47**	73	26.63	**OW 73**	105	8.56	**OW 99**	150	19.39
OW 22	38	1.93	**OW 48**	74	18.29	**OW 74**	106	1.93	**OW 100**	152	95.21
OW 23	41	1.86	**OW 49**	76	12.33	**OW 75**	107	32.55	**OW 101**	153	1.95
OW 24	43	2.00	**OW 50**	77	21.18	**OW 76**	108	50.44	**OW 102**	155	86.06
OW 25	44	1.85	**OW 51**	78	1.67	**OW 77**	109	1.62	**OW 103**	161	108.10
OW 26	46	27.96	**OW 52**	79	1.69	**OW 78**	110	1.55	**OW 104**	162	29.88
BW 01	30	65.72	**BW 08**	126	373.37	**BW 15**	135	91.10	**BW 22**	156	68.29
BW 02	93	50.33	**BW 09**	127	681.80	**BW 16**	136	61.94	**BW 23**	157	60.38
BW 03	97	55.02	**BW 10**	128	74.31	**BW 17**	141	307.76	**BW 24**	158	63.42
BW 04	111	215.36	**BW 11**	129	142.22	**BW 18**	143	84.27	**BW 25**	159	71.06
BW 05	115	236.45	**BW 12**	130	69.37	**BW 19**	146	523.16	**BW 26**	160	80.80
BW 06	119	51.25	**BW 13**	131	226.35	**BW 20**	151	64.71	**BW 27**	163	56.83
BW 07	120	127.35	**BW 14**	132	951.53	**BW 21**	154	82.04	**-**	-	-
SW 01	1	1.90	**SW 07**	9	2.10	**SW 13**	34	1.95	**SW 19**	60	33.32
SW 02	3	1.89	**SW 08**	10	2.07	**SW 14**	42	1.86	**SW 20**	66	21.37
SW 03	4	1.94	**SW 09**	11	2.07	**SW 15**	45	2.15	**SW 21**	84	30.68
SW 04	5	1.92	**SW 10**	12	29.09	**SW 16**	47	1.73	**SW 22**	98	304.58
SW 05	7	1.99	**SW 11**	13	29.79	**SW 17**	51	24.71	**SW 23**	137	25.25
SW 06	8	118.16	**SW 12**	31	2.16	**SW 18**	54	23.83	**-**	-	-

Table 4.40 Water Quality Indices of Pre-Monsoon water samples which were affected beyond water quality standards in Mulki River basin

During pre-monsoon period, 55% of the open well waters found to be in the highly desirable category for drinking water based on water quality indices, whereas 5% of them found to be unfit for drinking (Fig. 4.119). At the same time 31% of the pre-monsoon open well waters found to be of desirable quality whereas 5% each of them fall in the moderately suitable and very poor quality categories. The average water quality index (WQI) is found to be about 30.55 ranging from a minimum of 1.38 to a maximum of 713.43 (Table 4.40). At the same time, the Pre-Monsoon bore well waters found to have no samples falling in the highly desirable (HD) or desirable (D) category, whereas 37% falls in the unfit for drinking (UFD) and 15% in the very poor (VP) water quality categories. In the moderately suitable (MS) and poorly suitable (PS) categories, the percentages are 15% and 33% respectively. The average water quality index (WQI) is found to be about 182.82 ranging from a minimum of 50.33 to a maximum of 951.53 (Table 4.40). The major percentage (91%) of the surface water sources comprising ponds and lakes are of low water quality indices making them of good quality for consumption. The average water quality index (WQI) in these sources is found to be about 28.98 ranging from a minimum of 1.73 to a maximum of 304.58 (Table 4.40).

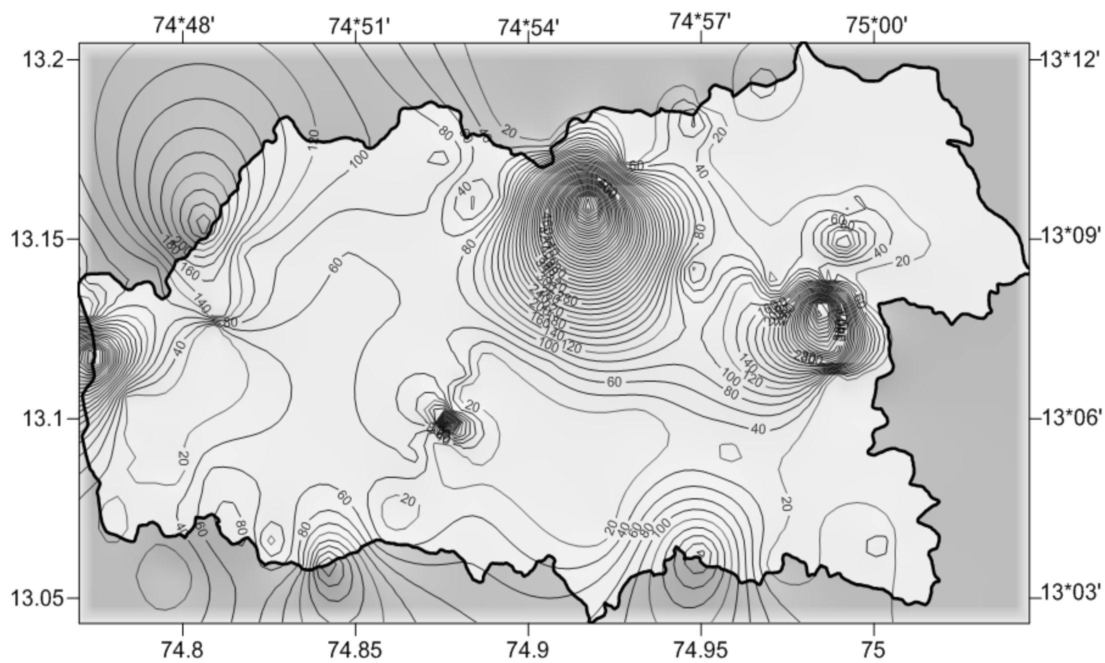

Fig. 4.118 Spatial variation and distribution of Water Quality Index for Pre-Monsoon groundwater at Mulki River Basin

During the post-monsoon, the water quality indices are found to be very high only in some pockets where the geology and other external processes might have influenced the quality of the water (Fig. 4.120). The concentrations and distribution of high water quality indices at the inland area shows similarity with the pre-monsoon WQI distribution (Fig. 4.118), but with comparatively lesser values. This clearly shows the influence of geology besides the climatic factors in the water quality indices of the area. During the post-monsoon, the WQI is comparatively less due to the dilution process of water infiltrating through the aquifer during heavy monsoon in this area.

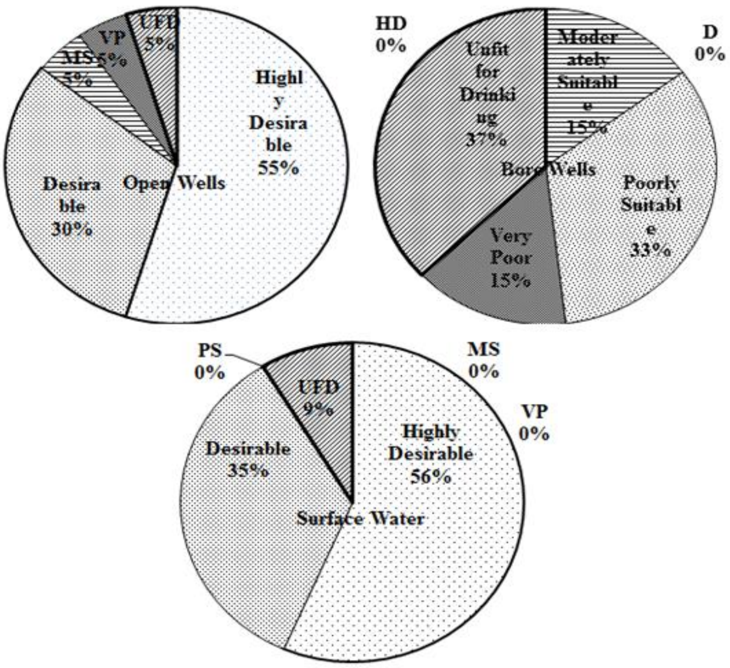

Fig. 4.119 Pie diagrams showing the Water Quality Index Rating and their percentage in the Mulki River Basin samples during Pre-Monsoon

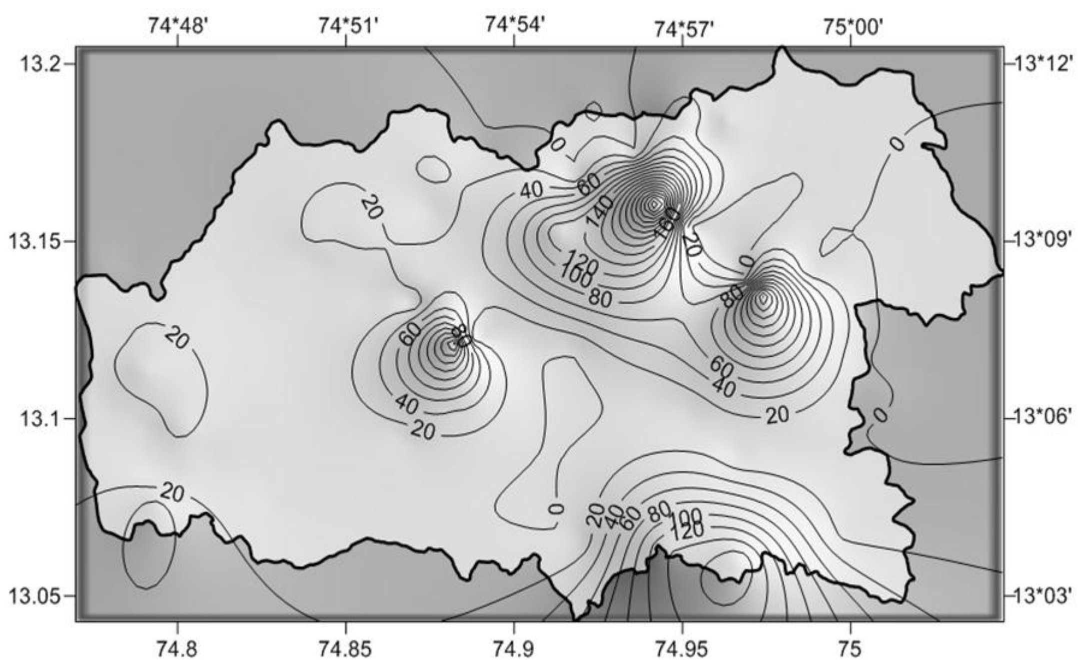

Fig. 4.120 Spatial distribution of Water Quality Index for Post-Monsoon groundwater at Mulki River Basin

Source No.	Sample No.	WQI	Source No.	Sample No.	WQI	Source No.	Sam-ple No.	WQI	Source No.	Sample No.	WQI
OW1	1	28.66	**OW25**	28	2.26	**OW49**	56	2.55	**OW73**	82	51.33
OW2	4	3.43	**OW26**	29	2.40	**OW50**	57	2.50	**OW74**	83	2.79
OW3	5	3.80	**OW27**	30	2.10	**OW51**	58	2.69	**OW75**	84	2.51
OW4	6	4.03	**OW28**	31	2.36	**OW52**	59	1.99	**OW76**	85	2.95
OW5	7	3.61	**OW29**	32	2.26	**OW53**	60	26.43	**OW77**	86	9.51
OW6	8	3.36	**OW30**	33	2.28	**OW54**	61	24.90	**OW78**	87	2.85
OW7	9	3.51	**OW31**	34	2.32	**OW55**	62	23.15	**OW79**	88	4.02
OW8	11	3.82	**OW32**	35	2.43	**OW56**	63	8.30	**OW80**	89	2.60
OW9	12	3.61	**OW33**	36	2.50	**OW57**	64	21.26	**OW81**	90	2.55
OW10	13	3.86	**OW34**	37	2.42	**OW58**	65	11.33	**OW82**	91	3.48
OW11	14	3.17	**OW35**	39	2.51	**OW59**	66	16.84	**OW83**	92	135.10
OW12	15	3.71	**OW36**	41	2.88	**OW60**	67	15.58	**OW84**	94	25.20
OW13	16	3.58	**OW37**	42	2.58	**OW61**	68	17.15	**OW85**	95	16.10
OW14	17	3.89	**OW38**	43	2.60	**OW62**	69	2.17	**BW1**	2	133.20
OW15	18	3.69	**OW39**	45	3.01	**OW63**	71	2.59	**BW2**	3	266.10
OW16	19	36.57	**OW40**	46	2.75	**OW64**	72	2.71	**BW3**	10	211.70
OW17	20	4.51	**OW41**	47	2.58	**OW65**	73	2.78	**BW4**	38	2.80
OW18	21	20.34	**OW42**	48	2.60	**OW66**	74	32.05	**BW5**	40	380.90
OW19	22	8.13	**OW43**	49	2.48	**OW67**	76	8.72	**BW6**	44	252.00
OW20	23	31.37	**OW44**	51	2.83	**OW68**	77	2.40	**BW7**	50	3.10
OW21	24	2.07	**OW45**	52	2.63	**OW69**	78	9.61	**BW8**	70	38.10
OW22	25	1.83	**OW46**	53	2.55	**OW70**	79	28.56	**BW9**	75	40.00
OW23	26	2.07	**OW47**	54	2.60	**OW71**	80	3.65	**BW10**	93	179.10
OW24	27	2.27	OW48	55	2.67	**OW72**	81	2.73	-	-	-

Table 4.41 Water Quality Indices of Post-Monsoon water samples from Mulki River basin

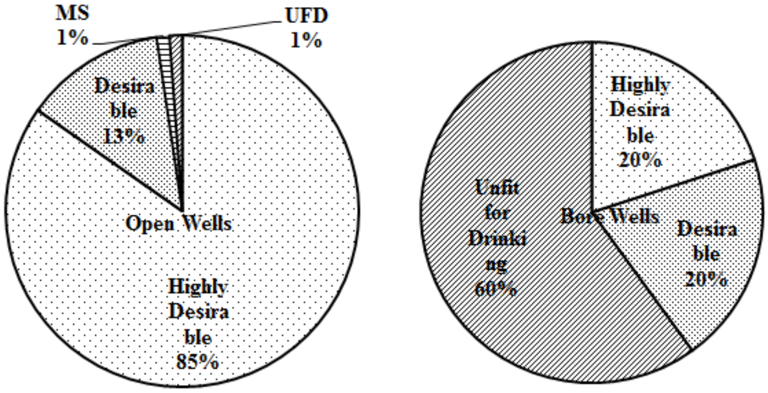

Fig. 4.121 Pie diagrams showing the Water Quality Index Rating and their percentage in the Mulki River Basin samples during Post-Monsoon

During post-monsoon period, about 85% of the open well waters are found to be in the highly desirable (HD) category whereas another 13% falls in the desirable (D) category for drinking water based on water quality indices. Only one percent each is found to be of moderately suitable (MS) and unfit for drinking (UFD) water categories (Fig. 4.121). The average water quality index (WQI) is found to be about 9.21 ranging from a minimum of 1.83 to a maximum of 135.14 (Table 4.40). At the same time in the post-monsoon bore well waters, about 60% is found to be unfit for drinking (UFD) category, whereas only 20% each are found to be in the highly desirable and desirable water categories based on WQI classification (Fig. 4.121). The average water quality index (WQI) found to be about 150.69 ranging from a minimum of 2.76 to a maximum of 380.86 (Table 4.41).

WQI		0-20	21-40	41-60	61-80	81-100	>100
Rating		Highly Desirable (HD)	Desirable (D)	Moderately suitable (MS)	Poorly suitable (PS)	Very Poor (VP)	Unfit for Drinking (UFD)
Ranking of WQI		1	2	3	4	5	6
Pre-Monsoon	Open well	OW1-4, OW6-25, OW29-30, OW44-46, OW48-49, OW51-53, OW59, OW63-68, OW71, OW73-74, OW77-79, 82, 87, OW89, 91, OW97-99 & OW101	OW 5, OW26-28, OW31-40, OW42-43, OW47,50, OW54-57, OW60-62, OW69, OW72, 74 & OW 81	OW76, OW80, OW85, OW86, OW90	NIL	OW 92, OW94, OW95, OW102	OW58, OW70, OW84, OW103
	Bore well	NIL	NIL	BW2, BW3, BW6,BW27	BW1, BW 10, BW 16, BW20-26	BW15, BW 18	BW4-5, BW7-9, BW11, 13, BW14, 17 & BW19
	Surface water	SW1-5, SW7-9, SW13-16	SW10, SW11, SW17-21, SW23	NIL	NIL	NIL	SW6 & SW 22.
Post-Monsoon	Open well	OW2-15, OW17-19, OW21-52, OW56, OW58-69, OW71-72, OW74-82, OW85	OW1, OW16, OW20, OW53-55, OW57, OW70, OW84	OW73	NIL	NIL	OW83
	Bore well	BW4 & BW7	BW8 & BW9	NIL	NIL	NIL	BW1-3, BW5-6 &BW10

Table 4.42 Water sample classification based on Water Quality Index at Mulki River basin

The detailed analysis of the Water Quality Index (WQI) classification of both the pre- and post-monsoon water samples from Mulki River Basin is given above (Table 4. 42). This analysis clearly shows that during pre-monsoon, the water quality has been affected considerably and the bore well water is found to be more vulnerable than the other sources. During post-monsoon the WQI has been considerably decreased indicating the desirable (D) to highly desirable (HD) ranking for almost all the open well sources and many of the bore well sources. The influence of precipitation and infiltration is clear in this regard.

4.9 MULTI-RECTANGULAR DIAGRAM (MRD): In order to overcome the difficulties of classical and Tri-linear diagram in the interpretation of groundwater quality data, and to examine the multi-variate association of chemical constituents present in groundwater, another recent scheme of Multi-Rectangular Diagram (Sen and Ahmad 2002, Ahmad *et al.* 2003) has been made use of in the present study. It not only presents the information about the cations and anions separately, but also gives very clear hydrochemical facies classifications. MRD eliminates the drawbacks of classical trilinear diagrams effectively. Hydrogeochemical processes active in shaping the chemistry of groundwater can also be determined from this methodology. The procedure is very simple in comparison to Piper diagrams. All the major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) are plotted on horizontal axis, and the major anions (HCO_3^-, CO_3^-, SO_4^{2-}, Cl^-) are drawn on vertical axis. Each of the axes is further divided into three adjacent and non-overlapping minor axes, and each one of these minor axes represents the respective cation and anion pairs completely.

Although, in accordance with the classical trilinear diagram three cations or anions are considered on the corresponding axes, there is no restriction for increasing the minor axis number in MRD. Again in this scheme, milliequivalent per liter percentages of total cations and anions are each considered as 100 percent as they are in the Piper diagram. From each chemical analysis of a groundwater sample, the highest cation and anion are picked up and then plotted as a point in the respective field. The diagram is divided into nine major square fields and each major field is further divided into four sub-areas in order to decide about dominance or non-dominance of cations and anions. On the whole, the diagram carries 36 sub-areas and each sub-area delivers complete information about the respective cation and anion pair which falls in that area (Fig. 4.122). Twelve sub-areas are available for each cation and anion respectively. Hydrogeochemical processes shaping the chemistry of groundwater during its flow can also be inferred from the present diagram to some extent. The first, second, and fourth sub-areas give a mixed type of water, whereas the third sub-area in each major square shows both the cation and anion dominance in water type.

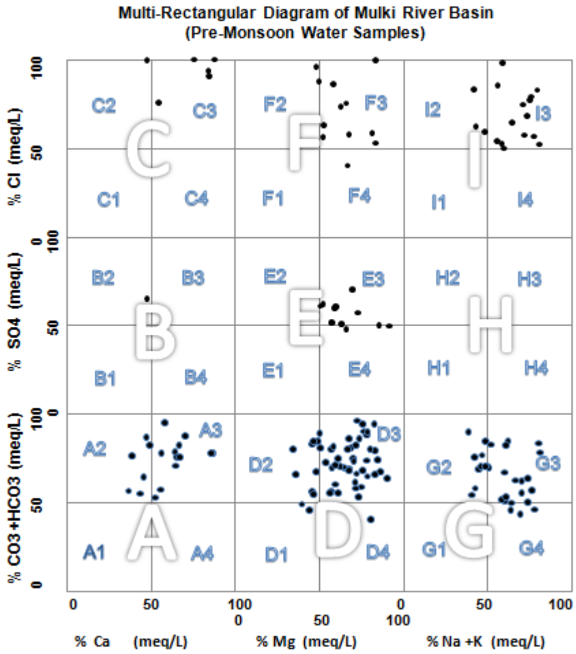

Fig. 4.122 Multi-Rectangular Diagram of Pre-Monsoon groundwater samples in Mulki River Basin

From the analysis (Table 4.43), it has been found that the predominant facies during pre-monsoon (Fig. 4.123) in the Mulki River Basin is Magnesium Bicarbonate water type (36%), followed by Sodium Bicarbonate (20%), Calcium Bicarbonate (12%), Sodium Chloride (11%), Magnesium Chloride (8%), Magnesium Sulphate (8%) and Calcium Chlroide (4%). Bicarbonate facies is totally dominating in the study area where chloride facies stand next showing the influence of the mixing up (Fig. 4.122). Waters falling in square 'A' are indicative of freshwaters in recharge areas where considerable movement of water has not taken place. The sub-area 'A2' shows that ion exchange has occurred in which Ca in the water has been replaced most probably by Na from the sediments/rocks through which water has moved. Sub-area 'A3' gives the indication of calcite dissolution. The dominance of Magnesium Bicarbonate indicates the dissolution of dolomite minerals in the underlying rocks. Dominance in

'F' and 'I' facies indicates either a mixing of water from coastal area or water getting older along its flow path dissolving halite and dolomite.

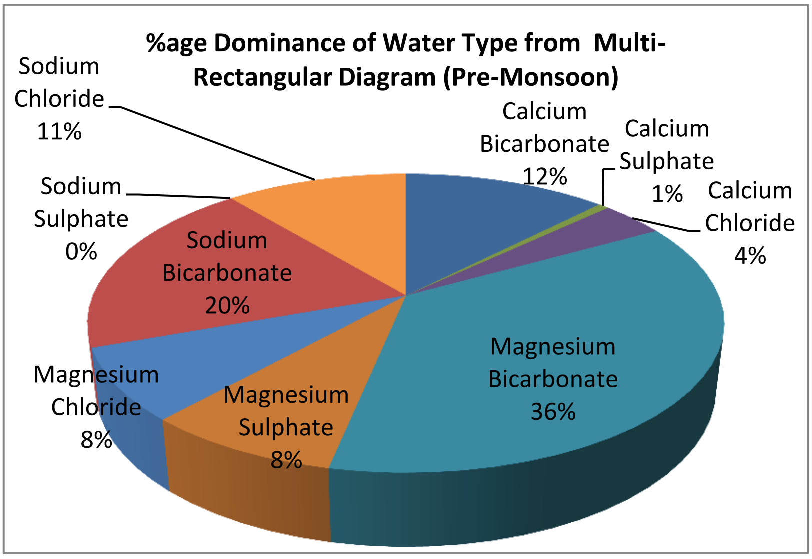

Fig. 4.123 Pie diagram showing percentage dominance of water type from Multi-Rectangular Diagram of Mulki River Basin (Pre-Monsoon)

Water Type	Sample Numbers	No. of samples	%age
Calcium Bicarbonate	SW 01, SW 05, SW 08, SW 11; OW2, OW4, OW5, OW7, OW 09, OW 11, OW 15, OW 17- OW 19, OW 21, OW 46, OW 58, OW 62, OW 83	**19**	**12**
Calcium Sulphate	OW63	**1**	**1**
Calcium Chloride	SW 13, SW 18, SW 19, SW 20, OW 37, OW 54	**6**	**4**
Magnesium Bicarbonate	SW 03, SW 04, SW 07, SW 09, SW 14, SW 23; BW 02- 05, BW 07- 14, BW 16, BW 17, BW 19, BW 22, BW 25, BW 26, BW 27; OW 01, OW 24, OW 25, OW 27, OW 34, OW 42, OW 53, OW 59, OW 60, OW 64, OW 65, OW 66, OW 69, OW 70, OW 71, OW 73, OW 74, OW 75, OW 78 -OW 82, OW 84, OW 86-OW 90, OW 92, OW 93	**56**	**36**
Magnesium Sulphate	BW 15, BW 19, BW 20, OW 91, OW 94, OW 95, OW 98, OW 99, OW 100, OW 101, OW 102, OW 103, OW 104	**13**	**8**
Magnesium Chloride	SW 16, SW 17, SW 22, BW 18, OW 10, OW 23, OW 30,OW 44, OW 61, OW 76, OW 77, OW 97	**12**	**8**
Sodium Bicarbonate	SW 02, SW 06, SW 10, SW 12, SW 15, SW 21, BW 01, BW 23, BW 24 OW 03, OW 06, OW 12, OW 20, OW 28, OW 29, OW 32, OW 35, OW 36, OW 39, OW 43, OW 45, OW 47, OW 48, OW 50, OW 51, OW 52, OW 55, OW 56, OW 72, OW 96	**30**	**19**
Sodium Sulphate		**0**	**0**
Sodium Chloride	BW 06, OW 08, OW 13, OW 14, OW 16, OW 22, OW 26,OW 31, OW 33, OW 38, OW 40, OW 41, OW 49, OW 57,OW 67, OW 68, OW 85	**17**	**11**

Table 4.43 Groundwater characterization and Water type from the MRD (Pre-Monsoon)

During post-monsoon, the characteristics of groundwater quality have changed especially in the open well water (Fig. 4.124). The predominant water type facies during post-monsoon season (Fig. 4.125) is found to be bicarbonates especially Sodium bicarbonate water (68%) dominating, followed by Sodium Chloride water type (18%) and Calcium bicarbonate water type (11%) indicating ion exchange and dissolution. Water samples in the sub-area A3 (Fig. 4.124) give the indication of calcite dissolution. Since the predominant water samples fall in the Sodium bicarbonate facies, it indicates the natural behaviour of the water in a sedimentary terrain.

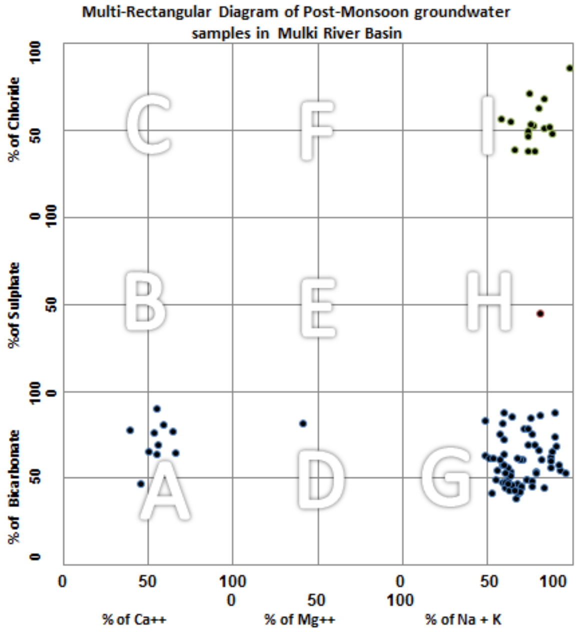

Fig. 4.124 Multi-Rectangular Diagram of Post-Monsoon groundwater samples in Mulki River Basin

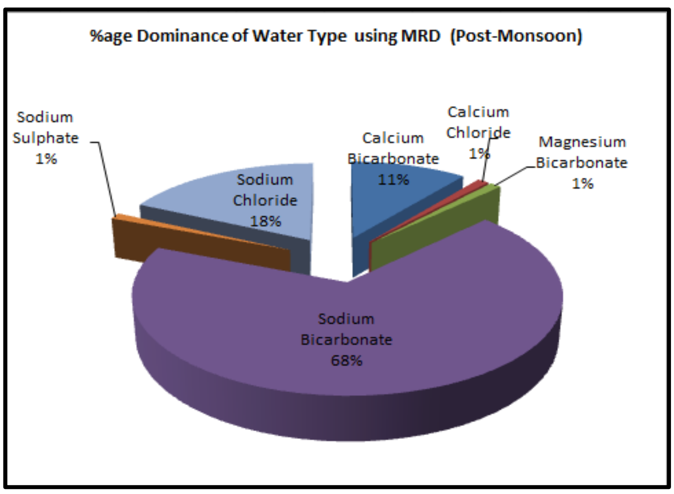

Fig. 4.125 Pie diagram showing percentage dominance of water type from Multi-Rectangular Diagram of Mulki River Basin (Post-Monsoon)

The analysis of Multi-Rectangular Diagrams (MRD) of groundwater samples plotted for pre-monsoon and post-monsoon periods indicate that the predominant water type of Magnesium bicarbonate facies is completely changed to dominant Sodium bicarbonate facies during post-monsoon in Mulki River basin. This may be attributed to the ion exchange and dissolution happening in this area, after a heavy monsoon, which is a highly porous lateritic terrain underlain by weathered granitic rocks. The influence and mixing up of coastal waters can also be noticed in both the seasons from the MRDs. This study also reveals the advantage of MRD over the Piper diagram where the dominant type in the post-monsoon period is not clear, whereas MRD of post-monsoon clearly defines the dominance of Sodium bicarbonate facies (68%) water type in the study area. The studies compare well with other type of analysis made in the present study.

4.10 CONCLUSIONS: Groundwater quality being the important factor in development and sustainability along the fast developing coastal tract of Dakshina Kannada and Udupi districts interspersed with river basins of coastal, midland and highland draining rivers, its systematic quality analysis and mapping will give the zones of suitability for various purposes. The study of groundwater quality of Mulki River basin shows the influence of geology, climate and anthropogenic activities on the water quality of the basin. An integration of various water quality parameters in a geoinformatic platform is found to be a better and faster tool in analyzing and understanding spatial variation of the water quality, its vulnerability and its probable cause in temporal and spatial domain in the study area for the sustainable development of groundwater. Groundwater Vulnerability maps and Water Quality Index maps are valuable derivative maps that show, quantitatively or qualitatively, certain characteristics of the sub-surface environment that control the vulnerability of groundwater to contamination. It has been observed that the coastal area is more vulnerable in respect of various quality parameters such as turbidity, pH, Calcium, Chloride, TDS and Total Hardness and it extends up to 7 Km from the coast especially along the alluvial plain indicating the influence of rapid urbanization and industrialization in water quality deterioration.

Based on the various computations, geostatistical analysis and geoinformatic applications of about twenty two physico-chemical water quality parameters analyzed and seven significant irrigation water quality parameters derived for pre- and post-monsoon seasons, the following conclusions were arrived which may open up a door to the proper management through sustainable development of the water resources in the study area.

An analysis on the hydrogeochemistry of the groundwater samples from Mulki river basin revealed that in the study area an average of 42% open wells and 89% bore wells show negative Schoeller Index indicating cation-anion exchange reactions. And about 58% of the open well and 11% of the bore well water samples show positive values indicating Base Exchange reaction. This also point towards the significant difference in the bore well water chemistry where the chloro-alkaline disequilibrium dominates with a cation-anion exchange, whereas in the open well water chemistry Base Exchange reaction slightly predominates or both Base Exchange and cation-anion exchange almost balance. Majority of the bore well samples show negative chloro-alkaline ratio indicating the discharge zone whereas in the case of the open wells 58% wells show positive chloro-alkaline ratio indicating the recharge zone .

The ratio of alkali ions vs. chloride ions in both seasons show the alkali is balanced by the chloride ions in majority of samples. When almost all the pre-monsoon and post-monsoon bore well water samples show sodium: chloride ratio above one, implying the silicate weathering of the rocks in deeper source of the study area, only 56% of the pre-monsoon and 45% of post-monsoon open well waters show silicate weathering of the rocks in shallow zone in the study area. From these it can be inferred that the bore well waters, except near the coast, are influenced by the silicate weathering of the igneous rocks, whereas the open well waters are influenced by the clay mineral reaction except those near the coast, influenced by the chloride dissolution from the salt water ingression in the study area.

The HCO_3^- vs. (Ca^{2+}+Mg^{2+}) ratio suggests that the bicarbonate chemistry is almost reverse during pre-monsoon and post-monsoon seasons in the study area. When a large fraction of (Ca^{2+}+Mg^{2+}) is derived from non-carbonate source and to be balanced by some other anions like SO_4^{2-} and Cl^- suggesting multiple sources during pre-monsoon, sufficient dissolution of the percolating water with bicarbonate leaching happens with Ca+Mg fractions during post-monsoon. The plot of sulphate-chloride relations in the study area explains the multiple origins of carbonates of calcium and magnesium during pre-monsoon period whereas the dissolution in carbonates leaching as the only source during post-monsoon. But in both the cases, the origin of bicarbonate can be predominantly attributed to the dissolution in carbonates. The plot of (Ca^{2+}+Mg^{2+}) vs. (HCO_3^-+SO_4^{2-}) for pre-monsoon shows that majority of the groundwater samples fall above the 1:1 equiline indicating reverse ion exchange, whereas during post-monsoon they fall below the equiline suggesting the dominance of ion exchange process. The deviation from the 1:1 equiline plot of (Ca^{2+}+Mg^{2+}) vs. (HCO_3^-+SO_4^{2-}) during post-monsoon suggests that dissolution reactions of calcite, dolomite and gypsum are not dominant in the system. The groundwater data of the study area along with the above analysis suggests that weathering of alumina-silicate minerals like plagioclase, mica, amphiboles and pyroxenes are major contributors for Na, K, Ca, Mg and HCO_3 along with minor addition of Ca, Mg and HCO_3 from dissolution of carbonates.

Analysis of Gibb's diagram suggests that 85% of bore well water samples and 68% of open well water samples during pre-monsoons fall in the Rock Water Interaction Domain, whereas 7.5% each fall in the Precipitation Domain and Evaporation Domain in bore wells, and 29% and 3% fall in Precipitation Domain and in the Evaporation Domain in open wells. From this, it can be inferred that during pre-monsoon season Rock interaction Domain is having a dominating influence on the groundwater whereas in post-monsoon season Precipitation domain influences open well water.

The geochemical evolution of groundwater has been assessed using methods suggested by Piper, Handa, Schoeller and Stuyfzand and the following conclusion were arrived. In the groundwater chemistry of the study area analyzed through Piper Trilinear diagram, the order of cations abundance is found to be Mg>Na>K>Ca and that of anions Cl>HCO_3>SO_4>NO_3 during pre-monsoon, and it is Na>K>Ca>Mg for cations and HCO_3>Cl >NO_3>F for post-monsoon respectively. The noticeable predominance of the bicarbonate type (90%) in the bore well samples during post-monsoon shows the distinct facies of bore well sources in the study area. The water chemistry and mixing up of the ionic facies indicate the study area belongs to a coastal environment. The total hydrochemistry in the study area is dominated by alkaline earth (64%) and strong acids (55%) with carbonate hardness (33%) (secondary alkalinity) and primary salinity (26%) influenced by the weathered granitic gneisses and leached laterite besides the influence of saline water. More than one fourth of the samples (27%) also fall in the mixed zones indicating balance on anion-cation pair. The difference in the hydrochemistry during pre-monsoon and post-monsoon periods indicates the influence of weathering, infiltration, mixing and leaching in the study area. During pre-monsoon, if the alkaline earth (83%) exceeds the alkalis, it is alkalis (62%) which exceed alkaline earth during post-monsoon period indicating the possibility of different origin. During both the pre- and post-monsoon periods, the strong acids (51% and 61% respectively) exceeds week acids with carbonate hardness (42% and 21% respectively) and primary salinity (12% and 44% respectively). Again this shows the variation in the origin and mixing of the water types in the study area during two different seasons i.e., before and after heavy monsoon indicating the influence of weathering and heavy rainfall in this area.

Analysis of groundwater samples using Multi-Rectangular Diagrams (MRD) clearly shows the predominance of bicarbonate facies in the study area, where magnesium bicarbonate facies is changed to Sodium bicarbonate facies during post-monsoon indicating ion exchange and dissolution chemical processes happening in this area after heavy monsoon. The influence and mixing up of coastal waters can also be noticed in both the seasons from the MRDs. This study also reveals the advantage of MRD over the Piper diagram where the dominant type of Sodium bicarbonate facies in the post-monsoon period is not clear in the latter one.

According to Handa’s classification, major part of the study area (64% of the total samples) is characterised by waters of permanent hardness where the pre-monsoon (97% of pre-monsoon) samples contribute much towards this. But during post-monsoon period the temporary hardness predominates (52%) over permanent hardness. When majority of the pre-monsoon samples fall in A_1 and A_2 category of permanent hardness it is in the A_3 category the post-monsoon samples fall. This information could be conveniently used for developing groundwater for domestic, agricultural and industrial purposes. Almost all the samples (99%) during both the seasons show very low to low salinity and low sodium hazard satisfying the irrigational water quality requirements.

According to Schoeller's concept of water types, which is related to the evolution of groundwater with respect to chemistry reveals that types III and IV (chloride dominated) contribute to 72% of the groundwater samples analyzed during both the seasons of 2009. This indicates that the majority of groundwater in this study area is having a greater residence time in the aquifers. The carbonate dominated water (type I) is totally absent during post-monsoon period showing the Base Exchange and fluxing of the same with chloride or sulphate during post-monsoon. The sulphate dominated over chloride water (type II) is represented by 39% of the samples during pre-monsoon and by 7% during post-monsoon periods.

According to Stuyfzand (1989) classification, which aim at defining natural types of water based on major cations and anions, four water types based on chloride viz: Brackish, Fresh, Oligohaline and Very Oligohaline; five sub water type based on alkali viz: Very Low, Low, Moderately Low, Moderate and Moderately High; nine water facies viz: (Na+K) HCO_3, (Na+K) Cl, (Na+K) mixed, $CaHCO_3$, Ca mixed, $MgHCO_3$, $MgSO_4$, $MgCl_2$ and Mg mixed; and three significant environment viz: fresh water intrusion, adequate flushing and no significant environment have been identified in the study area. Majority of the pre- and post-monsoon samples (82% & 86% respectively) belongs to Oligohaline (g) water type indicating the presence of chloride ions in the samples showing the long residence time of the water in the aquifer. About 11% of the open wells and 23% of the bore wells are found to be of fresh water type. The very low alkaline sub-type water (51%) predominates over others being low alkaline water (24%), moderately low alkaline water (17%), moderate alkaline water (5%) and moderately high alkaline water (2%) following the decreasing order. During pre-monsoon, the most predominant water type in the study area is found to be $MgHCO_3$ facies (41%), and the predominant cation the Mg (95%) and anion the HCO_3 (41%); whereas during post-monsoon Alkali (Na+K) mixed facies (45%) found to be predominant being alkali (Na+K) (81%) the cations and HCO_3 (34%) the anions respectively predominating. In the bore well waters, $MgHCO_3$ facies (65%) predominates during pre-monsoon whereas $CaHCO_3$ facies (50%) predominates in the post-monsoon period. It is worth to notice that during pre-monsoon, Mg is the predominant cations whereas it is almost absent during post-monsoon, besides the total absence of sulphate during post-monsoon. This will probably explains the extensive leaching actions of the groundwater over the laterite or highly weathered calc-alkali feldspars and clay minerals of overlying granitic rocks in this area during heavy monsoon. During pre-monsoon, environment indicating fresh water intrusion at anytime and anywhere predominates (66%) with surplus sodium and magnesium, whereas during post-monsoon environment indicating adequate flushing with water of constant temperature predominates (59%) with sodium and magnesium in equilibrium. Majority of the bore wells (93%) show the freshwater intrusion with sodium and magnesium in surplus, whereas majority of the open wells (56%) show the adequate flushing with water of constant temperature with sodium and magnesium in equilibrium. About 12% of the pre-monsoon open well samples belong to the no significant environment category also.

Based on groundwater chemistry three sets of strong relationships existing between major cations and anions of groundwater in the study area have been established using correlation coefficient of different physico-chemical water quality parameters in different sources and different seasons. A high significant positive relationship of competitive ions established between SO_4^{2-} & Cl^- in open wells and Na^+ & Ca^{2+} in bore well samples, and that of affinity ions between SO_4^{2-} & Mg^{2+} in open wells and Na^+ & Cl^- in the bore well water samples indicate the contamination of sources through anthropogenic and natural processes of saline water intrusion generating hard water in the pre-monsoon. In the post-monsoon open well water samples also this high significant positive relationship is established between the Na^+ & Cl^- and Na^+ & HCO_3^-. Among noncompetitive ions relationship, a high significant positive relationship of ions has been established between Na^+& K^+ in the pre-monsoon open well and surface water samples indicating the influence of weathering and leaching. Significant positive correlation has been established by Fe & Na, SO_4^{2-}& HCO_3^-, Na^+ & HCO_3^-, SO_4^{2-} & Mg^{2+}, Ca^{2+} & Mg^{2+} and Cl^- & HCO_3^- in the open well water samples during pre-monsoon, whereas during post-monsoon it is among Ca^{2+} & Na^+, SO_4^{2-}& Cl^-, SO_4^{2-}& HCO_3^-, SO_4^{2-} & Mg^{2+}, SO_4^{2-} & Ca^{2+}, Ca^{2+} &Mg^{2+}, Na^+& K^+ and HCO_3^-& Cl^- . The correlation of ions in the pre-monsoon and post-monsoon samples are almost similar except among Fe & Na, Na^+ & HCO_3^- relations present in pre-monsoon and Ca^{2+}&Na^{+}, SO_4^{2-}&Cl^{-}, SO_4^{2-} & Ca^{2+} and Na^{+}& K^{+} established in the post-monsoon open well water samples. In the bore well samples, significant positive correlation has been established only by HCO_3^{-}&K^{+} during pre-monsoon, whereas during post-monsoon it is among SO_4^{2-}& Mg^{2+}, Na^{+} & Cl^{-} and Ca^{2+} & Mg^{2+} indicating the influence of rock weathering and leaching. The high positive relationship established among various ions of competitive, non-competitive and affinity ions in the pre-monsoon open well water samples suggests the influence of the natural and anthropogenic contaminations in these water sources. But there is no such strong relationships established in the cases of post-monsoon bore well water indicating the absence of such influence in those water resources.

When various physico-chemical water quality parameters of the samples collected from the study area have been compared with the drinking water standards of National (BIS 1991) and International (WHO 1993) agencies, the important water quality parameters in the study area are found to be dominantly well within the permissible limit of drinking water standards prescribed except at a few places. Even though the hydrochemistry of groundwater is attained by the geochemistry of the aquifer or overlying rocks, it has not been greatly influenced to contaminate beyond permissible limit to certain extent except a very few parameters. Majority of the open well waters in the lateritic aquifers of the study area demonstrate low pH value indicating the acidic nature influenced by the laterite aquifer. The acidic nature of bore well waters which enhanced during the post-monsoon season might have been imparted due to the improper casing in the lateritic overburden. The turbidity and iron content in the bore well waters can also be attributed to the low quality and improper casing adopted in these wells. A very few groundwater and surface water samples near to the coast and river trace has shown the influence of saline water intrusion. Majority of the open well water samples (87%) and bore well water samples (80%) were having low fluoride concentration (<0.6ppm) than the minimum desirable limit of WHO drinking water standards.

The analysis of the pre- and post-monsoon water samples from the study area reveals, that a total of about 27% pre-monsoon water samples comprising 20% of open wells, 48% of bore wells and 35% of surface water samples were contaminated, whereas about 19% of post-monsoon groundwater samples comprising 14% of open wells and 60% of bore wells were contaminated and are beyond permissible limit of drinking water standards. Other than this, 53% of pre-monsoon and 80% of post-monsoon open well water samples, 7% of pre-monsoon and 10% of post-monsoon bore well water samples, and 85% of the surface water samples have been affected by pH (predominantly acidic) beyond permissible limit of drinking water standards. In the open wells of the study area, about ten drinking water quality parameters have been affected with a maximum of seven in certain samples (OW30) during pre-monsoon, whereas only about seven parameters with a maximum of three in any sample have been affected during post-monsoon season. In the bore well water samples of the study area, about seven drinking water quality parameters have been affected with a maximum of three in any samples during pre-monsoon, whereas only four parameters with a maximum of three in any sample have been affected during post-monsoon season. In the surface water sources it is about eleven drinking water quality parameters that have been affected with a maximum of nine in certain samples during pre-monsoon. The study revealed that the drinking water qualities of pre-monsoon groundwater samples especially open wells have been affected more compared to the bore wells in the region. The less contamination during post-monsoon may be due to the groundwater recharging, flushing and dilution of the open well water during heavy monsoon in the study area. The drinking water qualities of surface water sources during pre-monsoon have been affected more compared to groundwater sources in the study area.

In order to understand the suitability of the water resources in the study area for irrigation purposes, about nine important characteristics such as total salt concentration (EC), Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Percentage Sodium (% Na), Permeability Index (PI), Magnesium Hazard (MH), Chloride, Sulphate and Chloride/Bicarbonate ratio have been computed and analyzed. A great variation is noticed in irrigation water suitability based on different characteristics and is found to be 95% (pre-monsoon) and 100% (post-monsoon) based on EC, 100% (pre-monsoon) and 98% (post-monsoon) based on SAR, 84% (pre-monsoon) and 33% (post-monsoon) based on % Na, and 60% (pre-monsoon) and 03% (post-monsoon) based on RSC. Based on EC and SAR, more than 95% of waters in the study area can be used for irrigation without the fear of salinity hazard. Based on Wilcox (1955) diagram relating electrical conductivity to sodium percent shows that 97% of the post-monsoon samples are Excellent for irrigation whereas only 93% of pre-monsoon samples found to be suitable for irrigation falling in the categories of permissible to Excellent. But, almost all the samples (97%) of post-monsoon and majority (60%) of pre-monsoon showed very high value of Residual Sodium Carbonate making the major water resources in the study area unfit for irrigation without proper corrective measures. Continued usage of high residual sodium carbonate water affects the yields of crops. On the basis of Doneen's classification, majority of the water samples (60.39%) fall in Class-II whereas 12% in Class I in the Doneen's chart, implying that the majority of pre-monsoon water is of good quality for irrigation purposes. All the post-monsoon samples are of excellent quality for irrigation purposes thanks to its high permeability index (PI) falling in the Class-I (75%) and Class-II (25%) water types only. From the magnesium hazard analysis of the post-monsoon water samples, 92% are found to be suitable for irrigation purposes, whereas only 31% of the pre-monsoon samples are found to be suitable for irrigation. While 34% of open well waters and 52% of surface waters during pre-monsoon are found to be suitable for irrigation based on MH, all the bore well waters during pre-monsoon are found to be unsuitable for irrigation purposes. Based on Chloride concentration 97% of the water samples are found to be suitable for irrigation purposes, except a few along the coast where the saline water migration might have contaminated the surface and open well water sources. The water resources in the study area are found to be excellent for irrigation regarding sulphate concentration. From the chloride-bicarbonate ratio analysis, about 22% of the water resources in the area comprising 30% of the surface waters, 24% of open wells and 8% of the bore well sources have been contaminated with saline water intrusion and is not suitable for irrigation purposes.

In order to understand the variation and distribution pattern of different water quality parameters they have been plotted and extrapolated in spatial and temporal domain using geographic information system (GIS) platform and found to be a better tool in understanding the quality variation of groundwater in a spatial and temporal domain. The spatial distribution maps of different water quality parameters suggest that the geology of the area has a significant influence in the concentration of certain parameters in the groundwater in addition to the seasonal climatic influence and localized anthropogenic interference observed. The temporal variation could be due to the fluctuation of the groundwater table and infiltrating rainwater other than outside influence in the natural system. The water quality vulnerability map based on standard water quality parameters has been found to be a better and faster tool in demarcating the vulnerable area for the sustainable development of the water resources. The study also revealed that the coastal area is more vulnerable in respect of various quality parameters such as pH, Turbidity, Total Hardness, TDS, Calcium and Chloride which extends up to seven kilometers from the coast especially along the alluvial plain indicating the influence of rapid urbanization and industrialization in water quality deterioration.

An analysis of the Water Quality Indices (WQI) and its mapping in spatial and temporal domain in the study area is found to be a faster and better tool in assessing and rating the suitability of groundwater for drinking water based on quality weightage. The spatial and temporal variation of the same is found to be a very good tool in assessing the source of contamination and its management. The very high WQI at the coastal front near the mouth of the river and its extension along the river course upstream up to a certain distance during pre-monsoon indicates the influence of saline water and its migration along tidal water in this area. Other places where very high water quality indices noticed in the inland area suggests the influence of geology in groundwater quality stressed by the spatial distribution of WQI. The temporal variation in distribution pattern and density of WQI points to the significant role of precipitation and infiltration playing in the determination of water quality.

Proper integration of these hydrogeochemical data with geology, geomorphology, hydrometeorology and hydrogeophysical analysis on a GIS platform can open up new vistas for the sustainable development and management of the water resources in the study area.

Chapter 5

Hydrogeophysical Studies

CHAPTER 5

HYDROGEOPHYSICAL STUDIES

5.1 INTRODUCTION: One of the primary constraints to economic and social development in many parts of the world is the difficulty in obtaining reliable water supplies for local population. In arid regions, surface water is not available on a permanent basis, while in humid regions it is often contaminated. As a result, commonly groundwater is the only permanent and safe source of water. In many developed and developing countries there is not only a heavy reliance on groundwater as a primary drinking water source but also as a supply of water for both agriculture and industrial use. The reliance on groundwater is such that it is necessary to ensure that there are significant quantities of water and the water is of a good quality. The need to develop groundwater resources, therefore, has become a matter of some urgency - especially in tropical and subtropical areas where the deterioration of an already fragile environment has been exacerbated by various population pressures. The use of geophysics for both groundwater resource mapping and for water quality evaluation has increased dramatically over the last few years in large part due to the rapid advances in microprocessors and associated numerical modeling solutions.

5.2 GEOPHYSICS AND GEOLOGY: The study of the earth using physical measurement at the surface is known as geophysics. It is the branch of science in which the important principles, processes and methods of physics are applied to solve many geological problems. It involves the interpretation of the measurements taken from those parts of the earth hidden from direct view to obtain useful information on the structure and composition of the concealed zones solving most subsurface geological problems. The capabilities of exploration geophysics can be explained by understanding the types of methods, and the techniques to be employed in processing and interpreting geophysical data. The utilities of these methods are increasing day by day and are attracting geologists for solving certain unsolved problems. These methods are widely used in the field of mining ores, oil and gas, civil engineering, groundwater exploration, etc. The most commonly used geophysical methods are resistivity, seismic and magnetic methods. Most of these methods were used mainly for hydrocarbon exploration at depths greater than 1000 meters or so. Later these methods have been used for near-surface exploration of groundwater within depths of 250 meters. Groundwater applications of near-surface geophysics include mapping the depth and thickness of aquifers, mapping aquitards or confining units, locating preferential fluid migration paths such as fractures and fault zones, and mapping contamination to the groundwater such as that from saltwater intrusion. Groundwater development for drinking and irrigation purposes in the rural areas of Karnataka is mainly through dug wells and bore wells in the sedimentary rocks such as laterite, alluvial and coastal sedimentary formations, whereas it is through deep bore wells from the adjoining gneissic/granitic 'hard rock' areas. The quality and quantity of water in an underground aquifer can be evaluated based on the geophysical surveys especially electrical resistivity methods along with the geology of the area in a cost effective manner.

5.3 HARD ROCKS: Hard rock is a general and rather vague term for all kinds of igneous and metamorphic rocks typically found in Precambrian shield areas which are among the oldest parts of the earth's crust. The most common hard rocks are gneisses or granites (Dijon 1985). Unlike sedimentary rocks, the hard rocks have no primary porosity. It is only their secondary porosity, resulting from fracturing and weathering, which permits the flow and storage of groundwater. Hard rocks while mostly solid, non-porous, and absolutely impervious, can hold large amounts of water in networks of cracks, joints, fractures or faults or along contacts between rocks of various types. Such openings result mainly from tectonic movement in the earth's crust. Where exposed to certain climatic conditions, these rocks are subjected to extensive weathering, which may create further conditions favourable for the infiltration and storage of groundwater. Karnataka state is predominantly underlain by 'hard rocks', and the occurrence, movement and development potential of groundwater in these rocks are mainly controlled by structural framework and weathering (Dhoolappa 1994). The yield of a well in hard rock terrain depends on the thickness of weathered zones, intensity, spacing and continuity of factures or structural features, saturation of these underground spaces with the water filled in, etc. Geophysical exploration surveys can be used for locating such structures and weathered zones which may hold water in it.

5.4 HYDROGEOPHYSICAL PROSPECTING: Geophysical prospecting methods are now being increasingly used in groundwater exploration for i) identifying the groundwater potential zones, ii) assuming the rate of pollutant travel from the source of contamination, iii) determining the direction of groundwater flow at a given point, iv) identifying the presence of dykes, fissures, faults, etc., and v) getting information with regard to subsurface lithology. Among the hydrogeophysical methods commonly employed in subsurface investigations, the electrical resistivity method has particular advantage in hydrogeology as it responds to variations in conductivity or resistivity of the groundwater bearing formations. Electrical resistivity method has gained considerable importance in the field of groundwater exploration because of its low cost, easy operation and efficiency to detect the water bearing formations.

5.5 ELECTRICAL RESISTIVITY METHOD: This is the most commonly used geophysical technique which gives direct indications to the occurrence of groundwater and its quality in the subsurface formations. The method is based on the principle that electrical resistivity or conductivity of a geological formation is dependent upon the material as well as upon the porosity and the water content of the formation. Out of all the geophysical prospecting methods, the Electrical Resistivity Method is the most versatile, economical and extensively used method for groundwater exploration (Zohdy *et al*. 1974).

5.5.1 Resistivity: Resistivity (ρ) is the resistance offered for the flow of electric current by a unit cube of substance when voltage is applied across the opposite faces. This inherent physical property of a substance is independent of size and shape of the substance. The inverse of resistivity is termed as conductivity (σ). The resistance offered by a substance is a function of the resistivity, size and shape. The resistance offered by the substance with regular shapes such as cylinders, cubes, etc., can be determined with the formula $\mathbf{R = \rho . L / A}$, where '**ρ**' is the resistivity of the substance, '**L**' is the length of the substance, and '**A**' is the area of cross-section of the substance.

5.5.2 True and Apparent Resistivity: All geological formations possess a property called electrical resistivity which determines the ease with which the electrical current flows through them. Usually it is represented in ohm-meter, a standard unit. For homogeneous formations, the electrical resistivity that is measured represents the true resistivity.

The apparent resistivity of a geological formation is equal to the resistivity of fictitious homogeneous and isotropic medium, in which, for a given electrode arrangement and current strength, the potential difference measured is equal to that for given homogenous medium. The apparent resistivity depends upon the geometry and resistivity of the elements constituting the given geologic medium. It does not represent the average resistivity and it can be lower than the lowest and higher than the highest resistivity within the subsurface to which it pertains.

5.5.3 Electrical Resistivity Surveying: This method is useful to investigate the nature of subsurface formations by studying the variations in their resistance to flow of electrical current and hence determine the occurrence of groundwater. Resistivity method is based on the electrical resistivity/conductivity contrast between the water bearing layers and the adjacent layers. In resistivity method, a known amount of electric current (DC or low frequency AC) is passed into the ground between two points through current electrodes on the ground surface, and the resulting potential difference between the two points (potential electrodes) is measured. The current injection and potential measurement give the apparent resistivity of the earth for that particular electrode arrangement. The objectives of this method in the field of groundwater exploration are to locate groundwater bearing formations, estimation of depth of the water table, thickness and lateral extent of aquifers, depth to bed rock, delineation of weathered zone, stratigraphic and structural conditions such as fractures, dykes, distribution and configuration of saltwater/fresh water interface, etc.

Resistivity of geological formations varies significantly between their dry and saturated states. Resistivity values of rocks are controlled by chemical composition of the minerals, density, porosity, water content, water quality and temperature. The value of formation resistivity also depends on the direction of electrode spread and the nature of the top layer in hard rock area. Resistivity varies to a large extent in different rocks. Igneous and metamorphic rocks show a range of 10^2 and 10^6 ohm-meters and the sedimentary rocks show 10° to 10^5ohm-meters. However, in the porous formations such as highly weathered and fractured rocks and unconsolidated sediments, the resistivity is controlled more by the amount and quality of water present, than the actual rock resistivity. Since the inhomogeneity exists in the rocks below the ground and the electrical excitation decreases away from the source, the exact determination of the spatial distribution of electrical parameters in three dimensions will be apparent. This makes the interpretation to be based on gross idealization which lacks uniqueness. Hence the survey and interpretation of electrical measurements must rely on available geological information.

There are basically two types of resistivity surveys (Rao, G.T. 1992) called Profiling and Vertical Electrical Sounding (VES). While the latter is used to determine the electrical resistivity variations with depth, the former is used for delineating horizontal variations of resistivity in subsurface formations. In profiling, inter-electrode distance is kept constant and the measurements are made by progressively shifting the entire arrangement as a whole. This is useful in locating the lateral inhomogeneity like faults, fractures, dykes, etc., which have indirect bearing on the groundwater movement and accumulation. In VES, the inter-electrode distance is increased symmetrically with respect to the measurement point which is the center of the electrode system. The data obtained by this method can be quantitatively interpreted for various geoelectric parameters like depths, thickness and resistivity. These geoelectric layers will then be translated into hydrogeological layers using the knowledge of groundwater conditions in the area. In geophysical investigations for groundwater exploration, depth to bedrock determination, etc., the electrical resistivity method can be used to obtain quickly and economically the details about the location, depth and resistivity of subsurface formations. One of the main advantages of resistivity method is that it has great resolving power. It uses an artificial source of energy, rather than the natural fields of force such as one used in gravity and magnetic surveying. Therefore, the source-detector separation can be altered to achieve optimum separation which effectively controls the depth measurement.

5.5.4 Measurement of Electrical Resistivity: The main aim of electrical resistivity survey is the measurement of electrical resistivity of the subsurface formations (Bhattacharya and Patra 1968). In general, four electrodes are required to measure the resistivity of subsurface formations. A current of electrical intensity 'I' is introduced between one pair of electrodes (A and B or source and sink) called current electrodes in the earth formation. The potential difference (ΔV) produced as a result of current flow is measured across a second pair of electrodes (M and N) called potential electrodes or probes. The apparent resistivity (ρa) measured is **K*(ΔV)/I**, where 'K' (also represented as 'G') is the geometrical constant. This geometrical constant 'K' depends on the distance between the electrodes and their arrangements. This factor can be calculated as follows:

The electrical potential (V) at a distance (r) from a single point electrode placed on the surface of a uniform half-space can be expressed as $V = I/2\pi r$. Potential due to two or three sources can be added algebraically. Hence potential difference (ΔV) developed between the potential electrodes M and N is expressed as $\Delta V = (\rho I/2\pi) * K$, where '**ρ**' is the resistivity of a homogenous earth and the geometrical constant $K = (1/AM - 1/BM - 1/AN + 1/BN)$. Thus the geometrical constant can be calculated knowing the electrode arrangement or set up (Fig. 5.1). Since subsurface is heterogeneous under normal conditions, the measured resistivity is a weighted mean of the resistivity of all the individual bodies of rock materials which make up the earth and is termed as "apparent resistivity" (ρa).

True resistivity of a formation is calculated based on a set of apparent resistivity values, obtained by measuring the current and potential differences between two electrodes (A & B) driven into the ground. The field procedure involves sending a known amount of current through two metal stakes and measuring the potential difference across the inner two potential electrodes (M & N) which are placed inside the current electrodes. If the distances between the current electrodes are increased, current penetrates deeper and deeper into the ground.

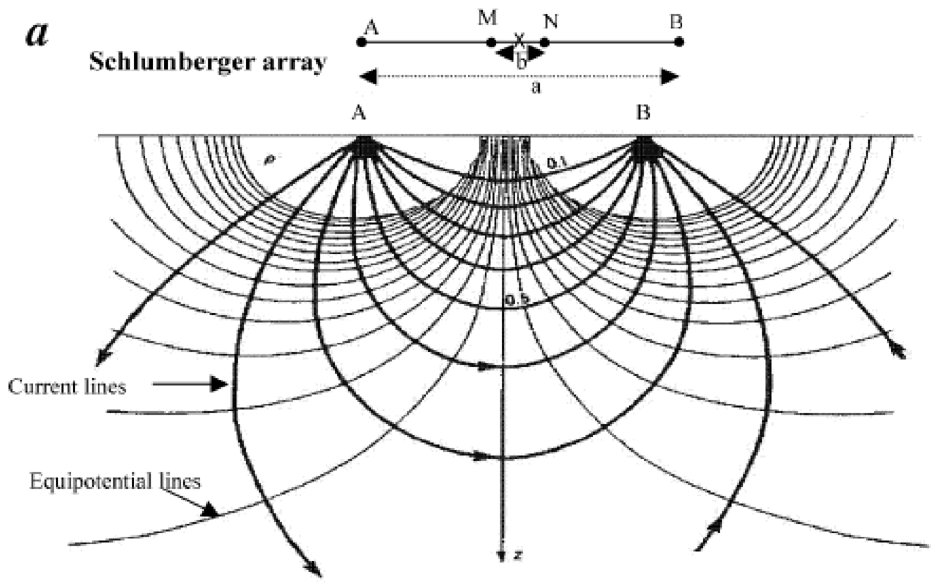

Fig. 5.1 Electrode Arrangement for Resistivity Determination

By plotting apparent resistivity values as ordinate and electrode spacing as abscissa on double logarithmic paper, a smooth curve can be obtained passing through different points. This curve is called vertical electrical sounding curve or field curve. From these field curves, layer thickness can be determined and subsurface hydrogeological conditions then be interpreted by using anyone of the following interpretation techniques:

a) Use of master curves (Orellana and Mooney 1966)
b) Interactive computer modeling (Jupp and Vozoff 1975, Vozoff and Jupp 1975)
c) Automatic computer inversion (Moscow State University 2002)
d) Inverse slope method (Sankaranarayana and Ramanujachary 1967)
e) Direct slope technique (Baig 1980) and
f) Other approximate empirical techniques (Ballukraya *et al.* 1983)

5.5.5 Electrode Configuration: In general, the electrode arrangements may be classified broadly into two categories such as, (i) those in which all the four electrodes are placed along a straight line viz: Wenner array, Schlumberger array, etc., and (ii) those in which the pairs of current and potential electrodes are separated and four electrodes are not necessarily along a straight lines viz: dipole-dipole array, etc. The

Schlumberger and Wenner arrays are used for shallow investigations. Dipole systems are usually employed for deeper studies. Schlumberger electrode configuration has been employed in the investigation because of its advantages over other methods both in the field survey as well as in the interpretation of data.

5.5.5.1 Schlumberger Configuration: In this array all the four electrodes are placed along a straight line and the potential gradient is measured at the mid-point by keeping the potential electrodes close to each other (Fig. 5.2). Four electrodes are placed along a straight line from a reference point 'O'. Current is sent through the outer current electrodes A and B and the potential is measured across inner potential electrodes M and N. The separation between the potential electrodes is kept small compared to the current electrode separation. For good results, it is usually <1/5 of current electrode spacing and the errors introduced will be less than 3%. Keller and Frischknecht (1966), Bhimasankaran *et al.* (1969) have demonstrated certain practical, operational and interpretational advantages of this method over other methods. The main advantage claimed for the Schlumberger array is the possibility it provides for removing lateral resistivity effects. Therefore, Schlumberger electrode arrangement has been employed in the present investigation.

A M N B

!---------------------------------!---O---!---------------------------------!

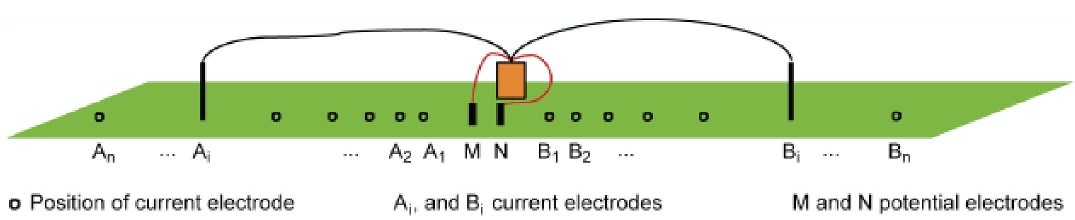

Fig. 5.2 Electrode configuration for Schlumberger array

The configuration factor for Schlumberger array is

$$K = \frac{(AB/2)^2 - (MN/2)^2}{(MN/2)} * \pi/2$$

5.5.6 Procedure for Resistivity Measurement: There are basically two approaches for making resistivity measurements viz., horizontal resistivity profiling and vertical electrical sounding (VES). In profiling, the electrode arrangement is not altered. Inter-electrode separation is kept constant and the measurements are made by progressively shifting the entire arrangement as a whole. This gives the lateral variations of the resistivity of subsurface formations. This is useful in locating the lateral non-homogeneities like faults, fractures, dykes, narrow buried valleys, etc., which have control over groundwater movement and accumulation. Vertical electrical sounding is used to study the vertical variations of resistivity and characters of the ground with depth at a given point. This technique is also called as 'electrical drilling' or 'depth sounding', because it provides information about variation of the electrical resistivity with respect to depth. In this method, the inter electrode distance is increased symmetrically with respect to the measurement point which is the center of the electrode system. The data obtained by this method can be quantitatively interpreted for various geoelectrical parameters like depth, thickness and resistivity. These geoelectrical layers will be then translated into hydrogeological layers using the knowledge of groundwater conditions of the area.

Many authors have carried out Vertical Electrical Soundings for the groundwater prospecting in hard rock terrains (Chandra *et al*. 1983, Lokesh *et al*. 1983, Ramanujachary and Balakrishna 1985, Shenoy and Lokesh 2000) and applied various empirical methods (Sankaranarayana and Ramanujachary 1967, Patangay *et al*. 1977, Baig 1980, Ballukraya 1996, Ballukraya *et al*. 1981, 1983, 1988, 1989) for the interpretations besides the traditional curve interpretation techniques (Orellana and Mooney 1966).

5.6 METHODOLOGY: Considering the depth of penetration factor and geology of the terrain, Vertical Electrical Soundings (VES) with Schlumberger array have been carried out in 129 stations using IGIS made Signal Stacking Resistivity Meter (SSR-MP-AT) in different parts of the Mulki River basin for the assessment and evaluation of groundwater potential and scope for its exploration. Direct reading digital signal stacking resistivity meter (dual mode) of up to 16 times signal stacking is used in the present study to make resistivity measurements. The voltage required to send current into the ground is applied from high voltage generator power pack unit with rechargeable batteries with a step up generator. Here, automatically the system recognizes the resistance offered by the earth layers and sends the high voltage current according to the requirements. Stainless steel electrodes are used as both current and potential electrodes.

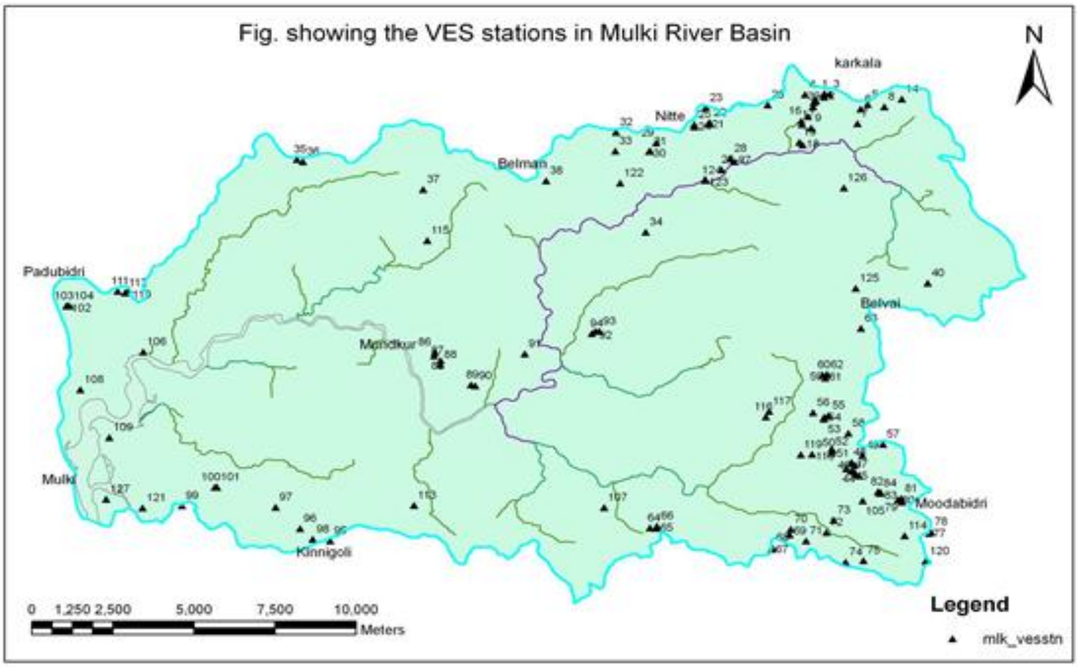

Fig. 5.3 VES stations in the Mulki River Basin

The electrical resistivity surveys have been carried out at a number of selected sites in the basin to identify the occurrence of groundwater potential zones in different geological set up (Fig. 5.3). Since the general geological succession of the area is of a hardrock terrain of granites and granitic gneisses, overlaid by a sequence of variegated leached clay followed by highly porous laterite of varying thickness with a thin veneer of topsoil, there can not be any specific classfication for the geological set up in the area. But it can be broadly classified in to three region considering different parameteres viz: (i) hardrock terrain which is dominant over a large area of the basin where the granitic gneisses and laterite outcrops interspersed with each other; (ii) Lateritic plateau region, which falls in the southeastern part with thick laterite overburden over the granitic gneiss; (iii) coastal belt with coastal alluvium overlaid over the laterite which falls along the western part of the study area. Five stations were selected near to the coastal stretch (Fig. 5.4) in the alluvial planes, whereas other stations are in the lateritic terrain and hard rock terrain where the granite or granitic gneisses are exposed besides the plain land and plateau. Considering the depth of penetration factor and geology of the terrain, Schlumberger electrode configuration up to a maximum current electrode separation of 240 metres was usually adopted in majority of the cases except a few stations where the possibility of spreading was not possible. In order to understand the deep fractures and confined aquifers in this basin (Raju *et al.* 1994) a maximum electrode spacing of 600 meters also have been carried out at few selected places. Computerized Curve interpretation techniques using IPI2 Win (Lite) program (Moscow State University 2002) has been utilized for the analysis of the VES values using inversion techniques, and the resistivity sections (Plates 5.1 - 5.14) and interpretation charts (Table 5.1) have been prepared. The details of the analysis and interpretations are discussed below.

5.7. RESISTIVITY LAYERS: There are up to a maximum of six layers identified in the study area depending on the apparent resistivity of the underlying rocks. This variation can be noticed through a two layer curve at Sampige of Puthige village to six layer curves at Moodbidre, Kuntalpadi, Bappanadu, Nitte, Halasinakatte and Jarigakatte in the study area. A minimum of two layers indicate either an unconfined aquifer or a zone with topsoil and the resistant rock at the bottom depending on the resistivity values. Predominantly four layers situation in the area suggests that there are possibilities of confined aquifers in the hard rock terrain of the study area from which most of the bore wells tap groundwater. There are a lot of variations in the apparent resistivity of these various layers below the ground and the details are given in the Table 5.1.

5.7.1 Top Layer: The top layer in most cases consists of weathered regolith of loose top soil, with a mean apparent resistivity of about 16,874Ωm. This high resistivity in this layer might be due to the moisture content or dryness of the top soil besides its chemical composition. Thickness of this layer varies from 0.13 metres to 28.40 metres with an average of 1.86 metres (Table 5.2). The spatial variation of its depth from the surface and the variation in apparent resistivity are represented in Fig. 5.4. This shows the variation in weathering and the capability for infiltration depending on the thickness.

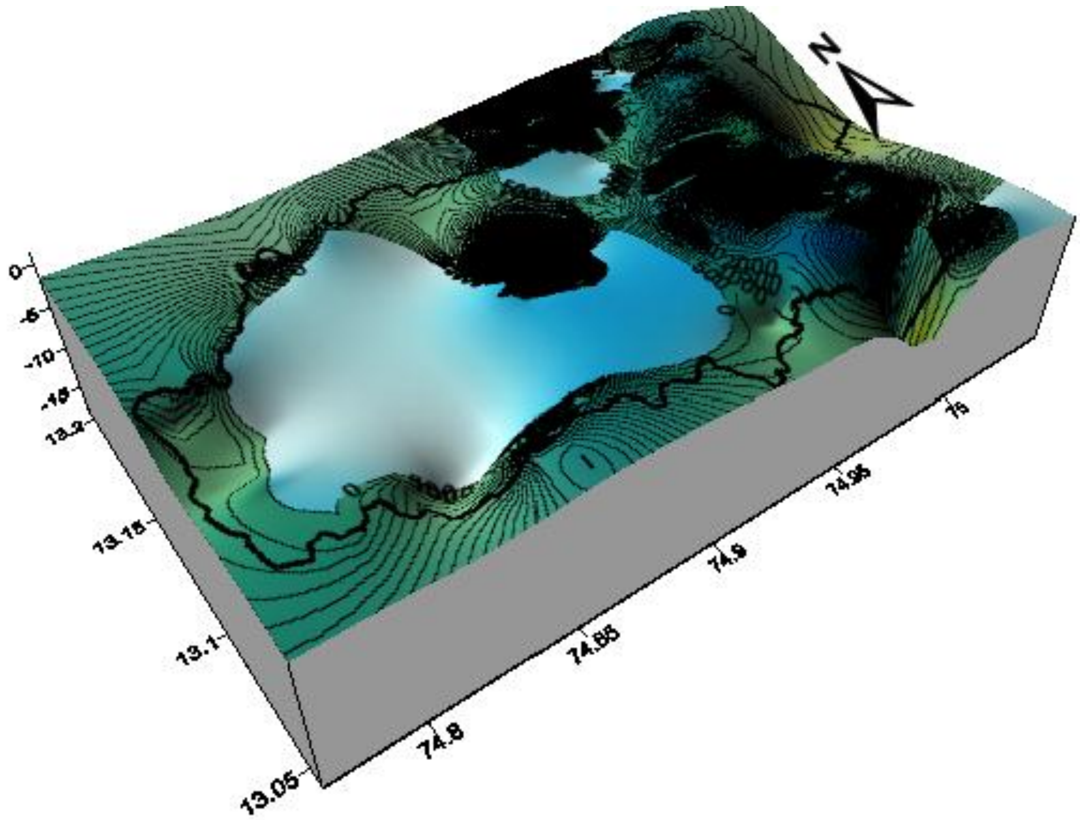

Fig. 5.4 Depth variation of topsoil (Layer 1) with its iso-resistivity contours overlaid

5.7.2 Second Layer: The second layer, in many cases being the laterite shows the average resistivity of about 4444 Ωm which represents the porosity and dryness of these beds. The low resistivity of this layer in some cases may be due to the saline water ingression or the saturated zones with clay belt in it. At two places in Bappanadu and Kolnadu it is mainly due to the saline water ingression at such shallow depth in the alluvial beds. The average thickness of this second layer is 7.84m which shows the tendency of weathering and water holding capacity of this layer (Table 5.2). The spatial variation of the depth from the surface and the resistivity represented by iso-resistivity curves are represented in a surfer plot (Fig. 5.6). Near the valley portions and the lateritic plateau area, the depth of this layer is deep giving potential thickness for accumulation of groundwater which is represented by low resistivity contours. Most of the open wells are located in this zone and is significant in the drinking water and irrigation capacity of the area. Depending upon the thickness and the resistivity the yield of these structures vary.

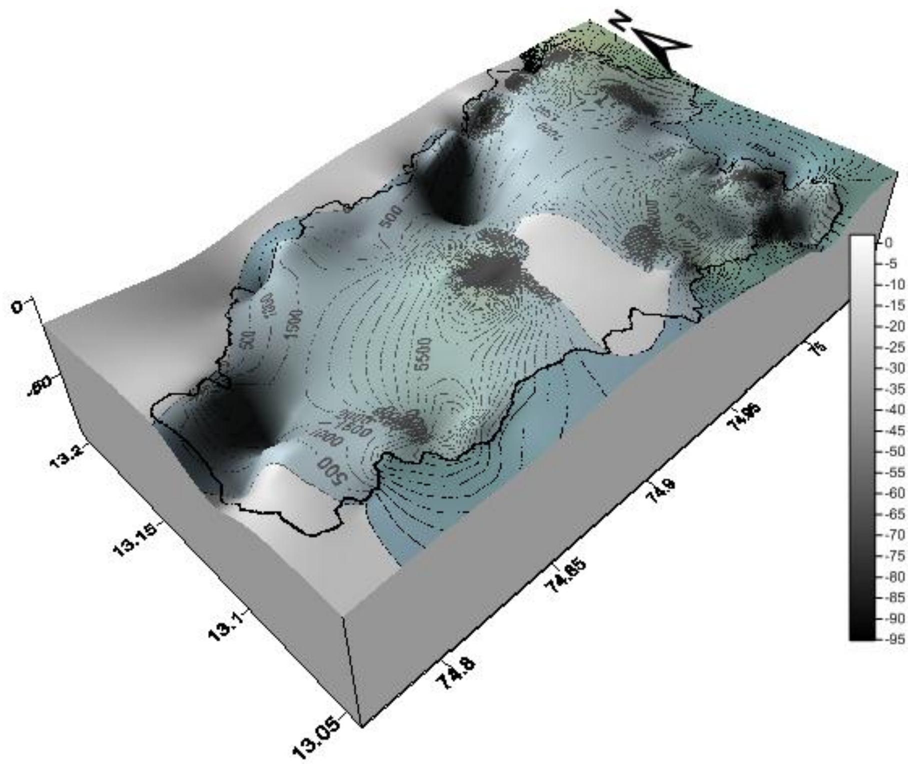

Fig. 5.5 Depth variation of Second layer with its iso-resistivity contours overlaid

5.7.3 Third Layer: The third layer, in many cases weathered granite/granitic gneisses or even the hard granite shows an average resistivity value of 6421 Ωm. The low resistivity of this layer in certain places (Gajani in Karnad is of 0.389 Ωm and at Bappanadu of 1.2 Ωm) at a very shallow depth of 4 meters shows that they are of alluvial beds with saline water in the aquifer (Table 5.2). The geology of the area has a definite control over the thickness and resistivity of this area (Fig. 5.7). Predominantly they are of H-type curves indicating shallow aquifer. Secondly K-type of curves also predominate indicating deeper unconfined aquifers in the clay belt zone. At certain stations it is saturated clay bed yielding water to open wells. A few case of A-type curves indicate very hard rock, where it is dry laterite overlying the hard impervious granite at the bottom. These areas are not suitable for open wells or bore wells construction. Q-type curve with very low resistivity value at Gajani shows the saline water aquifer at very shallow depth, whereas in other cases, it indicates the good yielding aquifer. The thickness of this layer varies from 0.35m to 93.7m with an average thickness of 15.17m. At Belvai area, where the lateritic plateau formations rest above the bed rock have a thickness of up to 100metres. In this area, the open wells yield good amount of water thanks to its highly porous thick laterite aquifers. At Pulkeri, Sanoor the high resistive layer is of about 70m thick showing an almost impermeable rock without any aquifer in it.

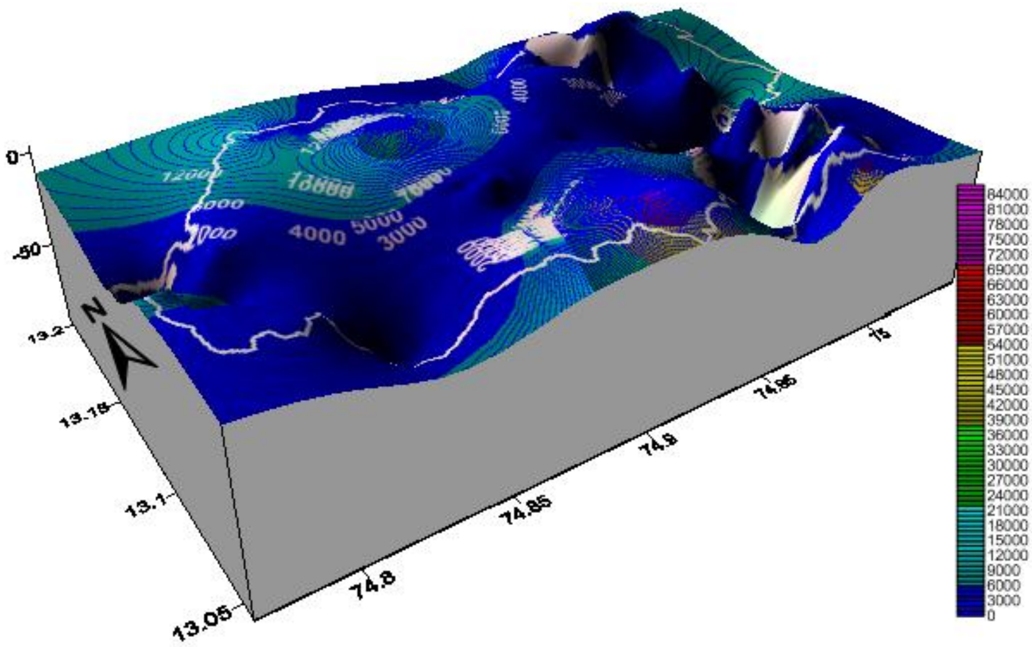

Fig. 5.6 Depth variation of 3rd layer with its iso-resistivity contours overlaid

5.7.4 Fourth Layer: The fourth layer, usually of high resistance is characteristic of the hard bed rock and if the value is less it indicates the fractured or weathered zone with a confined aquifer. The average resistivity value of this layer is 12745 Ωm. The thickness varies from 0.161m. to 83.6m. with an average thickness of 18.9m. (Table 5.2). The very low values at Belvai, Moodbidri and Kuntalpadi area shows that they are high yielding fracture zones in the granitic or gneissic bed rock (Fig. 5.8). Depending upon the thickness the yield also varies in this zone. Belvai area shows highly fractured zone of confined aquifer at deeper level. The values of <200 Ωm indicate high yielding confined aquifer zones in this area.

5.7.5 Fifth layer: The fifth layer shows high resistivity values. In some cases, resistivity value of < 200 Ωm indicates high yielding confined aquifers. The thickness of this zone varies from 7.9 to 37.5 m with an average thickness of 19.81m (Table 5.2). The spatial distribution of the depth variation in fifth layer and the iso-resistivity represented by the contours are represented below (Fig. 5.9).

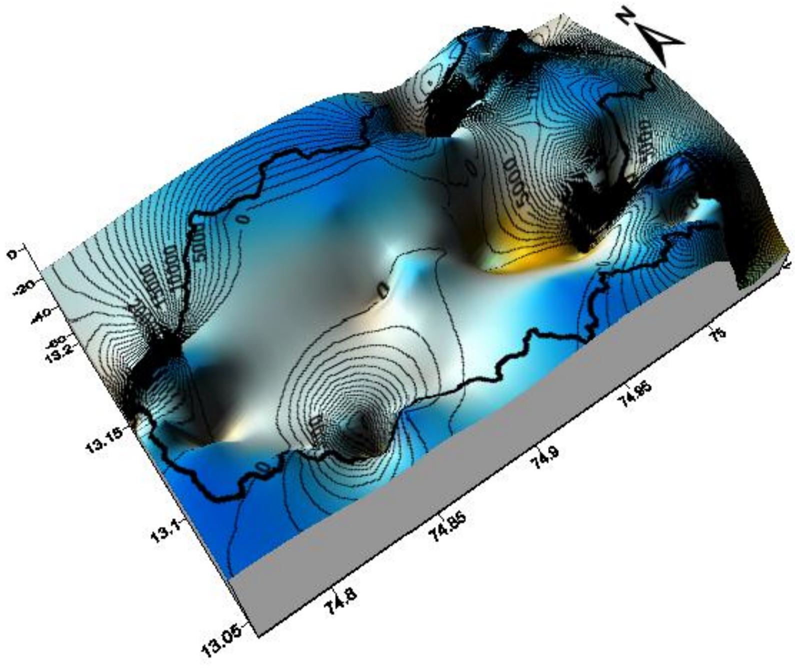

Fig. 5.7 Depth variation of 4th layer with its iso-resistivity contours overlaid

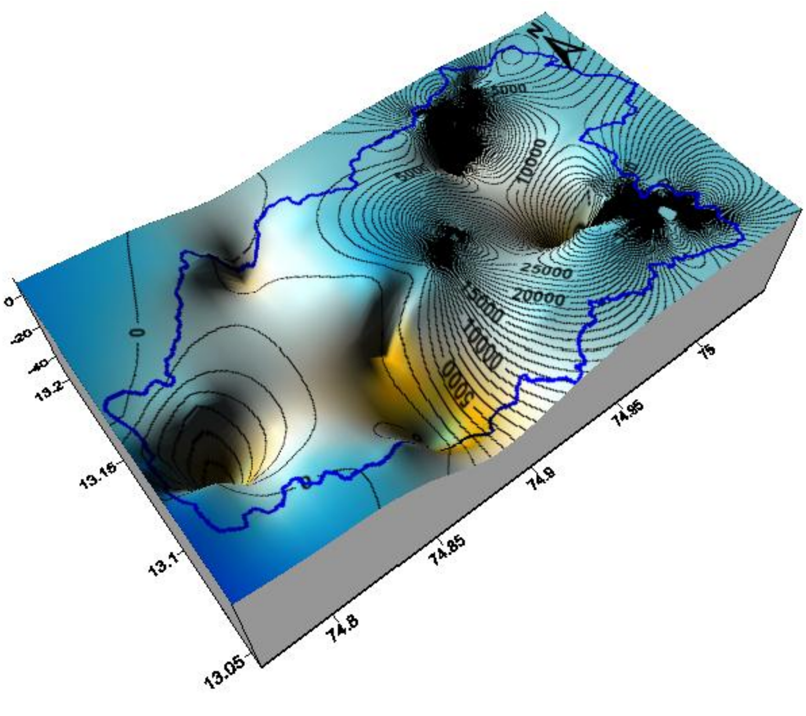

Fig. 5.8 Depth variation of 5th layer with its iso-resistivity contours overlaid

5.7.6 Sixth Layer: The sixth layer, in few cases, is found to indicate deeper confined aquifers. Except three stations, the other six stations show very low resistivity at deeper layer indicating deep aquifers in the underlying granitic bed.

VES	LAYER 1			LAYER 2			LAYER 3			LAYER 4			LAYER 5			LAYER 6	No. of	Type of curve	Curve	Depth to bed
NO.	ρ1	h1	d1	ρ2	h2	d2	ρ3	h3	d3	ρ4	h4	d4	ρ5	h5	d5	ρ6	Layers		type	rock
VES 001	1515	0.43	0.43	577	5.72	6.15	15177	11.30	17.45	28.6							4	ρ1>ρ2<ρ3>ρ4	HK	6.15
VES 002	479	5.58	5.58	88076	5.32	10.90	96.4										3	ρ1<ρ2>ρ3	K	10.90
VES 003	755	0.36	0.36	1736	6.10	6.46	6450	3.59	10.05	1398							4	ρ1<ρ2<ρ3>ρ4	AK	6.46
VES 004	1595	3.86	3.86	1608	0.33	4.19	45.2										3	ρ1<ρ2>ρ3	K	4.19
VES 005	25,000	0.55	0.55	15108	5.09	5.64	19198	70.00	75.64	9482							4	ρ1>ρ2<ρ3>ρ4	HK	5.64
VES 006	1575	3.34	3.34	6536	9.66	13.00	0.936										3	ρ1<ρ2>ρ3	K	13.00
VES 007	13800	0.15	0.15	6389	4.28	4.43	1917										3	ρ1>ρ2>ρ3	Q	4.43
VES 008	2007	1.13	1.13	124	4.84	5.97	16965										3	ρ1>ρ2<ρ3	H	5.97
VES 009	1065	1.03	1.03	86.7	1.13	2.16	317	3.07	5.23	77.5	6.74	11.97	881				5	ρ1> ρ2 <ρ3 >ρ4 <ρ5	HKH	2.16
VES 010	6667	1.36	1.36	702	0.96	2.32	5651	2.98	5.30	308	4.19	9.49	4805				5	ρ1> ρ2< ρ3 >ρ4< ρ5	HKH	2.32
VES 011	2509	0.81	0.81	1191	1.15	1.96	16702	2.54	4.50	1576	6.05	10.55	14934	14.50	25.05	27.1	6	ρ1 >ρ2< ρ3> ρ4 <ρ5> ρ6	HKHK	1.96
VES 012	7387	1.24	1.24	3168	0.47	1.71	115	1.53	3.24	1252	0.80	4.04	37850	7.92	11.96	27.1	6	ρ1> ρ2> ρ3< ρ4 <ρ5> ρ6	QHAK	1.71
VES 013	10293	1.49	1.49	87.4	0.69	2.18	3472										3	ρ1> ρ2 <ρ3	H	2.18
VES 014	11226	0.90	0.90	28825	1.18	2.08	4377	9.12	11.20	76180	14.70	25.90	277				5	ρ1< ρ2> ρ3< ρ4 >ρ5	KHK	2.08
VES 015	1911	4.11	4.11	13.5	3.51	7.62	143										3	ρ1> ρ2< ρ3	H	7.62
VES 016	1449	1.71	1.71	884	10.20	11.91	176	9.36	21.27	1909							4	ρ1 >ρ2>ρ3< ρ4	QH	11.91
VES 017	6736	0.99	0.99	908	1.29	2.28	7738	3.14	5.42	483	8.57	13.99	7866	14.20	28.19	12.1	6	ρ1> ρ2< ρ3> ρ4< ρ5> ρ6	HKHK	2.28
VES 018	22700	0.13	0.13	1197	3.79	3.92	160	43.20	47.12	82233							4	ρ1> ρ2> ρ3 <ρ4	QH	3.92
VES 019	6265	1.33	1.33	867	2.01	3.34	2252	18.10	21.44	916							4	ρ1 >ρ2 <ρ3 >ρ4	HK	3.34
VES 020	1610	1.74	1.74	2548	0.78	2.52	1985	39.22	41.74	127616							4	ρ1 <ρ2> ρ3< ρ4	KH	2.52
VES 021	2981	0.65	0.65	16846	0.87	1.52	1499	2.62	4.14	27849	4.74	8.88	4089				5	ρ1 <ρ2> ρ3 <ρ4 >ρ5	KHK	1.52
VES 022	23173	0.95	0.95	3619	3.44	4.39	1318	4.16	8.55	24065	7.78	16.33	3209				5	ρ1> ρ2> ρ3< ρ4 >ρ5	QHK	4.39
VES 023	462	1.29	1.29	92.3	1.65	2.94	779	3.55	6.49	86.6	8.75	15.24	16500				5	ρ1> ρ2< ρ3 >ρ4 <ρ5	HKH	2.94
VES 024	3273	6.29	6.29	1653	36.60	42.89	33821										3	ρ1> ρ2 <ρ3	H	42.89
VES 025	2849	2.91	2.91	1174	19.00	21.91	75111										3	ρ1> ρ2< ρ3	H	21.91
VES 026	3431	0.80	0.80	572	3.54	4.34	1152	13.90	18.24	87500							4	ρ1> ρ2< ρ3 <ρ4	HA	4.34
VES 027	998	1.07	1.07	160	1.12	2.19	10274	4.47	6.66	137	8.76	15.42	65377				5	ρ1> ρ2< ρ3> ρ4< ρ5	HKH	2.19
VES 028	1384	0.73	0.73	506	7.17	7.89	1455	39.00	46.90	39500							4	ρ1 >ρ2 <ρ3< ρ4	HA	7.89
VES 029	575000	0.23	0.23	3024	3.04	3.27	406	3.83	7.10	1065	83.60	90.70	82.2				5	ρ1> ρ2> ρ3< ρ4> ρ5	QHK	3.27
VES 030	13600	0.23	0.23	3293	1.77	2.00	1297	7.63	9.63	844	28.50	38.13	1400				5	ρ1> ρ2> ρ3> ρ4< ρ5	QQH	2.00
VES 031	7798	0.71	0.71	1378	7.47	8.18	273	7.13	15.31	2359	37.90	53.21	26.9				5	ρ1> ρ2> ρ3 <ρ4> ρ5	QHK	8.18
VES 032	2558	2.28	2.28	748	9.94	12.22	240	15.60	27.82	20565							4	ρ1> ρ2> ρ3< ρ4	QH	12.22
VES 033	185000	0.27	0.27	449	0.11	0.39	3837	7.25	7.64	26450	11.30	18.94	1042				5	ρ1> ρ2 <ρ3< ρ4> ρ5	HAK	0.39
VES 034	320	2.31	2.31	150	2.93	5.24	3080										3	ρ1> ρ2< ρ3	H	5.24
VES 035	9698	3.74	3.74	596	32.00	35.74	23500										3	ρ1> ρ2< ρ3	H	35.74
VES 036	628	0.46	0.46	2067	0.86	1.32	73.8	0.35	1.67	295	0.16	1.83	1137	26.10	27.93	3920	6	ρ1< ρ2> ρ3< ρ4< ρ5< ρ6	KHAA	1.32
VES 037	3496	4.19	4.19	531	16.60	20.79	3758										3	ρ1> ρ2 <ρ3	H	20.79
VES 038	1395	0.76	0.76	464	3.32	4.08	5668	4.69	8.77	697							4	ρ1> ρ2< ρ3> ρ4	HK	4.08
VES 039	270	0.51	0.51	16603	2.24	2.75	1984										3	ρ1< ρ2> ρ3	K	2.75
VES 040	9100	10.80	10.80	1039	8.96	19.76	16319	16.30	36.06	54.1							4	ρ1> ρ2 <ρ3> ρ4	HK	19.76
VES 041	3998	1.47	1.47	8585	2.32	3.79	1582	12.90	16.69	514							4	ρ1< ρ2 >ρ3> ρ4	KQ	3.79
VES 042	3998	1.47	1.47	8585	2.32	3.79	1582	12.90	16.69	514							4	ρ1< ρ2 >ρ3> ρ4	KQ	3.79
VES 043	12088	1.19	1.19	4357	3.09	4.28	1073	6.98	11.26	173.9	7.88	19.14	1125				5	ρ1 >ρ2> ρ3> ρ4< ρ5	QQH	4.28
VES 044	155000	0.44	0.44	5049	4.83	5.27	309	18.80	24.07	1732							4	ρ1> ρ2> ρ3< ρ4	QH	5.27
VES 045	9692	0.81	0.81	6404	4.17	4.98	330	45.60	50.58	24723							4	ρ1> ρ2> ρ3< ρ4	QH	4.98
VES 046	16800	0.14	0.14	193	0.59	0.74	92093	4.09	4.83	14500	6.36	11.19	10600				5	ρ1> ρ2< ρ3 >ρ4 >ρ5	HKQ	0.74
VES 047	5903	1.14	1.14	4046	4.74	5.88	375	25.10	30.98	4587							4	ρ1> ρ2> ρ3< ρ4	QH	5.88
VES 048	4505	1.34	1.34	8734	1.15	2.49	826	9.13	11.62	319	44.00	55.62	56067				5	ρ1< ρ2> ρ3> ρ4 <ρ5	KQH	2.49
VES 049	3063	0.58	0.58	949	10.50	11.08	54.8	14.20	25.28	912							4	ρ1> ρ2> ρ3 <ρ4	QH	11.08
VES 050	2484	0.50	0.50	22433	0.82	1.31	1586	6.45	7.76	622							4	ρ1< ρ2 >ρ3 >ρ4	KQ	1.31
VES 051	32500	0.25	0.25	2779	3.39	3.64	446	8.35	11.99	58.8	11.20	23.19	60962				5	ρ1> ρ2 >ρ3> ρ4< ρ5	QQH	3.64
VES 052	25649	0.42	0.42	2600	3.16	3.58	706	6.45	10.03	41.3	10.20	20.23	41411				5	ρ1> ρ2 >ρ3 >ρ4 <ρ5	QQH	3.58
VES 053	16581	0.90	0.90	4437	3.93	4.83	1296	6.36	11.19	133	14.70	25.89	1270				5	ρ1> ρ2> ρ3> ρ4< ρ5	QQH	4.83
VES 054	8543	2.78	2.78	1705	5.17	7.95	320	36.30	44.25	42379							4	ρ1> ρ2 >ρ3< ρ4	QH	7.95
VES 055	615	0.42	0.42	6199	0.83	1.25	244	14.10	15.35	110	35.80	51.15	8710				5	ρ1< ρ2> ρ3> ρ4 <ρ5	KQH	1.25
VES 056	12575	1.20	1.20	2045	8.71	9.91	125	22.10	32.01	77032							4	ρ1 >ρ2> ρ3< ρ4	QH	9.91
VES 057	30669	1.05	1.05	1759	7.53	8.58	473										3	ρ1> ρ2 >ρ3	Q	8.58
VES 058	3371	0.54	0.54	1195	14.30	14.84	231	41.10	55.94	23959							4	ρ1> ρ2> ρ3< ρ4	QH	14.84
VES 059	13276	0.85	0.85	421	0.84	1.68	3404	1.11	2.79	773	41.70	44.49	4861				5	ρ1> ρ2< ρ3> ρ4< ρ5	HKH	1.68
VES 060	16812	0.82	0.82	1973	5.46	6.28	460	93.70	99.98	35256							4	ρ1> ρ2> ρ3< ρ4	QH	6.28
VES 061	51500	0.32	0.32	5817	1.52	1.84	1067	9.96	11.80	131	14.90	26.70	467				5	ρ1> ρ2 >ρ3 >ρ4< ρ5	QQH	1.84
VES 062	7770	2.29	2.29	1166	22.40	24.69	198	17.30	41.99	78191							4	ρ1 >ρ2> ρ3< ρ4	QH	24.69
VES063	15193	1.56	1.56	1191	7.80	9.36	234	38.10	47.46	1.15							4	ρ1> ρ2> ρ3> ρ4	QQ	9.36
VES 064	859	3.78	3.78	366													2	ρ1 >ρ2		3.78

Table 5.1 Analysis details of Vertical Electrical Sounding (VES) curves in Mulki River Basin (contd…)

VES	LAYER 1			LAYER 2			LAYER 3			LAYER 4			LAYER 5			LAYER 6	No. of	Type of curve	Curve	Depth to bed
NO.	ρ1	h1	d1	ρ2	h2	d2	ρ3	h3	d3	ρ4	h4	d4	ρ5	h5	d5	ρ6	Layers		type	rock
VES 065	643	0.51	0.51	15600	12.10	12.61	19600										3	ρ1< ρ2 <ρ3	A	12.61
VES 066	717	0.95	0.95	232	22.40	23.35	4675	8.64	31.99	13.1							4	ρ1 >ρ2< ρ3 >ρ4	HK	23.35
VES 067	5781	2.24	2.24	1647	10.30	12.54	119	43.60	56.14	15334							4	ρ1> ρ2> ρ3< ρ4	QH	12.54
VES 068	13677	1.37	1.37	4050	7.23	8.60	125	12.20	20.80	12.2							4	ρ1> ρ2 >ρ3> ρ4	QQ	8.60
VES 069	16244	1.01	1.01	4906	7.59	8.60	318	36.30	44.90	15500							4	ρ1> ρ2> ρ3< ρ4	QH	8.60
VES 070	13324	1.16	1.16	1140	28.40	29.56	357	22.10	51.66	15500							4	ρ1> ρ2> ρ3< ρ4	QH	29.56
VES 071	4379	29.40	29.40	29632	12.10	41.50	98.8										3	ρ1< ρ2> ρ3	K	41.50
VES 072	4336	0.35	0.35	33.4	5.69	6.04	10176										3	ρ1> ρ2< ρ3	H	6.04
VES 073	449	0.53	0.53	147	0.91	1.44	1804	2.41	3.85	58.1	21.80	25.65	656				5	ρ1> ρ2< ρ3> ρ4 <ρ5	HKH	1.44
VES 074	1961	4.64	4.64	105	5.15	9.79	85704										3	ρ1> ρ2< ρ3	H	9.79
VES 075	46.1	0.31	0.31	1649	66.50	66.81	14500										3	ρ1< ρ2< ρ3	A	66.81
VES 076	4063	2.29	2.29	34	2.72	5.01	69381										3	ρ1> ρ2< ρ3	H	5.01
VES 077	2979	1.57	1.57	1282	11.30	12.87	64.2	12.90	25.77	61496							4	ρ1 >ρ2> ρ3< ρ4	QH	12.87
VES 078	957	3.47	3.47	2160	4.65	8.12	73.9	10.40	18.52	66286							4	ρ1< ρ2 >ρ3< ρ4	KH	8.12
VES 079	4304	2.21	2.21	2204	39.50	41.71	658										3	ρ1> ρ2> ρ3	Q	41.71
VES 080	3669	1.11	1.11	229	1.14	2.25	1433	3.00	5.25	101	12.80	18.05	44836				5	ρ1> ρ2< ρ3> ρ4< ρ5	HKH	2.25
VES 081	4371	1.35	1.35	1261	8.24	9.59	95	10.70	20.29	6485							4	ρ1> ρ2> ρ3< ρ4	QH	9.59
VES 082	3685	1.18	1.18	1219	14.40	15.58	366	14.80	30.38	4655							4	ρ1 >ρ2> ρ3< ρ4	QH	15.58
VES 083	459	16.10	16.10	25624	14.90	31.00	271										3	ρ1 <ρ2 >ρ3	K	31.00
VES 084	15690	0.44	0.44	1217	2.00	2.44	476	4.85	7.29	1510	6.77	14.06	641	37.50	51.56	100000	6	ρ1> ρ2 >ρ3< ρ4 >ρ5 <ρ6	QHKH	2.44
VES 085	1280	0.55	0.55	6263	1.16	1.71	1107	4.97	6.68	96.7	18.30	24.98	311				5	ρ1< ρ2 >ρ3 >ρ4< ρ5	KQH	1.71
VES 086	1129	0.53	0.53	6703	0.87	1.40	1307	4.56	5.96	122	20.20	26.16	358				5	ρ1< ρ2> ρ3> ρ4< ρ5	KQH	1.40
VES 087	355000	0.25	0.25	1873	6.90	7.15	121	5.26	12.41	977							4	ρ1 >ρ2> ρ3 <ρ4	QH	7.15
VES 088	27500	0.26	0.26	3559	2.76	3.02	1107	6.62	9.64	143	11.10	20.74	1945	18.00	38.74	14.4	6	ρ1> ρ2> ρ3 >ρ4< ρ5> ρ6	QQHK	3.02
VES 089	12.3	0.93	0.93	62329	3.67	4.60	515										3	ρ1< ρ2 >ρ3	K	4.60
VES 090	12651	0.27	0.27	421	7.86	8.13	1681	15.50	23.63	124							4	ρ1> ρ2 <ρ3> ρ4	HK	8.13
VES 091	776	1.48	1.48	344	1.73	3.21	1448	4.01	7.22	144	9.12	16.34	2484				5	ρ1> ρ2< ρ3> ρ4< ρ5	HKH	3.21
VES 092	2384	1.05	1.05	264	12.00	13.05	723										3	ρ1> ρ2< ρ3	H	13.05
VES 093	3566	1.02	1.02	1879	4.58	5.60	205	5.43	11.03	765	52.90	63.93	24174				5	ρ1> ρ2> ρ3 <ρ4 <ρ5	QHA	5.60
VES 094	739	0.56	0.56	187	0.80	1.36	853	1.57	2.93	143	19.40	22.33	43779				5	ρ1> ρ2< ρ3> ρ4 <ρ5	HKH	1.36
VES 095	10779	0.66	0.66	2522	5.08	5.74	548	12.70	18.44	1820							4	ρ1> ρ2> ρ3 <ρ4	QH	5.74
VES 096	1096	0.92	0.92	1992	2.29	3.21	1183	18.70	21.91	10027	22.30	44.21	124				5	ρ1< ρ2> ρ3< ρ4> ρ5	KHK	3.21
VES 097	1509	6.77	6.77	10193	7.08	13.85	1913	40.10	53.95	19500							4	ρ1< ρ2> ρ3< ρ4	KH	13.85
VES 098	4393	1.85	1.85	1256	12.40	14.25	5583	14.30	28.55	591							4	ρ1> ρ2< ρ3> ρ4	HK	14.25
VES 099	671	1.47	1.47	3819	0.34	1.81	568										3	ρ1< ρ2> ρ3	K	1.81
VES 100	2220	1.69	1.69	428	0.91	2.60	1461	6.27	8.87	52.1	13.50	22.37	375				5	ρ1> ρ2 <ρ3> ρ4< ρ5	HKH	2.60
VES 101	4179	5.34	5.34	16.6	6.41	11.75	149										3	ρ1> ρ2< ρ3	H	11.75
VES 102	125	0.96	0.96	651	4.80	5.76	293	15.20	20.96	2711	20.60	41.56	12.3				5	ρ1< ρ2> ρ3< ρ4> ρ5	KHK	5.76
VES 103	574	2.43	2.43	1669	3.04	5.47	302	11.20	16.67	1868	38.70	55.37	14.3				5	ρ1< ρ2> ρ3 <ρ4 >ρ5	KHK	5.47
VES 104	1688	3.36	3.36	56.2	4.10	7.46	230	51.40	58.86	11262							4	ρ1> ρ2< ρ3 <ρ4	HA	7.46
VES 106	785	4.32	4.32	1236	40.80	45.12	205										3	ρ1< ρ2> ρ3	K	45.12
VES 107	526	0.74	0.74	31.2	0.94	1.68	86185										3	ρ1 >ρ2< ρ3	H	1.68
VES 108	531	3.43	3.43	39.6	29.50	32.93	11585										3	ρ1> ρ2< ρ3	H	32.93
VES 109	18.1	1.28	1.28	0.398	1.97	3.25	10.7										3	ρ1> ρ2 <ρ3	H	3.25
VES 110	503	0.92	0.92	161	0.76	1.67	2814	2.20	3.87	142	8.25	12.12	683				5	ρ1> ρ2< ρ3> ρ4< ρ5	HKH	1.67
VES 111	5054	0.83	0.83	574	7.90	8.73	43.4	8.07	16.80	61301							4	ρ1> ρ2> ρ3< ρ4	QH	8.73
VES 112	373	1.31	1.31	5263	2.55	3.86	5.8	6.98	10.84	4252							4	ρ1< ρ2> ρ3< ρ4	KH	3.86
VES 113	2993	0.59	0.59	1494	1.06	1.65	4443	1.74	3.39	652	19.70	23.09	114	23.90	46.99	69545	6	ρ1> ρ2< ρ3> ρ4> ρ5< ρ6	HKQH	1.65
VES 114	30600	0.19	0.19	3238	3.64	3.83	763	11.40	15.23	108							4	ρ1> ρ2> ρ3> ρ4	QQ	3.83
VES 115	4195	4.21	4.21	375	11.90	16.11	44500										3	ρ1> ρ2< ρ3	H	16.11
VES 116	3536	0.62	0.62	9026	0.94	1.55	1532	8.91	10.46	223	44.30	54.76	35753				5	ρ1< ρ2 >ρ3> ρ4< ρ5	KQH	1.55
VES 117	96692	0.27	0.27	1758	3.56	3.83	1219	7.36	11.19	178	13.80	24.99	1179				5	ρ1> ρ2 >ρ3 >ρ4 <ρ5	QQH	3.83
VES 118	2749	1.77	1.77	1486	12.40	14.17	203	15.40	29.57	11500							4	ρ1> ρ2> ρ3< ρ4	QH	14.17
VES119	2755	1.64	1.64	1605	6.14	7.78	799	68.70	76.48	11.5							4	ρ1> ρ2> ρ3> ρ4	QQ	7.78
VES 120	2706	0.23	0.23	7559	4.48	4.71	1563	7.57	12.28	283	54.50	66.78	16658				5	ρ1< ρ2> ρ3> ρ4< ρ5	KQH	4.71
VES 121	62.2	0.54	0.54	4.69	1.82	2.36	1.21	4.13	6.49	30.5	5.63	12.12	1.16	12.60	24.72	220	6	ρ1> ρ2> ρ3< ρ4> ρ5< ρ6	QHKH	2.36
VES 122	531	3.43	3.43	39.6	29.60	33.03	11585										3	ρ1> ρ2< ρ3	H	33.03
VES 123	2.11	0.92	0.92	1.22	8.11	9.03	740										3	ρ1> ρ2< ρ3	H	9.03
VES 124	292	1.07	1.07	1724	103.00	104.07	4923										3	ρ1< ρ2< ρ3	A	1.07
VES 125	665	1.43	1.43	204	1.88	3.31	5592	4.92	8.23	215	11.30	19.53	24500				5	ρ1> ρ2< ρ3> ρ4 <ρ5	HKH	3.31
VES 126	3965	0.93	0.93	773	1.27	2.20	5033	2.73	4.93	231	6.33	11.26	4941	14.30	25.56	8.29	6	ρ1> ρ2< ρ3> ρ4< ρ5> ρ6	HKHK	2.20
VES 127	38031	1.52	1.52	1108	0.67	2.19	1888		2.19								3	ρ1 >ρ2< ρ3	H	2.19
VES 128	337	0.49	0.49	11744	0.94	1.44	491	32.20	33.64	1752							4	ρ1< ρ2 >ρ3< ρ4	KH	1.44
VES 129	579	1.02	1.02	10.5	2.94	3.96	0.389		3.96								3	ρ1> ρ2> ρ3	Q	3.96

Table 5.1 Analysis details of Vertical Electrical Sounding (VES) curves in Mulki River Basin

Layer	Parameters	No. of data	Maximum	Minimum	Median	Mean	Std. Dev.	Skewness	Kurtosis	K-S Dist.
Layer 1	ρ1 (Ωm)	128	575000.00	2.11	3322.00	16874.12	62898.23	7.08	55.64	0.39
Layer 1	h1 (meters)	128	29.40	0.13	1.04	1.86	3.18	6.16	47.32	0.29
Layer 1	d1 (meters)	128	29.40	0.13	1.04	1.86	3.18	6.16	47.32	0.29
Layer 2	ρ2 (Ωm)	128	88076.00	0.40	1330.00	4444.03	10595.25	5.57	37.09	0.34
Layer 2	h2 (meters)	127	103.00	0.11	3.93	7.84	12.86	4.52	26.69	0.27
Layer 2	d2 (meters)	127	104.07	0.39	5.01	9.68	13.69	3.84	19.86	0.25
Layer 3	ρ3 (Ωm)	127	92093.00	0.39	1073.00	6421.37	16699.79	3.95	15.63	0.35
Layer 3	h3 (meters)	91	93.70	0.35	9.12	15.17	16.87	2.28	6.01	0.24
Layer 3	d3 (meters)	91	99.98	1.67	12.41	20.79	19.09	1.68	3.08	0.18
Layer 4	ρ4 (Ωm)	91	127616.00	1.15	912.00	12744.65	24916.51	2.51	6.23	0.32
Layer 4	h4 (meters)	45	83.60	0.16	12.80	18.90	17.08	1.81	3.68	0.22
Layer 4	d4 (meters)	45	90.70	1.83	22.33	27.39	19.13	1.34	1.56	0.25
Layer 5	ρ5 (Ωm)	45	65377.00	1.16	1945.00	12188.62	18542.54	1.63	1.51	0.30
Layer 5	h5 (meters)	9	37.50	7.92	14.50	18.78	8.99	1.17	1.29	0.24
Layer 5	d5 (meters)	9	51.56	11.96	27.93	31.19	12.36	0.42	-0.22	0.26
Layer 6	ρ6 (Ωm)	9	100000.00	8.29	27.10	19308.22	37908.87	1.79	1.87	0.44
	No. of layers		6	2	4	4	1	0	-1	0
	Depth to bed rock		66.80 m.	0.40 m.	4.90 m.	8.80 m.	10.76 m.	2.68	8.39	0.22

Table 5.2 Statistical analysis of the VES curve interpretation data

5.8 RESISTIVITY CURVES: The type of resistivity curve gives an idea about the aquifer type and its characteristics. From the analysis of apparent resistivity values of different layers (ρ1, ρ2, ρ3,…….ρ6) it is found that there are about 25 type of curves, represented by a two layer curve of dry zone at Sampige of Puthige village to six layer curves with deep confined aquifers at Moodbidre, Kuntalpadi, Bappanadu, Nitte, Halasinakatte and Jarigakatte (Table 5.1). The analysis of the resistivity curves in the study area and their representation in terms of aquifer characteristics with the probable rock types are given below (Table 5.3). Based on field investigations in different geological terrains of Mulki River basin, a general probable sequence of rocks is arrived at, which is as follows (Fig. 5.9). This sequence may vary depending on the terrain as given in Table 5.3.

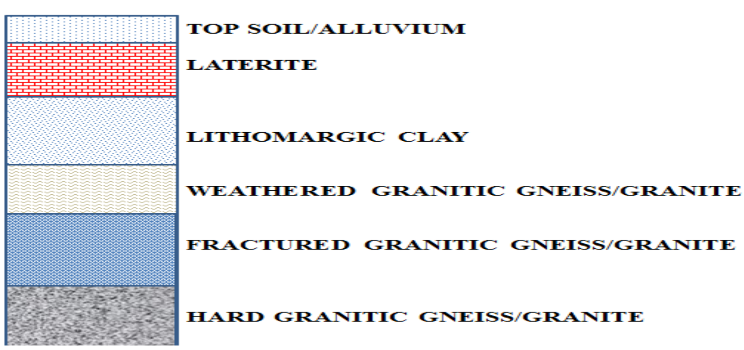

Fig. 5.9 General probable sequence or pseudo section of lithology in the study area

Sl. No.	LAYERS	Type of Curve	No. of Stati -ons	Aquifer Zone	Probable Rock Type
1	**2**		01	Dry Zone	Top Soil/Granite
2	**3 Layer**	A	03	Dry zone	Topsoil/ Dry Laterite / Granite
3		H	20	Unconfined Aquifer	Top soil/Laterite/Granite or gneiss
4		K	09	Unconfined aquifer	Top soil/dry laterite/ weathered granite
5		Q	04	Unconfined aquifer	Top soil/ highly porous laterite/clay
6	**4 Layers**	AK	01	Dry zone	Topsoil/ dry laterite / weathered/ fractured Granite or gneiss
7		HA	03	unconfined aquifer	Topsoil/ porous laterite / hard Granite
8		HK	08	Confined aquifer	Topsoil/ porous laterite / Hard Granite/ fractured granite or gneiss
9		KH	05	Unconfined aquifer/dry zone	Topsoil/dry laterite/ weathered zone/ granite or gneiss
10		KQ	03	Good yielding confined aquifers	Laterite/granite/fractured granite or gneiss
11		QH	22	Unconfined aquifer. Third layer good yielding zone	Top soil/ porous laterite/lithomarge clay/weathered granite/hard Granite
12		QQ	04	Unconfined aquifer	Top soil/porous laterite/clay/weathered granite or gneiss . Thick clay belt below highly porous laterite
13	**5 Layers**	HAK	01	Unconfined aquifer, Dry Zone	Topsoil/laterite/granite
14		HKH	12	2nd layer good unconfined aquifer, 4th layer good Confined aquifer	Top soil/highly porous laterite with clay/ hard granite/fractured granite or gneiss
15		KHK	05	Confined aquifer, yield versus resistivity, poor yield	Topsoil/laterite/granite or gneiss
16		KQH	06	4th layer yield zone, Confined aquifer	Topsoil/laterite/granite/fractured granite, compact rock
17		QHA	01	3rd layer good yielding zone	Topsoil/weathered granite/fractured granite/compact rock or gneiss
18		QHK	03	Unconfined 3rd layer, confined 5th layer	Topsoil/laterite/weathered/fractured granite, compact rock/fractured granite or gneiss
19		QQH	07	Unconfined aquifer	Topsoil/porous laterite/clay/weathered granite/granite or gneiss
20	**6 Layers**	HKHK	03	2nd unconfined, 4th & 6th confined aquifers. high yield	Topsoil/porous laterite/granite/ fractured granite/granite or gneiss
21		HKQH	01	Confined aquifer	Topsoil/porous laterite/granite/ fractured granite/granite or gneiss
22		KHAA	01	Confined aquifer 3rd & 4th layer	Topsoil/porous laterite/granite/ fractured granite/granite or gneiss
23		QHAK	01	3rd unconfined, 6th confined aquifer	Topsoil/porous laterite/granite/ fractured granite/granite or gneiss
24		QHKH	02	Saline water ingresses	Topsoil/porous laterite/granite/ fractured granite/granite or gneiss
25		QQHK	01	4th layer unconfined, 6th layer confined	Topsoil/porous laterite/granite/ fractured granite/granite or gneiss

Table 5.3 Resistivity curve types and their probable lithology and aquifer zones in the Mulki River basin

5.9 DEPTH OF BEDROCK: The depth of bedrock is very important information in the determination of yield of a well and its development. If the thickness of the overburden is more, it will be of much utility in the case of open wells tapping the unconfined aquifers, whereas it is adverse situation in case of bore well development. This will also give an idea about the size of the open well to be constructed depending upon the yield requirements, especially in the hard rock area where the recuperation is very slow. The spatial variation of the depth of bedrock in Mulki River basin is plotted using the Surfer 10 software and found to be varying a lot from the coastal area to the head of the river. The geology of the area is found to be a dominating factor in deciding the depth of bedrock. It is found, that towards the mouth of the river, the bedrock is deep compared to the middle of the basin (Fig. 5.10). The well density of open wells is found to be very high in this area. The lateritic plateau region of Moodbidri-Belvai belt is found to have the bedrock at deeper levels. This indicates the control of the intrusive body, found along the middle of the study area trending from Karkala to Kinnigoli stretch, on the depth of bedrock variation. This area contains a good number of high yielding deep open wells. A cross section of the Mulki River basin along the East west direction (Fig. 5.11) also indicates the depth of bedrock variation in coastal area to the hard ridge and beyond up to the lateritic plateau of Moodbidri-Belvai. The depth to bedrock varies from 0.03meters at Kemmannu, Nitte Panchayath to 66.81 metres at Moodbidri. The average depth to bedrock is about 8.79meters from surface (Table 5.1). More than 76% of the soundings showed less than 10metres depth to the hard bedrock. This may be due to the geology of the area where the residual laterite is formed out of the underlying granitic gneiss. Since the Laterite is highly porous, this zone store a lot of water during the monsoon season and empties fast during summer due to the groundwater flow. Many of the wells in the study area dry up during summer season and an alternate source of water is necessary in the area for drinking water. The steep slopes of the terrain also enhance underground water flow depleting the resource early.

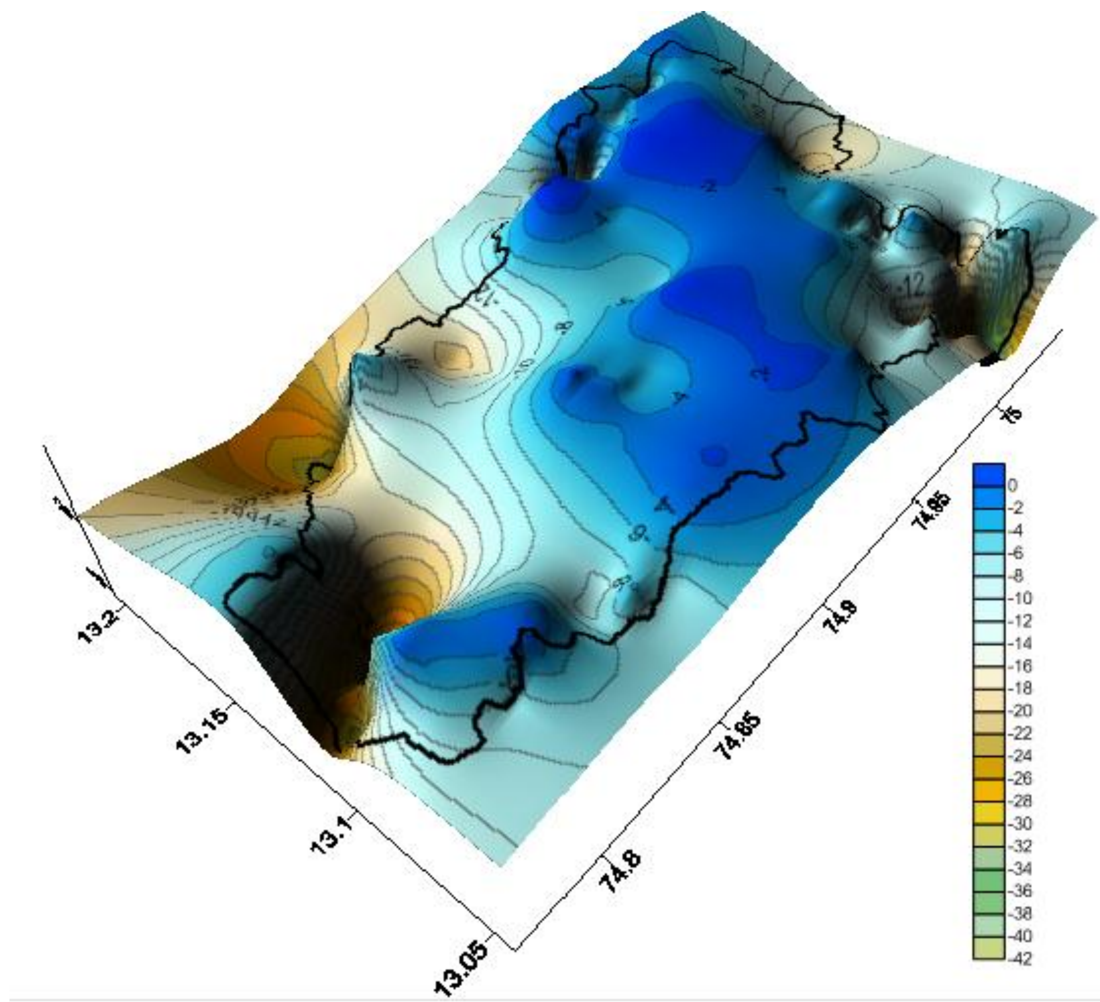

Fig. 5.10 Variation in depth of bedrock from surface deduced from VES Data

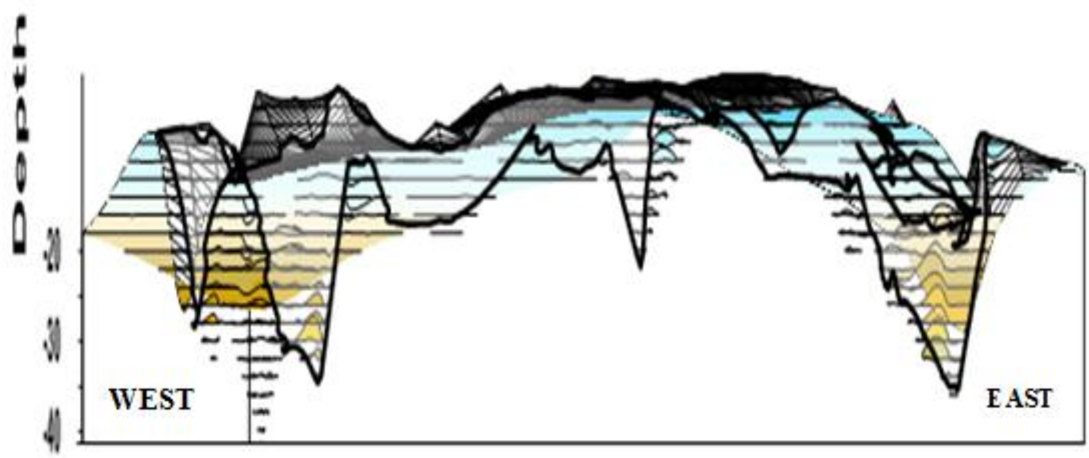

Fig. 5.11 East-West profile of Mulki River Basin showing the variation in depth to the bedrock from surface

5.10 AQUIFER THICKNESS: The aquifer thickness gives an idea about the yield of a well. The aquifer thickness (top/shallow aquifer) and depth deduced from the VES curve interpretation (Table 5.1) are plotted at their VES locations using Surfer 10 software and the result obtained shows the spatial variation of the thickness over the depth of aquifer. The depth indicator gives an idea about the slope of the aquifer whereas the contours give the thickness variation spatially (Fig. 5.12). This indicates the slope of the groundwater flow towards the valley portions and the thickness of aquifers concentrated in some pockets showing the potential of these zones for groundwater development.

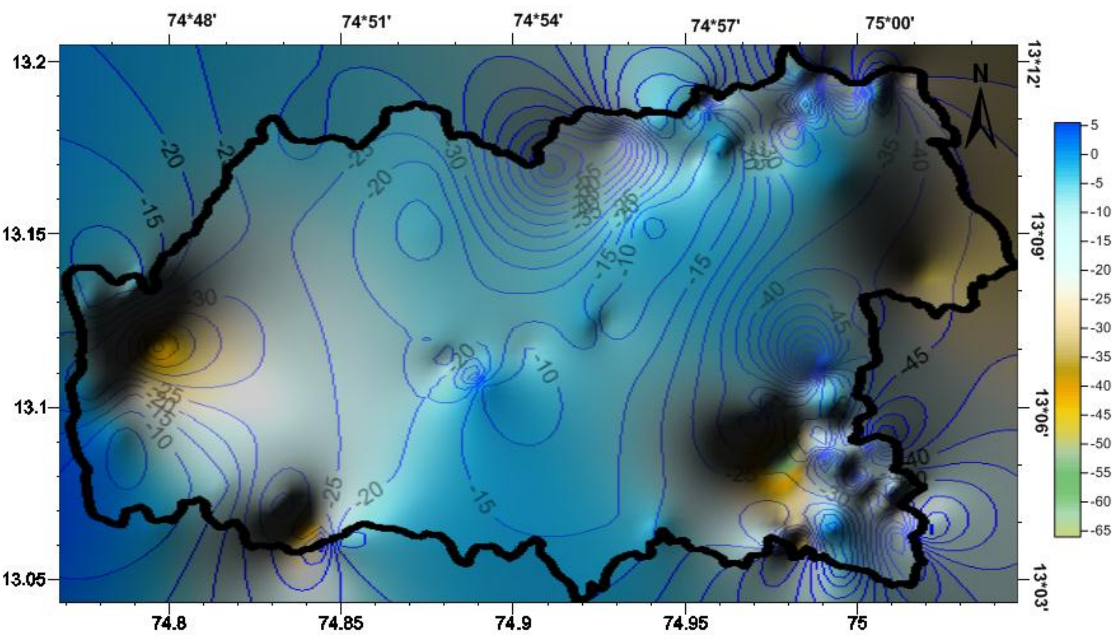

Fig. 5.12 Variation in thickness over depth of aquifer in Mulki River basin based on VES interpretation

(Contours show the thickness of aquifer and the colour variation shows the aquifer depth from the surface)

5.11 ISO-RESISTIVITY CONTOURS: Iso-resistivity maps are useful for delineating the low apparent resistivity zones which may be useful in locating the groundwater prospecting zones. This will also give an idea about the trend of the weathering, saturation of the soils and rock, and presence of fractures in the study area. Iso-resistivity contour maps of the study area (Fig. 5.13 – Fig. 5.20) were prepared by plotting the apparent resistivity values, corresponding to the electrode spacing (AB) of 3m, 10m, 20m, 30m, 40m and 60m to understand the shallow low resistivity zones; whereas 80m, 100m, 120m, 140m, 160m, 180m, 200m, 220m respectively to understand the low resistivity zones at deeper levels in the study area.

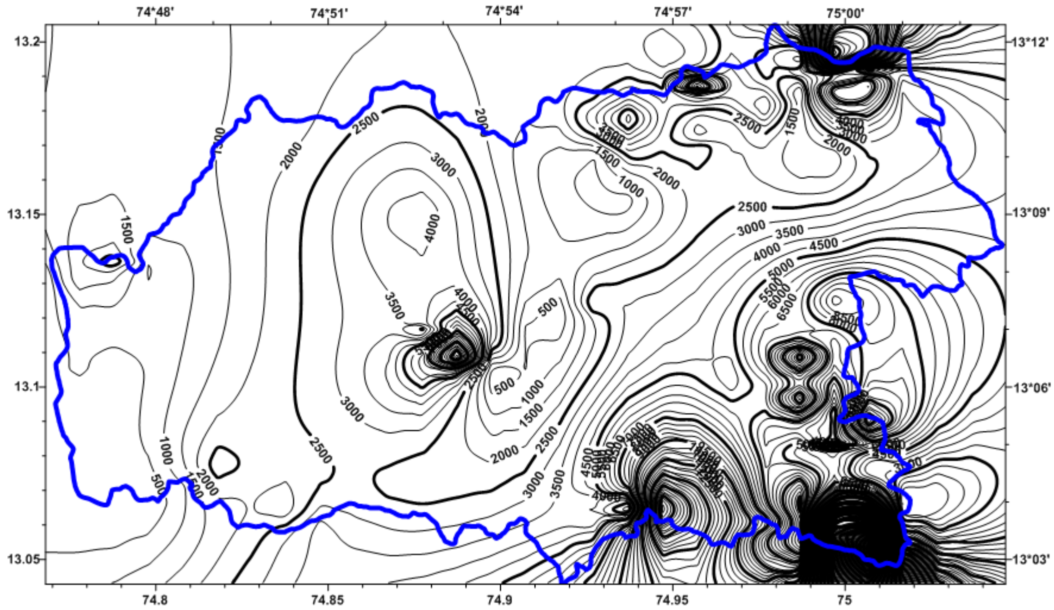

Fig. 5.13 Iso-resistivity contours for 3meter current electrode spacing

The low values in the iso-resistivity contours of 3meters near the coastal area and the valley region shows the saturation of top soil by moisture (Fig. 5.13). The value shows an increasing trend towards the exposed hilly terrain in the study area.

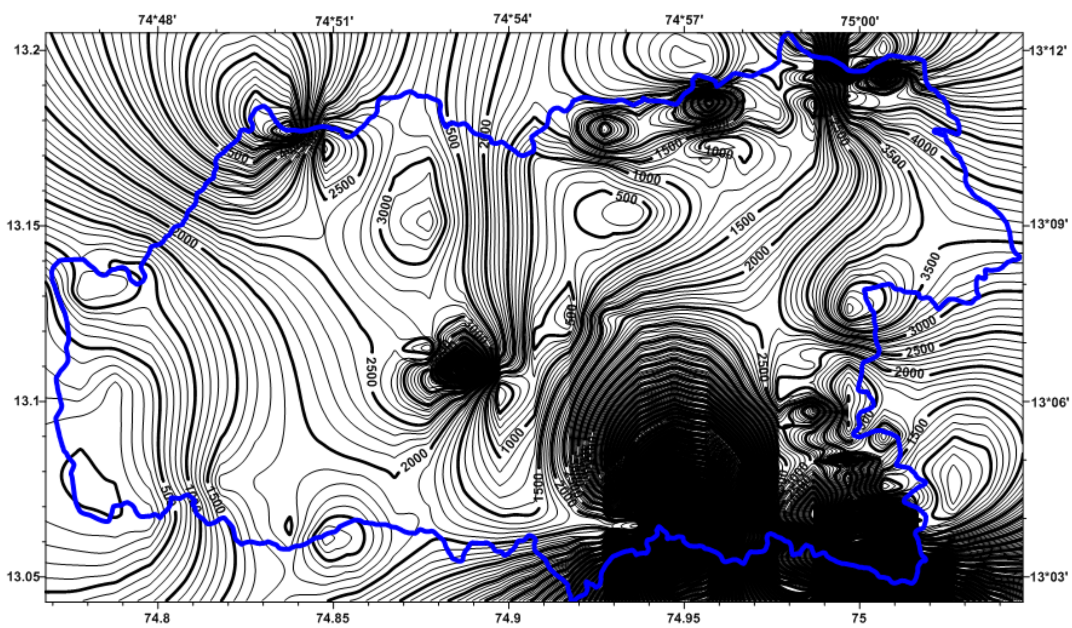

Fig. 5.14 Iso-resistivity contours for 10meter current electrode spacing

Fig 5.14 shows low resistivity zones in the coastal region where a number of shallow wells within a shallow depth of 5m exists. Some pockets of low resistivity zones in the inland valley regions are also indicated by the 10meters contour map.

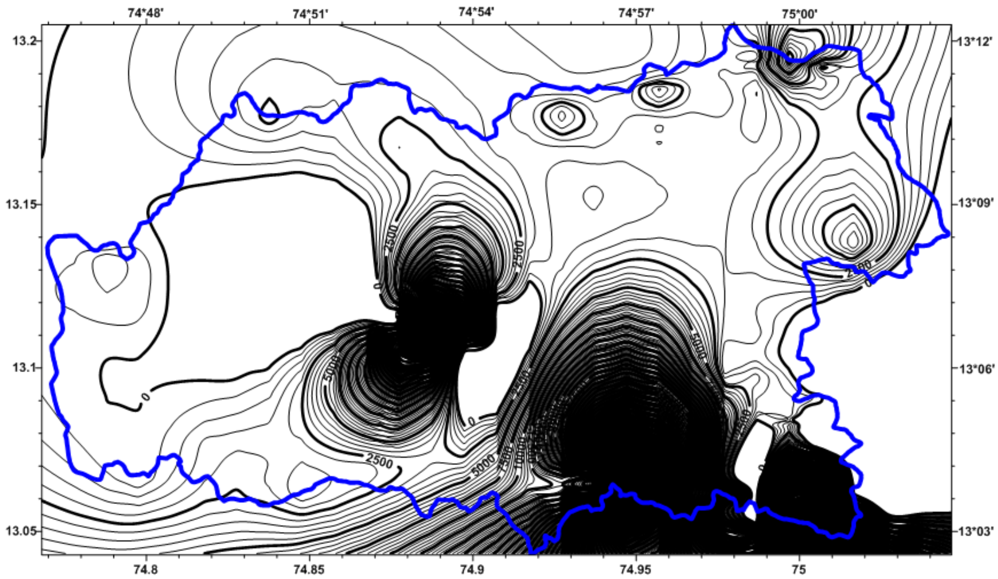

Fig. 5.15 Iso-resistivity contours for 20meters current electrode spacing

The trend of low resistive zone is spread in a wider area thanks to the shallow laterite aquifer existing in the area (Fig. 5.15). The low lying areas are characterized by the laterite aquifer at an approximate depth of about 10metres. Many of the open wells located in the study area fall in this zone and depth.

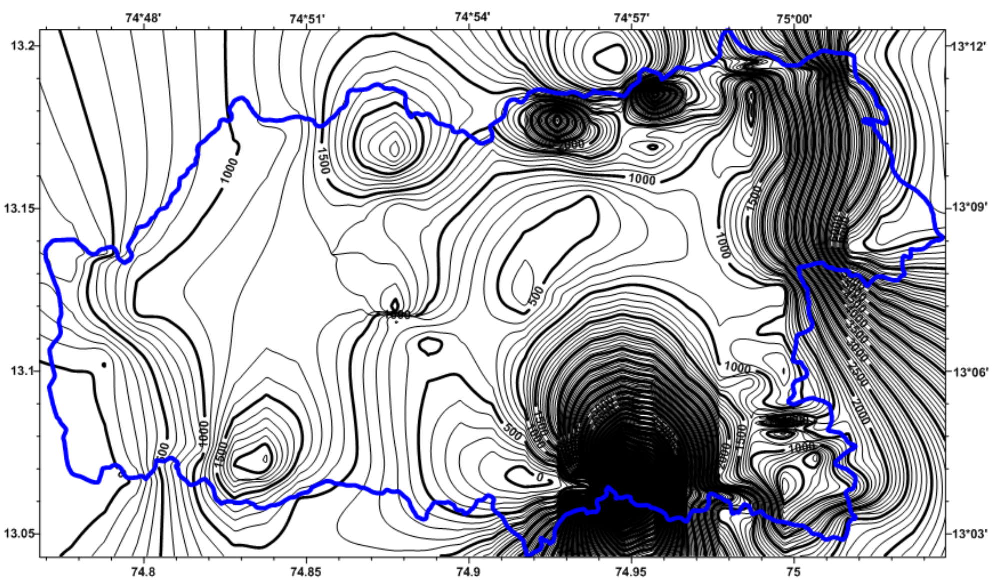

Fig. 5.16 Iso-resistivity contours for 30meter current electrode spacing

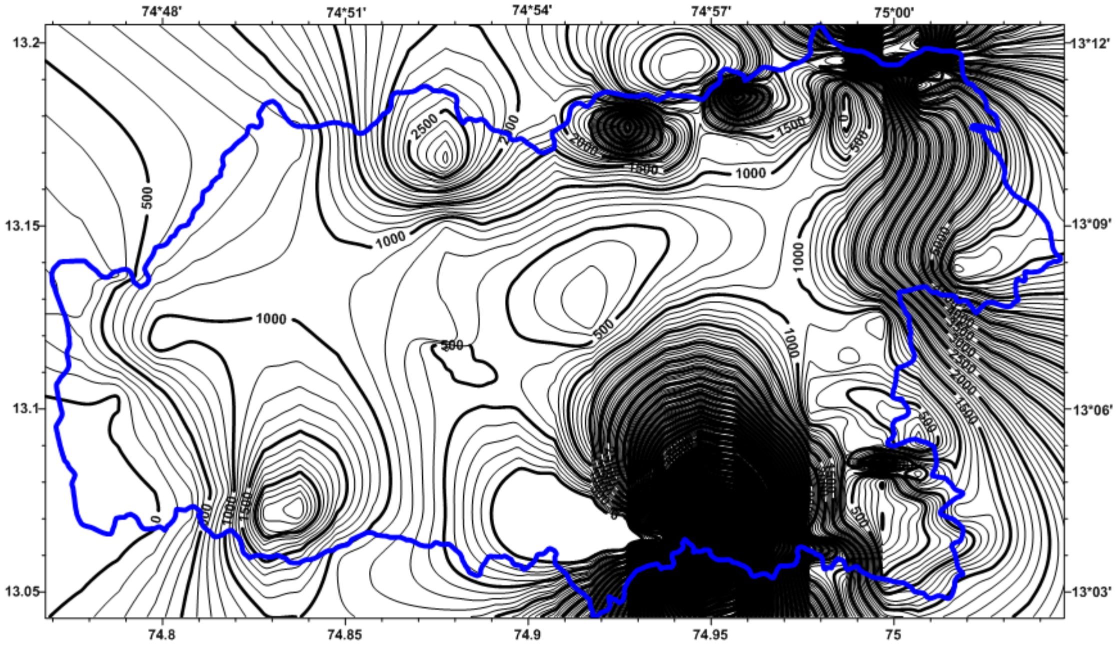

Fig. 5.17 Iso-resistivity contours for 40meter current electrode spacing

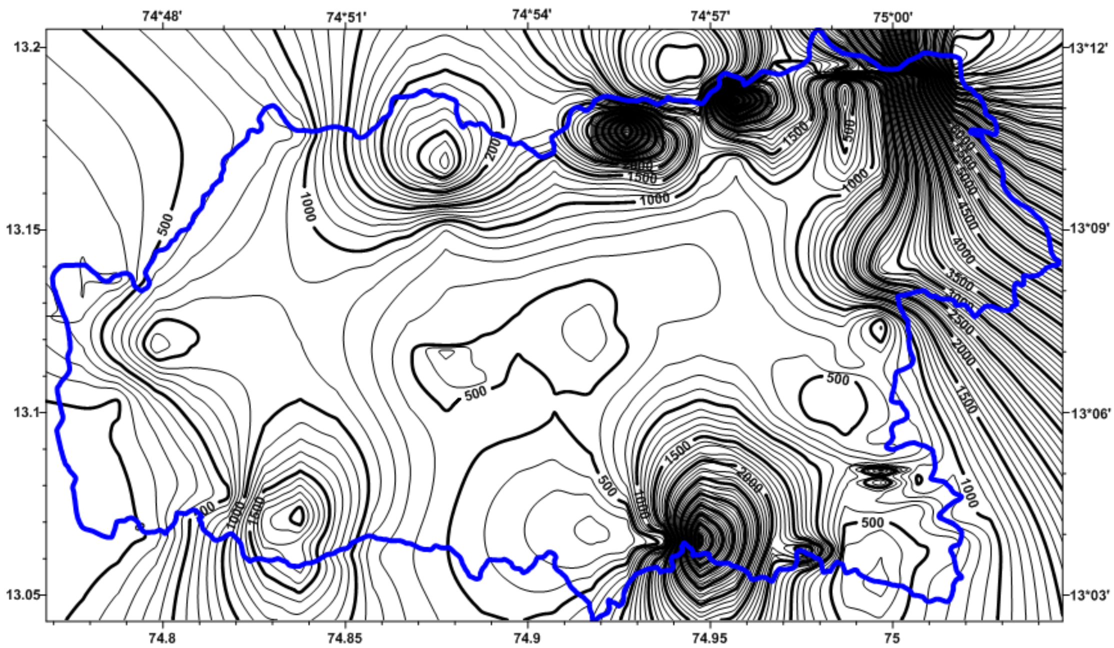

Fig. 5.18 Iso-resistivity contours for 60meter current electrode spacing

The iso-resistivity contour maps of the study area for up to 60meters current electrode spacing (Fig. 5.16 to Fig. 5.18) shows the trend of shallow aquifer zones with low apparent resistivity concentrated towards the valley portions and towards the coastal front. This spatial distribution can be used for the location of the shallow wells in unconfined aquifers especially in the lateritic and alluvial zones in the study area.

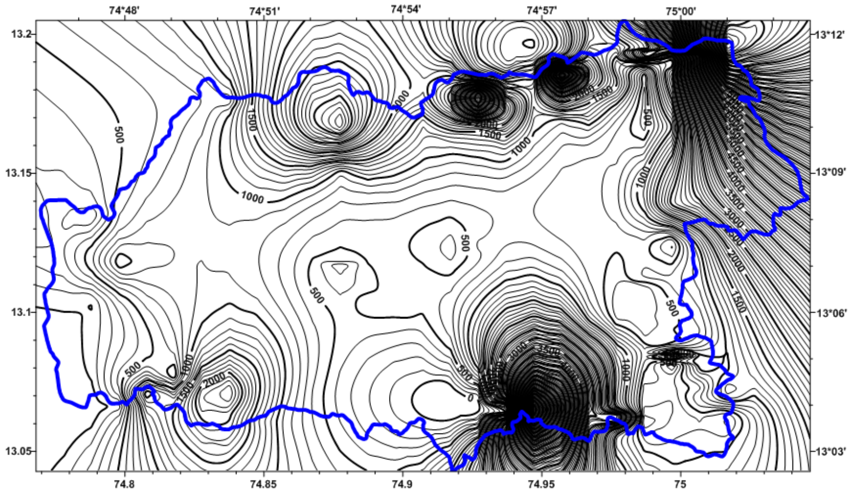

Fig. 5.19 Iso-resistivity contours for 80meter current electrode spacing

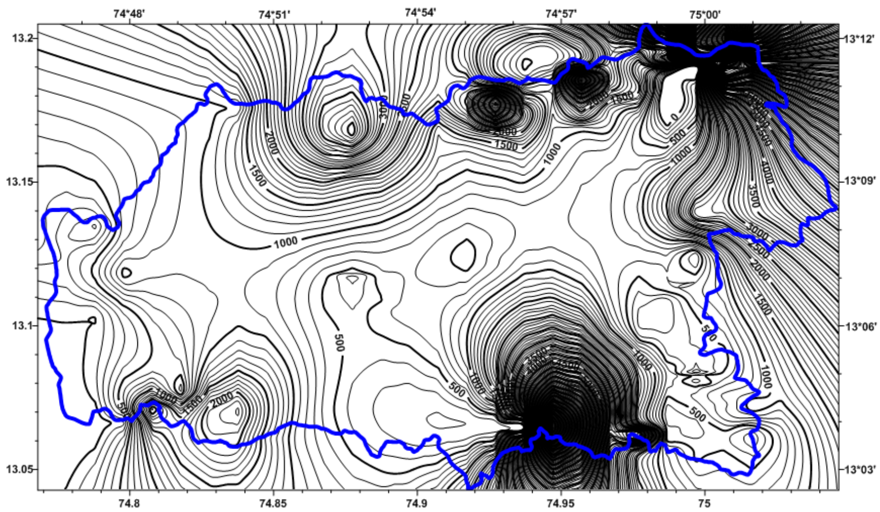

Fig. 5.20 Iso-resistivity contours for 100meter current electrode spacing

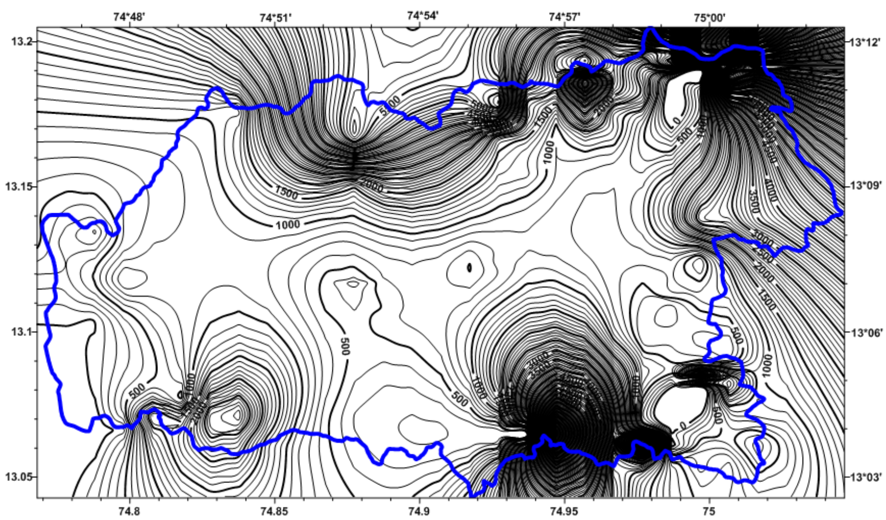

Fig. 5.21 Iso-resistivity contours for 120meter current electrode spacing

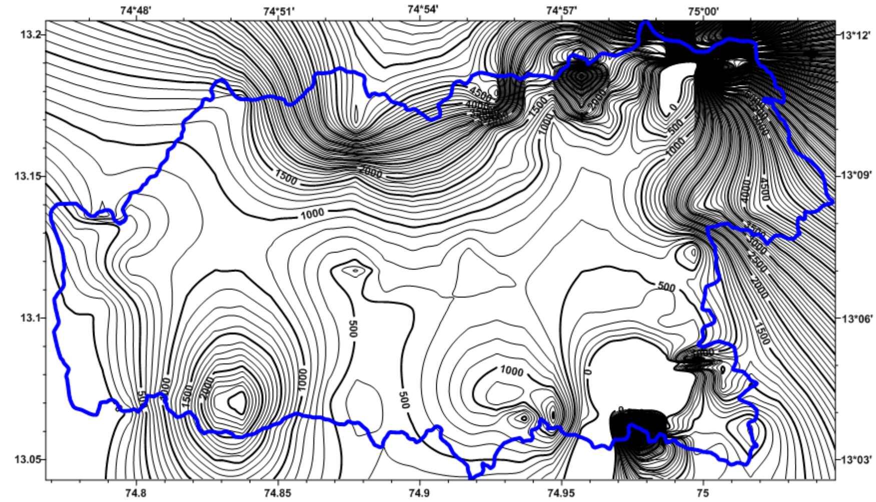

Fig. 5.22 Iso-resistivity contours for 140meter current electrode spacing

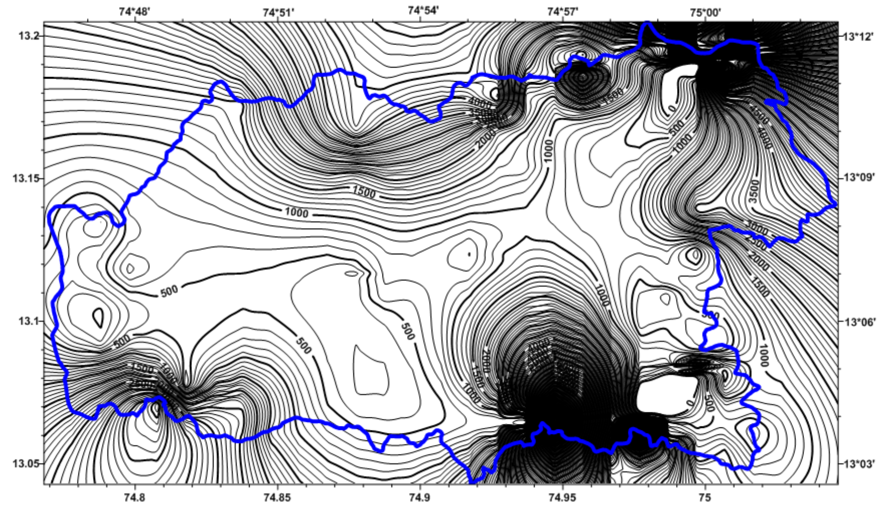

Fig. 5.23 Iso-resistivity contours for 160meter current electrode spacing

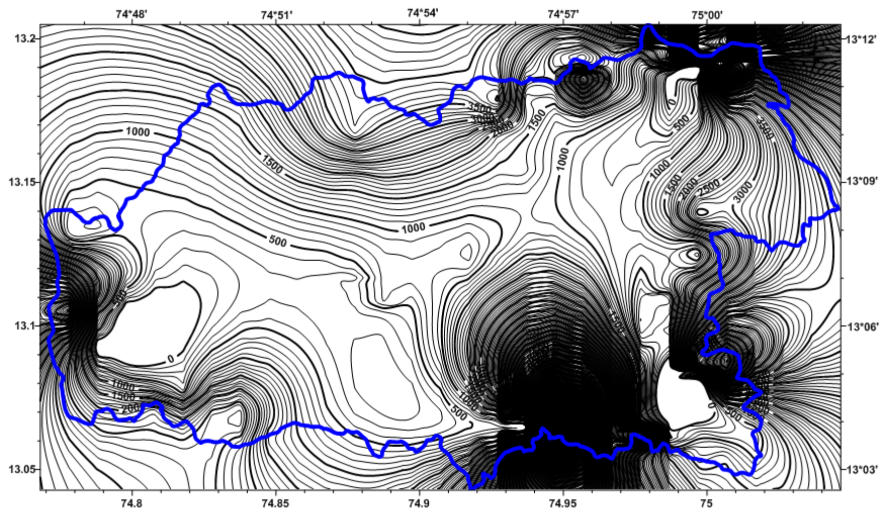

Fig. 5.24 Iso-resistivity contours for 180meter current electrode spacing

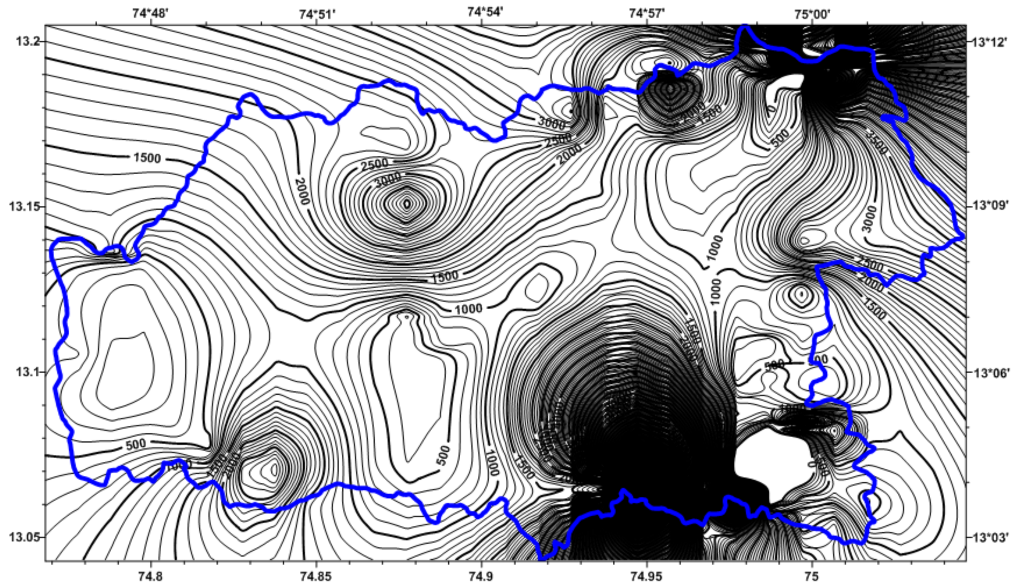

Fig. 5.25 Iso-resistivity contours for 200 meter current electrode spacing

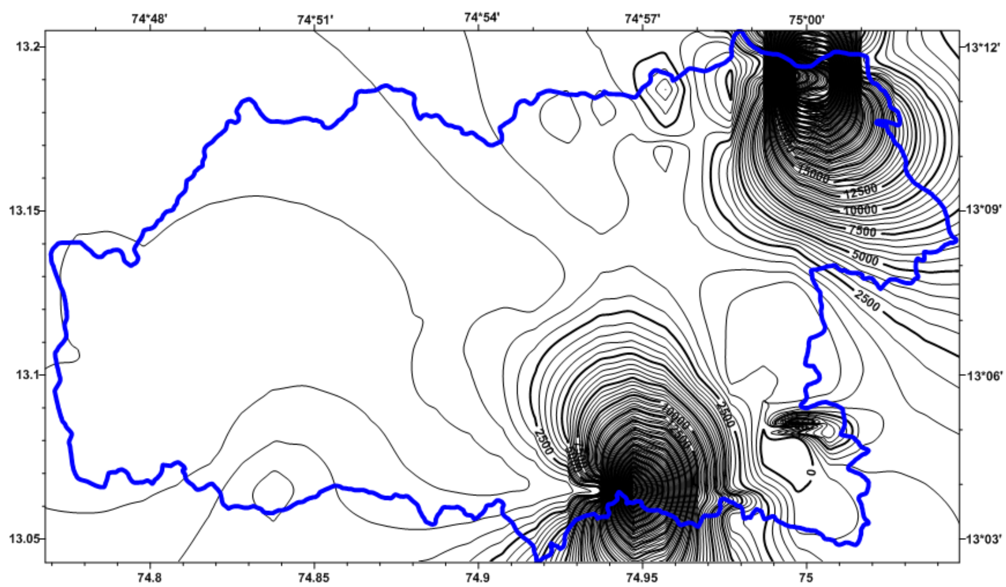

Fig. 5.26 Iso-resistivity contours for 240meter current electrode spacing

Iso-resistivity maps of 80metres to 120 meters current electrode configurations show a definite trend which is similar in nature and is more influenced by the valley trend and lineaments of the study area (Fig. 5.19 – Fig. 5.21). The other iso-resistivity contours (Fig. 5.22 – Fig. 5.26) of 120 meters to 240 metres show similar trends where the topography, river course and the structure of the area influenced the low resistivity and resistivity variation in the study area. From these maps, low resistivity zones can be easily identified for further exploration.

5.12 RESISTIVITY STUDIES ON DIFFERENT GEOLOGIC TERRAINS: In order to understand the resistivity variation in different lithological conditions in the study area, the basin has been classified in to three major zones viz: (i) Hardrock terrain (ii) Lateritic Terrain and (iii) Coastal Terrain.

5.12.1 Hard Rock Terrain: There are up to six layers identified in the hard rock terrain spread over the Mulki River basin. The top layer thickness is varying in the hard rock terrain of the study area and is very shallow in most of the regions of study area. It indicates the weathering trend in the hard rock terrain as well as the percolation of the water. At many places where the topsoil thickness is very shallow, the second layer is generally very hard granite rock where there is no chance of water percolation in it. At other places where the second layer is laterite, the thickness of the laterite is less and the groundwater storage and movement completely depends on the slope and topography of the region. In many places the third layer is either thin or start with a high resistivity which indicates hard rock. When it is thin, it indicates the weathered granite or thin lithomarge clay resting above the granitic gneiss. The fourth and fifth layers found to be hard granite or granitic gneiss rock where the presence of the fractures indicates low resistivity. The sixth layer at few places with very low resistivity showed a high yielding fractured granite or granitic gneiss zone in these hard rock terrains (Table 5.1). The spatial variation in depth to the bedrock and the shallow aquifer from the surface is depicted in Fig. 5. 27 and variation in thickness in different region is depicted in Fig. 5. 28.

5.12.2 Lateritic Terrain: In Lateritic terrain of Mulki River basin, spread over almost the entire basin, up to six VES layers have been identified based on resistivity variations. The top layer thickness shows high variation in different regions. It is high in the Belvai-Moodbidri plateau region which is bounded on its western boundary by an intrusive hard rock ridge. This is significant since it enhances the accumulation of groundwater in the unconfined aquifers in this area. The second and third layers consisting of laterite and lithomarge clay form the unconfined aquifers in these areas. There is a lot of variation noticed in the resistivity values of the laterite in this area. Very low resistivity values in the fourth, fifth and sixth layers of this region indicate the presence of highly saturated fractures in the underlying granitic gneiss (Table 5.1). The spatial variation in depth to the bed rock and the shallow aquifer from the surface is depicted in Fig. 5.29 and variation in thickness in different region is depicted in Fig. 5.30.

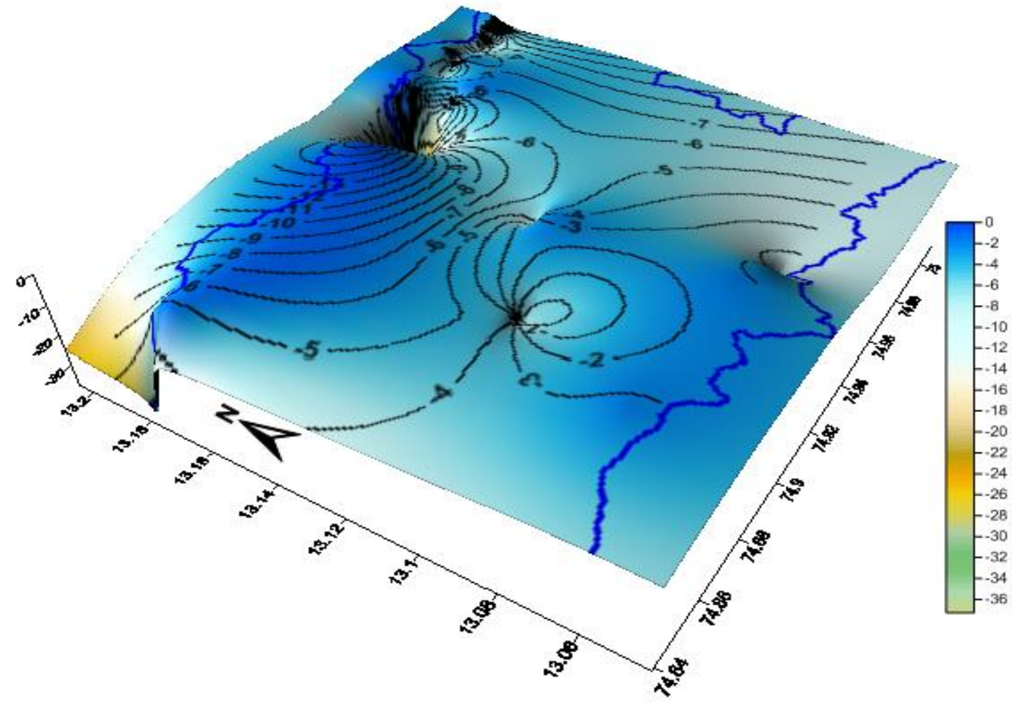

Fig. 5. 27 Depth to bedrock and depth to shallow aquifer in Hard Rock Terrains (contours depict the depth to shallow aquifer in Hard Rock Terrains while 3D elevations represents the depth to bedrock from the surface)

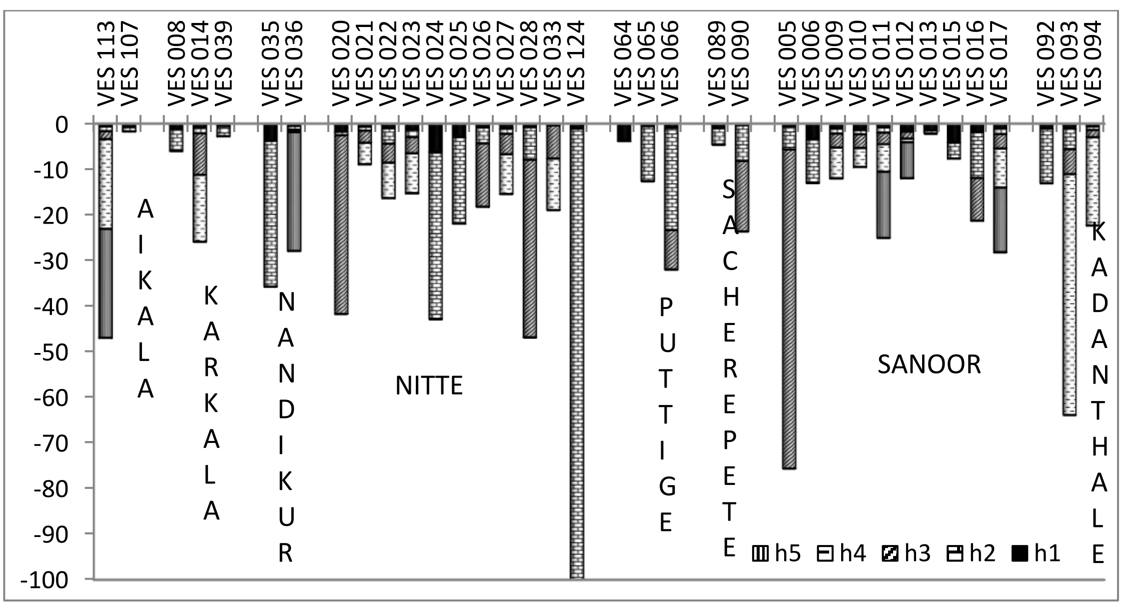

Fig. 5.28 Showing the depth and thickness of each layer in the various regions of Hard Rock Terrains in the Mulki River basin

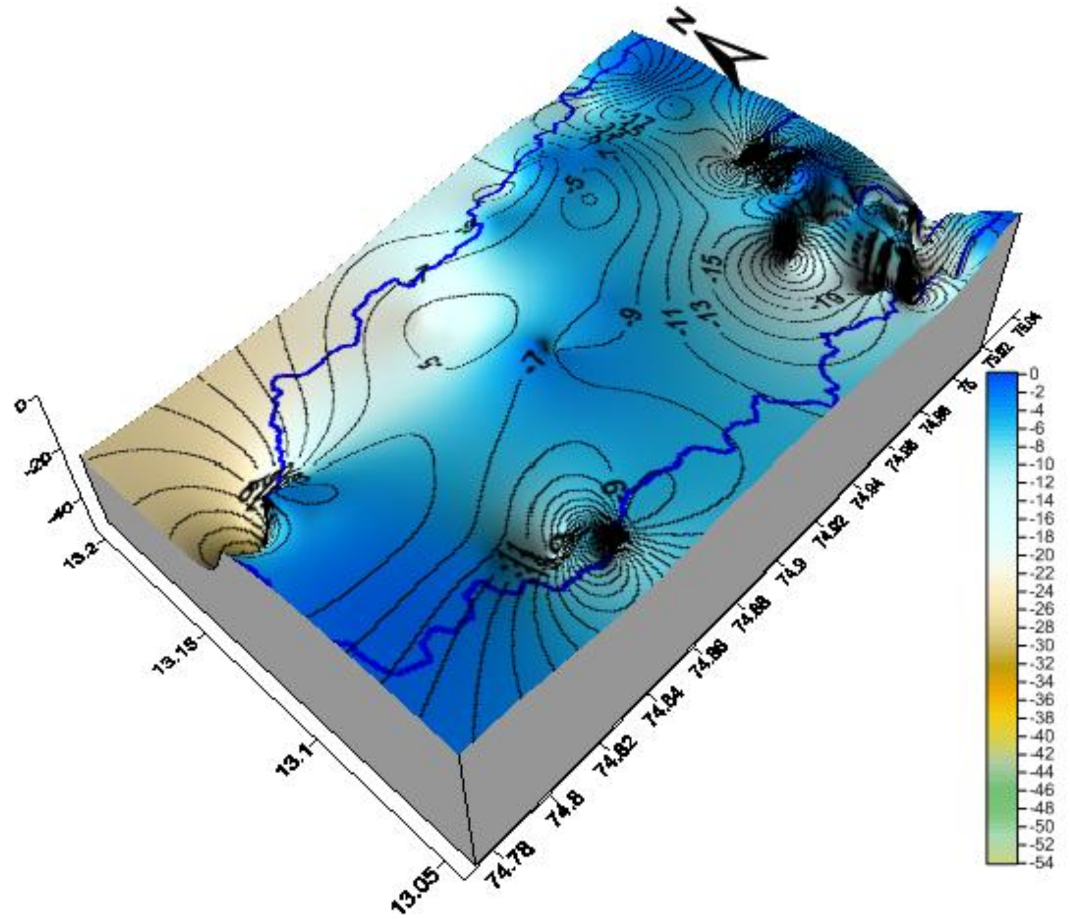

Fig. 5.29 Depth to bedrock and depth to shallow aquifer in Laterite Terrains (contours depict the depth to shallow aquifer in Laterite Terrains while 3D elevations represents the depth to bedrock from the surface)

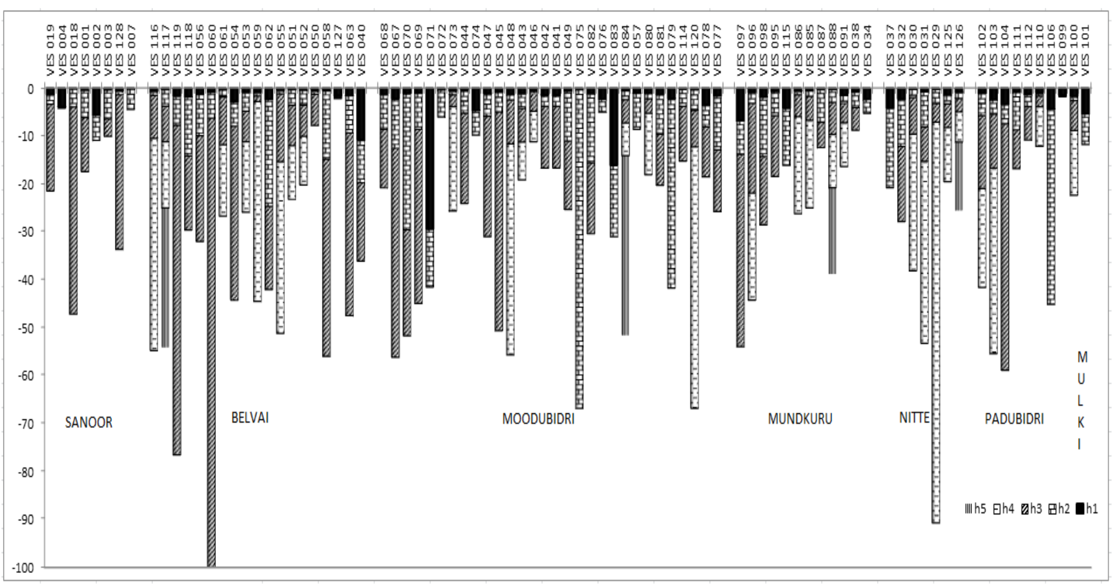

Fig. 5. 30 Showing the depth and thickness of each layer in the various regions of Laterite Terrains in the Mulki River basin

5.12.3 Coastal Terrain: The coastal region is found to have a first layer thickness of up to 4metres below which alluvium of 2meters to 40metres thick accumulated. At Hejmadi Kodi, the second layer (VES 108, VES 122) found to have saline water with very low apparent resistivity which directly rests on the hard rock of high apparent resistivity. But the deep resistivity survey conducted at Hejmadi revealed that even though the high resistivity zone starts at a shallow depth, the fourth and sixth zones are of very low resistivity indicating highly saturated confined aquifer zones in this area (Table 5.1). The shallow aquifer zone is found to be saline in this area. The entire belt is contaminated with saline water ingression which has been indicated through very low apparent resistivity which is again confirmed through the water quality analysis (Radhakrishnan *et al.* 2011a, b). The spatial variation in depth to the bedrock and the shallow aquifer from the surface is depicted in Fig. 5.31 and the salinity intrusion in the resistivity cross-sections along the coastal terrain with the depth and resistivity of different layers are depicted in Fig. 5.32.

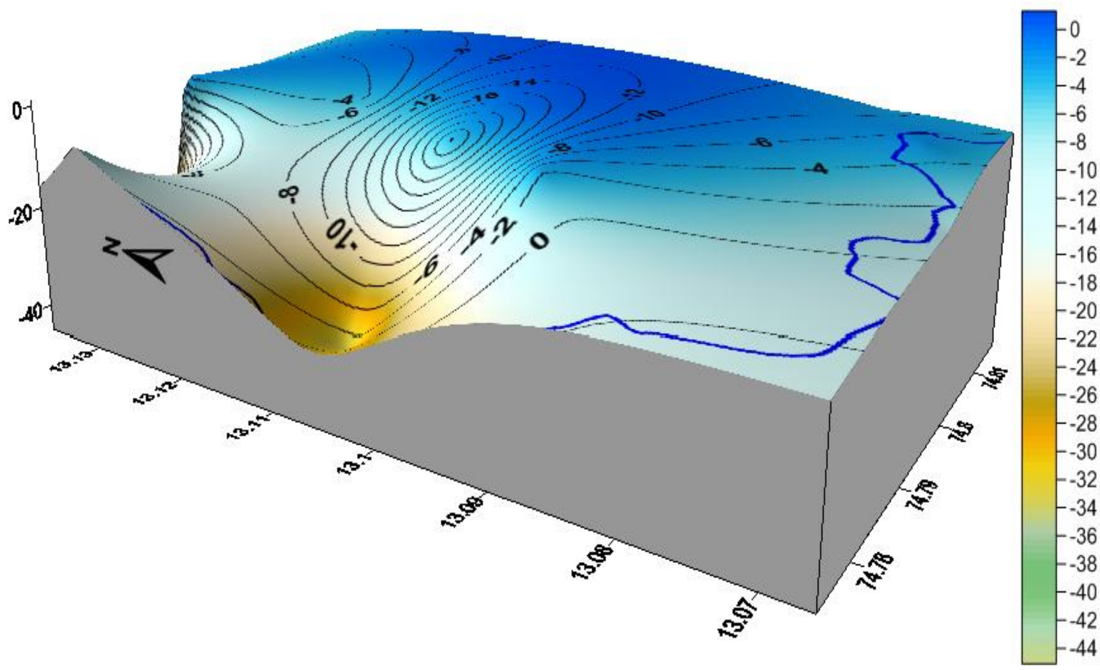

Fig. 5.31 Depth to bedrock and depth to shallow aquifer in Coastal Terrain (contours depict the depth to shallow aquifer in Coastal Terrain while 3D elevations represents the depth to bedrock from the surface)

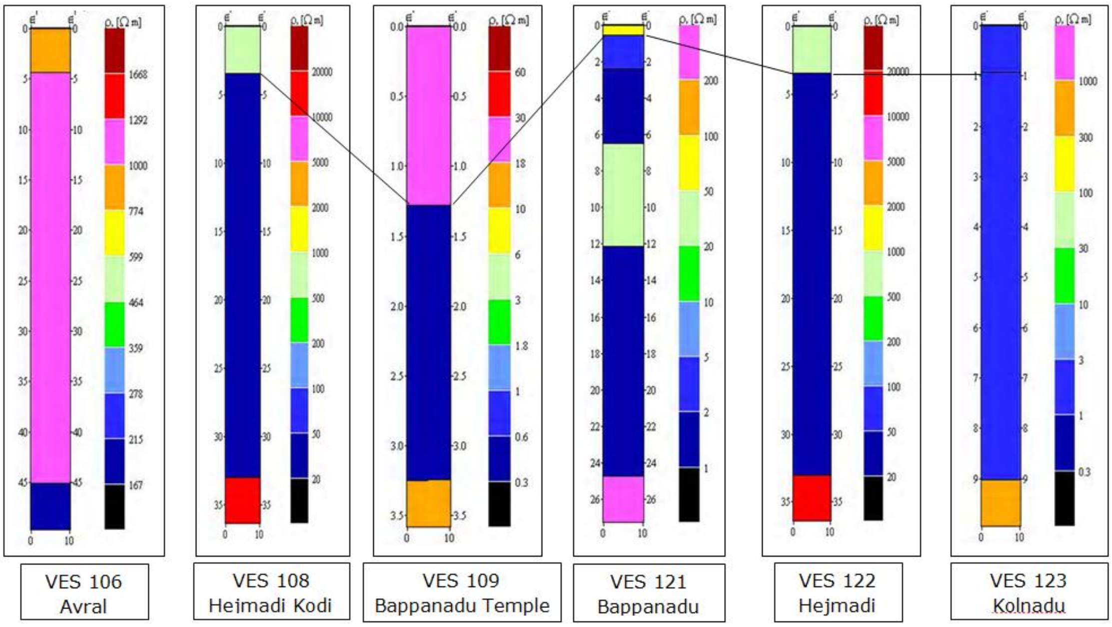

Fig. 5.32 Showing the salinity intrusion in the resistivity cross-sections along the Coastal Terrain of the Mulki River Basin with the depth and resistivity of different layers

5.13 DEEP RESISTIVITY SURVEYS IN THE STUDY AREA: In order to understand the deeper layers in the study area, an attempt has been made with a maximum electrode spacing of 600 meters depending upon the availability of such long leveled topographic stretch. The results were interpreted with inverse slope method (Sankaranarayana and Ramanujachary 1967) using custom made software to identify the minor fractures which usually go unnoticed (Ramanujachary and Balakrishna 1985, Rao G.T. 1992). The survey has been carried out in three typical regions i.e., Hard rock terrain, Lateritic terrain and Coastal terrain. The results of the inverse slope curves and corresponding apparent resistivity sections are given below (Figs. 5.33 - 5.36). In the hard rock terrain of Kemmannu at Nitte, the resistivity is found to be increasing with depth indicating no fracture zone even up to 180 meters (Fig. 5.33) representing the local variation in the area. But the resistivity values from 66 meters to 88 meters may indicate a fracture zone (not saturated) but require the evidence of drilling report to prove the same. If fractures are present, then this fractured zone could be utilized for the artificial recharge of surplus rainwater during monsoon. At Belvai laterite plateau (Fig. 5.34), even up to 183metres no fractured zone with groundwater saturation could be located. But from 85m to 117m, a low resistivity zone compared to the upper and lower zones could be noticed which may be dry fractured zone since it shows a value very near to 1000 Ohm-meters. At Sanoor, again a lateritic terrain, deep fracture zones were found at 117m-133meters below the ground surface (Fig. 5.35). At coastal area near Hejmadi, low resistivity zones were found at different levels of 27m - 40m, 60m-73m, 87m-100m indicating the potential zones for groundwater prospecting (Fig. 5.36). But quality of the groundwater should be evaluated with proper analysis before exploitation.

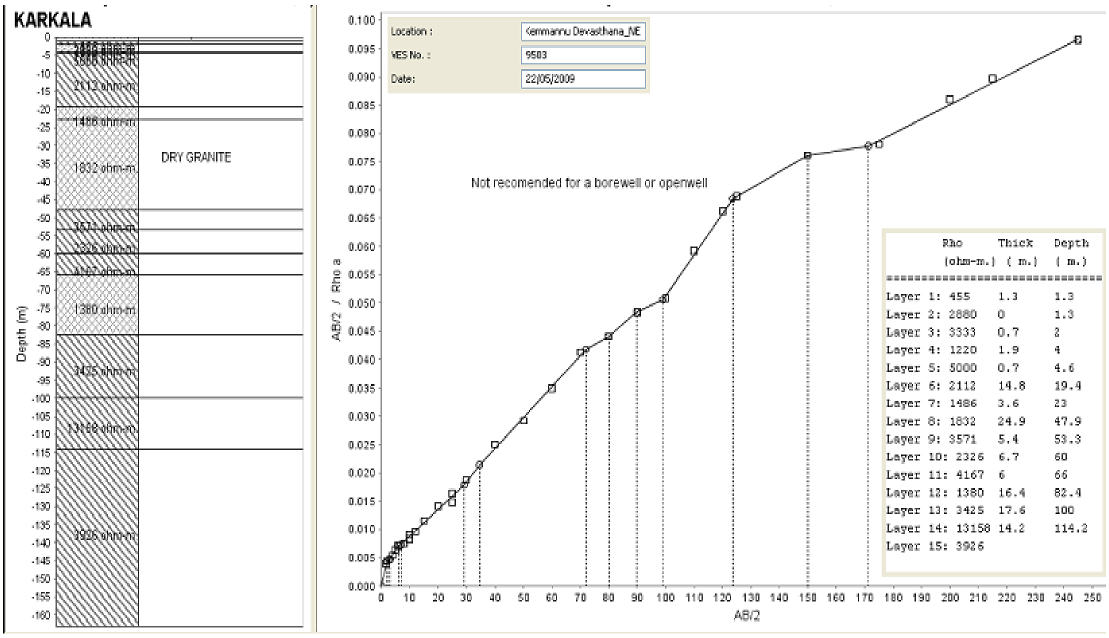

Fig. 5.33 VES curve (Inverse slope) of Deep Resistivity survey carried out at Kemmannu (Granitic gneiss terrain)

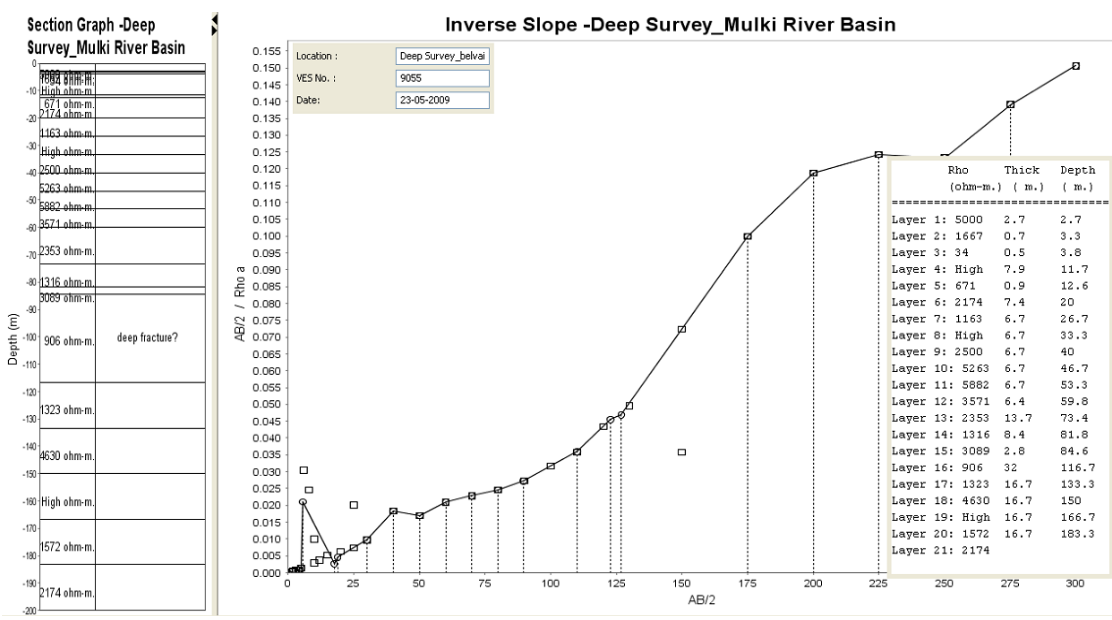

Fig. 5.34 VES curve (Inverse slope) of Deep Resistivity survey carried out at Belvai Plateau (Lateritic Terrain)

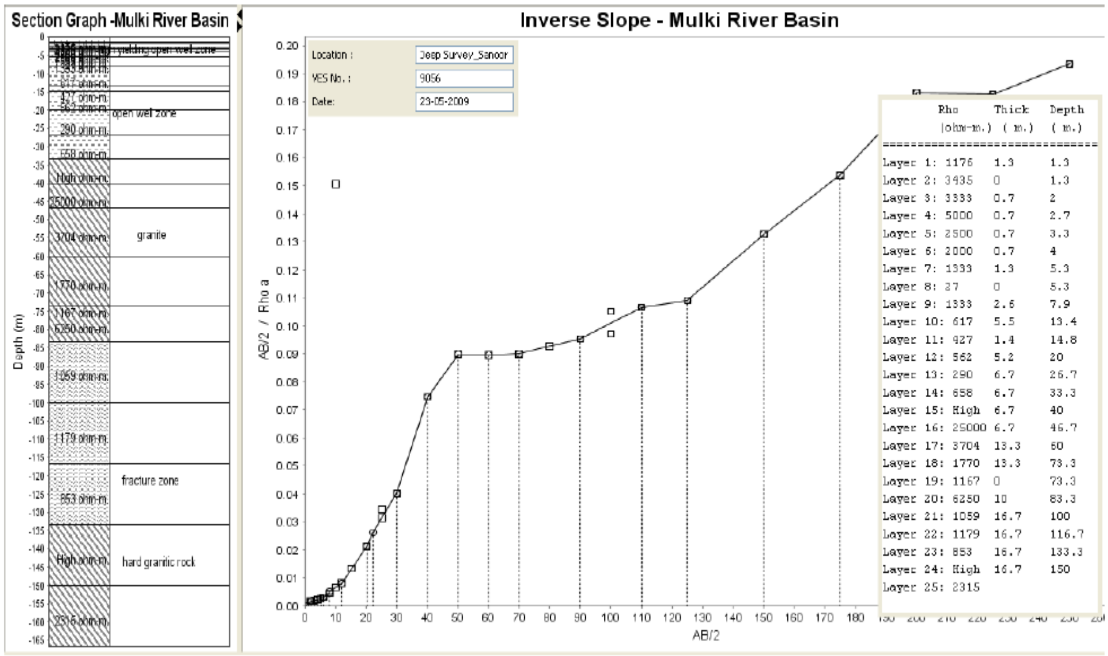

Fig. 5.35 VES curve (Inverse slope) of Deep Resistivity survey carried out at Sanoor (Laterite)

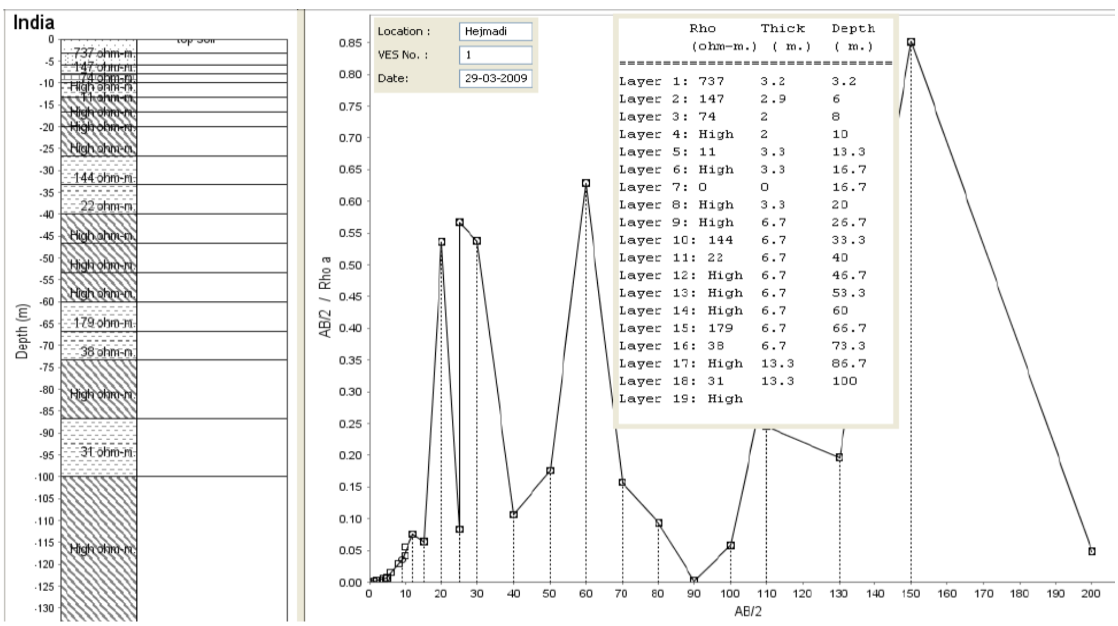

Fig. 5.36 VES curve (Inverse slope) of Deep Resistivity survey carried out at Hejmadi (Coastal terrain)

5.14. LIMITATIONS OF RESISTIVITY SURVEYS IN THE STUDY AREA:

Electrical Resistivity method is one of the best methods available for the groundwater exploration since it is economical and fast compared to other methods. The success of this method depends on the knowledge of the geohydrological and geoelectrical properties of the formations and how best their interrelationships are established in a geological terrain. The results of the resistivity data should be supplemented with the well inventories. The errors are quite possible due to many external factors like the power line, telecommunication cables, pipelines, conductive bodies, etc., which should be carefully avoided.

In hard rock terrains, weathered and fractured zones are considered as the main sources of groundwater. The yield of a well in hard rock terrain depends mainly on the thickness of weathered layer, and the spacing and density of the saturated fractures and joints present in it. But many times these thin zones of saturated fractures may escape from being identified due to very high apparent resistivity of enclosing rocks and poor resolution of apparent resistivity curves (Ramanujachary and Balakrishna 1985).

Laterites, which are predominantly exposed in the study area, vary in resistivity depending on their porosity and saturation. Since they are poor conductors in dry state, the resistivity measurements also become difficult in these terrains due to high contact resistance at the current electrodes. High induced polarization characteristics of moist and clayey laterites, underlying the hard and dry laterites also pose problems. Another problem usually caused in the lateritic terrain is of lateral non-homogeneities.

In coastal area, the very low resistivity imparted due to the saline water with clay gives very poor readings to be recorded with most of the resistivity instruments available.

In urban areas, there are limitations for systematic electrical resistivity field investigations due to space constraints in spreading the electrodes and due to various interferences caused due to roads, power lines, underground cables, pipelines, fences, dwellings, buildings, etc.

Since the study area is of undulating topography, it was very difficult to find level grounds for the electrode spreading. Another threat for the deep investigation was the availability of linear stretches for spreading the electrodes arrangements.

The non-availability of the drill data or litholog is another constraint in establishing the range of resistivity for the dry rocks and its saturated counterparts. If the VES data could be supplemented with reliable drilling data, probably the best comparisons with lithology could be made in the study area to evolve a certain definite range of resistivity to confirm the deep fractures and its saturation.

5.15 CONCLUSIONS: The Vertical Electrical Soundings using Schlumberger array has been found to be an effective tool in determining the bedrock and aquifer characteristics of the Mulki river basin. The layer parameters based on the resistivity values and the cross-sections analyzed with computer modeling are found to be matching with the geology or litholog of the area. From the above studies, the confined and unconfined aquifer zones in the study area could be identified. Depending upon the curve type and the thickness of layers along with knowledge of local geology, the yield can be empirically predicted.

The wide variation in resistivity and thickness of the first layer indicates variation in weathering, soil moisture and infiltration capacity of top soil. The variation in resistivity values of second layer represents the porosity and dryness of the commonly occurring laterite beds. The very low resistivity of second layer shows the saline water ingression or the highly saturated zones of clay layer. The second layer is found to be the most favourable zone for the open wells, and its thickness and resistance are significant in respect of the drinking water and irrigation water supply. The third layer, usually represented by weathered granite/granitic gneisses or even the hard granite is of importance according to their apparent resistivity and thickness. The very low resistivity of this zone, at a very shallow depth, shows that they are of alluvial beds with saline water in the aquifer. Depending on the curve types the categorization were made as shallow aquifers (H-type curve), deeper unconfined aquifers (K- type curve), hard rock where dry laterite is overlying the hard impervious granite (A-type curve), and saline water aquifer at very shallow depth along the coast or a good yielding aquifer (Q-type curve). Saline water ingression is found to occur up to certain distance near to the coast at shallow depth. The fourth layer, usually of high resistance is characteristic of the hard bedrock and if the value is less it indicates the fractured zone with a confined aquifer. Depending upon the thickness, the yield also varies in this zone. The fifth layer with < 200Ωm represents a highly fractured zone of high yielding confined aquifer at deeper level. The sixth layer in few cases indicates deeper confined aquifers with very low resistivity values in the basin. Deeper resistivity surveys may give clue to the deeper low resistivity zone indicating the potential confined aquifers.

The bedrock in the study area is found to be at an average depth of 8.83 meters from the surface. The variation in the thickness and apparent resistivity of the formations is found to be controlled by the topography, geology, weathering, and the quality of water present in it. From the above studies, confined and unconfined aquifer zones in the study area are identified. Laterites and alluvium (2^{nd} layer) are found to be good unconfined aquifers which vary in thickness in the area. Deeper layers (3^{rd} to 6^{th}) are found to have confined aquifers in the granite or granitic gneisses of this area. The values of apparent resistivity and the thickness of layers coupled with the experience and knowledge of local geology will enhance the prediction of the empirical yield of the well.

Chapter 6

Hydrometeorological Studies

CHAPTER 6

HYDROMETEOROLOGICAL STUDIES

6.1 INTRODUCTION: Hydrometeorology is the study of the atmospheric processes which affect the water resources of the earth through their inter-relationships. The availability of water, one of the prime requisites for groundwater recharge, is basically assessed in terms of non-committed surplus monsoon runoff, which as per present water resource development scenario is being unutilized. This component can be assessed by analyzing the monsoon rainfall pattern, its frequency, number of rainy days, and maximum rainfall in a day and its variation in space and time. The important hydrometeorological elements are precipitation or rainfall, temperature, relative humidity, wind, sunshine, evaporation and evapotranspiration. Hydrometeorological data is used to decipher the rainfall pattern, evaporation losses and climatological features. These data are useful to determine the water balance of an area or a basin for planning, developing and managing its water resources. Since the meteorological phenomena have a definite influence on the geohydrology of the area, the different aspects of the same are discussed below with the analysis of the available hydrometeorological data.

6.2 CLIMATE AND SEASON: Climate is often defined as ‘average weather’ i.e., in terms of the mean and variability of temperature, precipitation and wind over a period of time (IPCC 2007). The Indian Meteorological Department divides the Indian climatic year into four seasons: (i) the relatively cool winter from December to February (ii) the dry hot summer from March to May (iii) the southwest monsoon from June to September and (iv) the northeast monsoon or retreating monsoon of October and November (Jagannadhasarma 2005).

The winter period starts by about mid-December and extends up to February. Extended effects of the 'Northeast Monsoon activity' in the south and the 'Western Disturbances' in the north of the country are the features of this period. Extra-tropical low pressure systems passing through the northern part of the country from east to west, mainly during November to April, is termed as 'Western Disturbances' (Reddy

J.R.P. 2008). Winter rains and severe cold waves are the result of the movement of these systems.

The summer period or the hot season from March to May is the traditional period when the winter pattern of pressure and winds gets disturbed prior to the establishment of the monsoon and hence, is often referred as 'Pre-Monsoon' season. This season is characterized by heavy dust haze and extremely high temperature over north India and yields very little rainfall. Land and sea breeze effect is prominent over the coastal areas during this season. The frequency of thunderstorms increases progressively over south India with increased influx of moist air from the sea (Prasad *et al*, 2006). As the season advances, a few tropical cyclones form in the Indian seas, but they generally move north or northwest and strike the Bengal, Bangladesh or Myanmar coasts. Convective activity is essential for the occurrence of thunder and dust storms. With the advance of summer, thunder activity becomes pronounced in April and May due to ground heating mainly over inland stations.

The southwest monsoon (popularly known as monsoon) blows in from sea to land and usually hits on the southern part of Kerala in the west coast early in June and reaches most of South Asia by the first week of July. This is the principal rainy season of India and receives about 75% of the annual rainfall over a major portion of the country (Subramanya 2008). The onset of monsoon is accompanied by high south-westerly winds at speeds of 30-70 kmph and low pressure regions at the advancing edge.

The north-east monsoon starts at the retreat of the south-west monsoon and forms severe tropical cyclones creating low pressure areas in Bay of Bengal resulting in heavy rainfall. The period October to December is referred to as 'Northeast monsoon' season over peninsular India. This blows from the north-east part of the country and gives intense rainfall particularly in the east coast. Earlier this period was also referred to as 'post-monsoon season' or 'retreating southwest monsoon season' (Anandakumar *et al*. 2008).

6.2.1 Climate of the Study Area: The climate of Udupi and Dakshina Kannada district is marked by heavy rainfall, high humidity and oppressive hot weather influenced by the Arabian Sea and the network of streams and rivers. The Climatic year may be divided into four seasons as follows:

i) Pre-Monsoon season: The pre-monsoon season spreads over March to May is hot summer with oppressive weather throughout the day. The weather is humid due to westerly sea breeze. The maximum temperature is experienced around 2pm and minimum around 3am.

ii) South-West Monsoon season: This monsoon period spreads over June to September is the principal rainy season giving maximum rainfall to this area. The region experiences highest rainfall during July with high velocity winds. During this period depression in the Arabian Sea and frequent floods in the coastal areas are common.

iii) North-East monsoon season: It is the monsoon season spread for a period of October to November mainly due to the north-eastern wind blows. Retreating of south-west monsoon is noticed in October, and north-easterly monsoon is experienced during November. And it may extend up to mid-December with minor showers.

iii) Post-Monsoon Season: December-February is the dry season with no showers having a moderately pleasant climate which can be considered as the winter period. Extended effects of the 'north east monsoon activity' in the south and the 'western disturbances' in the north of the country are the features of this period. This can be considered as the post-monsoon season since this period follows the two monsoon seasons in the study area.

The study area falls under tropical humid climatic conditions and generally a hot humid climate prevails throughout the year in the area. Irrigation considerably influences the heat and moisture exchange in the system at the land-air interface. It contributes to higher water consumption by crops, high soil moisture content, lower temperatures and great humidity of the air as well as to micro climate changes in general in the vicinity of the irrigated areas. When large areas are irrigated, significant meteorological changes may occur at the surface-air layer that contributes not only to micro-climate improvement of the area, but probably to local evaporation reduction as well.

6.3 TEMPERATURE: Being nearer to the coast, the area experiences a typical maritime climate with moderate low variations around an average temperature of about 26.5°C. Although March, April and May can be considered as the hottest months of the year, the day temperature does not reach the maximum as cool breeze from the sea blows towards the land. The oppressive heat is thus relieved by the comparatively cool sea breeze. The day temperatures recorded during 2004-2005 on monthly basis at Udupi which is the nearest station to which the data is available as shown below (Table 6.1). The lowest average temperature recorded is during July when the heaviest rainfall occurs and the highest average temperature is during April, which is the dry spell of the year. In general, the temperature decreases with the onset of southwest monsoon and increases with the retreat of monsoon.

6.4 HUMIDITY: The weather is humid throughout the year and particularly so in the south-west monsoon season. Humidity reaches the maximum during the monsoon due to heavy precipitation, low temperature and limited evaporation. The highest humidity recorded was 95% during July 2005 and the lowest was 27% during April, 2004. The maximum average humidity is usually recorded during June-July where the highest rainfall occurs and the minimum during April when the dry spell occurs (Table 6.1).

	Temperature (^oC)			Relative Humidity (%)			Vapour Pressure (Pascal)	
Month	2004	2005	Mean	2004	2005	Mean	Saturation (es)	Actual (ea)
January	25.7	25.4	25.6	34	43	38.5	3251.92	1251.99
February	26.8	26.3	26.6	34	43	38.5	3449.05	1327.88
March	27.9	27.9	27.9	29	42	35.5	3731.63	1324.73
April	28.9	28.5	28.7	27	41	34.0	3908.41	1328.86
May	28.8	26.4	27.6	70	55	62.5	3667.15	2291.97
June	25.8	25.7	25.8	79	85	82.0	3290.54	2698.24
July	24.9	25.0	25.0	60	95	77.5	3138.42	2432.27
August	25.3	24.9	25.1	57	57	57.0	3166.47	1804.89
September	25.4	25.4	25.4	56	85	70.5	3223.22	2272.37
October	25.9	26.1	26.0	54	69	61.5	3339.38	2053.72
November	27.0	26.4	26.7	45	68	56.5	3479.49	1965.91
December	25.6	25.6	25.6	43	63	53.0	3261.54	1728.62

Table 6.1 Monthly average temperature and relative humidity during 2004 & 2005

From the above parameters the saturation vapour pressure and actual vapour pressure in Pascal have been derived using the standard equations. The actual vapour pressure (ea) has been derived by multiplying the saturation vapour pressure with relative humidity of that month. Saturation vapour pressure (es) has been calculated using the standard formula,

$$es = 611 * \exp(17.27t/237.3+t)$$

where 'es' is the saturation vapour pressure and 't' mean monthly temperature in °C. The maximum and minimum actual vapour pressures noticed in the study area during the observation period of 2004 and 2005 are 2698.24 Pascal (June) and 1251.99 Pascal (January) respectively.

6.5 CLOUDINESS: Sky is densely clouded on almost all the days during the southwest monsoon, which sets in the first week of June and continues till the end of September. The dense cloud setting usually starts in late April with the maximum cloud formation occurring in May/June. The numbers of such heavily clouded days are only a few in the post-monsoon months of October and November. In the remaining months, sky is generally clear.

6.6 WIND: Winds are strong and more than 60% of the time it blows from south, southwest and west directions between May and September. During June and July (first half of south-west monsoon) and in October (first half of north-east monsoon), winds are strong (17.09km/hr at 2 meters, and 15.95km/hr at 6 meters above the ground level). During other seasons, especially from October to January, it blows mainly from north, north-east and east directions; while between February and April, it blows from north, north-east and east for about 50% of the time (forenoons) and from southwest and west directions for the remaining 50% of the time (afternoons). Wind speed in the study area varies from 10.18 to 17.87 km/hr. The land-sea breeze occasionally attains a speed as high as 20km per hour.

6.7 EVAPORATION AND EVAPOTRANSPIRATION: Evapotranspiration is the total water lost from a cropped or irrigated land due to evaporation from the soil and transpiration by the plants. Generally evaporation rate is very low during monsoon (July-August) and it gradually increases from October and reaches the maximum in

May. Evapotranspiration plays an important role in the estimation of water potential from an area or a basin during different periods of the year. If sufficient moisture is always available to completely meet the needs of vegetation fully covering the area, the resulting evapotranspiration is called 'potential evapotranspiration' (PET). Potential evapotranspiration critically depends on the soil and plant factors but depends essentially on the climatic factors. The real evapotranspiration occurring in a specific situation is called 'actual evapotranspiration' (AET). Except in a few specialized studies, all applied studies in hydrology use PET instead of AET as a basic parameter in various estimations related to water utilization connected with evapotranspiration process (Subramanya 2008). Due to the lack of reliable field data and difficulties of obtaining reliable evapotranspiration data have given rise to a number of methods to predict PET by using climatological data. In the present study, two popular empirical methods Blanney-Criddle formula and Thornthwaite formula based on available climatological data have been used to derive the potential evapotranspiration (PET) in the study area.

Blanney-Criddle (1950, 1962) formula uses only the mean monthly temperature and location of the place. It can be given as

$$PET = (1/40).p.(9/5)\ T + 32$$

where 'PET' is the potential evapotranspiration in centimetres, 'T' the temperature in °C and 'p' the monthly day time hours expressed as a percentage sun shine hours. The average monthly PET obtained by this method is 165.41mm and varies from a maximum of 182.04 mm in May to a minimum of 148.57 mm in February during the observation period (Table 6.2). Since, Blanney-Criddle expression gives only the reference crop evapotranspiration, this value is to be multiplied by the corresponding value of the crop factor (K). This may vary from growing season to maturation and harvesting time. Since rice or paddy being the main cultivation in this area, the monthly crop factor for rice (Reddy J.R.P. 2008) has been considered in the computing of actual evapotranspiration (AET) in the study area (Table 6.2). According to Malhotra and Prasad (1987), an evaporation loss of about 33% of the annual rainfall has been occurring in this coastal area due to the actual evapotranspiration which is almost equal to the AET computed (30%) by the

Thornthwaite method. The potential evapotranspiration loss from the study area computed using Blanney-Criddle expression is at the rate of about 1985 millimetres (46.6% of annual rainfall), but the actual evapotranspiration computed is only 30% per annum. It indicates that the crops in this area does not transpire much water since it has been cultivated during the predominant rainy season, but contribute towards the enhanced humidity in this area during the cultivated season.

Month	Temp. (°C)	p (%)	PET (mm)	K (Crop factor)	AET (mm)
January	25.6	8.01	156.21	0.00	0.72
February	26.6	7.45	148.57	0.00	0.57
March	27.9	8.44	173.44	0.00	15.47
April	28.7	8.41	175.97	0.85	33.00
May	27.6	8.92	182.04	1.00	171.03
June	25.8	8.72	170.88	1.15	196.51
July	25.0	8.98	172.62	1.30	224.41
August	25.1	8.78	169.49	1.25	211.86
September	25.4	8.27	160.66	1.10	176.72
October	26.0	8.29	163.32	0.90	146.99
November	26.7	7.81	156.33	0.00	94.61
December	25.6	7.96	155.45	0.00	6.78
Annual	-	-	1984.99	1.08	1278.68

Table 6.2 Potential evapotranspiration for the study area (*after* Blanney-Criddle)

According to Thornthwaite (1948) the water need of a particular crop is directly dependent on the air temperature and the length of day light. He has given the following relationship to estimate potential evapotranspiration based on mean monthly temperature.

$$PET = 1.6\ L_a.b\ (10T/I)^a$$

where 'PET' is the potential evapotranspiration in mm. for a month, 'b' the average daily sun shine hours for the month (i.e. b = total sun shine hours in a month/12*no. of days in the month, whereas it is taken as one considering 12 hours sun shine per day). This should be multiplied by a correction factor (L_a) related to the latitude of the place. 'T' is the mean monthly temperature in ˚C, 'I' is the temperature efficiency index

i.e., $I= \sum_{n=1}^{n=12} i_m$ where $i_m = (T/5)^{1.514}$

The empirical constant ‘a’ = $(6.75*10^{-7}I^3) - (7.71*10^{-5}I^2) + (17.92*10^{-3}I) + 0.49239$. The average monthly potential evapotranspiration (PET) for the study area so obtained is 134.48 mm and varies from a maximum of 185.28 mm in April to a minimum of 114.75 mm in January during the observation period (Table 6.3). The potential evapotranspiration loss estimated from the study area by this method is at the rate of about 1614 millimetres per annum i.e., about 38% of the rainfall receiving in this area. From these studies it can be assumed that a maximum of about 38% to 46.6% of the rainfall can be lost as potential evapotranspiration in the study area against the actual evapotranspiration (30%) computed.

Month	T (°C)	$i_{m=(T/5)^{1.514}}$	$I = \sum_{n=1}^{n=12} i_m$	a	b	L_a	PET (mm)
January	25.6	11.818	148.419	3.661	1	0.982	114.75
February	26.6	12.525	148.419	3.661	1	0.910	122.38
March	27.9	13.502	148.419	3.661	1	1.030	166.10
April	28.7	14.093	148.419	3.661	1	1.036	185.28
May	27.6	13.283	148.419	3.661	1	1.098	170.19
June	25.8	11.958	148.419	3.661	1	1.072	128.89
July	25.0	11.401	148.419	3.661	1	1.104	118.26
August	25.1	11.504	148.419	3.661	1	1.076	117.82
September	25.4	11.713	148.419	3.661	1	1.020	116.65
October	26.0	12.135	148.419	3.661	1	1.014	126.31
November	26.7	12.633	148.419	3.661	1	0.962	132.07
December	25.6	11.853	148.419	3.661	1	0.978	115.10

Table 6.3 Potential evapotranspiration for the study area (*after* Thornthwaite, 1948)

6.8 PRECIPITATION OR RAINFALL: South-West monsoon (popularly known as monsoon), the principal rainy season spread over a period of about four months (June-September) is the main contributor of water in the west coast of India. During the north east monsoon (October-November) also, heavy and intense rainfall occur contributing towards the water requirement of the area. During the other two seasons, post-monsoon or winter (December-February) and pre-monsoon or summer (March-May) rainfall used to be very little, but may occur due to cyclonic effects. The intensity of the rainfall is also a factor in determining the infiltration and the groundwater storage. Rainfall with a low intensity of 2.5mm/hour is called as light rain, between 2.5mm/hour to 7.5mm/hour is termed as moderate rain and when it exceeds 7.5mm/hour it is termed as heavy rain. Usually the moderate rain with a steady soaking nature is more beneficial for the groundwater storage. The major part of the study area experiences a heavy rainfall and it is highest at Karkala which falls on the north eastern part of the basin.

Out of fourty rain gauge stations spread over the entire erstwhile Dakshina Kannada District, there are only about three rain gauge stations located within the study area. These are located at three extremes of the basin where one is at Mulki, the mouth of the river and the other two at Karkala and Moodbidri, the northeast and southeast border of the river basin where it originates. These three rain gauge stations viz: Mulki, Moodbidri and Karkala falling within the basin have been considered for the study. The rainfall data for maximum number of years available with each station has been analysed for the calculation of mean annual rainfall and its variation in space and time. The analysis of available rainfall data for 42 years (1968-2009) from Karkala, 21 years (1989-2009) from Moodbidri and 37 years (1973-2009) from Mulki have been carried out to understand the trend and pattern of the same.

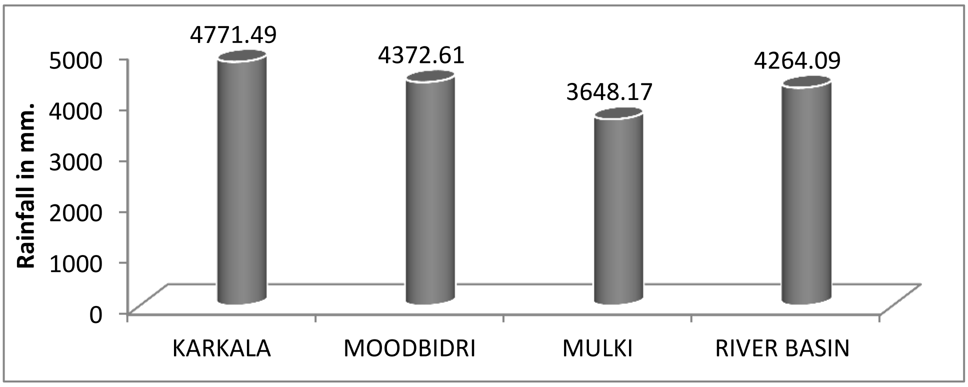

Fig. 6.1 Average annual rainfall of the study area and at its three rain gauge stations

The rainfall of the study area is uneven and shows an overall decreasing trend for the last four decades. The bulk of the rainfall i.e. over 86% occurs during south-west monsoon season and the intensity is maximum during July with a monthly mean of 1326.40mm rainfall. The Mulki River basin falling partly in Karkala Taluk of Udupi district gets about 4260.76 mm annual average rainfall, which is highest in Karnataka state (Fig. 6.1). The highest annual rainfall received was 6602.51 mm during 1975 at Karkala and the minimum 2527 mm during 2002 at Mulki. The temporal variation of rainfall is confined to five to six months in a year and the number of rainy days varies. The maximum rainy days recorded during the past four decades in the basin were 161 at Karkala during the year 1990 and 1978, and the minimum 66 days recorded at Mulki during 1973. The maximum rainy days recorded at Moodbidri were 159 days during the year 1990, whereas in Mulki it was 144 days in the year 1999. The minimum rainy days recorded at Karkala were 124 during the years 1979 and 1995, whereas it was 94 days during 2007 at Moodbidri. Even though no specific trend can be noticed in the distribution of rainy days and rainfall in the study area, a decreasing trend in the rainy days as well as in the rainfall intensity could be noticed from the northeastern side to the southwest or to the west in the study area. Annual average rainfall in the study area is about 3996mm during the last decade but is 4261mm average for the last four decades showing a decreasing tendency of the rainfall in recent years (Fig. 6.2). The rainfall shows an increasing trend from southwest in Mulki to northeast in Karkala where Moodbidri lies in between. During the last decade (2000-2009), the maximum annual rainfall recorded was of 5422.4mm at Karkala during 2009 and a minimum of 2527mm during 2002 at Mulki (Fig. 6.2). The rainfall is often associated with wind velocity. Floods are common in low lying areas adjacent to the banks of rivers during monsoon.

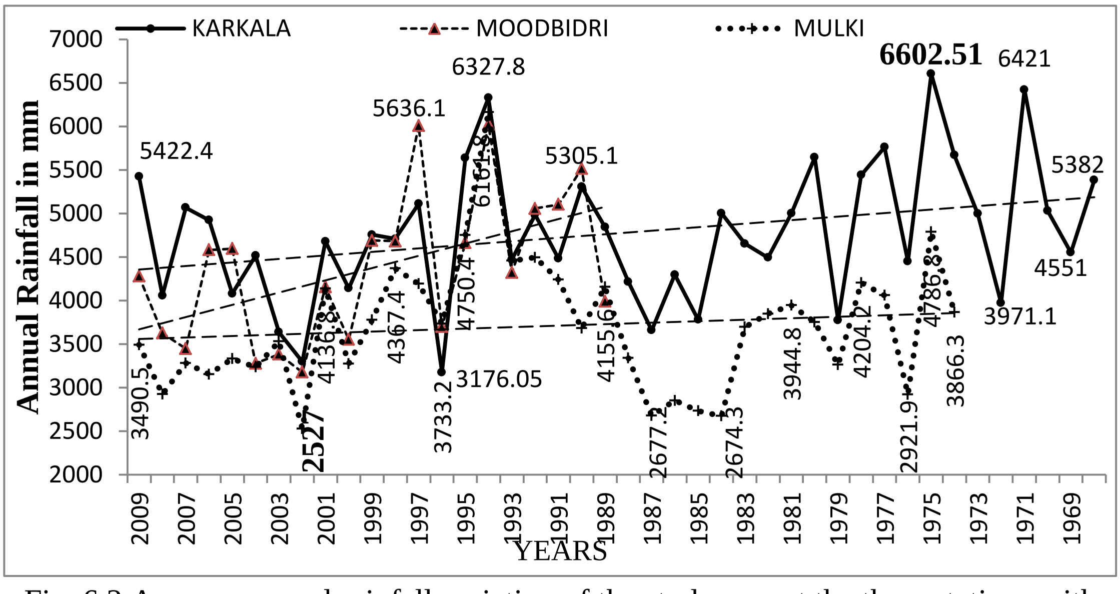

Fig. 6.2 Average annual rainfall variation of the study area at the three stations with their trend line at each station

6.8.1 Normal Rainfall of the Study Area: The normal rainfall is the average value of rainfall at a particular date, month or year over a lengthy period of a specified 30-years or not less than 20 years (Putty 2010). The normal annual rainfall of Karkala and Mulki are found to be 4612mm and 3680mm respectively for 30 years (2009-1980) period, whereas at Moodbidri it has been found to be about 4183 mm for 20 years (2009-1990) period. The mean normal annual rainfall of the study area is found to be about 4158 mm. Since the normal annual rainfall exceeds 2500 mm in the study area, Mulki River Basin can be considered as a region falling in the wet climatic zone (Strahler and Strahler 1992).

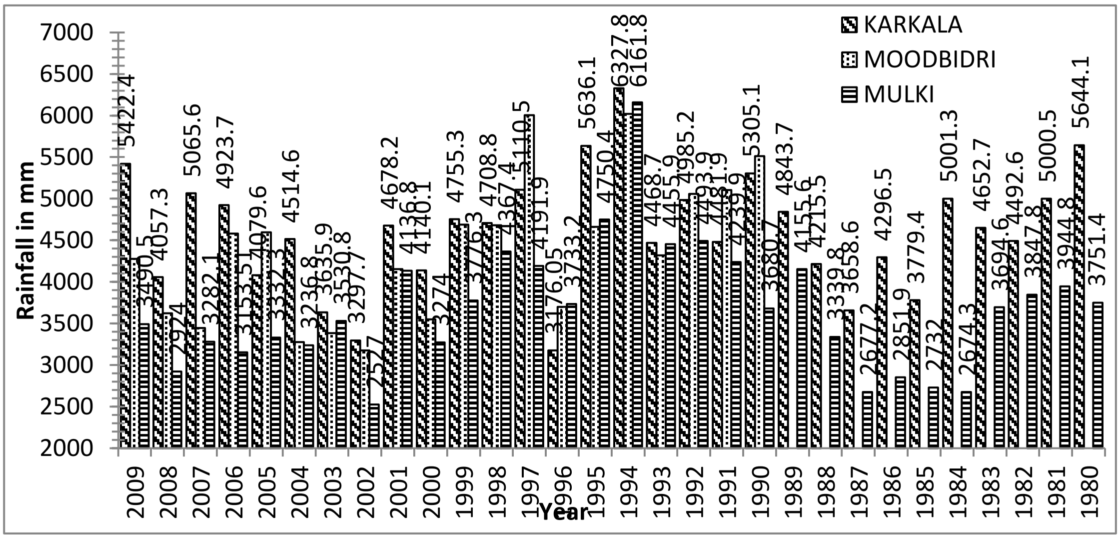

Fig. 6.3 Normal annual rainfall variation in the study area at its three stations

If the observed rainfall in any year is less than the normal annual rainfall then it is called a deficient year or a dry year and in the converse it is called a surplus year or a wet year (Reddy J.R.P. 2008). The analysis for the wet and dry years for the three rain gauge stations of Mulki River basin is given below (Table 6.4). Out of the 30 years period, 14 years (47%) are found to be deficient years or dry years at both Mulki and Karkala point stations, whereas at Moodbidri eight years (40%) out of 20 years period are found to be dry years. This shows a balance between the dry and wet years indicating the balance in distribution of the rainfall in the area. The temporal and spatial variation of rainfall also could be noticed from the analysis table (Table 6.4). Mulki River basin experienced a dry spell of deficient years at all point stations during 1985-1988, 2000, 2002-2004 and 2008, whereas it was during the years 1980-1981, 1983, 1990, 1992, 1994-1995, 1997-1999 the basin experienced a wet spell of surplus years. A subtle pattern of trend in the periodicity of cumulative years in wet or dry period can be observed (Table 6.4) in the study area. The highest surplus rainfall or wet year occurred during 1994 during the past three decades with all the three stations showing more than 6000mm annual average rainfall.

Year	Dry Year			Wet Year		
	Karkala	Moodbidri	Mulki	Karkala	Moodbidri	Mulki
1980	-	-	-	5644	-	3751
1981	-	-	-	5001	-	3945
1982	4493	-	-	-	-	3848
1983	-	-	-	4653	-	3695
1984	-	-	2674	5001	-	-
1985	3779	-	2732	-	-	-
1986	4297	-	2852	-	-	-
1987	3659	-	2677	-	-	-
1988	4216	-	3340	-	-	-
1989	-	-	-	4844	-	4156
1990	-	-	-	5305	5514	3681
1991	4482	-	-	-	5104	4240
1992	-	-	-	4985	5058	4494
1993	4469	-	-	-	4321	4456
1994	-	-	-	6328	6022	6162
1995	-	-	-	5636	4663	4750
1996	3176	3699	-	-	-	3733
1997	-	-	-	5111	6007	4192
1998	-	-	-	4709	4681	4367
1999	-	-	-	4755	4690	3776
2000	4140	3552	3274	-	-	-
2001	-	4155	-	4678	-	4137
2002	3298	3177	2527	-	-	-
2003	3636	3384	3531	-	-	-
2004	4515	3277	3237	-	-	-
2005	4080	-	3332	-	4596	-
2006	4057	-	3154	4924	4582	-
2007	-	3447	3282	5066	-	-
2008	-	3625	2924	-	-	-
2009	-	-	3491	5422	4280	-

Table 6.4 showing the wet and dry years for the three rain gauge stations in Mulki River basin

6.8.2 Area-Mean Rainfall: The volume of water received by an area, especially catchment is very important in hydrology and irrigation designs. Estimation of area-mean forms the fundamental step, and various methods such as Arithmetic Mean, Thiessen Polygon Method and Isohyet Methods are the commonly used ones. Using ArcGIS 10 version and Surfer 10 version the Thiessen Polygon and Isohyet Map were prepared and analysed for the average rainfall and total rainfall in the study area.

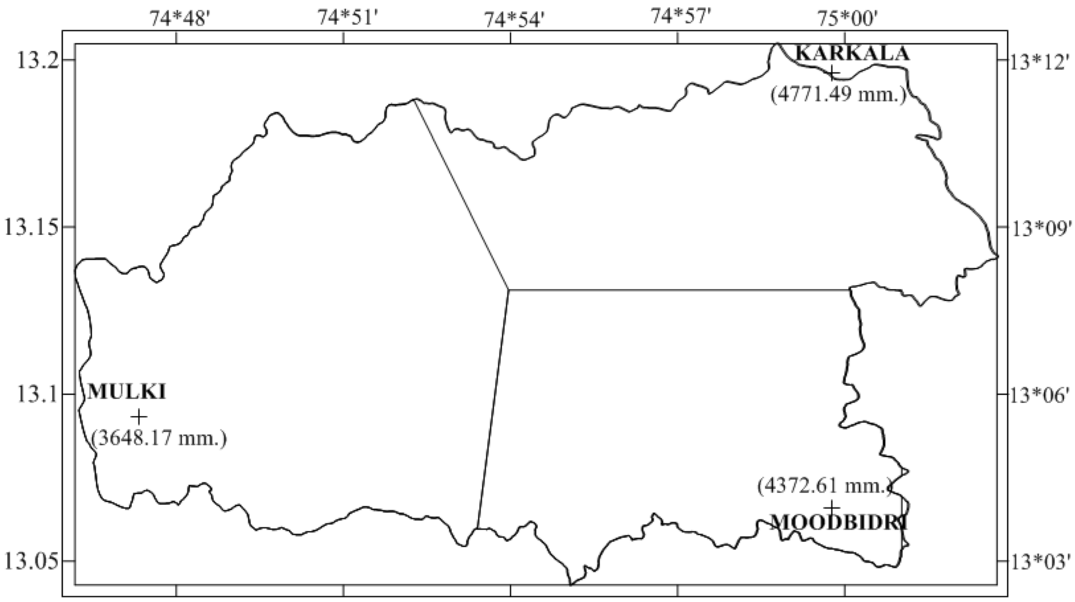

Fig. 6.4 Thiessen polygon for estimation of average rainfall in Mulki River Basin

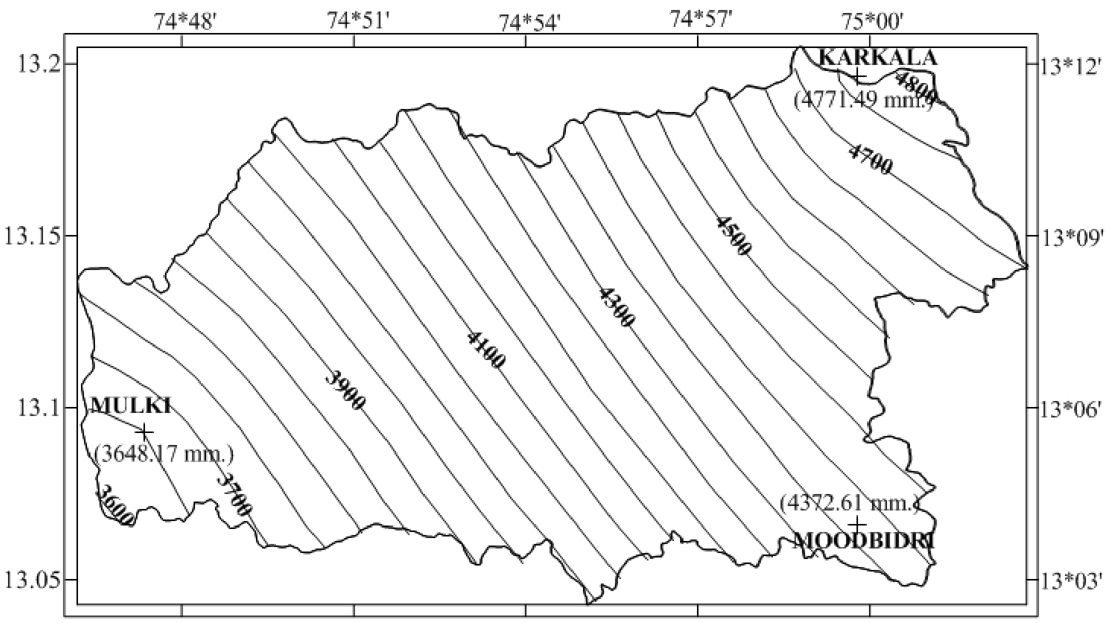

Fig. 6.5 Isohyet map for estimation of average rainfall in Mulki River Basin

The annual mean rainfalls received by the Mulki River basin computed by Arithmetic Mean, Thiessen Polygon (Fig. 6.4) and Isohyet Map (Fig. 6.5) are given in Table 6.5. The Thiessen Polygon gives the weightage factor, and the Isohyet Map gives the distribution pattern of the rainfall in the study area. From these analyses it could be concluded that there is a great variation in spatial distribution of rainfall in the study area, and the rainfall intensity increases from the coastal region towards the north-eastern part of the basin. This can be attributed to the Western Ghats in the north-eastern part of the study area.

Method	Mean Annual Rainfall	Total Amount of Rainfall in the Mulki river basin
Arithmetic Mean	4264.09 mm	1496.70 x 10^6 cubic meters
Thiessen Polygon	4189.45 mm	1470.51 x 10^6 cubic meters
Isohyet	4324.25 mm	1517.81 x10^6 cubic meters

Table 6.5 Area-Mean annual and total quantity of annual rainfall in Mulki river Basin

6.8.3 Temporal and Spatial Variations in Rainfall and Rainy Days: It is a well-known fact that due to the vagaries of nature and change in local climatic conditions, there is a considerable variation in temporal and spatial distribution of annual rainfall in an area. So the length of rainfall data records to be considered is an important factor in the analysis of rainfall. If the frequency distribution of mean annual rainfall becomes stable after a certain period, the addition of further years of observations does not add significantly to the accuracy. The length or period of record needed to achieve stability varies between seasons and regions. For updating the changes in environment and land use, the distribution of rainfall also is an important factor.

The available recorded rainfall data of all the days of each month in a year obtained from the three rain gauge stations viz: Karkala, Mulki and Moodbidri has been analysed. The average monthly rainfall, rainy days, number of observations (31 or 30 days), highest and lowest rainfall of each year, annual rainfall, annual rainy days and annual number of observations (365/366 days) were calculated for all the three locations and plotted as variation graphs and pie diagrams. The average annual rainfall for the last four decades (1970-2009) was found to be around 4260.76mm which is higher than the last decade's (2000-2009) annual average of 3995mm (Fig. 6.2), indicating the declining tendency of rainfall. Since the volume of storm water depends on the area of the basin which is about 350 square kilometres, it is calculated as 1495.53 x 10^6 cubic metres which can be stored or utilised within the basin allowing maximum infiltration avoiding runoff from the basin.

The mean monthly rainfall (Table 6.6) of the study area has been calculated using the maximum number of data available in each station. The variations of the mean monthly rainfall of all the stations have been plotted and given below (Fig. 6.6). From this study, it can be inferred that at Karkala and Moodbidri which are on the eastern side of the area, the rainfall is maximum during July, whereas it is maximum at Mulki during June indicating the influence of southwest monsoon hitting the coastal area first. It can also be inferred that the monsoon picks up suddenly during June and reaches the peak during July, declining sharply up to September, and then decreases gradually till November indicating the end of monsoon season in this area.

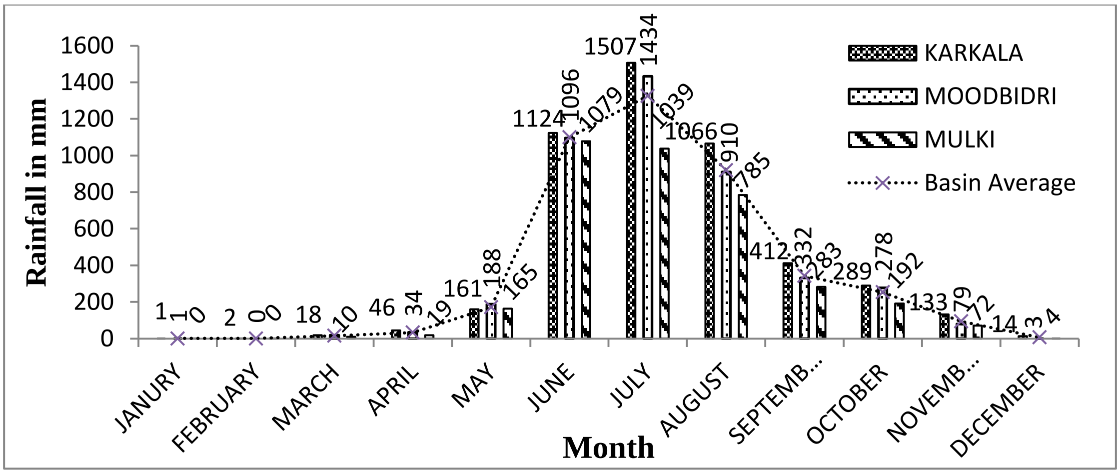

Fig. 6.6 Mean monthly variation of rainfall in Mulki River Basin

January	**February**	**March**	**April**	**May**	**June**
0.72 mm	0.57 mm	15.47 mm	33.00 mm	171.03 mm	1099.55 mm
July	**August**	**September**	**October**	**November**	**December**
1326.40 mm	920.38 mm	342.37 mm	253.20 mm	94.61 mm	6.78 mm

Table 6.6 Mean Monthly Rainfall in Mulki River Basin

<u>6.8.3.1 Karkala:</u> Being the highest rainfall location in the study area, about fourty two years rainfall data spread over 1968 to 2009 were tabulated and analysed for annual

rainy days, average rainfall on rainy days, monthly total rainfall, monthly average rainfall (Fig. 6.6), annual total rainfall and average annual rainfall. The maximum and minimum rainfall of each year has also been noted along with this statistics. From this analysis, the average annual rainfall of Karkala is found to be about 4771.49mm. The maximum rainfall received was 6602.51 mm during 1975 and the minimum 3176.05 mm during 1996 (Fig. 6.7).

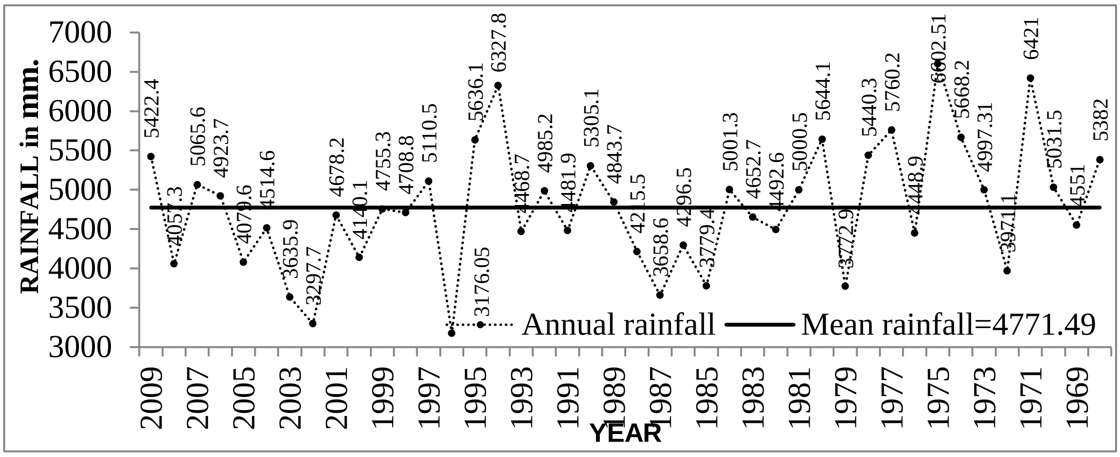

Fig. 6.7 Rainfall variations at Karkala during 1968-2009

The annual rainy days vary from 124 (during 1995) to 161 days (during 1978) with a mean annul of 145 rainy days. The average rainfall per day varies from 13 mm (during 2000) to 45.5 mm (1995) with an average of 32.15mm during these rainy days (Fig. 6.8).

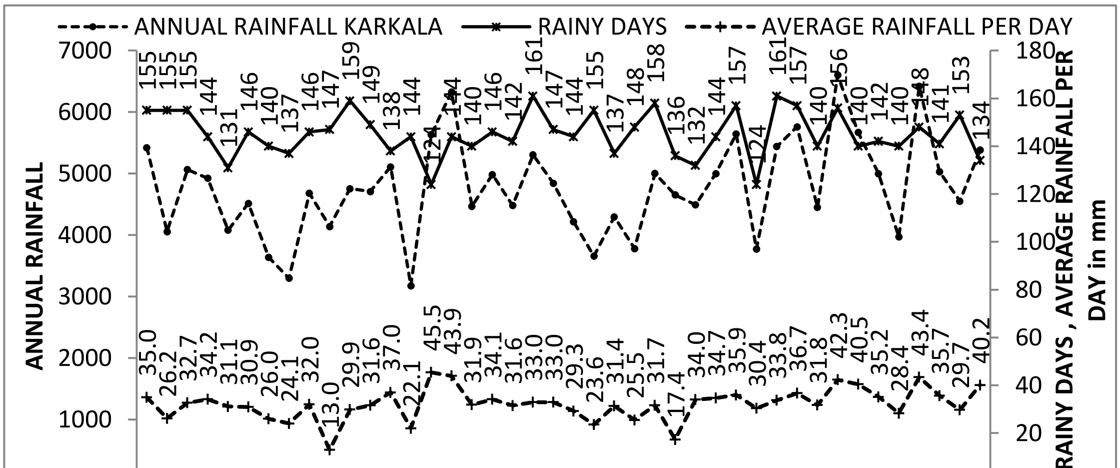

Fig. 6.8 Variations in mean rainy days and daily rainfall at Karkala during 1968-2009

For studying the rainfall of each month of a year, graphs were plotted by taking the monthly rainfall as the ordinate and the months as abscissa (Fig. 6.9). The highest monthly rainfall recorded (2538mm) so far was during July 1968 and during the last three decades 2373.2 mm in July 2009. A gradual declining trend of monthly rainfall except some anomalies could be noticed in the rainfall variation curve of Karkala (Fig. 6.9). Cyclic peak and low in the monthly rainfall curve but not in certain repeated period indicates a pattern in rainfall distribution at Karkala which is vague.

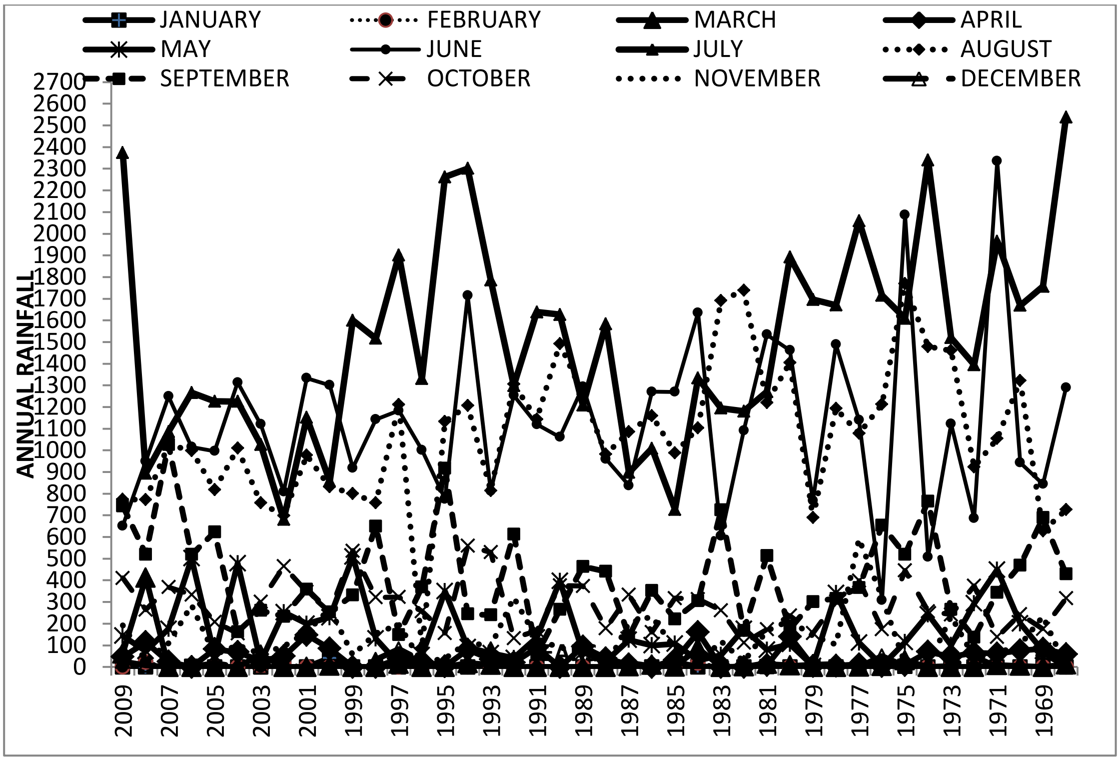

Fig 6.9 Monthly rainfall variations at Karkala during 1968-2009 (42 years)

From the mean monthly rainy days, it can be observed that number of rainy days in August is comparatively higher than that of June. During March and May the rainy days fluctuate indicating unexpected shower due to cyclonic effects. A regular pattern of variation in rainy days can be observed during July and August in alternate years indicating a balance in distribution pattern of rain in temporal domain (Fig. 6.10). It is interesting to note that during March 2008, about nine days of rain occurred whereas the number of rainy days in other months declined sharply in this particular year. Normally a positive relation between the number of rainy days and the annual rainfall could be established in the study area (Fig. 6.10).

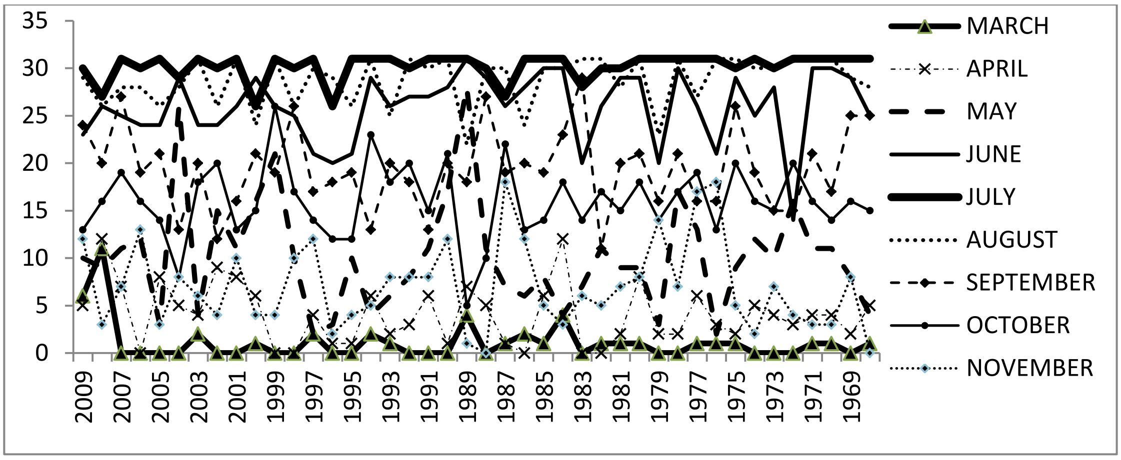

Fig. 6.10 Variations in mean monthly rainy days at Karkala during 1968-2009

<u>6.8.3.2 Moodbidri:</u> About twenty one years of rainfall data spread over 1989 to 2009 were tabulated and analysed for monthly rainy days, monthly total rainfall, monthly average rainfall, total annual rainfall and average annual rainfall. From this analysis, the average annual rainfall of Moodbidri is found to be about 4372.61 mm (Fig. 6.11). The maximum rainfall received was 6022.4 mm during 1994 and the minimum 3176.9 mm during 2002 (Fig. 6.11).

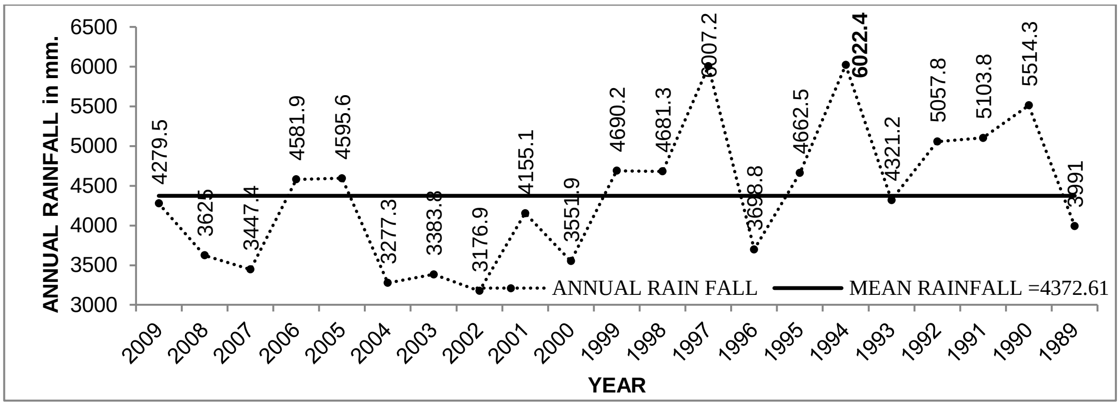

Fig. 6.11 Rainfall variations at Moodbidri during 1989-2009

The annual rainy days vary from 94 days during the year 2007 to 159 days during the year 1990 with a mean annual of 125 rainy days. The average rainfall per day varies from 25mm during the year 2002 to 53.2mm during the year 1997 with an average of 35.13mm during the rainy days (Fig. 6.12). Normally a positive relation between the number of rainy days and the annual rainfall could be established in the study area (Fig. 6.12).

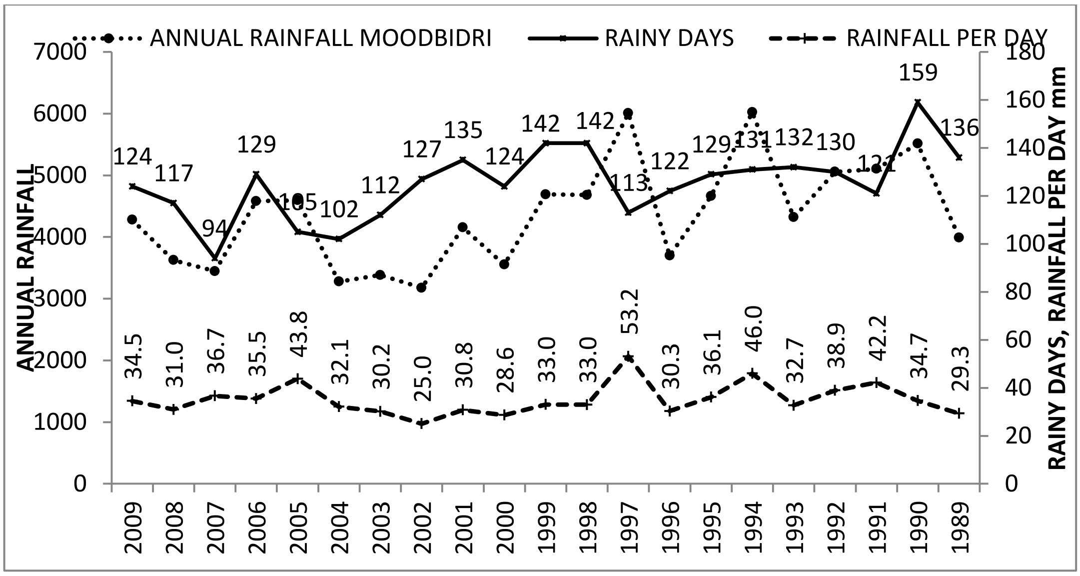

Fig. 6.12 Variations in mean rainy days and daily rainfall at Moodbidri (1989-2009)

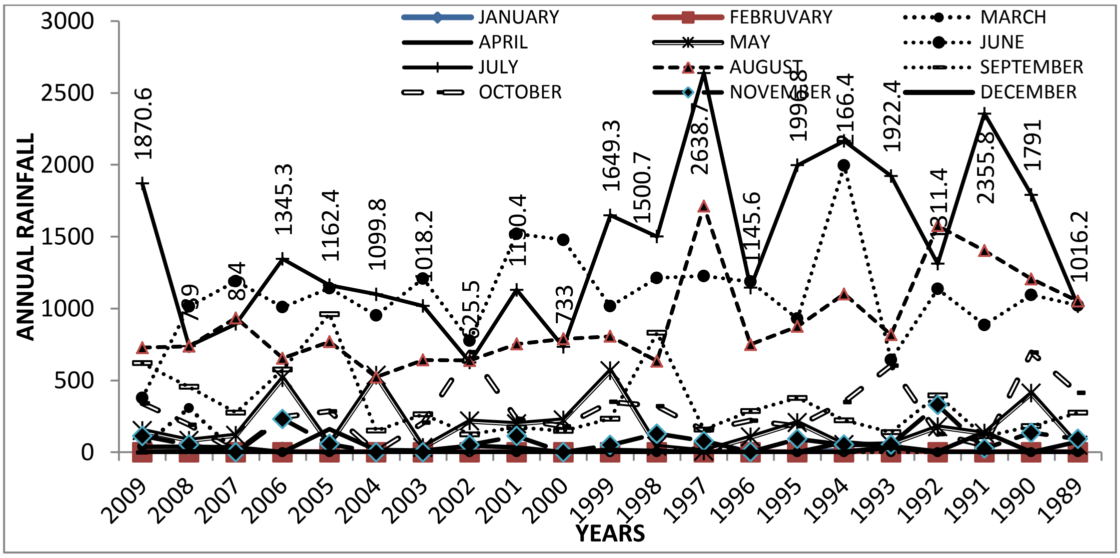

Fig 6.13 Monthly rainfall variations at Moodbidri during 1989-2009 (21years)

From the analysis of the monthly rainfall plot, the highest value recorded at Moodbidri can be noted as 2638.7mm during July 1997. A gradual declining trend of monthly rainfall except for a few anomalies could be noticed in the rainfall variation curve of Moodbidri also (Fig. 6.13). Even with an erratic distribution of rainfall pattern, alternative ups and downs in the rainfall pattern of same months in consecutive years can be noticed indicating some hidden pattern in the rainfall distribution.

6.8.3.3 Mulki: Being the coastal station located at the mouth of the river, about thirty seven years of rainfall data spread over 1973 to 2009 were tabulated and analysed for monthly rainy days, monthly total rainfall, monthly average rainfall, annual total rainfall and average annual rainfall. The Mulki station received an average annual rainfall of about 3647.94mm, the least in the study area (Fig. 6.14). The maximum rainfall received was 6161.8 mm during 1994 and the minimum 1464.3 mm during 1973 (Fig. 6.14).

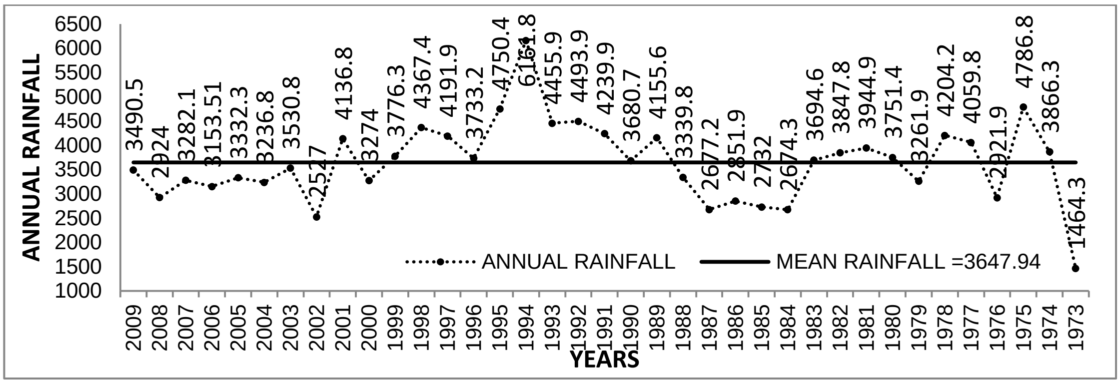

Fig. 6.14 Rainfall variations at Mulki during 1973-2009

The annual rainy days vary from 66 days during the year 1973 to 144 days during the year 1999 with a mean annual of 117 rainy days. The average rainfall per day varies from 12.3mm during 1973 to 51.3mm during 1994 with an average of 35.13mm during the rainy days (Fig. 6.15). A positive correlation between the number of rainy days and the annual rainfall could be established in the study area (Fig. 6.15).

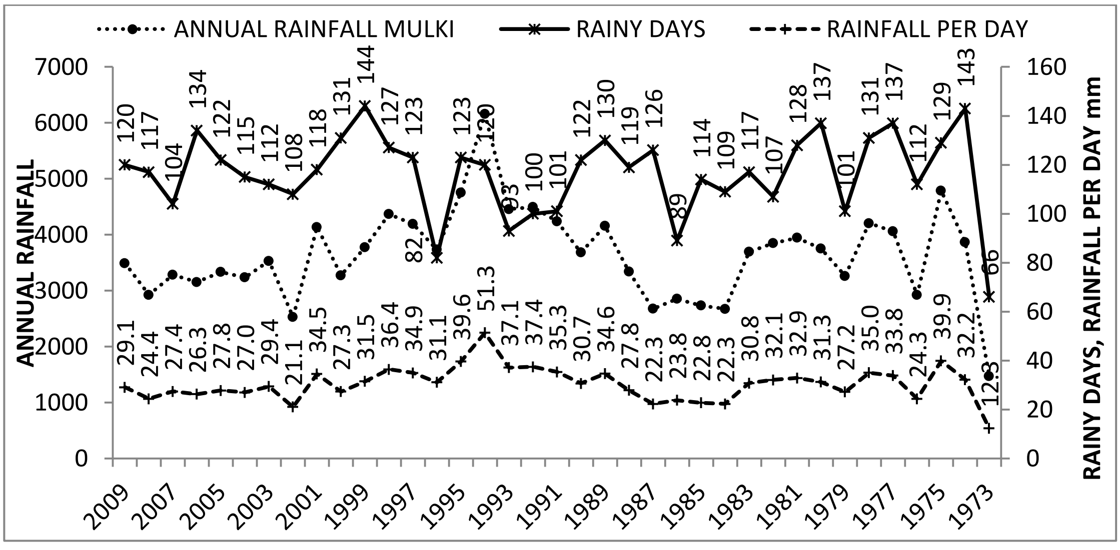

Fig. 6.15 Variations in mean rainy days and daily rainfall at Mulki (1973-2009)

Monthly rainfall data analysis of Mulki shows a gradual declining trend of monthly rainfall during almost all months of the following years after a peak in 1994. The highest monthly rainfall recorded at Mulki was 2278.8mm during June 1994. The same year other monsoon months also recorded highest rainfall compared to other years (Fig. 6.16).

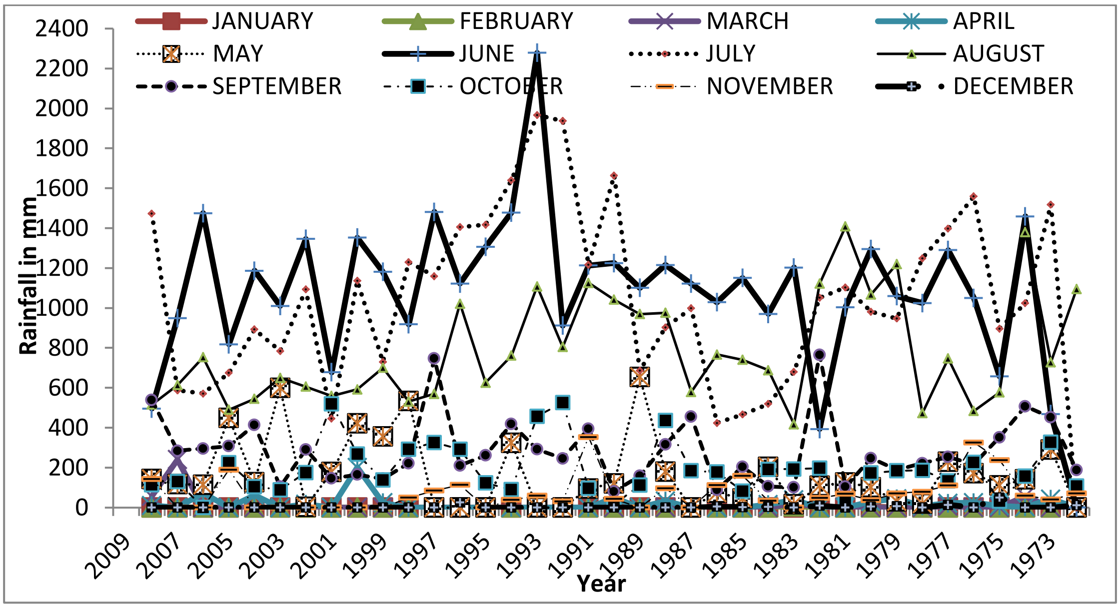

Fig 6.16 Monthly rainfall variations at Mulki during 1973-2009 (37years)

6.8.4 Periodicity in Rainfall Pattern and Moving Average of Rainfall: Usually the point rainfall of a station due to the considerable fluctuation in temporal distribution may not give a discerning trend in the rainfall of the locality. For observing the trend in rainfall for a period of consecutive years moving average technique is used. The periodicities in rainfall pattern could be better discerned by the method of moving averages or moving means, which will smoothen the high frequency fluctuations of a time series and enable the trend to be noticed (Subramanya 2008). If the rainfall at a place over a number of years is plotted as a bar graph it will not show any trend or cyclic pattern in the rainfall due to wide variations in the consecutive years. Usually the moving averages are calculated for three or five (odd numbers) consecutive years for identifying the long term trends in the rainfall at that station. In the present study moving averages for three, five and seven years have been plotted as the ordinate and the time in the reverse chronological order as abscissa to understand the trend of the periodicity in rainfall pattern (Figs. 6.17- 6.19). From these moving average curves plotted, a nine year trend of continuous variation could be noticed. Among these, the moving average curves of Mulki shows very clear trend in the rainfall pattern.

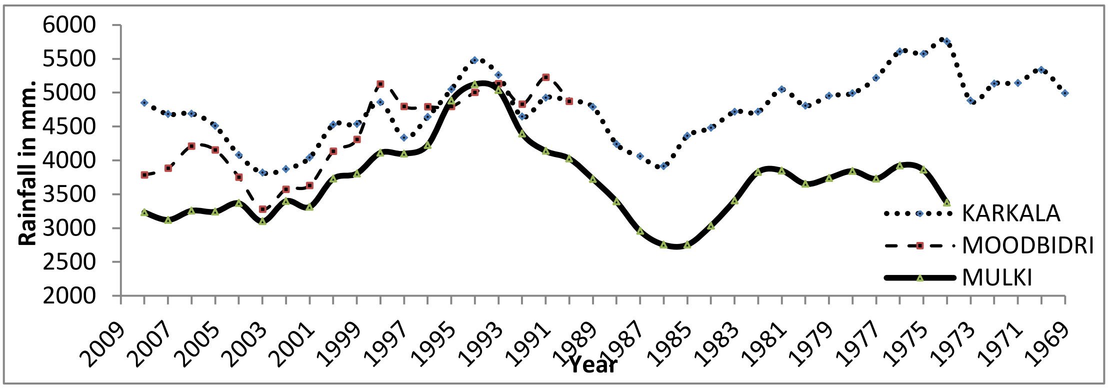

Fig. 6.17 Three years moving average curve of the basin in all three stations

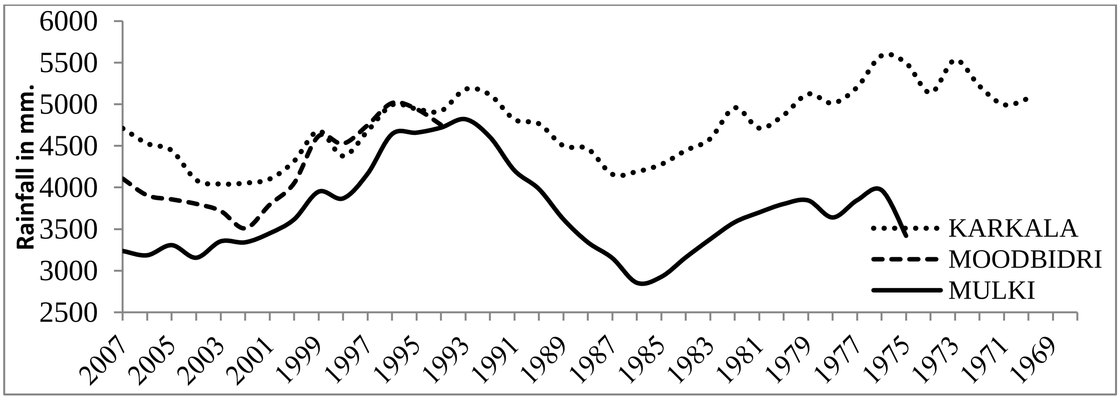

Fig. 6.18 Five years moving average curve of the basin in all three stations

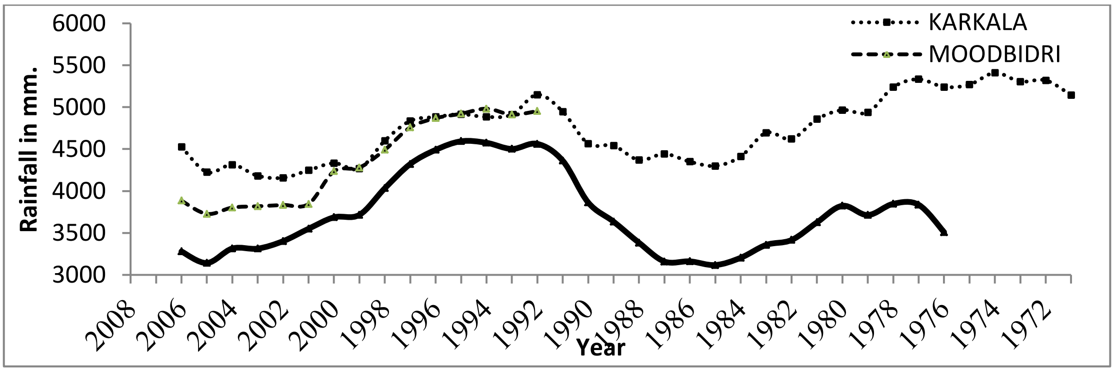

Fig. 6.19 Seven years moving average curve of the basin in all three stations

6.8.5 Frequency Analysis and Return Period: The purpose of the frequency analysis is to obtain a relationship between the magnitude of the event and its probability of exceedance. Probability studies will help to find out the value of the randomly varying annual rainfall that may be expected to get exceeded in a given number of years. For this analysis, the rainfall data of each station has been arranged in the descending order of its magnitude (x) and assigned a ranking order (m) within the length of observation period (N). The probability (P) of a rainfall event being equalled to or exceeded is given by the commonly used Weibull formula,

$$P = [m/ (N+1)]$$

The chance of being exceeded the magnitude (x) is called the 'probability of exceedance'. Considering the magnitude (x) having cent per cent dependability, the 'probability of exceedance' can be expressed as a percentage. According to this, even the lowest annual rainfall recorded in a time series has a chance less than one and cannot be zero (Subramanya 2008). Since the chance of rainfall being between zero and infinity is always equal to one (100%), the chance of rainfall being less than a given magnitude (x) represented as P (< x) is equal to 1 minus the probability of exceedance. The time period or the number of years once in which period a given magnitude is exceeded is called the 'Return period' or the 'Recurrence interval' of that magnitude (x) and is denoted by 'T'. The return period of a given rainfall magnitude is obtained as,

$$T = 1/P = (N+1)/m.$$

By plotting these values of rainfall variation against return period on a logarithmic axis called as probability plot, the rainfall magnitude of specific duration for any recurrence interval can be estimated by suitable interpolation and extrapolation.

The computation of the frequency (probability) and return periods of annual rainfall for the Karkala (Table 6.7), Moodbidri (Table 6.8) and Mulki (Table 6.9) has been given below with the probability plots and return period plots of the above stations (Fig. 6. 20 to Fig. 6.25).

6.8.5.1 Karkala: From the above analysis (Table 6.7), it could be understood that at Karkala, the highest annual rainfall showered is 6602.5mm and is the least dependable variable with 2.3% dependability and a return period of 43 years making it as a rare phenomenon. Rainfall in the range of 5668.2mm is having a dependability of 11.6% and a chance of returning in every decade (Fig. 6.20). Rainfall in the range of 5422.4mm to 5440.3mm has a chance of returning in every five years with 19 to 21 per cent dependability. Rainfall in the range of 4481.9mm to 4985.2mm has the chance of returning in every 2 years with 42 to 61 per cent dependence. Rainfall in the range of 3176.1mm to 4468.7mm has the chance of returning in every year with 97.7 to 67.4 per cent dependence. Rainfall of 3176.1mm at Karkala with a returning period of one year is the most dependable one, having 97.7% dependability (Fig. 6.21).

RANK (m)	ANNUAL RAINFALL (x in mm.)	PROBABILITY (FREQUENCY) P= m/(N+1); N=42	RETURN PERIOD T=1/P (Years)	RANK (m)	ANNUAL RAINFALL (x in mm.)	PROBABILITY (FREQUENCY) P= m/(N+1); N=42	RETURN PERIOD T=1/P (Years)
1	6602.5	0.023	43	22	4708.8	0.512	2
2	6421.0	0.047	22	23	4678.2	0.535	2
3	6327.8	0.070	14	24	4652.7	0.558	2
4	5760.2	0.093	11	25	4551.0	0.581	2
5	5668.2	0.116	9	26	4514.6	0.605	2
6	5644.1	0.140	7	27	4492.6	0.628	2
7	5636.1	0.163	6	28	4481.9	0.651	2
8	5440.3	0.186	5	29	4468.7	0.674	1
9	5422.4	0.209	5	30	4448.9	0.698	1
10	5382.0	0.233	4	31	4296.5	0.721	1
11	5305.1	0.256	4	32	4215.5	0.744	1
12	5110.5	0.279	4	33	4140.1	0.767	1
13	5065.6	0.302	3	34	4079.6	0.791	1
14	5031.5	0.326	3	35	4057.3	0.814	1
15	5001.3	0.349	3	36	3971.1	0.837	1
16	5000.5	0.372	3	37	3779.4	0.860	1
17	4997.3.	0.395	3	38	3772.9	0.884	1
18	4985.2	0.419	2	39	3658.6	0.907	1
19	4923.7	0.442	2	40	3635.9	0.930	1
20	4843.7	0.465	2	41	3297.7	0.953	1
21	4755.3	0.488	2	42	3176.1	0.977	1

Table 6.7 Computations for Probability-Magnitude-Return Period of rainfall at Karkala

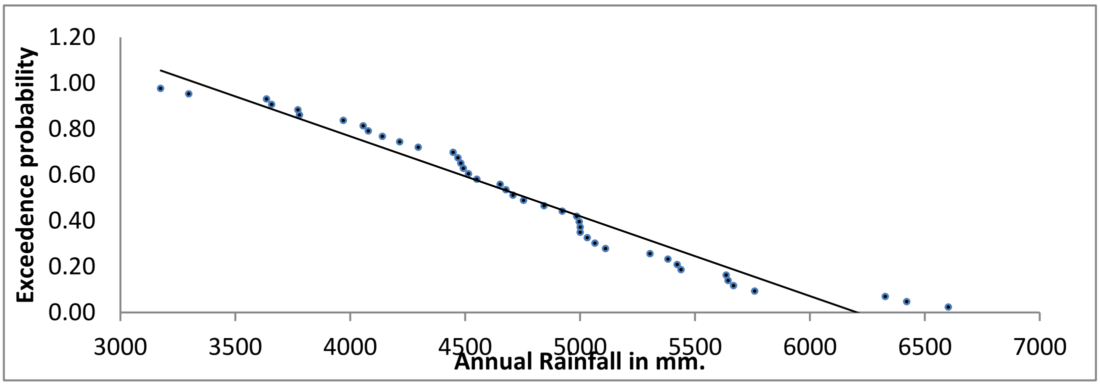

Fig. 6.20 Probability plot of rainfall at Karkala

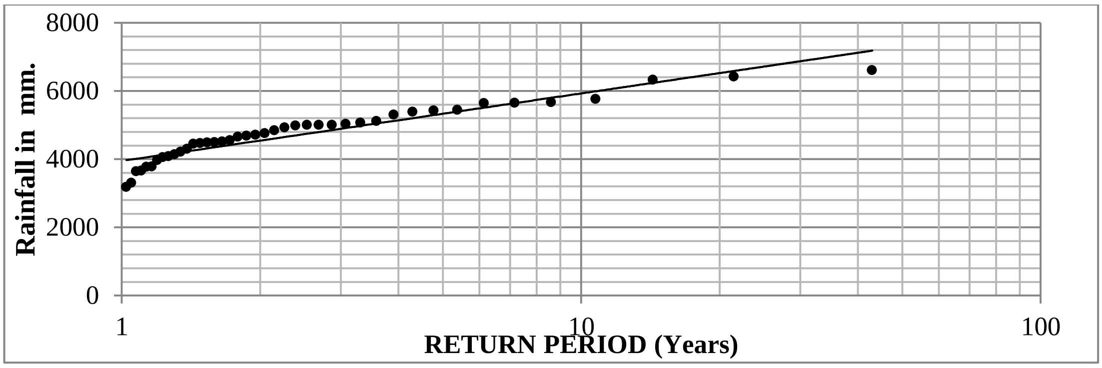

Fig 6.21 Return periods of annual rainfall at Karkala

6.8.5.2 Moodbidri: From the Probability-Magnitude-Return Period analysis of annual rainfall at Moodbidri (Table 6.8), it could be understood that the highest annual rainfall showered is 6022.4mm and is the least dependable variable with only 5% dependability and a return period of 22 years making it as a rare phenomenon. Rainfall in the range of 4662.5mm to 4681.3mm is having chance of returning in every three years with 36% to 32% dependability (Fig. 6.22). Rainfall in the range of 4595.6mm to 3991mm has the chance of returning in every 2 years with 41 to 64 per cent dependence. Rainfall in the range of 3698.8mm to 3176.9mm has the chance of returning in every year with 68% to 95% dependence. Rainfall of 3176.1mm, the least showered in Moodbidri with a returning period of one year is the most dependable one having 95% dependability (Fig. 6.23).

RANK (m)	ANNUAL RAINFALL (x in mm.)	PROBABILITY (FREQUENCY) P= m/(N+1); N=42	RETURN PERIOD T=1/P (Years)	RANK (m)	ANNUAL RAINFALL (x in mm.)	PROBABILITY (FREQUENCY) P= m/(N+1); N=42	RETURN PERIOD T=1/P (Years)
1	6022.4	0.05	22	12	4279.5	0.55	2
2	6007.2	0.09	11	13	4155.1	0.59	2
3	5514.3	0.14	7	14	3991	0.64	2
4	5103.8	0.18	6	15	3698.8	0.68	1
5	5057.8	0.23	4	16	3625	0.73	1
6	4690.2	0.27	4	17	3551.9	0.77	1
7	4681.3	0.32	3	18	3447.4	0.82	1
8	4662.5	0.36	3	19	3383.8	0.86	1
9	4595.6	0.41	2	20	3277.3	0.91	1
10	4581.9	0.45	2	21	3176.9	0.95	1
11	4321.2	0.50	2	-	-	-	-

Table 6.8 computations for Probability-Magnitude-Return Period of rainfall at Moodbidri

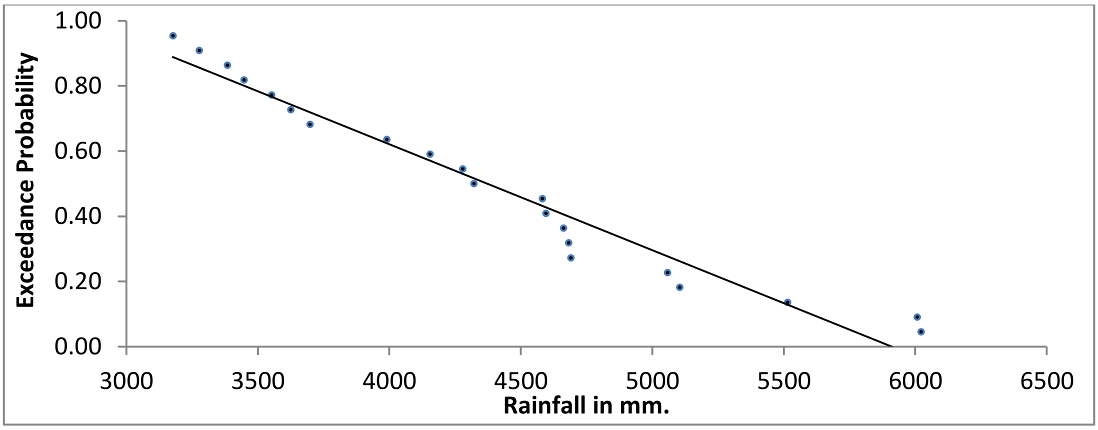

Fig. 6.22 Probability plot of rainfall at Moodbidri

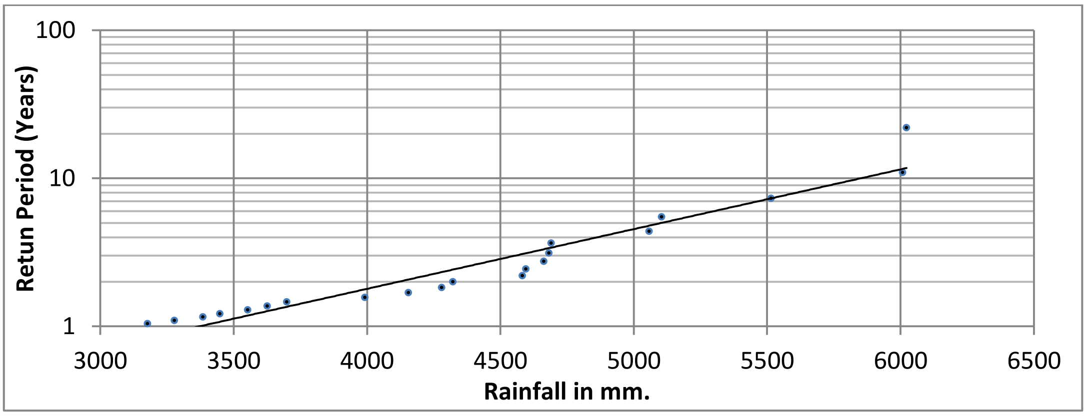

Fig 6.23 Return periods of annual rainfall at Moodbidri

6.8.5.3 Mulki: The Probability-Magnitude-Return Period analysis of annual rainfall at Mulki (Table 6.9) shows that the highest annual rainfall recorded at this station is 6161.8mm and is the least dependable variable with only 3% dependability and a return period of 38 years making it as an abnormal phenomenon. Rainfall in the range of 4493.9mm has the chance of returning in every decade with a dependability of 11% (Fig. 6.24 & Fig. 6.25). Rainfall in the range of 4136.8mm to 3847.8mm is having chance of returning in every three years with 29% to 39% dependability (Fig. 6.25). Rainfall in the range of 3776.3mm to 3282.1mm has the chance of returning in every 2 years with 42% to 63% dependence. Rainfall in the range of 3274mm to 1472.7mm has the chance of returning in every year with 68% to 97% dependence. Rainfall of 1472.7mm, the least recorded in Mulki with a returning period of one year is the most dependable one having 97% dependability (Fig. 6.25).

RANK (m)	ANNUAL RAINFALL (x in mm.)	PROBABILITY (FREQUENCY) P= m/(N+1); N=42	RETURN PERIOD T=1/P (Years)	RANK (m)	ANNUAL RAINFALL (x in mm.)	PROBABILITY (FREQUENCY) P= m/(N+1); N=42	RETURN PERIOD T=1/P (Years)
1	6161.8	0.03	38	20	3680.7	0.53	2
2	4786.8	0.05	19	21	3530.8	0.55	2
3	4750.4	0.08	13	22	3490.5	0.58	2
4	4493.9	0.11	10	23	3339.8	0.61	2
5	4455.9	0.13	8	24	3332.3	0.63	2
6	4367.4	0.16	6	25	3282.1	0.66	2
7	4239.9	0.18	5	26	3274	0.68	1
8	4204.2	0.21	5	27	3261.9	0.71	1
9	4191.9	0.24	4	28	3236.8	0.74	1
10	4155.6	0.26	4	29	3153.51	0.76	1
11	4136.8	0.29	3	30	2924	0.79	1
12	4059.8	0.32	3	31	2921.9	0.82	1
13	3944.8	0.34	3	32	2851.9	0.84	1
14	3866.3	0.37	3	33	2732	0.87	1
15	3847.8	0.39	3	34	2677.2	0.89	1
16	3776.3	0.42	2	35	2674.3	0.92	1
17	3751.4	0.45	2	36	2527	0.95	1
18	3733.2	0.47	2	37	1472.7	0.97	1
19	3694.6	0.50	2	-	-	-	-

Table 6.9 computations for Probability-Magnitude-Return Period of rainfall at Mulki

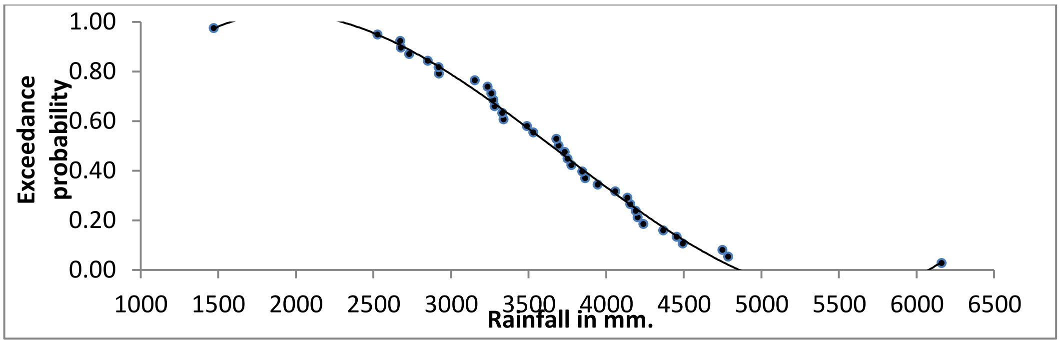

Fig. 6.24 Probability plot of rainfall at Mulki

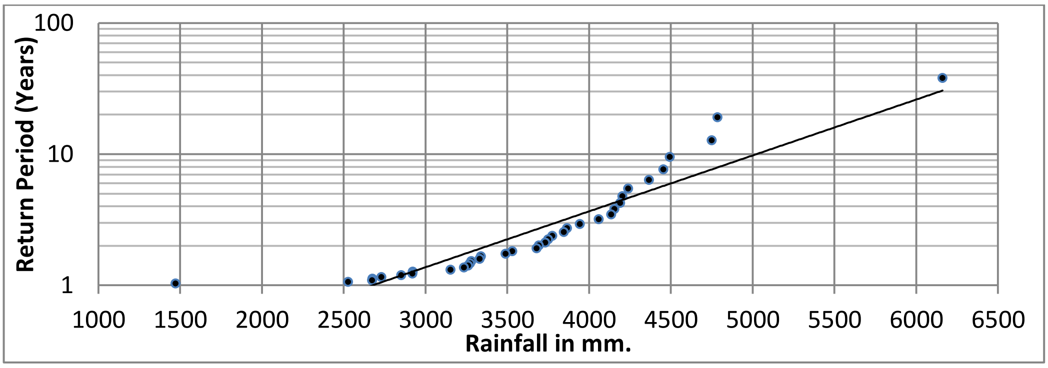

Fig 6.25 Return periods of annual rainfall at Mulki

6.8.6 Seasonal Distribution of Rainfall: The southwest monsoon accounts for nearly 75 to 90 per cent of the annual rainfall in most of the meteorological subdivisions of India including coastal Karnataka (Raj 1990). From the point of view of climate, depths of rainfall for the four seasons identified were tabulated for past fourty two years (2009 to 1968), and the total accumulated rainfalls of all months falling in these seasons were analysed. According to the intensity of rain and rainy days, twelve months were classified into four seasons such as Pre-Monsoon (March-May), Southwest Monsoon (June-September), Northeast Monsoon (October-November) and Post-Monsoon (December-February) for the analysis. In the study area, southwest monsoon spreads over a period of about four months accounts for about 87% of the rainfall. Following this, the northeast monsoon contributes another eight per cent of rainfall in the Mulki River basin. With torrential showers the hot moist pre-monsoon season contributes about five to six per cent rainfall. The general trend of southwest monsoon rainfall pattern over the years is decreasing except at Mulki, which has been maintaining a balance in rainfall trend over the years. The seasonal variation of rainfall in all the three stations of the study area has been discussed below.

6.8.6.1 Karkala: Being on the foot hills of Western Ghats, Karkala receives the highest rainfall in the Mulki River basin. From the rainfall plot (Fig. 6.26), a general decreasing trend in the southwest monsoon rainfall over the years could be observed. The pie diagram shows that the southwest monsoon contributes the highest rainfall of about 86% followed by northeast monsoon (9%) and pre-monsoon (5%) towards the annual rainfall at Karkala (Fig. 6.27).

From the statistical analysis (Fig. 6.28) of four decades of seasonal rainfall distribution, it has been found that the southwest monsoon contributes an average of 4108.7mm annual rainfall varying within a range of 2421.9mm to 5984.3 mm. The northeast monsoon contributes an average of 422mm with a varying range of 136.2mm to 989.9mm rainfall. The contribution of pre-monsoon to the annual rainfall varies from 7.9mm to 599mm with a mean value of 224.3mm, whereas that of post-monsoon is negligible. The other parameters are given below (Fig. 6.28).

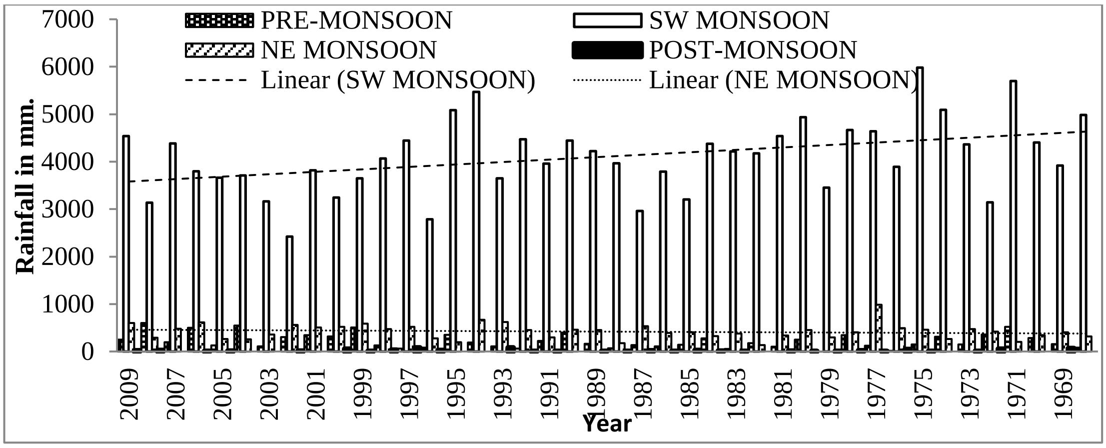

Fig. 6.26 shows the seasonal variation of rainfall pattern at Karkala with trend line

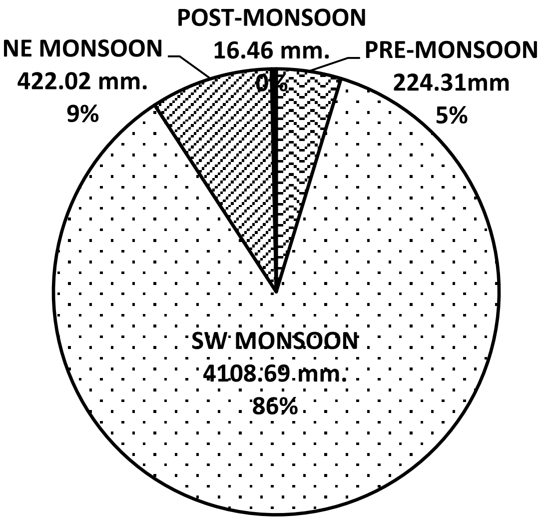

Fig. 6.27 Pie diagram of seasonal distribution for average annual rainfall at Karkala

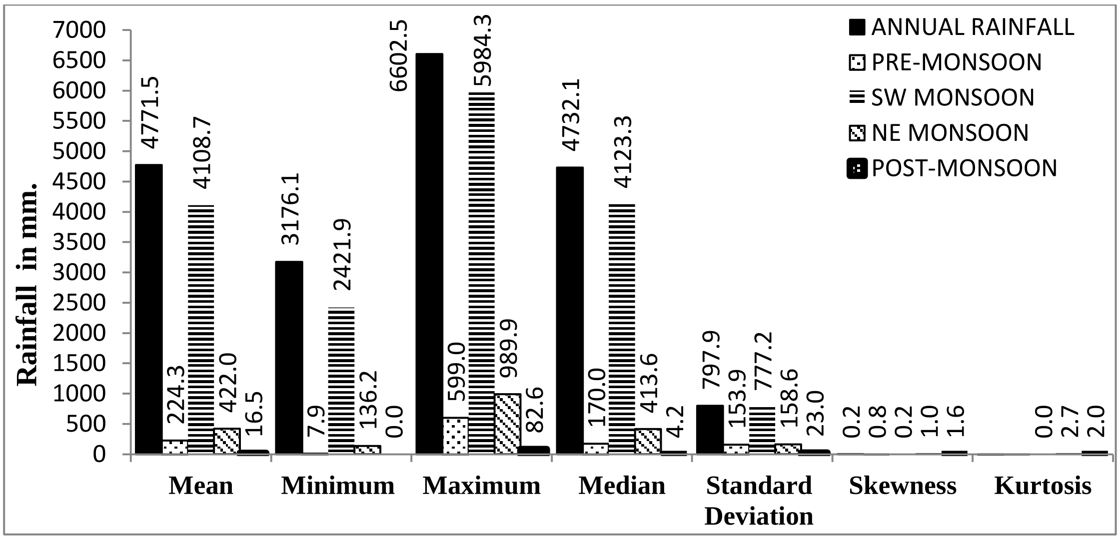

Fig. 6.28 showing the details of statistical analysis of rainfall data at Karkala

6.8.6.2 Moodbidri: Being on the south-eastern brim of the study area, Moodbidri receives an average of about 3771mm southwest monsoon rainfall contributing 86% of the annual rainfall in this area, whereas that from northeast monsoon and pre-monsoon is of 8% and 6% respectively (Fig. 6.29). The bar chart of rainfall variation diagram (Fig. 6.30) for a period of about two decades does not indicate any particular pattern for the variation in this area, but the trend line shows a decreasing rainfall pattern over the years.

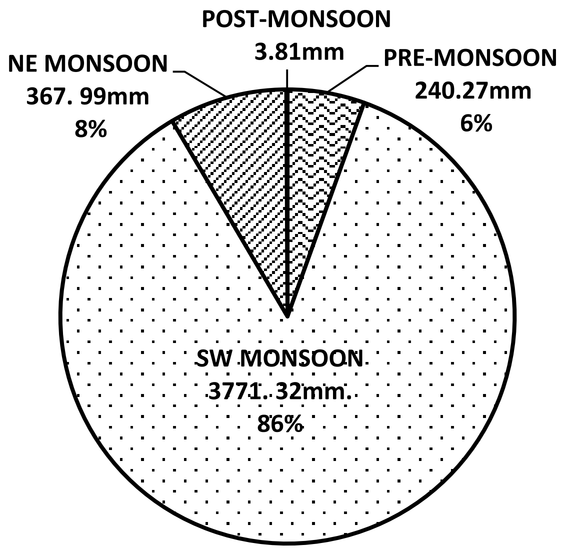

Fig. 6.29 Pie diagram for seasonal distribution of average annual rainfall at Moodbidri

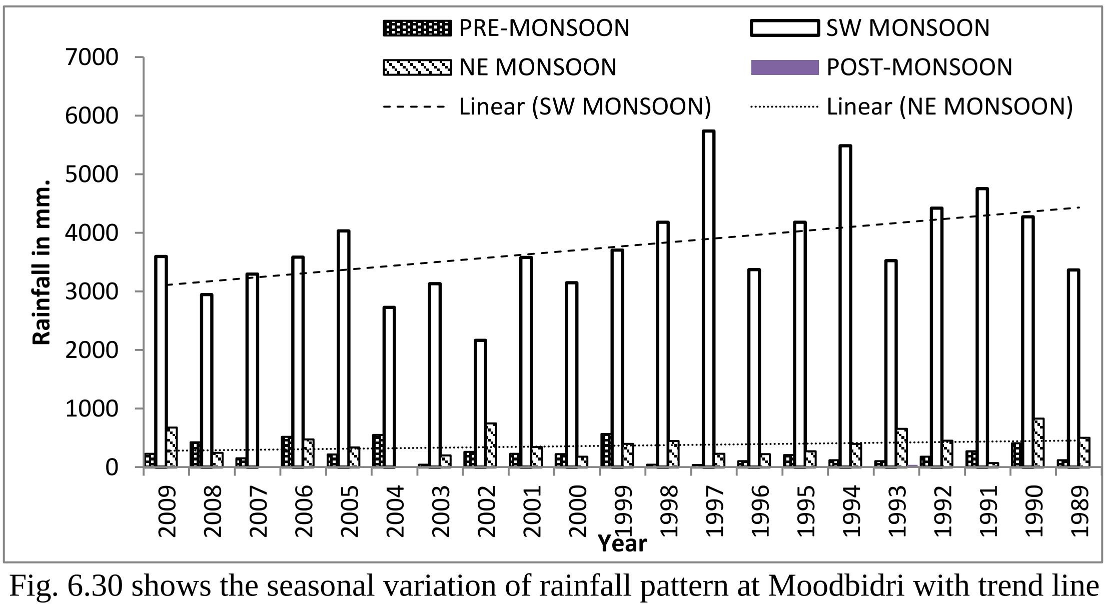

Fig. 6.30 shows the seasonal variation of rainfall pattern at Moodbidri with trend line

The statistical analysis (Fig. 6.31) of about twenty one years' rainfall data at this station shows an average contribution of 3771.3mm rainfall from the southwest monsoon which ranges from 2165.8mm to 5736.5mm. The northeast monsoon contributes an average of 368mm with a maximum of 830.4mm rainfall. The contribution of pre-monsoon to the annual rainfall varies from 41mm to 567.8mm with a mean value of 240.3mm. The other parameters are given below (Fig. 6.31).

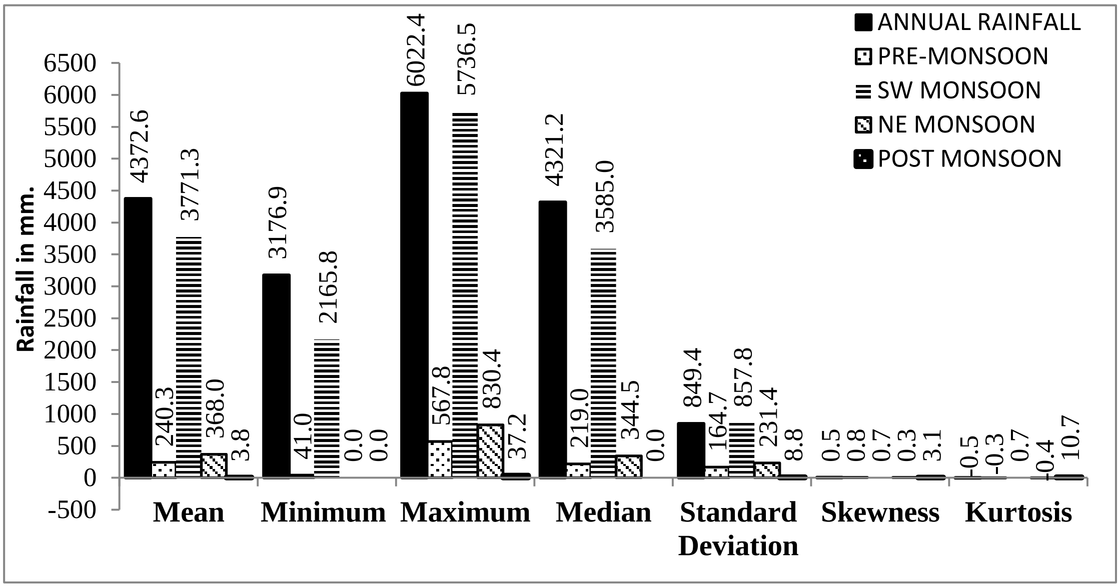

Fig. 6.31 showing the statistical analysis of rainfall at Moodbidri

<u>6.8.6.3 Mulki:</u> Mulki, being on the mouth of the basin receives an average of about 3186.1mm rainfall during southwest monsoon contributing 88% of the annual rainfall in this area, whereas that from northeast monsoon and pre-monsoon is of 7% and 5% respectively (Fig. 6.32). The trend line in the bar chart of rainfall variation diagram (Fig. 6.33) for a period of thirty seven years shows a balanced rainfall over the years unlike Karkala or Moodbidri. The statistical analysis (Fig. 6.34) of about thirty seven years' rainfall data at this station shows an average contribution of 3186.1mm rainfall from the southwest monsoon which ranges from 1282.4mm to 5645mm. The northeast monsoon contributes an average of 264.2mm with a maximum of 556.6mm rainfall, whereas that of pre-monsoon contribution is of 193.9mm with a maximum of 654mm to the annual rainfall. The other parameters are given below (Fig. 6.34).

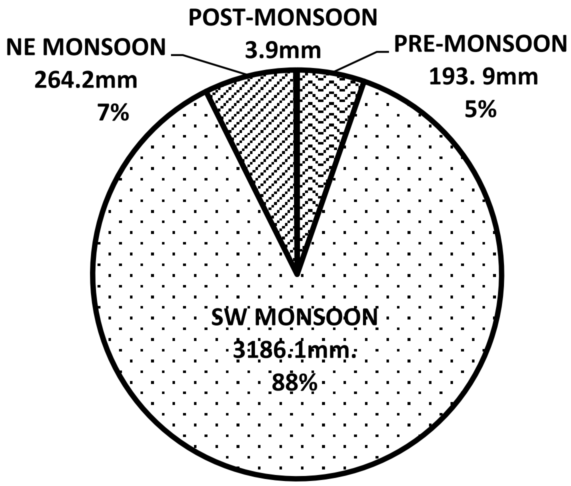

Fig. 6.32 Pie diagram of seasonal distribution for average annual rainfall at Mulki

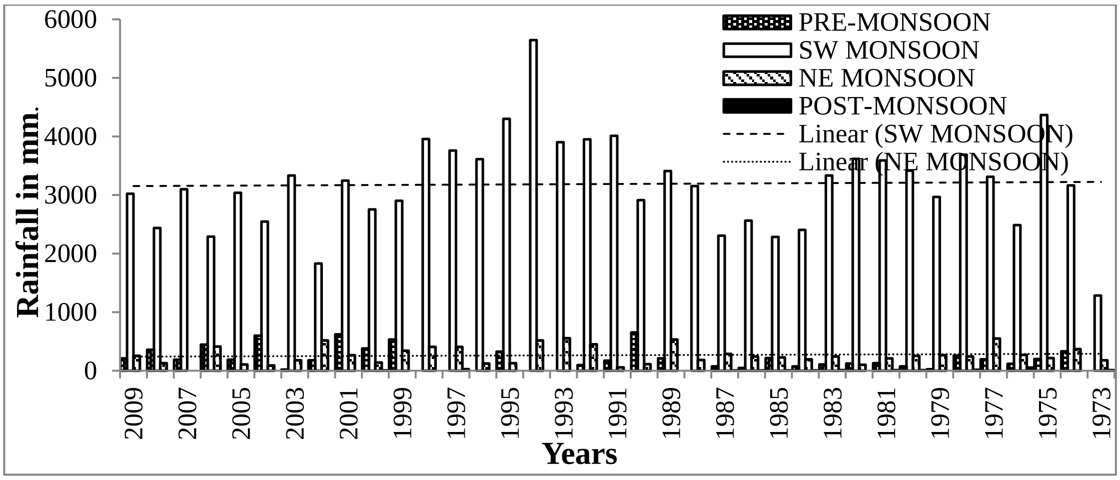

Fig. 6.33 shows the seasonal variation of rainfall pattern at Mulki with trend line

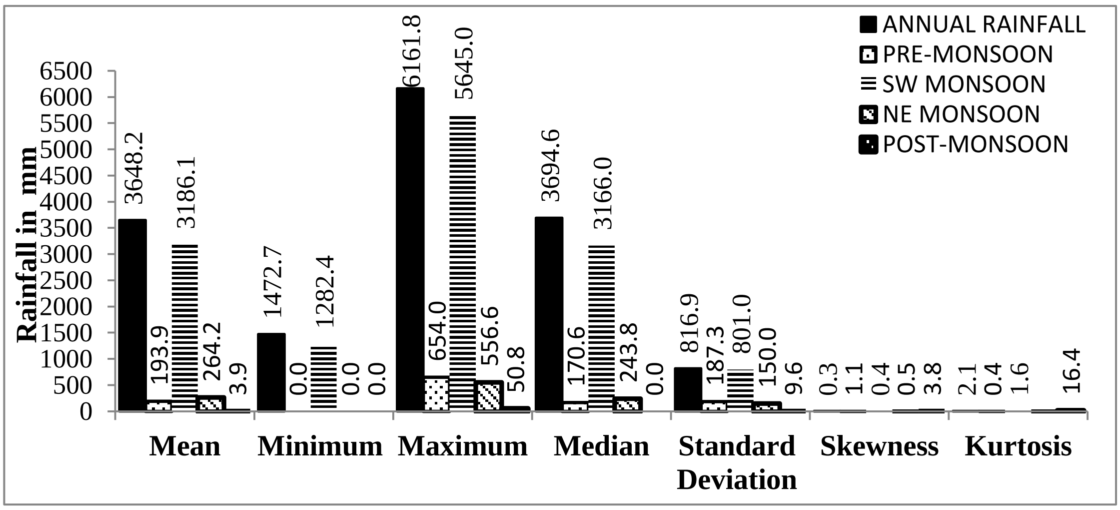

Fig. 6.34 showing the statistical analysis of rainfall at Mulki

6.9 WATER BALANCE STUDIES: For a quantitative evaluation of groundwater resources and its change under the influence of human activities a study on the groundwater balance is required (Sokalov and Chapman 1974). The study will reveal the basis for the rational use, control and distribution of groundwater resources in time and space. The method of calculating water balance is primarily from the point of view of climatic factors and its influence on the soil moisture (Thornthwaite 1948, Thornthwaite and Mather 1957, Blanney and Criddle 1950, 1962). Subba Rao and Subrahmanyam (1961) modified this concept and used for estimation of groundwater yield from peninsular India.

6.9.1 Thornthwaite Method: Thornthwaite (1948) suggested a method for calculating water balance from the meteorological data. Using this procedure, water surplus, water deficit, and actual evapotranspiration for Mulki River basin have been computed using average monthly precipitation and available mean monthly temperature data (2004 & 2005). The results of the potential evapotranspiration (PET) assessed using the Blanney-Criddle (1962) method has been used here for the computation. Infiltration is taken as 20% as per the studies conducted in this area (Udayakumar 2008) where laterite is overlying the granite/granitic gneiss basement rock. The runoff in this area has been obtained as 51.5%. The results are given in Table 6.10 and Fig. 6.35.

	P (mm)	PET (mm)	P–PET (mm)	Infiltra-tion (mm)	K (crop factor)	AET (mm)	Deficit (mm)	Surplus (mm)	Runoff
January	**0.72**	**156.21**	**-155.49**	**0.00**	**0**	**0.72**	**155.49**	**0.00**	**0.00**
February	**0.57**	**148.57**	**-148.00**	**0.00**	**0**	**0.57**	**148.00**	**0.00**	**0.00**
March	**15.47**	**173.44**	**-157.98**	**0.00**	**0**	**15.47**	**157.97**	**0.00**	**0.00**
April	**33.00**	**175.97**	**-142.96**	**0.00**	**0.85**	**33.00**	**142.97**	**0.00**	**0.00**
May	**171.03**	**182.04**	**-11.02**	**0.00**	**1**	**171.03**	**11.02**	**0.00**	**0.00**
June	**1099.55**	**170.88**	**928.67**	**219.91**	**1.15**	**196.51**	**0.00**	**928.67**	**683.13**
July	**1326.40**	**172.62**	**1153.77**	**265.28**	**1.3**	**224.41**	**0.00**	**1153.77**	**836.70**
August	**920.38**	**169.49**	**750.89**	**184.08**	**1.25**	**211.86**	**0.00**	**750.89**	**524.45**
September	**342.37**	**160.66**	**181.71**	**68.47**	**1.1**	**176.72**	**0.00**	**181.71**	**97.17**
October	**253.20**	**163.32**	**89.88**	**50.64**	**0.9**	**146.99**	**0.00**	**89.88**	**55.57**
November	**94.61**	**156.33**	**-61.72**	**0.00**	**0**	**94.61**	**61.72**	**0.00**	**0.00**
December	**6.78**	**155.45**	**-148.67**	**0.00**	**0**	**6.78**	**148.67**	**0.00**	**0.00**
Annual	**4264.09**	**1984.99**	**2279.10**	**788.38**	**1.08**	**1278.68**	**825.84**	**3104.93**	**2197.03**
P - Precipitation, PET - Potential Evapotranspiration, K - Crop factor, I - Infiltration, AET - Actual Evapotranspiration, D - Deficit, S - Surplus, RO - Runoff									

Table 6.10 Water budget computation for Mulki River basin from Meteorological data

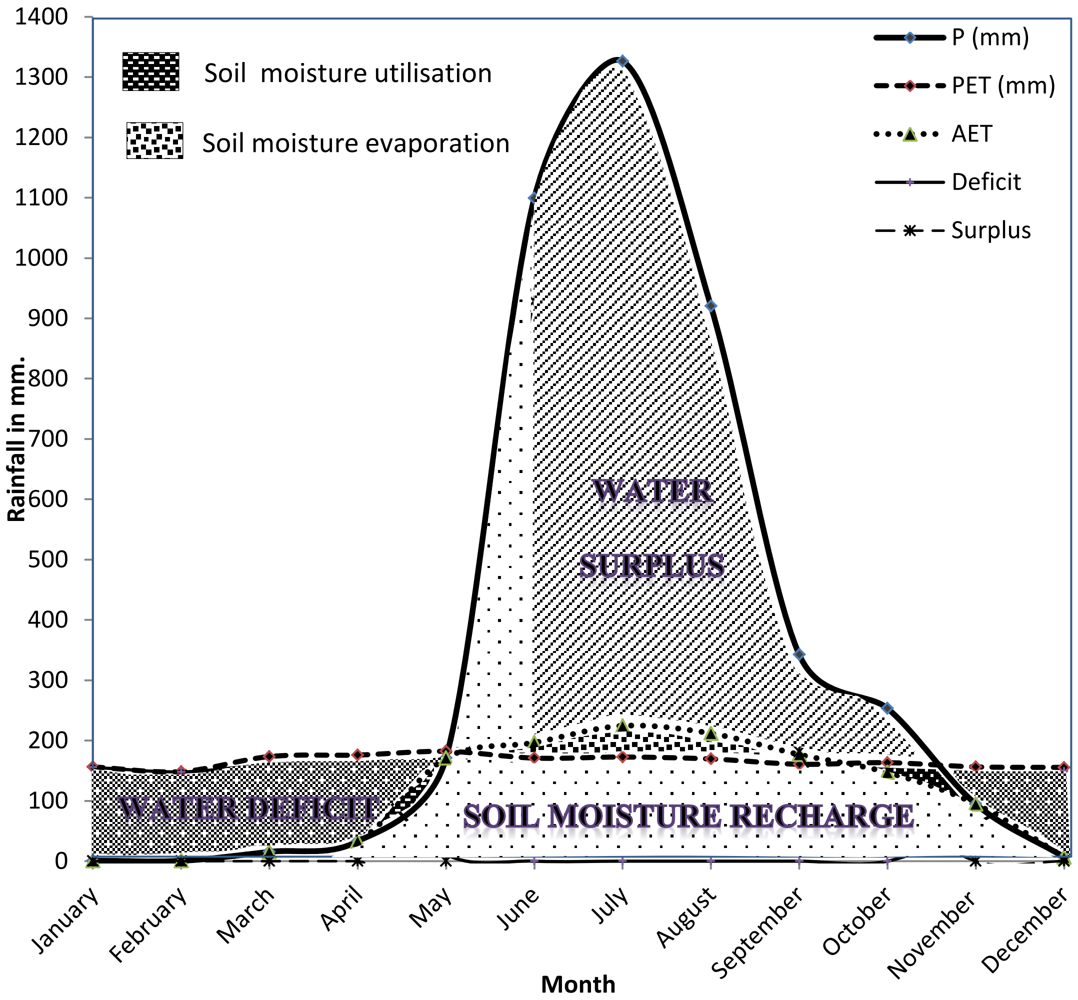

Fig. 6.35 Water budget for Mulki River basin from Meteorological data

From this water balance analysis, it has been estimated that the potential evapotranspiration is about 46.6% (1984.99mm) and the actual evapotranspiration considering crop factor, rainfall, etc. as about 30% (1278.68mm) in the study area. From the analysis it has been found that the study area suffers from a water deficiency of 19.4% (825.84mm) during pre- and post-monsoon period. But for about a period of five months (June-October) the study area gets surplus water of about 72.8% (3104.93mm). But due to less infiltration only about 20% of it will be stored as groundwater. Considering this factor of underground storage, about 35% (1490.72mm) of rainfall will be surplus and will be joining as runoff. The high humidity present in the atmosphere during the monsoon season can be attributed to the excess soil moisture transpiration contributed by the crop factor especially the paddy cultivated in this area (Fig. 6.35). The high runoff of about 51.5% (2197.03mm) from this area could be utilised to improve the infiltration and storage of groundwater potential in this area depending upon the geology and topography of the region. Site specific watershed management practices may be carried out to improve the groundwater storage and prevent soil erosion in this area.

6.10 CONCLUSIONS: The study area falls under tropical humid climatic conditions, and generally a hot humid climate prevails throughout the year in the area. Irrigation considerably influences the heat and moisture exchange in the system at the land-air interface. It contributes to higher water consumption by crops, high soil moisture content, lower temperatures and great humidity of the air as well as to micro climate changes in general in the vicinity of the irrigated areas.

The temperature decreases with the onset of southwest monsoon and increases with the retreat of monsoon. Humidity reaches the maximum during the monsoon due to heavy precipitation, low temperature and limited evaporation. The actual vapour pressure reaches its maximum during rainy season and diminishes subsequently reaching its minimum during January. Generally evaporation rate is very low during monsoon (July-August) and it gradually increases from October and reaches the maximum in May. The maximum potential evapotranspiration in this area is about 38% to 46.6% of the rainfall whereas the actual evapotranspiration computed is about 30%.

The rainfall of the study area is uneven and shows an overall decreasing trend for the last four decades. Annual average rainfall in the study area is about 4264mm average for the last four decades whereas it is 3996mm during the last decade showing a decreasing tendency of the rainfall in recent years. By Thiessen polygon method, the study area is found to receive about 1470.51 x 10^6 cubic meters of storm water (against 1495.53 x 10^6 cubic meters of arithmetic mean method) with an average annual rainfall of 4189.45mm in the basin. Spatial and temporal variation in the distribution of rainfall and its magnitude in the study area show the influence of Western Ghats besides the direction and velocity of wind in the coastal area. Mulki River Basin can be considered as a region falling in the wet climatic zone since the mean normal annual rainfall (4158 mm) of the study area for a period of 30years is found to be more than 2500mm. Out of the 30 years period, 14 years (47%) are found to be deficient years or dry years at both Mulki and Karkala point stations, whereas at Moodbidri 8 years (40%) out of 20 years period are found to be dry years indicating a balance in distribution of rainfall in wet and dry years. The highest surplus rainfall or wet year occurred during 1994 with more than 6000mm annual average rainfall at all stations in the basin. The bulk of the rainfall i.e. over 86% occurs during southwest monsoon season and the intensity is maximum during July with a monthly mean of 1326.40mm rainfall. The Mulki River basin falling partly in Karkala Taluk of Udupi district gets about 4260.76 mm annual average rainfall, which is the highest average rainfall in Karnataka State. The highest annual rainfall received was 6602.51 mm during 1975 at Karkala and the minimum was 2527 mm during 2002 at Mulki.

The temporal variation of rainfall is confined to five to six months in a year and the number of rainy days varies. The maximum rainy days recorded during the past four decades in the basin were 161 days at Karkala during the year 1990 and 1978 and the minimum 66 days recorded at Mulki during 1973. Normally a positive relation between the number of rainy days and the annual rainfall could be established in the study area along with a decreasing trend in the rainy days as well as in the rainfall intensity from the northeastern side (Karkala) to the southwest or to the west (Mulki) in the study area. Average annual rainy days varies from 145 days at northeast side (Karkala) to 125 days at southeast (Moodbidri) and 117 days at southwest (Mulki) indicating a decreasing trend from northeast to southwest. The average rainfall per day varies from 32.15mm at northeast side (Karkala) to 35.13mm each at southeast (Moodbidri) and southwest side (Mulki) indicating a decrease from south to north, probably indicating the reduction of moisture content due to the movement of monsoon from south to north.

From the analysis of mean monthly rainfall variations, it can be inferred that at Karkala and Moodbidri on the eastern side of the area, the rainfall is maximum during July, whereas it is maximum at Mulki during June indicating the influence of south west monsoon hitting the coastal area first. It can also be inferred that the monsoon picks up suddenly during June and reaches the peak during July, declining sharply up to September, and then decreases gradually till November indicating the end of monsoon season in this area. From the analysis of the moving average curves, a nine year trend of continuous variation in rainfall pattern could be noticed.

From the frequency probability analysis of magnitude and return period of rainfall in the basin, it has been found that at Karkala the rainfall in the range of 4468.7mm to 3176.1mm have the chance of returning every year with 67.4% to 97.7% dependence, whereas at Moodbidri the rainfall in the range of 3698.8mm to 3176.9mm have the chance for returning every year with 68% to 95% dependence. At Mulki, rainfall in the range of 3274mm to 1472.7mm found to have the chance of returning every year with 68% to 97% dependence. This shows a spatial and temporal variation in the distribution of rainfall within the basin itself.

From the analysis of seasonal distribution of rainfall, the climatic year in the study area has been classified into four seasons such as Pre-Monsoon (March-May), South-West Monsoon (June-September), North-East Monsoon (October-November) and Post-Monsoon (December-February). This study also revealed that the major contributor of the rainfall (i.e, about 87%) in the study area is from the southwest monsoon spread over a period of four months. Following this, the northeast monsoon contributes another eight per cent of rainfall in the Mulki River basin. With torrential showers the hot moist pre-monsoon season contributes about five to six per cent rainfall in the study area. The general trend of southwest monsoon rainfall pattern over the years is decreasing except at Mulki, which has been maintaining a balance in rainfall trend over the years.

From the quantitative evaluation of hydro-meteorological data, the water budget of the study area for the rational use, control and distribution of groundwater resources in time and space has been prepared. From this analysis, it has been estimated that the potential evapotranspiration is about 46.6% (1984.99mm) and the actual evapotranspiration considering crop factor, rainfall, etc., as about 30% (1278.68mm) in the study area. From the analysis it has been found that the study area suffers from a water deficiency of 19.4% (825.84mm) during pre- and post-monsoon period. But for about a period of five months (June-October) the study area receives surplus water of about 72.8% (3104.93mm). But due to less infiltration of only about 20% owing to its geological conditions, only about 788.38mm has been stored as groundwater in this area. This indicates that a good percentage of rainfall of about 35% (1490.72mm) will be surplus and is joining as runoff every year. From these studies, it can be assessed that out of the 1496.70 x 10^6 cubic meters of precipitation available in the basin, only about 276.72 x 10^6 cubic meters is stored as groundwater. Leaving apart the evapotranspiration, the remaining is lost as runoff of about 771.16 x 10^6 cubic meters per annum which could be utilised by suitable site specific watershed management practices including rainwater harvesting methods in this area for sustainable development. Moreover, conjunctive use of rainwater, surface water and groundwater should be practised to have a sustainable development and management for effective use of water resources in this area.

Chapter 7

Groundwater Assessment and Management

CHAPTER 7

GROUNDWATER ASSESSMENT AND MANAGEMENT

7.1 INTRODUCTION: The increase in water use has obviously affected both surface and groundwater supplies to a large extent and many areas of the country have clearly shown telltale signs of acute water crisis. For a sustainable development of the water resources, proper assessment and management plan for the same is essential. Watershed development or river basin management is the way for augmenting groundwater recharge. The control parameters for a watershed as a physical system are geological, geomorphological, hydrological and hydrogeological which on a scientific basis are hardly considered during the planning and execution of most watershed projects. This chapter deals with the geohydrological assessment of the basin and discusses some management plans.

Mulki River basin, covering an area of about 350 square kilometers spreads in 43 villages of 17 Panchayats supports a huge population of about 2,04,743 people with many commercial, educational and industrial establishments along with the agricultural fields (Fig. 7.1). The major Panchayats falling in this basin are Balkunje, Bola, Belman, Beluvai, Inna, Kallamundkoor, Kanthavara, Kilpadi, Kinnigoli, Mulki, Mundkur, Nitte, Padubidri, Palimar, Puttige, Sanoor and Moodbidri Municipality. Agriculture, especially by tank fed irrigation was the life line of these villages. Community based irrigation system and cattle breeding became a part of the life style here in these villages. Village tanks and their preservation were traditions and culture but are encroached or silted in due course and abandoned. Even though these villages receive heavy rainfall of more than 4200mm average, the present situation is scarcity for water in many parts during the beginning of the summer itself. Many of the tanks have dried up and the open wells too have dried up. People are now more oriented towards the groundwater resources for their agricultural purposes also. Groundwater contributes to about eighty per cent of the drinking water requirements in the rural areas, fifty per cent of the urban water requirements and more than fifty per cent of the irrigation requirements of the basin. The booming urbanisation, modern agricultural practices, fast industrial development, etc., give stress on the water resources due to over exploitation of surface water and groundwater resources of this matured coastal watershed. Now the people have to depend on the centralized water supply schemes for their irrigation also, other than their daily maintenance requirements. The entire river basin stretching in an area of about 350 square kilometers receives about 1,500x10^6 cubic meters of water per annum spread over a period of about five to six months rainy season. But from the hydro meteorological analysis of the basin it has been found that about 35% of this water is joining the sea every year without proper utilization and only 276.72x10^6 cubic meters of water is stored as groundwater. For the proper utilization of the water which is going as waste (about 771.16X10^6 cubic meters) during the rainy seasons, proper planning, development and management techniques are required at village level itself.

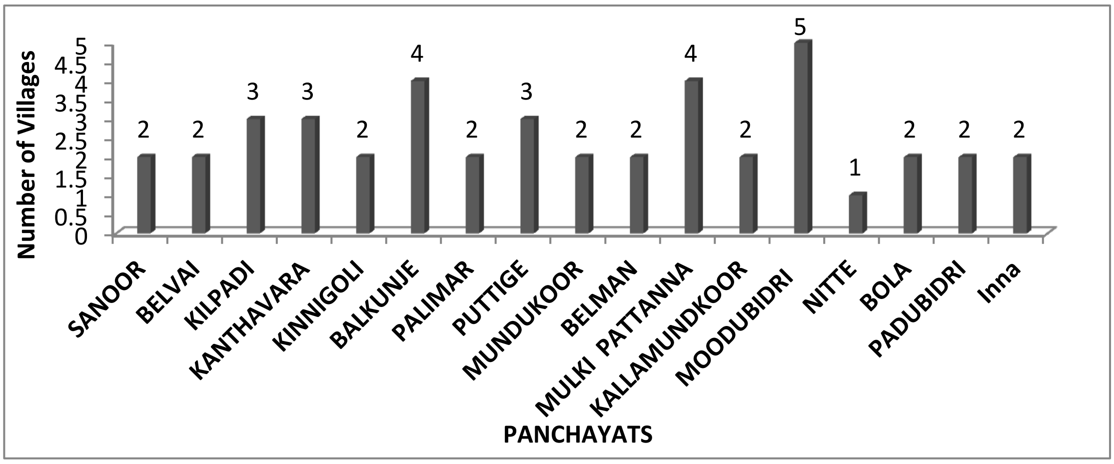

Fig. 7.1 Showing the number of villages in each Panchayats of the Muki river basin

7.2 METHODOLOGY: For the sustainable development and management of the resources, the preliminary requirement is to understand the prevailing situation and the requirements of the water resources. For this, available data from the Panchayats regarding its human and livestock population, agricultural lands, community water supply schemes, irrigated and cultivable areas, etc., were collected and analyzed. Due to the lack of reliable data and its registration, the real need analysis cannot be achieved. But a rough estimation in this regard is carried out to understand the tip of the iceberg problem. A decade long monthly water table fluctuation data of three open wells and two bore wells set up by the Karnataka State Mines and Geology department has been analyzed to understand the groundwater fluctuation in this basin. About 36 open wells spread across the river basin have been observed for a period of one year to understand the groundwater fluctuation and its relation to the climatic situations in the basin. Hydrometeorological data analyzed during the studies has been used for the planning and management of the water resources in the Mulki river basin. In order to understand the resource planning and management at village level, Google Earth imageries have been used for mapping the microwatersheds and traditional rainwater harvesting structures like tanks, ponds, etc., thanks to its high resolution true colour pictures and DEM. An integration of all the above data were carried out on a GIS platform for the better understanding of groundwater development and management of the basin.

7.3 WATER RESOURCES: For the planning and sustainable development of any area, an evaluation of the water resources and its proper management is very important. Here an attempt is made to understand the same through various analyses, especially through the water table fluctuation analysis.

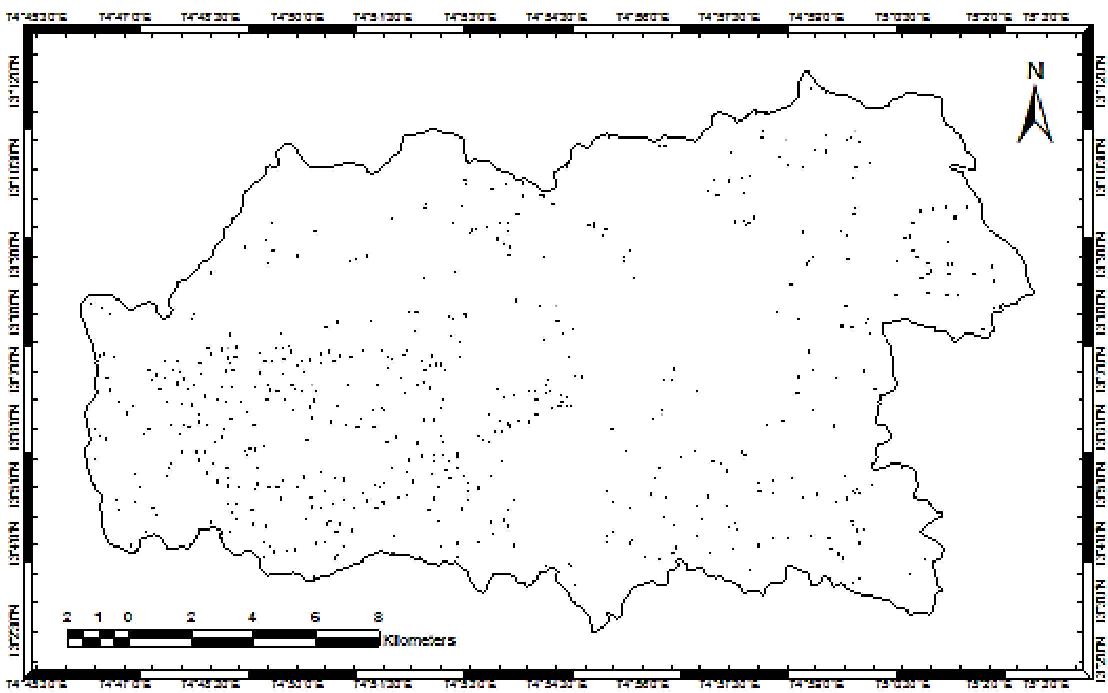

Fig.7.2 Well density map of Mulki river basin

7.3.1 Well Density: As a preliminary investigation, the well density map (Fig. 7.2) of the river basin has been prepared from the SOI topographic sheets (1988) and field surveys. This shows a very high density of groundwater extraction structures in the low lying areas of alluvial soils and lateritic terrain which are high potential zones for groundwater.

7.3.2 Water Table Fluctuation: Water table fluctuation is mainly governed by the climate, topography and geology of the area. Water level fluctuation is also caused by the evaporation during summer. Water level fluctuation is primarily governed by the specific yield of the material in the fluctuation zone. All the factors remaining the same, the water level fluctuation is invariably proportional to specific yield (Karanth 1987). The rise and fall of the water level in the region is an annual feature due to well defined seasonal rainfall. The depth to water level reaches maximum in April and minimum in July. And there onwards it takes a steep slope.

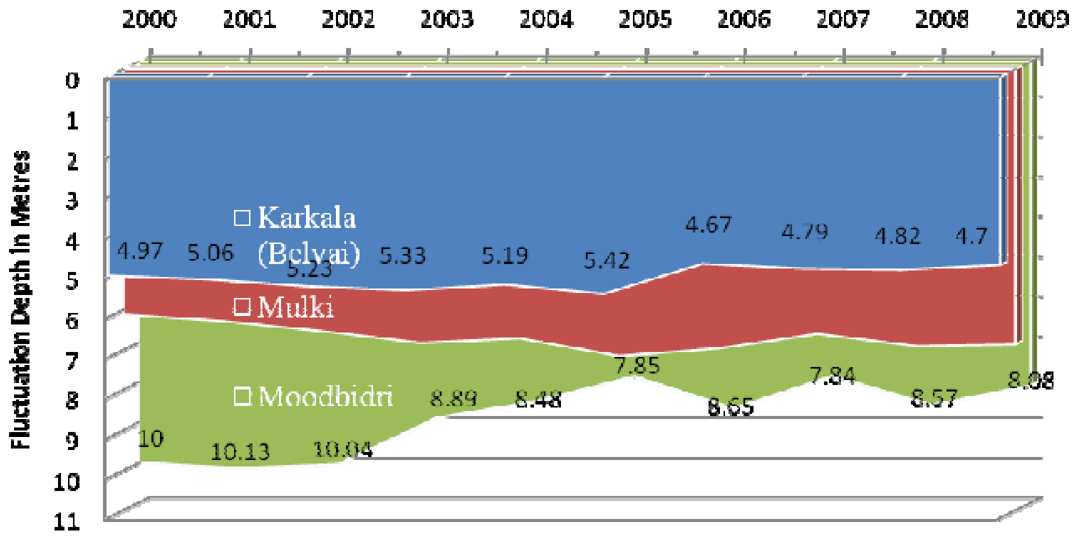

Fig. 7.3 Showing the water table fluctuation of the three observation wells in the Basin over a decade during 2000-2009

The daily water table fluctuation data from three observation wells (open wells) put on three different geomorphological and geological conditions of the basin monitored by Karnataka State Mines and Geology department has been analyzed for the groundwater fluctuation in this area (Fig. 7.3). These stations have been located almost at three strategic locations of the basin, one at Mulki, the river mouth, and the others at Karkala and Moodbidri, the extreme ends of the basin at a longitudinal profile from the mouth. Average water table fluctuation for ten years (2000-2009) from these three observation wells is found to be about 6.85 meters with a variation of

4.67m to 10.13m. The trend lines of water table fluctuation in granitic and alluvial terrain show almost a uniform nature whereas in Moodbidri lateritic plateau it is highly fluctuating with a decreasing trend in water table variation. Since the water table fluctuation is directly proportional to the specific yield (Karanth 1987), and reflects the draft, this can be utilized for calculating the average annual draft from the basin. So the average annual groundwater draft from the basin can be estimated as $2{,}404.35 \times 10^6$ cubic meters.

In hard rock terrain, the water table fluctuation is much less compared to the Lateritic terrain or alluvial terrain. The decline in water table fluctuation over the years at Moodbidri may be due to the fast urbanization during the last decade, or the rainfall variation during these years. In order to understand the trend of water table in the study area, well inventories have been carried out during April-May, the pre-monsoon months of 2008 and 2009, and the water table data have been plotted using the weighted average method in ArcMAP 9.1 version (Figs. 7.4 & 7.5). These maps indicate the deep water table of up to 14meters during peak summer in the lateritic terrain showing the high porosity and enhanced rate of groundwater flow in this region.

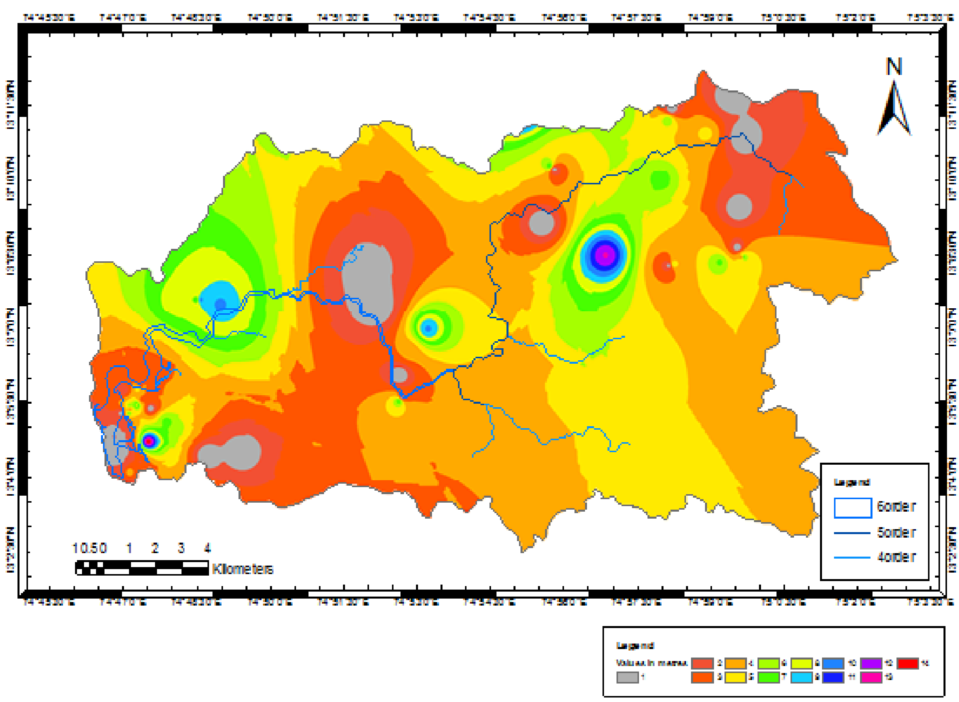

Fig. 7.4 Water Table Contour Map of Mulki river basin for April 2008

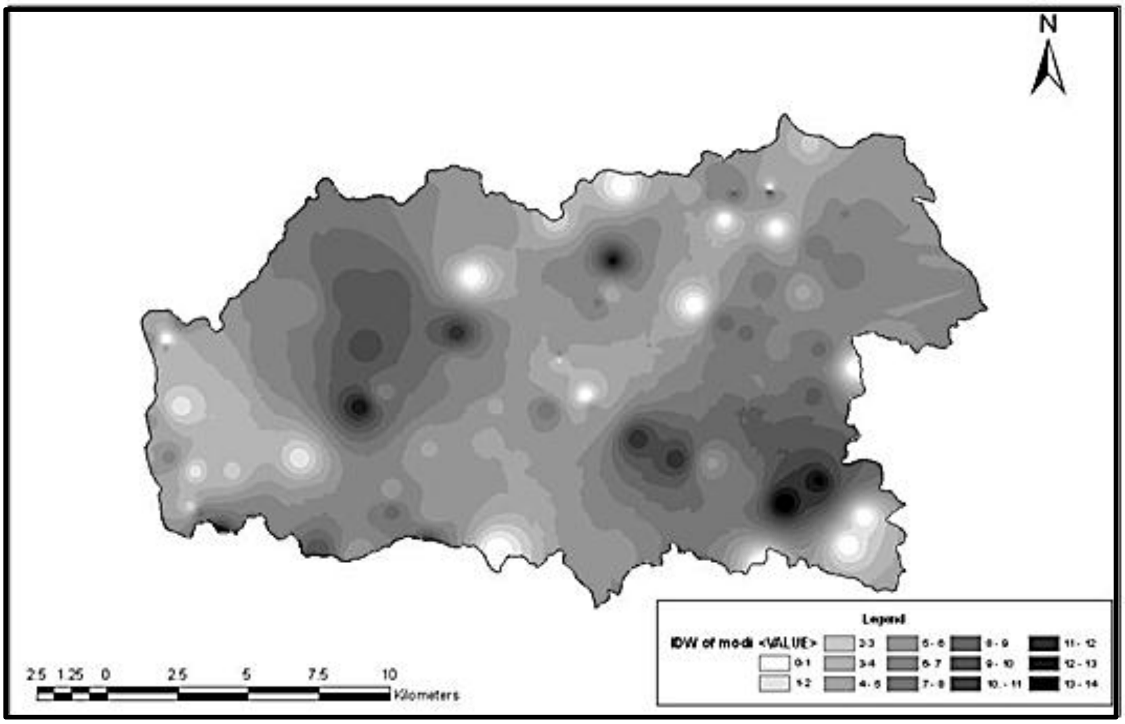

Fig. 7.5 Water Table Contour Map of Mulki river basin during April-May 2009

In order to understand the annual water table recharge and discharge in the study area, water table fluctuation of 36 observation wells spread across the basin have been monitored monthly for one year period during January to December, 2010 (Fig. 7.6).

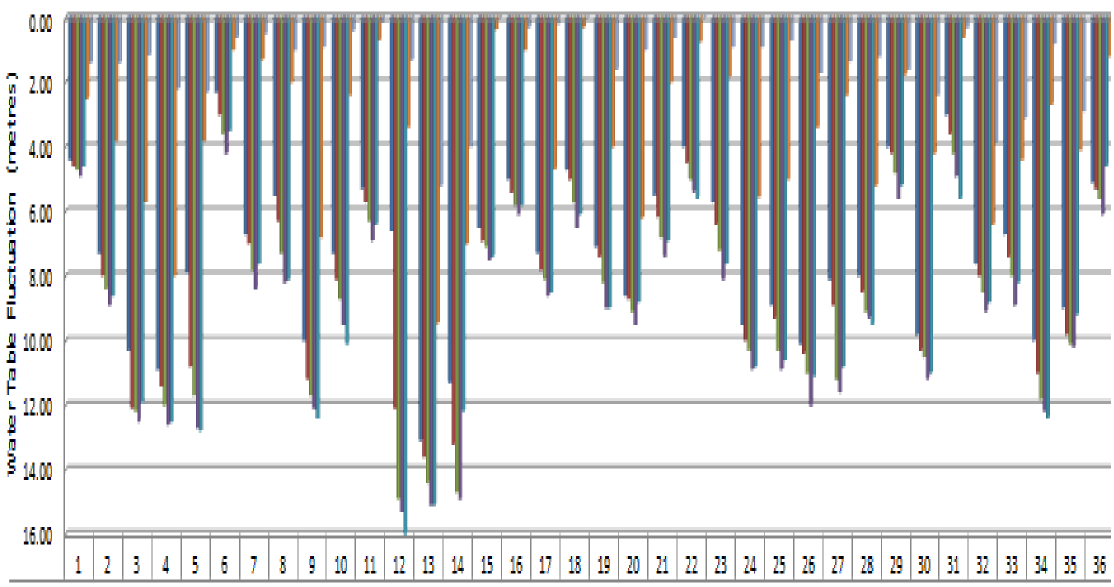

Fig. 7.6 Showing the depth to water table in 36 observation wells during the observation period

The well depths range from 4.90m observed near Mundkur (valley) to 18meters at Guddeyangadi (on the top of lateritic plateau). Depth to water level is comparatively lower (4.2m during peak summer at Mundkur) near the river courses and alluvial plains, whereas it is very high in lateritic region (16 meters at Mithabail) (Fig. 7.6). The steep variation in water table represents the topography and geology of the area other than the climate. Water level fluctuates differently in the pre-monsoon and post-monsoon periods indicating different controlling factors for the two seasons (monsoon and non-monsoon). For the non-monsoon, the fluctuation of water table mostly reflects the stress side (abstraction and air temperature), whereas that during the monsoon it is predominantly controlled by recharge.

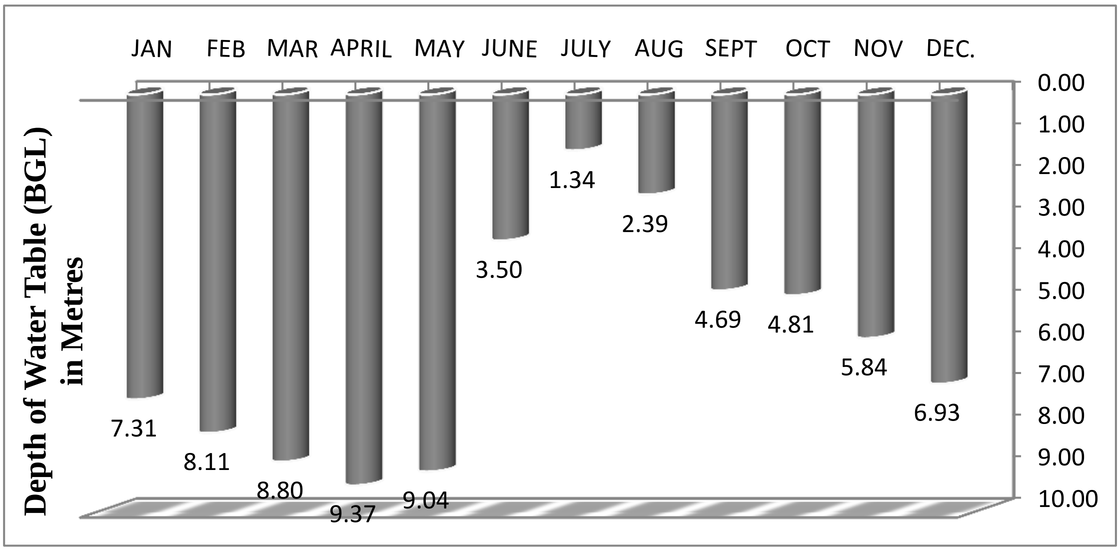

Fig. 7.7 Showing the monthly average water table fluctuation in the Mulki River Basin during 2010

The monthly average water table of the observed wells in the study area shows a sharp declining trend during July to December, whereas during January to May (Pre-Monsoon) the trend is gentle compared to other seasons (Fig. 7.7). This shows that the groundwater flow is maximum during the rainy season since the evapotranspiration is minimum during these months. These observations also showed an average annual water table decline of 6 meters in the Mulki River basin where the fluctuation varies from 1.34m to 9.37m during the whole year. So during the year 2010 we can say that the average annual draft (loss) from the basin was around 2,106

$x10^6$cubic meters from the groundwater storage of the basin. The maximum water level rise was during July and the minimum rise during April. This shows that the water level rise starts immediately after rainfall indicating high infiltration through the highly porous laterite resting above the shallow granitic bedrock in the study area.

By overlaying the water table contour of the study area over the surface map of corresponding well depth, the trend of the water table fluctuation could be understood. The water table contour follows the well depth of the terrain from the surface or it can be said that the water table is parallel to the topography of the terrain (Fig. 7.8) during the peak summer or April.

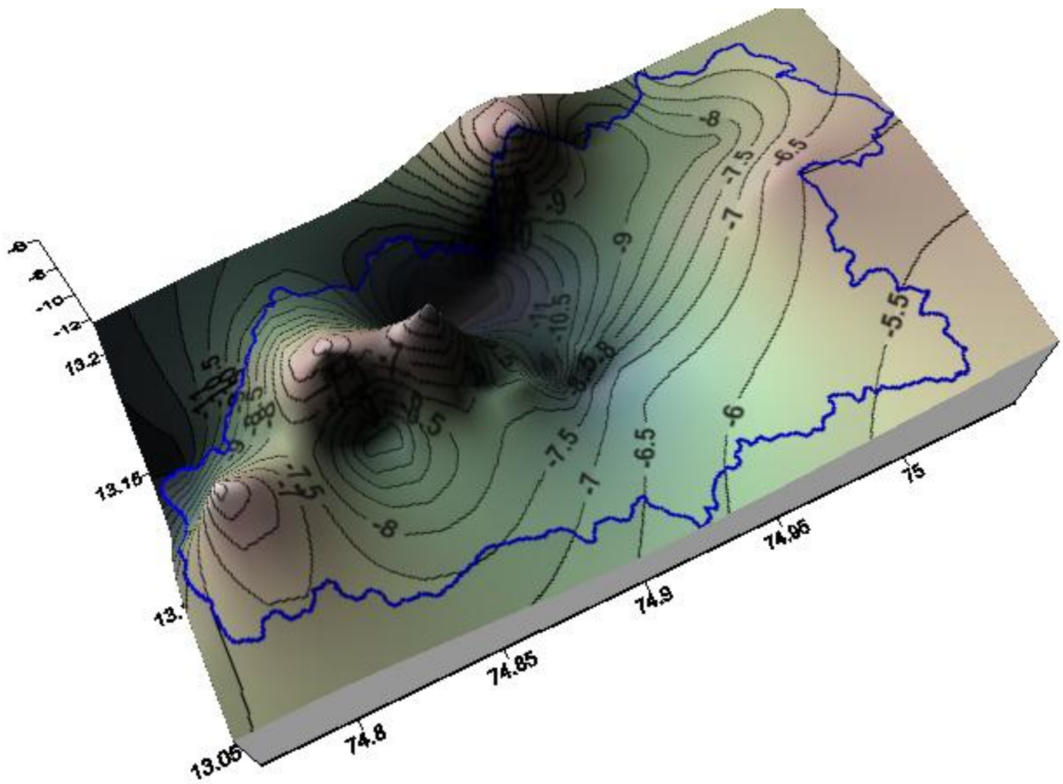

Fig. 7.8 Water Table Contours (April) overlaid on the well depth surface map of the study area

But during July, the heavy monsoon period, the water table contour decreases from the southeastern side of the area towards West or North-West in the area (Fig. 7.9). The aquifers are deeper in the mid part of the area where the river sweeps and it is less in the hilly plateau area in the Pranthya-Moodbidri-Belvai belt. The influence of the intrusive ridge on the western side of it may be the cause for this phenomenon.

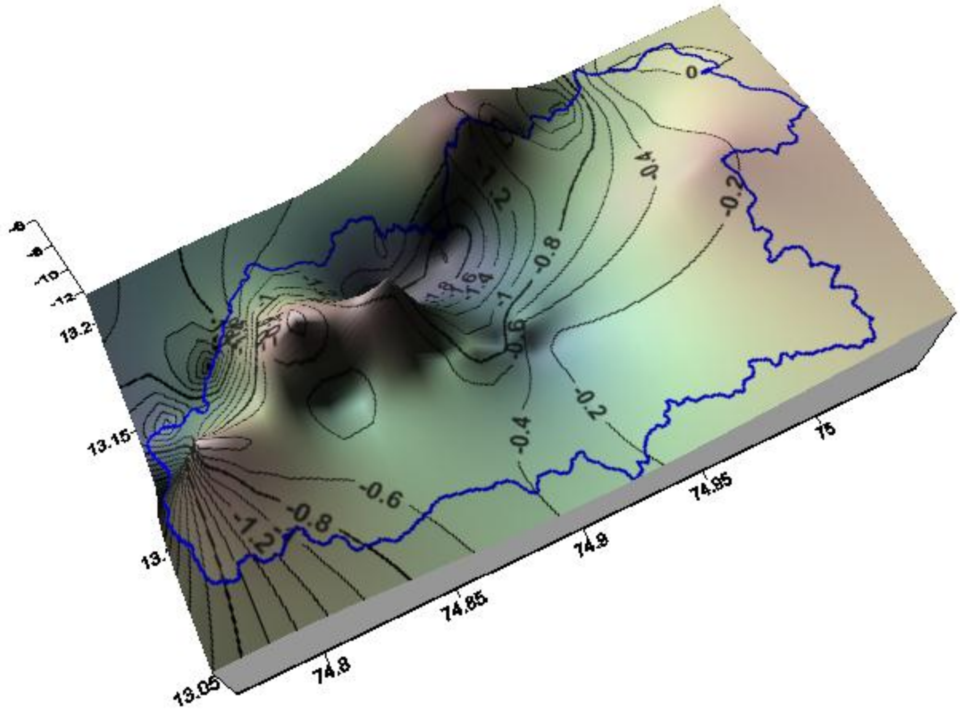

Fig.7.9 Water table contours (July) overlaid on the well depth surface map of the study area

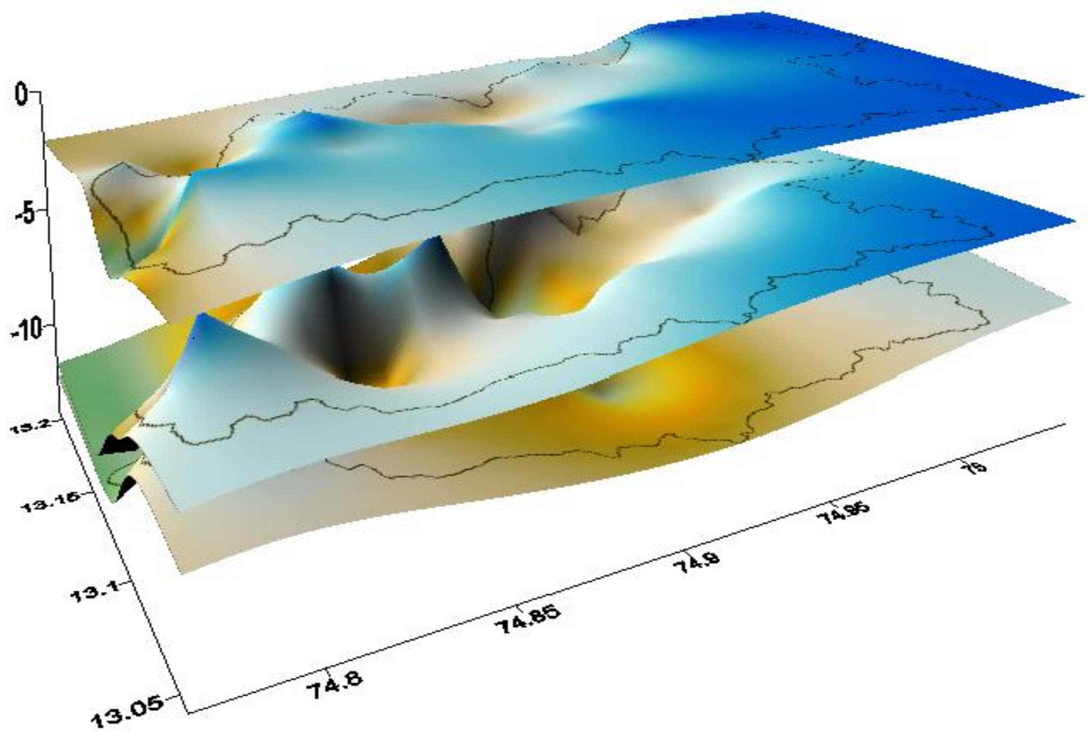

Fig.7.10 Overlay of water table surface maps of July (top) and April (Middle) over the Well depth surface map

The over lay of the surface maps of water table of April and July over the well depth (Fig. 7.10) indicates the potential area of water storage and its depletion during the peak summer. This points to a fact that heavy annual decline in water table is mainly along the river course and valley portion and may be caused due to the groundwater flow and discharge to the streams.

7.4 WATER REQUIREMENTS: Based on the data available with the Panchayats and other agencies, a rough estimate of the water requirement is made based on the human population, cattle population and cultivated area in each of the Panchayats falling in the basin (Table 7.1). Here the estimation is based on the assumption that the per capita water consumption is 140 liters/day whereas for the cattle it is 35liters/day. The crop water requirement is estimated based on the seasonal cultivation requirement which is about 4950.75cubic meters/acre.

SL. NO.	PANCHAYAT	Area Sq.Km.	Population	Consumption cubic meteres	Cattle	Consumption cubic meters	Cultivated Sq.Km.
1	SANOOR	3833.00	6905	352846	772	9862	18.39
2	BELVAI	6346.73	10181	520249	400	5110	30.46
3	KILPADI	2873.82	7246	370271	467	5966	13.71
4	KANTHAVARA	4918.69	3921	200363	300	3833	23.60
5	KINNIGOLI	3791.06	9053	462608	119	1520	18.33
6	BALKUNJE	2201.85	9081	464039	566	7231	10.56
7	PALIMAR	3347.57	7122	363934	430	5493	16.06
8	PUTTIGE	5399.10	8918	455710	223	2849	25.91
9	MUNDUKOOR	4783.00	7681	392499	298	3807	29.95
10	BELMAN	2640.33	7740	395514	333	4254	12.67
11	MULKI PATTANNA	24848.54	37469	1914666	110	1405	119.27
12	KALLAMUNDKOOR	5092.22	3885	198524	490	6260	24.44
13	MOODUBIDRI	39.62	18389	939678	125	1597	0.19
14	NITTE	9708.05	12363	631749	390	4982	46.60
15	BOLA	2814.75	2307	117888	635	8112	13.51
16	PADUBIDRI	3185.68	14177	724445	355	4535	15.29
17	INNA	2527.12	3668	187435	530	6771	11.87
	Total	88351.13	170106	8692417	6543	83587	430.81

Table 7.1 Showing the water requirements of Panchayats in the Mulki River basin

A broad assessment of groundwater balance available in the area has been calculated based on Rainfall- recharge method devised by the National Bank for Agricultural and Rural Development (NABARD 1984) (Table 7.2). Groundwater assessment has been done for the whole year to avoid the complication arising due to seasonal variations.

In a year, the aquifers in the area are recharged to an extent of 28,590 hecta-metres and net annual recharge of 24,302 ha.m. is available for development. The annual net draft from the aquifer is estimated to be 993.93 ha.m. only and a balance potential of 23,308 ha.m. is available for future utilization, but unevenly distributed in the area.

A.	**Annual Recharge**	
	Area of the basin	35,100 hectares
	Average Annual rainfall	4.264m.
	Annual storm water in the area	1,50,000 hecta.meters
	Infiltration from rainfall (20% of rainfall)	0.79m/annum
	1. Recharge from Rainfall	27,729 h. m.
	2. Recharge from surface water Irrigation	
	Crop type	Paddy
	Area irrigated	4,308 hectares
	Average water depth	0.5m
	Irrigation water	2,154 ha.m.
	Seepage factor	40%
	Monsoon	-
	Non monsoon	861.6 hectametres
	Total annual recharge	28,590 hectametres
	Net annual recharge available for development = 85% of the total annual recharge	**24,302.01 ha.m.**
B.	**Annual Draft**	
	1. Groundwater draft due to irrigation	
	Total Number of energised wells	638
	Average Discharge of well in a year (assumed)	0.85 ha.m.
	Draft due to energised wells	542.3 ha.m.
	2. Groundwater draft due to population and livestock	
	Draft due to Population	869.24 ha.m.
	Consumption due to livestock (Cattle)	8.36 ha.m.
	Total draft due to population and livestock	877.6 ha.m.
	Gross annual draft	1,419.9 ha.m
	Net Annual draft (70% of gross annual draft)	**993.93 ha.m.**
C.	**Groundwater Balance** (Net annual recharge available for development – net annual draft)	**23,308.08 ha.m.**

Table 7.2 Broad assessment of groundwater resources in Mulki River basin

7.5 WATER MANAGEMENT STUDIES OF THE MULKI RIVER BASIN: The need for water resource development and management arises in an attempt to mitigate droughts, moderate floods and harvest the runoff water which otherwise goes as waste. The development of water resources mainly includes water conservation techniques. This involves increasing the recharge from precipitation with the creation of sub-surface and surface storages which are capable of impounding maximum monsoon rainfall. Storing of harvested runoff water can be accomplished with the help of various water conservation techniques and this conserved water can be recycled and used at critical stages of crop growth through open dug wells, bore wells, etc.

Water characteristics like *inflows* (precipitation, surface water inflow, and groundwater inflow), *water use* (evaporation, evapotranspiration, irrigation and drinking water) and *outflows* (surface storage, groundwater storage and root zone storage) are the principal factors to be taken care of in sustainable water management. Rainwater harvesting forms the major component of water management along with groundwater recharge, maintenance of water balance and economic use of water. Traditionally, people used many techniques to harvest the rainwater for future use and they played very important role in the rural water management of India from very ancient times. But in due course of time, these traditional structures and cultures were lost in modernity. Sustainable water resource development and management require the rehabilitation and development of these Traditional Rainwater Harvesting Structures (TRWHS) and microwatersheds.

7.5.1 Delineation of Microwatersheds and Tanks: The main land use/land cover in the area is rain fed agriculture, wasteland with/without scrubs in the plains and undulating land and scrub forests with forest blanks on the hills other than built-up area. Due to paucity of groundwater for irrigation, the rain fed agriculture lacks sufficient soil moisture to support good agriculture. The agriculture areas along the streams are constantly washed out and undergo sheet erosion, thus converting valuable agricultural land into unproductive wastelands. The degraded ecosystem has affected the life of the residents within the microwatersheds.

The rainwater which enters the ground is immediately discharged into the Sea because of porous laterite formations resting above the hard and impervious igneous or metamorphic rocks in this area (Suresh M. 1989). Even the groundwater is prone to adverse effect of salt water intrusion which affects the crop yield in the coastal areas. Since many of the TRWHS'/tanks' catchment areas belong to microwatersheds, the demarcation of the same is a must for the sustainable water resource development and management at rural level. Conventional methods of using the available SOI topographic maps and field survey may consume a lot of time and money without getting a synoptic view of the area and doubtful existence of these structures. An alternate method is to use satellite imageries of high resolution which is costly and require specialized skills and facilities.

Google Earth and Vikimapia, the free websites providing high resolution online imageries, have been utilized for the identification and delineation of tanks/TRWHS and microwatersheds at village level. The advantages of synoptic view, 3D view, and enhancement characteristics up to the required level due to its high spatial resolution make this data more relevant. User friendly, free downloadable, cloud free images, with three dimensional geographic specifications give more advantages over the IRS satellite imageries. By utilizing the option of dimensional measurements, the interested features are measured in required units. The land use/land cover has been determined using online Wikimapia. By using area measuring function, the approximate areas of cultivated agricultural land, land under forest and uncultivated land were found which are 27%, 36% and 37% respectively. Using the tone, colour, shape and associated features the TRWHS have been identified and delineated (Fig. 7.11) and later locations rectified and mapped with corrected longitude and latitude using Garmin GPS receiver of 8m. positional accuracy in the field (Fig. 7.12). The area has been divided into grid wise screenshot frames with uniform scale and downloaded to prepare the uncontrolled mosaic of the same using Photoshop software. This mosaic is printed in the flex sheet as a base map for synoptic visualization, delineation and easy handling in the field during ground truth verification which is found to be a cost effective method.

7.5.1.1 Traditional Rainwater Harvesting Structures (Tanks): In the study area 73 tanks or TRWHS (Table 7.3) covering about 13.5 hectares of the basin have been identified and located (Fig. 7.12). The number of tanks is found to be about one tank per 4.8 sq. Km. area on an average, but is found to be varying depending on the terrain, local needs and facilities. Assuming an average depth of about 1.6 meters for these tanks, it can store approximately 0.216 million cubic meters (MCM) of water during rainy season. Considering the runoff from this study area, it may be negligible but for the rain fed agriculture like paddy, etc., it is important during the monsoon season spread over one third of the year. So the local authority with community participation has to give more stress on rehabilitating these old structures with building up of new Rainwater harvesting structures which will improve the soil moisture and water table in this area.

Fig. 7.11 Aerial view of Keplaje Tank from Google earth picture and adjacent high elevation

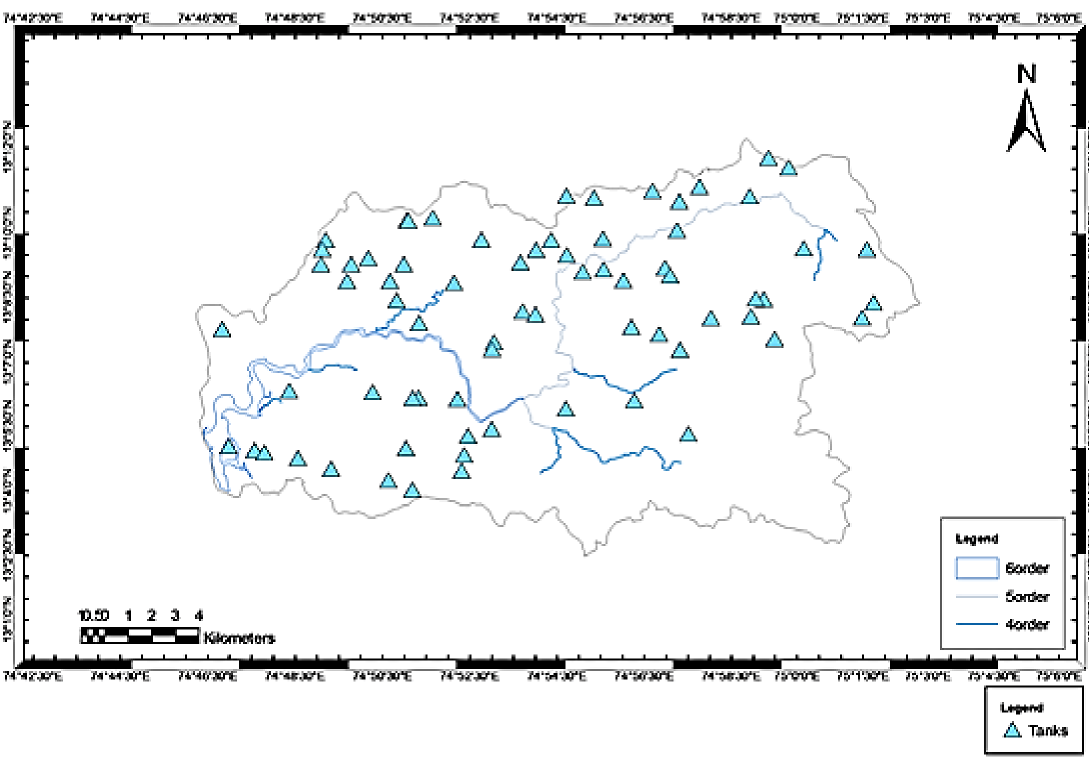

Fig. 7.12 Map showing locations of Tanks in Mulki River Basin

Agricultural operation has been found in clustered strips (about 27% of the basin area) irrigated by a good practice of rain fed TRWHS where people traditionally used their wisdom locating them ideally in the micro- and mini-watersheds. Rehabilitating old TRWH structures and increasing the population of Rainwater Harvesting Structures to at least one in every Sq. Km. area, more than 50 per cent of the runoff water can be utilized. The Google earth pictures can be effectively utilized for the cost effective planning and sustainable development of microwatersheds and rehabilitation studies of traditional rainwater harvesting structures.

Tank No.	Longitude	Latitude	Area (hectares)		Tank No.	Longitude	Latitude	Area (hectares)
1	74.98167	13.19778	0.403		38	75.02475	13.13394	1.692
2	74.98917	13.19611	3.770		39	74.78064	13.12952	0.104
3	75.01333	13.42667	0.086		40	74.8557	13.13188	0.010
4	74.99694	13.19222	0.400		41	74.93673	13.13033	0.101
5	74.96274	13.18472	0.121		42	74.88433	13.12445	0.049
6	74.91194	13.18128	0.019		43	74.88344	13.12173	0.021
7	74.9225	13.18056	0.010		44	74.95531	13.12142	0.126
8	74.94489	13.18322	0.046		45	74.99158	13.12578	0.228
9	74.98194	13.18111	0.194		46	74.80606	13.10556	0.018
10	74.86083	13.17278	0.694		47	74.83792	13.10513	0.235
11	74.85111	13.17183	0.055		48	74.85533	13.1029	0.063
12	74.85156	13.17173	0.046		49	74.85312	13.10273	0.088
13	74.95511	13.1791	0.174		50	74.87022	13.10243	0.120
14	74.95418	13.1679	0.010		51	74.93785	13.10191	0.020
15	74.82	13.1641	0.312		52	74.88333	13.0908	0.360
16	74.86898	13.1474	0.010		53	74.91167	13.09861	0.097
17	74.87951	13.16422	0.010		54	74.78307	13.08413	0.029
18	74.90609	13.16407	0.010		55	74.87444	13.08816	0.177
19	74.92583	13.16472	0.010		56	74.95848	13.08888	0.125
20	75.00258	13.1608	0.010		57	74.85075	13.08333	0.137
21	75.02649	13.16048	0.010		58	74.79305	13.08251	0.087
22	74.81825	13.15479	0.078		59	74.79675	13.08166	0.459
23	74.81858	13.16048	0.093		60	74.87284	13.08069	0.165
24	74.82982	13.15479	0.085		61	74.80944	13.07944	0.010
25	74.83628	13.15708	0.097		62	74.82205	13.07538	0.013
26	74.90039	13.1603	0.010		63	74.84391	13.07086	0.051
27	74.91206	13.15833	0.010		64	74.85306	13.06722	0.216
28	74.84978	13.15481	0.040		65	74.87194	13.07444	0.010
29	74.8944	13.15545	0.010		66	74.93378	13.14841	0.221
30	74.91822	13.15169	0.010		67	74.96724	13.1338	0.270
31	74.94953	13.15334	0.010		68	74.98728	13.14111	0.010
32	74.95142	13.15036	0.010		69	74.9825	13.13447	0.010
33	74.8282	13.14816	0.124		70	74.98422	13.14128	0.050
34	74.84448	13.14814	0.010		71	74.94736	13.1275	0.946
35	74.84708	13.14069	0.010		72	74.92611	13.15276	0.010
36	74.89522	13.13642	0.010		73	74.9002	13.13526	0.090
37	75.02911	13.13969	0.070					

Table 7.3 TRWHS/Tanks location and their dimensions

<u>7.5.1.2 Microwatersheds:</u> The watershed being the fundamental unit for the resource development due to its confinement within a geographical boundary with its drainage network is considered to be best for development and management. Microwatersheds are watersheds with moderate slope but bounded by water divides having an area of 10-20 Sq. Km. They are watersheds of first and second order streams in any area. The identification, delineation and development of such microwatersheds are important for the water conservation, development and management practices at village level planning. 56 microwatersheds covering 13% of the basin area varying from 8.16 hectares to 356 hectares (Table 7.4) have been identified and delineated in this study area (Fig. 7.13) demarcating their boundaries using Google Earth imageries, and were mapped overlaying IRS imageries and drainage networks over DEM with the help of virtual GIS of the basin prepared.

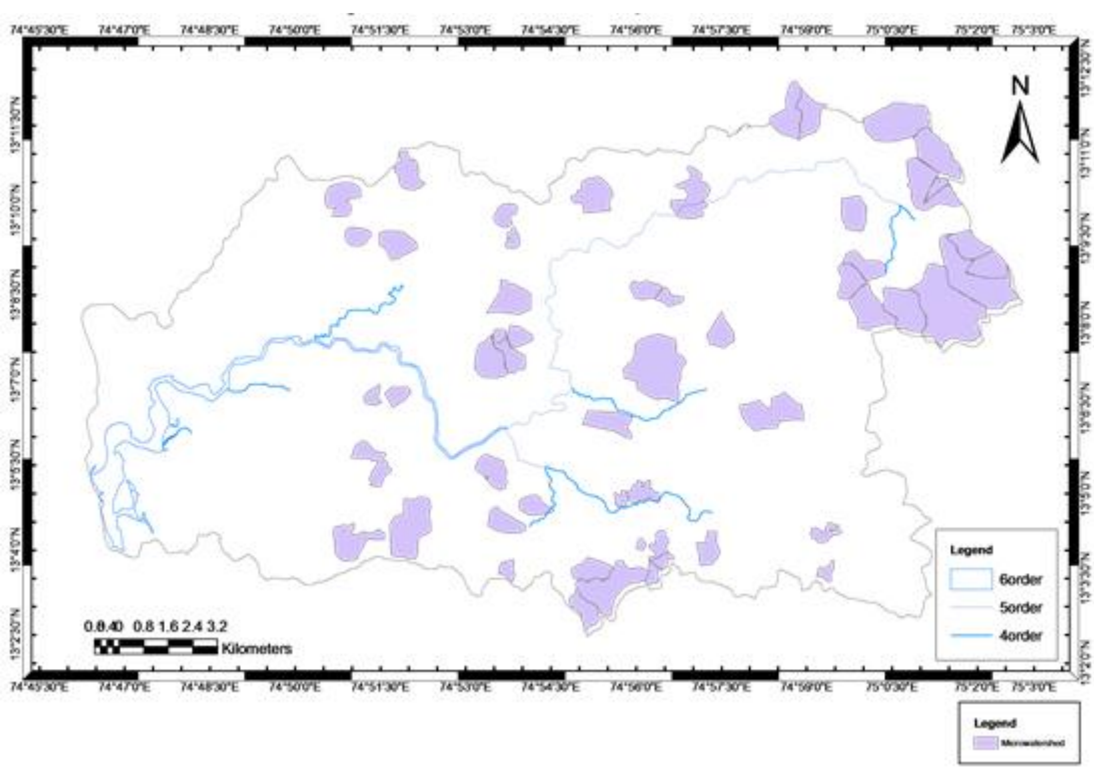

Fig. 7.13 Map showing microwatersheds in Mulki River Basin

No.	Perimeter (m)	Area (Hect-ares)		No.	Perimeter (m)	Area (Hect-ares)		No.	Perimeter (m)	Area (Hectares)
1	2113.4	23.85		20	3520.0	68.73		39	7284.1	148.84
2	3434.5	68.39		21	3775.6	66.99		40	2853.7	22.57
3	3675.8	61.00		22	4808.0	121.32		41	4297.8	105.43
4	6771.6	172.89		23	4923.9	141.62		42	2563.7	39.22
5	2307.2	22.33		24	9016.5	355.99		43	2182.1	21.66
6	3073.0	35.65		25	3580.6	82.08		44	2072.9	22.73
7	2056.3	19.53		26	3719.3	74.96		45	2309.8	34.79
8	1112.4	8.19		27	9428.2	235.94		46	4304.8	99.68
9	1931.7	16.79		28	5788.0	104.07		47	1412.2	14.30
10	3553.9	46.80		29	2861.8	40.07		48	2447.6	39.44
11	3224.3	54.64		30	5893.6	189.21		49	4212.7	56.30
12	2147.9	19.10		31	2602.6	34.64		50	3992.0	96.25
13	3511.3	33.21		32	4363.6	84.06		51	5049.1	103.78
14	6995.0	293.43		33	2824.4	46.97		52	4450.7	77.31
15	3179.1	59.42		34	3248.1	61.31		53	3430.7	76.51
16	2761.0	45.63		35	3817.4	74.47		54	3813.7	71.17
17	2378.4	28.49		36	5806.7	147.88		55	4195.1	85.56
18	5921.0	115.87		37	5518.1	195.81		56	2313.5	38.82
19	3364.0	76.92		38	5030.9	131.54				

Table 7.4 Microwatersheds and their areal extension in the Mulki River basin

7.5.2 Groundwater Management: Rainwater falling on every square kilometre of land area in a year, if properly utilized, will make significant changes in the water budget of a region and augment the water supply systems. Most of the village communities and city planners of the past had the vision to construct small and large tanks to collect and store rainwater but they now lie in a state of neglect. Giving life to these, apart from constructing new and cost effective rainwater harvesting structures can yield huge benefits. Public participation is as important as government initiatives in the implementation of this. Building codes need revision to make rainwater harvesting mandatory for all new constructions. Construction of various rainwater harvesting structures in public places and watershed management structures in waste lands could enthuse the public.

The efficient management of the water resources for sustainable development in the study area can be attained through the conjunctive use of surface water and groundwater for irrigation and drinking water purposes, considering the same as a single entity enclosed within a naturally bounded watershed area. For the practical implementation of the conclusions derived from the output of the research requires practicing of the methods suggested below.

Considering watershed as the basic unit for implementation of the water resource management, for the soil and water conservation to protect bi-geo resources of the area, the following soil and water conservation measures have to be practiced. First of all, the characterization of microwatersheds and prioritization of their development should be carried out. Since the implementation should be along the microwatershed development line, the various soil and water conservation practices mentioned below which were adopted elsewhere and found suitable and useful for the study area should be planned and site specific structures have to be constructed utilizing the locally available resources and keeping in mind economic considerations. In order to attain this, a comprehensive water resources action plan should be designed. This is a multi-action package which would arrest the flow of water on slope, hence prevent the transportation of silt / soil from higher level to that of lower level, thus helping in the soil and water conservation process. For the successful implementation, monitoring and existence of any such system require the support and participation of the people and it should be ensured before anything begins. People's participation and collective action are critical ingredients for watershed management. Sustainability, equity and participation are the three basic elements of participatory watershed management. So watershed management committees should be formed of the beneficiaries and other stakeholders for the implementation and monitoring of the programme. According to the availability of the financial support and locally available resources, the mini- and micro-watershed development scheme prioritized should be implemented through various tasks in planned steps.

The groundwater prospect map prepared from a very good database could be utilized for identifying favourable zones (prospective zones) around the problem villages, thereby narrowing down the target areas for putting up groundwater extraction structures in addition to identifying suitable zones / sites for planning recharge structures to improve the sustainability of drinking water sources. The subsurface storages have advantages of being free from the adverse effects like inundation of large surface area, loss of cultivable land, displacement of local population, substantial evaporation losses and sensitivity to earthquakes. No gigantic structures are needed to store water. The structures required for recharging groundwater reservoirs are of small dimensions and cost effective such as check dams, farm ponds, percolation tanks, surface spreading basins, pits, sub-surface dykes, etc., and these can be constructed with local knowhow. The underground storage of water would also have beneficial influence on the existing groundwater regime. The deeper water levels in many parts of the study area either of natural occurrence or due to excessive groundwater development, may be substantially raised, resulting in reduction on lifting costs and energy saving. The quality of natural groundwater would substantially improve in the coastal area. The conduit function of aquifers can further help in natural subsurface transfer of water to various need centers, thereby reducing the cost intensive surface water conveyance system. Next step is to work out design of suitable recharge structures, their numbers, type, storage capacity and efficiency considering the estimated storage space and available source water for recharge. Some of the water conservation structures and measures are described below.

7.5.2.1 Check Dams: These structures can be constructed on lower order streams (up to 3rd order) with medium slopes. The structures will reduce runoff velocity, hence minimizing erosion and improving groundwater recharging capacity.

Check dams are proposed where water table fluctuations are very high and the stream is influent or intermittently effluent. The catchment areas vary widely but an average area of about 25 ha should be there. The parameters needed to be considered for the construction of check dams are slope, soil cover and its thickness, and hydrological conditions such as rock type, thickness of weathered strata, fracture, depth to the bed rock, etc. There should be some irrigation wells in the downstream of the proposed structure. The structure will serve dual purpose. Firstly it reduces runoff velocity thereby minimizing erosion and secondly allows the retained water to percolate and thus results in increased recharge in the wells located downstream of the structure. The check dam sites could be selected commencing from upper reaches of the streams such that the base of the upper dam is at the crest of the next one and the height is about half the depth of the stream.

7.5.2.2 Groundwater Dam/ Shallow Sub-surface Dyke: It is a sub-surface barrier across stream, which retards the base flow and stores water upstream below ground surface. The water level in upstream part of groundwater dam rises saturating otherwise dry part of aquifer. The site where sub-surface dyke is proposed should have shallow impervious layer with wide valley and narrow outlet. After selection of site, a trench of 1-2 m wide is dug across the breadth of the stream down to impermeable bed. The trench may be filled with clay or brick / concrete wall up to 0.5m below the ground level.

7.5.2.3 'Nala' Bund: **'**Nala' bunds are structures constructed across 'nala' streams (4th order) for checking velocity of runoff, increasing water percolation and improving soil moisture status. These structures are constructed using locally available materials. The main objective of the construction of 'nala' bunds is to impound surface runoff, coming from the catchments to facilitate percolation of stored water into the soil substrate (subsurface) with a view to raise groundwater level in the zone of influence of the 'nala' bund. The feasibility of site for locating 'nala' bund depends upon technical and economic considerations. The site should be selected in relatively flatter 'nala' where the slope of the 'nala' should not be more than two percent as far as possible. The catchment area of the 'nala' bund should not be less than 40 ha, the 'nala' bund should have soils with adequate permeability and good fracture development to facilitate good groundwater recharge.

7.5.2.4 Minor Irrigation Tank: Minor irrigation tanks are structures constructed across nalas/streams for checking velocity of runoff, increasing water percolation and improving soil moisture regime. These tanks can be constructed to create reservoirs for providing irrigation through a canal system during the critical periods of crop growth.

7.5.2.5 Spring Water Harvesting System: Spring water being fresh and free from pollution is a highly desirable source of community water supply. Since the water emerges at the ground surface along the hill face due to the internal hydraulic pressure of the groundwater system, no pumping is required. A series of tanks could be constructed to store and distribute this water. At two places in the study area near

Belvai, spring water emerges which meets the drinking water quality standards. This could be harvested throughout the year.

7.5.2.6 Gully Plugging: These are the smallest soil and water conservation structures built across gullies in hilly areas carrying drainage of tiny catchments during rainy season. These are built with locally available materials like stone boulders, earth, weathered rock, brushwood, etc. Sand bags or brickworks may also be used to strengthen the bund. Gully plugs may be chosen wherever there is local break in slope to permit accumulation of adequate water behind the bund. The height of individual plug depending upon land slope can be of 2 to 3 m above 'nala' bed and progressively tapering off on side slope. A number of gully plugs may be provided on the same gully or 'nala', one below the other at every hundred meter separation or so depending on the conditions.

7.5.2.7 Gabion Structure: This kind of check dam is commonly constructed across small streams to conserve stream flow with practically no submergence beyond stream course. Small bund across the stream is made by putting locally available boulder in a steel of mesh wires and anchored to the stream banks. The height of such structures is around 0.5 m and is normally used in the stream with width of less than 10 m. The excess water overflows this structure storing some water to serve as source for recharge. Due to the accumulation of the silt content of stream water in due course of time, and with growth of vegetation along, the bund becomes quite impermeable and helps in retaining surface water runoff for sufficient time after rain to recharge the groundwater body.

7.5.2.8 Boulder Check: It is a temporary structure of 1.2 to 2.5 m deep and 6 m wide to stabilize the vegetative cover by holding some water and soil to facilitate the growth of vegetation. It is usually suggested for small and medium gullies where boulder / rubbles are available. A number of boulder / rubble checks along the lower order streams which are starting from higher elevation areas are suggested to arrest head ward erosion, soil loss and check the velocity of runoff of downstream.

7.5.2.9 Contour Bunding: These are small earthen bunds and structures built horizontally in parallel rows across the hill slope. These help in augmenting soil moisture and prevent erosion of topsoil. This technique is more suitable in low rainfall area where monsoon runoff can be impounded by constructing bunds on the sloping ground all along the contour of equal elevation. The flowing water is intercepted before it attains the erosive velocity by keeping suitable spacing between the bunds. The spacing between two contour bunds depends on the slope of the area and the permeability of the soil. Contour bunding is suitable on land with moderate slope without involving terracing and can be practiced in the study area with an upstream contour trench in order to avoid the soil erosion.

7.5.2.10 Contour Trenching**:** These are trenches made in parallel rows across the hill slope in order to divert the water in these drains. This will enable the water to stop running along the slope protecting the soil and will infiltrate the water augmenting the recharge. This method can be adopted along the hill sides since the study area covers laterite on the top which will infilter water to the aquifer below improving groundwater conditions.

7.5.2.11 Bench Terracing**:** Sloping land with surface gradient up to 8% having adequate soil cover can be leveled through bench terracing for bringing under cultivation. It helps in soil conservation and holding runoff water on terraced area for longer duration giving rise to increased infiltration recharge. The width of individual terrace should be fixed depending upon the slope of the land. The upland slope between two terraces should not be more than 1:10 and the terrace should be leveled.

7.5.2.12 Farm Ponds: The dugout farm ponds are also recommended to harness the excess runoff, and use the same water for irrigation. The farm pond locations are proposed in the natural depressions or in valley portions, to facilitate storage and irrigation by gravity. Many such farm ponds are there in the study area but require a revival through desiltation and maintenance for enhanced infiltration.

7.5.2.13 Drains: Drains will channelize the excess water flowing over the surface. Field drains remove excess water and salts from the field. Seepage drains intercept the surface and subsurface flow and prevent it from recycling the adjoining fields, and carrier drains link field drains to main or sub-drains.

7.5.2.14 Percolation Tanks and Pits: will help in percolation of the water stagnating it from free flow. These can be constructed in highly permeable soils like the laterite soil which is abundant in this area.

7.5.2.15 Surface Water Spreading Basins: The storm water flowing above the stream channels and along the slopes can be diverted and spread along the plain paddy fields etc., to allow more infiltration into the groundwater. These water also could be diverted to granite/laterite quarry for storing, distributing and recharging purposes. Abandoned quarries could be utilized as artificial lakes which may help the water storage and recharging.

7.5.2.16 Interbund Land Management: This land management practise can be adopted in the study area to reduce the surplus runoff to drain excess water from fields. Field bunds with boulders have also been recommended which help in reducing soil erosion along with water conservation within the field.

7.5.2.17 Traditional Rainwater Harvesting Structures: One of the traditionally adopted rainwater harvesting practice is through construction of tanks and collecting the runoff water for irrigation. In addition to the surface irrigation, part of the water stored in these tanks indirectly contributes to groundwater recharge. The area under tank irrigation has reduced over a period of time due to reduction in tank storage capacity because of silting. Revival of these tanks through desilting is a feasible solution to increase the storage capacity and groundwater recharge. There are many tanks which have been silted and abandoned through years. The revival of them will improve the water harvesting in the study area.

7.5.2.18 Desiltation of Tanks: The human activities coupled with rain and wind action cause movement of surface soil in the form of sediments and these sediments are ultimately collected in the tanks as silt. The deposition of silt over the years reduces the storage capacity of tanks and infiltration to the groundwater. In order to restore the original glory of these water bodies, desiltation must be practiced in these tanks. But community based efforts have to be made to take up massive desilting program in these tanks in a phased manner, which helps in conservation of excess rainwater and recharging shallow aquifers. The desilted material can be used in the brick kiln works, tile manufacturing, road building, land filling, etc., which provides work to the labourers during the off-season.

Other than the above cited engineering methods or structures, alternate land use practices and rational methods of agricultural practices such as contour farming, strip cropping, agro-forestry which involves introduction of woody plants (trees and shrubs) with agricultural crops on the same unit of land, afforestation, etc., along the slope can also be adopted in the study area.

7.6 CONCLUSIONS: The water management studies revealed that the study area is having surplus storm water and groundwater balance but is not used properly to tap the irrigation potential of the area. The open wells in the study area are deepened up to 18 meters in the lateritic terrain, whereas it is shallow in the valley portions or hard rock terrains. Depth to water level is comparatively lower near the river courses and alluvial plains, whereas it is very high in lateritic region. The water level in the study area is found to be fluctuating from a very shallow level of 4.2m to 16m. Annual average water table fluctuation is found to be about 6.85 meters in the Mulki River basin taking into consideration the average of three stations located at different lithology and three corners of the basin for a decade observation. During the year 2010, average annual water table decline was 6 meters and the average annual draft (loss) from the basin was around 2,106 $x10^6$cubic meters. The annual fluctuation varied from 1.34m to a maximum of 9.37m. The trend lines of water table fluctuation in granitic and alluvial terrain for a decade observation show almost a uniform nature whereas in lateritic plateau it is highly fluctuating with a decreasing trend over the years. The maximum water level rise was during July and the maximum water table depth was during April. This shows that the water level rise starts immediately after rainfall indicating high infiltration through the highly porous laterite resting above the shallow granitic bed rock in the study area. The monthly average water table of the observed wells in the study area shows a sharp declining trend during July to December, whereas during January to May (Pre- Monsoon) the trend is slow compared to other seasons. This indicates a trend of maximum groundwater flow during the rainy season where the evapotranspiration is minimum during these months. The aquifers are found to be thicker in the mid part of the area where the river flows. In hard rock terrain, the water table fluctuation is much less compared to the Lateritic terrain or alluvial terrain. The steep variation in water table depends on the topography and geology of the area besides the climate. Water table is found to be roughly following the topography of the area during non-rainy seasons. The heavy annual decline in water table is mainly along the river course and valley portion, and may be caused due to the groundwater flow and discharge to the streams. In a year, the aquifers in the area are recharged to an extent of 28,590 hectametres and net annual recharge of 24,302 ha.m. is available for development. The annual net draft from the aquifer is estimated to be 993.93 ha.m. only and a balance potential of 23,308 ha.m. is available for future utilization, but unevenly distributed in the area.

73 Traditional Rainwater Harvesting Structures (TRWHS) with a density of one in every 4.8 sq.km. covering about 13.5 hectares area of the basin have been identified and delineated, but are found to be defunct without proper maintenance. Cultivated agricultural area of about 27% in the basin has been found in clustered strips, irrigated by a good practice of ideally located rain fed TRWHS. The study also revealed that rehabilitating old TRWH structures and increasing the number of Rainwater Harvesting Structures to at least one in every Sq. Km. area, more than 50 per cent of the runoff water can be utilized. The sharp decline in water table is observed in the highly porous lateritic plateau region of the study area where the rainwater harvesting structures and watershed management practices have to be adopted. Even the small showers in pre-monsoon period show an increase of up to one metre (0.3 m to 1 m) in the water table depicting the infiltration capacity and recharge of the wells. By proper understanding of the geology and geomorphology of the area the groundwater development and management can be adopted. 56 microwatersheds covering 13% of the Mulki River basin have been identified, delineated and mapped. Development of microwatersheds and traditional rainwater harvesting structures can improve the water resource management of this area for drinking and irrigational purposes. There is an urgent need to rehabilitate the silted and abandoned tanks of this area which may improve the water table of this area enhancing agriculture and socio-economic conditions of the area. The efficient management of the water resources for sustainable development in the study area can be attained through the conjunctive use

of surface water and groundwater for irrigation and drinking water purposes, considering the same as a single entity bounded within a naturally bounded watershed area. Various site specific rainwater harvesting methods and watershed management practices could be adopted in the study area based on the needs and availability of the resources to effectively manage the water resources in this area for sustainable development.

Remote Sensing and GIS techniques are found to be efficient tools in identifying, delineating and mapping of microwatersheds and TRWHS for sustainable development and management of water resources. The Google earth imageries can be effectively utilized for the cost effective planning and development of microwatersheds and rehabilitation studies of traditional rainwater harvesting structures which is established through a study of the same in Mulki River basin for sustainable development.

Chapter 8

Remote Sensing and Geoinformatic Applications

CHAPTER 8

REMOTE SENSING AND GEOINFORMATIC APPLICATIONS

8.1 INTRODUCTION: Geoinformatics is the modern scientific term used to the integrated approach of collection, storage, measurement, integration, analysis, management and display of diversified earth based spatial data. This gives complete information of a region in a computer system encompassing a broad range of disciplines including Surveying, Mapping, Photogrammetry, Remote Sensing (RS), Geographic Information System [GIS] and the Global Positioning System [GPS]. Remote sensing is mainly concerned with obtaining information about an object, area or phenomenon through an analysis of the data acquired by a device which is not in contact with the object, area or phenomenon under investigation. Remote sensing is a powerful tool for mapping, inventorying, monitoring and managing of natural resources due to the inherent advantages of synoptic viewing, repetitive imaging and capability to study inaccessible areas in a real/near real time at a low cost. GIS is a decision supporting computer based data information system for collecting, storing, integrating, analyzing and presenting diversified geographically tagged spatial information of a region. GPS on the other hand allows us to locate our self on the georeferenced earth co-ordinates by means of earth's longitude-latitude system. Since geoinformatics can provide us with various thematic and integrated maps, it has already become a great tool for the better planning, development and management of our natural resources. It has applications in all disciplines including geology, engineering, environmental studies, resource management, etc., where a high quality spatial information system is required as an effective decision making tool. Thus Geoinformatics has become an important tool in man's quest for exploration, and an essential means for resource mapping, development and management.

8.2 GEOINFORMATICS IN GROUNDWATER EXPLORATION: The use of aerial photographs in groundwater investigations gained impetus in the 1950's. Howe (1958) mentioned the procedure of applying air photo-interpretation in the locations of groundwater. With the advent of American Landsat since July 1972, Satellite remote sensing has gained significance as a powerful aiding tool for regional mapping for groundwater and other natural resources. Earlier studies conducted using satellite data were more of a research nature, but now a stage has been reached where remote sensing has become operational. During the last three decades, satellite data have been extensively used by the geologists world over mainly for groundwater targeting along with other uses. Initially, the coarser spatial resolution data (about 80 m) from the previous satellites namely Landsat 1, 2 and 3 were mainly used for regional level studies and mapping. The subsequent satellites namely Landsat 4 and 5, SPOT, IRS-1A and 1B have provided medium resolution data (around 20-30m in multi-spectral and 10m in panchromatic mode). However, due to the coarser spatial resolution and the consequent limitation of the scale up to which it can be enlarged, the satellite data were not of much use in conducting detailed studies and mapping. Thus, by and large the entire geological community was looking for the satellite data with higher spatial resolution for large scale mapping and detailed studies.

Large number of studies has been carried out using remote sensing to assess the groundwater prospects in India. The major among them is the National Drinking water Mission. Under this hydrogeomorphological maps were prepared using satellite data on 1:250,000 scale for all 447 districts in the entire country and has been identified about 1.6 lakh drinking water problem villages (NRSA 1988, Reddy *et al.* 1996). By using Landsat MSS image, aerial photos and conventional methods 57 potential well sites have been located in Bundhelkhand region of U.P (Chathurvedi 1983). Basappa Reddy and Gaikwad (1985) used Landsat images to delineate groundwater potential zones in fractured crystalline rocks mainly composed of granite gneiss and schist in parts of Karnataka. Gupta and Ganesha Raj (1988) compared the information derived on groundwater prospect zones from 1:250,000 and 1:50,000 scales of Landsat Thematic Mapper data. Their study showed that the large scale data gives more details than small scale one. Reddy *et al.* (1996) used the IRS -1C data and found that the high-resolution PAN data are useful in identifying more precise location of faults, fractures and other prospective groundwater zones on the ground with reference to field boundaries. The high resolution data are useful in providing spatial information on the status of groundwater usage for irrigation. Further, the PAN data in synergism with the multispectral LISS-III data were found useful in groundwater resource estimation/budgeting, mapping of overexploited areas and identification of problem villages, etc., for systematic planning and development of groundwater to meet drinking and irrigational requirements in the rural areas. Krishnamurthy *et al.* (1992) assessed the potentials of various digital image processing techniques in groundwater prospecting. They studied the typical hard rock terrain in parts of Raichur district and found that certain techniques like Filtering and Principal Component Analysis are useful in delineating groundwater prospect zone. Krishnamurthy *et al.* (1996) assessed the groundwater potential of three areas in Karnataka having differing geological and geomorphological set up and evaluated the potential using the IRS LISS data. Gupta and Ganesha Raj (1992) showed the importance of integrating well data with the satellite imageries in a study carried out in Pavagada Taluk mapping different geomorphic units using the Landsat TM data. Their study clearly brought out the importance of available bore well data to narrow down the prospective zone using remote sensing. Ganesha Raj (1990) assessed the groundwater prospects of typical lateritic terrain of Kasaragod District, Kerala through hydrogeomorphological mapping using IRS- 1A LISS-II False Colour Composite. Favourable sites for artificial recharge of groundwater were identified using IRS LISS-II data in Nagpur district by integrating information on structures, lithology and other relevant parameters (Jeyaram *et al*. 1992). Different thematic layers such as lithology, lineaments, landforms, slope, drainage density and soils were integrated using weighted aggregation method in GIS environment to demarcate groundwater potential zones (Krishnamurthy *et al.* 1996).

The prospect of groundwater resource, which is vital in the socio-economic development of an area, is ultimately governed by geology and geomorphology (landforms) of that region. Thus, for any type of economic development and planning, geological and geomorphological maps with their hydrological characteristics form the basic inputs. From the interpretation of satellite imagery in conjunction with sufficient ground truth information, it is possible to prepare hydrogeomorphological maps which will give significant information on the geology, geomorphology, drainage pattern, soil, land use/land cover, structural pattern and recharge conditions which ultimately define the groundwater regime. With the advent of high resolution satellite imageries, by virtue of its improved sensor capabilities, higher spatial resolution (IRS-P6 with MSS 5.8m; IKONOS-1m & 4m, Orb view and Geoeye with 0.5m) and availability of stereoscopic data, now it is possible to collect detailed information about various parameters which control the occurrence and movement of groundwater. GIS and remote sensing applications have been used by numerous workers in delineation of groundwater potential zones (Venkatachalam *et al.* 1991, Ghose 1993, Krishnamurthy *et al.* 1996, Pradeep 1998, Saraf and Choudhary 1998, Sankar 2002, Khan and Moharana 2002, Javed and Wani 2009, Sreedevi *et al*. 2009). This chapter deals with the application of geoinformatics in the extraction and analysis of various data obtained through different processes of studies and sources.

8.3 METHODOLOGY: The following satellite imageries of the study area (IRS_P6_L4_MX_05012006 (path: 11524, row: 63 & 64), IRS_P6_L3_05012005 (path: 97 & 98, row: 63 & 64), IRS_1C_L3_09122001 (path & row: 98, 64), IRS_1C_L3_28122001 (path & row: 97, 74)) procured from Government of India's National Remote Sensing Centre (NRSC), Hyderabad have been utilised for the various analysis in addition to the true colour high resolution images of Google earth and Survey of India (SOI) topographic maps (Toposheets). Firstly, the digital format of the study area's base map has been prepared mosaicing the scanned images of SOI topographical maps. Then the satellite imageries having spatial resolution of 23.5m obtained from LISS-III (Linear Image Sensing Scanner-III) and of 5.8m obtained from LISS-IV (MX mode) sensors of RESOURCESAT or Indian Remote Sensing Satellite (IRS-P6) have been rectified in such a manner that the spatial co-ordinates correspond to its geographic co-ordinates. Then these images were resampled using nearest neighbourhood method and further utilized for various analysis and interpretation (Fig. 8.1). Google earth images, which are having a very high resolution of about 1m resolution in true colour have been utilised mainly for the reconnaissance survey, Land Use/Land Cover Map preparation, location of micro watersheds and tanks in the study area. The satellite imageries were pre-processed and enhanced for visual and digital image analysis using different functions available in Earth Resource Data Analysis System (ERDAS) Imagine 9.1 version software.

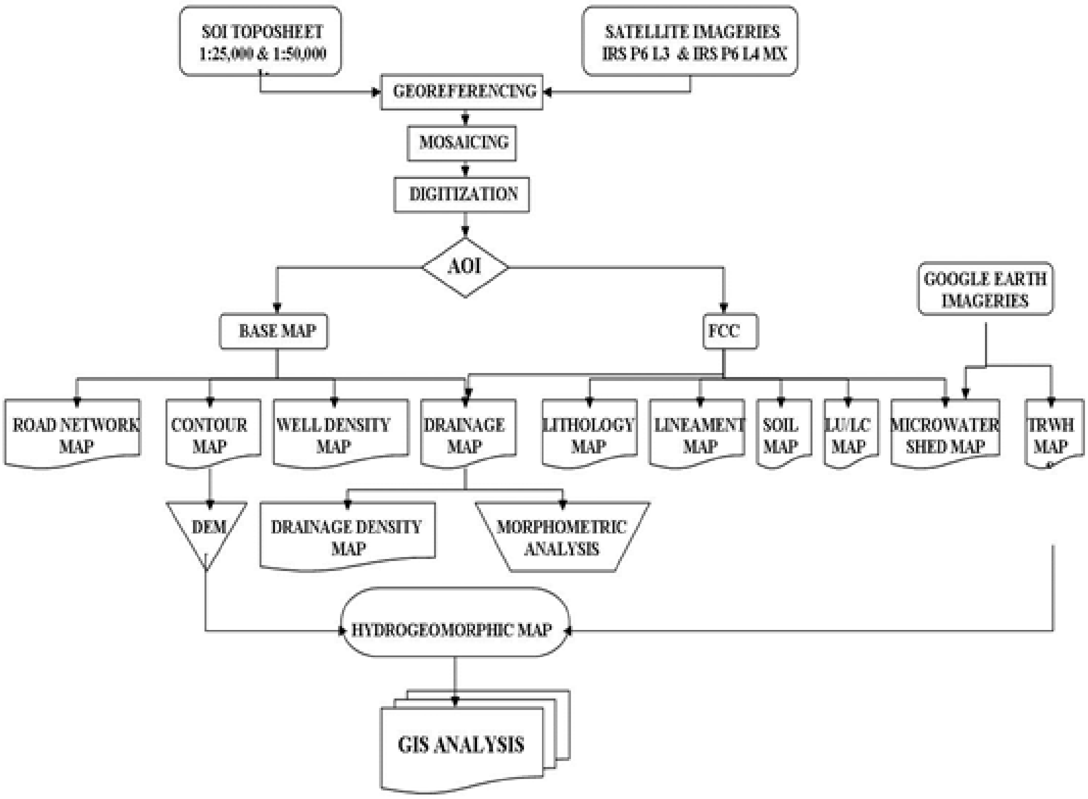

Fig. 8.1 Flow chart of the Geoinformatic Application Methodology used in the present study

8.3.1 Digital Image Processing (DIP): DIP is the manipulation of digital images through computer aided application of algorithms on digital images and extracting information for analysis and interpretation. Since remotely sensed data are usually of digital images, data processing is usually considered as digital image processing using computers. The raw data received, from the imaging sensors on the satellite platforms contains flaws and deficiencies, which can be overcome by undergoing several steps of processing in order to obtain the originality of the data and extract the required information from the image. This varies from image to image depending on the type of image format, initial condition of the image, the information of interest, and the composition of the image scene. The information of different earth features are usually stored as brightness values (BV) according to their spectral signatures or reflectance properties. This information is stored in pixels (picture elements) as specific Digital Numbers (DN), which may vary from zero to a higher value depending on the radiometric resolution. Usually an eight bit data which is in common use will have 256 DN value variations in an eight bit data of radiometric resolution. There are a number of procedures/methods available for image data manipulation (Lillesand and Kiefer 2000, Schowengerdt 1997) which can be broadly grouped into three categories, viz: i) Pre-processing or Image rectification and restoration, (ii) Image enhancement, and (iii) Image classification. ERDAS Imagine 9.1 version software has been used for the processing and analysis in the present studies.

8.3.1.1 Pre-Processing or Image Rectification and Restoration: These operations are intended to eliminate noise in the data, and correct the errors caused due to geometric distortions and radiometric errors. The standard products availed (IRS_P6_L3_05012005 and IRS_P6_L4_MX_05012006) from the NRSC were of pre-processed data free from the common distortions and errors. Therefore, the data has been directly used for image enhancement and classification after georeferencing the same. The georeferencing of the scenes have been carried out with reference to the ground control points (GCP) elicited from the SOI toposheets (48K/16NE, 48K/16NW, 48K/16SW & 48K/16SE and 48 O/4) using rubber sheeting methods, and prepared the mosaic of the area using weighted cutline method. The projection applied in this georeferencing was of Geographic Latitude/Longitude with spheroid Everest 1956 and datum Indian (India, Nepal). The registration was carried out by assigning permanent, sharp, corresponding and well spread adequate number of ground control points (GCP) on the digital image. Accuracy of the geometrically corrected image was checked by overlaying the rectified topographical map on the digital data, and swiped vertically and horizonally to check any shift in the corresponding permanent features. These have been converted and resampled into a Universal Transverse Mercator (UTM) projection with WGS 84 and zone 43 north for easy carrying and analysis in different platforms.

8.3.1.2 Image Enhancement: These operations of various image processing techniques like contrast stretching, edge enhancement, principal component analysis (PCA), resolution merge, unsupervised and supervised classification were carried out to extract the maximum information of the study area. The enhancement techniques increased the visual distinction between features contained in the scene and were stored as enhanced files in the computer for further analysis. False Colour Composite (FCC) of the study area has been prepared after image rectification, geometric correction, georeferencing, digitizing and editing in different scale. Then the Area of Interest (AOI) has been extracted by subsecting the Mulki river basin outline shape file above it. Various thematic maps have been prepared using digital and visual image interpretation techniques (Fig. 8.1). Integrated with other collateral data, the area has been analysed through manual and computerised methods in a GIS framework using ArcGIS 9.x and 10 versions. The Digital Elevation Model (DEM) of the Mulki river basin has been prepared using ERDAS imagine 9.1 version and found to be a good tool in extrapolating the micro watersheds, slope detection, runoff characteristics and other hydrogeomorphological characteristics of the basin.

8.3.1.2.1 Contrast Stretching: Contrast generally refers to the difference in luminance or grey level values in an image which is an important characteristic feature. It can be defined as the ratio of the maximum intensity to the minimum intensity over an image (Navalagunda 2002). Contrast enhancement techniques expand the range of brightness values in an image so that the image can be efficiently displayed in a manner desired by the analyst. The density values in a scene are literally pulled further apart, that is expanded over a greater range. The effect is enhanced visual contrast between two areas of different uniform densities. This enabled to discriminate easily between areas initially having a small difference in density. Contrast enhancement can be carried out by a linear or non-linear transformation. Linear contrast enhancement, often referred to as linear contrast stretch, is the simplest contrast stretch algorithm in which it expands the original input brightness values to make use of the total dynamic range or sensitivity of the output device. This has been performed after looking at the image histogram and deciding the minimum and maximum brightness values assigning extremely black and extremely white respectively. The remaining pixel values are distributed linearly between these extremes. When an area having different terrain classes is linearly stretched, it will enhance some features and saturate or degrade some others (Muralikrishna 1992). Contrast stretched IRS data products have been used for preparing geological map, landform map, drainage map and land use/land cover map. Various digital enhancement techniques such as linear stretching, Intensity-Hue-Saturation (HIS) and FCCs using ERDAS Imagine image processing software have been found useful in extracting the geomorphic features.

8.3.1.2.2 Filtering Techniques: Spatial filtering is a context dependent operation, which alters the grey level of a pixel according to its relationship with grey levels of other pixels in the immediate vicinity. Typical high pass filters, which produce sharp images with linear features and edges highlighted, are essentially based on convolution (Laplacian filters) techniques. Image enhancements that de-emphasize or block the high spatial frequency details are low frequency or low-pass filters. The directional filters enhance the features in a particular direction and are useful in detecting lineaments, which are oriented in that direction. Lineament/structural map was prepared by adopting the above filtering techniques and further refined using visual interpretation.

8.3.1.2.3 Edge Enhancement: For many remote sensing earth science applications, the most valuable information that may be derived from an image is contained in the edges surrounding various objects of interest. Edge enhancement delineates these edges and makes the shapes and details comprising the image more conspicuous and perhaps easier to analyse. Edges can be enhanced using either linear or non-linear edge enhancement techniques. Laplacian (LAP) convolution is a linear combination of pixels used to highlight points, lines, and edges in the image and thus suppresses uniform and smoothly varying regions. Edge enhanced image was used to refine the lineament /structural map.

8.2.1.2.4 Band Ratioing: Sometimes, differences in brightness values from identical surface materials are caused by topographic slope and aspects, shadows or seasonal changes in sunlight, illumination angle and intensity. These conditions may hamper the ability of an interpreter or classification algorithm to identify correctly surface materials or land use in a remotely sensed image. Ratio transformation of the remotely sensed data can, in certain instances, be applied to reduce the effects of such environmental conditions and it may also provide unique information not available in any single band that is useful for discriminating between soils and vegetation. Band ratioed images can be meaningfully interpreted because they can be directly related to the spectral properties of the materials (Mishra H.C. 1998). The potential advantage of band ratioing is that greater contrast between or within classes might be obtained for certain patterns of spectral signatures. Ratioed images of the study area helped little due to thick vegetation cover in preparing geological map.

8.2.1.2.5 Principal Component Analysis (PCA)**:** This is a pre-processing transformation that creates new images from the uncorrelated values of different images. This is accomplished by a linear transformation of variables that corresponds to a rotation and translation of the original co-ordinate system. Principal component analysis operates on all bands together. Thus it alleviates the difficulty of selecting appropriate bands associated with the band ratioing operation. Principal component analysis describes the data more efficiently than the original band reflectance values (Laurini *et al.* 1992). Principal component images may be analyzed as separate black and white images, or as a colour composite. Principal component techniques are particularly appropriate in areas where little prior information concerning the region is available. This has been used for spatial merging or data fusion of the images in the study area.

8.2.1.2.6 Intensity-Hue-Saturation (IHS) Techniques: The red, green and blue input is manipulated by a three dimensional transformation to obtain the "Intensity" – the total brightness of colour, "Hue" – the dominant or average wave length of the light contributing to a colour and "Saturation" - the degree of purity of colors relative to grey. This enhancement is particularly useful in deriving better perceptible and interpretable images. Transformation of Red, Green, Blue (RGB) components into IHS components provide more control over colour enhancements and can also be used as a technique of data fusion. Data generated by IHS helped in the preparation of maps such as geology, structure, landform, land use/land cover, etc.

8.3.2 Visual Image Processing (VIP): Visual Image processing makes use of the excellent ability of the human mind to qualitatively evaluate spatial patterns in an image. Since human brains can deduce and correlate elements in a better way than computer, the extraction of desired information could be achieved in an efficient and effective way by using several basic interpretation keys or elements (Sabins 1997).

Using the basic interpretation keys such as (i) colour/tone (ii) texture (iii) pattern (iv) shape (v) size (vi) location and (vii) association along with the drainage and topography various thematic maps such as land use/Land cover (LU/LC) map, hydrogeomorphological map, etc., have been prepared for various types of analysis and have been utilized in different chapters. All these interpretation elements are qualitative attributes and they are subjective depending on the experience and personal bias of an interpreter. Among the above elements tone and texture are the functions of brightness, contrast and resolution of the image while size, shape and pattern are dependent on the scale of an image.

8.3.3 Geographic Information System (GIS): Advances in the field of data interpretation and analysis have necessitated the use of powerful tools within the computer environment. The set of tools applicable to the geographical data constitutes the Geographic Information System (GIS). GIS is computer system using software and hardware tools applied to geographical data for integration of capturing, storing, querying, retrieving, analysing, transforming and displaying spatial data for solving complex planning and management problems. GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps (David J.M. *et al.* 1991). These abilities distinguish GIS from other information systems and make it valuable in different fields for explaining events, predicting outcomes and planning strategies. GIS-generated map has many layers of information for many ways of thinking about a geographic space. Map making and geographic analysis are not new, but the GIS perform these tasks in a better and faster way. This tool (software and hardware) has made the data handling and analysis much easier with meaningful research outcomes. GIS has the advantage of handling attribute data in conjunction with spatial features, which was totally impossible with manual cartographic analysis. It stores both spatial and non-spatial data layer by layer either in raster or vector format. This tool makes the data handling job easier and meaningful. It is more versatile for analysing a large data base and large areal extent. GIS facilitates repetitive model application with considerable ease and accuracy. Integration of various parameters, which control the occurrence, and movements of groundwater such as lithology, structures, landforms etc., in GIS environment has been highly useful in identifying prospective zones; and integration of geophysical and geological data helps in furthering down the target areas for exploration/recharge.

Areas of GIS application can range from natural resources management to crime control and near real-time applications like flood warning and war operations. GIS can build three dimensional models, where the topography of a geographical location can be represented with an x, y, z data model known as Digital Terrain (or Elevation) Model (DTM/DEM). The x and y dimensions of a DTM represent the horizontal plane, and z represents spot heights for the respective x, y coordinates. The data are represented by a DEM array (grid cells) or a Triangulated Irregular Network (TIN). The data sets derived from a Digital Terrain Model can be used to analyze environmental phenomena or engineering projects that are influenced by elevation, aspect or slope (Demers M.N. 1999).

In the present study, various thematic maps prepared using conventional and remote sensing data were transferred in to a GIS environment. The GIS application has been used in the analysis of hydrogeomorphology, hydrogeochemistry, hydrogeophysics, geohydrology and hydrometeorological analysis in the present study and has been detailed in each chapter.

8.3.4 Global Positioning System (GPS): Global Positioning system has revolutionized positioning concepts; though it started primarily as a navigation system, it has wide range of geodetic, geophysical, navigational, marine, military and social applications. The NAVASTAR GPS (Navigation Satellite Timing and Ranging Global Positioning System) is a satellite-based radio navigation system providing precise three-dimensional position, navigation and time information to suitably equip users everywhere on a continuous basis (Goodchild 1992). GPS receivers observe signals transmitted by satellites and achieve sub-meter accuracy in point positioning. It has many advantages over the conventional methods in locating positions since it doesn’t require intervisibility between points and is based on satellite visibility. Garmin made hand held GPS receiver with 8 meters positional accuracy has been used in locating water sampling stations, well inventories, VES stations, tank locations, locating the land use/Land cover features during ground truth verification process, etc.

8.3.5 Application Software: Various application software have been utilised in the present study for analysing the satellite imageries and integrating the thematic maps and collateral data.

8.3.5.1 Image Processing and GIS: ERDAS IMAGINE 9.x and ArcGIS 9x. and 10 softwares have been used for processing, analysing, and mapping the spatial and attribute data of the studies conducted in the basin.

8.3.5.1.1 ERDAS IMAGINE: Version 9.1 and 9.3 is used in the present study at different stages. It is a raster graphics editor and remote sensing application software designed by ERDAS Inc. for image processing. It is aimed primarily at geospatial raster data processing and allows the user to prepare, display and enhance digital images for use in GIS or in CADD software. It is a toolbox allowing the user to perform numerous operations on an image and generate an answer to specific geographical questions.

8.3.5.1.2 ArcGIS: Version 9.1 and version 10 is utilized at different stages of the analysis. It is a suite consisting of a group of geographic information system (GIS) software products produced by ESRI. It is full-featured GIS software for visualizing, managing, creating, and analyzing geographic data. At the desktop GIS level, ArcGIS includes ArcReader, which allows one to view and query maps created with the other ArcGIS products; ArcMap, which allows one to view spatial data, create layered maps, and perform basic spatial analysis. ArcEditor, which, in addition to the functionality of ArcView, includes more advanced tools for manipulation of shape files and geodatabases or ArcInfo which includes capabilities for data manipulation, editing, and analysis. ArcMap is the main component of ESRI's ArcGIS suite of geospatial processing programs, and it is used primarily to view, edit, create, and analyse geospatial data. ArcMap allows the user to explore data within a data set, symbolize features accordingly, and create maps. In addition, it is possible to create and manipulate data sets to include a variety of information.

8.4 REMOTE SENSING APPLICATIONS IN GROUNDWATER INVENTORY: The main trends of satellite remote sensing for groundwater targeting are: a) Drainage network analysis for hydrologic clue b) Mapping landforms, land use and changes there in, soils related to hydrologic conditions, etc., c) Geologic mapping vis-à-vis groundwater controls such as Lineament mapping for "open" fracture traces d) Mapping vegetation and drainage anomalies as indicators for groundwater and e) Integrated hydrogeomorphological mapping. Information on lineaments/structures (faults/fractures/joints etc.), lithology, landforms, land use/land cover, slopes, terrain, soils, settlements, etc., can be derived using satellite data in conjunction with collateral data and field observations. This information can be integrated to assess the suitability of the sites identified for setting up groundwater abstraction structures. For this various thematic maps have been prepared.

8.4.1 Thematic Maps: Thematic maps have been prepared on five important keys viz: Topography, Drainage, Geology, Land Use/ Land Cover and Tone to identify landforms to locate the zones of groundwater potential area by various methods.

<u>8.4.1.1 Base Map:</u> The base map of the study area has been prepared from Survey Of India Toposheets 48K/16NE, 48K/16NW, 48K/16SW & 48K/16SE (1:25,000 scale) & 48 O/4 (1:50,000 scale). The map has been digitized to prepare the base map (Fig. 1.4) and contour map (Fig. 8.2) of the study area.

<u>8.4.1.2 False Colour Composite (FCC):</u> False Colour Composite of the study area (Fig. 8.3) has been prepared after image rectification, georeferencing, geometric correction, digitizing and editing in different scales. This mapping procedure removes geometric distortions of the image and changes the co-ordinate system of the image to spatial database co-ordinate system. Maximum possible Ground Control Points [GCPs] are selected, uniformly over the total area for better interpolation. Then image processing and generation of classified information from False Colour Composite (FCC) have been carried out. Digital enhancement techniques have been used as they help to improve the feature sharpness and contrast for simple interpretation along with visual interpretation techniques.

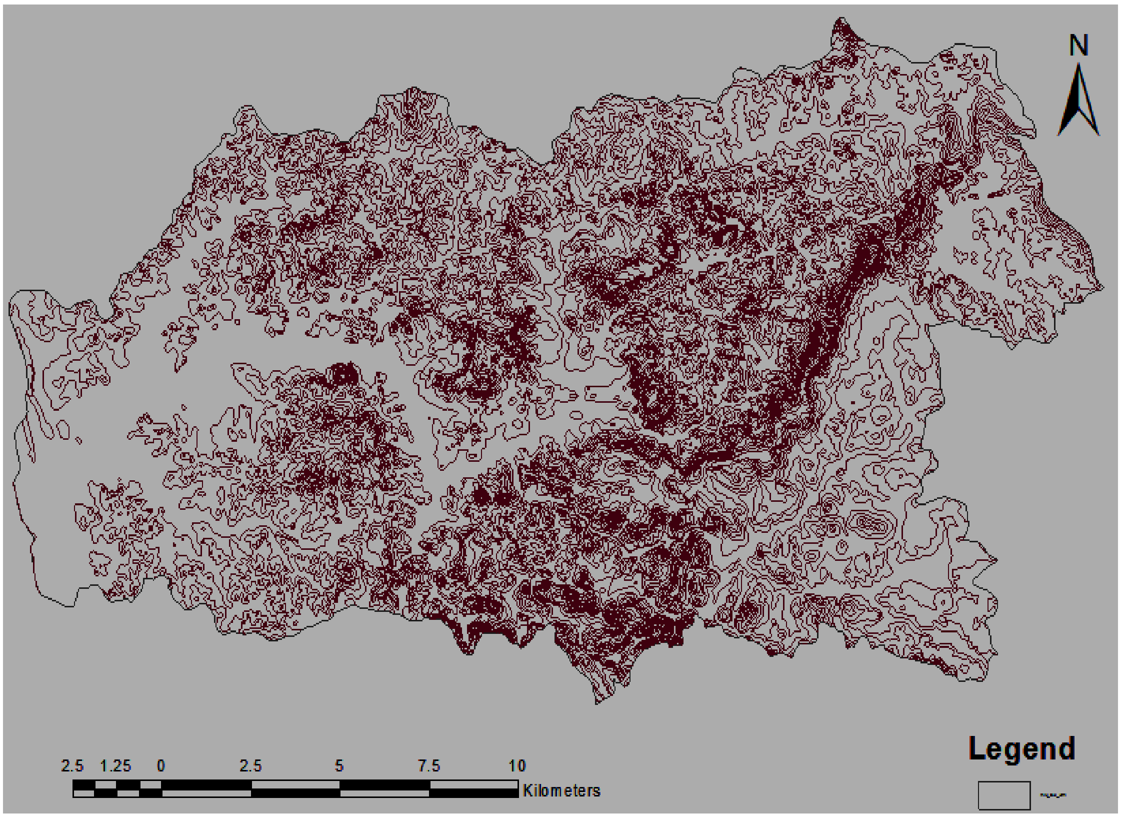

Fig. 8.2 Contour Map of the Mulki River basin

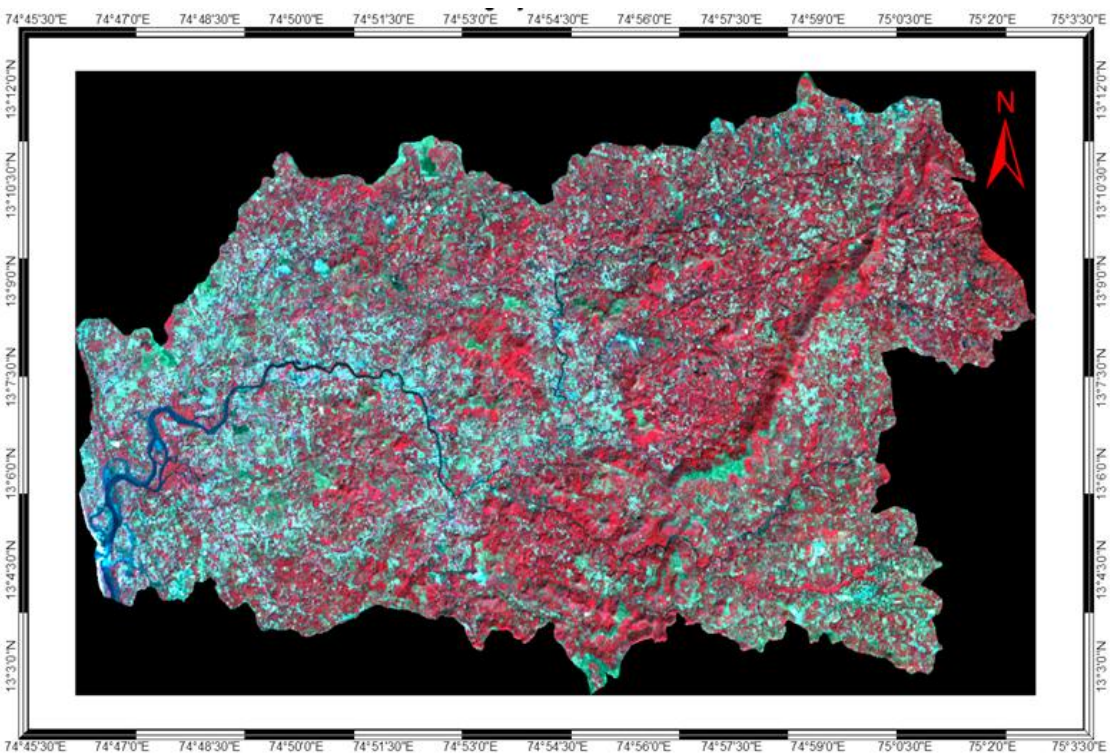

Fig. 8.3 False Colour Composite of the Mulki River Basin (IRS-P6 LISS III)

(13-01-2005)

8.4.1.3 Drainage Map: The drainage map (Fig. 2.1) has been generated from the SOI topographical maps. The drainage network has been updated using the satellite imagery of IRS-P6 LISS 4 MX data. Morphometric analysis has been carried out and the various morphometric variables such as drainage density and frequency were determined by conventional methods and the maps were prepared (Fig. 2.20 & Fig. 2.24). The important drainage patterns were delineated based on the drainage map of the area which has been used for further interpretation in terms of structure, geomorphology, and land use patterns.

8.4.1.4 Geomorphologic Map: Geomorphological Map of the area (Fig. 2.3) depicting various major geomorphological features or land forms have been generated using the satellite data by visual interpretation and digital analysis in conjunction with other collateral data and ground truth data. The criteria adopted for the identification and grouping of landforms of specific genetic types are the overall appearance (morphography), the shape/surface geometry (morphometry), the underlying geology, relief forming processes, and association of forms as described by Chorley (1957), Dikshit (1983) and Shibani Maitra (2001).

8.4.1.5 Slope and Aspect Maps: Slope and Aspect Maps (Fig. 2.27 & Fig. 2.28) which will be helpful in understanding the occurrence and movement of surface and groundwater have been prepared from the contour maps that had been generated from the topographical map of 1:25,000 scale.

8.4.1.6 Geological Map: Geological Map (Fig. 3.5) of the Mulki river basin has been updated using the IRS satellite data by visual and digital image interpretation techniques in conjunction with the existing geological maps and topographical maps followed by limited field checks. Major lineaments and their orientations are represented in the geological map.

8.4.1.7 Lineament Map: Lineament Map (Fig. 3.23) of the study area has been prepared and the isolation of lineaments from man-made structures (Fig. 3.21) and its prominence (Fig. 3.22) using band 3 and band 4 has been illustrated. Lineaments, being surface manifestations of structurally controlled linear or curvilinear features, are identified on the satellite imagery by their relatively straight tonal alignments. A lineament is defined as large-scale linear feature, which expresses itself in terms of topography of the underlying structural features. The term lineament and its derivatives have been used in a variety of ways (O'Leary *et al.* 1976, Hobbs 1904, Gold 1980). Lineaments can be joints, fractures, dyke systems, straight course of streams and vegetation patterns. They are variously named as 'fracture zones', 'shear zones', 'trend lines' and 'tectonic trends' (Auden 1954, Eremenko 1964, Sastri and Raiverman 1968).

In hard rock terrains, lineaments represent zones of faulting and fracturing resulting in increased secondary porosity and permeability. In hard rock areas, the movement and occurrence of groundwater depends mainly on the secondary porosity and permeability resulting from folding, faulting, fracturing, etc., (Radhakrishna 1968) and points of intersections of lineaments serve as potential zones for yielding wells. They are good indicators for groundwater accumulation and provide the pathways for groundwater movement and are geohydrologically very important. There are many lineaments which intersect each other in the study area and help in improving the groundwater condition of the study area. Photo-lineaments generally represent the surface traces of fractures in bedrock, projected more or less vertically upwards to the erosion surface by various mechanisms. Lineament mapping using IRS-P6 FCC of the study area was based on tonal, textural, topographic and curvilinearities and rectilinearities. Lineament density of an area can indirectly reveal the groundwater potential, since the presence of lineaments usually denotes a permeable zone. Areas with high lineament density are good for groundwater development (Haridas *et al.* 1998). High values of lineament density are recorded in the study area having moderate groundwater prospects.

Srinivasan and Sreenivas (1977) identified the presence of ENE-WSW, NE-SW, NW-SE, NNW-SSE, N-S and E-W trending lineaments in the Indian subcontinent. They also analysed the lineaments over the entire Karnataka State (Sreenivasan and Sreenivas 1977, DOS 1990). Some of the major lineaments of Karnataka represent faults, and there is a good correlation between some lineaments and the deep faults (Kaila *et al.* 1979). The lengths of lineaments vary from a few kilometres to hundreds of kilometres. Kowalic and Gold (1976) suggested a length wise classification of lineaments/linear features. The classification is as follows:

i) Short/Minor lineaments (1.6 km to 10 km.)

ii) Intermediate lineaments (10 km to 100 km)

iii) Long/Major lineaments (100 km to 500 km)

iv) Mega lineaments (>500 km)

Ganesha Raj (1994) identified 69 major lineaments (length >100 kms) in Karnataka State and correlated the major lineaments map of Karnataka with geological map of Karnataka. The groundwater potential of the minor lineaments has been exploited extensively. A good number of intermediate lineaments (length 10-100km) are present in the rocks of Karnataka.

Lineament mapping was done on the basis of changes in topographic slopes, relief patterns, crest type, drainage type and image characteristics. The single most dominant factor for picking up lineaments on the satellite data is the linearity of tone/texture. Presence of natural vegetation along the lineaments was one of the key recognition elements on the satellite data. The Mulki river basin has a number of minor lineaments and about 10 intermediate lineaments in the study area. At least two major lineaments are passing through the basin extending up to Western Ghats (Fig. 3.23) and another two major lineaments across the basin parallel to the coast. Most of these lineaments control the drainage pattern of this area (Fig. 3.21). Due to their intersection they can be considered as good source depending upon the depth and connection.

8.4.1.8 Soil Map: Soil Map of the area (Fig. 3.28) has been prepared using ArcMap features.

8.4.1.9 Digital Elevation Model (DEM): The term digital elevation model or DEM is frequently used to refer to any digital representation of a topographic surface, however, most often it is used to refer specifically to a raster or regular grid of spot heights depicting a three dimensional topographical view of the study area. In DEMs, a raster file containing elevations at regularly-spaced surface co-ordinates over an area is interpreted using specialized computer software which creates a three-dimensional rendering of the surface. The DEM is the simplest and most common form of digital representation of topography.

The DEM of the Mulki river basin has been prepared from the SOI Toposheets of 1:25,000 scale with a contour interval of 10 m. This vector contour map has been rasterised using ERDAS imagine 9.1 version and the DEM of the area has been prepared (Fig. 8.4). This has been found to be a good tool in extrapolating the sub-basins (Fig. 2.2), micro-watersheds, slope detection, runoff characteristics and other hydrogeomorphological characteristics of the basin.

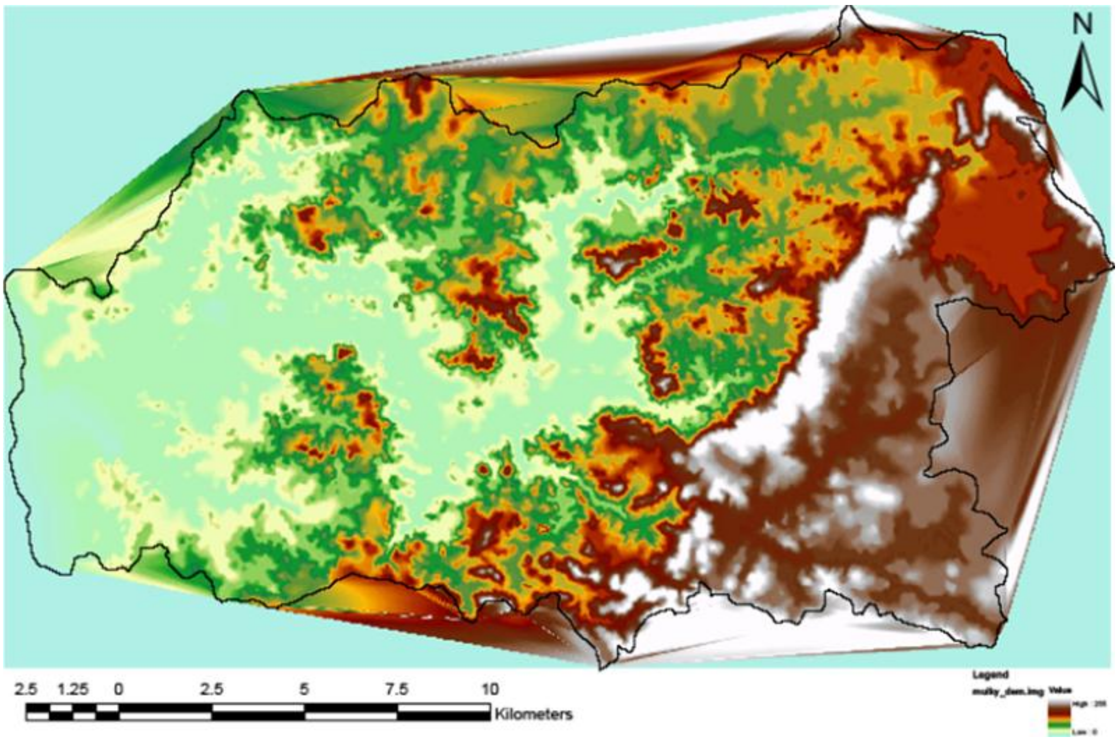

Fig. 8.4 DEM of the Mulki River Basin

8.4.2 Land Use/Land Cover (LU/LC) Analysis: Remote sensing makes significant contribution in the areas of land use/land cover data collection. Knowledge of both land use and land cover is important for socio-economic planning of a region. While the 'land use' relates to human activities like residential, institutional, commercial, recreational, etc., the 'land cover' term relates to the various types of features present on the earth surface (Lillesand and Keifer 2000). Urban buildings, lakes, trees, etc., are all examples of land cover. The term ‘land use’ relates to the human activity associated with a specific piece of land. Although ‘land use’ is generally inferred based on the cover, yet both the terms being closely related are interchangeable. The information gained like land-use/land-cover permits a better understanding of the land utilization aspects on cropping patterns, fallow lands, forest, wastelands and surface water bodies, which is essential for the planning of sustainable development and management of water resources.

Conventional ground methods of land use mapping are labour intensive, time consuming and are done relatively infrequently. These maps will soon become outdated with the passage of time, particularly in a rapid changing environment. In recent years, satellite remote sensing techniques have been developed, which have proved to be of immense value for preparing accurate land use /land cover maps and monitoring changes at regular intervals of time. In case of inaccessible region, this technique is perhaps the only method of obtaining the required information at a cost effective basis.

Urban and agricultural land uses are two of the most commonly recognised high-level classes of use. At any one point or place, there may be multiple and alternate land uses, the specification of which may have a political dimension. Information on land use/land cover (LU/LC) permits a better understanding of the cropping pattern and land utilisation aspects of fallow lands, forest, waste lands and surface water bodies which are vital for planning and development. Land use/land cover information is needed for the optimal utilisation and management of land and water resources of the country (Rao, D.P. 1995). There are two methods of preparing LU/LC map i.e., supervised and unsupervised classification.

8.4.2.1 Classification: It is the process of assigning a thematic class to an individual pixel that represents the radiance detected at the sensor. The result of classification is a transformed image consisting of the discrete values for the classes of interest instead of the continuous values, which are measured in terms of the DN (Digital Number) or the Brightness Value (BV). Generally, image classification is the phenomenon to reduce the number of bands into a single band raster file. Image classification is employed for extracting the information classes of the interest. Land cover classification of the image data depend on the diverse circumstances of the image acquired. Different conditions like the sun illumination, cloud cover, other atmospheric conditions, crop growth in a particular season etc., affect the classification process.

Image classification or the 'partition of the feature space' can be done in two ways: Supervised and Unsupervised classification. In the supervised classification, the operator defines his classes of interest by selecting the training samples in an image on the basis of his/her knowledge of the area. In the unsupervised classification, the image is partitioned into homogenous spectral clusters using some clustering algorithm. These spectral clusters are accomplished on the basis of some spectral similarities. During 1970s the USGS invented a land use and land cover (Anderson *et al.* 1976) classification system for use with remote sensing data. The basic concepts and structure of the system is still applicable today. Even in the recent times for the LU/LC mapping, the people still follow the basic structure originally invented by the USGS (Lillesand and Kiefer 2000).

The basic USGS Land Use and Land Cover mapping method utilize the concept and have designed to use four "levels" of information. Level 1 was originally designed for the use with the low to moderate resolution satellite data such as Landsat Multispectral Scanner (MSS) images. The images with resolutions of 20 to 100 m are more suitable for this level of mapping. Level II was invented for the use with the small-scale aerial photographs. The images with resolutions of 5 to 20 m are relevant for this level of mapping. The most suitable and widely used image type for this level has been high altitude colour infrared photographs. The other data sources in which level II LU/LC mapping can be utilized are Landsat Thematic Mapper and the Enhanced Thematic Mapper Plus, SPOT, IRS (Indian Remote Sensing) satellites, etc. For mapping at Level III, supplementary information, in addition to that rendered from the medium-scale images is required. The image data sets with resolution of 1 to 5 m is relevant in this category. Mostly, high-spatial resolution images and the aerial photographs can be used as the data sources at this level. The last level of mapping, that is of Level IV requires substantial amounts of additional information in addition to that obtained from aerial images. The images having resolutions of .3 to 1.0 m is appropriate in this level. The image data sources that come under this category are large scale aerial photographs.

There are various algorithms available to classify specifically a multispectral image like the Box Classifier, Minimum Distance to Mean Classifier and the Maximum Likelihood Classifier. The 'Box Classifier' takes the maximum and minimum limits of a class. Basically, it defines the mean and standard deviation per class to acquire a box-like area in the feature space. The 'Minimum Distance to Mean Classifier' (MDM) defines the cluster centres. When this classification is carried out, the Euclidean distance from an unknown pixel to various cluster centres is computed. The pixel is assigned to a class to which the distance to the mean DN value of that class is least. The 'Maximum Likelihood Classifier' (MLC) takes the class variability into account. The MLC classifier considers the cluster centre, its shape, size and orientation. This can be executed by computing a statistical distance recognized on the mean values of the classes and the covariance matrix of the clusters. The pixel is assigned to the class to which it has the highest probability.

8.4.2.2 Classification of Mulki River Basin: The Land use/Land cover map of Mulki River basin (Fig. 8.6) has been derived from IRS_P6_MX_4 imagery dated 05-01-2006 using Supervised Maximum Likelihood Classifier. Since a small portion of the area in the coastal track is missing due to the non-availability of the cloud free image in this resolution, the LU/LC map of the remaining area has been prepared for the study. But utilizing the Google earth imageries of very high resolution but of true colour the land use/land cover of the remaining area has been studied (Fig. 8.7). During supervised classification, utilisations of SOI topographical map (for basic information such as transportation network, tanks, streams, etc., along with sufficient ground truth verification have been made to assign the land parcel to the identified feature in the imageries (Fig. 8.5). Different categories of land use/land cover were demarcated by visual/digital interpretation techniques (Anderson *et al.* 1976). Patterns of vegetation and other land features have been identified by visual analysis of imageries using mainly tonal variations, textural pattern, shapes and associations (Reddy and Reddy 1996). Land-water interchanges and vegetation types have been distinguished in FCC, making use of the differences in the contrast applying filtering and contrast stretching methods. The land use/land cover classification upto level III for various categories of the entire study area was done based on the Google Earth and National Remote Sensing Centre (NRSC) guidelines (Table 8.1). The GCPs obtained from GPS surveys were used for validating the maps. The various thematic maps prepared using conventional and remote sensing data were transferred to GIS environment. The secondary data collected from various departments have been used directly or indirectly. About eighteen land cover/land use parcels have been identified in the study area and mapped as follows: built up area, paddy field, agriculture plantations, cultivated land, coconut plantation, areca plantation, casuarina plantations, dense forest area, mangrove forest, waste land, sandy beach, recent alluvium, granite/gneissic rock outcrops, islands, quarry, river or streams, water bodies and wetlands, and prawn culture ponds.

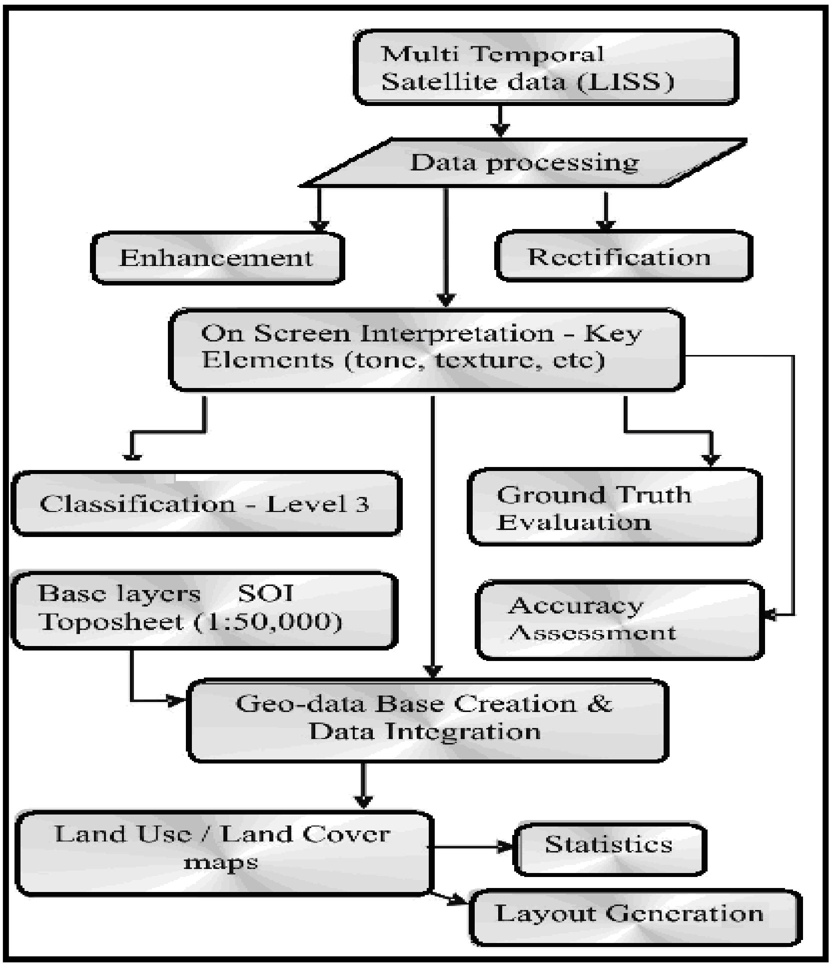

Fig. 8.5 Flow chart showing the methodology adopted for the LU/LC Map preparation

Sl. No.	Level - I	Level – II	Level – III
1	Built-up land	Town/cities	Mixed residential
		Village	Hotels/Beach resort
		Residential	Roads
		Commercial and services	Railway line
		Transportation	Port facilities
		Recreational	Stadium/play ground
		Industrial	Park
2	Agricultural land	Cropland	Single crop / Rabi
		Plantation	Double crop / Kharif + Rabi
		Fallow land	Mixed crop
		Plantation	Coconut
		Plantation	Casuarina
		Plantation	Rubber
		Plantation	Areacanut
		Plantation	Eucalyptus
3	Forest	Scrub forest	Dense scrub
		Dense forest	Sparse scrub
		Mixed forest	Coastal scrub
		Mangroves	Mangroves
4	Waste land	Salt affected land	Salt pans
		Marshy / Swampy	Sandy Beach
		Sandy area	Rocky beach
		Rocky area	Marine Rocky island
		Barren Rocky	Dense scrub
		Land with scrub	Sparse scrub
		Land without scrub	Barren rocks
5	Water bodies	River / streams	Deep water
		Sea	Shallow water
		Tanks / pond	Shallow tank/pond
		Bays / estuaries	Estuary with shoals

Table 8.1 Level III Classification for the Land use/ Land cover Map

Built up land includes stabilized residential and commercial areas in villages and Townships. They are mainly concentrated along the road sides.

In the agricultural land, Paddy fields are recognized as open fallow lands or cultivated agricultural area. Plantation mainly constituted of coconut and arecanut found in the proximity of streams and rivers and along the coastal region. They also include cashew and rubber plantation found along the hill slopes and hill tops of barren land.

Forest area identified by its various red colours include thick and dense canopy of all trees which predominantly remain green throughout the year. Grass/shrub area is identified by its unique red colour and grown along the river channels and shallow areas. Open scrub area is identified by its less dense and low canopy interspersed with open land and rock exposures. Degraded or open scrub land can be converted into productive areas by increasing soil moisture either by constructing suitable rain water harvesting structures or by afforestation and pasture land development. Degraded or open scrub lands occupy relatively higher topography and steep slope areas. These areas are generally prone to degradation or erosion.

Waste lands include beach, barren land, rocky exposures, etc. Laterite exposures are almost barren terrain with hard gravelly laterite and sometimes formed in plateaus. Rock exposures are mainly gneissic, granitic and intrusive rock masses outcropped here and there in the area. Quarries have been identified as a separate land parcel in order to understand their significance in geoenvironmental studies and they are devoid of vegetation and ripped off rock and soil cover in an area of rocky exposures. Barren lands are places devoid of soil cover with no vegetation, which can be developed by proper irrigation methods or suitable crops.

Stream/Water bodies include natural course of flowing rivers and streams along with the tanks, lakes and lagoons. Most of these are non-perennial. Wetlands/shallow lands are mainly along the coastal area and river tracts where the natural vegetation is high with mangrove forest.

Based on these the groundwater potential map of the study area can be prepared. The details of the LU/LC analysis are given in Table 8.2 and Fig. 8.7. Good groundwater potential zones include the coastal plain which consists mainly of alluvium which is highly porous and permeable. This is evidenced by the high density of wells in this area. Lateritic plateau, flood plains and valley fills in the study area also are good potential aquifers. Moderate groundwater potential zone in the study area belongs to lateritic area with varying thickness overlying the granitic gneiss below. Gneiss and dolerite dykes are interspersed in this terrain as outcrops. Groundwater potential in this area depends on the thickness of laterite, depth of weathered zone, and fractured zones within the gneisses. Poor groundwater potential zone is mainly due to exposure of highly resistant rocks like granites and gneisses and other hard rocks. These are generally high runoff areas.

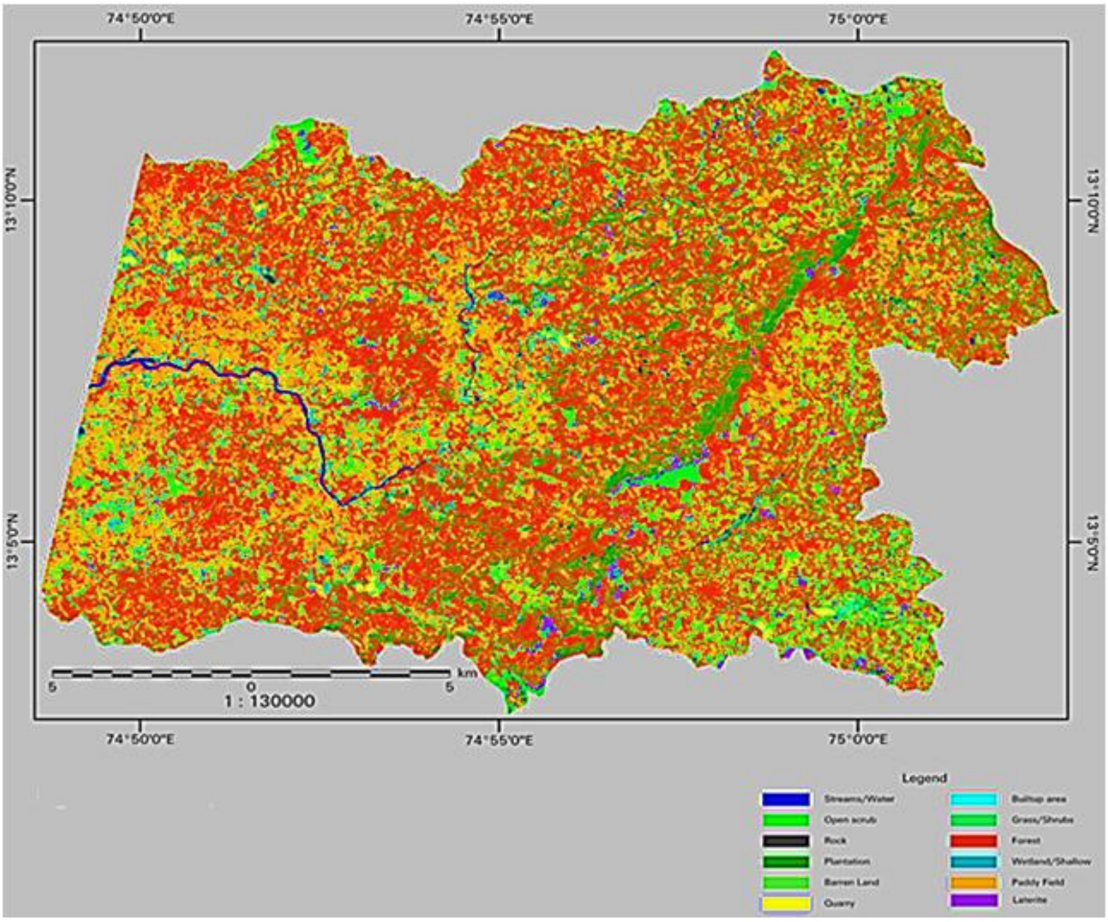

Fig. 8.6 Land Use/Land Cover Classification Map of Mulki River basin

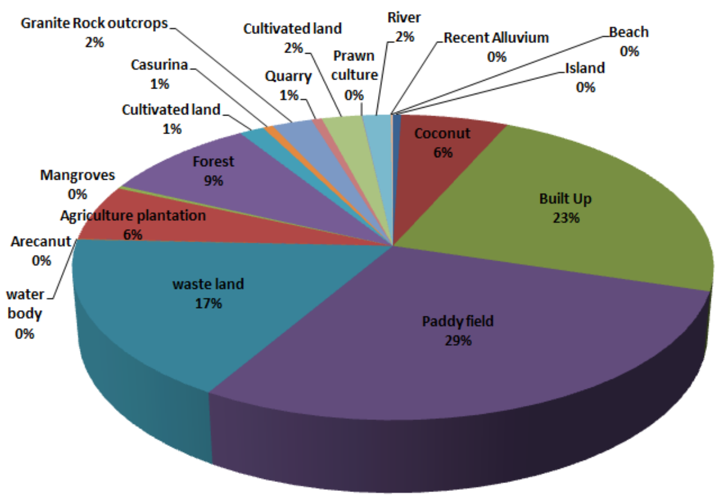

Fig. 8.7 Pie chart showing distribution of LU/LC of Mulki River Basin

Sl. No.	LU/LC	Area (Sq. Km)	Percentage (%)
1	Built Up Area	81.67	23
2	Paddy field	102.11	29
3	Agriculture plantations	20.87	6
4	Coconut plantations	21.99	6
5	Cultivated land	13.28	3
6	Casuarina plantations	2.13	1
7	Areca plantations	0.03	0
8	Forest Area	31.82	9
9	Mangroves forest	1.13	0
10	Waste land	60.86	17
11	Beach	0.10	0
12	Recent Alluvium	0.29	0
13	Granite Rock outcrops	8.18	2
14	Islands	1.66	0
15	Quarry	2.15	1
16	River	5.84	2
17	Water body	0.25	0
18	Prawn culture	0.11	0

Table 8.2 Showing the areal spread of different LU/LC parcels in Mulki river basin

8.4.3 Hydrogeomorphological Units: Hydrogeomorphologically the study area can be broadly be divided in to three zones i.e. runoff zone, infiltration zone and discharge zone based on the geomorphic landforms, terrain conditions and lithological characteristics**.** The delineation of the hydrogeomorphic units was aimed at demarcating area of groundwater recharge/discharge and potential zones for development. The structural hills, residual hills and linear ridges constitute runoff zones, whereas the buried pediments and pediments represent zones of infiltration. Alluvial plains and valley fills act as discharge zones.

A hydrogeomorphological map shows various landforms present in the area such as Coastal Plains, Valley/Valley Fill, Pedeplains, Lateritic Mesas, Plateau, Flood Plains, Linear Ridge, Inselbergs and Residual hillocks, Dykes, Fractures, Faults, Trend lines, Lithology, etc. The features will vary depending upon the terrain (hard rock terrain, alluvial terrain, etc.). For each of the landform groundwater prospects is assigned based on type of landform, lithology, structure, soils, land use/land cover, drainage, topography, etc., This preliminary map can be finalized by integrating field observations and collateral data. Thus the final map showing groundwater prospects in terms of poor, moderate, good, etc., can be made. Further follow up through hydrological and geophysical methods will lead to selection of sites for drilling.

8.4.3.1 Coastal Plains: Coastal plains are extending from beach to interior, for about 4 to 5 km. almost trending North-South direction and are defined by lithology consisting of unconsolidated sediments of sand, silt, clay and gravel. It shows smooth texture and extensive agricultural activity. It shows sharp contact with buried pediment with irregular boundary outline. The major land use activity is agriculture. However at places natural tree cover is also reported intermingled with cropland. The relief is defined by gently sloping surface towards the west defined by the course of River. Coastal plains consist mainly of alluvium which is highly porous and permeable and therefore act as a good aquifer. A large number of shallow open wells are dug in the region to meet water requirements of the people living in the area.

8.4.3.2 Pedeplains: Pedeplains cover a large part of the area with gently undulating topography. These are the laterites and lateritic soils. Groundwater prospects in pedeplains are moderate. Small gullies and erosional surfaces are common in pedeplain. Topographical elevation of pedeplain surfaces range from 20 metres to 60 metres above mean sea level.

8.4.3.3 Lateritic Mesas: On the Eastern side of the basin separated by the elongated intrusive body of NE-SW trending ridge a vast stretch of laterite mesa has been identified. They are table like land, which is broad, elevated and almost levelled. This extends from Moodbidri-Pranthya in south to Belvai in the north. Laterite is underlain by granitic gneiss. Lithomarge clay of varying thickness evidenced from bore well drilling is sandwiched between hard laterite and gneiss. Groundwater gets recharged in this region due to high porosity and permeability of overlying laterite. A large number of bore wells have been drilled in this region to exploit the saturated fractured zone.

8.4.3.4 Flood Plains: Mainly consists of sand, silt and clay sediments on banks of the rivers and near river mouths. Since sands make good aquifers, they are considered as good groundwater potential zones. A good number of open wells are seen on either side of the river in this area and the groundwater gets recharged in these wells from the river. These wells are used as irrigation source in addition to drinking purposes.

8.4.3.5 Valley fill zones: These are elongated depressions formed due to high rate of erosion within the pedeplain. Most of these valley fill zones are structurally controlled and are identified along the tributaries of the rivers. Valley fills are products of streams dumping their sediment load along their courses due to obstruction or reduction in their flow velocity. Since they have high moisture content, they are characterized by natural vegetation and can be identified on FCC data by the linearity of tone and texture, subdued topography and accumulation of colluvial material derived from the surrounding uplands.

8.4.3.6 Inselbergs and residual hillocks: Inselbergs are low-lying isolated hillocks of gneisses and granites of varying size and shapes, mostly located within pedeplain. These inselbergs are usually high runoff areas. The prospect for groundwater is very poor in these areas.

Residual hillocks have been found in the middle part of the area. These are erosional remnants of gneisses. The groundwater prospects in these areas are very poor and depend on the thin weathered portion of gneisses. It generally acts as runoff zone and is considered very poor to poor in terms of groundwater prospects.

In many of these areas, people used their traditional wisdom and the traditional rain water harvesting structures like tanks have been built either individually or on community basis. People used the traditional watershed management techniques such as contour bunding and terracing in these areas to cultivate paddy and other crop during Kharif seasons. Paddy fields can be seen in terraced stretches where the rainwater also has been infiltrated. Thin veneers of lateritic soils are exposed in these areas where the farmers cultivate adopting the tank irrigation.

8.4.3.7 Linear Ridge: It is present as a NE-SW trending residual hillock of an intrusive rock. This ridge is having higher elevation than the confining water divide. This elongated prominent ridge is characterized by massive structure and high resistance to erosion with elevations ranging from 150 metres to 245 metres above MSL. They

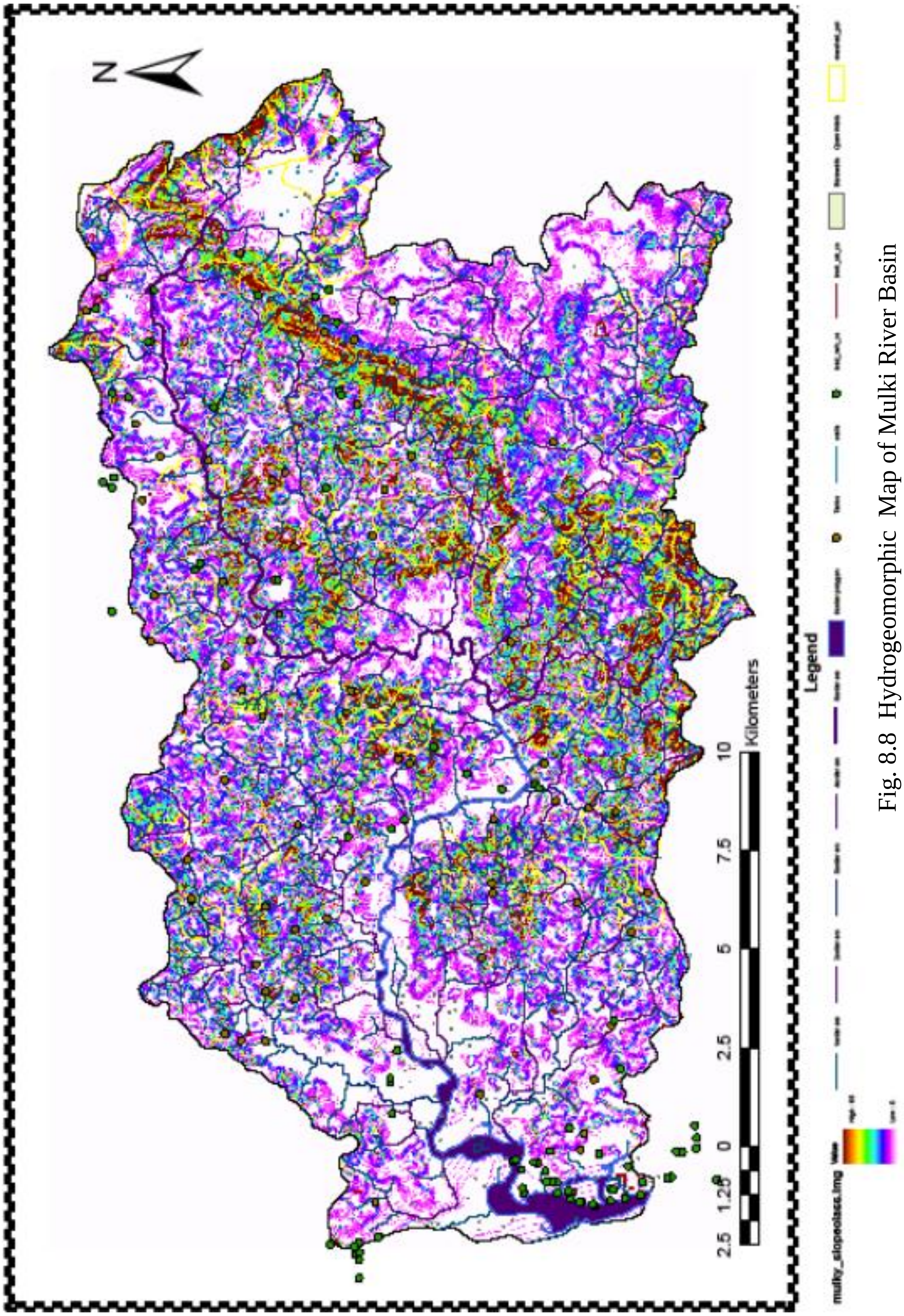

Fig. 8.8 Hydrogeomorphic Map of Mulki River Basin

exhibit light brown to dark tone, coarse texture and linear shape, and occupy eastern part of the watershed. Extremely shallow to moderately shallow soils have developed due to mechanical weathering, with scanty vegetation and cashew plantations. This hydrogeomorphic unit acts as runoff zone and hence groundwater potential is very poor. Two springs have been noticed in the foothills of this hill range. Based on the above studies, a hydrogeomorphic map (Fig. 8.8) has been prepared for the Mulki River basin combining well density, slope, microwatersheds, traditional rainwater harvesting structures, etc., which will give an idea about the planning for the sustainable development and management of water resource in this area.

8.5 CONCLUSIONS: For the effective preparation of various thematic maps such as base map, contour, drainage networks, road networks, lineaments, DEM, slope, drainage density, well density, microwatersheds, tanks, Land Use/Land Cover, hydrogeomorphology, etc., and for their integration, geoinformatics is found to be an effective tool. The high resolution IRS_P6_L4_MX image is found to be more effective in supervised classification, delineation and mapping of Land use/Land cover, groundwater prospective zone mapping, etc. Hydrogeomorphologically the study area can broadly be divided in to three zones i.e. runoff zone, infiltration zone and discharge zone based on the geomorphic landforms, terrain conditions and lithological characteristics. High values of lineament density are recorded in the study area having moderate groundwater prospects. Integration of various parameters, which control the occurrence, and movement of groundwater such as lithology, structures, landforms etc., in GIS environment has been found to be highly useful in identifying prospective zones. Integration of this with geophysical and geological data helps in narrowing down the target areas for further exploration and also to select proper recharge area. Groundwater prospects of an area can be assessed and prospective zones in the area can be identified and marked on the hydrogeomorphological/groundwater potential map.

Chapter 9

Sustainable Development of Mulki River Basin

CHAPTER 9

SUSTAINABLE DEVELOPMENT OF MULKI RIVER BASIN

9.1 INTRODUCTION: Traditional Rainwater Harvesting Structures (TRWHS) and Microwatersheds played very important role in the rural water management and sustainable development of our country from ancient times (Agarwal and Sunitha 1998). Historically, Traditional Rainwater Harvesting Structures (TRWHS) such as Tanks, Ponds, etc., with community participation contributed significantly in the groundwater recharge of the hard rock area maintaining soil moisture level and well irrigation to support the agriculture even during the dry spell.

The State of Karnataka is well known for tank irrigation and accounted for one fourth of the tanks in the country. The State of Karnataka had about 40,810 tanks before 1960 and it had come down to 40,012 by 1986. Of which, about 39 per cent of the tanks had a command area of less than 10 acres (Gowda *et al.* 1995). The tank system lost its importance during 1980's due to various reasons (Radhakrishna B. P. 2003). The Dakshina Kannada and Udupi Districts receive heavy rainfall and yet the area experiences scarcity of fresh water right from midsummer (Saivasan 1998) due to its highly porous laterite formations resting above the hard and impervious granitic gneisses. Even the groundwater is prone to adverse effect of salt water intrusion which affects the crop yield in the coastal areas. There were about 2102 tanks in Dakshina Kannada districts which have a cultivable command area of about 13,061 hectares (Gowda *et al.* 1995). These TRWHS which were the backbone of rural economy had been neglected without community involvement. These hearts and veins of the villages had been neglected into relative insignificance with the introduction of large scale centralized water supply systems or tube well supply, resulting in the silting up of these tanks, depriving the farmers the irrigation and drinking water. For the rehabilitation of these structures a systematic study is required to identify, delineate and map them basin wise since they form a natural boundary for collection and accumulation of rainfall in an area.

Watershed management is an integrated approach to the management of natural resources that aims at securing the living conditions of local communities in a sustainable manner. Watershed management has emerged as a new paradigm for planning, development and management of land, water and biomass resources with a focus on social and environmental aspects following a participatory approach. A watershed is a clearly defined natural hydrologic unit (NRCS 1995) with an unambiguous topographic boundary available on the basis of stream network. It can also be defined as the total area of land above a given point on a waterway that contributes runoff to the flow at that point (Hanson 1954). Water harvesting forms an integral component of any watershed development programme. Although the meaning of watershed is of public knowledge, it is important to emphasize that the microwatershed (Khan et *al*. 2001) must be considered as a scope for planning under social, economic, environmental and operational approach, besides the territorial and hydrological approach traditionally considered. Since many of the TRWHS'/tanks' catchment areas belong to microwatersheds, the delineation of the same is a must for the sustainable water resource development and management at rural level.

In the Mulki river basin, an average annual rainfall of about 4264 mm is recorded for the last four decades. Even though the area receives a surplus water of about 72.8% (3104.93mm) during the monsoon period, it suffers from a water deficiency of about 19.4% (825.84mm) during pre- and post-monsoon period. The end result is that a good percentage of rainfall i.e., about 35% (1490.72mm) is discharged as runoff every year after its share of evapotranspiration and groundwater infiltration. That means, out of the 1496.70 x 10^6 cubic meters of precipitation available in the basin, an average of about 771.16 x 10^6 cubic meters per annum is lost as runoff. If this huge water resource potential is harvested which is unevenly distributed in the study area, through appropriate methods of collection and dissemination, probably the problem of water scarcity and unequal distribution pattern can be solved in this area. Rainwater harvesting and artificial recharging of groundwater through various methods such as rehabilitation of traditional rainwater harvesting structures (TRWHS) and roof top rainwater harvesting systems (RTRWHS) can be adopted in this area to tackle the problem considering its water needs, topography, geology, meteorology, etc. So, by proper understanding of the geology and geomorphology of the area, sustainable groundwater development and management can be adopted. The groundwater quality in the study area in general is found to be good to excellent for drinking and irrigation purposes and can be utilized for storage and consumption for later periods.

Even though the area is comprised of more than 73 traditional tanks or rainwater harvesting structures, it has been found that they are not maintained properly or utilized fully. Development of microwatersheds and traditional rainwater harvesting structures can improve the water resource management of this area for drinking and irrigational purposes. One case study each for the rehabilitation of an abandoned silted tank and a roof top rainwater harvesting structure has been undertaken to understand the possibilities for the sustainable development and management of the water resources in the study area.

9.2 REHABILITATION STUDIES OF AN ABANDONED TRADITIONAL RAINWATER HARVESTING STRUCTURE: Rural areas in India have been dotted with traditional rainwater harvesting structures which has been silted and abandoned due to poor maintenance. But the rehabilitation of these structures will improve the conditions of irrigation and drinking water supply.

9.2.1 Introduction: Even though the coastal districts of Dakshina Kannada receive an average annual rainfall of about 3974 mm, this part of Karnataka suffers an acute shortage of water. Since the hard rock outcrops comprising of granite, granitic gneiss and charnockites criss-crossed by doleritic dyke intrusions with highly porous laterite capping dominate major part of this area, storage of groundwater is very less compared to many other parts of Karnataka. But the traditional water harvesting structures built individually or through community participation by the enterpreneuring farmers made the rural area rich in bio-diversity and agriculture (Agarwal and Sunitha 1998). The flux in migration to cities, and quarrying activities has affected these traditional water harvesting structures.

Nitte, a village abundant with lot of granitic outcrops and shallow lateritic soil cap has been blessed with a heavy rainfall of about 4771 mm/annum and belongs to a region of highest rainfall in the Peninsular India. Even though situated in a high rainfall area of the country, the Nitte area experiences acute shortage of water during peak summer season of the year due to its geology, geohydrology and geomorphological peculiarities. The Nitte Panchayat has good number of traditional rainwater harvesting structures (TRWHS) likes ponds, tanks, etc., which are endangered now due to siltation, encroachment and poor maintenance (Radhakrishnan and Lokesh 2009, 2010c). The problem can be addressed only if we can understand the availability of the resources and practice the best way of management methods through sustainable development (Radhakrishna B.P. 1997, Pacey and Cullis 1986, Pettijohn 1998, Prakash and Prasanna Kumar 2003, Rangaraju 2004). In order to understand the significance of these traditional, abandoned water harvesting structures and the role they played in the water management and economy of these hard rock area, the following studies have been taken up. An abandoned and silted traditional rainwater harvesting structure (Fig. 9.1) at Nitte village falling in Mulki River basin has been taken up to understand the feasibility of rehabilitation of such deserted, silted tanks and their significance in the water development operation in the rural areas of Dakshina Kannada Districts.

9.2.2 Methodology: After a reconnaissance survey carried out in the Mulki River basin, it was found that the Nitte area has been dotted with a number of traditional rainwater harvesting structures, which have been neglected due to siltation, improper management and encroachment. One among them, a silted earthen bund at Parappady area behind the Nitte Panchayat Office has been selected for the analysis to understand the present situation and its significance in the rural area.

Community survey (Pacey and Cullis 1986) has been carried out to understand the water and sanitary problems in the area of influence of the tank. A detailed survey of the tank using plane table and dumpy level has been carried out and the map was prepared (Fig. 9.2). The existing alignment and the length of the bund has been marked and plotted to study the engineering details of the bund and tank. Taking a point on the bund as bench mark, a contour of free board level and another contour of the base of the bund was marked. Silt samples were collected along a selected cross section at randomly selected points in the tank area to understand the silt deposition over the area (Fig. 9.3). The samples were collected by driving hollow PVC pipes into the ground up to a depth where it reaches the natural hard ground and then the height of silt collected in the pipe was measured and the amount of silt deposited has been calculated (Table 9.1).

Fig. 9.1 Photograph of the silted tank under investigation at Nitte village

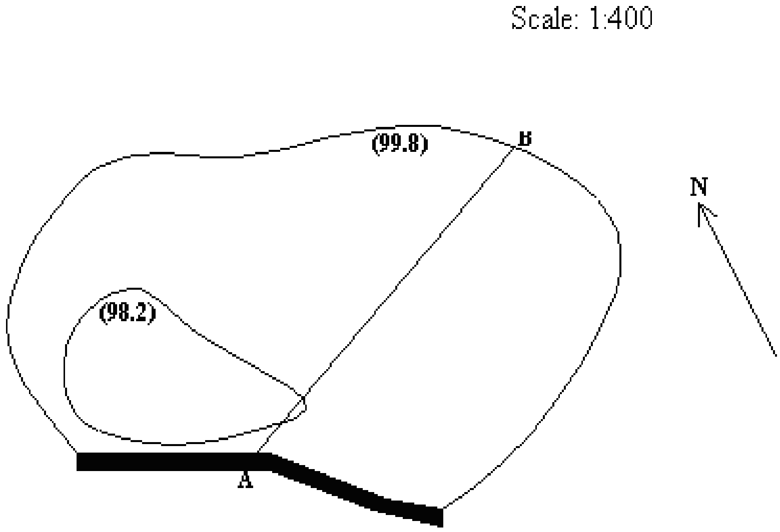

Fig. 9.2 Map of the silted tank under investigation at Nitte village

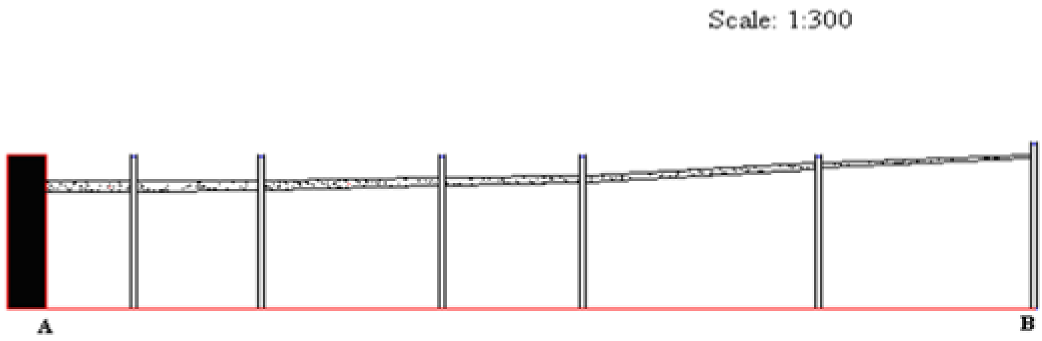

Fig. 9.3 Pattern of silt deposition in the tank area along the chosen section

9.2.3 Results and Discussion: From the community survey, it has been found that there was gradual reduction of water table in the open wells after the siltation of the tank occurred over a period of time, and now the people nearby the tank area face acute shortage of water during peak summer which has compelled them to depend on the Panchayat water supply scheme which is erratic and non-dependable for irrigation (Radhakrishnan K. 2007b). It was found that the quarry dust was the major silt deposited all along the tank area and the same accumulated in the tank bed over a period of time due to the inflow of the quarry dust (which is quite common in rural areas of Dakshina Kannada districts) from its small catchment during rainy seasons. The survey also revealed the fact that a major portion of the silt has been accumulated near the bund as compared to the other area in the tank showing a flux of water during rainy seasons. A few caving also have been noticed in certain parts of the bunds, other than missing of pitching stone boulders indicating the weakness of the bund structure due to anthropogenic interference.

Area within the 99.8m contour	2503.10 m^2
Area within the 98.2m contour	303.60 m^2
Total silt deposited within the area of 99.8m contour with an average deposit of 0.4m over the entire area	1001.24 m^3
Total silt deposited within the area of 98.2m contour with an average deposit of 0.7m over the entire area	212.52 m^3

Table 9.1 showing the details of capacity contours and silt survey of the tank

Based on the above studies, a cost benefit analysis for the rehabilitation of the existing traditional rainwater harvesting structure (TRWHS) at Parapady has been prepared as below (Table 9.2).

(i) Cost Estimation for Desilting of the Tank and Restoration of the Bund:	
Area within the 99.8m contour	2503.10 m^2
Area within the 98.2m contour	303.60 m^2
The Average volume of the tank basin taking the height of the bund up to free board from the base as 1.6 mts	(2503.1+303.6)/2 x1.6 = 2245.36 m^3
Total silt deposited within the area of 99.8m contour with an average deposit of 0.4m over the entire area	2503.10 x 0.4 =1001.24 m^3
Total silt deposited within the area of 98.2m contour with an average deposit of 0.7m over the entire area	303.6 x 0.7 = 212.52 m^3
Average volume of silt deposited	606.88 m^3
Total cost of desilting the tank area @ Rs.55/ m^3	Rs. 33,378.40
Total volume of granite boulders required for the filling of cave in the bund structure	4 m^3
Total cost for the restoration of the bund @ Rs.1,000/ m^3	Rs. 4,000.00
Hence the total cost for the rehabilitation of the bund	**Rs. 37,378.40**
Total storage capacity of the tank	28,52,240 lts
Surface Storage (S.S): Assuming an evaporation of 20%, total water stored in the tank	22,81,792 lts
Total rainwater received by the basin area with an average annual rainfall of 4600mm	2,503.10 x 4.600 =11,514.26 m^3 =1,15,14,260 lts
Infiltration (I): Assuming 30% Infiltration of water in the area, expected volume of rainwater that gets infiltrated	1,15,14,260 lts x 0.30 =34,54,278 lts
Total water storage = Surface Storage + Infiltration	= **57,36,070 lts**
(ii) Benefit Estimation:	
Per capita water consumption/annum (@ 135lts/day as per WHO)	49,275 lts.
No. of people that can be supported with this infiltrated water which recharges the open wells in the nearby community (assuming only 80% usage of infiltrated water)	56
Assuming 4 people in family, number of families that can support with this water source	14
Assuming cost of water @ Rs. 15/m^3, the total benefit that can be achieved by effectively utilizing this bund	**Rs.75,678.00/ annum**
Double the cost of rehabilitation investment can be reaped in the same year itself	

Table 9.2 Cost-Benefit analysis for restoration of the Bund and desilting the Tank

9.2.4 Conclusions: The extensive quarrying operation in the microwatersheds is one of the causes for the silting up of traditional water harvesting structures of rural areas in Dakshina Kannada districts. Since agriculture became unattractive and non-profitable, community participation in maintaining the water harvesting structures diminished causing the encroachment and desertion of the water harvesting structures. The rehabilitation work may improve the surface water storage capacity of this silted, abandoned Traditional Rainwater Harvesting Structure (TRWHS) which can be used for irrigating the nearby fields and farms in this microwatershed. Infiltration to the groundwater table due to the enhanced storage may recharge the nearby wells and can take care of the water needs of families around this structure for the entire year. The removed silt can be used for earth filling in the nearby road construction work. The cost of desiltation is much less compared to the benefit in terms of surface water collection, groundwater recharge and silt materials for other purposes such as road making (Radhakrishnan and Lokesh 2009).

Similar studies may be carried out to identify and rehabilitate abandoned and silted Rainwater Harvesting structures in watersheds at Panchayat level using satellite pictures and cadastral maps. These can be studied in detail in a similar manner and their feasibility for effective usage can be analyzed. Awareness campaign and community participation at village level with local government support will definitely save these dying traditional rainwater harvesting structures and serve the community in a better way improving the resource availability.

9.3 FEASIBILITY STUDIES FOR SUSTAINBLE DEVELOPMENT OF WATER RESOURCES THROUGH ROOFTOP RAINWATER HARVESTING:

Nitte Education Trust (NET) Campus at Nitte being a fast developing hamlet falling in the Mulki River Basin has been taken for the feasibility studies for sustainable development and water management due to its ever increasing water demand and acute shortage in supply to cope up with the water needs.

9.3.1 Introduction: NET campus at Nitte with its sprawling area of about 45 Acres is having six institutions housed, and is in the heart of the Nitte village. It supports a total population of about 4800 people. Out of this, the hostels and quarters in the campus support a population of about 900 people throughout the year. Besides this, the Campus maintains a good garden and greenery along with its forest cover. The campus is located at an elevation of about 80mts. above Mean Sea Level (MSL) and lies between 74°56´E- 74°57´E longitude and 13°10´ N to 13°11´ N latitude in the Survey of India Toposheet No. 48K/16. The area has an average annual rainfall of about 4771 mm which is distributed in three seasons i.e. pre-monsoon, monsoon and post-monsoon. Though the area receives a heavy rainfall, it still experiences acute shortage of water in peak summer season. Against this backdrop, it has become necessary to examine various options for meeting the water requirements of the community. In this regard, an analysis of the existing situation of the area is required for implementation of a cost effective project which is technically feasible and socially desirable. Rooftop Rainwater Harvesting and storage systems, along with artificial recharging of the groundwater through rainwater harvesting are the dependable management tool for balancing the requirement for a sustainable development. The bore wells, the main source of water are depleting its resources in due course of time decreasing in their yield. So to meet the water requirements of the residential and floating population at NET Campus, Nitte institutions management is compelled to search for an alternate water resource to sustain. Conjunctive use of rainwater along with groundwater may resolve the issue of acute water shortage problem in the campus during summer period.

9.3.2 Methodology: Water requirements of the campus, various components of rooftop rainwater harvesting system, existing water supply schemes, pumping details and cost involved, present system of water harvesting structures, etc., have been analyzed thoroughly in order to prepare a detailed layout, design, estimation and costing for Rooftop Rainwater Harvesting structures in the campus to manage the water requirement of the campus effectively. The cost-benefit analysis also has been carried out to understand the feasibility of the project which can be implemented elsewhere.

9.3.3 Components of Rooftop Rainwater Harvesting: N.E.T. campus, Nitte having a population of about 4719 including the residential and floating population requires approximately about 260 m^3 of water per day including gardening as per the standards specified by WHO. It has about 23 small and large buildings of different roof areas and slopes with a total catchment area of about 16,408.94 m^2. Having an average annual rainfall of about 4600 mm. in this area, the buildings in the campus can collect about 60,384.90 m^3 of water per annum. And the average rooftop collection per day will be 656.35 m^3 (Pacey and Cullins 1986).

Presently, the existing three sump tanks available in the campus have a storage capacity of about 176.97m^3. The total volume of water pumped from the bore wells and open wells in to the sumps every day is 194.48 m^3 and this entire volume is consumed in one day in the campus. It must also be noted that, the water requirement calculated as per the WHO standards amounts to about 218.14 m^3 while the volume of water with which the campus has to content is just 194.48 m^3. This gives a clear idea of the water situation in the campus.

9.3.4 Rainfall: The rainfall data of the area for the past 42 years have been considered (Figs. 6.8 & 6.12) to understand the maximum average rainfall and average annual rainy days in order to design the system.

Considering the erratic nature of the rainfall, an average of about 4600mm per annum has been considered as the maximum rainfall, and 132 days which is around 4.4 months as maximum rainy days in designing pipe diameters and lay out distance of the drain pipes for the proposed water harvesting systems. The campus can rely entirely on the rainwater for all its needs and be self-sufficient without the need to use the bore wells and open wells during these months. This in turn helps in reducing the pumping cost and also helps in improving the water table.

9.3.5 Pumping Details: The supply of water to the campus is from three open wells and three bore wells at present. And the major demand in summer used to be met by all the bore wells which operate for almost 24 hours a day and a part by the open wells. But in rainy seasons the demand is met only by open wells with a small contribution from two bore wells. The pump usage, total yield, operating cost and other required details are calculated and found that a 7.5 HP pump is being used for a yield of just 3000GPH which lays a lot of stress on the bore wells. This might be one of the reasons for the drying up of many bore wells in the campus where similar scenario might have existed. The total pumping cost have been worked out for the rainy season of about 4.4 months and found that about 1, 41,676 rupees will cost for the same. This huge amount per annum can be saved if rooftop rainwater harvesting is practiced. The cost can be further saved if the rooftop water can be collected in a tank constructed above the lintel level of the fourth floor and the water can be used for even flushing toilets in the same floor and also in the floors below.

9.3.6 Existing Rooftop Rainwater Harvesting System in the Campus: The existing rainwater harvesting system (Fig. 9.4) established in the campus during 2003, is not functioning properly due to the poor designing, improper management and lack of periodical maintenance. The drain pipes of 2" diameter were provided at an interval of 10 ft. apart, and they are then connected to reducers and conveyed through 4" diameter pipes to the filter unit. The filter unit consists of 2 layers of sand and gravel. The filtered water is carried to a storage tank but is of poor quality and has foul smell. The overflow of the filter tank is conveyed to an abandoned bore well for recharge which may even contaminate the deep source of groundwater. The recharge pits located in a few places in the campus are not designed properly and is not serving its purpose.

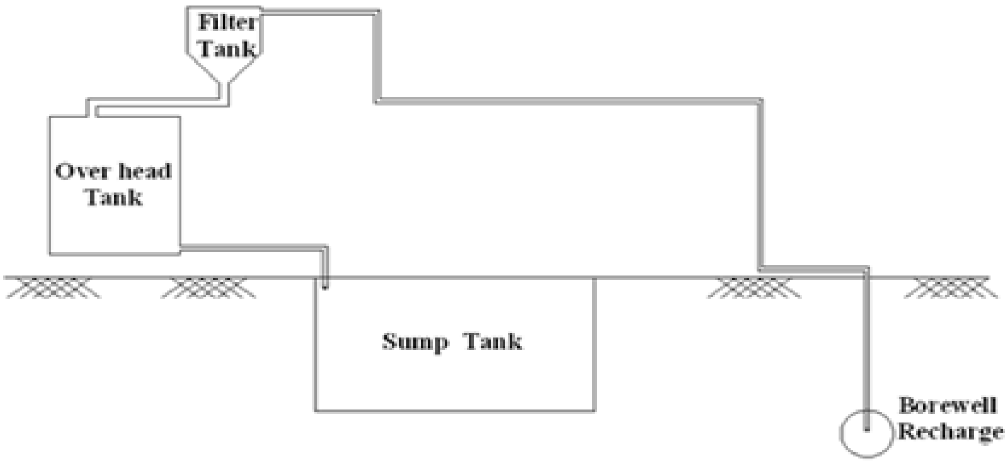

Fig. 9.4 Schematic representation of the existing rainwater harvesting structure

9.3.7 Design, Layout, Estimation and Costing of a Rooftop Rainwater Harvesting Structure: The rooftop harvesting system usually comprises of a Roof as clean as possible as a collector of rainfall, a Storage Tank, Collection Pit, Gutter arrangement to transport water from the rooftop to the storage tank, First Flush System to divert the dirty water, Filter Unit to remove debris/silt etc. (Agarwal A. 2000).

<u>9.3.7.1 Design and Layout:</u> Emphasis has been laid on saving the pumping cost in the rainy season by using the rainfall for the daily consumption in the campus. In this regard, the capacity of the tank required in addition to the existing storage has been calculated. The estimation for constructing the new sump tanks and plumbing cost has been calculated. The excess water collected will be conveyed to the recharge pits provided at suitable locations (Fig. 9.5).

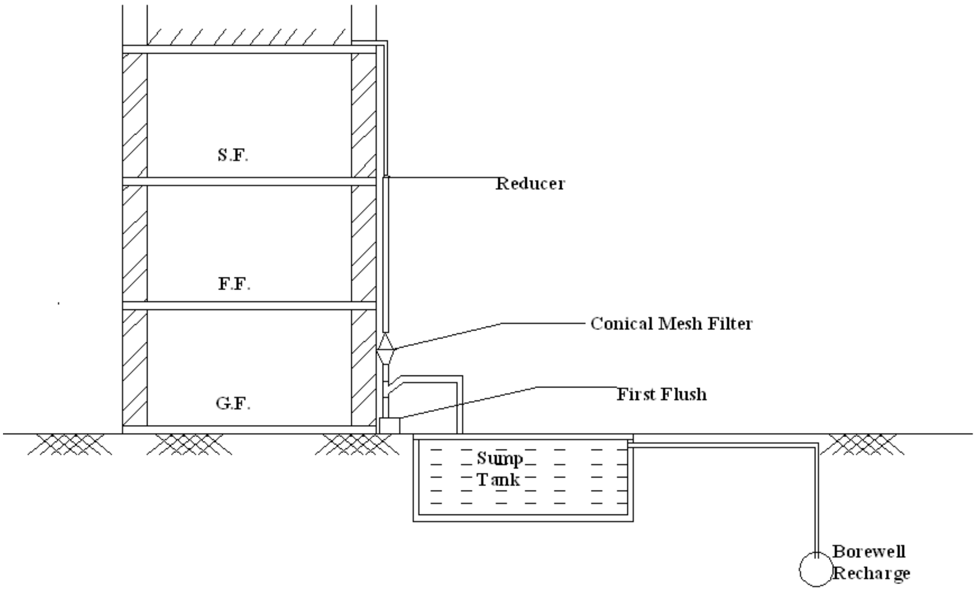

Fig. 9.5 Schematic representation of the proposed rainwater harvesting structure

From the available rainfall data of the Nitte area, an average daily rainfall of 40mm (H) was considered for the design and found that it may require about one hour for draining the water completely from the rooftop as computed below.

If Hydraulic Depth ‘H’ is 0.04 metre, head at the inlet will be half of it i.e, 0.02 metre. Since we know that $V= C_d \times (2 \times g \times h)^{1/2}$, Where ‘V’ is Velocity of flow, ‘C_d’ Coefficient of discharge, ‘g’, Acceleration due to Gravity, ‘h’, Head at the inlet, Velocity is obtained as 0.501 m/sec.

Considering the available rooftop area in the old blocks of the campus, a roof area of about 50ft x 20ft is available for water harvesting. Total volume of water (Q) that will be collected per day on this roof will be 15.24m x 6.1m x .04 = 3.717 m^3.

Assuming the diameter of the pipe as 2'' the area of c/s of the pipe will be,

$$A = 2.027 \times 10^{-3} \, m^2$$

We know that Discharge $Q = A \times V = 2.027 \times 10^{-3} \times 0.501 = 1.016 \times 10^{-3} \, m^3/sec.$

Therefore time 't' required to empty the water collected is $= 3.717 / (1.016 \times 10^{-3})$

$$t = 3658.46 \text{ sec} = 1 \text{ Hr and } 59 \text{ sec}$$

The rainfall is not same throughout the rainy season. Hence the drain pipes have to be designed taking into consideration the maximum rainfall in a day also. Here the time required by drain pipes to drain off the water when the rain is about 190mm in a day is found to be 2 hrs 13 minutes as below:

$H = 190/1000$; so $h = H/2 = 95/1000$. Hence 'V' is obtained as 1.092m/sec.

Total volume of water (Q) that will be collected per day on this roof will be

$$15.24m \times 6.1m \times .19 = 17.66 \, m^3.$$

Assuming the diameter of the pipe as 2'', the Area of c/s of the pipe,

$$A = 2.027 \times 10^{-3} \, m^2.$$

So the discharge will be $2.027 \times 10^{-3} \times 1.092 = 2.213 \times 10^{-3} \, m^3/sec.$

Therefore time required to empty the water collected is

$$17.66 / (2.213 \times 10^{-3}) = 7980.12 \text{ secs}$$

$$= 2 \text{Hrs and } 13 \text{ min.}$$

From the above analysis it is found that a pipe of 2" diameter is sufficient to drain the rooftop water effectively. Since the average rainy hours spread across the whole day the water will empty simultaneously from the roof without any delay in discharge from the roof top.

9.3.7.2 Filtration System: The filtration system consists of three main components i) Conical mesh filter (Fig. 9.6) to remove the leaves and other solid particles coming from catchments, ii) First flush system, to ensure that runoff from the first spell of rain, is flushed out and does not enter the system and iii) Filtration tank (Fig. 9.7), **f**or the purification of harvested rooftop water. These filters can be employed for treatment of water to effectively remove suspended particles like clay and dust, color and microorganisms from the water. The existing system (Fig. 9.4) is lacking these arrangements except filter tank.

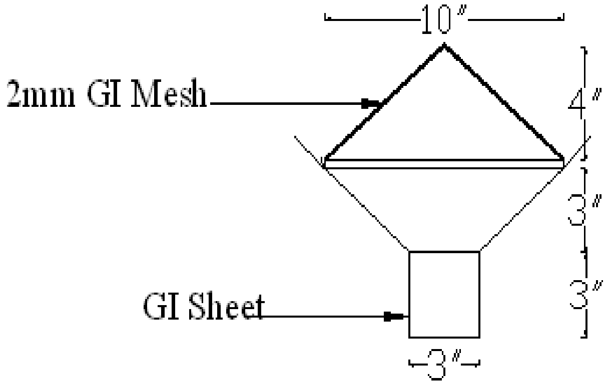

Fig. 9.6 Conical Mesh filter

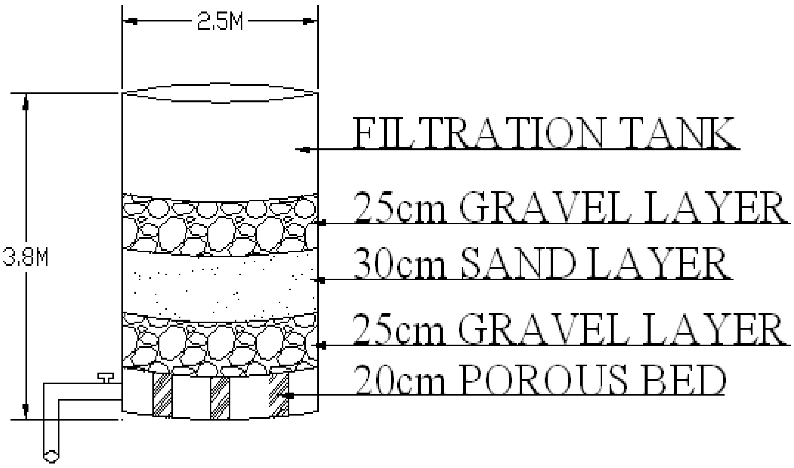

Fig. 9.7 Cross section of the filter tank

9.3.7.3 Capacity of Proposed Sump Tanks: Taking into consideration the daily requirement of water in the campus, the tanks that have been proposed to overcome the shortage have been given in Table 9.3. After the construction of these new sumps a total storage capacity of 336.97 m^3 will be achieved. While the total daily requirement is about 218 m^3, the extra volume of storage acts as standby in case there is less rainfall.

Sump Tank	Volume in m^3	Estimated Cost	Cost/ m^3
Near old Administrative Block (S2)	40	Rs. 1,00,724.31	Rs. 2518
Near Ladies Hostel (S3)	60	Rs. 1,42,904.35	Rs. 2382
Near Gents Hostel (S5)	60	Rs. 1,48,404.35	Rs. 2473.41
Total	160	Rs. 3,92,033.01	

Table 9.3 Estimated Storage and Cost of the Proposed Sumps in the Campus

9.3.7.4 Estimation and Costing: The conveyance system has been designed in such a way that instead of using the larger diameter pipes throughout the length, smaller 2" diameter pipes have been used at collection points at the rooftops to reduce the cost. And these pipes will then be connected to reducers and will be conveyed to the storage tanks through larger 3" diameter pipes at the delivery end. The various components of the drain and storage system have been worked out and found that an average of two rupees fourty six paisa have to be invested per liter (Table 9.3). The layouts of the drain system are shown below (Figs. 9.8 – 9.11). The plans and cross sections of the proposed sumps are given in the figures below (Figs. 9.12 – 9.15).

9.3.7.5 Recharge System: The excess water collected in the sumps can be used for recharging bore wells and open wells (Agarwal A. 2000, Agarwal and Sunitha 1991, 1998). In case of bore wells, holes of 4mm to 6mm may be drilled into the bore well casing at regular intervals up to a depth of about 8 ft – 10 ft from the surface. It is then covered with nylon mesh by wrapping it around the casing. The settling tank is about 8 – 10 ft in diameter with a depth of about 8ft - 10 ft. It may be packed with gravel at the bottom and sand at top. The water can be directly let into these pits and allowed to recharge the bore well naturally. Where open wells are present near the sumps, the excess water which is already filtered is directly let into the open wells through the pipes.

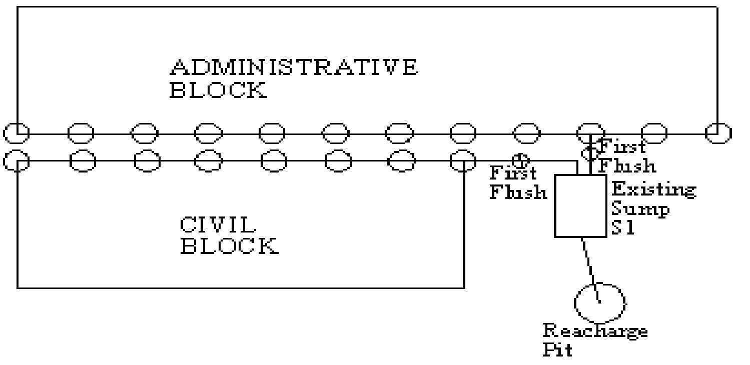

Fig. 9.8 Schematic Plumbing Layout of Collection System for Sump S1

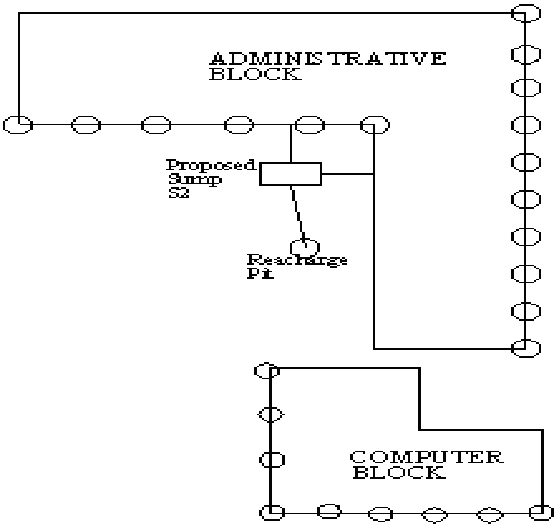

Fig. 9.9 Schematic Plumbing Layout of Collection System for Sump S2

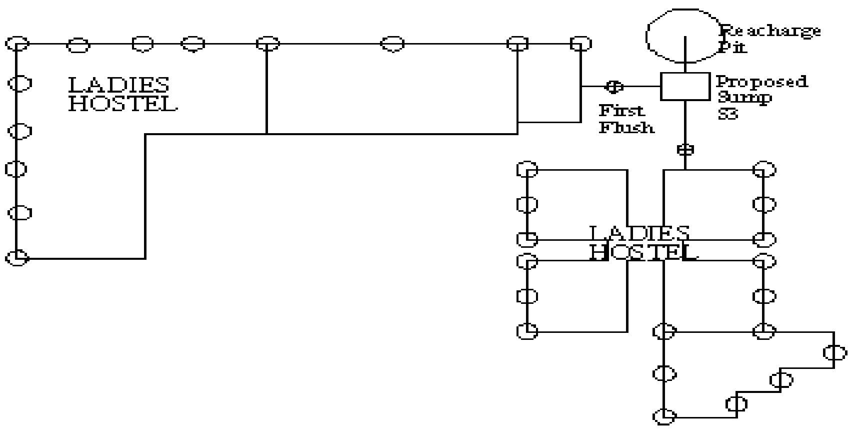

Fig. 9.10 Schematic Plumbing Layout of Collection System for Sump S3

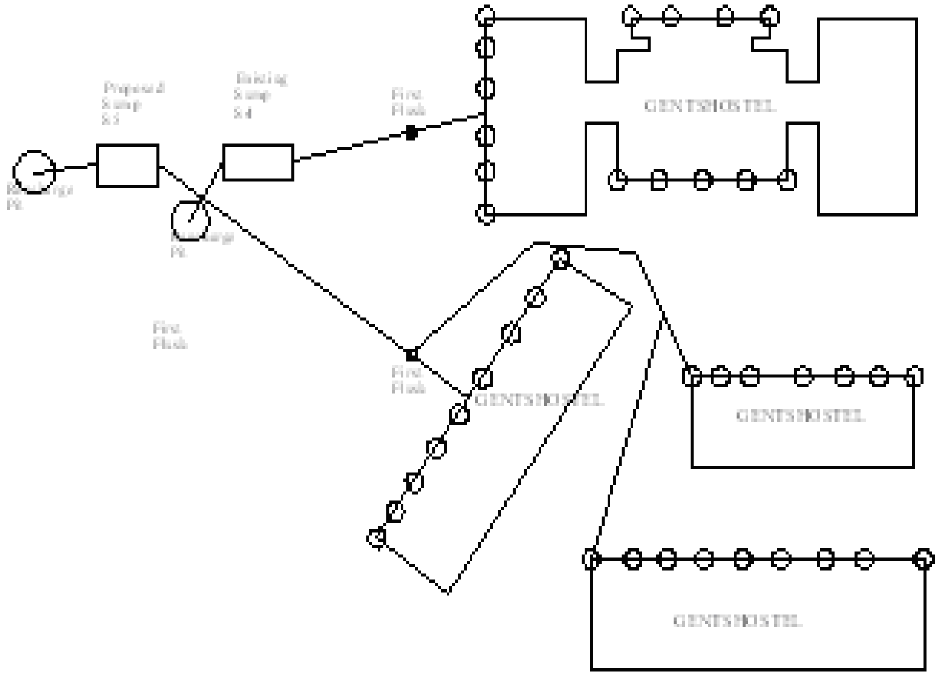

Fig. 9.11 Schematic Plumbing Layout of Collection System for Sumps S4 & S5

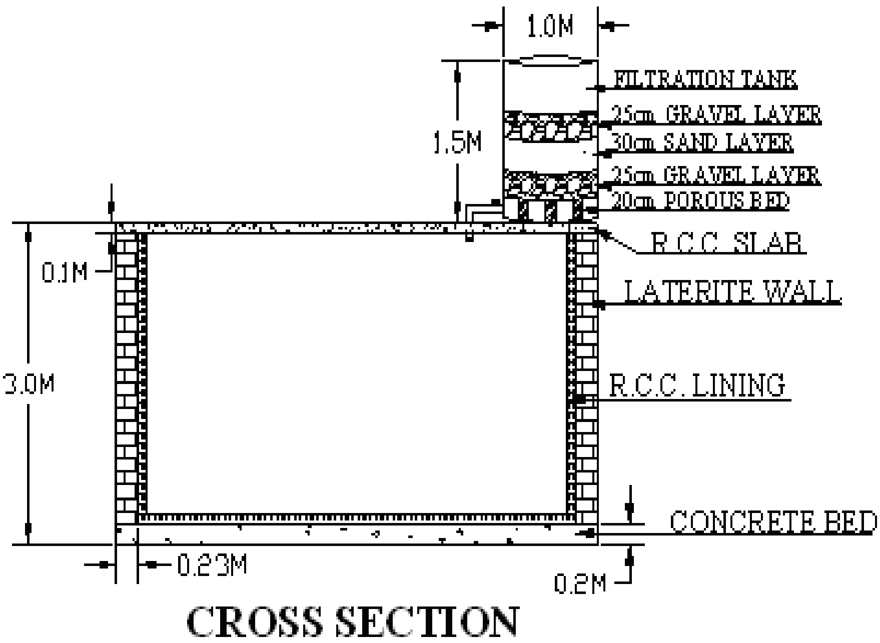

Fig. 9.12 Cross Section of the Proposed Sump S2 near Old Administrative Block

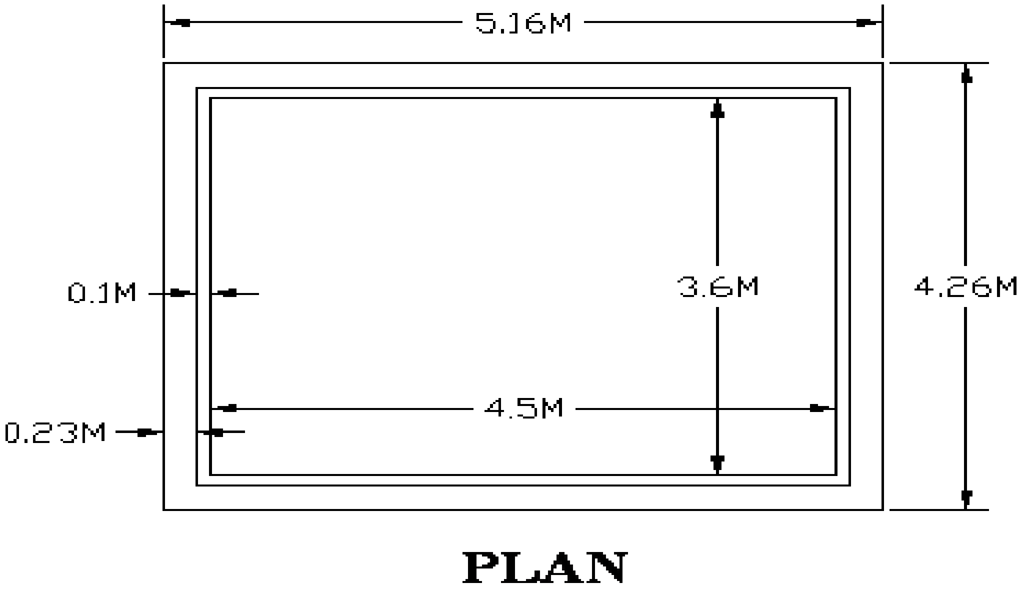

Fig. 9.13 Plan of the Proposed Sump S2 near Old Administrative Block

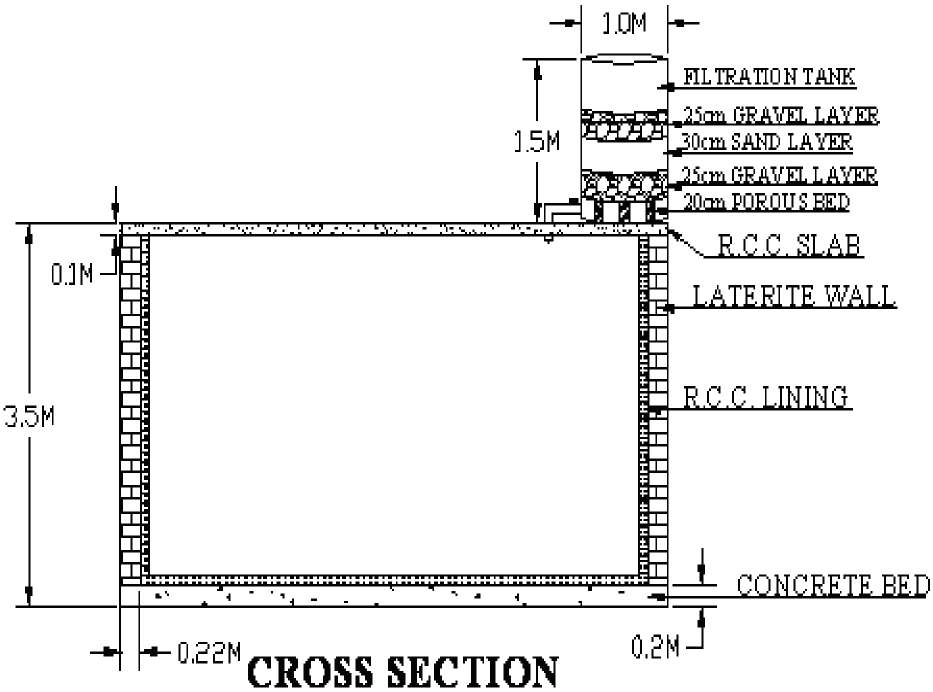

Fig. 9.14 Cross Section of the Proposed Sumps S3 near Ladies Hostel & S5 near Gents Hostel

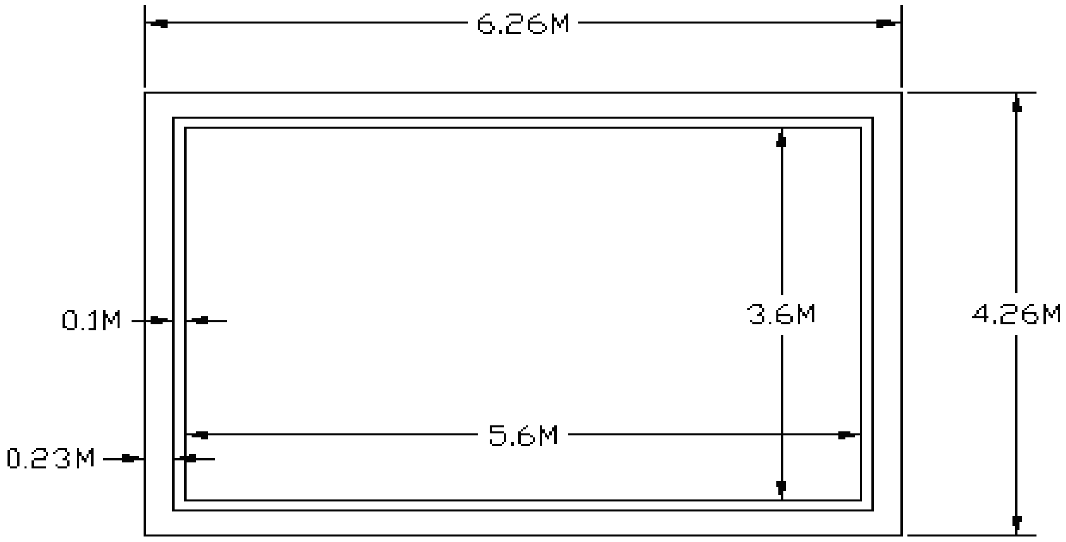

Fig. 9.15 Plan of the Proposed Sumps S3 near Ladies Hostel & S5 near Gents Hostel

9.3.8 Conclusions: Rooftop Rainwater Harvesting System is found feasible for the sustainable development of the water resource management of the NET campus, Nitte. Based on the available rainfall data and campus water requirements, a few Rooftop Catchments have been identified in the campus and suitable Rainwater Harvesting system with proper plan, lay out, design, costing and estimation is proposed with three new sump tanks to store this additional harvested water to manage the campus needs (Radhakrishnan and Lokesh 2010b). The various components of the drain and storage system have been worked out and found that an average of two rupees fourty six paisa have to be invested per liter. This source is more than enough to meet the daily water requirement of the campus during the rainy days stretching a period of about 4.4 months in a year and the establishment cost of it can be regained within three years after which the institution can save an annual pumping cost of about Rs. 1,40,000/-. By avoiding the usage of water from the open wells and bore wells during rainy days, the groundwater table will be improved, preserving the resource for summer seasons. Conjunctive use of rainwater and groundwater is suggested for resolving the water scarcity problem of NET Campus, Nitte for sustainable development and management of the water resources in the campus.

Chapter 10

Conclusions and Recommendations

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS: According to River Basin classification, as per Central Groundwater Board (CGWB), Mulki River basin codified as NTRV014 is a sub basin of Netravati (NTRV) which again is a sub basin (No.1) of Periyar Basin (24^{th} Indian Basin) which covers the southwestern coast of India. The significant findings of the studies conducted in this basin to understand its geohydrological conditions are summarized below:

1. Mulki River Basin, spread over 350 sq. km. drainage area in two coastal districts of Dakshina Kannada and Udupi, is a 6^{th} order closed rectilinear midland draining coastal river basin which exhibits modified dendritic pattern of drainage in general with parallel, rectangular and radial drainage patterns in its different sub-basins. Mulki river basin being a part of Coastal Landform terrain is dominantly covered by Kanara Pediplain with a small stretch of coastal lowland terrain.
2. Major structural disturbance affected the river, dissecting it into three parts pulling down the middle part towards south. The major lineaments trending almost in the E.NE-W.SW control the higher order streams and the lineament fabric aligned in N-S, NW-SE, NE-SW control the lower order streams in this area.
3. Geomorphic evidences and morphometric relations strongly indicate neotectonic activities and regional uplift in this area. This has been supported by the rose diagrams of streams and hypsometric curves of the sub-basins. The gabbroic ridge and structural hillocks also support this view.
4. The basin is having a very coarse graded drainage texture with predominant sheet flow and erosion in this area. The undulating topography with monadnocks, inselbergs, residual hillocks and ridges, flood plain deposits, meandering course and drainage network controlled by lineament fabric favours the groundwater accumulation. But, the drainage texture and drainage density indicate a poor recharge in this area due to the impervious rocks and steep slopes. So, proper

control of surface water movement, through an effective topographic terrain management will favour the geohydrological conditions of the area.

5. Geological investigation of the basin reveals that the basin comprises mainly of Granitic gneisses intruded with South Kanara granite batholiths, with occasional laterite capping on top of the mounds and plateaus besides the unconsolidated river and marine sediments. Basic intrusive of Dolerite, Gabbro and Norite are found criss-crossing the area shaping the hillocks, ridges and mounds in the terrain. The N.NW-S.SE trending dolerite dykes are numerous and relatively abundant in granite. Dolerite and gabbroic dykes show multiple joints related to the stresses. Acidic intrusive of Quartz and pegmatite veins are also found in the study area which are very significant in the storage and movement of groundwater.
6. Thick elevated stratified sediments, cross beddings and steep meandering rivers in the middle reaches of the river channel along with the multiple joints found in the gabbroic mass near Sachcharepete-Bola point towards the neogenic tectonic activity in the area.
7. The joints pattern crossing in an obtuse angle in a rectilinear basin shape indicates the strong influence of structural disturbance in the area. These joints pattern may be responsible for the groundwater potential of this otherwise hard rock area. Many sets of joints are in the E.NE-W.SW directions where the river also trend in the same direction. Other major trends of the lineaments are NE-SW, N-S, E-W and NW-SE. There are some lineaments extending up to the Western Ghats from the basin which are highly potential for groundwater explorations.
8. Lineament studies confirm the earlier report of three active faults in the area which are responsible for the offset of the river and recent upliftment of the terrain. The major trend of the river course is determined by the master joint extended in the northern side of the basin giving an asymmetry to the drainage basin. The parallel drainage pattern of the higher order streams are determined by the lineaments in the study area. The major trends of the lineaments are in E-W, W.NW-E.SE, NE-SW, N-S, N.NE-S.SW, N.NW-S.SE and NW-SE directions according to their density.
9. Majority of the foliations found in the rocks are oriented in the W.NW-E.SE to NW-SE directions. The foliations are dipping towards N to NE and majority of the

foliations found to be within 40°-50° dipping category. Granites shows northerly dipping strike joints of 30°-40° and 70°-80° trending in the N80°W-S80°E direction other than vertical dip joints. These are very important clues in the prospecting of groundwater in these hard rock terrains.

10. The soil study of the area reveals that there are about seven genetic types of soils spread over the basin. And they can be broadly divided into four types depending on their origin and geohydrological condition such as alluvial soils, loamy soils, gravelly clayey skeletal soil and lateritic soils of different encrustations. The soils and geological structures such as lineaments and joints in the otherwise hard and impervious rocks have an influence on the geohydrological conditions of the area.
11. The hydrogeochemical analysis of about 21 physico-chemical parameters of the water samples collected from the study area in three seasons of pre- and post-monsoon periods revealed that most of the groundwater samples are suitable for irrigation quality requirements, and are well within the permissible limits of drinking water standards.
12. The study of groundwater quality in Mulki River basin shows the influence of geology, climate and anthropogenic activities on the water quality of the basin. An integration of various water quality parameters in a geoinformatic platform found to be a better and faster tool in analysing and understanding spatial variation of the water quality, its vulnerability and its probable cause in temporal and spatial domain in the study area for the sustainable development of groundwater.
13. From the Groundwater Vulnerability maps and Water Quality Index maps it has been observed that the coastal area is more vulnerable in respect of various quality parameters such as Turbidity, pH, Calcium, Chloride, TDS and Total Hardness, and it extends up to 7 kilometres from the coast especially along the alluvial plain indicating the influence of tidal fluctuation, geology and anthropogenic activities in water quality deterioration.
14. An analysis on the hydrogeochemistry of the groundwater samples from Mulki river basin revealed that in the study area an average of 42% open wells and 89% bore wells show negative Schoeller Index indicating cation-anion exchange reactions. And about 58% of the open well and 11% of the bore well water samples show positive values indicating Base Exchange reaction. This also point

towards the significant difference in the bore well water chemistry where the chloro-alkaline disequilibrium dominates with a cation-anion exchange, whereas in the open well water chemistry Base Exchange reaction slightly predominates or both Base Exchange and cation-anion exchange almost balance. Majority of the bore well samples show negative chloro-alkaline ratio indicating the discharge zone whereas in the case of the open wells 58% wells show positive chloro-alkaline ratio indicating the recharge zone .

15. The ratio of alkali ions vs. chloride ions in both seasons shows the alkali is balanced by the chloride ions in majority of samples. When almost all the pre-monsoon and post-monsoon bore well water samples show silicate weathering of the rocks in deeper source of the study area, only about 50% open well waters show silicate weathering of the rocks in the shallow zones in the study area. From these it can be inferred that the bore well waters except near the coast are influenced by the silicate weathering of the igneous rocks, whereas the open well waters are influenced by the clay mineral reaction except those near the coast influenced by the chloride dissolution from the salt water ingression in the study area.
16. The HCO_3^- vs. $(Ca^{2+}+Mg^{2+})$ ratio suggests that the bicarbonate chemistry is almost reverse during pre-monsoon and post-monsoon seasons in the study area. The plot of sulphate-chloride relations in the study area explains the multiple origins of carbonates of calcium and magnesium during pre-monsoon period whereas the dissolution in carbonates leaching as the only source during post-monsoon. The plot of $(Ca^{2+}+Mg^{2+})$ vs. $(HCO_3\text{-}+SO_4^{2-})$ for pre-monsoon shows reverse ion exchange, whereas during post-monsoon they show dominance of ion exchange process. The groundwater analysis suggests that weathering of alumina-silicate minerals like plagioclase, mica, amphiboles and pyroxenes are major contributors for Na, K, Ca, Mg and HCO_3 along with minor addition of Ca, Mg and HCO_3 from dissolution of carbonates.
17. Gibb's diagram suggests that during pre-monsoon season Rock Interaction Domain is having a dominating influence on the groundwater, whereas in post-monsoon season Precipitation Domain influences Open well water.

18. In the groundwater chemistry, the order of cations abundance found to be Mg>Na>K>Ca and that of anions Cl>HCO_3>SO_4>NO_3 during pre-monsoon, and it is Na>K>Ca>Mg for cations and HCO_3>Cl>NO_3>F for post-monsoon respectively. The noticeable predominance of the bicarbonate type (90%) in the bore well samples during post-monsoon shows the distinct facies of bore well sources in the study area. The water chemistry and mixing up of the ionic facies indicate the study area belongs to a coastal area. The total hydrochemistry in the study area is dominated by alkaline earth and strong acids with carbonate hardness (secondary alkalinity) and primary salinity influenced by the weathered granitic gneisses and leached laterite other than the influence of saline water. More than one fourth of the samples also fall in the mixed zones indicating balance on anion-cation pair. The difference in the hydrochemistry during pre-monsoon and post-monsoon periods indicates the influence of weathering, infiltration, mixing and leaching in the study area. During pre-monsoon, if the alkaline earth exceeds the alkalis, it is alkalis which exceed alkaline earth during post-monsoon period indicating the possibility of different origin. During both the pre- and post-monsoon periods, the strong acids exceed week acids with carbonate hardness and primary salinity. Again this shows the variation in the origin and mixing of the water types in the study area during two different seasons i.e., before and after heavy monsoon indicating the influence of weathering and heavy rainfall in this area.
19. Analysis of groundwater samples using Multi-Rectangular Diagrams (MRD) clearly shows the predominance of bicarbonate facies in the study area, where magnesium bicarbonate facies is changed to Sodium bicarbonate facies during post-monsoon indicating ion exchange and dissolution chemical processes happening in this area after heavy monsoon. The influence and mixing up of coastal waters can also be noticed in both the seasons from the MRDs. This study also reveals the advantage of MRD over the Piper diagram where the dominant type of Sodium bicarbonate facies in the post-monsoon period is not clear in the latter one.
20. According to Handa's classification, major part of the study area is characterised by waters of permanent hardness where the pre-monsoon samples contribute much

towards this. But during post-monsoon period the temporary hardness predominates over permanent hardness. When majority of the pre-monsoon samples fall in A_1 and A_2 categories of permanent hardness it is in the A_3 category the post-monsoon samples fall. This information could be conveniently used for developing groundwater for domestic, agricultural and industrial purposes. Almost all the samples during both the seasons show very low to low salinity and low sodium hazard satisfying the irrigational water quality requirements.

21. According to Schoeller's concept of water types, which is related to the evolution of groundwater with respect to chemistry reveals that Types III and IV (chloride dominated) contribute to 72% of the groundwater samples analysed during both the seasons of 2009. This indicates that majority of the groundwater in this study area is having a greater residence time in the aquifers. The carbonate dominated water (Type I) is totally absent during post-monsoon period showing the Base Exchange and fluxing of the same with chloride or sulphate during post-monsoon. The sulphate dominated over chloride water (Type II) is represented by 39% of the samples during pre-monsoon and by 7% during post-monsoon periods.
22. According to Stuyfzand (1989) classification, which aim at defining natural types of water based on major cations and anions, four water types based on chloride viz: Brackish, Fresh, Oligohaline and Very Oligohaline; five sub water type based on alkali viz: Very Low, Low, Moderately Low, Moderate and Moderately High; nine water facies viz: (Na+K) HCO_3, (Na+K) Cl, (Na+K) mixed, $CaHCO_3$, Ca mixed, $MgHCO_3$, $MgSO_4$, $MgCl_2$ and Mg mixed; and three significant environment viz: fresh water intrusion, adequate flushing and no significant environment have been identified in the study area. Majority of the pre- and post-monsoon samples (82% & 86% respectively) belongs to Oligohaline (g) water type indicating the presence of chloride ions in the samples showing the long residence time of the water in the aquifer. About 11% of the open wells and 23% of the bore wells found to be of fresh water type. The very low alkaline sub-type water predominates over others being low alkaline water, moderately low alkaline water, moderate alkaline water and moderately high alkaline water following the decreasing order. During pre-monsoon, the most predominant water type in the study area is found to be $MgHCO_3$ facies, and the predominant cat ion the Mg^{2+}

and anion the HCO_3^-; whereas during post-monsoon Alkali (Na+K) mixed facies found to be predominant being alkali (Na+K) the cat ions and HCO_3^- the anions respectively predominating. In the bore well waters, $MgHCO_3$ facies predominates during pre-monsoon whereas $CaHCO_3$ facies predominates in the post-monsoon period. It is worth to notice that during pre-monsoon Mg^{2+} is the predominant cat ions whereas it is almost absent during post-monsoon, other than the total absence of sulphate during post-monsoon. This will probably explains the extensive leaching actions of the groundwater over the laterite or highly weathered calc-alkali feldspars and clay minerals of overlying granitic rocks in this area during heavy monsoon. During pre-monsoon, environment indicating 'fresh water intrusion at anytime and anywhere' predominates with surplus sodium and magnesium, whereas during post-monsoon environment indicating 'adequate flushing with water of constant temperature' predominates with sodium and magnesium in equilibrium. Majority of the bore wells show the freshwater intrusion whereas majority of the open wells show the adequate flushing with water of constant temperature. About 12% of the pre-monsoon open well samples belong to the 'no significant environment' category also.

23. Based on groundwater chemistry three sets of strong relationships existing between major cations and anions of groundwater in the study area have been established using correlation coefficient of different physico-chemical water quality parameters in different sources and different seasons. A high significant positive relationship of competitive ions established between SO_4^{2-} & Cl^- in open wells and Na^+ & Ca^{2+} in bore well samples, and that of affinity ions between SO_4^{2-} & Mg^{2+} in open wells and Na^+ & Cl^- in the bore well water samples indicate the contamination of sources through anthropogenic and natural processes of saline water intrusion generating hard water in the pre-monsoon. In the post-monsoon open well water samples also this high significant positive relationship is established between the Na^+ & Ca^{2+} and Na^+ & HCO_3^-. Among non-competitive ions relationship, a high significant positive relationship of ions has been established between Na^+ & K^+ in the pre-monsoon open well and surface water samples indicating the influence of weathering and leaching. Significant positive correlation has been established by Fe & Na, SO_4^{2-}& HCO_3^-, Na^+ & HCO_3^-, SO_4^{2-}

& Mg^{2+} , Ca^{2+} & Mg^{2+} and Cl^- & HCO_3^- in the open well water samples during pre-monsoon, whereas during post-monsoon it is among Ca^{2+} & Na^+, SO_4^{2-}& Cl^-, SO_4^{2-}& HCO_3^-, SO_4^{2-} & Mg^{2+} , SO_4^{2-} & Ca^{2+} , Ca^{2+} & Mg^{2+}, Na^+& K^+ and HCO_3^- & Cl^- . The correlation of ions in the pre-monsoon and post-monsoon samples are almost similar except among Fe^{2+} & Na^+, Na^+ & HCO_3^- relations present in pre-monsoon and Ca^{2+}&Na^+, SO_4^{2-}& Cl^-, SO_4^{2-} & Ca^{2+} and Na^+& K^+ established in the post-monsoon open well water samples. In the bore well samples, significant positive correlation has been established only by HCO_3^-& K^+ during pre-monsoon, whereas during post-monsoon it is among SO_4^{2-}& Mg^{2+}, Na^+ & Cl^- and Ca^{2+} & Mg^{2+} indicating the influence of rock weathering and leaching. The high positive relationship established among various ions of competitive, non-competitive and affinity ions in the pre-monsoon open well water samples suggests the influence of the natural and anthropogenic contaminations in these water sources. But there is no such strong relationships established in the cases of post-monsoon bore well water indicating the absence of such influence in those water resources.

24. When various physico-chemical water quality parameters of the samples collected from the study area have been compared with the drinking water standards of National (BIS 1991) and International (WHO 1993) agencies, the important water quality parameters in the study area are found to be dominantly well within the permissible limit of drinking water standards prescribed except at a few places. Majority of the open well waters in the lateritic aquifers of the study area demonstrate low pH value indicating the acidic nature influenced by the laterite aquifer. The acidity, turbidity and iron content in the bore well waters can be attributed to the low quality and improper casing adopted in these wells. A very few groundwater and surface water samples near to the coast and river trace has shown the influence of saline water intrusion. Majority of the open well water samples and bore well water samples were having low fluoride concentration (<0.6ppm) than the minimum desirable limit of WHO drinking water standards.

25. The analysis of the pre- and post-monsoon water samples from the study area reveals, that a total of about 27% pre-monsoon water samples comprising 20% of open wells, 48% of bore wells and 35% of surface water samples were contaminated, whereas about 19% of post-monsoon groundwater samples

comprising 14% of open wells and 60% of bore wells were contaminated and are beyond permissible limit of drinking water standards. Other than this, 53% of pre-monsoon and 80% of post-monsoon open well water samples, 7% of pre-monsoon and 10% of post-monsoon bore well water samples, and 85% of the surface water samples have been affected by pH (predominantly acidic) beyond permissible limit of drinking water standards.

26. In the open wells of the study area, about ten drinking water quality parameters have been affected with a maximum of seven in certain samples during pre-monsoon, whereas only about seven parameters with a maximum of three in any sample have been affected during post-monsoon season. In the bore well water samples of the study area, about seven drinking water quality parameters have been affected with a maximum of three in any samples during pre-monsoon, whereas only four parameters with a maximum of three in any sample have been affected during post-monsoon season. In the surface water sources it is about eleven drinking water quality parameters that have been affected with a maximum of nine in certain samples during pre-monsoon. The study revealed that the drinking water qualities of pre-monsoon groundwater samples especially open wells have been affected more compared to the bore wells in the region. The less contamination during post-monsoon may be due to the groundwater recharging, flushing and dilution of the open well water during heavy monsoon in the study area. The drinking water qualities of surface water sources during pre-monsoon have been affected more compared to groundwater sources in the study area.
27. In order to understand the suitability of the water resources in the study area for irrigation purposes, about nine important characteristics such as total salt concentration (EC), Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Percentage Sodium (% Na), Permeability Index (PI), Magnesium Hazard (MH), Chloride, Sulphate and Chloride/Bicarbonate ratio have been computed and analysed. A great variation is noticed in irrigation water suitability based on different characteristics and is found to be 95% (pre-monsoon) and 100% (post-monsoon) based on EC, 100% (pre-monsoon) and 98% (post-monsoon) based on SAR, 84% (pre-monsoon) and 33% (post-monsoon) based on % Na, and 60% (pre-monsoon) and 03% (post-monsoon) based on RSC. Based on EC and SAR

more than 95% of waters in the study area can be used for irrigation without the fear of salinity hazard. Based on Wilcox (1955) diagram relating electrical conductivity to sodium per cent shows that 97% of the post-monsoon samples are Excellent for irrigation whereas only 93% of pre-monsoon samples found to be suitable for irrigation falling in the categories of permissible to Excellent. But, almost all the samples (97%) of post-monsoon and majority (60%) of pre-monsoon showed very high value of Residual Sodium Carbonate making the major water resources in the study area unfit for irrigation without proper corrective measures. Continued usage of high residual sodium carbonate water affects the yields of crops. On the basis of Doneen's classification, majority of the water samples (60.39%) fall in Class-II whereas 12% in Class I in the Doneen's chart, implying that the majority of pre-monsoon water is of good quality for irrigation purposes. All the post-monsoon samples are of excellent quality for irrigation purposes thanks to its high permeability index (PI) falling in the Class-I (75%) and Class-II (25%) water types only. From the magnesium hazard (MH) analysis of the post-monsoon water samples, 92% found to be suitable for irrigation purposes, whereas only 31% of the pre-monsoon samples found to be suitable for irrigation. When 34% of open well waters and 52% of surface waters during pre-monsoon found to be suitable for irrigation based on MH, all the bore well waters during pre-monsoon found to be unsuitable for irrigation purposes. Based on Chloride concentration 97% of the water samples found to be suitable for irrigation purposes, except a few along the coast where the saline water migration might have contaminated the surface and open well water sources. The water resources in the study area found to be excellent for irrigation regarding sulphate concentration. From the chloride-bicarbonate ratio analysis, about 22% of the water resources in the area comprising 30% of the surface waters, 24% of open wells and 8% of the bore well sources have been contaminated with saline water intrusion and is not suitable for irrigation purposes.

28. In order to understand the variation and distribution pattern of different water quality parameters they have been plotted and extrapolated in spatial and temporal domain using geographic information system (GIS) platform and found to be a better tool in understanding the quality variation of groundwater in a spatial and

temporal domain. The spatial distribution maps of different water quality parameters suggest that the geology of the area has a significant influence in the concentration of certain parameters in the groundwater other than the seasonal climatic influence and localized anthropogenic interference observed. The temporal variation could be due to the fluctuation of the groundwater table and infiltering rainwater other than outside influence in the natural system. The water quality vulnerability map based on standard water quality parameters has been found to be a better and faster tool in demarcating the vulnerable area for the sustainable development of the water resources. The study also revealed that the coastal area is more vulnerable in respect of various quality parameters such as pH, Turbidity, Total Hardness, TDS, Calcium and Chloride which extends up to seven kilometres from the coast especially along the alluvial plain indicating the influence of rapid urbanization and industrialization in water quality deterioration.

29. An analysis of the Water Quality Indices (WQI) and its mapping in spatial and temporal domain in the study area found to be a faster and better tool in assessing and rating the suitability of groundwater for drinking water based on quality weightage. The spatial and temporal variation of the same found to be a very good tool in assessing the source of contamination and its management. The very high WQI at the coastal front near the mouth of the river and its extension along the river course upstream up to a certain distance during pre-monsoon indicates the influence of saline water and its migration along tidal water in this area. Other places where very high water quality indices noticed in the inland area suggests the influence of geology in groundwater quality stressed by the spatial distribution of WQI. The temporal variation in distribution pattern and density of WQI points to the significant role of precipitation and infiltration playing in the determination of water quality.
30. By proper integration of these hydrogeochemical data with geology, geomorphology, hydrometeorology and hydrogeophysical analysis data on a GIS platform can open up new vistas for the sustainable development and management of the water resources in the study area.
31. In hydrogeophysical studies, the Vertical Electrical Sounding (VES) using Schlumberger array has been found to be an effective tool in determining the

bedrock and aquifer characteristics of the Mulki river basin. The bedrock in this area found to be at an average depth of 8.83 metres varying from 0.39 metres to 66.81 metres from the surface. The layer parameters based on the resistivity values and the cross section analysed with computer modelling are found to be matching with the geology or litholog of the area. The resistivity of the terrain is represented by 2 layer curves to 6 layer curves indicating its variation in groundwater potential and depth of bed rock. The top layer has an average thickness of about 1.83 metres varying from place to place depending on the weathering. The second layer has an average thickness of about 7.84 metres and resistivity variation noticed depending on the geology and aquifer characteristics. The third layer is of unconfined aquifer zones with an average thickness of about 15metres represented predominantly by H & K types of curves other than Q-type representing saline water aquifer, and A-type representing dry zone. Fourth and fifth layers represent deeper confined aquifers or impermeable rock with varying resistivity values. From the above studies, confined and unconfined aquifer zones in the study area were identified. The variation in the thickness and apparent resistivity's of the formations found to be controlled by the topography, geology, weathering, and the quality of water present in it. Depending upon the resistivity and thickness of layers coupled with knowledge of local geology, the yield can be predicted. Based on resistivity cross- sections the saline water transgression along coastal stretch also has been established.

32. The hydrometeorological investigation of the basin reveals a very high average rainfall of about 4264 mm. with regional and temporal variation with in the basin itself. The rainfall in the study area is uneven spread for a period of four to five months duration with an average daily rainfall of about 35mm/day, and shows an overall decreasing trend for the last four decades. The rainfall decreases from northeast to southwest in the study area showing maximum at Karkala and minimum at Mulki. Rainfall in the basin is found to be maximum during July. From the analysis of the moving average curves, a nine year trend of continuous variation in rainfall pattern could be noticed. The climatic year in the study area has been classified into four seasons such as Pre-Monsoon (March-May), South-West Monsoon (June-September), North-East Monsoon (October-November) and

Post-Monsoon (December-February). The major contributor of the rainfall with more than 87% in the study area is found to be from the southwest monsoon. The river basin falls under the wet climatic zone and a balance in distribution of rainfall in wet and dry years is found in this area. Out of the 1496.70 x 10^6 cubic meters of storm water available in the basin, only 276.72 x 10^6 cubic meters is stored as groundwater, whereas about 771.16 x 10^6 cubic meters per annum is lost as runoff, which could be utilised by site specific watershed management practices and suitable rainwater harvesting methods in this area for sustainable development. Conjunctive use of rainwater along with groundwater and surface water could be planned for the sustainable development and management of the water resources in this area.

33. The water management studies revealed that the study area is having surplus storm water and groundwater balance but is not used properly to tap the irrigation potential of the area.
34. Depth to water level is comparatively lower near the river courses and alluvial plains, whereas it is very high in lateritic region.
35. Annual average water table fluctuation is found to be about 6.85 meters in the Mulki River basin.
36. Approximately about 2,404.35x10^6 cubic meters groundwater is found to be declining (drafted) from the storage every year, but is replenished during monsoon again.
37. The water level rise starts immediately after rainfall indicating high infiltration through the highly porous laterite resting above the shallow granitic bed rock in the study area.
38. The monthly average water table of the observed wells in the study area shows a sharp declining trend during July to December, whereas during January to May (Pre-Monsoon) the trend is gentle compared to other seasons. This shows that the groundwater flow is maximum during the rainy season since the evapotranspiration is minimum during these months.
39. Water table is found to be roughly following the topography of the area during non-rainy seasons.

40. The aquifers in the area are recharged to an extent of 28,590 hectametres and net annual recharge of 24,302 ha.m. is available for development. The annual net draft from the aquifer is estimated to be 993.93 ha.m. only and a balance potential of 23,308 ha.m. is available for future utilization, but unevenly distributed in the area.
41. From the Land Use/Land Cover studies it is found that 45% of the study area is covered by agricultural land where 29% of the area is covered by paddy fields and another 16% with other cultivated lands, whereas 17% of the area is found to be wastelands indicating the possibility for rainwater harvesting and underground recharge.
42. About 73 Traditional Rainwater Harvesting Structures (TRWHS) with a density of one in every 4.8 sq.km. covering about 13.5 hectares area of the basin have been identified and delineated, but are found to be defunct without proper maintenance. Cultivated area of about 29% in the basin has been found in clustered strips, irrigated by a good practice of ideally located rain fed TRWHS like tanks, ponds, etc. The study also revealed that rehabilitating old TRWH structures and increasing their number to at least one in every Sq. Km. area, more than 50 per cent of the runoff water can be utilised.
43. About 56 microwatersheds covering 13% of the Mulki River basin have been identified, delineated and mapped. Development of microwatersheds and traditional rainwater harvesting structures can improve the water resource management of this area for drinking and irrigational purposes. There is an urgent need to rehabilitate the silted and abandoned tanks of this area which may improve the water table of this area enhancing agriculture and socio-economic conditions of the area.
44. Remote Sensing and GIS techniques are found to be efficient tools in identifying, delineating and mapping of microwatersheds and TRWHS for sustainable development and management of water resources. The Google earth pictures can be effectively utilized for the cost effective planning and development of microwatersheds and rehabilitation studies of traditional rainwater harvesting structures which is established through a study of the same in Mulki River basin for sustainable development.

45. Integrated approach using Geoinformatics is found to be a good tool for the sustainable development and management of river basins or watersheds. The integration of various data derived from different geohydrological studies and thematic maps prepared out of them in a GIS platform could broadly delineate the groundwater potential zones of the study area based on the geomorphic landforms, terrain conditions and lithological characteristics. High values of lineament density are recorded in the study area indicating moderate groundwater prospects.
46. Case studies of a rooftop rainwater harvesting structure and restoration of a silted tank proved to be highly useful cost effective and eco-friendly methods for the sustainable development and management of the rainwater resources in the Mulki River Basin. Further other watershed development methods at micro- and mini-watershed levels are found to be effective for the sustainable water resource development and management in the study area.

10.2 RECOMMENDATIONS: Based on the results and conclusions, the following recommendations are made for the practical implementation and for further studies to be carried out.

10.2.1 Recommendations for Implementation:

1. Usually all our developmental activities take place based on administrative units such as district, taluk, block, panchayat and village, which resulted in imbalance and sometimes, no development at all. Watershed being the fundamental unit for the natural resource development and management confined within a natural geographical boundary, it is recommended to implement any resource developmental activity from this basic unit.
2. In nature all the resources are inter-linked and thus, the integrated developmental approach is the best solution for optimal development and management of the water resources in the study area.
3. Since the groundwater and surface water are considered as a single entity and interconnected to each other, the conjunctive use of the same is suggested for the sustainable development of the water resources in the study area.
4. The social and economic development of any region is closely interlaced with the manner of its natural resource management. The unplanned use and

overexploitation of resources will result in various kinds of land degradation, biomass deterioration and siltation of tanks. So a holistic approach of integrating conventional methods with cost effective methods of geomatics has been recommended in planning for local and regional development based on watershed approach.

5. Utilization of freely available Google Earth GIS, maps, images and DEMs are recommended for cost effective planning and development of resources in microwatersheds at village level.
6. A watershed being a confined area, the main function of it is to receive the incoming precipitation and then dispose it off. This being the essence of soil and water conservation, watershed characterization and prioritization is the strategic method recommended in the study area for the sustainable development and management of the water resources.
7. It is recommended to rank and prioritize the already identified and delineated microwatersheds of the river basin the order in which they have to be taken up for development.
8. Overlaying thematic maps upon Digital Elevation Model (DEM) at micro-watershed level can be done for designing and locating sites for water harvesting structures and to identify the suggested land use and its beneficiaries. A water resources action plan may be prepared by integrating basic thematic layers such as land use / land cover, hydro-geomorphology, slope, soil and drainage. This is a multi-action package which would arrest the flow of water on slope, hence prevent the transportation of silt / soil from higher level to that of lower level, thus helping in the soil and water conservation process.
9. Management of watershed encompasses various activities from watershed delineation to monitoring. The suitability of land for development as well as for groundwater occurrence is not only based on a set of physiographic, geohydrological and geomorphological characteristics of the land but also on the economic factors. So characterization of a watershed should be carried out through monitoring of these influencing parameters before the developmental activities begin.

10. People's participation and collective action are critical ingredients for watershed management. Sustainability, equity and participation are the three basic elements of participatory watershed management. So creating awareness among the people about watershed management at micro and mini level, and ensuring their participation in monitoring and maintaining the same through their equity is a must for the success of the implementation for sustainable development.
11. Based up on the suitability of the terrain for a subsurface reservoir and need of the people, design of suitable recharge structures, their numbers, type, storage capacity and efficiency considering the estimated storage space and available source water for recharge should be worked out. Cost estimates of artificial recharge structures required to be constructed in identified areas should also be worked out based on the available data and resources. With the locally available resources and local knowhow the cost effective groundwater recharging structures of small dimensions such as check dams, 'nala' bunds, percolation tanks, farm ponds, surface spreading basins, pits, sub-surface dykes, etc., have been recommended for construction at suitable identified sites. Other than these, in order to reduce the velocity of runoff, soil erosion and to increase the infiltration which helps in increasing in situ moisture conservation, a series of measures like contour bunding, contour trenching, contour border strips, graded border strips, live barriers, ridges and furrows, leveling the ground, diverting stream water to paddy fields, inter bund land management and surplus runoff arrangement to drain excess water from fields are suggested.

10.2.2 Recommendations for Future Research Work:

1. Development and updating of a Geohydrological Geographic Information System (GIS) for Mulki River Basin for its sustainable development.
2. Prioritization of watershed development and watershed management studies in Mulki River Basin using GIS.
3. Geohydrological modelling for the Mulki River basin for sustainable development and management of its water resources.
4. Impact study of different watershed management techniques in selected micro- and mini-watersheds in the study area.

5. Experimental studies on the suitability and impact of selected watershed management techniques in the study area.
6. Delineation and Mapping of high yielding deep potential groundwater aquifers and lineaments in Mulki River basin using integrated methods of Geomatic applications and Geophysical (Electrical Resistivity and Geomagnetic profiling) studies.
7. Study of Neotectonic Activities and its impact on groundwater regime in the study area with special reference to morphometry and geological structures.
8. Study on significance of microwatersheds and Traditional Rainwater Harvesting Structures in the groundwater potential of the Mulki River basin.
9. Influence of Nandikur Thermal Power Plant in the surface water and groundwater reservoirs of Mulki River Basin.
10. Integrated Geohydrological studies of Coastal Aquifers in Mulki River Basin.
11. Environmental Impact Analysis of on-going industrial and developmental activities on the geohydrological regime of Mulki River basin.
12. Impact of fertilizers and pesticides on the groundwater quality of Mulki River Basin.

References

REFERENCES

Abrahams, A.D. (1984) "Channel networks: a geomorphological perspective". *Water Resources Research*, v.20, pp.161-168.

Agarwal, Anil (2000) "A Water Harvesting Manual for Urban Areas". Centre for Science and Environment, New Delhi, P. 35.

Agarwal, Anil and Sunitha Narain (1991) "Rainwater Harvesting" Centre for Science and Environment, New Delhi.

Agarwal, Anil and Sunitha Narain (1998) "Dying Wisdom". Centre for Science and Environment, New Delhi.

Agrawal, G. D. (1999) "Diffuse agricultural water pollution in India". *Water Science & Technology*, v.39, pp.33-47.

Ahmad, N., Sen, Z. and Ahmad, M. (2003) "Groundwater Quality Assessment using Multi-Rectangular Diagrams". *Groundwater*, National Groundwater Association, v.41, no.6, pp.828-832.

Akram, J. and Mushtaq, H.W. (2009) "Delineation of Groundwater Potential Zones in Kakund Watershed, Eastern Rajasthan using Remote Sensing and GIS Techniques". *Jour. Geol. Soc. India*, v.73, pp.229-236.

Aldwell, C.R. (1997) "Hydrogeology and sustainable agriculture, Maharashtra, India". *Environ. Geol*., v.32, no.2, pp. 93-99.

All India Soil and Land Use Survey (AISLUS) (1990) "Watershed Atlas of India" Ministry of Agriculture, Govt. of India, IARI Campus, New Delhi.

All India Soil and Land Use Survey (AISLUS) (1996) "Soil Map of Karnataka" Ministry of Agriculture, Govt. of India, IARI Campus, New Delhi.

Aller, L., Lehr, J.H., Petty, R. and Bennet, T. (1987) "DRASTIC" a standardized system to evaluate groundwater pollution using Hydro-geologic setting". *Jour. Geol. Soc. India*, v.29, no.1, pp.23-37.

Ambazhagan, S. and Archana, M. Nair (2004) "Geographic Information System and groundwater quality mapping in Panvel Basin, Maharashtra, India". *Environ. Geol.*, v.45, pp.753-761.

Anandakumar, S., Subramani, T and Elango, L. (2008) "Spatial variation and Seasonal Behaviour of Rainfall pattern in lower Bhavani river Basin, Tamil Nadu, India". *Ecoscan, International Journal of Environmental Sciences*,v.2, no.1, pp.17-24.

Anantha Padmanabha A.L. (1990) "Geology of Dupadakatte, Sanuru and adjacent areas". Unpublished M.Sc., dissertation submitted to University of Calicut. 87p.

Anderson, J.R., Hardy, E.E., Roach, J.T. and Witmer, R.E. (1976) "A Land Use and Land Cover Classification System for Use with Remote Sensor Data". *Geological Survey Professional Paper* No. 964, U.S. Government Printing Office, Washington, D.C., p. 28.

Anon (2002) "How to Analyse Rainfall Data". Hydrology Project Training Module #SWDP-12, DHV Consultants BV & DELFT Hydraulics, New Delhi, pp. 1-40.

Asadi, S.S., Padmaja V. and Reddy, A.M. (2007) "Remote Sensing and GIS techniques for Evaluation of Groundwater Quality for Municipal Corporation of Hyderabad (Zone -V), India" . *Int. Jour. Environ. Research and Public Health*, v.4, no.2, pp.45-52.

APHA, AWWA, WEF (1995) "Standard Methods for the examination of water and wastewater", 19^{th} Edn., American Public Health Association, Washington D.C.

Aravindan, S. and Chandrashekhar, H.N.V. (2004) "Groundwater Quality in the Hard Rock Area of the Gadilam River Basin, Tamil Nadu". *Jour. Geol. Soc. India*, v.63, pp.625-635.

Auden, J.B. (1954) "Erosional pattern and fracture zones in Peninsular India". *Geological Magazine*, v.91, pp.89-101.

Aurora, S.N. (1985) "Paragenesis of Uraninite and associated ore minerals in the Pre-Cambrian Oligomictic conglomerate from Walkunje, South Kanara District, Karnataka, India". *Jour. Geol. Soc. India*, v.26, pp.17-181.

Awasthy, S.K. and Krishnamurthy, K.V. (1979) "Geology of part of Puttur and Sullia Taluks, South Kanara district, Karnataka". Progress report for the field season 1978-1979, Geol. Surv. India, Karnataka, south circle. pp.1-11.

Ayers, R.S. and Wascot, D.W. (1985) "Water quality for Irrigation". FAO Irrigation and Drainage Paper No. 20, Rev. 1, FAO Rome.

Back, W. (1966) "Hydrochemical facies and groundwater flow patterns in the northern parts of Atlantic coastal plain". *USGS Prof. Paper* 498-A, U.S. Government Printing Office, Washington, D.C.

Badrinath, Krishnappa, Rao, A.M. and Balakrishna (1984) "Features and constraints of the coastal soils of Karnataka". *Technical Bulletin*, no.1, NARP Station, University of Agricultural Sciences, Brahmavara.

Baig, M.Y.C. (1980) "Direct slope techniques of determining absolute resistivity", *Journal of Institution of Engineers (Ind.),* v.61, pp.55-60.

Balasubramanian, A. (1986) "Hydrogeological investigations in the Tambraparni River Basin, Tamil Nadu". Unpublished Ph.D. Thesis submitted to Mysore University, 349p.

Balsubrahmanyan, M.N. (1963-1967) "Progress reports on systematic mapping in part of South and North Kanara Districts, Karnataka State". Unpublished progress reports during field seasons 1963-1967, Geol. Surv. India, Culcutta.

Balasubrahmanyan, M.N. (1975) "The age of the dykes of South Canara, Mysore State". *Geol. Surv. India, Misc. Pubn. No.23*, pp.231-239.

Balasubrahmanyan, M.N. (1978) "Geochronology and geochemistry of archaean tonolitic gneisses and granites of South Kanara district, Karnataka State, India". In: *Archaean geochemistry* by Windley, B.F. and Naqvi, S.M. (Editors), Elseviers Publishers, pp.57-77.

Balasubrahmanyan, M.N., Bishui, P.K., Chandy, K.C., Gupta, S.N., Jana, N.K., Paul, D.K., and Prasad, R. (1982) "New Rb-Sr age of Kanara granite, South Kanara District, Karnataka State". *Jour. Geol. Soc. India*, v.23, pp.402-405.

Ballukraya, P.N. (1996) "Differentiating conductive and resistive inhomogeneities: A new approach in groundwater exploration". *Current Science*, v.71, no.11, pp.926-931.

Ballukraya, P.N., and Ravi, R. (1999) "Characterisation of groundwater in unconfined aquifers of Chennai". *Jour. Geol. Soc.India*, v.54, no.01, pp-13.

Ballukraya, P.N., Jegatheesan, M.S. and Reddy, Rukmangada B. and Baratan, R. (1988) "Delineation of geological contacts by Electrical Resistivity Soundings". *Jour. Assoc. Expl. Geophys.*, v. IX, no.1, pp.31-36.

Ballukraya, P.N., Sakthivadivel, R., and Baratan, R. (1981) "Inadequacies in the techniques of resistivity method for location of water well sites in hard rock areas". *Nordic Hydrology*, v.12, pp.185-192.

Ballukraya, P.N., Sakthivadivel, R., and Baratan, R. (1983) "Breaks in resistivity sounding curves as indicators of hard rock aquifers". *Nordic Hydrology*, v.14, pp.33-40.

Ballukraya, P.N., Sharma, K.K., Reddi, Rukmangada B. and Jegatheesan, M.S. (1989) "Identification of Lateral inhomogeneities from VES curves". *Jour. Assoc. Expl. Geophys*., v. X, no.4, pp.171-183.

Banerjee, P.K. (1993) "Quaternary tectonics and climatic record in tropical weathering profiles". *Current Science,* v. 64, nos. 11& 12, 10&25, pp.921-923.

Banerjee, P.K. (1994) "On a possible programme of multi-element resource prospecting within and below the Laterite regolith of Karnataka". *Geo Karnataka*, MGD Centenary Volume, Karnataka Assistant Geologists Association, Bangalore.

Bartarya, S.K. (1993) "Hydrochemistry and rock weathering in a sub-tropical Lesser Himalayan river basin in Kumaun, India". *Jour. Hydrol*., v.146, pp.149-174.

Basappa Reddy, M. and Gaikwad, R.L. (1985) "Use of Remote sensing Techniques for targeting groundwater in fractured crystalline rocks: Two case studies from Karnataka". *Proc. of sixth Asian conference on Remote sensing*, Hyderabad.

BGS (2000) "Groundwater Quality: Southern India". *WaterAid guidance information sheets*, WaterAid India office, British Geological Survey, pp.1-4.

Bhat, H.G. (1995) "Long-Term Shoreline Changes of Mulki-Pavanje and Nethravathi-Gurupur Estuaries, Karnataka". *Jour. Ind. Soc. Remote Sensing*, v. 23, No. 3, pp.147-153.

Bhatt, C.M., Littoria, P.K. and Sharma, P.K. (2008) "Geomorphic signatures of active tectonics in Bist Doab interfluvial tract of Punjab, NW India". *Jour. Ind. Soc. Remote Sensing,* v.36, no.4, pp.361-373.

Bhattacharya, P.K and Patra, H.P. (1968) "Direct Current Geoelectric Sounding: Principles and interpretation", Elsevier, Amsterdam. pp.25-30.

Bhimasankaram, V.L.S., Murali, S. and Tarkov, A.G. (1969) "A comparative study of the Wenner and Schlumberger configurations in the electrical resistivity methods of prospecting". *NGRI Bulletin,* v.7, no.4, pp.159-167.

Bijumol Jose (2008) "Groundwater Information Booklet, Udupi District**,** Karnataka". Central Groundwater Board, South Western Region, Bangalore, pp.1-21.

BIS (1963) "Indian Standard Specification for irrigation water", Bureau of Indian Standards IS: 2296, Govt. of India, Calcutta.

BIS (1991, 1993) "Indian Standard Specification for drinking water", *Bureau of Indian Standards IS: 10500,* Govt. of India, Calcutta.

Biswas, S.K. (1988) "Structure of the Western Continental Margin of India and Related Igneous Activity". *Memoir of the Geol. Soc. India*, v.10, pp.371-390.

Blanney, H.F and Criddle, W.D. (1950) "Determining water requirements in irrigated areas from climatological and Irrigation data". USDA Irrigation and Water Conservation, SCS TP-96.

Blanney, H.F and Criddle, W.D. (1962) "Determining consumptive use of irrigation water requirements". *USDA Technical Bulletin*, No.1275, Washington, D.C.

Blaszezynski J.s. (1997) "Landform Characterization with Geographic Information Systems". *Photogram. Engg. & Remote sensing*, v. 63, no.2, pp.83-191.

Bower, H. (1978) "Groundwater Hydrology" International Student edition.

Bull W. and McFadden L. (1977) "Tectonic geomorphology of north and south of the Garlock Fault California", In: *Geomorphology in Arid regions* (ed.) Doehring D O (Binghamton: State University of New York), pp. 115–138.

Cardona, A., Rivera, J.J.C., Alvarez, R.H. and Castro, E.G. (2004). "Salinization in coastal aquifers of arid zones: An example from Santo Domingo, Baja California Surv. Mexico". *Environ. Geol.*, v.45, pp.350-366.

Carroll (1962) "Rainwater as a chemical agent of geological processes- A review". *USGS Water supply paper* 1535, pp.18-20.

Cerling, T.E., Pederson, B.L. and Damm, K.L.V. (1989) "Sodium-Calcium ion exchange in the weathering of Shales: implications of global weathering budgets". *Geology*, v.17, pp.552-554.

CGWB (1998) "Groundwater Development perspective in Dakshina Kannada District, Karnataka State". Central Groundwater Board (CGWB), South Western Region, Bangalore, pp.1-35.

CGWB (2008) "Groundwater Information Booklet - Udupi District, Karnataka", Central Groundwater Board (CGWB), South Western Region, Bangalore, pp.1-21.

CGWB and CPCB (2000) "Status of Groundwater Quality and Pollution Aspects in NCT-Delhi, January 2000".

Chandra P.C., Ramakrishna, A. and Singh, H. (1983) "Results of geoelectrical surveys for groundwater in parts of Cannanore District, Kerala". *Jour. Assoc. Expl. Geophys*., v. III, no.4, pp.11-15.

Chathurvedi, R.S. (1983) "Integrating Remote sensing techniques in groundwater exploration – A typical case study from Bundelkhand region in Uttar Pradesh". *Proc. Nat. Symp. on Remote Sensing in Development and Management of Water Resource*s, Ahmedabad.

Chen, Y., Sung, Q. and Cheng, K. (2003). "Along-strike variations of morpho-tectonics features in the Western Foothills of Taiwan: tectonic implications based on stream-gradient and hypsometric analysis". *Geomorphology,* v. 56, pp.109–137.

Chettti, S.B. (1997) "Geomorphological and Lineament studies for Groundwater targeting in Hire Halla basin using Remote Sensing data*". Proc. Nat. Sem. on Hydrogeology of Pre Cambrian Terrains and hard rock areas*. Karnatak University, Dharward, India, pp. 225-228.

Chopra, R., Dhiman, R.D. and Sharma, E.K. (2005) "Morphometric Analysis of sub-watersheds in Gurdaspur District, Punjab using Remote Sensing and GIS Techniques". *Jour. Ind. Soc. Remote Sensing*, v.33, no.4, pp.531-539.

Chorley, R.J., Donald E.G. and Pogorzelski, H.A. (1957) "A new standard for estimating drainage basin shape." *Am. Journal of Science*, v. 255, pp.138-141.

Chow, Ven T. (Ed.). (1964) "Handbook of Applied Hydrology". McGraw Hill Inc., New York, 372p.

Ciccacci, S., D'Alessandro, L., Fredi, P. and Lupia-Palmeri, E. (1992). "Relations between morphometric characteristics and denudational processes in some drainage basins of Italy". Zeitschfirt fur *Geomorphology,* v.36, pp.53–67.

Clarke, J.I. (1966) "Morphometry from Maps, Essays in Geomorphology". Elsevier Publ. Co., New York, pp.235-274.

Coates, D.R. (1958) "Quantitative geomorphology of small drainage basins of Southern Indiana". Project NR 389-042, Tech. report 10, Columbia University, Dept. of Geology, ONR Geography branch, New York.

Collins, R. and Jenkins, A. (1996) "The impact of agricultural land use on stream chemistry in the middle hills of the Himalayas, Nepal". *Jour. Hydrol*., v.185, pp.71-86.

Collin, M.L. and Melloul, A.J. (2003) "Assessing groundwater vulnerability to pollution to promote sustainable urban and rural development". *Journal of Cleaner Production*, v.11, pp. 727–736.

CPCB (2008) "Status of Groundwater Quality in India -part II". Central Pollution Control Board, Ministry of Environment Forests, Govt. of India, Groundwater Quality Series: GWQS/ 10/2007-2008, pp.1- 367.

D'Alessandro, L., Del Monte, M., Fredi, P., Lupia-Palmeri, E. and Peppoloni, S., (1999) "Hypsometric analysis in the study of Italian drainage basin morphoevolution. Transactions", *Japanese Geomorphological Union*, v.20, pp.187–202.

Datta, P.S. and Tyagi, S.K. (1996) "Major ion chemistry of groundwater in Delhi area: chemical weathering processes and groundwater flow regime". *Jour. Geol. Soc. India*, v.47, no.2, pp.179-188.

Dehbozorgi, M., Pourkermani, M., Arian, M., Matkan, A.A., Motamedi, H. and Hosseinias A. (2010) "Quantitative analysis of relative tectonic activity in the Sarvestan area, Central Zagros, Iran". *Geomorphology*, v.121, no.3-4, pp.329-341.

David, J. M., Goodchild, M.F. & David W. Rhind (1991) "Geographic Information Systems, Principles and Applications." 360p.

Davis, J.C. (1985) "Statistical and Data Analysis in Geology" 2nd Ed., John Wiley and Sons, New York.

Davis, S.N. and De Wiest, R.J.M. (1966) "Hydrogeology". Wiley, New York.

Davis, W.M. (1889) "The Rivers and Valleys of Pennsylvania". *Nat. Geogra. Mag.*, v.1, pp.183-253.

Davis, W.M. (1899) "The Geographical Cycle". *Geogra. Jour.*, v.14, pp.481-504.

Davis, W.M. (1895) "The Development of certain English Rivers", *Geogra. Jour.*, v.5, pp.127-137, 142.

Demers. M.N. (1999). "Fundamentals of Geographic Information Systems". Second Edition, John Wiley and Sons Inc., 450p.

Devaraju, T.C. and Khanadali, S.D. (1993) "Lateritic bauxite profiles of South-Western and Southern India- characteristics and Tectonic significance" . *Current Science*, v.64, pp. 919-921.

Dhoolappa, G. (1994) "Special highlights of Groundwater Exploration in Karnataka", *Geo Karnataka*, MGD Centenary volume, pp.381-383.

Dijon, R. (1985) "Groundwater in Hard Rocks". *Nature and Resources*, v. XXI, no.3, pp.2-11.

Dinesh, A.C. (2011) "bAd Calculator - a freeware for bearing and drainage calculation". *Proceedings of National Seminar on Coastal Hazards, Resources and Management.* Mangalore University, p.18.

Dinesh, A.C., Markose, Vipin J. and Jayappa, K.S. (2012) "Bearing, azimuth and drainage (bAd) calculator: A new GIS supported tool for quantitative analyses of drainage networks and watershed parameters". *Computers & Geosciences*, v.48, pp.67–72. *http://dx.doi.org/10.1016/j.cageo.2012.05.016.*

Dikshit, K.R. (1983). "Introduction: Contribution to Indian Geography II." *Geomorphology*. Heritage Publication, New Delhi, India, pp.1-16.

Doneen, L.D. (1964) "Notes on water quality in agriculture". Published as a water science and engineering paper 4001, Department of water sciences and engineering, Univ. of California.

Dornkamp, J.C. and King, C.A.M. (1971) "Numerical analyses in geomorphology: an introduction". St. Martin Press, New York, 372 P.

D.O.S (Department of Space) (1990) "Atlas on Hydrogeological maps of India, Karnataka and Goa." Govt. of India Publication.

Douglas, E.B. and Leo, W.N. (1977) "Hydrogeochemical relationships using partial correlation coefficient". *Water Resource Bull*., v.13, pp.843-846.

Drever, J.I. (1982) "The geochemistry of natural waters". Prentice Hall, Eaglewood Cliffs, New Jercey.

Drury, S.A. (1984) "A Proterozoic intracratonic basin, dyke swarms and thermal evolution in South India'. *Jour. Geol. Soc. India*., v.25, pp.437-444.

Drury, S.A. and Holt, R.W. (1980) "The tectonic framework of the south Indian craton, a reconnaissance involving LANDSAT imagery". *Tectonophysics*. v.65, pp.11-15.

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

Dutta, D., Sharma, J.R. and Adiga, S. (2002) "Watershed Characterization, Prioritization, Development Planning and Monitoring – Remote Sensing Approach". *Technical Report, RRSC,* ISRO Bangalore. P.68.

Dwivedi, S.L. and Vandana Pathak (2007) "A preliminary Assignment of Water Quality Index to Mandakini River, Chithrakoot". *Indian Jour. Enviro. Proc*., v.27, no.11, pp.1036-1038.

Eaton, F.M. (1950) "Significance of carbonates in irrigation waters". *Soil Sci.*, v.39, pp.123-133.

Elango, L., Kannan, R., and Senthil Kumar, M. (2003) "Major ion chemistry and identification of hydrogeochemical processes of groundwater in a part of Kancheepuram district, Tamil Nadu, India". *Journal of Environmental Geoscience*, v.10, pp.157-166.

ERDAS Field Guide (1999) "Earth Resources Data Analysis System". ERDAS Inc. Atlanta, Georgia. p. 628.

Eremenko, N.A. (1964) "Oil and gas possibilities of West Bengal". *ONGC Bulletin*, v.1, pp.11-25

ESRI (2000) "ArcView Help Topics, version 9". ArcView Help, Environmental System Research Institute. Inc.

Fakir, Y., Mernissi, M.E., Kreuser, T. and Berjami, B. (2002) "Natural tracer approach to characterize groundwater in coastal Sahel of Qualidia (Morocco)". *Environ. Geol*., v.43, pp.197-202.

Faure, G. (1998) "Principles and applications of geochemistry". 2nd edn. Prentice Hall, Eaglewood Cliffs, New Jersey.

Fisher, R.S. and Mullican, W.F. (1997) "Hydrochemical evolution of Sodium Sulfate and Sodium Chloride groundwater beneath the northern Chihuahuas desert, Trans-Peccos, Texas, USA". *Hydrogeol. Jour*., v.10, pp.455-474.

Ganesha Raj, K. (1990) "Hydrogeomorphological mapping of Kasaragod district using LISS-II data". *Bhu-Jal News*, Quart. Jour. of Central Groundwater Board, v.5, No.4, pp.28-31.

Ganesha Raj, K. (1992) "Groundwater prospective zone mapping of Chamarajnagar Taluk, Karnataka using IRS data". Paper presented at the *National Seminar on Recent Trends in Prospecting of Earth Resources*, March 18-20, Dept. of Geology, Anna University, Madras.

Ganesha Raj, K. (1994) "Major lineaments of Karnataka and their significance". In: *Geo Karnataka*, MGD centenary volume, pp.303-313.

Gardiner, V. (1995) "Channel networks: Progress in the study of spatial and temporal variations of drainage density". In: Gurnell, A. and Petts, G.E. (Eds.), *Changing river channels*, Wiley, New York, pp.65-85.

Garrote, J., Heydt, G.G. and Cox R.T. (2008) "Multi-stream order analyses in basin asymmetry: A tool to discriminate the influence of neotectonics in fluvial landscape development (Madrid Basin, Central Spain)". *Geomorphology*, v.102, no.1, pp.130-144.

GSI (1981) "Geological and mineral map of Karnataka and Goa". Scale 1:500000, Geological Survey of India, Culcutta.

GSI (2005) "Resource Map of Dakshina Kannada and Udupi Districts". Geological Survey of India, Map Division, Hyderabad.

Ghose, R (1993) "Remote sensing for analysis of groundwater availability in an area with long unplanned mining history". *Jour. Ind. Soc. Rem. Sens*., v.21, pp.119-126

Gibbs, R.J. (1970) "Mechanism of Controlling World's Water Chemistry". *Science*, v.170, pp.1080-1090

Gold, D.P. (1980) "Structural geology". In Seigal, B.S. and Gillespie, A.R. (eds.) *Remote sensing in Geology*, John Wiley and Sons, pp.419-483

Goodchild, M.F. (1992) "Geographical Information Science". International *Journal of geographic Information Systems*, v.6, no.1, pp.31-45.

Gopalkrishna, G.S., Kantharaj, T. and Balasubramaniam (2004) "Morphometric Analysis of Yagachi and Hemavathi river Basins around Alur Taluk, Hassan District, Karnataka, India". *Jour. Appld. Hydrology*, v.17, no.1, pp.9-17.

Gorokhovich, Y. and Voustianiouk, A. (2006) "Accuracy assessment of the processed SRTM based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics". *Remote sensing of Environment*, v.104, pp. 409-415.

Gottschalk, L.C. (1964) "Reservoir sedimentation". In: V.T. Chow (ed), *Handbook of Applied Hydrology*. McGraw Hill Book Company, New York, Section 7-1.

Gowda, K., Ramaswamy, V. and Gowda, C. (1995) "Economics of Tank Rehabilitation and Management through Community Participation – A Case Study". *Proceedings of the National Workshop on Traditional Water Management for Tanks and Ponds*, Eds. Pundarikanthan and Jayashekhar., Centre for Water Resources and Ocean Management, Anna Univ., Madras, pp. 218-224.

Gregory, K.J. (1976) "Drainage networks and climate". In: Derbyshire, E. (Ed.) *Geomorphology and Climate*. Wiley, Chichester, pp.289-315.

Gregory, K.J. and Gardiner, V. (1975) "Drainage density and climate". *Zeitschrift for Geomorphology*, v.19, p.287-298.

Gregory, K.J. and Walling, D.E. (1973) "Drainage basin form and process: a geomorphological approach". Wiley, New York, pp. 456.

Gupta, I. C. (1979) "Use of Saline Water Agriculture in Arid and Semi-arid Zones of India", Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, p.210.

Gupta, A.K. and Ganesha Raj, K. (1988) "Groundwater Potential Zone Mapping: Study using two different scales of imagery", *Bhu-Jal News*, Quart. Jour. of Central Groundwater Board, v.3, no.4, pp.09-11.

Gupta, A.K. and Ganesha Raj, K. (1992) "Correlation of Bore well data with imagery interpreted groundwater prospect zone maps", *Bhu-Jal News*, Quart. Jour. of Central Groundwater Board, v.7, no.1, pp.10-16.

Gupta, S., Dendele, P.S., Verma, M.B. and Maithani, P.B. (2009) "Geochemical Assessment of Groundwater around Macherla-Karempudi area, Guntur District, Andhra Pradesh". *Jour. Geol. Soc. India*, v.73, no.2, pp.202-212.

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

Handa, B.K. (1975) "Geochemistry and Genesis of Fluoride contained Groundwater in India". *Groundwater*, v.13, pp.275-281.

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

Hanson, H.C. (1954) "Dictionary of Ecology", Crown Publishers, New York.

Haridhas, V.R., Aravindan, S. and Girish Gopinath (1998) "Remote sensing and its applications for groundwater favorable area identification*". Quart. Jour. GARC*, v.6, pp.18-22.

Hauque, K.E. (2009) "Geochemical Assessment of Groundwater in the Foothills Area of Siliguri, Darjiling District, India". *International Journal of Earth Sciences and Engineering,* v.02, no.02, pp. 135-144.

Hem, J.D. (1985) "Study and interpretation of the chemical characteristics of natural water" (3rd ed.). *U.S. Geol. Sur. Water-Supply paper* no. 2254, 263p.

Hobbs, W.H. (1904) "Lineaments of the Atlantic border region". *Geol. Soc. Am. Bull*., no.15, pp.483-506.

Horton, R.E. (1932) "Drainage Basin Characteristics" *Trans. Amer. Geophys. Union*, v.13, pp. 350-361.

Horton, R. E. (1945) "Erosional Development of Streams and their Drainage Basins: Hydrophysical approach to Quantitative morphology", *Bulletin. Geol. Soc. America*., v. 56, pp.275-370.

Howard, A.D. (1990) "Role of hypsometry and planform in basin hydrologic response". *Hydrological Processes*, v.4, pp.373–385.

Howe, R.H.L. (1958) "Procedures of applying Air-Photo-interpretation in the location of Groundwater". *Photogramm. Engg.*, v.24, no.1, pp. 35-49.

Hurtrez, J.E., Sol, C. and Lucazeau, F. (1999) "Effect of drainage area on hypsometry from an analysis of small-scale drainage basins in the Siwalik Hills (central Nepal)". *Earth Surface Processes and Landforms*, v. 24, pp.799–808.

Indian Standard Institution (1991) "Drinking water standards, Table 1 Substances and characteristics affecting the acceptability of water for domestic use 18, 10500", New Delhi, pp.1-5.

IPCC, Climate Change (2007) "The physical Science Basis". Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, U.K. and New York, NY, USA.

Jagannathan, V. (1994) "Groundwater Perspective". *Jour. Geol. Soc. India*, v.43, pp.317.

Jagannadhasarma, V.V. (2005) "Rainfall analysis pattern in the coastal zone of Krishna-Godavary Basin, Andhra Pradesh, India. *Journal* of *Applied Hydrology*. Vol. XVIII: No.1&2. pp 1-11.

Jai Kiran, K.P. (2000) "Urban Groundwater Management". *Jour. Geol. Soc. India*, v.55, no.1, pp.102-103.

Jana, M. M. & Haque, K. E. (1999) "Groundwater Potental in Parts of the Siliguri Police Station Area, Darjiling, W. B., India", *Geog. Review of India*, v.61, no.02, pp.145-155.

Javed, A. and Wani, M.H. (2009) "Delineation of Groundwater Potential Zones in Kakund Watershed, Eastern Rajasthan using Remote sensing and GIS techniques". *Jour. Geol. Soc. India*, v.73, no.2, p.229-236.

Jeen, S.K., Kim, J.M., Ko, K.S., Yum, B and Chang, H.W. (2001) "Hydrogeochemical characteristics of groundwater in a mid-western coastal aquifer system, Korea". *Geosci. Jour*., v.5, pp.339-348.

Jeere, D.S., Shashidharan, K., Guha, A. and Khangan, V.W. (2008) "The study of the relationship between the soil chemistry and water system in parts of Kuhi mineral belt area, Nagpur district, Maharashtra". *Jour. Geol. Soc. India*, V.71, no.4, pp.557-568.

Jeyaram, A., Faruqi, S.A., Karale, R.L. and Sinha A.K. (1992) "Groundwater Investigations using IRS LISS–II data in Nagpur district", Natural Resource Management – a new perspective.

Joshi, Veena, Tambe, D. and Gorakh, D. (2009) "Geomorphometry and fractal Dimension of a Riverine Badland in Maharashtra" *Jour. Geol. Soc. India*,v.73, no.3, pp.355-370.

Jupp, D.L.B. and Vozoff, K. (1975) "Stable iterative methods for the inversion of geophysical data". *Geophys. J. R. Astr, Soc*., pp. 957-976.

Kale, Vishwas S. and Shejwalkar, N. (2008) "Uplift along the western margin of the Deccan Basalt Province: Is there any geomorphometric evidence? " *J. Earth Syst. Sci.*, v. 117, no. 6, pp. 959–971.

Kaila, K.L., Chowdhury, K.R., Reddy, P.R., Krishna, V.C., Hari Narain, Subbotin, S.I., Sollogub, V.B., Chekunov, A,V., Kharektchko, G.E., Lazarenko, M.A. and Ilchenko, T.V. (1979) "Crustal Structure along Kavali-Udupi profile in the Indian peninsular shield from deep seismic sounding". *Journal Geol. Soc. India*, v.20, no.7, pp.307-317.

Karanth, K.R. (1987) "Groundwater Assessment, Development and Management". Tata McGraw Hill, New Delhi, 610p.

Keerthiseelan, K., Kapoor, S.K., Suresh, A. and Prakash,T.R. (2001) "Salinity intrusion from tidal recharge and its impact on groundwater qualities in Goa state". *Jour. Geol. Soc. India*, v.57, pp.257.

Keller, E. (1986) "Investigation of active tectonics: Use of surfacial earth processes". In Wallace, R.E (Eds.). *Active Tectonics Studies in Geophysics*., National Academy Press., Washington D.C., pp.136-147.

Keller, G.V. and Frischknecht, F.C. (1966) "Electrical methods in geophysical prospecting". Pergamon Press, 517p.

Keller, E.A. and Pinter, N. (2002). "Active Tectonics. Earthquakes, Uplift, and Landscape". Prentice Hall, New Jersey, 362p.

Kelley, W.P. (1946) "Alkali soils – their formation properties and reclamation". Reinold Publ. Corp., New York. pp. 124-128.

Khan, M.A. and Moharana, P.C. (2002) "Use of Remote sensing and Geographic Information System in the delineation and characterization of groundwater prospect zones". *Jour. Ind. Soc. Rem. Sens*., v.30, pp.131-141.

Khan, M.Q.I., Venkataratnam, L., Rao, B.R.M., Rao, D.P. and Subrahmanyam, C. (2001) "International Classification and Codification of Watersheds and River Basins". *Jour. of Water Resources Planning and management,* v. 127, no.5, pp.306-315.

Khurshid, S. and Zaheerudin (2004) "Geochemistry of groundwater: An overview of sporadic fluoride and nitrate contamination in parts of Yamuna basin, India". *Jour. Appld. Geochem.,* v.6, no.1, pp.25-35.

Kirkby, M.J. (1987) "Modelling some influences of soil erosion, landslides and valley gradient on drainage density and hollow development". *Catena,* Suppl., no.10, pp.1-14.

Kowalic, W.S. and Gold, D.P. (1976) "The use of Landsat-1 imagery in mapping lineaments in Pennsylvania" In *proc. First international conference on the new basement tectonics*, Utah Geological Association Publication-5, pp.236-249.

Krishnamurthy, A.V. (1972) "Regional assessment of bauxite depostis (coastal bauxite) in South Kanara District." Unpublished report of Geol. Surv. India.

Krishnamurthy, J. and Srinivas, G., (1995) "Role of Geological and geomorphological factors in groundwater exploration: a study using IRS LISS data". *Int. Jour. Remote sensing*, v. 16, no. 14, pp. 2595-2618.

Krishnamurthy, J. and Srinivas, G. (1996) "Demarcation of geological and geomorphological features of parts of Dharwar Craton, Karnataka using IRS LISS II data*",* *Ind. Jour. of Remote Sensing*, v.17, no.16, pp.3271-3288.

Krishna Murthy, J., Manavalan, P. and Saivasan, V. (1992) "Application of digital Enhancement techniques for groundwater exploration in a hard rock terrain". *Int. Jour. Remote sensing*, v. 13, no. 15, pp. 2925-2942.

Krishna Murthy, J., Venkatesh Kumar, N., Jayaraman, V. and Manivel, M. (1996) "An approach to demarcate groundwater potential zones through remote sensing and Geographic Information Systems". *Int. Jour. of Remote sensing*, v.17, no.10, pp.1867-1884.

Krishnamurthy, N.S. and Praksh, B.A. (2000) "Groundwater investigation in part of Alwar district, Rajasthan". *Jour. Geol. Soc. India*, v.56, pp.151.

Kukkillaya, J. Pradeep, Mohammed Kunhi, A. and Abdul Rahiman, A.K. (1992) "Basic and Ultrabasic Dykes as potential aquifers in hard rock terrain". *Bhu-Jal News*, pp.14-19.

Kulkarni, Himanshu (1992) "Delineation of Shallow Deccan Basaltic Aquifers from Maharashtra using Aerial Photointerpretation". *Photonirvachak*, v. 20, nos.2&3, pp.129-138.

Kulkarni, Himanshu (1998) **"**Watershed development and management- A moment seeking inputs in earth science". *Jour. Geol. Soc. India*, v.52, pp.239.

Kulkarni, Himanshu, Deolankar, S.B., Lalwani, A. and Lele, V.A. (1994) "Integrated Remote Sensing as an Operational Aid in Hydrogeological Studies of Deccan Basalt Aquifers". *Asian- Pacific Remote Sensing Journal*, v.6, no.2, pp.9-18.

Kurumbein, W.C and Graybill, F.A. (1965) "An Introduction to Statistical Models in Geology". McGraw-Hill, New York.

Langbein, W.B. (1947) "Topographic Characteristics of drainage basins". *U.S. Geol. Surv. Water-Supply Paper*, 986(C), pp.157-159.

Laratine, C., Delibrias, G. and Rajagopalan, G. (1990) "Palaeomangroves of Karnataka coast, Karnataka and their implications on late Pliestocene sea level changes". In: Jain, K.P. and Tiwari, R.S. (editors), Proc. Symp. Vistas in Indian Palaeo Botany", *Palaebotanist*, v.38, pp.370-378.

Laurini, R. Thompson. (1992) "Fundamentals of Spatial Information Systems". *Academic Press*, London, 390p.

Lowrance, R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., Correl, D.L., Gilliam, J.W., Robinson, J.L., Brinsfield, R.B., Staver, K.W., Lucas, W. and Todd, A.H. (1997). "Water quality functions of riparian forest buffers in Chesapeake Bay watersheds". *Environmental Management*, v.21, pp.687-712.

Lerner, D.N., Yang, Y., Barrett, M.H. and Tellam, J.H. (1999) "Loading of non-agricultural nitrogen in urban groundwater". *In:* J.B. Ellis (Ed.*), Impacts of urban growth on surface and groundwater quality*, IAHS Publ. No.259, IAHS Press, pp.117-123.

Lifton, N.A., Chase, C.G. (1992) "Tectonic, climatic and lithologic influences on landscape fractal dimension and hypsometry: implications for landscape evolution in the San Gabriel Mountains, California". *Geomorphology*, v.5, pp.77–114.

Lillesand, Thomas N. and Kiefer, R.W. (2003) "Remote sensing and image interpretations". 6th edition, John Wiley and sons, New Delhi, 556p.

Lloyd, J.W. and Heathcote, J.A. (1985) "Natural inorganic hydrochemistry in relation to groundwater: an introduction". Clarendon Press-Oxford, U.K. 296p.

Lokesh, K.N., Naganna, C. and Srinivas, G. (1983) "Resistivity Surveys for Groundwater in Bangalore University Campus". *Jour. Assoc. Expl. Geophys*., v. III, no.4, pp.35-39.

Malhotra, K. and Prasad, R. (1984) "Some important aspects of Water Resources in Karnataka". Pub. Dept. Civil Engg., I.I.Sc., Bangalore, India.

Manjushree, T.M., Joseph, S. and Thomas, J. (2009) "Hydrogeochemistry and Groundwater Quality in the Coastal Sandy Clay Aquifers of Alappuzha District, Kerala". *Jour. Geol. Soc. India*, v.74, no.4, pp.459-468.

Melton, M.A. (1957) "An analysis of the relations among elements of climate, surface properties and geomorphology". *Technical Report 11*, Dept. Geol., Columbia University, Proj.NR389-042., Off.of Nav.Res., New York, P.102.

Melton, M.A. (1958) "Geometric properties of mature drainage systems and their representation in an E4 phase space". *Journal of Geology*, v.66, pp.35-54.

Melton, M.A. (1959) "A derivation of Strahler's Channel-ordering system". *Journal of Geology*, v.67, pp.345-346.

Mercado, A. (1985) "The use of hydrochemical pattern in carbonate, sand and sandstone aquifers to identify intrusion and flushing of saline water". *Groundwater*, v.23, pp.335-344.

Meybeck, M. (1987) "Global chemical weathering of surficial rocks estimated from river dissolved rock". *American Jour. Sci.*, pp.401-428.

Mesa, L. M. (2006) "Morphometric analysis of a subtropical Andean basin (Tucuman, Argentina)". *Environ Geol* , v.50, pp.1235–1242.

Miller, V.C. (1953) "A Quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee". Proj. NR 389-402, Department of Geology, Tech Rep 3, Columbia University, ONR, New York.

Mishra, H.C. (1998) "Geographic Information System Handbook". 260p.

Mithanthaya, I.R. (1990) "Study of South Kanara Granites". Unpublished M.Tech. Thesis submitted to Mangalore University.

Mohan, R., Singh, A.K., Tripati, K. and Nhotri, G.C. (2000) "Hydrochemistry and quality assessment of groundwater in main industrial area". *Jour. Geol. Soc. India*, v.55, no.01, pp-77.

Molin P., Pazzaglia, F. J. and Dramis, F. (2004) "Geomorphic expression of active tectonics in a rapidly-deforming forearc, Sila Massif, Calabria, Southern Italy." *Am. J. Sci.*, v. 304**,** pp.559–589.

Montgomery, D.R. and Dietrich, W.E. (1989) "Source areas, drainage density and channel initiation". *Water resources Research*, v.25, pp.1907-1918.

Montgomery, D.R. and Dietrich, W.E. (1992) "Channel initiation and the problem of landscape scale." *Science*, v.255, pp.826-830.

Mooney, H.M. and Orellana, E. (1966) "Master Tables and Curves for Vertical Electrical Soundings over layered structures". *Intercieneia* , Madrid, Spain., P.166.

Morisawa, M.E. (1962) "Quantitative Geomorphology of some Watersheds in the Apalachians Plateau". *Bull. Geol. Soc. America.*, v.73, p.1025-1046.

Morisawa, M. (1985) "Rivers: Form and Process". Longman, New York, P.222.

Moscow State University (2002) "IPI2Win (VES-IP) software for Vertical Electrical Sounding", Geoscan-M Ltd., Moscow, Russia.

Muralidharan, D., Athavale, R.N., Rangarajan, R. (1992) "Measurement of natural recharge in India". *Jour. Geol. Soc. India*, v.39, no.03, pp.235.

Murali Krishna I.V. (1992) "Remote Sensing applications and GIS recent trends." Tata Mc Graw Hill Publishing Company Ltd. New Delhi. 275p.

Muthuraman, K., Tiwari, M.P. and Mukhopadyaya, P.K. (1992) "Salinity of groundwater of Purna basin-its genesis", *Jour. Geol. Soc. India*, v.38, no.05, pp-50.

Nag, S.K. (1998) "Morphometric analysis using remote sensing techniques in the Chaka sub-basin, Purulia district, West Bengal". *J. Indian Soc. Remote Sensing*, v.26, nos.1&2, pp. 69-76.

Nag, S.K. and Chakraborty, S. (2003) "Influence of rock types and structures in the development of drainage network in hard rock area". *J. Indian Soc. Remote Sensing*, v.31, no.1, pp.25-35.

Naganna, C. (1966) "Petrology of the rocks of St. Mary islands near Malpe, South Kanara district, Mysore State". *Jour. Geol. Soc. India*, v.7, pp.110-117.

Nagaraja, G.H. (1967) "Bauxite deposits of Baindur, South Kanara District, Mysore State". Geological Studies No.3, Dept. of Mines and Geology, Karnataka.

Narasimhan, T.N. (1990) "Groundwater in peninsular Indian shield". *Jour. Geol. Soc. India*, v.36, no.04, pp.353.

Narayana, A.C., Pandarinath K., Karbassi, A.R., and Raghavan, B.R. (1991) "A note on silica sand of South Canara Coast, Karnataka, India". *Jour. Geol. Soc. India*, v.37, pp.164-171

Natural Resources Conservation Service (NRCS) (1995) "Mapping and Digitizing Hydrologic Units". National Instruction No. 170-304, U.S. Dept. of Agriculture, Washington D.C. http://www.nhq.nrcs.usda.gov/hu/ni170304.html.

National Remote Sensing Agency (1988) "District wise hydrogeomorphological mapping of the country using satellite data under National Drinking Water Technology Mission NRSA-DOS, Hyderabad.

National Remote Sensing Agency (1995) "Integrated Mission for Sustainable Development" Technical guidelines, Department of Space, Government of India, Hyderabad.

Navalagunda, R.R. (2002). "Readings in Remote Sensing, Technology issue, Resource Management section." Program Planning & Evolution Division, NRSA, 125p.

NEERI (1988) "Manual on Water and Wastewater Analysis" National Environmental Research Institute, Nagpur, 331p.

Ohmori, H. (1993) "Changes in the hypsometric curve through mountain building resulting from concurrent tectonics and denudation". *Geomorphology*, v.8, pp. 263-277.

O'Leary, D.W., Driedman, J.D., and Pohn, H.A. (1976) "Lineaments, linear, lineation: some proposed new standards for old terms". *Geol. Soc. Am. Bull*., no.87, pp.1463-1469.

Orellana, E. and Mooney, H.M. (1966) "Master tables and curves for vertical electrical sounding over layered structures". Madrid Intercientia, Spain. 150p.

Pacey, A. and Cullis, A. (1986) "Rainwater Harvesting: the collection of rainfall and runoff in rural areas". Intermediate Technology Pub., London, UK, P.216

Panchiappan, R.P., Bhishm, M.K., Manikavasagam, R. and Balakrishna, S. (2004) "Hydrochemical Characteristics of Groundwater in the Nainital Lake Basin: Implication on the Landslide Hazards", *Jour. Geol. Soc. India*, v.64, pp.139-145

Pandian, K. and Sankar, K. (2007) "Hydrogeochemistry and groundwater quality in the Vaippar River basin, Tamil Nadu". *Jour. Geol. Soc. India*, v.69, pp.970-982.

Patangay, N.S., Srisailakanth, A. and Bhimasankaram, V.L.S. (1977) "Prediction of Groundwater yield of wells in Granites by means of resistivity sounding method". *Geophysical Case Histories of India*, v.1, pp.161-168.

Pawar, N.J. (1993) "Geochemistry of carbonate precipitation from groundwater in basaltic aquifers", *Jour. Geol. Soc. India*, v.41, no.02, pp.119.

Pawar, N.J. and Shaikh, I.J. (1995) "Nitrate pollution of groundwaters from shallow basaltic aquifers, Deccan Trap Hydrologic Province, India". *Environ. Geol.*, v.25, pp.197-204.

Pérez-Peña, J. V., Azañón J. M. and Azor, A. (2009) "CalHypso: An ArcGIS extension to calculate hypsometric curves and their statistical moments. Applications to drainage basin analysis in SE Spain". *Computer & Geosciences,* v.35, pp.1214-1223.

Pettijohn, W.A. (1998) "Introduction to Artificial Recharge" Scientific Publishers, Jodhpur.

Philip., G. and Singhal, B.B.S. (1992) "Importance of Geomorphology for Hydrogeological study in Hard rock terrain: an example from Bihar Plateau through remote sensing". *Ind. Jour. of Earth Sciences*, v.19. no.4, pp.177-188.

Pichamuthu, C.S. (1967) "The Pre Cambrian of India". In: Rankama, K. (editor), *The Pre-Cambrian*, John Wiley and Sons, New York, c.3, pp.1-96.

Piper, A.M. (1944) "A graphical procedure in the chemical interpretation of groundwater Analysis". *Trans. Amer. Geophy. Union*, v.25, pp.914-923.

Piper, A.M. (1953) "A graphic procedure in the geochemical interpretation of water analysis". *USGS Groundwater Note,* no.12, 63p.

Powar, K. B (1981) Lineament fabric and dyke pattern in the western part of the Deccan Volcanic Province". *Geol. Soc. India Memoir, v.* 3, pp**.** 45–57.

Powar, K. B. (1993) "Geomorphological evolution of Konkan coastal belt and adjoining Sahyadri uplands with reference to Quaternary uplift". *Current Science*, v. 64, pp. 793-796.

Powar, K. B. and Patil, D. N. (1980) "Structural evolution of the Deccan Volcanic Province: A study based on LANDSAT-1 imageries". *Proceedings 3rd Indian Geology Congress,* Poona. *pp.* 235–253.

Pradeep, K.J. (1998) "Remote sensing technique to locate groundwater potential zones in Upper Urmil River basin, district Chaatarpur, India". *Jour. Ind. Soc. Rem. Sens*., v.26, pp.135-147.

Prakash and Prasanna Kumar (Ed.) (2003) "Rainwater Harvesting (Urban and Rural solutions)". *Proceedings of National Workshop on Rainwater Harvesting* PESC of Engg., Mandya, 122p.

Prasad, A.L., Sarkar, S., Singh, R.P., Kafatos, M. (2006) "Interannual variability of vegetation cover and rainfall over India". *Advances in Space Reasearch. v.*39, pp.79-87.

Prescott, J.A., and Pendleton, R.L. (1947) "Laterites and Lateritic soils". *Technical communication No.47 of the Commonwealth Bureau of Soils Science*, Rothamsted Experimental station, Harpenden, England.

Priya, K.L, Prince, A.G, Paul, J.P. and Leon, C.D.A. (2010) "Assessment of Groundwater Quality in the Singanallur sub-basin of Coimbatore city". In (Eds. Srinivas Raju and Vasan, A.) *Proceedings of National Conference on Sustainable Water Resources Management and Impact of Climate Change*, B.S. Publications, Hyderabad, pp. 468-474.

Putty, M.R.Y. (2010) "Principles of Hydrology". I.K. International Publishing house Pvt. Ltd., New Delhi, 427p.

Qinghai, G., Yanxin, W., Xubo, G. and Teng, M. (2007) "A new model (DRARCH) for assessing groundwater vulnerability to arsenic contamination at basin scale: a case study in Taiyuan basin, northern China". *Environ. Geol.*, v.52, pp. 923-932.

Rachna Raj, Mulchandani, N., Bhandari, S., Maurya, D. M. and Chamyal, L. S. (2004) "Channel shifting of a highly sinuous meandering river in alluvial plain, Vishwamitri river, Mainland Gujarat". *Curr. Sci.*, v.86, no.12, pp.1647-53.

Radhakrishna, B.P. (1965) "The occurrence of bauxite along West coast of Mysore, South India". *Jour. Geol. Soc. India*, v.6, pp.62-66.

Radhakrishna, B.P. (1968) "Our groundwater resources and how to utilize them". Mysore Geological Association, no.20, 16p.

Radhakrishna, B.P. (1993) "Neogene Uplift and geomorphic rejuvenation of the Indian Peninsula". *Curr. Sci.*, v.64, nos.11&12, pp.787-793.

Radhakrishna, B.P. (1997) "Rainwater Harvesting". *Jour. Geol. Soc. India*, v.50, no.3, pp.247-254.

Radhakrishna, B.P. (2003) "Groundwater Recharge". *Jour. Geol. Soc. India*, v.62, no.8, pp.135-138.

Radhakrishna, B.P. and Vaidyanathan, R. (editors) (1994) "Geology of Karnataka". *Geol. Soc. India special publications*, pp.1-298.

Radhakrishnan K. (2007a) "Feasibility Studies of Roof Top Rainwater Harvesting at N.E.T. Campus, Nitte". Proc. All India seminar on *'Challenges in Socio-Economic* *and Infrastructural Developments- Emerging Technology, (CIDET-07)',* The Institution of Engineers (India), Interdisciplinary Co-ordination Committee (ICC), Mangalore.

Radhakrishnan K. (2007b) "Rehablitation Studies of Traditional Rainwater Harvesting Structures- A Case Study". Proc. All India seminar on *'Challenges in Socio-Economic and Infrastructural Developments- Emerging Technology, (CIDET-07)',* The Institution of Engineers (India), Interdisciplinary Co-ordination Committee (ICC), Mangalore.

Radhakrishnan K. (2007c) "Identification, Delineation and Mapping of Microwatersheds and Traditional Rainwater Harvesting Structures in Mulki River Basin for Sustainable Development". Proc. All India seminar on *'Challenges in Socio-Economic and Infrastructural Developments- Emerging Technology, (CIDET-07)',* The Institution of Engineers (India), Interdisciplinary Co-ordination Committee (ICC), Mangalore.

Radhakrishnan K. and Lokesh, K.N. (2009) "Rehabilitation Studies on an abandoned Traditional Rainwater Harvesting Structure". Proc. National conference on '*Recent Trends and Challenges in Civil Engineering (RTCCE-09)',* Kavikulaguru Institute of Technology & Science, Ramtek, Maharashtra, pp.102-107.

Radhakrishnan K. and Lokesh, K.N. (2010a) "Integrated Approach for Hydrogeochemical Studies of Mulki river Basin, Coastal Dakshina Kannada Districts of Karnataka". Proc. National conference on *'Sustainable Water Resources Management (SWaRM 2010)*, National Institute of Technology Karnataka, Surathkal.

Radhakrishnan K. and Lokesh, K.N. (2010b) "Feasibility Studies for Sustainable development on Water Resources". Proc. National conference on *'Sustainable Water Resources Management (SWaRM 2010)'*, National Institute of Technology Karnataka, Surathkal.

Radhakrishnan, K. and Lokesh, K.N. (2010c) "Remote Sensing and GIS Techniques for Delineation and Mapping of Microwatersheds and Traditional Rainwater Harvesting Structures in Mulki River Basin for Sustainable Development". In Eds: *Srinivas Raju K. and Vasan, A.*, Proc. National conference on '*Sustainable Water Resources Management and Impact of Climate Change'*, Birla Institute of Technology and Science-Pilani, Hyderabad., B.S. Publications, Hyderabad**.** pp.292-302.

Radhakrishnan, K. and Lokesh, K.N. (2011) "Morphometric Evidences for Neotectonism in the Mulki River Basin of Coastal Karnataka, India" *International*

Jour. of Earth Sciences and Engg., Cafet-Innova Technical Society, Hyderabad. v.4, no.4, pp. 643-650.

Radhakrishnan, K., Shenoy, K. Narayana and Lokesh, K.N. (2011a) “Hydro geochemical studies of groundwater along the coastal region of Mulki-Udupi, Karnataka state, India”. *Proceedings of the International Engineering Symposium* (IES2011-96), Kumamoto University, Japan, Ch:C7, sec.1, pp.1-8.

Radhakrishnan, K., Shenoy, K. Narayana and Lokesh, K.N. (2011b) “Hydro geochemical studies of groundwater along the coastal region of Mulki-Udupi, Karnataka state, India”. *International Jour. of Earth Sciences and Engg.*, Cafet-Innova Technical Society, Hyderabad. v.4, no.7-Spl Issue, pp.333-339.

Raj, Y.E.A. (1990) “Some standard subdivision wise distribution of sourth west monsoon rainfall of India”. *Jour. of Applied Hydrology*, v.3, no.1, pp.31-36.

Rajashekharaiah, B.L. (1973) “Aluminous laterite deposits of Peduvare plateau along Baindoor, Coondapur Taluk, South Kanara District”, Geological Studies, No.55, Dept. of Mines and Geology, Karnataka, 31p.

Raju, K.C.B., Prakash, V.S. and Sooryanarayana, K.R. (1994) “Deep Aquifers in granitic terrain of Dakshina Kannada, Karnataka”. *Geokarnataka*, MGD centenary volume, pp.384-387.

Raju, N.J. (2007) “Hydrogeochemical parameters for assessment of groundwater quality in the upper Gunjanaeru River basin, Cuddapah district, Andhra Pradesh, South India”. *Environ. Geol*., v.52, pp.1067-1074.

Raju, N.J., Kotaiah, B. and Reddy, T.V.K. (2009a) “Biogeochemical aspects in and around a sewage farm at Tirupati, Andhra Pradesh, India”. *Environmental Conservation*, Switzerland, v.18, no.3, pp.267-269.

Raju, N.J., Ram, P. and Sangita Dey (2009b) “Groundwater Quality in the Lower Varuna River Basin, Varanasi District, Uttar Pradesh”. *Jour. Geol. Soc. India*, v.73, no.2, pp.178-192.

Rakesh Kumar, Lohani, A.K., Snajay, K., Chatterjee, C and Nema, R.K. (2001) “GIS based morphometric analysis of Ajay River basin up to Sarath gauging site of south Bihar”. *Jour. Appld. Hydrology*, v.14, no.4, pp.45-54.

Ramakrishna (1998) “Groundwater”, Handbook, India, 556p.

Ramakrishnaiah, C.R., Sadashivaiah, C. and Ranganna, G. (2009) “Assessment of Water Quality Index for the groundwater in Tumkur Taluk, Karnataka, India”. *E-Journal of Chemistry*, v.6, no.2, pp.523-530. http://www.e-journals.net.

Ramakrishnan, M. and Harinadhababu, P. (1981) "Western Ghat Belt". In: Swaminatha, J. and Ramakrishnan, M. (editors). Early Precambrian Supracrustals of South Karnataka. *Mem. Geol. Surv. India*, v.112, pp.147-161.

Ramanujachary, K.R. and Balakrishna, S. (1985) "Resistivity Investigations in different geological terrains". *Groundwater News*, pp.1-15.

Ramappa, R. and Suresh, T.S. (1997) "The Morphometric Analysis of Lokapavani River basin, Karnataka, India". *Proceedings of Seminar on Hydro Geology of Pre-Cambrian Terrains and Hard Rock Area.*, Karnatak University, Dharwad., pp. 22-29.

Ramesan, V. (1989) "Research and development in water resources", *Jour. Geol. Soc. India*, v.34, no.04, pp.345.

Ramesh, K.S., Elango, S. and Adiga, S. (2001) "Prioritisation of watersheds of Dakshina Kannada District, Karnataka using Remotely sensed data". Paper presented at Int. Workshop on *Integrated Water Management* held at Bangalore University, Bangalore during June 21-23, 2001.

Ranganna, G., Gajendragad, M.R., Lokesh, K.N. and Anantha Kumar (1994) "Integrated study of water balance and management of river catchment of Dakshina Kannada district, Karnataka State". Project report submitted to the Ministry of Water Resources through CBIP, New Delhi.

Ranganna, G., Somanatha, G.S., Gurappa, K.M., Nagaraj, M.K., Gajendragad, M.R. and Subba Rao (1986) "Groundwater Potential and quality , pollution problems and mitigative thereof, Dakshina Kannada district (Karnataka State)". Consolidated report on student projects from 1979-1985, KREC, Surathkal.

Rangaraju (Ed.) (2004) "Proceedings of National workshop on Groundwater Recharge". Dept. of Civil Engineering, BIET, Davangere. P.120.

Rao, D.P. (1995) "Report on area statistics of Land Use and Land cover generated using Remote Sensing Techniques". Land Use, Cartography & Map Printing Group, National Remote Sensing Agency, Dept. of Space, Govt. of India, 15p.

Rao, Diwakara, V., Naqvi, S.M., Satyanarayana, K., and Hussain, S.M. (1974) "Geochemistry and Origin of the Peninsular Gneissses of Karnataka, India". *Jour. Geol. Soc. India*, v.15, no. 3, pp.226-299.

Rao, Gangadhar. T. (Ed.), (1992) "Lecture Notes for the training courses on groundwater exploration techniques", National Geophysical Research Institute, Hyderabad. pp.1-294.

Rao, Jagannadha M., Durgaiah, B., Saradhi, V.B., Jaisankar, G., Rao, P.D. and Ganesh, K.M. (2007) "Spatial variability of groundwater chemical quality in part of Nalgonda district, Andhra Pradesh". *Jour. Geol. Soc. India*, v.69, no.5, pp.983-988.

Rao, Ram Mohan G. (1968) "Geology of part of Bantwal, Belthangadi and Karkala Taluk, South Kanara district, Karnataka". Unpublished report of Geol. Surv. India.

Rao, Y.S., Reddy, T.V.K. and Nayudu, P.T. (1997) "Groundwater quality in the Niva River basin, Chittoor district, Andhra Pradesh, India". *Environ. Geol*., v.31, no.1, pp.56-63.

Rastogi, R.A. and Sharma, T.C. (1976) "Quantitative analysis of drainagae basin characteristics". *Jour. Soil and Water conservation of India*, v.26, nos.1&4, pp.18-25.

Ravindra, B.M. (2007) "Geological Map of Karnataka" in *Geologists' Diary 2007*, Karnataka Assistant Geologists' Association, Bangalore.

Ravindra, B.M. and Janardhan, A.S. (1981) "Preliminary report on Aegirine Augite bearing Syenite near Sulliya town, Dakshina Kannada district, Karnataka." *Jour. Geol. Soc. India*, v.22, pp.399-402.

Reddy, Anji M. (2004) "Remote Sensing and GIS". BS Publication, Hyderabad, 418p.

Reddy, Anji M. and Reddy, K.M. (1996) "Performance analyses of IRS bands for land use/land cover classification system using maximum likelihood classifier". *International Journal of Remote Sensing*, v.17, no.13, pp.2505-2515.

Reddy, Jaya Rami P. (2008) "A textbook of Hydrology". Lakshmi publications, New Delhi. 530p.

Reddy, P.R., Vinod Kumar, K. and Seshadri, K. (1996) "Use of IRS-1C data in Groundwater studies", *Current Science*, v.70, no.7, pp. 600-605.

Reza, Selim, A.H.M., Hoogendoorn, J., Zhou, Y and Nonner, J. (2008) "Statistical Analysis and Interpretation of Water Quality Data of the Vitens Well Fields". *Jour. Geol. Soc. India*, v.71, no.4, pp.513-526.

Richards, L.A. (1954) "Diagnosis and improvement of saline and alkali soils". Agricultural Handbook: 60, U.S. Depart. Agri., Washington D.C., 160p.

Roy, A.K. (1997) "Developments and Use of Remote sensing in Groundwater Targeting in Hard rock terrains". *Proc. Nat. Sem. Hydrogeology of Pre Cambrian Terrains and hard rock areas*, Karnatak University, Dharward, India.

Rudraiah, M., Govindaiah, S. and Vittala, S.S. (2008) "Morphometry using Remote Sensing and GIS techniques in the sub basins of Kagna river basin, Gulbarga district, Karnataka, India". *Jour. Ind. Soc. Remote Sensing*, v.36, no.4, pp.351-360.

Sabins, F.F. (1997). "Remote Sensing: Principles and Interpretation." 3rd edn. WH Freeman and Company, New York, 494p.

Saha, D., Dhar, Y.R. and Sikdar, P.K. (2008) "Geochemical Evolution of Groundwater in the Pleistocene Aquifers of South Ganga Plain, Bihar" *Jour. Geol. Soc. India*, v.71, no.4, pp.473-482.

Saivasan, V. (1998) "Groundwater Development perspective in Dakshina Kannada District, Karnataka State", AAP1996-97, No. GWD/1/98, Report of Central Groundwater Board, SW region, Ministry of Water Resources, Government of India, Bangalore. pp.1-29.

Saleh, A., Al-Ruwaih, F. and Shehata, M. (1999) "Hydrogeochemical processes operating within the main aquifers of Kuwait." *Jour. Arid Environ*., v.42, pp.195-209.

Sami, K. (1992) "Recharge mechanism and Geochemical processes in semi-arid sedimentary basins, Eastern Cape, South Africa". *Jour. Hydrol*., pp.27-48.

Sankar, K. (2002) "Evaluation of groundwater potential zone using remote sensing data in Upper Vaigai river basin, Tamil Nadu, India". *Jour. Ind. Soc. Rem. Sens*., v.30, pp.119-129.

Sankaran, A.V. (1997) "Southern India develops a hunch back", *Curr. Science*, Vol. 72, No.3, pp.160-161.

Sankaranarayana, P.V. and Ramanujachary, K.R. (1967) "An Inverse Slope method of determining absolute resistivity". *Geophysics*, v.32, no.6.

Saraf, A.K. and Choudhary, P.R. (1998) "Integrated Remote sensing and GIS for groundwater exploration and identification of artificial recharge sites". *Int. Jour. Rem. Sens*., v.19, pp.1825-1841.

Sarin, M.M., Krishnaswamy, S., Dilli, K., Somayajulu, B.L.K. and Moore, W.S. (1989) "Major ion chemistry of the Ganga-Brahmaputra river system: weathering processes and fluxes to the Bay of Bengal, *Geochim. Cosmochim. Acta*., v.53, pp.997-1009.

Sastri, V.V. and Raiverman, V. (1968) "On the basin study programme of the Cretaceous and Tertiary sediments in the Cauvery basin". *Mem. Geol. Soc. India*, no.2, pp.143-152.

Sathyamoorthy, S. Dhakshinamoorthy, N. and Balasubramanian, A. (1993) "Hydrogeochemical Studies of Tiruchirappalli Aquifers, Tamilnadu". *Bhu-Jal News*, v.8, no.12, pp.10-12.

Schoeller, H. (1967) "Qualitative evaluation of groundwater resources (in methods and Techniques of groundwater investigation and development)". *Water resources series 33*, UNESCO, pp.44-52.

Schoeller, H. (1977) "Geochemistry of Groundwater". In: *Groundwater Studies-An international guide for Research and Practice.* UNESCO, Paris, Ch.15, pp.1-18.

Schowengerdt, R.A. (1997) "Remote Sensing: Models and Methods of Image Processing." 2nd Edn. Academy Press, New York, 522p.

Schumm, S. A. (1956) "The Evolution of Drainage Systems and Slopes in Bad lands at Perth Amboy, New Jersey", *Bull. Geol. Soc., America*, v.67, pp.597-646.

Schumm, S.A. (1963) "Sinuosity of alluvial rivers on the Great Plains". *Bull. Geol. Soc. Amer*., v.74, pp.1089-1100.

Sen, D. and Purandare, A. (1984) "Watershed Management – a viable proposition to develop northeastern region", Workshop on Watershed Management, Shillong, India NIRD Pub.

Sen, Zekai and Ahmad, N. (2002) "Multi-Rectangular Diagram Concept in Groundwater Quality Assessment and Application in Pakistan". *Water International*, v.27, no.2, pp. 271-278.

Shaji, E., Vinayachandran, N. and Thambi, D.S. (2009) "Hydrogeochemical characteristics of groundwater in coastal phreatic aquifers of Aleppey District, Kerala". *Jour. Geol. Soc. India*, v.74, no.5, pp.585-590.

Shekhargupta, P. S., Dandele, M.B., Vermaand, P.B. and Maithani (2009) "Geochemical Assessment Of Groundwater Around Macherla- Karempudi Area, Guntur District, Andhra Pradesh", *Jour. Geol. Soc. India*, v.73, no.2, pp. 202-212.

Sheng, T.C. (1990) "Watershed Management Field Manual, Watershed Survey And Planning". FAO Conservation Guide 13/6, Food And Agriculture Organization of UN, Rome, P.170.

Shenoy, K.N. (1999) "Hydrogeological Studies in Udupi Taluk of Coastal Karnataka, India". Unpublished Ph.D. Thesis submitted to Mangalore University. 392p.

Shenoy, K.N. and Lokesh K.N. (2000) "Electrical Resistivity Survey for groundwater exploration in Udupi Municipal Area". *Journal of Applied Hydrology*, v. XIII, nos.3&4, pp.30-35.

Shibani Maitra (2001) "Landforms and geomorphic classifications of part of the upper Baitarani River Basin". 175p.

Shih, R.D., Marcus, S.M. and Gnense, C.A. (1997) "Methemoglobinemia attributable to nitrate contamination of potable water through boiler fluid additives-New Jersey, 1992 and 1996". *Morb. Mortal Wkly. Rep*., v.46, pp.202-204.

Singh, A. (1989) "Digital Change Detection Techniques Using Remotely Sensed Data". *International Journal of Remote Sensing*, v.10, no. 6, pp. 989-1003.

Singh, A.K. and Hasnain, S.I. (1999) "Environmental geochemistry of Damodar river basin – east coast of India". *Environ. Geol*., v.37, pp.124.136.

Singh, A.K., Tewary, B.K. and Sinha, A. (2011) "Hydrochemistry and Quality Assessment of Groundwater in Part of NOIDA Metropolitan City, Uttar Pradesh". *Jour. Geol. Soc. India*, v.78, no. 6, pp.523-540.

Singh, D.S.H. and Lawrence, J.F. (2007) "Groundwater quality assessment of shallow aquifer using Geographical Information System in part of Chennai City, Tamil Nadu". *Jour. Geol. Soc. India*, v.69, no.5, pp.1067-1076.

Singh, S. and Singh, M.C. (1997) "Morphometric analysis of Kanhar river basin". *National Geographical J. of lndia, v.*43, no.1, pp.31-43.

Sivakumar, C. and Elango, L. (2008) "Assessment of water quality in Kalpakkam region, Tamil Nadu". *Nature, Environment and Pollution Technology*, v.7, no.4, pp.687-691.

Smith, K.G. (1950) "Standards for grading texture of erosional topography". *American Jour. Science*, v.248, pp.655-668.

Sokalov, A.A. and Chapman, T.G (Eds.) (1974) "Methods for Water Balance computations". *Studies and reports on Hydrology*, v.17, p.127, UNESCO.

Soman, S.K., Joshi, R., Neogi, G. and Mukherjee, M.M. (1999) "Geochemistry of groundwater over Sukhenda ultrabasic, basic rocks, Jaipur district, Orissa", *Jour. Geol. Soc. India*, v.73, no.04, pp.04.

Somasundaram, M.V., Ravindran, G. and Tellam, J.H. (1993) "Groundwater pollution of the Madras urban aquifer, India". *Groundwater*, v.31, no.1, pp.4-12.

Sreedevi, P.D., Subrahmanyam, K. and Shakeel A. (2005) "The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain". *Environmental Geology*, v.47, no.3, pp.412-420.

Sreedevi, P.D., Owais, S., Khan, H.H. and Ahmed, S. (2009) "Morphometric Analysis of a Watershed of South India using SRTM Data and GIS". *Jour. Geol. Soc. India*, v.73, no.4, pp.543-552.

Srinath, K. (1993) "Behavioural characteristics and protodyakonov strength study of Dakshina Kannada laterites". Unpublished M.Tech. thesis submitted to the Mangalore University.

Sreenivasan, R. and Sreenivas, B.L. (1977) "Some new geological features from the LandSat imagery of Karnataka". *Journal Geol. Soc. India*, v.18, no.11, pp.589-597.

Srinivasamoorthy, K., Vasanthavigar, M., Chidambaram, S., Anandhan, P. and Sharma, V.S. (2011) "Characterisation of Groundwater Chemistry in an Eastern Coastal Area of Cuddalore District, Tamil Nadu". *Jour. Geol. Soc. India*, v.78, no.6, pp.549-558.

Srivastava, V.C. (1976). "Geomorphological, Quartenary geological and geomorphological studies along Kudremukh-Mangalore belt". Unpublished report of Geol. Surv. India.

Srivastava, V.C. and Prasad, K.N. (1982) "Geomorphological and Quaternary geological studies around Coondapur and Udupi Taluks in Souh Kanara district, Karnataka". *Records of Geol. Surv. India*, v.114, pp.98-105.

Stamp, D. and Clark, A. (1981) "Glossary of geo-morphological terms". Longman's, London

Strahler, A.H. and Strahler, A.N. (1992) "Modern Physical Geography". John Wiley and sons Inc., New York.

Strahler, A.N. (1950) "Equilibrium Theory of Erosional Slopes approached by Frequency distribution analysis". *Amer. Jour. Sci*., v.243, pp.673-696, pp.800-814.

Strahler, A.N. (1952) "Hypsometric (Area-Altitude) Analysis of Erosional Topography, *Bull. Geol. Soc. America*., v.63, pp.1117-1142.

Strahler, A.N. (1956) "Quantitative Slope Analysis". *Bull. Geol. Soc. America*, v.67, pp. 671-696.

Strahler, A.N. (1957) "Quantitative analysis of watershed geomorphology". *Trans. Am. Geophys. Union*, v.38, pp.913-920.

Strahler, A.N. (1958) "Dimensional Analysis Applied to Fluvially Eroded Land Forms". *Bull. Geo. Soc. America*., v. 69, pp.2790-3000.

Strahler, A.R. (1964) "Quantitative Geomorphology of Drainage Basin and Channel Networks". In: *Handbook of Applied Hydrology* (Ed. V.T. Chow), Mc-Graw Hill Publications, pp.4.39-4.76.

Stumm, W. and Morgan, T.J. (1970) "Aquatic chemistry". Wiley, New York, 1022p.

Stuyfzand, P.J. (1989) "A new hydrochemical classification of water types. Regional characterisation of water quality" (Proceedings of the Baltimore symposium, May 1989). IAHS Publ. no. 182, pp.89-98.

Subba Rao, N. (1992) "Factors affecting optimum development of groundwater in crystalline terrain of Eastern Ghats". *Jour. Geol. Soc. India*, v.40, no.05, pp.462.

Subba Rao, N. (2001) "Geochemistry of groundwater in parts of Guntur district, Andhra Pradesh, India". *Environ. Geol*., v.41, pp.552-562.

Subbarao, N., and Krishnarao, G. (1990) "Intensity of pollution of groundwater in visakapatnam area, A.P, india". *Jour. Geol. Soc. India*, v.36, no.06, pp.670.

Subba Rao, B. and Subrahmanyam, V.P. (1961) "Estimation of yields from river basins by a modification of the water balance procedure of Thornthwaite". *Ind. Jour. of Meteorology and Geophysics*, v.12, no.2.

Subrahmanian, K.S. (2003) "Correspondence: Groundwater Recharge", *Jour. Geol. Soc. India*, v.62, pp. 649.

Subramanya, K. (2008) "Engineering Hydrology" Tata McGraw Hill, New Delhi, 434p.

Subrahmanya, K.R. (1994) "Post Gondwana tectonics of the Indian Peninsula". *Current Science*, v.67, no.7, pp.527-530.

Subrahmanya, K.R. (1996) "Active Interplate deformation in South India". *Tectonophysics*, Elsevier, New York, v. 262, pp. 231-241.

Subrahmanyam, V.P. and Upadhyay, V.P. (1982) "A study of rainfall pattern in Nepal". *Proc. of the seminar on hydrological investigation during the last 25 years in India*, Waltair, pp.43-50.

Subramani, T., Elango, L. and Damodarasamy, S.R. (2005) "Groundwater quality and its suitability for drinking and agricultural use in Chithar River basin, Tamil Nadu, India". *Environ. Geol*., v.47, pp.1099-1110.

Subramani, T., Rajmohan, N. and Elango, L. (2010) "Groundwater geochemistry and identification of hydrogeochemical processes in a hard rock region, Southern India". *Environ. Monit. Assess.*, v.162, pp.123-137.

Subramanian, V. (1987) "Environmental geology of peninsular river basin of India". *Jour. Geol. Soc. India*, v.30, no.05, pp-393.

Subramanya, K. (2008) "Engineering Hydrology" 3rd edition, Tata McGraw Hill Publishing Company Ltd., New Delhi. P.434.

Sujatha, D. and Reddy, B.R. (2006) "Nitrates in groundwater sources in southeastern part of Ranga Reddy district, Andhra Pradesh, India". *Jour. Appld. Geochemist.*, v.8, no.2, pp.169-180.

Sunil, B. Malegole and Shrihari, S. (2002) "Low pH phenomena in the coastal region of Karnataka- A case study". *K.R.E.C. Research Bulletin*, v.11, no.1, pp.24-26.

Szabolcs, I. and Darab, C. (1964) "The influence of irrigation water of high sodium carbonate content of soils". In: *Proc.8th International congress of Isss*, Trans. II: 803-812.

Tamta, S.R. (1994) "Possible mechanism for concentration of Fluoride in groundwater". *Bhu-Jal News*, v.9, no.2, pp.5-11.

Thornthwaite, Charles W. (1948) "An approach toward a rational classification of climate". *Geographic Review*, v.38, no.1, pp.55-94.

Thornthwaite, Charles W. and Mather, J.R. (1957) "Instructions and tables for computing potential evapotranspiration and the water balance". *Publications in Climatology*, v.X, no.1.

Todd, D.K. (1980) "Groundwater Hydrology", 2nd edn., John Wiley & Sons Inc., New York, 593p.

Toy, T.J. (1977) "Hill slope form and climate". *Geol. Soc. Amer. Bull.*, no.88, pp.16-22.

Tucker, G.E. and Bras, R.L. (1998) "Hill slope processes, drainage density and landscape morphology". *Water Resources Research*, v.34, pp.2751-2764.

Udayakumar, G. (2008) "Subsurface barrier for water conservation in Lateritic formations". Unpublished Ph.D. Thesis submitted to National Institute of Technology Karnataka, Surathkal, 169p.

Umar, R. and Ahmed, I. (2007) "Hydrochemical characteristics of groundwater in parts of Krishni-Yamuna basin, Muzzafarnagar district, Uttar Pradesh, India". *Jour. Geol. Soc. India*, v.69, pp.989-995.

Umar, R., Khan, M.M.A. and Absar, A. (2006) "Groundwater Hydrochemistry of a sugarcane cultivation belt in parts of Muzzafarpur district, Uttar Pradesh, India". *Environ. Geol.*, v.49, pp.999-1008.

Umar, R., Ahmed, I. and Alam, F. (2009) "Mapping Groundwater Vulnerable Zones Using Modified DRASTIC approach of an alluvial aquifer in parts of central ganga plain, western Uttar Pradesh". *Jour. Geol. Soc. India*, v.73, no.2, pp.193-201.

Valdiya, K.S. (2001) "Tectonic resurgence of the Mysore plateau and surrounding regions in cratonic southern India". *Curr. Sci.*,v.81, pp.1068–1089.

Vaidyanadhan, R. (1996) "Geo environment - an introduction", *Jour. Geol. Soc. India*, v.47, pp.392.

Vaidyanadhan, Singh, S.B., and Singh, U. K. K. P. (2002) "An Integrated Geophysical Approach for Groundwater Prospecting: A case study from Tamil Nadu". *Jour. Geol. Soc. India*, v.59, pp.147-158.

Valsangkar, A.B., Radhakrishnamurthy, C., Rao, K.V.S. and Beckinsale, R.D. (1981) "Palaeomagnetism and Potasium-Argon age studies of acid igneous rocks from the St. Mary's Islands". *Mem. Geol. Soc. India*, v.22, pp.265-276.

Venkatachalam, P., Murthy, C.V.S.S.B.R., Chowdhary, S. and Sharma, L.N. (1991) "Groundwater potential zone mapping using a GIS approach". *Asia-Pacific Remote Sensing Jour.*, v.4, pp.75-78.

Venkataraman, S. and Rao, M.K.M. (1990) "Hydrogeology and Groundwater potential of Dakshina Kannada District, Karnataka". Report of Central Groundwater Board, Bangalore, pp.1- 96.

Vennila, G. Subramani, T and Elango, L. (2008) "GIS Based Groundwater Quality Assessment of Vattamalaikarai Basin, Tamil Nadu, India". *Int. Jour. of Nature Environment and Pollution Technology*, v.7, no.4, pp.585-592.

Venugopal, H. (1986) "Hydrogeological investigations of Pavanje river basin through aerial photographs". Unpublished M.Tech. thesis submitted to KREC, surathkal.

Verstappen H. (1983) "The applied geomorphology". International Institute for Aerial Survey and Earth Science (I.T.C), Enschede, Netherlands, Amsterdam, Oxford, New York.

Vias, J.M., Andreo, B., Perles, M.J. and Carrasco, F. (2005) "A comparative study of four schemes for groundwater vulnerability mapping in a diffuse flow carbonate, 1948 aquifer under Mediterranean climatic conditions". *Environ. Geol.*, v.47, pp.586-595.

Viswanathiah, M.N., Rao, Krishna and Dasu, S.P.V. (1974) "Bauxites of Paduvare area, South Kanara, Karnataka, India". *Mineralogist*, v.15, pp.63-73.

Vozoff, K. and Jupp, D.L.B. (1975) "Joint Inversion of Geophysical data". *Geophys. J.r. Astr. Soc.*, pp.977-991.

Vrba, J. and Zeporozec, A. (1994) "Guidebook on mapping Groundwater vulnerability". *International contributions to Hydrogeology*, v.16, 129p.

Wakida, F. and Lerner, D.N. (2005) "Non-agricultural sources of groundwater nitrate: a review and case study". *Water Res.*, v.39, pp.3-16.

Walton, W.C. (1970) "Groundwater Resources Evaluation". Mc. Graw Hill Book Co., New York.

WHO (1993) "Guidelines for drinking water quality". 2nd edn., World Health Organization, Geneva, v.1,188p.

Widdowson, M. and Mitchell, C. (1999) "Large-scale stratigraphical, structural, geomorphological constraints for earthquakes in the southern Deccan Traps India: The case for denudationally driven seismicity". In: *Deccan Volcanic Province* (ed.) Subbarao K V, *Geol. Soc. India Memoir*, v. 43, pp. 245–274.

Wilcox, L.V. (1948) "The quality of water for irrigation uses". *U.S. Department of Agriculture, Tech. Bull.*, 1962. Washington D.C., 19p.

Wilcox, L.V. (1955) "Classification and use of irrigation water." *U.S. Department of Agriculture circular* 969, Washington D.C., USA.

Willgoose, G. (1994) "A physical explanation for an observed area– slope–elevation relationship for catchments with declining relief". *Water Resources Research*, v.30, pp.151–159.

Willgoose, G. and Hancock, G. (1998 "Revisiting the hypsometric curve as an indicator of form and process in transport-limited catchment". *Earth Surface Processes and Landforms*, v.23, pp.611–623.

Winston, R. B. (2000) "Graphical User Interface for MODFLOW, Version 4". U.S. Geological Survey Open-File Report 00-315, 27 p.

Winter, Thomas C., Harvey, Judson W., Franke, O. L., Alley, William M. (1998) "Groundwater and Surface Water: A Single Resource". *U.S. Geol. Surv. Circ.1139*, Denver, Colorado.

Zohdy, A.A.R., Eaton, G.P. and Mabey, D.R. (1974) "Application of surface geophysics to groundwater investigations". BK 2, chapter D1, Techniques of Water Resources investigation of USGS.

Plates

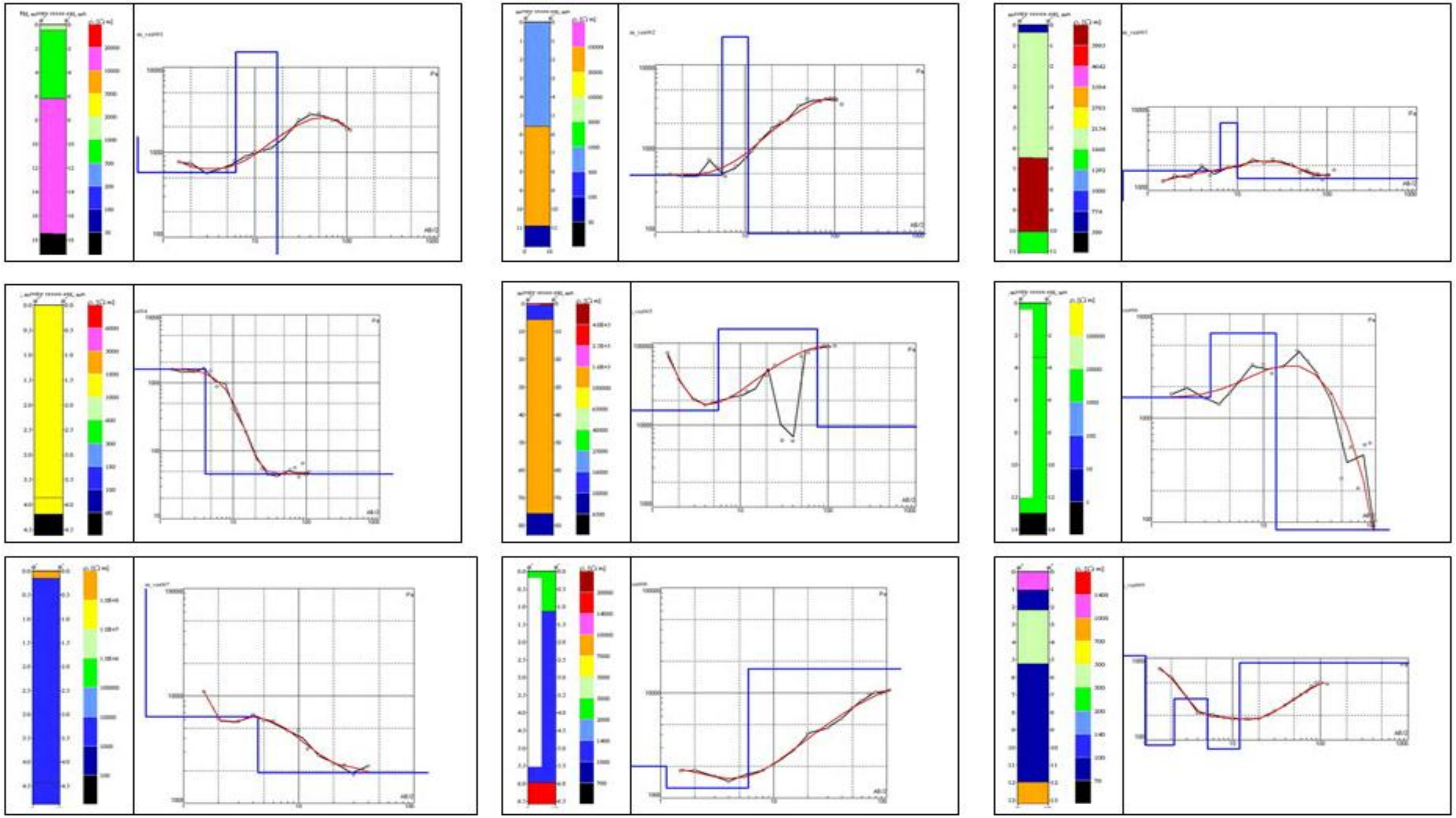

Plate 5.1 showing VES Curves and resistivity sections of stations 001-009 in Mulki River Basin

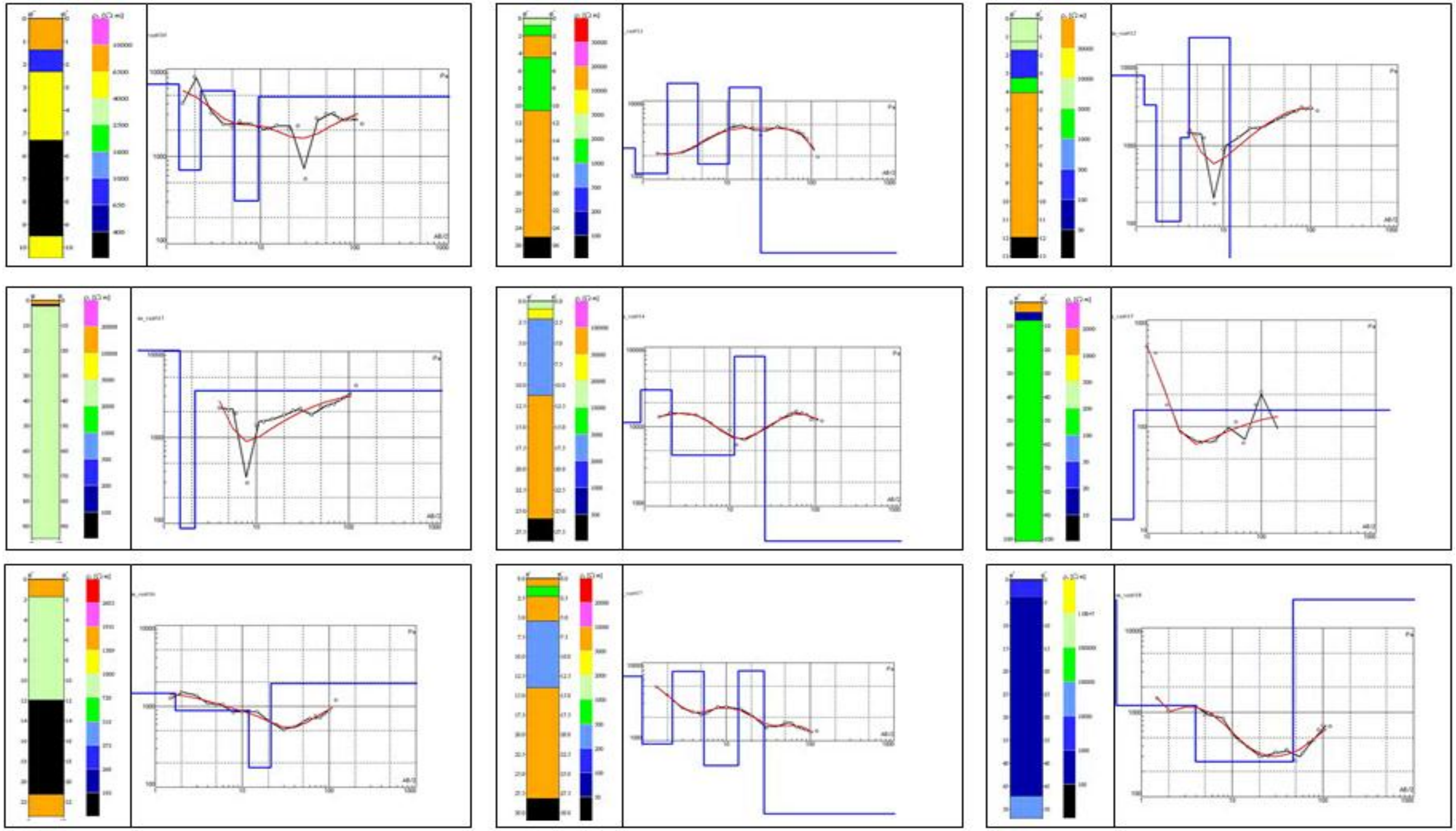

Plate 5.2 showing VES Curves and resistivity sections of stations 010-018 in Mulk i River Basin

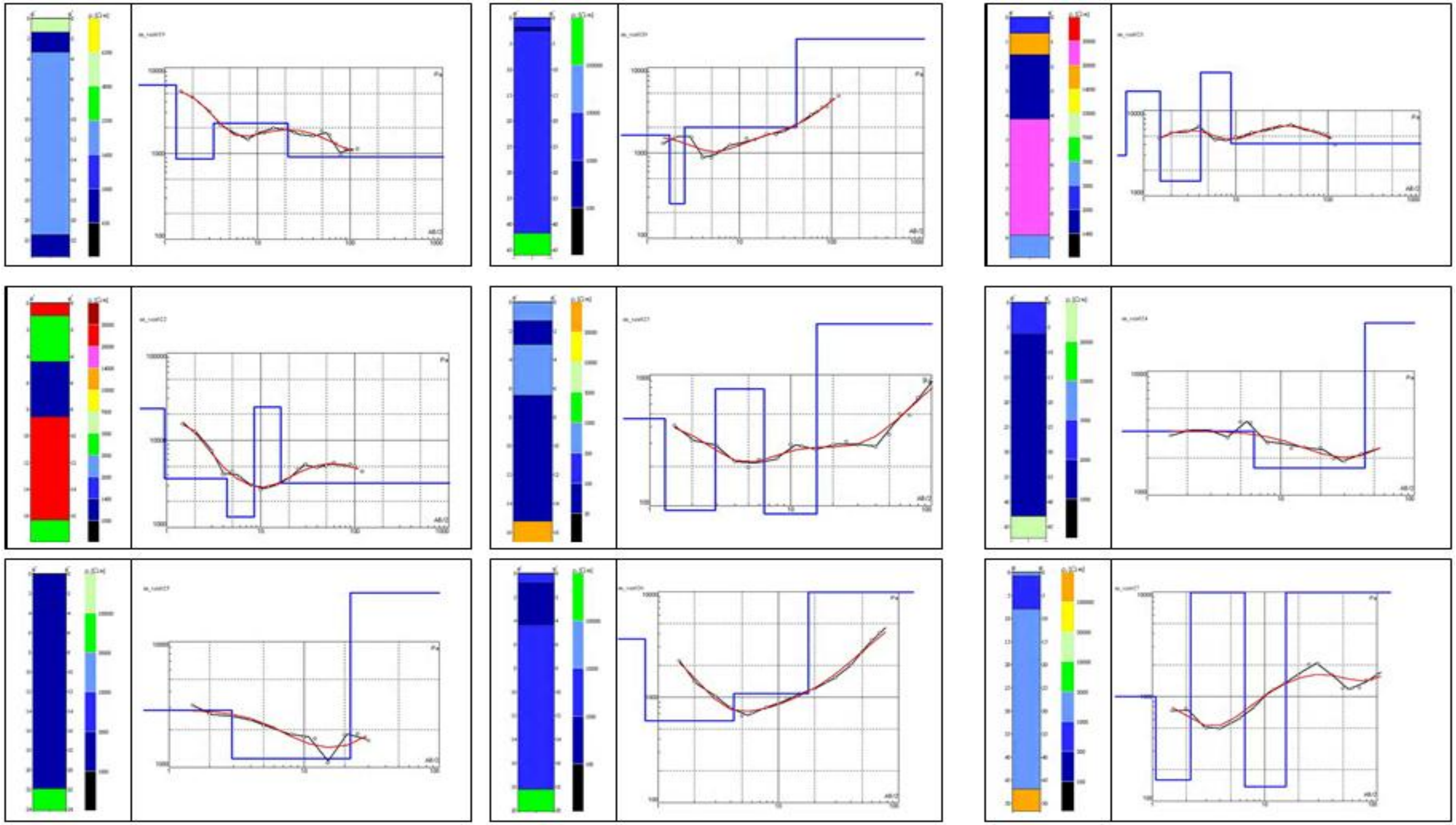

Plate 5.3 showing VES Curves and resistivity sections of stations 019-027 in Mulki River Basin

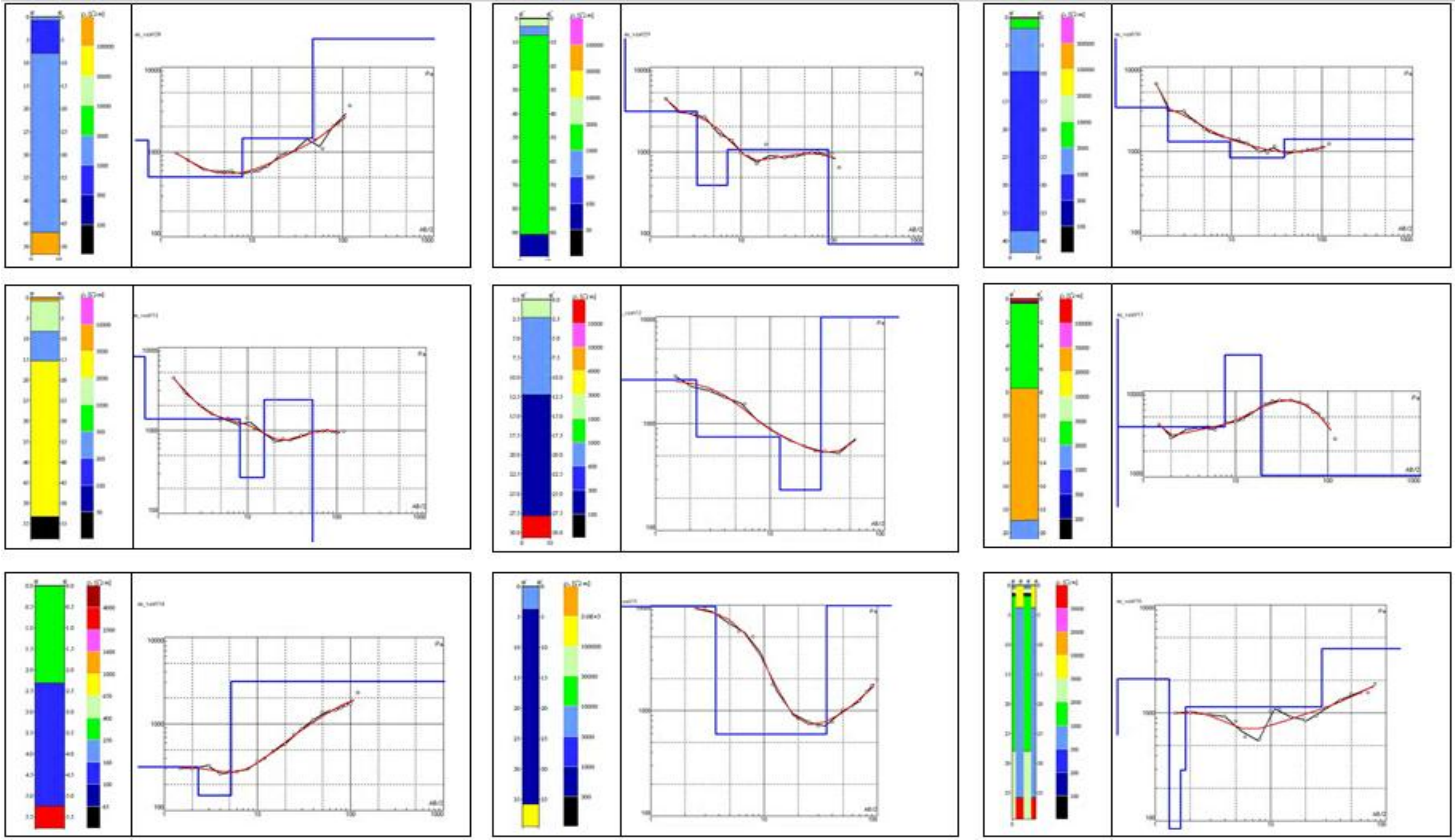

Plate 5.4 showing VES Curves and resistivity sections of stations 028-036 in Mulki River Basin

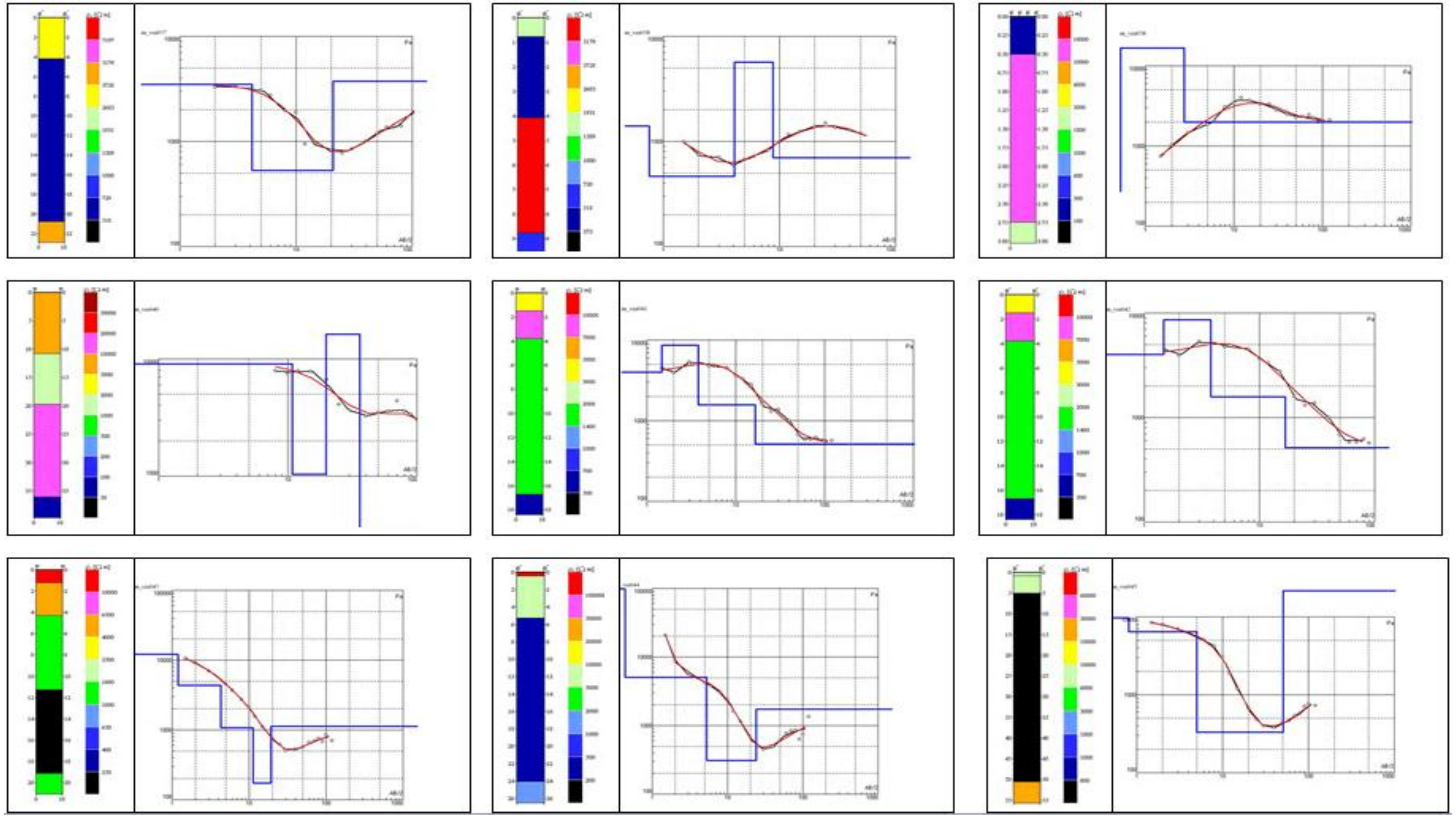

Plate 5.5 showing VES Curves and resistivity sections of stations 037-045 in Mulki River Basin

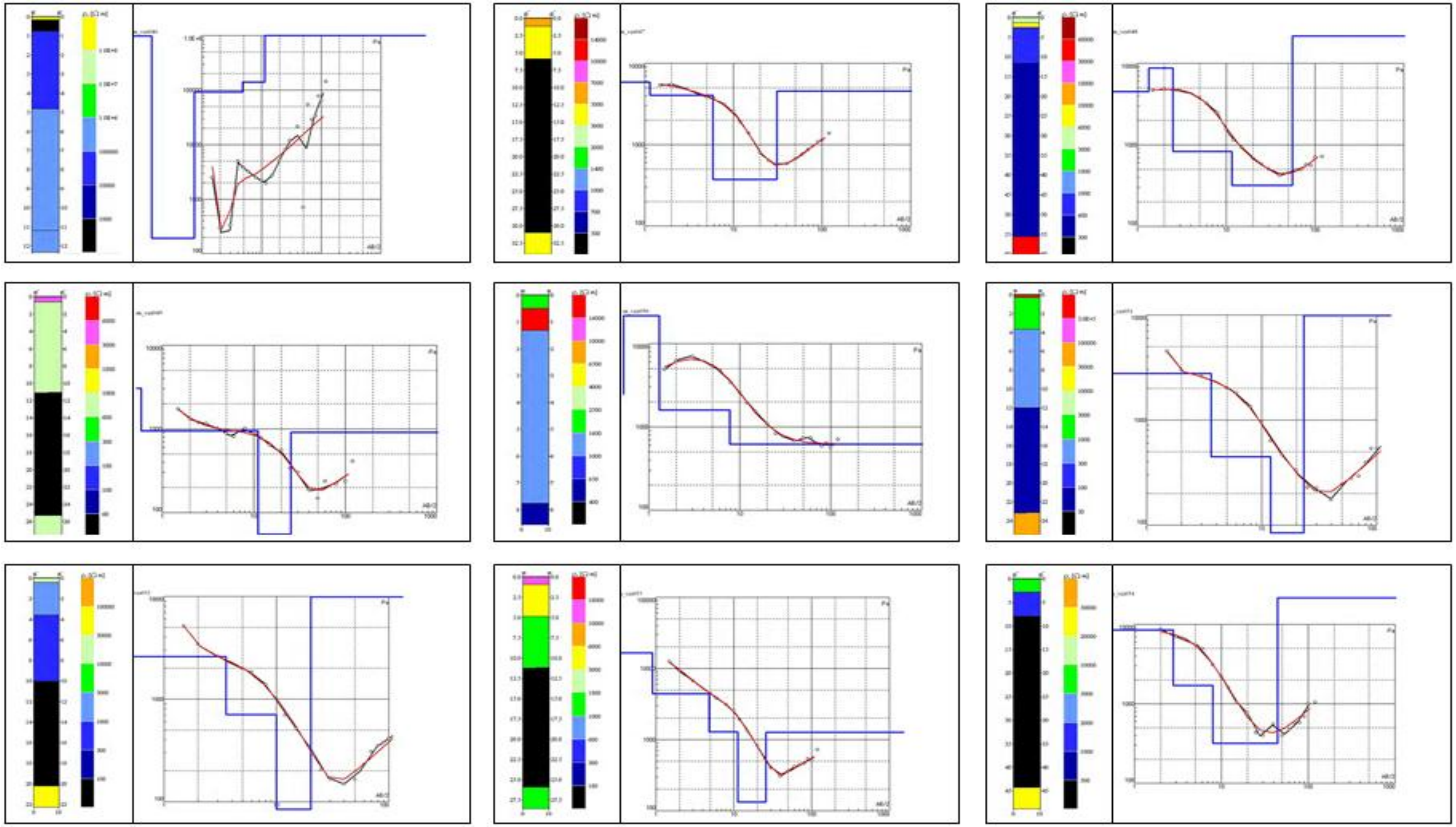

Plate 5.6 showing VES Curves and resistivity sections of stations 046-054 in Mulki River Basin

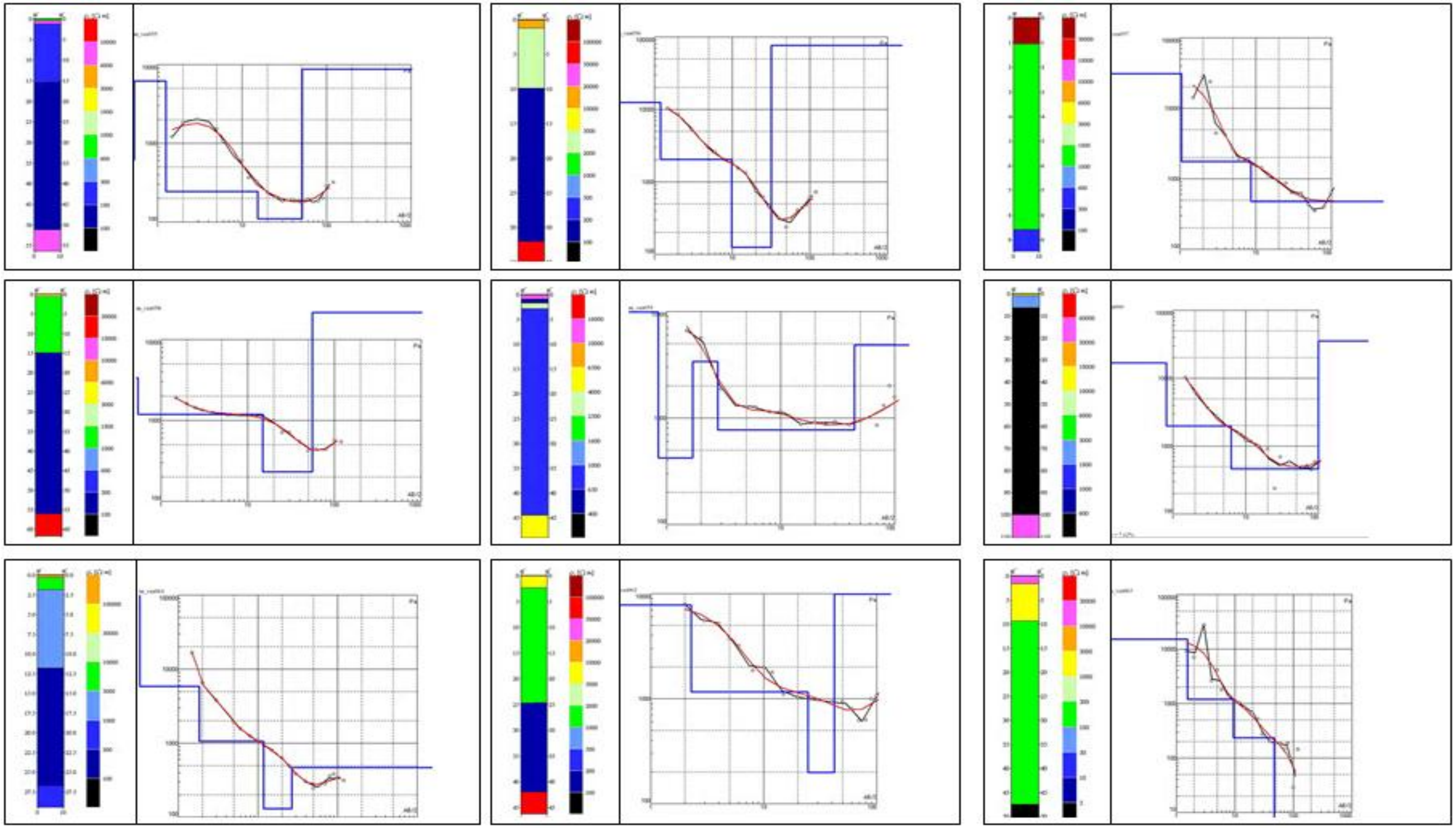

Plate 5.7 showing VES Curves and resistivity sections of stations 055-063 in Mulki River Basin

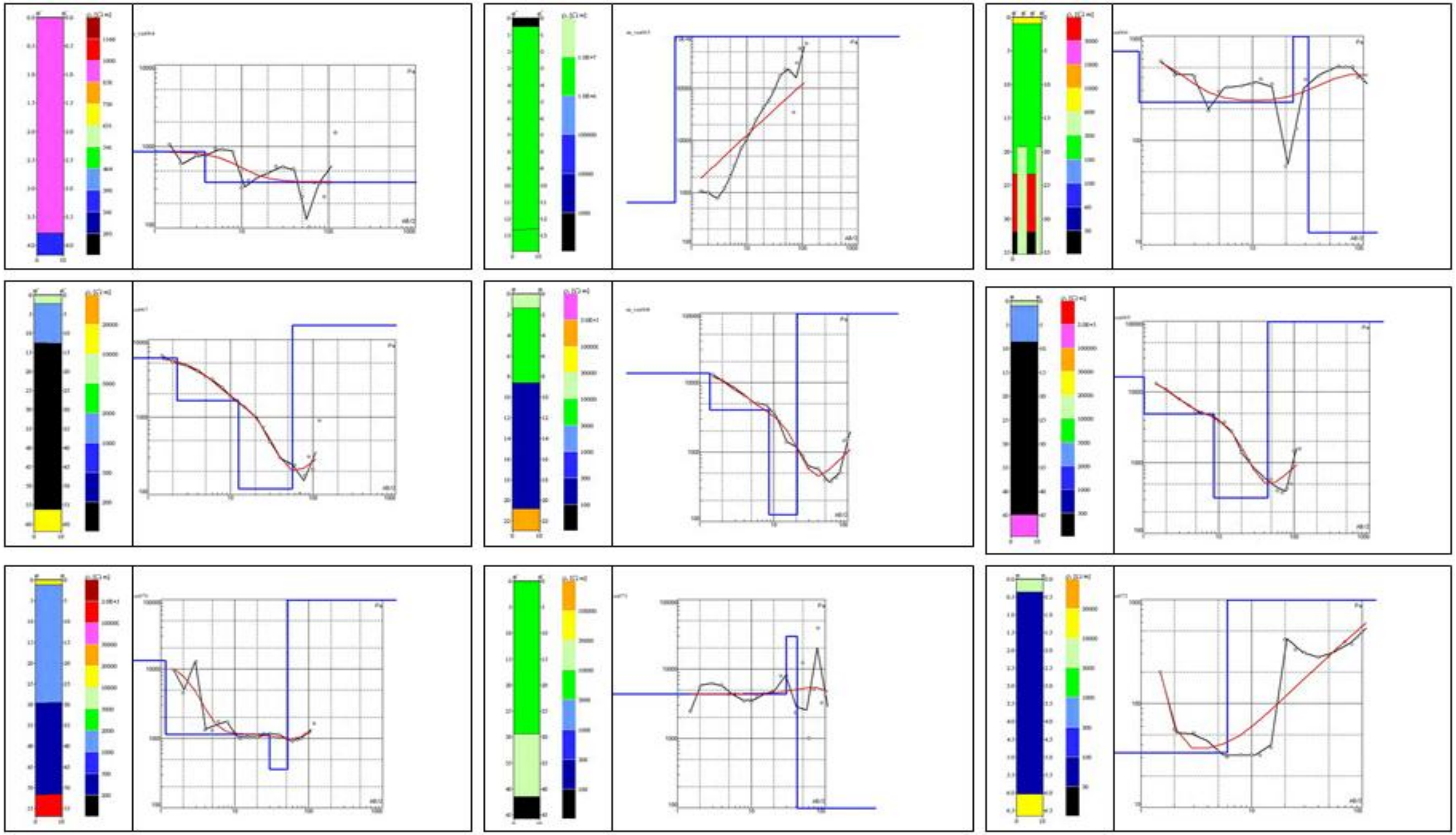

Plate 5.8 showing VES Curves and resistivity sections of stations 064-072 in Mulki River Basin

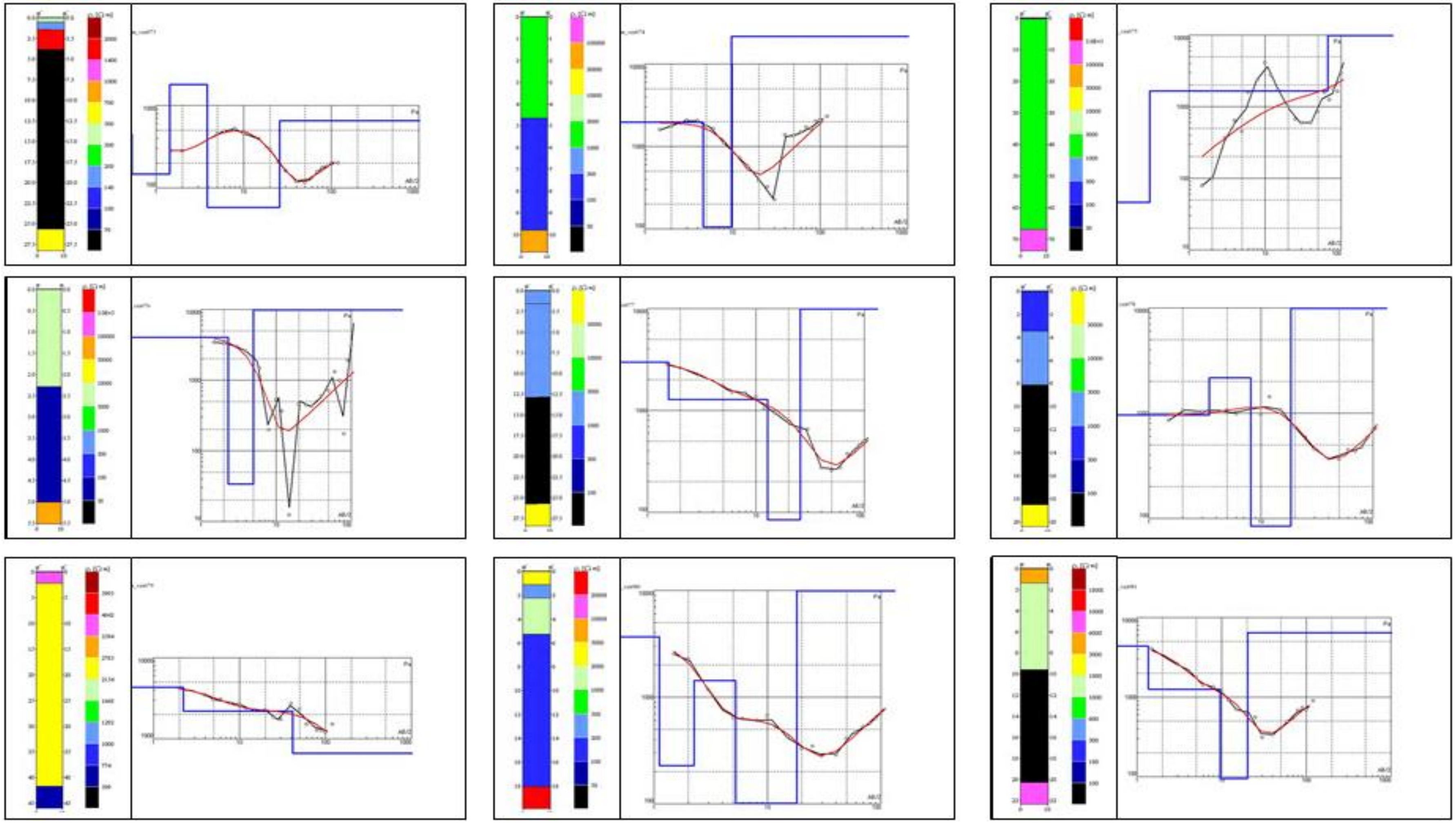

Plate 5.9 showing VES Curves and resistivity sections of stations 073-081 in Mulki River Basin

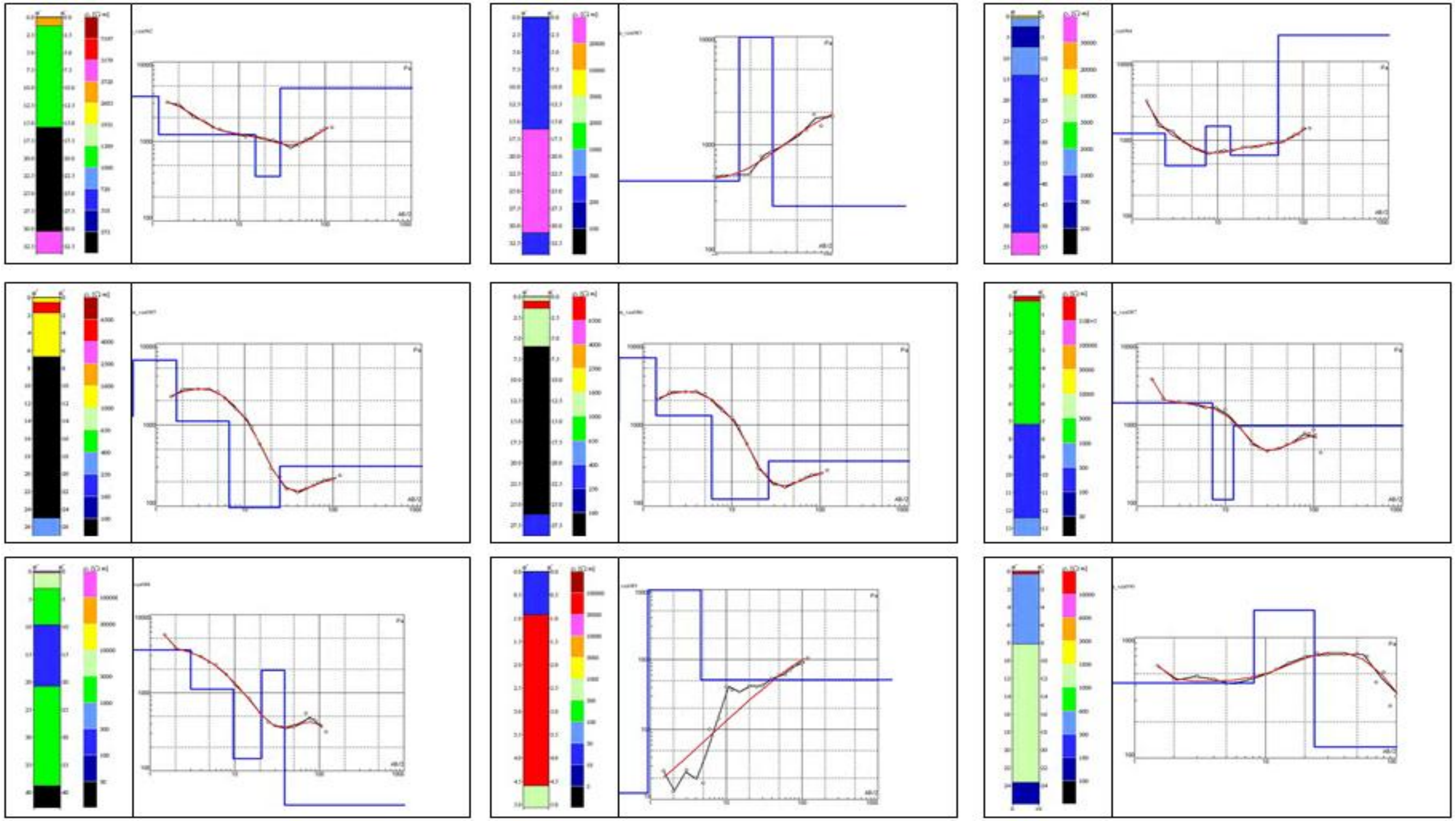

Plate 5.10 showing VES Curves and resistivity sections of stations 082-090 in Mulki River Basin

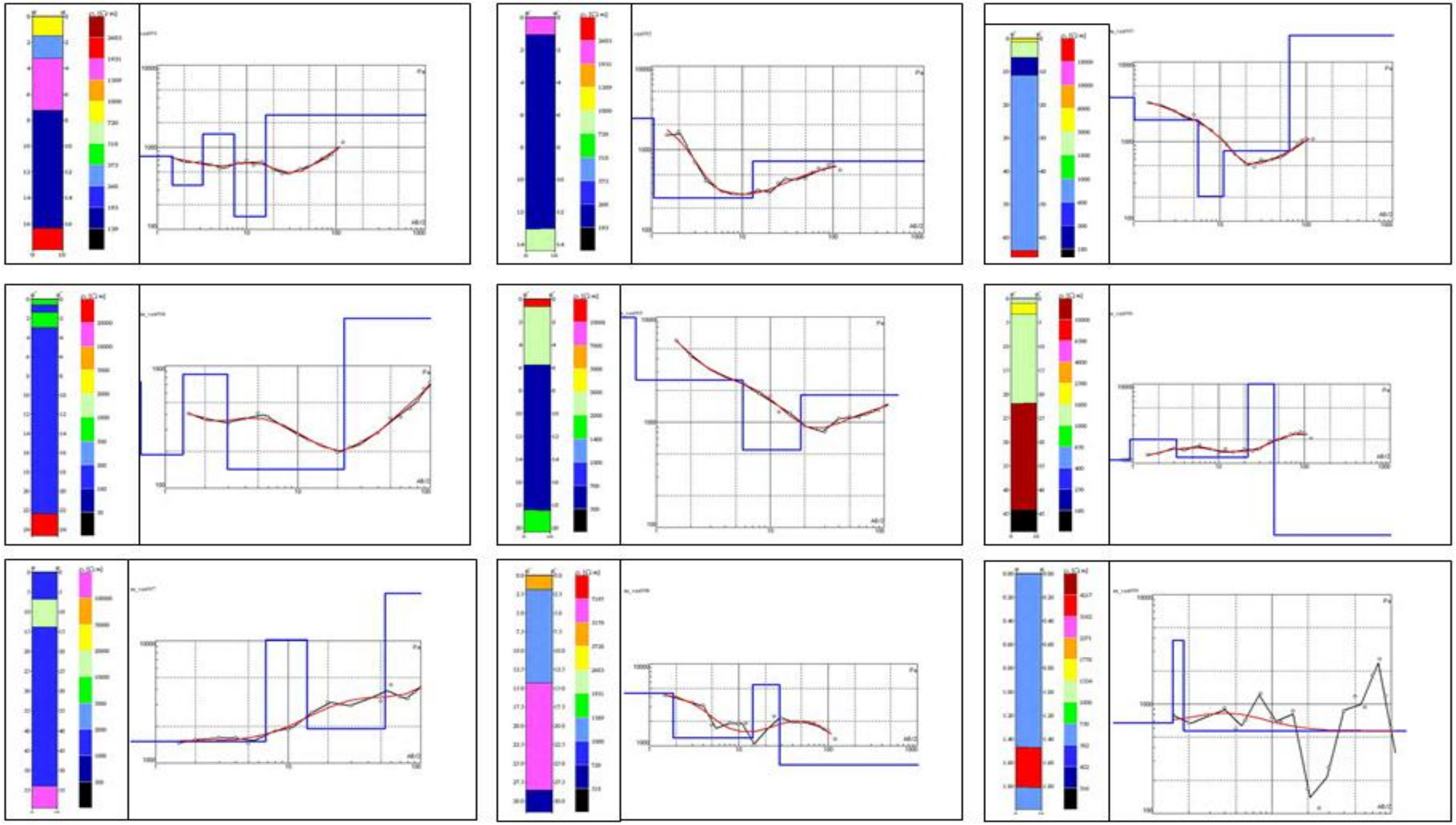

Plate 5.11 showing VES Curves and resistivity sections of stations 091-099 in Mulki River Basin

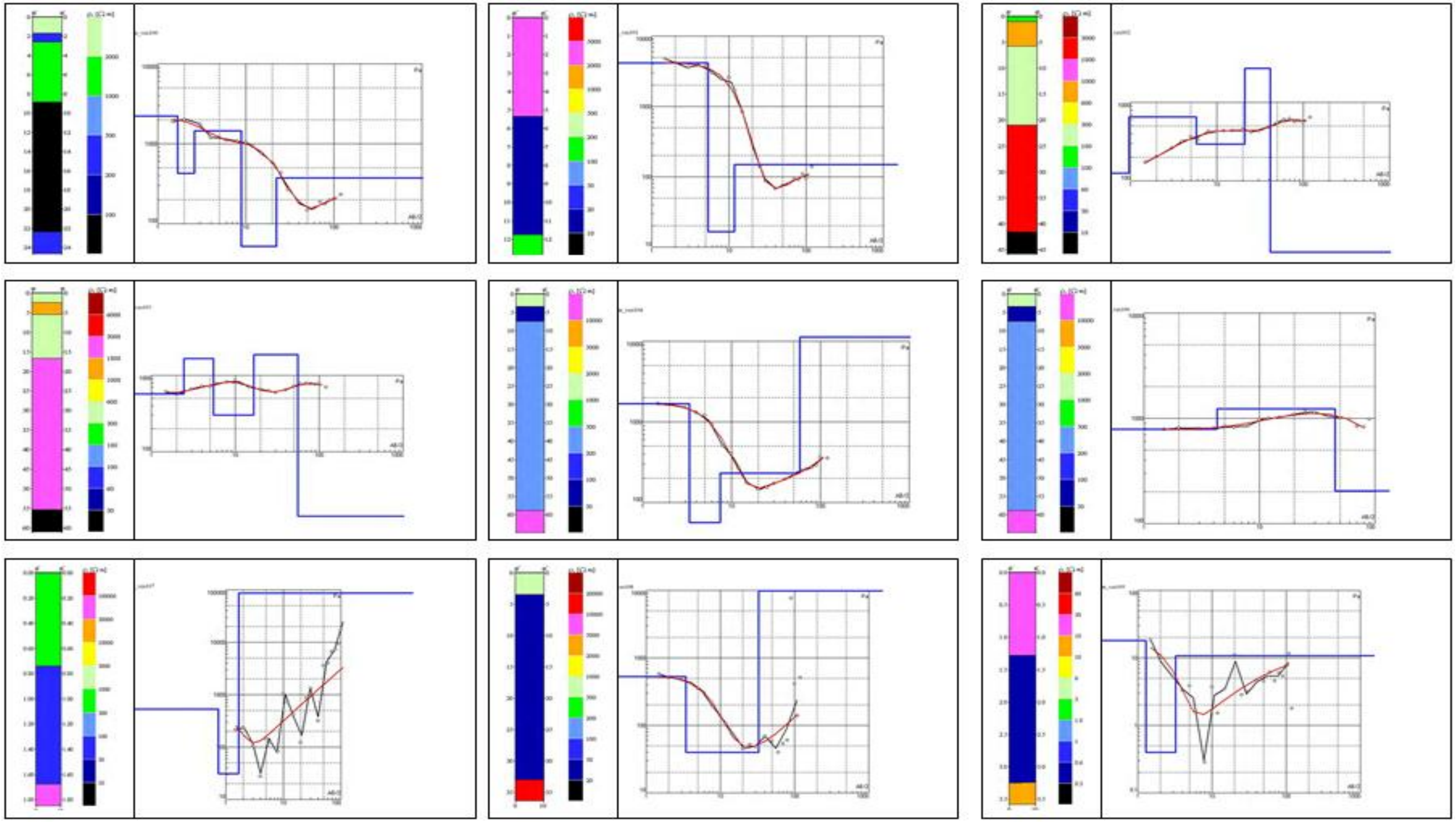

Plate 5.12 showing VES Curves and resistivity sections of stations 100-110 in Mulki River Basin

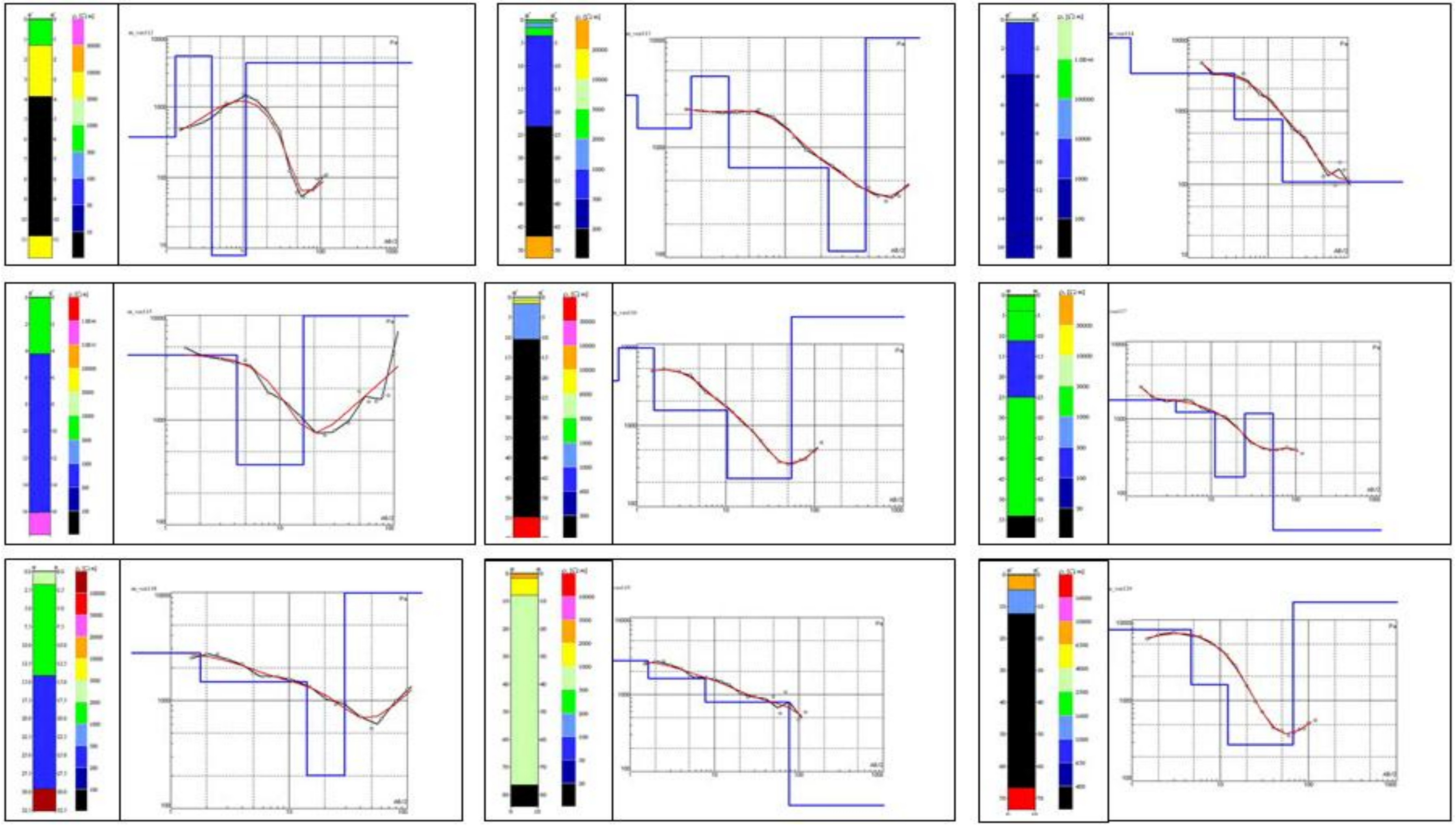

Plate 5.13 showing VES Curves and resistivity sections of stations 111-119 in Mulki River Basin

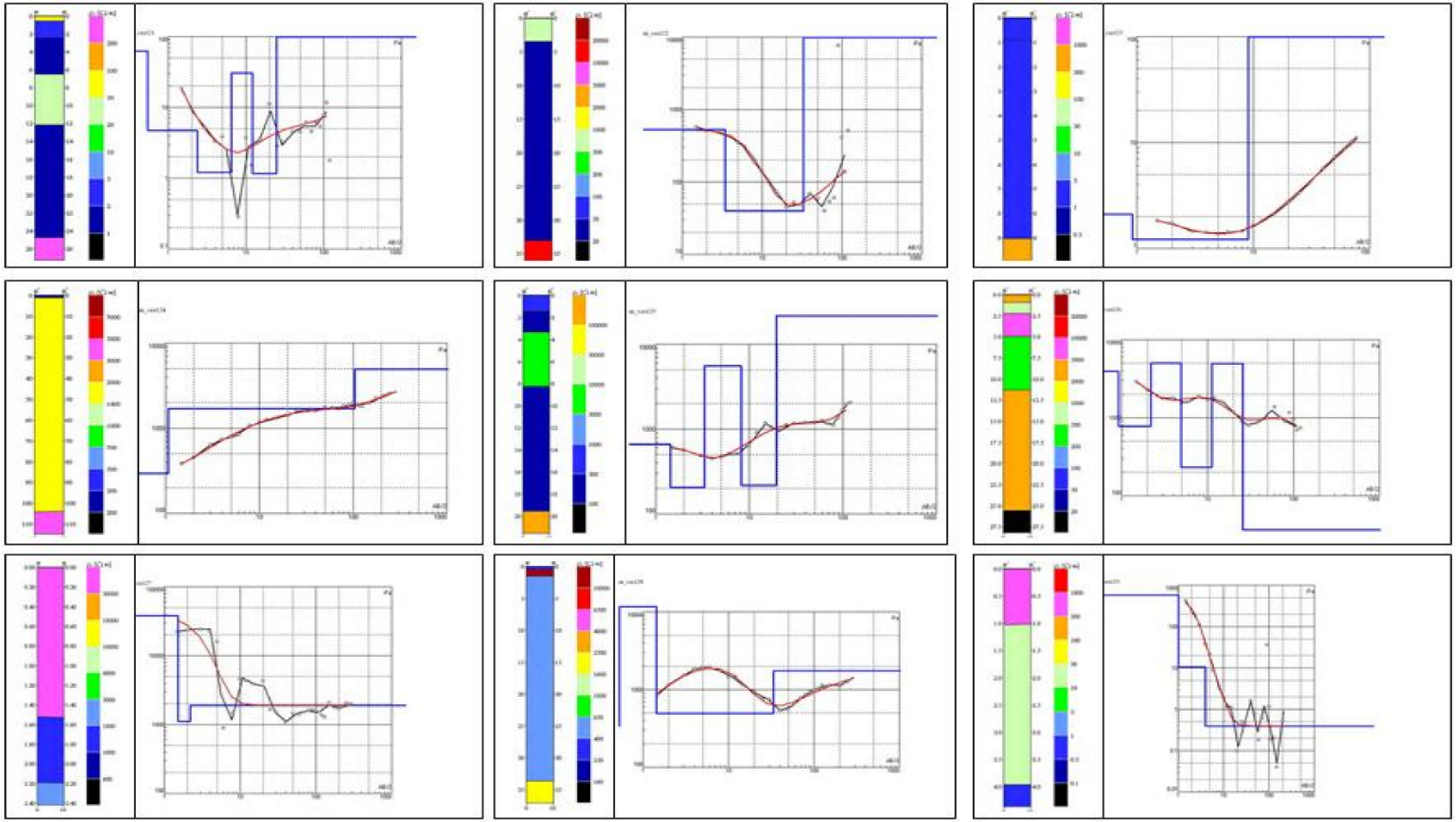

Plate 5.14 showing VES Curves and resistivity sections of stations 120-129 in Mulki River Basin

Appendices

APPENDIX -A						
DETAILS OF LINEAMENTS IN MULKI RIVER BASIN						
LID	Long1	Lat1	Long2	Lat2	Wt.Avg.Dir.	Dist.(Km)
0	74.96411	13.14784	75.01062	13.16719	N66E	5.476
1	74.95021	13.07333	74.98634	13.10177	N51E	5.031
2	74.98593	13.10144	74.99218	13.10129	S88E	0.677
3	74.99153	13.1005	74.99979	13.1059	N56E	1.078
4	75.01698	13.18881	75.00952	13.18198	S46W	1.108
5	74.99775	13.1774	75.00628	13.18118	N65E	1.015
6	75.00466	13.16911	75.03352	13.1662	S84E	3.141
7	74.92688	13.07619	74.9434	13.0827	N67E	1.931
8	74.95151	13.08556	74.91941	13.11796	N43W	5.006
9	74.94535	13.0827	74.9507	13.07651	S39E	0.9
10	74.8802	13.09221	74.91001	13.10922	N59E	3.742
11	74.91471	13.11859	74.9152	13.11113	S3E	0.832
12	74.90919	13.15115	74.91033	13.11875	S1E	3.605
13	74.87356	13.09904	74.88134	13.0911	S43E	1.22
14	74.86966	13.11984	74.87663	13.10142	S20E	2.183
15	74.87582	13.10555	74.87536	13.0972	S3W	0.93
16	74.93949	13.16514	74.93139	13.15433	S36W	1.487
17	74.92329	13.15751	74.93042	13.1537	S61E	0.881
18	74.92025	13.15469	74.92361	13.15814	N43E	0.529
19	74.94614	13.16339	74.94792	13.1672	N24E	0.466
20	74.93998	13.16402	74.94488	13.16373	S86E	0.531
21	74.94785	13.16704	74.9523	13.16704	N89E	0.482
22	74.97013	13.19198	74.9617	13.17308	S23W	2.291
23	74.9605	13.16947	74.96316	13.17451	N27E	0.631
24	74.97353	13.17721	74.98537	13.17721	N89E	1.281
25	74.82606	13.1276	74.86975	13.1196	S79E	4.815
26	74.85102	13.12412	74.85831	13.12381	S87E	0.791
27	74.84502	13.12745	74.84891	13.12714	S85E	0.423
28	74.84891	13.12714	74.85086	13.12364	S28E	0.442
29	74.83935	13.12729	74.84486	13.12523	S68E	0.639
30	74.79625	13.11614	74.80938	13.10964	S62E	1.595
31	74.8097	13.10885	74.81456	13.11361	N44E	0.747
32	74.81666	13.12092	74.82444	13.12172	N83E	0.847
33	74.82655	13.12751	74.82393	13.12167	S23W	0.709
34	74.79448	13.09406	74.77811	13.10024	N68W	1.902
35	74.87305	13.14335	74.92216	13.14099	S87E	5.324
36	74.9382	13.13893	74.95895	13.1402	N86E	2.251
37	74.94403	13.09813	74.96143	13.09976	N84E	1.893
38	74.97738	13.18118	74.95853	13.13285	S20W	5.767
39	74.91896	13.11741	74.95314	13.14443	N50E	4.767
40	74.95251	13.14422	74.96288	13.14816	N68E	1.205
41	74.92869	13.11214	74.89284	13.14685	N44W	5.791
42	75.04224	13.14808	74.99934	13.17428	N62W	5.703
43	75.0153	13.18484	75.01447	13.17164	S3W	1.47
44	74.9952	13.15174	75.00059	13.15966	N33E	1.056
45	74.91046	13.11132	74.92434	13.1099	S83E	1.512
46	74.89866	13.09284	74.90653	13.09	S69E	0.909
47	74.89692	13.10178	74.89845	13.09365	S10E	0.919
48	74.79154	13.11369	74.82929	13.05544	S32E	7.744
49	74.8038	13.06577	74.82741	13.07493	N68E	2.752
50	74.83504	13.11802	74.85659	13.11431	S79E	2.37
51	75.00224	13.1686	75.00142	13.16271	S7W	0.661
52	74.86159	13.0715	74.88562	13.07354	N85E	2.612
53	74.86612	13.12775	74.88914	13.07253	S22E	6.716
54	74.93325	13.12655	74.96578	13.14463	N59E	4.209
55	74.86881	13.13079	74.87647	13.13608	N54E	1.017
56	74.90261	13.06969	74.92664	13.06076	S69E	2.786
57	74.93429	13.09752	74.93616	13.09691	S71E	0.213
58	74.91896	13.1036	74.93616	13.09691	S68E	2.006
59	74.91482	13.10299	74.89323	13.14664	N28W	5.456
60	74.91147	13.18381	74.9295	13.17935	S75E	2.014
61	74.90446	13.10116	74.91917	13.10157	N88E	1.594
62	74.93325	13.12655	74.93491	13.11031	S7E	2.037
63	74.87253	13.14745	74.92806	13.14726	S89E	6.013
64	74.92413	13.14259	74.99209	13.1753	N63E	8.29
65	74.91749	13.16107	74.96557	13.16291	N87E	5.209
66	74.84337	13.13042	74.92815	13.17891	N59E	10.646
67	74.92469	13.13471	74.95743	13.1481	N67E	3.846
68	75.01751	13.18041	75.03009	13.17318	S59E	1.581
69	74.82714	13.1274	75.01992	13.1899	N71E	22.468
70	74.94444	13.06248	74.94224	13.08224	S89W	2.287
71	74.9337	13.12727	74.92898	13.14325	N55W	1.873
72	74.91481	13.11702	74.92427	13.13435	N27E	2.198
73	74.93516	13.14597	74.96039	13.14651	N88E	2.74
74	74.95022	13.07445	74.99215	13.15014	N28E	9.676
75	75.00286	13.12618	74.99506	13.1496	N17W	2.75
76	74.93715	13.10295	74.9593	13.11547	N59E	2.801
77	74.99306	13.18209	74.99775	13.1774	S44E	0.728
78	74.967	13.17185	74.97515	13.17646	N60E	1.042

79	74.93516	13.12546	74.94804	13.12872	N75E	1.447
80	74.98054	13.05848	74.9544	13.07518	N56W	3.392
81	74.96692	13.06846	75.01157	13.07772	N77E	5.102
82	74.96638	13.08189	74.97688	13.09432	N39E	1.832
83	74.88268	13.1485	74.88978	13.17156	N16E	2.762
84	74.90385	13.10514	74.91296	13.10583	N85E	0.989
85	74.90212	13.10194	74.90399	13.10582	N25E	0.477
86	74.9104	13.10808	74.91307	13.10768	S81E	0.293
87	74.89792	13.10235	74.90212	13.10194	S84E	0.457
88	75.01012	13.16163	75.03007	13.1647	N81E	2.212
89	75.01501	13.18423	75.0111	13.16512	S11W	2.175
90	74.94037	13.09481	74.95167	13.08407	S45E	1.723
91	74.94511	13.08351	74.94784	13.08653	N41E	0.447
92	74.99753	13.10984	75.00105	13.1135	N43E	0.558
93	74.85875	13.12578	74.86392	13.12369	S67E	0.605
94	74.79203	13.11306	74.79283	13.09534	S2E	1.973
95	74.77669	13.11278	74.78294	13.06644	S7E	5.196
96	74.85583	13.17265	74.85348	13.15338	S6W	2.157
97	74.81256	13.11165	74.816	13.12111	N19E	1.115
98	74.90711	13.11382	74.88029	13.13673	N48W	3.862
99	74.91804	13.10575	74.93158	13.10393	S82E	1.48
100	74.96021	13.11043	74.97869	13.14349	N28E	4.185
101	74.97843	13.15104	74.98884	13.15547	N66E	1.23
102	74.98025	13.15104	74.98051	13.14349	S1E	0.84
103	74.79283	13.08935	74.81079	13.0995	N59E	2.249
104	74.86702	13.18306	74.87014	13.17291	S16E	1.178
105	74.99471	13.10764	74.99722	13.09048	S8E	1.927
106	74.81909	13.14636	74.82967	13.15847	N40E	1.768
107	74.82147	13.11268	74.83407	13.11104	S82E	1.377
108	74.89759	13.06823	74.90989	13.07685	N54E	1.642
109	74.90789	13.08964	74.91077	13.07671	S12E	1.472
110	75.00724	13.14519	75.01217	13.16615	N12E	2.391
111	74.80435	13.12495	74.8065	13.11387	S10E	1.253
112	74.80435	13.12495	74.80932	13.12829	N55E	0.654
113	74.80873	13.13421	74.80873	13.12705	S0W	0.796
114	74.80795	13.13402	74.81418	13.13584	N73E	0.705
115	74.81476	13.14481	74.81367	13.13569	S6W	1.022
116	74.81476	13.14481	74.81924	13.15112	N34E	0.852
117	74.81924	13.15112	74.83258	13.15858	N60E	1.874
118	74.83843	13.16536	74.86961	13.17053	N80E	3.425
119	74.83668	13.15791	74.83959	13.16775	N16E	1.138

120	74.82873	13.15811	74.83682	13.15841	S82E	0.993
121	74.8698	13.17006	74.8774	13.17445	N59E	0.957
122	74.86078	13.08707	74.87601	13.09313	N67E	1.781
123	74.853	13.07981	74.85806	13.07695	S59E	0.634
124	74.80252	13.10117	74.80828	13.08809	S23E	1.582
125	74.79444	13.09535	74.80116	13.10132	N47E	0.985
126	74.79493	13.0941	74.79725	13.10634	N10E	1.384
127	74.8189	13.08781	74.82426	13.08065	S36E	0.985
129	74.81227	13.0858	74.82221	13.08505	S85E	1.08
130	74.8075	13.08809	74.81138	13.08818	N88E	0.42
131	74.82426	13.08065	74.83643	13.08334	N77E	1.352
132	74.83584	13.08321	74.84608	13.07752	S60E	1.277
133	74.84287	13.07713	74.85231	13.07905	N78E	1.045
134	74.85183	13.07809	74.85971	13.0866	N42E	1.275
135	74.85212	13.07991	74.85669	13.08526	N39E	0.774
136	74.87848	13.09288	74.879	13.08508	S3E	0.87
137	74.87384	13.08049	74.87898	13.08544	N45E	0.782
138	74.87745	13.0762	74.8796	13.0657	S11E	1.191
139	74.87862	13.06722	74.88622	13.06006	S45E	1.145
140	74.86148	13.06511	74.87297	13.07782	N41E	1.883
141	74.8604	13.07638	74.86936	13.08813	N36E	1.627
142	74.87374	13.07963	74.87752	13.07585	S44E	0.587
143	74.89654	13.06523	74.90336	13.07153	N46E	1.018
144	74.90287	13.07716	74.90327	13.06551	S1E	1.296
145	74.90346	13.06513	74.92499	13.05655	S67E	2.52
146	74.91739	13.06074	74.92382	13.06753	N42E	1.026
147	75.01538	13.05255	74.9921	13.06133	N68W	2.704
148	74.98791	13.06754	74.99132	13.06057	S25E	0.859
149	74.95684	13.0768	74.95625	13.07307	S8W	0.419
150	74.935	13.15165	74.95351	13.16378	N56E	2.475
151	75.03916	13.14134	75.02776	13.14793	N59W	1.456
152	75.00903	13.19683	75.00822	13.17808	S2W	2.087
153	75.00822	13.20161	75.02719	13.17219	S32E	3.863
154	75.03458	13.13295	74.9385	13.17743	N64W	11.519
155	74.9123	13.18097	74.86261	13.10622	S33W	10.476
156	74.88802	13.16634	74.9005	13.17055	N70E	1.448
157	74.90099	13.15298	74.90381	13.15728	N32E	0.567
158	74.89361	13.15882	74.91375	13.16645	N68E	2.35
159	74.9194	13.16425	74.9385	13.17743	N53E	3.108
160	74.90031	13.15451	74.90859	13.14849	S53E	1.123
161	74.86286	13.14157	74.86689	13.14609	N40E	0.665

162	74.86377	13.15076	74.86942	13.15354	N63E	0.733
163	74.86328	13.14857	74.86913	13.14399	S51E	0.813
164	74.84322	13.12965	74.83834	13.14493	N17W	1.779
165	74.83795	13.15533	74.83893	13.14626	S5E	1.014
166	74.89762	13.15071	74.87606	13.19428	N25W	5.379
167	74.89191	13.08618	74.89852	13.11617	N12E	3.41
168	74.94256	13.09957	74.96369	13.11666	N50E	2.975
169	74.95775	13.12802	74.96161	13.11498	S16E	1.509
170	74.95892	13.11943	74.96516	13.12058	N79E	0.687
171	74.93117	13.11983	74.9675	13.11695	S85E	3.947
172	74.98718	13.13108	74.98718	13.11256	S0W	2.06
173	74.98036	13.09862	74.98718	13.11256	N25E	1.717
174	75.00588	13.14407	75.0127	13.14063	S49E	0.917
175	74.86341	13.12547	74.86569	13.11967	S20E	0.691
176	74.94301	13.09675	74.96456	13.10449	N69E	2.488
177	74.95269	13.10022	74.9591	13.11223	N27E	1.504
178	74.96638	13.11729	75.02134	13.10955	S81E	6.014
179	74.86911	13.12177	74.89085	13.11559	S73E	2.453
180	74.87054	13.11837	74.87955	13.12451	N55E	1.191
181	74.90798	13.1345	74.91076	13.12952	S28E	0.63
182	74.91001	13.12804	74.91235	13.12202	S20E	0.715
183	74.90822	13.12012	74.92033	13.11031	S50E	1.706
184	74.90773	13.12321	74.91473	13.11833	S54E	0.932
185	74.90943	13.12678	74.91222	13.12917	N48E	0.402
186	74.90882	13.14595	74.91161	13.14107	S29E	0.621
187	74.91161	13.15047	74.91452	13.15416	N37E	0.518
188	74.93645	13.14592	74.94331	13.14334	S68E	0.797
189	74.93676	13.14036	74.95388	13.15251	N53E	2.294
190	74.94197	13.14385	74.95182	13.14798	N66E	1.162
191	74.92366	13.08084	74.93021	13.08965	N35E	1.21
192	74.80255	13.11875	74.80448	13.13208	N8E	1.497
193	74.79902	13.1191	74.79903	13.11645	S0W	0.295
194	74.79513	13.12624	74.79501	13.12255	S1W	0.411
195	74.79416	13.12374	74.79902	13.1191	S45E	0.737
196	74.78723	13.13207	74.78274	13.12528	S32W	0.898
197	74.77849	13.12313	74.78432	13.12611	N62E	0.713
198	74.77995	13.12456	74.77777	13.11468	S12W	1.124
199	74.81821	13.1215	74.82003	13.12638	N19E	0.577
200	74.8198	13.12575	74.83546	13.12794	N81E	1.713
201	74.82731	13.13757	74.83534	13.1252	S32E	1.627
202	74.83558	13.12103	74.8402	13.12401	N56E	0.599

203	74.82975	13.12341	74.83643	13.1208	S68E	0.78
204	74.81518	13.11328	74.8303	13.1232	N56E	1.995
205	74.84033	13.10818	74.85852	13.09939	S63E	2.199
206	74.86073	13.11117	74.87179	13.1142	N74E	1.245
207	74.8567	13.14402	74.85267	13.13574	S25W	1.019
208	74.89036	13.1257	74.89838	13.11551	S37E	1.428
209	74.8322	13.10767	74.83341	13.10008	S8E	0.854
210	74.83171	13.10246	74.83329	13.09579	S12E	0.761
211	74.83422	13.15377	74.84528	13.15949	N62E	1.355
212	74.83214	13.17757	74.83811	13.16274	S21E	1.771
213	74.83118	13.16817	74.83769	13.16133	S42E	1.037
214	74.82625	13.15455	74.83483	13.15091	S66E	1.014
215	74.87928	13.18082	74.87819	13.17415	S9W	0.751
216	74.86628	13.18081	74.86926	13.17048	S15E	1.193
217	74.90238	13.14654	74.90977	13.13472	S31E	1.539
218	74.87917	13.1557	74.8844	13.15296	S61E	0.642
219	74.89753	13.10213	74.90203	13.09785	S45E	0.681
220	74.86317	13.09188	74.8775	13.08725	S71E	1.636
221	74.88005	13.08665	74.88649	13.08535	S78E	0.712
222	74.90374	13.07869	74.91077	13.07671	S73E	0.793
223	74.85321	13.09295	74.85594	13.08437	S17E	0.998
224	74.88798	13.09666	74.89267	13.08965	S33E	0.931
225	74.80913	13.09328	74.82746	13.0927	S88E	1.987
226	74.82712	13.06413	74.83465	13.06615	N74E	0.846
227	74.77805	13.07718	74.79479	13.10136	N33E	3.243
228	74.79251	13.06946	74.77877	13.09738	N25W	3.443
229	74.88579	13.06047	74.89294	13.06059	N89E	0.774
230	74.88622	13.06006	74.88626	13.05464	S0E	0.604
231	74.89124	13.06904	74.89974	13.06047	S43E	1.325
232	74.91409	13.06089	74.91638	13.05381	S17E	0.825
233	74.92366	13.05286	74.93447	13.05894	N60E	1.351
234	74.91625	13.05422	74.92366	13.05286	S79E	0.817
235	74.90532	13.07143	74.91443	13.06881	S73E	1.029
236	74.89318	13.07607	74.90945	13.07464	S84E	1.77
237	74.8939	13.07761	74.89427	13.07261	S4E	0.557
238	74.93811	13.06239	74.93884	13.05763	S8E	0.535
239	74.93057	13.0931	74.92341	13.08131	S30W	1.523
240	74.91685	13.09274	74.92766	13.0937	N84E	1.175
241	74.90642	13.10534	74.91989	13.09191	S44E	2.087
242	74.95748	13.07327	74.95378	13.06394	S21W	1.113
243	74.95795	13.08996	74.95729	13.08251	S4W	0.831

244	74.91939	13.13869	74.92155	13.12892	S12E	1.111
245	74.92124	13.12833	74.93219	13.12788	S87E	1.187
246	74.90384	13.12666	74.91015	13.12388	S65E	0.75
247	74.90785	13.14012	74.911	13.14059	N81E	0.346
248	74.92023	13.15274	74.92303	13.14583	S21E	0.825
249	74.91646	13.16071	74.92435	13.17536	N27E	1.839
250	74.92366	13.06917	74.92983	13.07583	N42E	0.998
251	74.9666	13.06802	74.96771	13.05966	S7E	0.937
252	74.96416	13.06928	74.96228	13.0599	S11W	1.063
253	74.96164	13.0707	74.95718	13.06632	S44W	0.687
254	74.98863	13.05918	74.99555	13.06228	N65E	0.825
255	74.97909	13.09606	74.98911	13.09133	S64E	1.206
256	74.96907	13.10597	74.96968	13.09454	S2E	1.272
257	74.96968	13.09454	74.97547	13.09028	S52E	0.785
258	74.99239	13.12573	74.99737	13.10775	S15E	2.07
259	74.98935	13.13656	74.99069	13.12763	S8E	1.003
260	74.98049	13.12204	74.98231	13.11132	S9E	1.208
261	74.94663	13.10875	74.94247	13.11763	N24W	1.085
262	74.9364	13.1156	74.94259	13.12203	N43E	0.98
263	74.9585	13.12858	74.96239	13.12084	S26E	0.958
264	74.97283	13.1462	74.97065	13.13454	S10W	1.319
265	74.9687	13.14918	74.98048	13.14439	S67E	1.382
266	75.0241	13.16096	75.02798	13.14668	S14E	1.643
267	75.01669	13.17394	75.01851	13.16525	S11E	0.986
268	74.96955	13.17429	75.00466	13.16911	S81E	3.844
269	74.96785	13.1737	74.98194	13.18453	N51E	1.944
270	74.9789	13.19156	74.98194	13.18453	S22E	0.847
271	74.98534	13.19263	74.98172	13.18503	S24W	0.931
272	74.96214	13.17287	74.96603	13.17489	N61E	0.477
273	74.96785	13.1737	74.97363	13.17721	N58E	0.738
274	74.98812	13.1796	74.99512	13.18003	N86E	0.759
275	74.95461	13.1681	74.96639	13.16513	S75E	1.318
276	74.9359	13.17476	74.94149	13.16465	S28E	1.277
277	74.96401	13.16573	74.9815	13.16496	S87E	1.896
278	74.90424	13.16185	74.91372	13.14376	S26E	2.258
279	74.85954	13.15659	74.86638	13.14614	S32E	1.379
280	74.85979	13.13802	74.86903	13.13422	S66E	1.086
282	74.78033	13.10849	74.90733	13.15024	N72E	14.836
283	74.98898	13.18727	75.00466	13.16911	S39E	2.637
284	74.88716	13.08266	74.88969	13.07295	S14E	1.114
285	74.83452	13.11072	74.85002	13.11232	N83E	1.688

286	74.87266	13.14216	75.02112	13.10892	S76E	16.576
287	74.87157	13.1551	74.86997	13.12314	S2W	3.595
288	74.93645	13.14592	74.9337	13.12727	S8W	2.094
289	74.86968	13.13686	74.88327	13.13686	N89E	1.472
290	74.96645	13.14514	74.9632	13.1193	S7W	2.895
291	74.81806	13.09527	74.85176	13.10861	N67E	3.939
292	74.95667	13.15527	75.00723	13.17046	N72E	5.73
293	74.98521	13.18005	74.99636	13.16007	S28E	2.528
294	74.91319	13.10224	74.93248	13.10251	N89E	2.09
295	74.87665	13.06202	74.83006	13.18228	N20W	14.303
296	74.89305	13.13855	74.90645	13.11438	S28E	3.053
297	74.90242	13.1323	74.88134	13.13777	N75W	2.363
298	74.82225	13.14193	74.83214	13.15078	N47E	1.455
299	74.9373	13.06826	74.94121	13.08024	N17E	1.397
300	74.9347	13.08024	74.9373	13.08623	N22E	0.723
301	74.98338	13.11304	74.97772	13.09498	S16W	2.099
302	75.02398	13.12892	75.0194	13.13998	N21W	1.327
303	75.0055	13.13438	75.00212	13.14401	N18W	1.132
304	74.93912	13.15391	74.97739	13.15417	N89E	4.143
305	74.88472	13.12137	74.88656	13.1427	N4E	2.381
306	74.8134	13.10419	74.82901	13.09742	S65E	1.851
307	74.83917	13.08987	74.84724	13.09482	N57E	1.033
308	74.90726	13.16879	74.94399	13.06117	S18E	12.679
309	74.84411	13.15182	74.85583	13.15807	N61E	1.446
310	74.82823	13.1461	74.83682	13.15026	N63E	1.039
311	74.83685	13.05365	74.88338	13.09076	N50E	7.032
312	74.97158	13.04954	74.89572	13.0973	N57W	9.784
313	75.03097	13.04292	75.02787	13.04414	N68W	0.363
314	75.02787	13.04414	74.79651	13.11653	N72W	26.851
315	75.03137	13.04348	74.79936	13.14459	N65W	27.556
316	75.01325	13.16165	75.04844	13.16956	N77E	3.911
317	75.04259	13.16824	75.04976	13.1681	S88E	0.777
318	74.99925	13.16171	75.04325	13.14558	S69E	5.09
319	74.83029	13.1633	74.78347	13.10057	S36W	8.623

LIST OF PUBLICATIONS BASED ON PRESENT RESEARCH

I International Journal

1. **Radhakrishnan K. and Lokesh, K.N. (2011)** "Morphometric Evidences for Neotectonism in the Mulki River Basin of Coastal Karnataka, India". *International Journal of Earth Sciences and Engineering*, Cafet-Innova Technical Society, Hyderabad., ISSN 0974-5904, v.04, no.04, pp.643-650.

2. **Radhakrishnan K., Shenoy K. Narayana and Lokesh K.N. (2011)** "Hydrogeochemical studies of groundwater along coastal region of Mulki-Udupi, Karnataka State, India". *International Journal of Earth Sciences and Engineering*, Cafet-Innova Technical Society, Hyderabad., ISSN 0974-5904, v.04, no.7 (Spl. Issue), pp.333-339.

II International Conference

3. **Radhakrishnan K., Shenoy K. Narayana and Lokesh K.N. (2011)** "Hydrogeochemical studies of groundwater along coastal region of Mulki-Udupi, Karnataka State, India". Proceedings of *International Engineering Symposium (IES 2011)*, IES 2011-96, Kumamoto University, Japan., March 3-5, 2011., Ch: C7, sec.1, pp.1-8.

III National Conferences

4. **Radhakrishnan, K. (2007)** "Feasibility Studies of Roof Top Rainwater Harvesting at N.E.T. Campus, Nitte". Proc. All India seminar on *'Challenges in Socio-Economic and Infrastructural Developments- Emerging Technology, (CIDET-07)',* The Institution of Engineers (India), Interdisciplinary Co-ordination Committee (ICC), Mangalore during November 13-14, 2007

5. **Radhakrishnan, K. (2007)** "Rehabilitation Studies of Traditional Rainwater Harvesting Structures- A Case Study". Proc. All India seminar on *'Challenges in Socio-Economic and Infrastructural Developments- Emerging Technology, (CIDET-07)',* The Institution of Engineers (India), Interdisciplinary Co-ordination Committee (ICC), Mangalore during November 13-14, 2007

6. **Radhakrishnan, K. (2007)** "Identification, Delineation and Mapping of Microwatersheds and Traditional Rainwater Harvesting Structures in Mulki River

Basin for Sustainable Development". Proc. All India seminar on *'Challenges in Socio-Economic and Infrastructural Developments- Emerging Technology, (CIDET-07)',* The Institution of Engineers (India), Interdisciplinary Co-ordination Committee (ICC), Mangalore during November 13-14, 2007

7. **Radhakrishnan, K. and Lokesh, K.N. (2009)** "Rehabilitation Studies on an abandoned Traditional Rainwater Harvesting Structure". Proc. National conference on '*Recent Trends and Challenges in Civil Engineering (RTCCE-09)',* Kavikulaguru Institute of Technology & Science, Ramtek, Maharashtra, 18-19th Dec., 2009. pp.102-107

8. **Radhakrishnan, K. and Lokesh, K.N. (2010)** "Integrated Approach for Hydrogeochemical Studies of Mulki river Basin, Coastal Dakshina Kannada Districts of Karnataka". Proc. National conference on *'Sustainable Water Resources Management (SWaRM 2010)*, National Institute of Technology Karnataka, Surathkal, 7-9th January, 2010.

9. **Radhakrishnan, K. and Lokesh, K.N. (2010)** "Feasibility Studies for Sustainable development on Water Resources". Proc. National conference on *'Sustainable Water Resources Management (SWaRM 2010)'*, National Institute of Technology Karnataka, Surathkal, 7-9th January, 2010.

10. **Radhakrishnan, K. and Lokesh, K.N. (2010)** "Remote Sensing and GIS Techniques for Delineation and Mapping of Microwatersheds and Traditional Rainwater Harvesting Structures in Mulki River Basin for Sustainable Development". Proc. National conference on *'Sustainable Water Resources Management and Impact of Climate Change (SWRM 2010)'*, Birla Institute of Technology and Science-Pilani, Hyderabad, Eds: Srinivas Raju K. and Vasan, A., B.S. Publications, Hyderabad. ISBN:978-81-7800-226-2, pp.292-302

BRIEF RESUME

Radhakrishnan K.
M.Sc. (Geology)
M.Phil. (Marine Geology)
georadha2000@yahoo.co.in

Associate Professor
Department of Civil Engineering
N.M.A.M. Institute of Technology
(An Autonomous Institution under VTU)
Nitte – 574 110
Udupi District, Karnataka, India

Academics:

- B.Sc. Geology from Calicut University, 1st Class, 1984
- M.Sc. Geology from Calicut University,1st Class, 1986
- M.Phil. Marine Geology, Mangalore University,1st Class Distinction, 1988

Training Exposure:

- One month training in Groundwater Exploration Techniques at National Geophysical Research Institute (NGRI), Hyderabad under UNESCO fellowship
- Trained in ERDAS Imagine software at RSi India Soft tech Pvt. Ltd., Bangalore
- Certified Head Trainer, JCI University, Chesterfield, USA for its signature courses

IT Exposure:

Windows, MS office, Auto CAD, ArcGIS 9.x & 10.x, ERDAS Imagine 9.1, Surfer 10

Professional Experience:

- More than 23 years teaching experience in the Engineering College and handled subjects viz: Applied Engineering Geology, Hydrogeology, Remote Sensing and Geographic Information Systems, Environmental Studies, Elements of Civil Engineering and Building Engineering Science.
- About 2 years' experience in handling theory and practical classes for the Post Graduate (Marine Geology) students of Mangalore University.
- Handled elective subject on RS &GIS for M.Tech. students
- About 2 years research experience in Geological Survey of India
- About 6 months office and field experience in Kerala State Groundwater Department as Assistant Geologist
- More than 23 years' experience in Groundwater Exploration and consultancy services
- More than 16 years' experience in the field of soft skill training and motivational speaking

Projects Guided:

- Guided more than 16 undergraduate multidisciplinary Engineering student projects
- Eight of the projects have been funded by Karnataka State Council for Science and Technology (KSCST) and three selected for state level seminar cum exhibition during 2006, 2007 & 2012.
- Received state level Best Project of the Year (Commendation Certificate) Award from KSCST during 2007 for the student project carried out under his guidance and supervision.
- Received six 'Best Project of the year awards' in EXPRO under his guidance.

Membership of Professional bodies:

- Life Member and Fellow, Geological Society of India
- Life Member of Indian Society for Technical Education

Future plans:

Application of Geoinformatics in sustainable development and management of Groundwater and Natural Resources.