HYDROGEOLOGY AND HYDROCHEMISTRY OF THE AQUIFER SYSTEMS OF KUTTANAD AREA, KERALA: THEIR ROLE IN UNDERSTANDING THE EVOLUTION OF GROUNDWATERS

Thesis submitted to the
Cochin University of Science and Technology

by

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In partial fulfillment of the requirement for the award of the degree of
DOCTOR OF PHILOSOPHY
Under the Faculty of Marine Sciences

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DECLARATION

I do hereby declare that the thesis entitled 'Hydrogeology and hydrochemistry of the aquifer systems of Kuttanad area, Kerala: Their role in understanding the evolution of groundwaters', being submitted to the Cochin University of Science and Technology, in partial fulfillment of the requirements for award of the degree of Doctor of Philosophy under the faculty of Marine Sciences, is a bona fide record of the work carried out by me in the Department of Marine Geology and Geophysics, Cochin University of Science and Technology, under the supervision of Prof. A.C. Narayana, Professor, Centre for Earth & Space Sciences, University of Hyderabad, Hyderabad (Former Professor, Department of Marine Geology and Geophysics, Cochin University of Science and Technology, Kerala) and that this thesis has not previously formed the basis for the award of any other degree.

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Cochin
21-06-2014

CERTIFICATE

This is to certify that the thesis entitled "Hydrogeology and hydrochemistry of the aquifer systems of Kuttanad area, Kerala: Their role in understanding the evolution of groundwaters" is an authentic record of research work carried out by Mr. Vinayachandran N, under my supervision and guidance at the Department of Marine Geology and Geophysics, Cochin University of Science and Technology, in the Faculty of Marine Sciences, in partial fulfillment of the requirements for the degree of Doctor of Philosophy and no part thereof has been presented for the award of any degree in any University/ Institute.

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Vinayachandran N

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CHAPTER 1

INTRODUCTION

1.1 Background

Groundwater based irrigated agriculture and drinking water supply has increased many folds during the last few decades and sustainable development of groundwater resources has become the most important objective in groundwater management. Water supply and scarcity has received increasing attention primarily driven by alarming World Health Organization report that 1.1 billion people lack access to safe and affordable water for their domestic use (WHO, 2012). Many estimates agree that about two-third of the world population will be affected by water scarcity over the next several decades (Raskin et al., 1997; Seckler et al., 1998; Shiklomanov, 1998; Alcamo et al., 2000; Vorosmarty et al., 2000; Wallace and Gregory, 2002; Food and Agricultural Organization, 2003; United Nations Water Report, 2012). The conflict between water diversions to agriculture and maintaining aquatic ecosystems has received recent attention and environmental flow requirements (Smakhtin et al., 2004) are increasingly being taken into account to manage water allocations.

India faces a number of water related challenges, including increasing water scarcity and competition between different sectors and states. Groundwater irrigation has been expanding at a very rapid pace in India since 1970s and now accounts for over 60 percent of the total area irrigated in the country (Agriculture statistics, India, 2011). About 90% of the rural drinking water supply is also met from groundwater sources (CGWB, 2011). The most significant change in the groundwater scenario in India is that the share of bore well irrigation went up from a mere 1 percent during 1960-61 to 40 percent during 2006-07. The estimated number of open wells and bore wells in India is now around twenty-seven million; bore wells above account (Indian Agricultural Statistics, 2008) for >50%. The per capita availability of water in India has declined from over 3,000 cubic meters (Cu.M) per year from 1951 to about 1,820 Cu.M in 2011. Out of 5842 administrative units (Blocks/Taluks/Mandals/Districts) assessed for groundwater resources in India, 802 units are Over-exploited (Central Ground Water Board, 2011). Apart from these, there are 71 assessment units which are completely saline. Thus, groundwater conservation and its sustainable development has become one of the important alternative water management options which is easier to implement and more environmentally acceptable. Demarcation of aquifer systems and gathering information on its hydraulic properties and water quality parameters is essential for effective management of the groundwater resources.

There is a growing awareness towards integrated hydrogeological studies pertaining to the quantity and quality of groundwater resources around the world (Kemper, 2004). The increase in demand on groundwater resources has put many aquifer systems under stress and consequent environmental issues. Such issues could be addressed through proper management of the aquifer systems for sustainability, particularly in coastal and multi aquifer systems (Capaccioni et al., 2005; Misut and Voss, 2007).

The distribution and quality of waters vary from one region to another, influenced by the geology, geomorphology and climate. The chemical characteristics of waters in groundwater systems are evolved out of rock-water interactions in different geological environments and climatic conditions. The terrains and aquifer systems where freshwater exists in equilibrium with sea water are more vulnerable to detrimental effects of over exploitation of groundwater. The scenario may be much more complex in multi aquifer systems evolved under fluvio-marine environments in the geological past, such as the present study area.

It is essential to define the aquifer geometry, aquifer characteristics and the spatial distribution of groundwater in terms of quantity and quality for effective management of groundwater resources. Data on the levels of pollutants and the concentration of various water quality parameters over a period of time is very essential for planning strategies in developmental programmes.

Demarcation of aquifer systems and exploring the hydrogeological environment prevailing in the aquifer systems is the fundamental approach in hydrogeological study of any terrain. The aquifer systems developed in different geological terrains are closely related to its evolutionary history and the geological terrain with multi aquifer systems pose challenge in unraveling the groundwater regime associated with it. A more Comprehensive research on aquifer systems in hard rock and sedimentary formations, including the coastal aquifer systems has been carried out in various parts of the world as well as in India (Guler, 2003; Kemper, 2004; Jiang et al., 2009; Nagarajan and Singh, 2009; Mondal et al., 2010) during this decade. In resolving the intricacies involved in the study of coastal aquifers various researchers (Capaccioni et al., 2005; Ladouche and Weng, 2005; Birkle, 2006; Kacimov, 2008; Thilagavathi et al., 2012) have adopted different approaches.

The Kuttanad area, a coastal region in southwestern India, is known for its complex groundwater scenario with shallow water conditions, wetlands, multi aquifer systems and complex hydrochemical environment. Unique hydrogeological and hydrochemical environment in the multi-aquifer system of the Kuttanad are evolved out of the long evolutionary history of the sedimentary basin of Kerala (Nair, 2009; Narayana et al., 2001; Narayana and Priju, 2006). In the present study, an attempt has been made to understand the aquifer systems of Kuttanad area in terms of hydrogeology and hydrochemistry and the geo-hydrochemisty in these multi aquifer systems has been effectively used in deciphering the evolution of groundwater.

1.2 Objectives and scope of study

This is an attempt to understand the important factors that control the occurrence, development and hydrochemical evolution of groundwater resources in sedimentary multi aquifer systems. The primary objective of this work is an integrated study of the hydrogeology and hydrochemistry with a view to elucidate the hydrochemical evolution of groundwater resources in the aquifer systems. The following objectives are envisaged in the present study:

- To characterize the aquifer disposition and geometry of sand deposits in Recent alluvium and Tertiary sedimentary beds.
- Evaluation of the chemical quality of groundwater in time and space.
- To delineate the aquifer contamination/ pollution from fluoride, nitrate and salinity in the area.
- To trace out the evolutionary history of groundwater in the aquifer systems from the hydrogeology, hydrochemistry and isotope characteristics of the area.
- To elucidate the hydro-chemical processes involved in the evolution of groundwater in the study area.

The study is taken up in a typical coastal sedimentary aquifer system evolved under fluvio-marine environment in the coastal area of Kerala, known as the Kuttanad. The hydrogeological and hydrochemical scenario in this aquifer system is complex and related to the evolutionary history of the area. Hence, the objectives of the present study are focused on the above issues.

1.3 Review of literature

Previous studies related to the groundwater regime of Kuttanad are very limited. However, there are numerous regional studies which throw light on various aspects of Kuttanad. 'Systematic hydrogeological study' of the coastal parts of the Alleppey district was carried out by S. Ranganathan of erstwhile Groundwater Division of Geological Survey of India, Southern Region, Hyderabad during field season 1970-'71 and 1971-'72.

The first report on the hydrogeological scenario of Kuttanad was carried out under Swedish International Development Agency (SIDA) assisted coastal Kerala groundwater project (CGWB, 1992). The groundwater Management study of Alleppey district (Kunhambu, 2002) gives overall hydrogeology and groundwater management practices suitable for the district. The studies on the hydrogeology and hydrochemistry of Alleppey district (Vinayachandran, 2009, 2009a) covers part of the Kuttanad area.

The studies carried out by Lal Thompson (2004) on the hydrogeology of Alleppey district deals with the remote sensing and GIS application and depiction of the hydrogeological environment in Alleppey district. The environmental status and hydrogeological scenario of Ambalapuzha Taluk with special reference to flouride contamination in that area was carried out by Ajithkumar (2009).

Exploratory drilling operations in the coastal plains by Exploratory Tube Well Organization, Govt. of India and subsequently by CGWB during the period between 1973-82 provided important information on subsurface geology of the area. Other regional studies and technical papers which provide information on the groundwater regime of the area include that on the climate and rainfall (Paul and Abe, 1988; Verma, 1999; Bhowmick et al., 2000; Rajendran et al, 2002) and the lithostratigraphic classification of the sedimentary deposits (Raha et al., 1983; King, 1982; Foote, 1883; Soman, 1997). The tectonic history of the area and sediment deposition in the structural basin has been discussed by various workers (Desikachar, 1980; Rajamanikam et al., 1995; Siddique, et al., 1982; Nair and Sankar, 1994; Nair, 2003).

Researches on groundwater resource management and water quality have been in vogue during the last few decades and abundant literature is available on that. It has become necessary to adopt and invent newer technologies and tools in resolving the issues cropped up during the same period such as aquifer contamination, over exploitation, sea water intrusion in coastal aquifer systems, land degradation, global warming etc. (Unnikrishnan et al, 2006; Birkle et al., 2006; Rijsberman et al., 2006; Unni et al., 2006; Intergovernmental Panel on Climate Change (IPCC), 2008; Subba Rao et al., 2013). The newer technologies and tools could improvise the aquifer management in terms of quantity and quality all over the world (Satheesh and Lawrence, 2007).

The coastal Kerala is a part of the 'Kerala Konkan Basin' (KKB) which is generally cliffed and exposes Precambrian basement, Deccan Traps and discontinuous stretches of Tertiary sediments. The sedimentary sequence along the south Kerala coast which comprises the Kuttanad basin is a unique feature along the entire west coast and has been called as South Kerala Sedimentary Basin (SKSB) (Nair et al., 2009; Jayalekshmi et al., 2004). The sediments here range in age from earliest Miocene to Quaternary with a pronounced unconformity spanning Middle Miocene to Early Quaternary. The eastward extension of the KKB is assumed to be developed in response to the redistribution of the stress pattern following the India - Eurasia plate collision during early Miocene (Aitehison and Davis, 2001; Nair and Padmalal, 2004).

There have been a few reports on the Quaternary sediments of southwest coast of India (Agarwal et al., 1970; Rajendran et al., 1989; Kumaran et al., 2001; Nair 1996; Pawar et al., 1983; Narayana and Priju, 2006). A detailed study on the Quaternary sediments with reference to stratigraphic sequence and landform evolution has been made by Narayana and Priju (2006).

The lithological and electrical logs of bore holes in the kuttanad area indicated that Tertiary sediments (equivalent in age to Cuddalore and Rajahmundry sandstones of east coast) comprise of four distinct units namely; Alleppey, Vaikom, Quilon and Warkalai beds (Kunhambu, 2001).

Variations in geophysical borehole data reflect geological inhomogenities related to its petrology, mineralogy and structural organization and has been effectively used in demarcating different litho units (Scott Keys, 1986; Leonardi and Kumpel, 1998) and for classifying various stratigraphic units (Peter et al., 2004; Woods, 2006). The geophysical logs and liholog data was used by Klett et al. (2002) to generate lithofacies which allows the interpretation of shallow marine and continental deposits based on the sequential changes observed in the geophysical logs against various depositional environments. The same principle has been adopted widely in identifying aquifer systems and the quality of water in the aquifers employing electrical and gamma logging techniques (Majumdar and Pal, 2005; Buchanan and Trantafilis, 2009; Kumar et al., 2010; Paillet and Crowder, 1996). A similar approach has been made in the present study by using electrical logs and radioactive logs (natural gamma) for the demarcation of vertical and lateral variations in lithology and for identifying aquifer systems. Similarly, the conjunctive use of electrical resistivity log and isotope data on the Nubian Sand Stone aquifer of North east Africa could establish the recharge behavior in the aquifer system (Sultan et al., 2011). In this study the modern recharge obtained using rainfall-runoff and the information gathered from the isotopes, oxygen-18 and ^{3}H and ^{2}H in water were found to be in consistence with the interpretation of electrical resistivity profiles. In tracer applications for hydraulic conductivity measurements the resistivity logs are being used as effective tools (Bowling, 2006).

There are various analytical methods for aquifer evaluation for transmissivity and storativity from drawdown data during pumping or recovery data after stoppage of pumping (Theis, 1935; Ballukraya and Sharma, 1991; Bardsley, 1992; Li Zing et al., 2005; Willmann et al., 2007; Guinot and Cappelaere, 2009). The applicability of the method depends on the hydrgeological conditions and pumping limitations. In the case of pumping tests where initial water levels are missing or not representative, the analysis of recovery data by Samani and Pasandi (2003) method may yield good results. In the present study both drawdown and recovery data have been used for aquifer evaluation using Theis method and Samani and Pasandi method.

The process of dissolution of minerals in the host rock contribute significantly to the hydrochemistry of groundwater systems and have been the subject of most hydrochemical analysis in the literature (egs., Apambire et al., 1997; Abu-Jaber, 2001; Portugal et al., 2005; Wen et al., 2005; Coetsiers and Walravens, 2006; Zhu et al., 2007; Jasrotia and Singh, 2007; Cloutier et al., 2008; Moral, 2008; Banoeng-Yakubo et al., 2009). Literature is also rich in instances where groundwater is contaminated by sea water intrusion and anthropogenic activities (Westbrook et al., 2005; Martin et al., 2006; Trabelsi et al., 2007; Antonellini et al., 2008; Alcala and Custodio, 2008). The studies on the dissolution of minerals in Phreatic aquifers and their pollution from surface activities carried out by Ramesh and Elango (2012) in the Tondiar river basin of

Tamil Nadu shows the application of major and minor ions for a better understanding of potential water quality variations due to various factors. The chemical composition of water and its mineralization processes are imperative in classifying and assessing drinking water quality (WHO, 2004, 2006; Kozisek, 2005). Hydrochemistry was effectively used for tracing the origin and history of water by Capaccioni et al. (2005). A detailed hydrochemical and hydrogeological investigation on seawater intrusion and refreshening in a multi layer costal aquifer system by Capaccioni et al. (2005) provided new insights into the past and present relationship between freshwater and seawater in shallow and deep aquifers.

Tremendous work has been reported on the water quality and its relation to the geology, environment and health (Matthew and Keith, 2010). The water quality standards have been formulated by World Health Organization and many countries on drinking water, irrigation and Industrial uses (WHO, 2012; Bureau of Indian Standards, 1991). The studies on various agro-climatic regions in India shows the influence of climate on the enrichment of ions in groundwater (Umar and Ahmed, 2000; Ahmed et al., 2002; Sankar, 2002; Rajesh and Murthy, 2004; Ali, 2004; Rajmohan and Elango, 2005; Pandian, and Sankar, 2007). Suitability of water for irrigation has been assessed in many studies using various properties or ionic ratios (Gupta et al., 2009; Ramesh and Elango, 2012) and is followed in irrigation sector. The geomorphology and geology of an area influences the dissolution of minerals and enrichmentof ions in groundwater (Vinayachandran and Narayana, 2007).

The environmental isotopes $\delta^{18}O$ and $\delta^{2}H$ are excellent tracers for determining the origin of groundwater and widely used in studying the natural water circulation, groundwater movement and salinisation of groundwater systems. (D'Alessandro, et al., 2004; O'Driscoll et al., 2005; Tim et al., 2012; Wassenaar,et al., 2011; Ogrinc et al., 2008; Longinelli et al., 2008; Vandenschrick et al., 2002). It has also been used as indicators for intermixing of waters from more than one source in aquifer systems (Taylor and Howard, 1996). The hydrogeochemical and isotopic data of groundwaters of the different aquifers of the Ras Sudr-Abu Zenima area, southwest Sinai, Egypt were examined to determine the main factors controlling the groundwater chemistry and salinity by El-Fiky (2010) and the study reveals that the groundwater results from mixing between Ca-HCO_3 recharge water falling on the elevated Tableland (plateau) and the pre-existing groundwater to yield mixed water of the Mg-SO4 and Mg-Cl types. Lapworth et al. (2012) used stable isotopes in the study of residence time of shallow groundwater in West Africa and found a clear coupling between modern rainfall and active recharge in the study area. The application of isotopes has been used to seek solutions for the hydrological problems in many studies in India during the last decade and some of the studies are worth mentioning. The study on Ganga river- groundwater interaction using environmental isotopes by Navada and Rao (1991) could bring out the influent effluent and recharge characteristics in the study area. Navada et al. (1993) have used stable and radioactive isotope techniques for carrying out groundwater recharge studies in arid regions of Rajasthan. The lake-aquifer interaction could be established in the study carried out by Nachiappan (2000) using stable isotopes, deuterium and oxygen-18. The isotope hydrological investigations in arsenic infected areas of West Bengal by Shivanna et al. (2000) could successfully establish the source, residence time and dynamics of arsenic contamination of groundwater in the aquifer systems. Vaithianathan (2003) utilized tritium isotopes to determine age, rate and direction of flow of groundwater in coastal areas of Ramanathapuram district, Tamil Nadu. Suresh (2006) used stable isotopes to establish the recharge characteristics and mixing of waters in the coastal aquifers in southern part of Chennai Metropolitan area. Shivanna et al. (2006) used environmental isotopes (deuterium, oxygen-18, Tritium and Carbon-14) in the hydrochemical investigation for characterization of groundwater in Tiruvanmiyur coastal aquifer and could establish the interconnection and mixing of waters in the multi-aquifer system.

1.4 Study area

'Kuttanad' is a low-lying area in the western coast of Kerala bound between north latitudes $09^{0}10'$ and $09^{0}50'$ and east longitudes $76^{0}15'$ and $76^{0}35'$. It covers parts of

Alleppey, Kottayam and Pathanamthitta districts and falls in Survey of India toposheet Nos. 58 C/6, C/7, C/10 and C/11. The index map shows the location of the study area (Fig. 1.1).

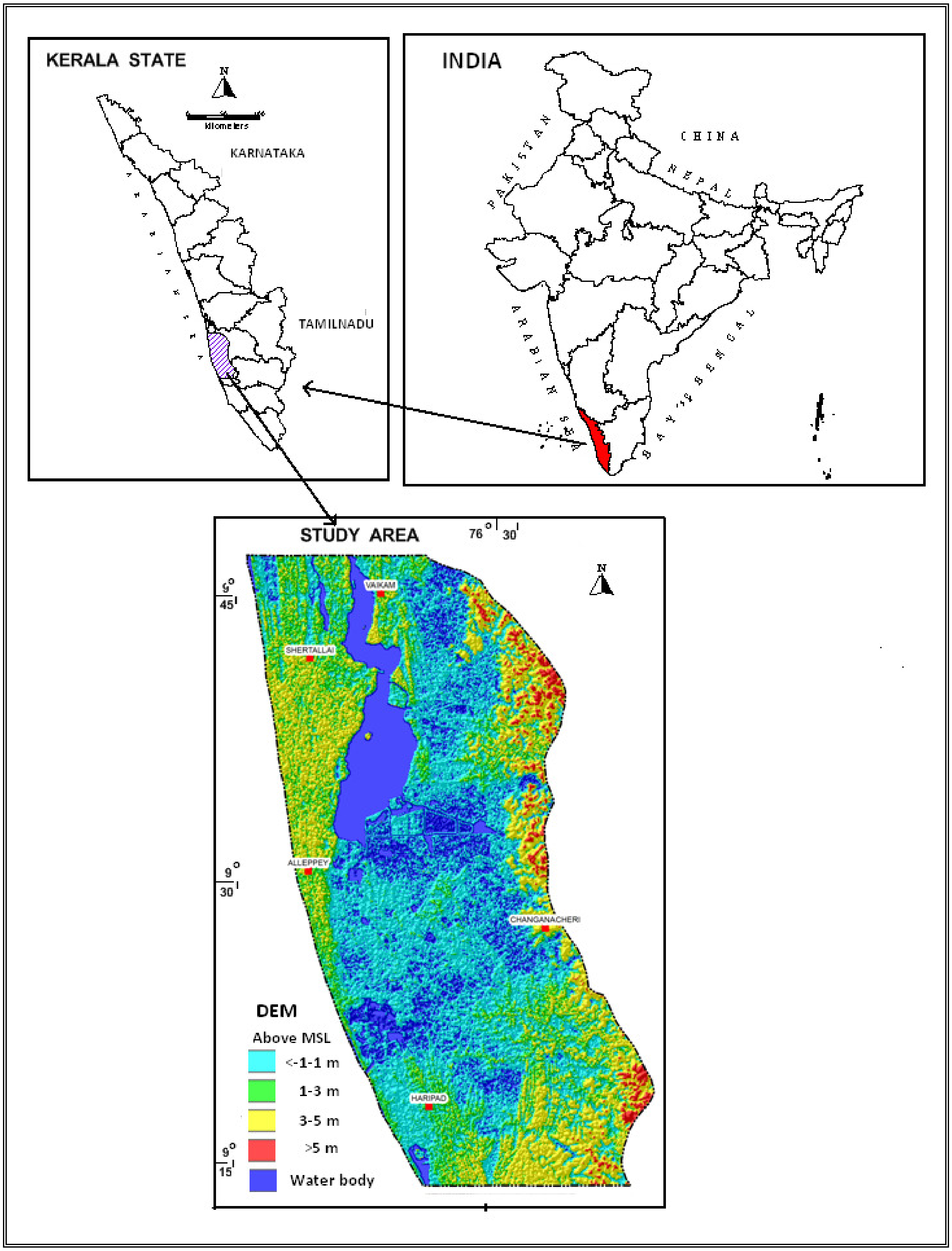


Fig. 1.1 Index map showing the location of the study area

The Kuttanad is about 1100 sq km in area, with three identifiable topographic features viz; the dry or Garden lands, wet lands and water bodies. The dry lands vary in elevation from 0.5 to 2.5 m above mean sea level and having an area of about 310 sq km. Most of the population of Kuttanad lives on these lands, located on the peripheral areas of Kuttanad. The wet lands include the water logged areas where land surface is slightly above the mean sea level (MSL) (area about 110 sq km) and the reclaimed areas from the lagoon (550 sq km) where the land surface is below MSL.The remaining area of about 130 sq km. is covered by lakes, rivers and channels. One barrier was constructed at Thannirmukkom in 1975 dividing the lagoon into two parts and is popularly known as the Thannirmukkom bund. The southern side of the barrier is known as Vembanad lake. In the present study the coastal area adjoining the kuttanad region is also included to get a comprehensive picture of hydrogeology of the area. Thus, the total area under study becomes 1,500 sq km.

Alleppey-Changanachery road, Ambalapuzha-Thakazhy-Edatuva road and Mavelikara - Kayamkulam road are the main roads in the area connecting NH 47 passing trhough the western part of the area with the MC road in the eastern extremity. The Madras-Trivandrum broad-gauge line passes through the southeastern portion connecting Kayamkulam-Mavelikara and Chengannur towns. Alleppey, the district headquarters has been connected by Ernakulam-Alleppey-Kayamkulam broad gauge line. Apart from these, Sherthalai, Kuttanad and Ambalapuzha taluks on the northern part of the area are criss-crossed by a number of navigable canals and are served by inland motor boats and country boats. Alleppey town is criss-crossed (connected) by navigable canals and is also connected to Cochin in the north and other important towns in the east (Bureau of Economics and Statistics, Govt. of Kerala., 2007).

The Kuttanad region of the coastal Kerala, is a low lying deltaic region dominated by wet lands and land mass criss-crossed by waterways. It is the lowest portion of a continuum land mass sloping from the high lands and merging with the low land deltaic formation of the four river systems viz; Achenkoil, Pamba, Meenachil, and

Muvattupuzha. A vast expanse of this region is lying up to 2.5 m below mean sea level and subjected to continued flood submergence during the monsoons. The paddy cultivation in this region is done by dewatering the Padasekarams (a cluster of water logged paddy fields) through ‘petti-para’ (temporary sheds with locally designed pump) by lifting the water and discharging it to the canals at higher elevation which ultimately discharge into sea.

The water supply schemes in the coastal areas totally depend on deep tube wells. There are pockets of poor quality water in the area. The scarcity of drinking water in the lean period (March-May) is quite common in many parts of the Kuttanad, particularly in remote villages located in the reclaimed land. In spite of good rainfall and presence of lake, canal and rivers, the fresh water availability for various domestic needs and cultivation is rather poor.

The irrigation practices in Kuttanad area are different from other parts of the country due to wetland and areas below mean sea level. The cultivation is of singular “puncha” crop using rainwater and occasionally with groundwater. The season of cultivation is different from the usual pattern of 'Virippu' (Kharif) and 'Mundakan' (Rabi). 'Punja' season is generally the period between 'mid-rabi and mid-summer season i.e. between November and February. Generally one crop of paddy is grown on the 'Punja' lands. Cultivation in the Punja lands is done in a special method. Temporary or semi permanent earthern bunds are constructed around the fields are prepared for agricultural operations. The periodical irrigation of paddy is carried out by letting the water through sluices in these bunds. The 'Punja lands' are divided into homogeneous physical entitites called "*Padasekharams*", which are contiguous stretches of wet lands. The 'Punja' lands account for nearly 80% of the wet lands in the Kuttanad region. The excessive use of large quantity of fertilizers has its impact on the crop yield and environment (Central Ground Water Board, 2002). The quantity applied to the crops in excess may leach to the soil in unsaturated zone and finally contaminates the groundwater. However, aquifer contamination from fertilizers is not reported from this area so far. The nature of soil, depth to water table, aquifer geometry, aquifer characteristics and groundwater gradient all have an influence over the contaminant migration, which has been one of the components of the present research work.

1.5 Topography

Kuttanad is a low-lying area near the western coast of Kerala and has three identifiable topographic features viz; the dry or Garden lands, wet lands and water bodies. The dry lands vary in elevation from 0.5 to 6.0 m above MSL in the study area and the population of Kuttanad lives on these lands. The wet lands include low-lying areas slightly above the MSL (area about 110 sq km.) and areas below MSL and areas reclaimed from the lagoon (550 sq km.). The lakes, rivers and channels cover an area of about 130 sq km.

Kuttanad is separated from the sea in the west and north-west by sandy beach ridges with elevations ranging from about 1.5-5.0 m above MSL. In the east and north-east, it is bordered by the undulating mid lands. The higher area in the southern part of Kuttanad is called upper Kuttanad and the area east and south east of upper Kuttanad have elevations up to 6.0 m above MSL. The core area of Kuttanad is 'Lower Kuttanad' with elevations ranging from -1.5 m to +1 m above MSL. North of Lower Kuttanad is named as North Kuttanad and the areas reclaimed from the Vembanad lake in the western part of north kuttanad have elevations in the range of 1.0 to 2.5 m below MSL.

1.6 Soils

On the basis of morphological and physico-chemical properties the soil survey branch of Department of Agriculture, Govt. of Kerala (1997) has classified the soils of Kuttanad into four types; viz. 1) Soils in coastal alluvium (entisols), 2) Soils in Riverine Alluvium (Inceptisols) 3) Brown hypidiomorphic soil (Alfisols) and 4) Lateritic soil (Oxisols). The soil map as per this classification is given in Figure 1.2.

Coastal Alluvial soil (Entisols)

These soils are seen along the western parts of the Alleppey district all along the coast (Fig. 1.2) and have been developed from recent marine and estuarine deposits. The texture is dominated by sand fraction and is extensively drained with very high permeability. These soils have low content of organic matter and are of low fertility level (Anon, 2012).

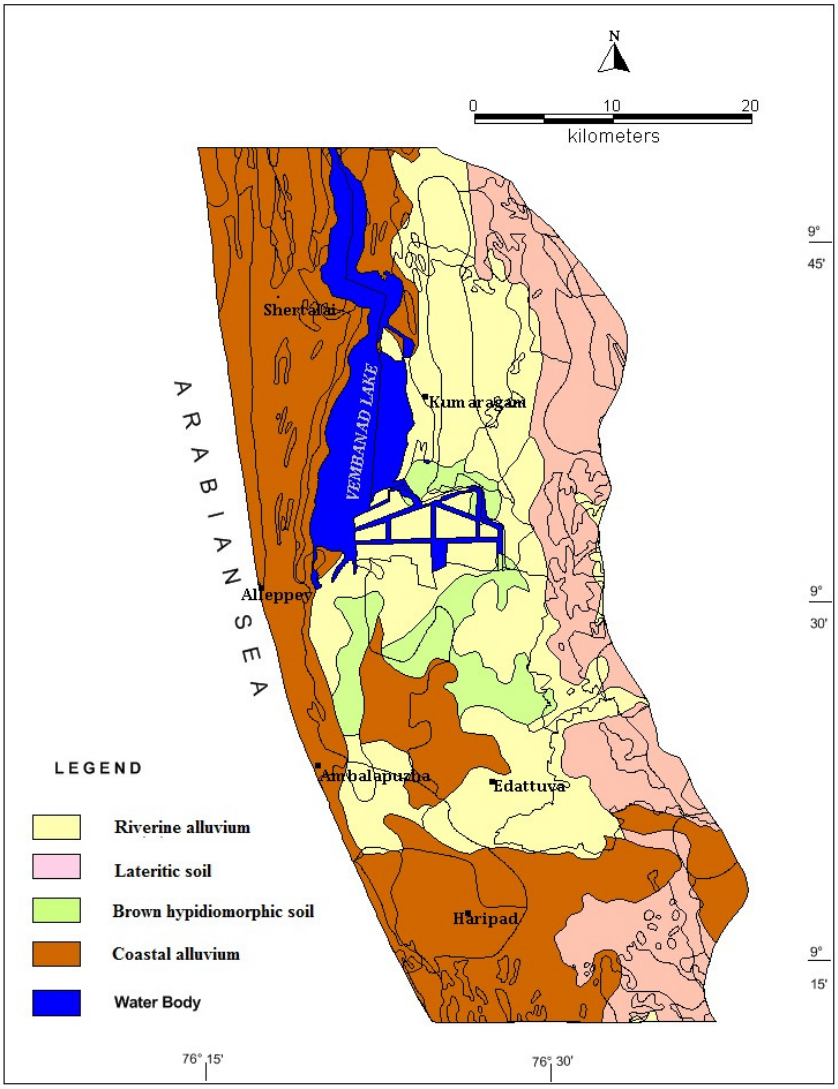


Fig. 1.2 The soil map of the area (modified after Land Use Board, Kerala, 2002)

Riverine alluviam Soils (Inceptiosols)

These soils occur mostly in the central pedi-plains and eastern parts of the area (Fig. 1.2) along the banks of Pamba river and its tributaries and show wide variation in their physico-chemical properties depending on the nature of alluvium that is deposited and characterised of the catchment area through which the river flows. They are very deep soils with surface textures ranging from sandy loam to clayey loam and moderately supplied with organic matter, Nitrogen and Potassium.

Brown hypidiomorphic soils (Alfisols)

These are mostly confined in the western low-lying areas of the area along the coast (Fig. 1.2). These soils have been formed as a result of transportation and sedimentation of material from the adjoining hill slopes and also through deposition by rivers and exhibit wide variation in their physical and chemical properties. They are poor in drainage condition and are moderately supplied with organic matter, Nitrogen, Potassium and deficient in lime and phosphate.

Lateritic soil (Oxisols)

The laterite soil is the resultant of weathering process of Tertiary and Crystalline rocks under tropical humid conditions and is seen in the eastern and south-eastern part of the area. Heavy rainfall and temperature prevalent in the area are conducive to the process of formation of this soil type and have been formed by leaching of bases and silica from the original parent rock with accumulation of oxides of Iron and Aluminum. They are poor in Nitrogen, Phosphorous, Potassium and low in bases. The organic content is also low and is generally acidic with pH ranging from 5.0 to 6.0. These soils are well drained and respond well to management practices. The soil map of the area modified after the Land Use of Kerala (Fig. 1.2) shows laterite exposures mainly in the eastern part.

1.7 Land use

As the density of population is very high there is lot of developments and interventions on land in the area. Because of socio-economic reasons the cropped area is being reduced over the years. It could be observed from the Table 1.1 and Fig. 1.3 that the total cropped area increased from 151% to 162% during the period 1985-90 and thereafter a decreasing trend is recorded. The land use map of the area exhibits that more than 90% of the land area is agricultural land (Fig.1.4).

Table-1.1 Land use over the years in the Kuttanad area (modified after Land Use Board, Kerala, 2002).

Sl.No.	Description	1985-86	1989-'90	2000-01	2005-06	2006-07	2007-08
1	Total geographical area(sq.km.)	1500	1500	1500	1500	1500	1500
2	Forest	Nil	Nil	Nil	Nil	Nil	Nil
3	Total cropped area	1560	1716	1386	1214.11	1137.63	1094.55
4	Net area sown	1030	1059	943	872.06	835.46	844.79
5	% of net area sown to total geographical area	72.84	74.89	66.69	61.84	59.18	59.9
6	Percentage of total cropped area to net sown area	151	162	147	139.22	136.16	129.56

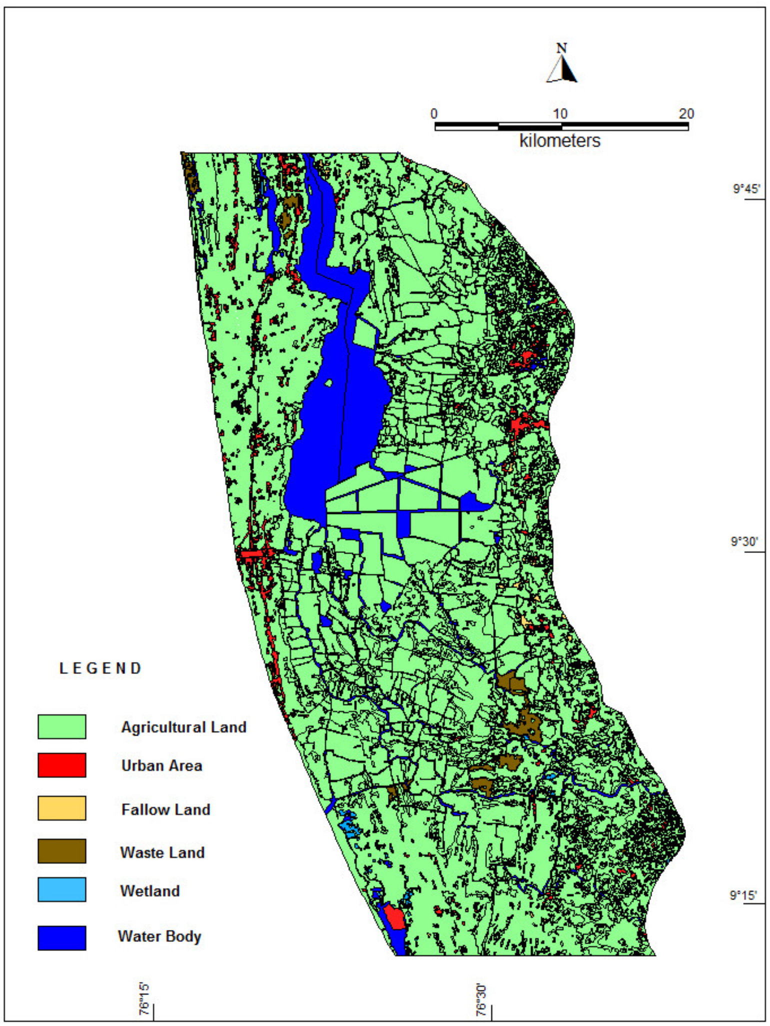


Fig. 1.3 Land use map of the area (modified after the map of land use board, Kerala (2002)

1.8 Crops and Irrigation

Agriculture is the main occupation of the population in the area. Paddy is the principal cultivated crop in the Kuttanad area and this region is known as the 'rice bowl' of Kerala. Other important crops are coconut and banana and plantation crops like rubber, cashew and pepper. Tapioca which is common food in the area is also grown. The wet lands of this area lie about 0.5 to 2 m below MSL and remains water logged almost throughout the year, being subjected to continued flood submergence during the monsoons.

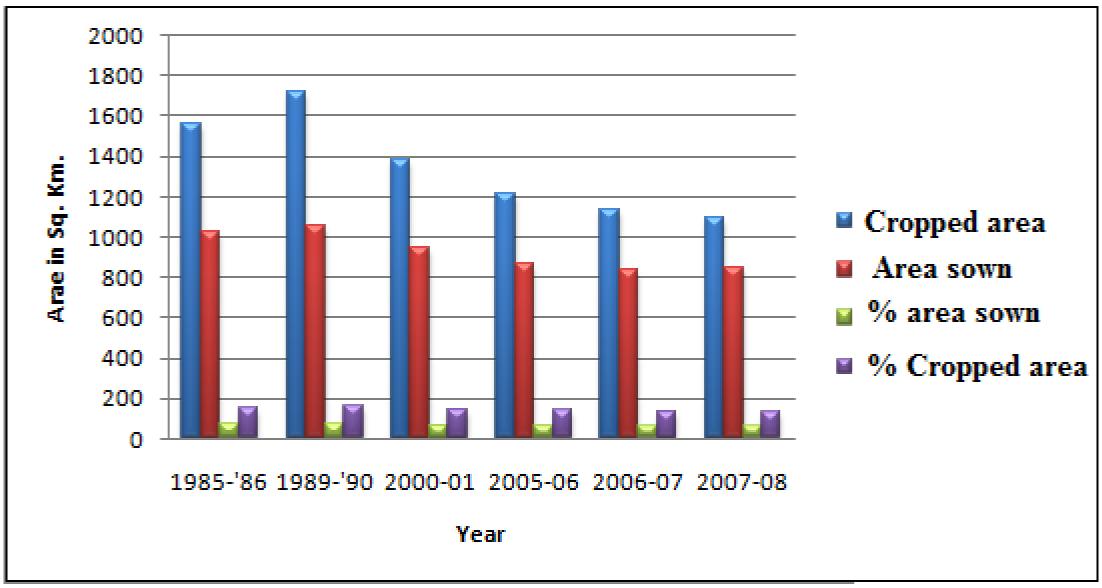


Fig. 1.4 Land use change over the years in the Kuttanad area

Paddy is grown in these wetlands under different agronomic conditions and seasons. The wet lands are broadly classified into 'Virippu' lands and 'Punja' lands, depending upon their elevation. In the relatively higher elevated Virippu lands, two crops of paddy are grown, one during 'Virippu' (April-August) season, and the other during the 'Mundakan' (September-December) season.

The wetlands, which are usually water logged and submerged for most part of the year are called the 'Punja" lands. The season of cultivation is different from the usual pattern of 'Virippu' (Kharif) and 'Mundakan' (Rabi). 'Punja' season is generally the period between 'mid-rabi and mid-summer season i.e. between November and February. Generally one crop of paddy is grown on the 'Punja' lands. Cultivation in the Punja lands is done in a special method

Temporary or semi permanent earthern bunds are constructed around the fields prepared for agricultural operations. Letting the water through sluices in these bunds helps in carrying out the periodical irrigation of paddy. The 'Punja lands' are divided into homogeneous physical entities called "*Padasekharams*", which are contiguous stretches of wetlands. The 'Punja' lands account for nearly 80% of the wetlands in the Kuttanad region. The *"Padasekharams*" are again classified into 3 broad categories, viz. the Karapadams, the Kayal lands and Karilands. The 'Karapadams' are generally situated along the water ways or constitutes the lower reaches of the eastern and southern periphery of Kuttanad, covering an area of 330 sq km. The fertility of these Karapadam lands is periodically replenished by the silt, deposited by the flood waters.

The 'Kayal lands' having an extent of 100 sq km. are spread over Chennamkary, Kainakary and Pulinkunnu areas of Kuttanad taluk with an elevation ranging from 1.5 to 2.5 m below MSL. These are lands which were recently reclaimed from the Vembanad lake.

1.9 Climate

The study area has a tropical humid climate with an oppressive summer and plentiful seasonal rainfall. The period from March to the end of May is the hot season. This is followed by the southwest monsoon season, which continues till the end of September. During October and major part of November southwest monsoon retreats giving place to the north east monsoon, and the rainfall up to December is associated with north-east monsoon season. There are 7 rain gauge stations located within the study area, which are maintained by the Central and State Government departments. They are located at Alleppey, Kayamkulam, Mavelikara, Cherthalai, Ambalapuzha, Chengannur, and Haripad. Based on 1991-2010 normal rainfall data, the area receives an average of

2965.4 mm as the normal rainfall. Out of this, southwest monsoon contributes the major part of the annual rainfall.

The southwest monsoon season from June to September contributes nearly 60.3% of the annual rainfall. The season is followed by the northeast monsoon season from October to December which contributes about 20.9% of the annual rainfall and the balance 18.8% is accounted for January to May months. The normal monthly rainfall for the rain gauge stations are given in Table- 1.2 and depicted in Fig. 1.5.

Table 1.2 Normal monthly rainfall (in mm) in the study area (1991-2010)

Stations	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alappuzha	26	35	65	137	395	651	588	333	306	363	337	53	3290
Cherthala	24	26	52	114	300	652	586	342	261	311	181	54	2903
Ambalappuzha	26	33	54	126	313	619	509	298	247	341	205	71	2842
Harippad	26	26	50	116	292	626	511	321	263	333	200	61	2823
Chengannur	30	29	70	162	306	631	568	386	294	341	230	66	3112
Mavelikara	25	25	63	142	319	688	587	370	289	357	219	74	3157
Kayamkulam	25	24	45	125	285	575	467	293	249	293	197	55	2632

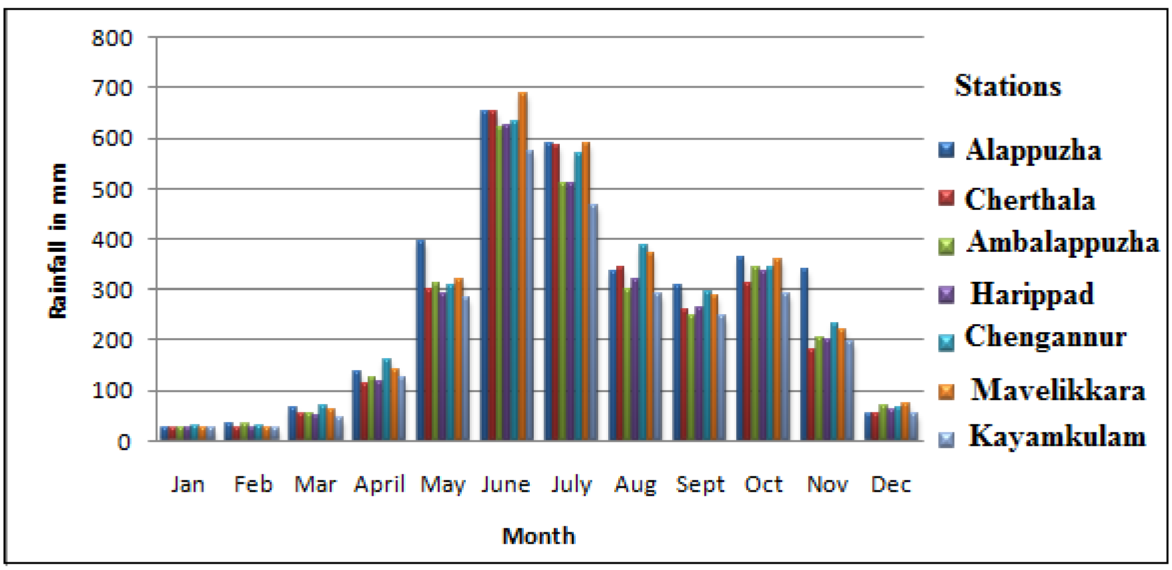


Fig. 1.5 Monthly rainfall pattern observed from rain gauge stations spread across the study area (source: IMD,2010)

The annual rainfall data pertaining to 1991-2010 period for select stations have been analysed and the various statistical parameters are given in Table-1.3. The co-efficient of variation of annual rainfall ranges from 16.3 to 24.5% with the lowest one for Alleppey and the highest one for Haripad.

Temperature

Generally March and April months are hottest and December and January months are coldest. At Alleppey the maximum temperature ranges from 28.8 to 32.7^{0}C whereas the minimum temperature ranges from 22.6 to 25.5^{0}C. The average annual maximum temperature is 30.7^{0}C and the average annual minimum temperature is 23.9^{0}C.

Table-1.3 Statistical analysis of annual rainfall data for the period 1991-2010.

Type of analysis	**Alleppey**	**Kayam-kulam**	**Maveli-kara**	**Cherthala**	**Ambala-puzha**	**Chengannur**	**Haripad**
No. of years of data analysed	20	20	20	20	20	20	20
Mean annual rainfall (mm)	3069.3	2570.3	2984.4	2816.5	2830.8	3096.7	2942.5
Standard deviation (mm)	498.9	612.7	686.5	543.4	533.7	577.3	721.6
Coefficient of variation (%)	16.3	23.8	23.0	19.3	18.9	18.6	24.5

Humidity

The humidity is higher during the monsoon period, June to September, ie about 87%. Throughout the year, the humidity is high during the morning hours.

Potential Evapotranspiration:

Evaporation is high during the months of January to April and it is low during the rainy months May to August. The maximum rate of 4.8 mm per day is recorded in the month of March and the lowest rate of 2.6 mm evaporation per day is recorded during July.

The annual Potential Evapo Transpiration (PET) for Alleppey is 1430 mm based on the data of last three decades. The highest PET is recorded during March amounting to 156.7 mm and the lowest of 58.3 mm is recorded during June. PET is less than rainfall during the period May to November. The monthly PET values are worked out by using

Thornthwaite's method (Thornthwaite, 1948). These values are overestimated since only the temperature values are considered for calculating the PET.

1.10 Hydrology

Five rivers viz; the Achenkovil, the Pamba and the Manimala, Meenachil and Muvattupuzha enter Kuttanad area from the south-west and branch through upper and lower Kuttanad. The Meenachil river enters Kuttanad from the east splitting into branches and draining into the Vembanad lake.

The Vembanad lake receives water from these five rivers and leaves Kuttanad in the north. The Muvattupuzha river enters the Vembanad lake before it is connected to the sea at Cochin. The Vembanad lake stretches beyond Cochin, to the north, where it receives water from the left branch of the Periyar River also.

Existing Hydraulic structures

Bunding of shallow parts of the lagoon started in the last century. The bunds were intended to create land on which paddy crop could be grown between the end of the monsoon season (November) and the dry season, before water becomes too saline for cultivation. The plots or "polders" formed by the bunds are called "padasekharams" locally. Due to gradual bunding activity, the area of *padasekharams* has risen to about 550 sq km.

Thannermukkom Barrier:

During 1975, a barrier was constructed across the lagoon at Thannermukkom in the north and a fresh water lake (Vembanad Lake) was created. The barrier was designed to prevent salinity intrusion in the dry season and also to retain the fresh water from the rivers flowing into the lake created by the barrier. Although the barrier has been relatively successful in keeping the water in Kuttanad fresh, in the course of time, it produced some adverse effects on fish population and tidal flushing of canals. The salt-water barrier at Thanneermukkom is kept fully opened during the monsoon period.

Thottappally Spillway:

During 1955, a spillway was built in the southern side at Thottappally to divert the flood waters of the Pamba, Manimala and Achenkovil rivers directly to the sea. The spillway is a large regulator with a sill at 2.15 m below MSL and 80 gates of 12 m width each. Although the purpose of the spillway was to keep the flood levels below the bund levels to allow cropping in the wet season, the requirements could not be fully met due to the fact that the channel leading to the spillway was not constructed as wide as originally planned. A sand bar with a level of 2 m above MSL blocks the opening to the sea and is cut by manual labour when the spillway is in use.

1.11 Drainage

The Kuttanad area receives the surface water mainly from Achenkovil, Pamba, Manimala and Meenachil rivers discharging into the Vembanad lake. The Meenachil river enters Kuttanad from the east splitting into branches and draining into the Vembanad lake. The rivers Pamba, Achenkovil and Manimala are all in their youthful stage and all of them are quick flowing perennial rivers. These are active in the denudation processes. The banks of the rivers are steep and high in the eastern parts and on approaching the coast, this diminishes considerably and shows gentle gradient near their confluence with backwaters. These rivers, with their tributaries and streamlets, exhibit a dendritic pattern of drainage in the eastern hilly area, while 'Trellis and 'Sub-Trellis' pattern are observed in the mid lands and 'Centripetal' type of drainage is observed in the Kuttanad area. Fig.1.6 shows the drainage pattern in the Kuttanad Region.

The Vembanad lake receives water from these four rivers and leaves Kuttanad in the north. The Muvattupuzha river enters the Vembanad lake before it is connected to the sea at Cochin. The Vembanad lake stretches beyond Cochin, to the north, where it receives water from the left branch of the Periyar River also.

The Pamba river is the third largest river in Kerala in terms of catchment area. It is formed by the confluence of Pamba, Kakki, Arudai, Kakkad and Kallar rivers. The Pamba river originates from the Peermed plateau in the Idukki district of Kerala. The river has a total length of 176 km. and a drainage area of 2235 sq km.

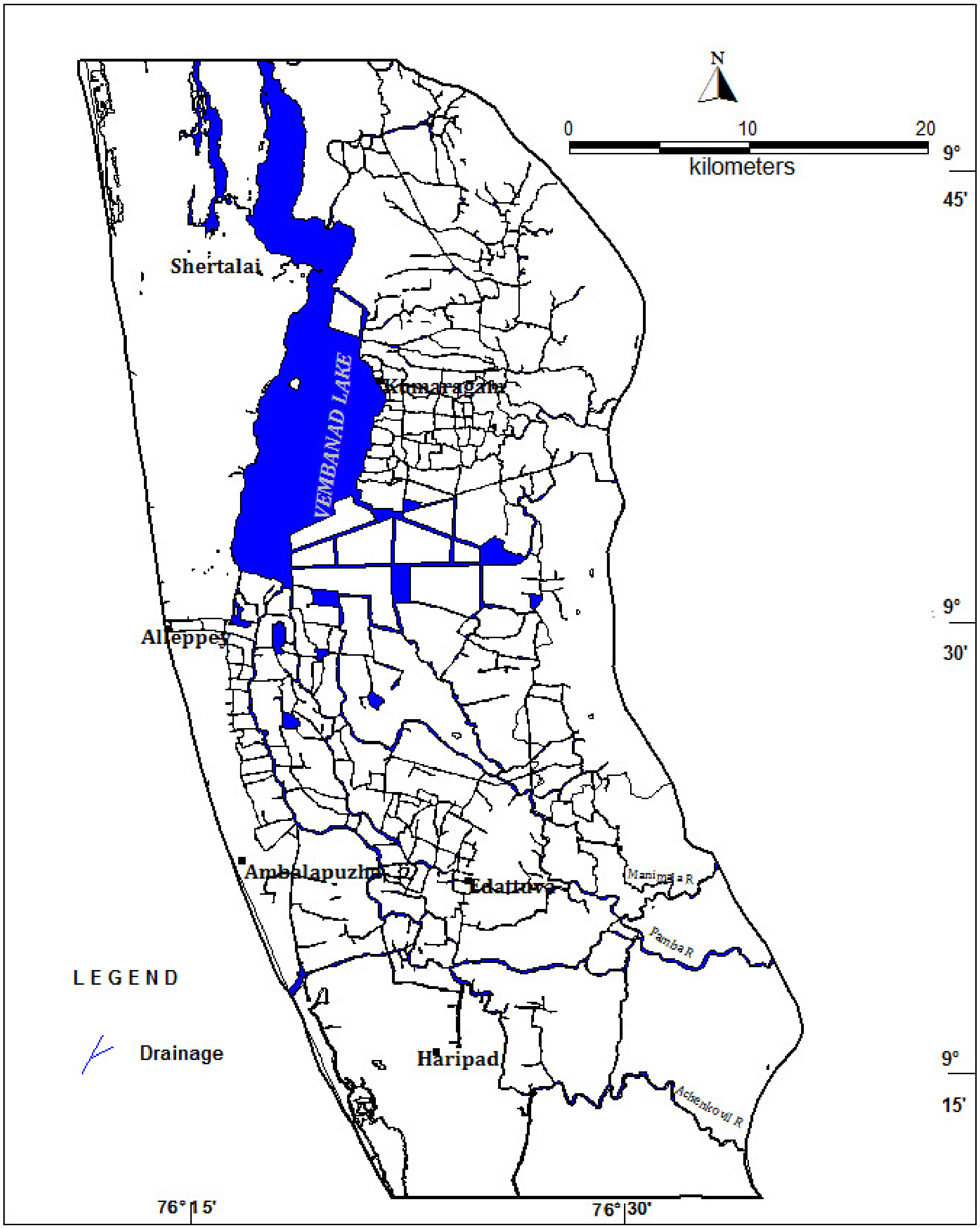


Fig. 1.6 The drainage map of Kuttanad area
(Modified after Land Use Board, Kerala , 2012)

Manimala river originates from Boardmala hills (1156 m AMSL) in the western ghats. The river is joined by Kokayar river near Kootikal. The river takes a southerly course up to Mundakkayam from where, it takes a westward course. Several small rivulets join the river till it reaches Manimala. From there, the river takes a meandering course till it confluences with Pamba at Neerettupuram. The length of the river is 90 km and the drainage area is 847 sq km.

Several streams originating from Pasukidamedu, Ramakkal Teri and Rishimalai in the western ghats join together to form the Achankovil river. It follows a northwesterly course up to Kumbazha where it is joined by the Kallar stream. From Kumbazha, it turns west and then turns southwards for about 5 km and continues in a westerly course up to Idappamon. Here, it turns northwest up to Thazhakkara and thereafter flows westwards. The river then splits into small distributaries and the main branch flows northwest join the Pamba river at Veeyapuram. The total length of the river is 128 km and drainage area is 1484 sq.km. All the 4 rivers viz. Pamba, Achenkovil, Manimala and Meenachil enters the Kuttanad area before draining into the Vembanad lake.

CHAPTER 2

GEOLOGY AND GEOMORPHOLOGY

2.1 Introduction

The Kerala region is an important part of the South Indian Precambrian terrain, comprised of granulites, granites, gneisses and green stones. The southern part of the State, south of Achankovil shear zone, exposes an assemblage of migmatised meta-sedimentary and meta-igneous rocks (khondalite-charnockite assemblage) and north of Achankovil shear zone up to the southern flank of the Palghat Gap, the rocks are predominantly charnockites. Chanockite-gneiss and a variety of other gneisses with occasional assemblages of metasediments in Idukki-Munnar region represent the western continuation of the Madurai block in Tamil Nadu. Northen flank of the Palghat Gap consists of meta-sedimentary sequence of khondalites and calc-granulite with crystalline limestone bands. Granulites, schists and gneisses, intruded by acid and alkaline plutones, constitute the northern most part of the State.

The most widespread rocks in Kerala are the charnockite and associated gneisses. These are pyroxene bearing granulites and gneisses and occupy a major part of the Westen Ghats and the midland regions of the State, especially in central and north Kerala. Large bands of charnockites are also observed within the south Kerala khondalite belt. These are the oldest rocks dated so far (3.2 billion years) in Kerala (Santhosh et al., 2013). In many localities enclaves of mafic granulites also occur within charnockites. Textural, mineralogical and geochemical variations are observed in chanockites from different localities. The map depicting various geological formations of Kerala are given in Fig.2.1 (GSI, 2005).

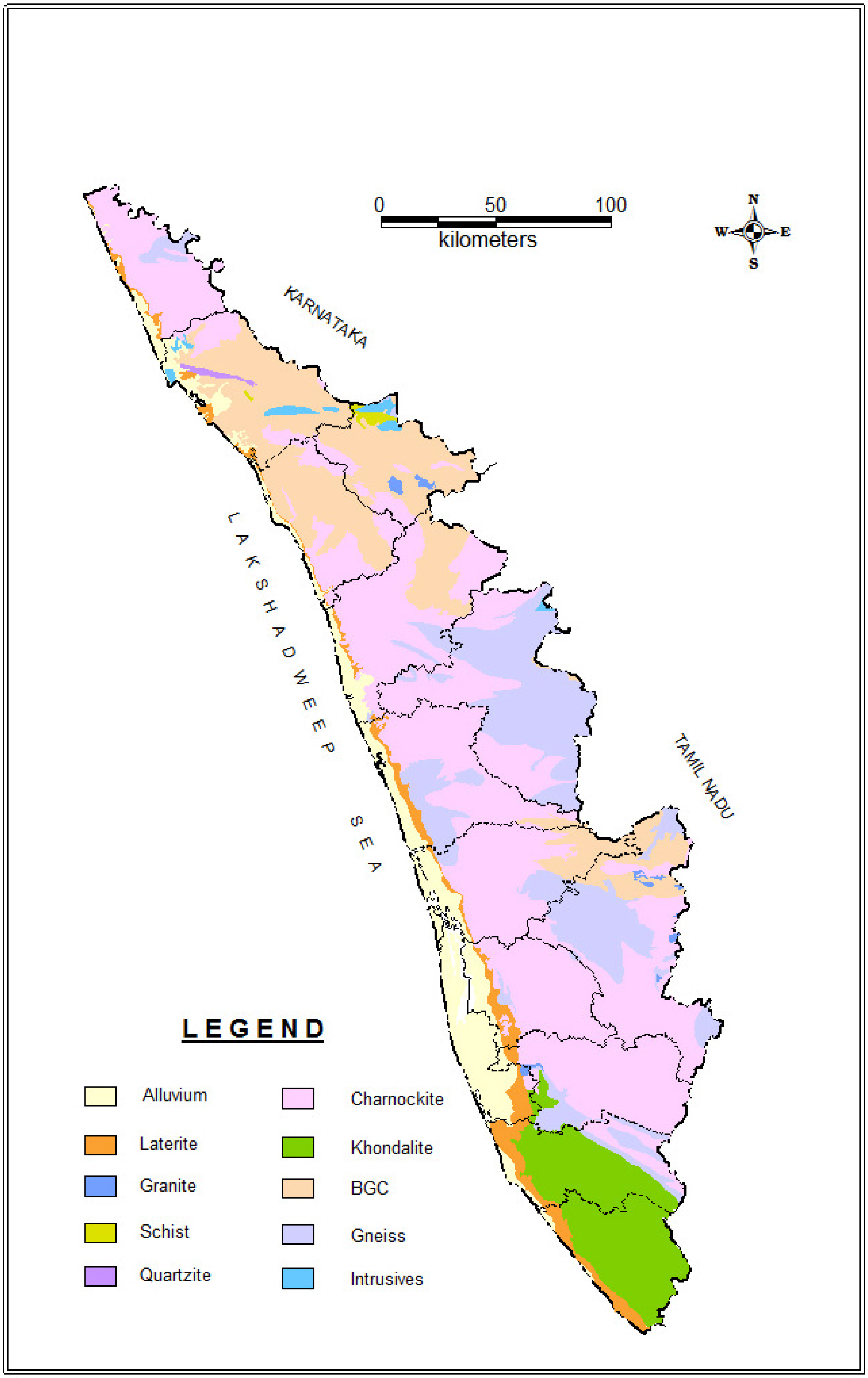


Fig 2.1 Map depicting various geological formations of Kerala (GSI, 2005)

Garnet-sillimanite gneiss, containing varying amounts of graphite and some quartz and orthoclase is termed as khondalite. Its occurrences are seen in various parts of the State. The largest patch is noticed in south Kerala association with garnet-biotite gneiss and garnetiferrous quartzofeldspathic gneiss. This occurs as linear belt; wedged between charnockite massifs. Another linear belt is observed in northen flank of the Palghat Gap, where it is seen in association with calc-granulite and crystalline limestone. Minor occurrences have been reported from Idukki-Munnar region and from southeast of Kasargod.

Intrusive phase within Kerala region includes sporadic occurrence of basic and ultrabasic bodies and dykes belonging to Lower-Middle Proterozoic age, pegmatites of Middle Proterozoic age, a host of younger granites (Late Precambrian-Early Palaeozoic age) with associated pegmatites, and later dolerite dykes, contemporaneous with Cretaceous-Palaeocene Deccan basalt magmatism. Pegmatites in north Kerala are relatively older and known for their muscovite mineralization (GSI, 2005).

The western continental margin of the Kerala coast has a 50 km wide continental shelf, hosting the Kerala-Konkan Basin (KKB). The nearshore shelf part contains an elastic sequence of marine shale and sand with a very few limestone inter beds and Cretaceous-Palaeocene sediments. The offshore basin, with over 4000 m thick of Late Cretaceous to Quaternary sediments, consists of limestone, sandstone and a pile of volcanic. The sediments display two major unconformities during Palaeocene-Early Eocene and Middle Eocene-Early Oligocene periods.

Tertiary and Quaternary sediments:

On land sedimentary formations, belonging essentially to Miocene and Quaternary periods unconformable overlie Precambrian rocks. Both marine and non-marine rocks of the Neogene period fringe the coastal tract in two major basins of deposition; (i) between Thiruvananthapuram and Ponnani in the south and (ii) between Kannur and Kasargod in the north at Cheruvathoor. These include rocks of the Vaikom formation, comprising gravel, coarse to very coarse sand with greyish clay and carbonaceous clay and seams of lignite; fossiliferous limestone, sands and clays of the Quilon formation and the overlying clays with lignite bed, sand, sandy clays and sandstone belonging to the Warkalli beds of the Late Miocene age.

The best exposures of Warkali beds are available in the cliff sections near Varkala. The major lithological units here are alternating beds of clays and sands, with thin lenticular bands of lignite. The sandstones are ferrugenous, gritty and locally clayey and the clays are usually variegated or mottled. These sandstone-clay horizons are underlain by fossiliferous calcareous formations known as Quilon beds. Best exposures of the Quilon beds are seen at S.Paravur, Padappakkara and Mayyand in Quilon district. These Tertiary formations have undergone deep weathering and lateritisation which very often masks them. Vaikom beds were first considered as part of Warkali. On a detailed study, these were found to underlie the Quilon beds and extend almost over the entire sedimentary basin. Best exposures are in the laterite sequence southeast of Vaikom and is termed as Vaikom beds (Rao et al, 1976). A horizon composed of highly carbonaceous clay and sandy clay below the Vaikom beds is identified as Alleppey beds. The palynological studies carried out by the Birbal Sahni Institute (Rao, 1988) have reported a rich polynological assemblage which conforms to Eocene age.

Sediments of Quaternary period, consisting of sands, lagoonal clays, shell deposits, teri sands etc. unconformably overlie the Neogene sediments. The Kerala coast consists of coastal alluvium comprising of sand and clay along the coastal and flood plain region overlaying the tertiary sediments and has a maximum thickness of 80 m at Alleppey (Nair et al., 2009). The development of coastal landforms and associated sedimentary environments are resulted from both the fluvial and marine processes. The peat and shell deposits of the Late Quaternary period occur at various onshore locations along the central Kerala coast. Occurrence of peat deposits at subsurface levels reveals mangrove vegetation was predominantly present along the coastal tracts in the Late

Quaternary period, subsequently inundated by the higher sea level, and led to the formation of peat deposits (Narayana et al., 2002).

In Kerala, laterites of more than one generation are present, and are confined to elevations of 600 m and below, over Precambrian and Tertiary sediments. Interface of the coastal plain and lowlands is occupied by laterite. Vast dissected lateritic mesas are present in parts of Malappuram, Kannur and Kasagod districts. Two lateritization cycles are known to exist in Kerala; Pre-Warkalli and Post Warkalli cycles. The laterite forms a definite geological horizon in the sedimentary sequence in the coastal area. It is found that at places the laterites have been eroded totally before the deposition of the Recent alluvium.

2.2 Stratigraphic sequence

The stratigraphy suggested by the Geological Survey of India (1995) is shown in Table 2.1. The unconsolidated coastal formations comprising sand, clay, flood plain deposits and lagoon deposits extending over the entire area represents the Recent alluvial formation overlying Tertiary formations. The thickness of this formation varies from 4 m to more than 80 m as seen around Thottapalli, Katoor and Nirkunnam.

Table-2.1: Stratigraphic sequences in Kuttanad area (GSI, 1995)

	Age	Formation	Lithology
Quaternary	Recent	Alluvium	Sand and clays along the coast and flood plain deposits
	Sub-recent	Laterite	Laterite capping over crystalline and sedimentary formations
Tertiary	Lower Miocene	Warkalai beds	Sandstones and clays with thin bands of lignite
	Lower Miocene	Quilon beds	Limestone and clay
	Oligocene to Eocene	Vaikom beds	Sandstone, clay and thin bands of lignite
	Eocene	Alleppey beds	Carbonaceous clay with minor lenses of fine sand
Unconformity			
	Archaean (crystalline formation)		Charnockites, khondalites and granites

The laterite of sub-Recent age is exposed in the south eastern parts of the area and overlies the crystallines. In the western part laterites are encountered in bore holes overlying Warkali beds with a maximum thickness of 74 m as encountered at Trikunnapuzha.

Tertiary sediments lie over the crystalline basement formations, in the Kuttanad area. The lithological and electrical logs of bore holes in the area indicate that Tertiary sediments (equivalent in age to Cuddalore and Rajahmundry sandstones of east coast) comprise of four distinct units namely Alleppey, Vaikom, Quilon and Warkalai beds. Thickness of the Tertiary formation varies in the basin but the maximum thickness is 600 m between Kattoor and Trikunnapuzha (Central Ground Water Board, 1992). All the four beds are encountered in bore holes drilled between Nallanickal and Arthungal. Residual laterite formations are encountered in the south-eastern parts of the Kuttanad area and granites are encountered in and around Chengannur area.

Warkali beds is the youngest formation in the Tertiary sequence with alternate layers of sand, clay and thin bands of lignite and the maximum thickness of Warkali is 100 m as encountered at Kallarkode.

Overlying the Vaikom beds is the Quilon beds consisting of grey compact limestone, calcareous clay and is generally associated with fine to medium sand. The maximum thickness of this formation is 116 m as encountered at Nirkunnam.

Vaikom beds derives its name from the place Vaikom, in Kottayam district, where it is exposed on the surface. The thickness of the formation in bore holes ranges from 25 to 238 m with minimum thickness in the western part of the district. In the eastern part of the area it is lateritised on the surface. This bed consists of thick sequence of coarse to very coarse sand, gravel and Pebble bed inter-bedded with ash grey clay and thin bands of lignite and peat.

Alleppey beds are the oldest Tertiary formation unconformably overlying the crystalline Archaean basement. Alleppey beds are mainly composed of carbonaceous clay with minor lenses of sand. The maximum thickness of the formation is not known since no bore hole has encountered the entire thickness of the formation and it is only encountered in the deeper bore holes drilled between Kattur and Nallanikkal section

Charnockites, Khondalites and granites form the basement. Charnockites and khondalites exposed in the study area have very limited areal extent. However, they are encountered in bore holes

2.3 Geology of Kuttanad area

The coastal alluvium and tertiary sediments lie over the crystalline basement formations, in the Kuttanad area. The lithological and electrical logs of bore holes in the area indicate that Tertiary sediments (equivalent in age to Cuddalore and Rajahmundry sandstones of east coast) comprise of four distinct units namely Alleppey, Vaikom, Quilon and Warkalai beds. Thickness of the Tertiary formation varies in the basin but the maximum thickness is 600 m between Kattoor and Trikunnapuzha (Kunhambu, 2001). All the four beds are encountered in bore holes drilled between Nallanickal and Arthungal. Residual laterite formations are encountered in the south-eastern parts of the Kuttanad area and granites are encountered in and around Chengannur area. The geological map of the study area is given in Figure 2.2 (GSI, 1995).

2.4 Structures

The deposition of Tertiary sediments has taken place in faulted crystalline basement. A deep seated fault in the crystalline basement passing through Quilon and east of Alleppey trending in NW-SE direction has been mapped through the studies carried out by ONGC in the offshore area of west coast (Rao and Srivatsava, 1984) and the tectonic map of Kerala coast and off shore is shown in Fig 2.3.

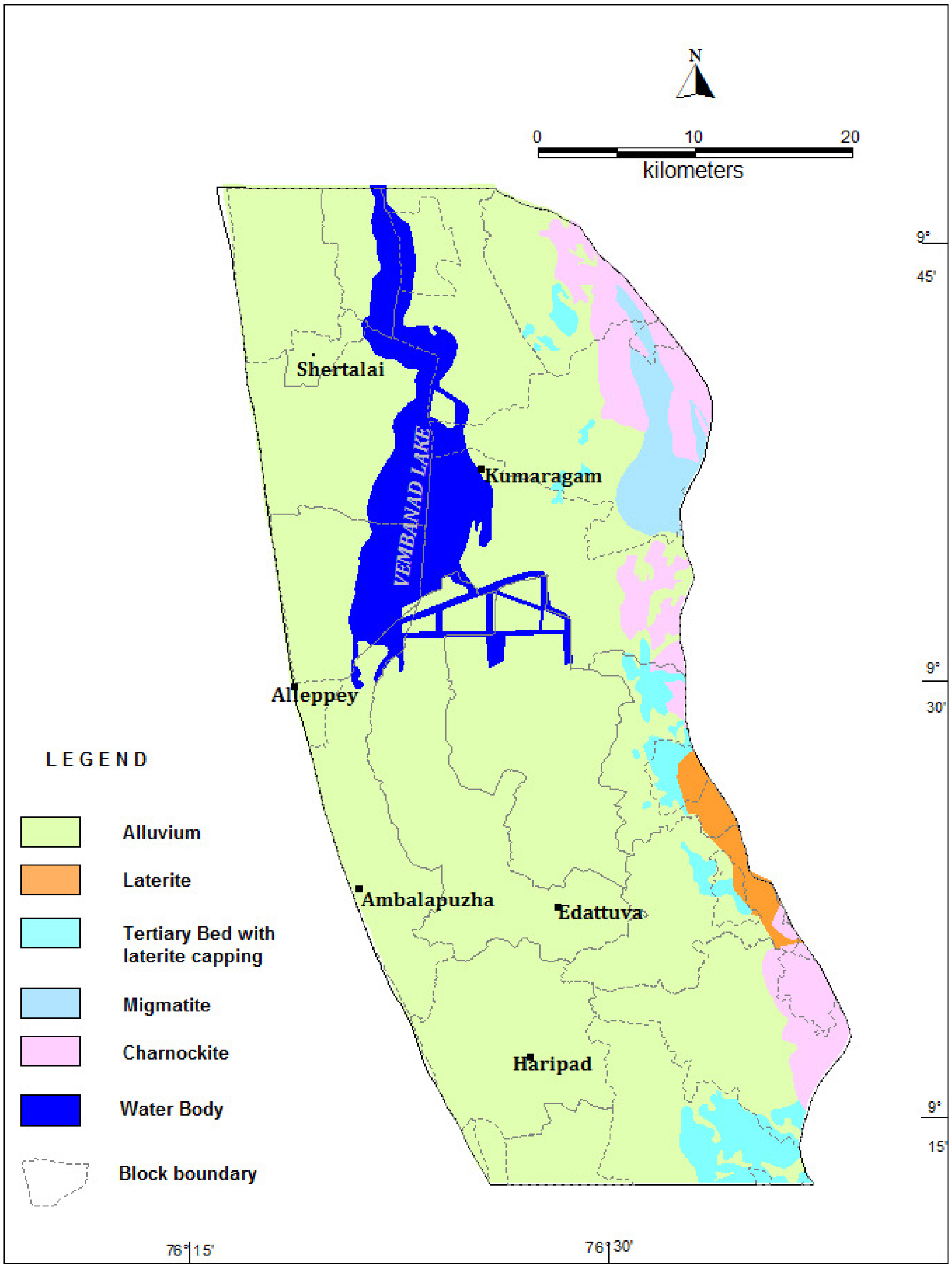


Fig.2.2 Geology of Kuttanad and adjoining area (Modified after GSI, 1995)

Many established fractures and shear zones having NW-SE to WNW-ESE trends that have been mapped in the Archaean terrains to the east of coastal belt are reflected clearly as lineaments in the landsat imageries (Varadaraj, 1988). The extension of these fractures noticed in hard rocks in to the coastal in Kuttanad is inferred. What we have as Vembanad lake today is probably an embankment of a large graben in the offshore.

These studies are of having great significance in understanding the hydrogeology of the Tertiary sediments in the coastal parts of Kuttanad area. The occurrence of peat, large trunks of buried forest in the Kuttanad tells the neotectonic activities in the area as reported by earlier researchers (eg: Nair et al., 2004; Valdiya and Narayana, 2007).

2.5 Vertical boundary and thickness of geological formations

The lithological data of fifteen bore wells were used for the preparation of panel diagrams and cross sections to study the lateral and vertical extent of various litho units. The cross sections and panel diagrams could bring out sub surface geology and lithological correlations were attempted. The geological cross section prepared during studies by SIDA assisted coastal Kerala Groundwater Project is given in Fig. 2.4. The details of bore well details in Kuttanad area are given Table 2.2.

The lithological data of 15 bore holes have been used to prepare the panel diagram (Fig 2.5) to bring out the vertical and lateral extension of the geological formations which is needed to define the aquifer geometry in Kuttanad area. The Figures 2.4 and 2.5 indicate that in the kuttanad area the sedimentary basin along the west coast is deep and have a thick pile of sediments whereas towards east it is deposited over basement at shallow depths. The sections are refined with more geological sections along the select section lines and could gather more information on the sub surface geology.

The geological sections prepared along the coast between Anjengo and Pariyapuram is given in Fig. 2.4 and the part of Kuttanad represented in the section is between Nallanikal and south of Chellanam. The thickness of Alluvium is maximum at Kattur which is in the order of 100 m.

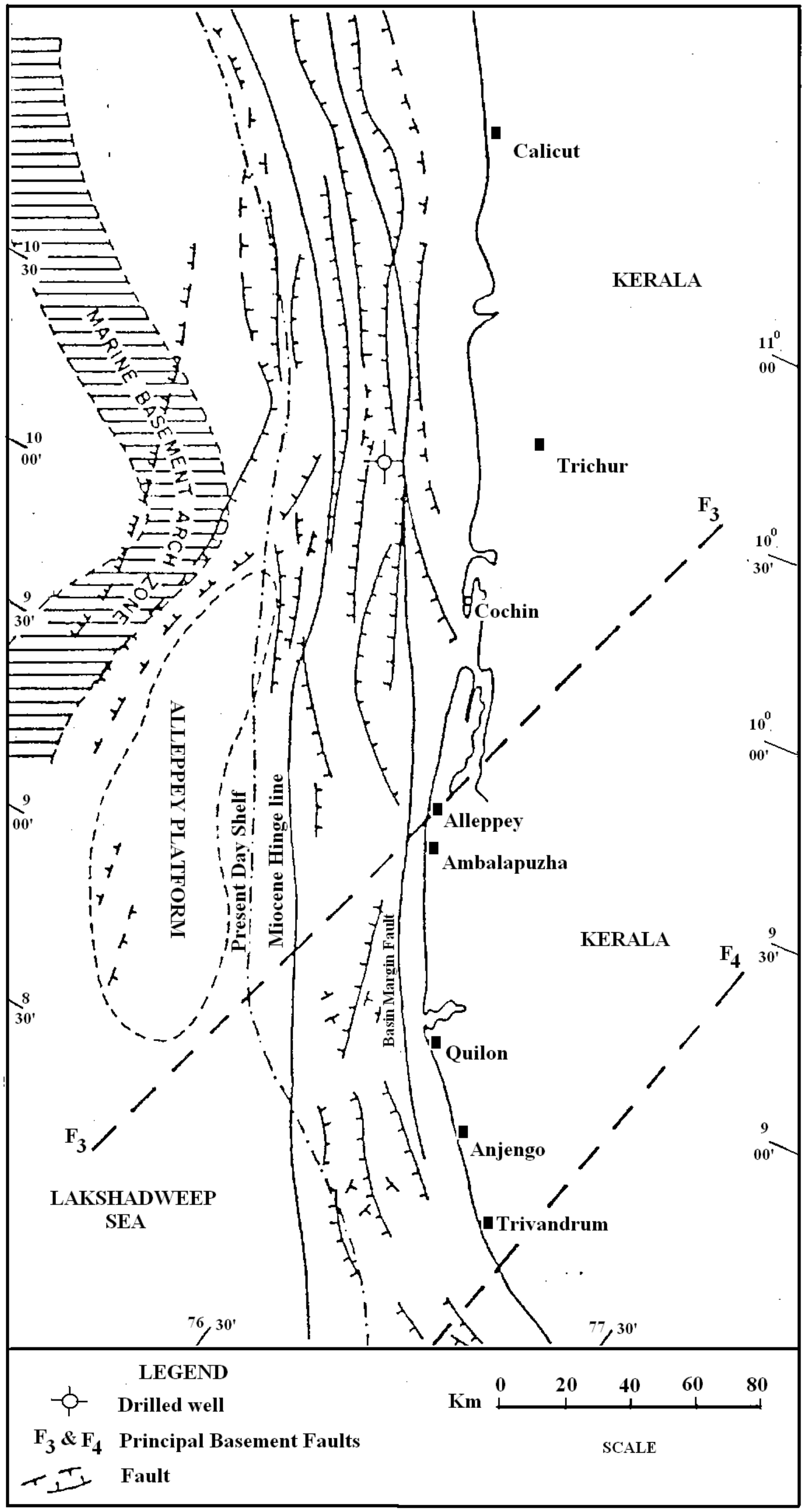


Fig 2.3 Tectonic map of Kerala coast and off shore (Rao, 1984)

Table 2.2 The details of bore wells in Kuttanad area used in the present study (CGWB, 1992)

Well No	Location & toposheet No.	Latitude in	Longitude in degrees	RL m AMSL	Depth drilled	Zones tapped (m)
1	Alisserey, 58 C/7	9.4861	76.3264	3.789,	247.56,	l-109-119.0, 123-128 .(Quilon)
2	Alisserey, 58 C/7	9.4861	76.3264	3.834	209	158-162, 170-174, 196-200.(Vaikom)
3	Arthungal, 58 C/7.	9.6589	76.2997	1.524	444.9	91-100(Warkalai)
4	Aryad, 58 C/6	9.5375	76.3292	4.166	400.1	102-114, 144-156.-Warkalai
5	Changanacheri, 58 C/11	9.4583	76.5333	1.448	35.6	19.81-22.86, 28.95-32.
6	Edattuva, 58 C/7.	9.3694	76.4764	1.178	205.6	78-84, 87-90.(Quilon), 99-105.(Vaikom)
7	Haripad, 58 C /7	9.2919	76.4625	2.13	55	38-50
8	Kalarkod, 58 C/7.	9.4583	76.3333	3.006	601	372-393, 408-416, 419-427.
9	Kallara, 58 C/6.	9.7028	76.4778	1.955	37.5	7.62-12.19, 15.85-24.38.
10	Kandiyur 58 C/12.	9.2481	76.5267	5.62	188.9	129.86-145.0(Vaikom)
11	Karthikapalli- 58 C/7.	9.2500	76.4500	3.12	450	70-76, 80-86.
12	Karumadi, 58 C/7.	9.3792	76.3917	1.15	437.04	247-256, 262-268, 271-280, 283-289, 298-307,310-
13	Karuvatta, 58 C/7.	9.3167	76.4125	3.036	428.2	259-263, 281-296, 354-365.(Vaikom)
14	Kattoor, 58 C/6.	9.5750	76.3036	2.091	504	299-308, 319-333.5, 351-355
15	kidangara, 58 C/7.	9.4194	76.4972	1.67	97.14	39-48, 67-74.4, 84.7-93.2.
16	Kottaram, 58 C/6	9.6972	76.3153	3.281	326.45	EW-148-151, 156-160, 162.5-165.5, 167.5-
17	KulashekaramangalamC/6.	9.7917	76.4000	4.082	54.86	13-17, 30-33, 39-48.(Vaikom)
18	Kumarakom, 58 C/6.	9.5861	76.4389	1.178	169	112-124.(Vaikom)
19	Mancombu, 58 C/7	9.4417	76.4222	1.11	258.51	37-42, 46.5-49.5, 54-68
20	Mannancherry 58 C/6	9.5806	76.3653	3.895	202.73	193-196 (Vaikom)
21	Muttom, 58C/8.	9.2486	76.4903	3.326	274.7	163-178, 180-185, 188-193, 201-218, 222-225
22	Nirkunnam, 58 C/7.	9.3917	76.3667	2.52	600.79	zones between 68 and 266 contains fresh water.
23	North Mararikolam,58 /C6	9.6264	76.3333	3.756	357.48	70-74, 78-82, 88-92.
24	Parumala, 58 C/11.	9.3306	76.5403	6.275	105.8	46.33-57.91,70.7-76.2, 78.02-81.07
25	Pattanakad, 58 C/6.	9.7444	76.3000	0.905	274.31	178-188, 191.4-194.5, 197.4-211.2
26	Payarattubagam, 58 C/6.	9.7125	76.4000	1.475	91.44	Nil
27	Pulikeezhu, 58 C/11	9.4333	76.5439	NA	88	25-28, 44-52, 56-61, 65-67 (Vaikom)
28	Ramankari, 58 C/7	9.4217	76.4575	0.882	116.9	103-110.(Vaikom)
29	Shertallai, 58C/6	9.6306	76.3278	4.663	237	33-39, 67-73, 83-89, 172-178, 197-203, 215-221
30	Thakattusseri, 58 C/5+1.	9.7722	76.3556	5.09	127.4	24.3-32.9, 37.8-42.6, 66.45-69.5, 89.0-90.83, 93.88-115.22.
31	Thakazhi, 58 C/7.	9.3667	76.4264	NA	304	Nil
32	Thottappalli, 58 C/7.	9.3153	76.3897	1.252	269.44	87-93, 106-120, 130-136, 164-174(Warkalai)
33	Thrikunnapuzha, 58 C/7.	9.2667	76.4083	1.145	600	111-122, 126-132 (Warkalai)
34	Thuravur, 58 B/4	9.7550	76.3194	2.672	222.8	87-93, 98-101.(Quilon)
35	Udayanapuram, 58 C/5	9.7750	76.3972	1.414	69.5	54.9-59.7, 64.6-66.5.

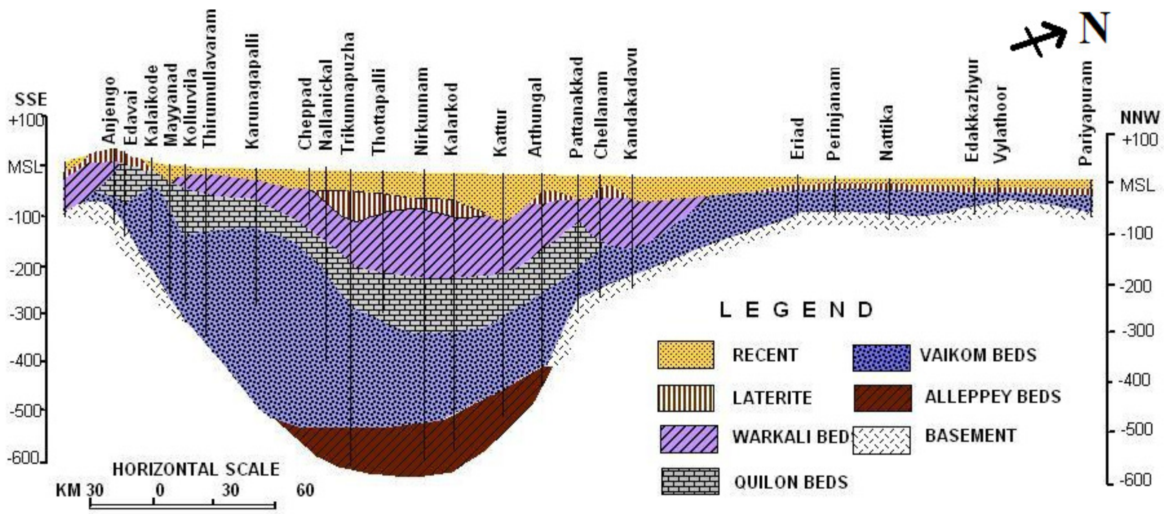


Fig. 2.4 Cross section showing the vertical boundary and formation thickness along the Kerala coast (CGWB-1992)

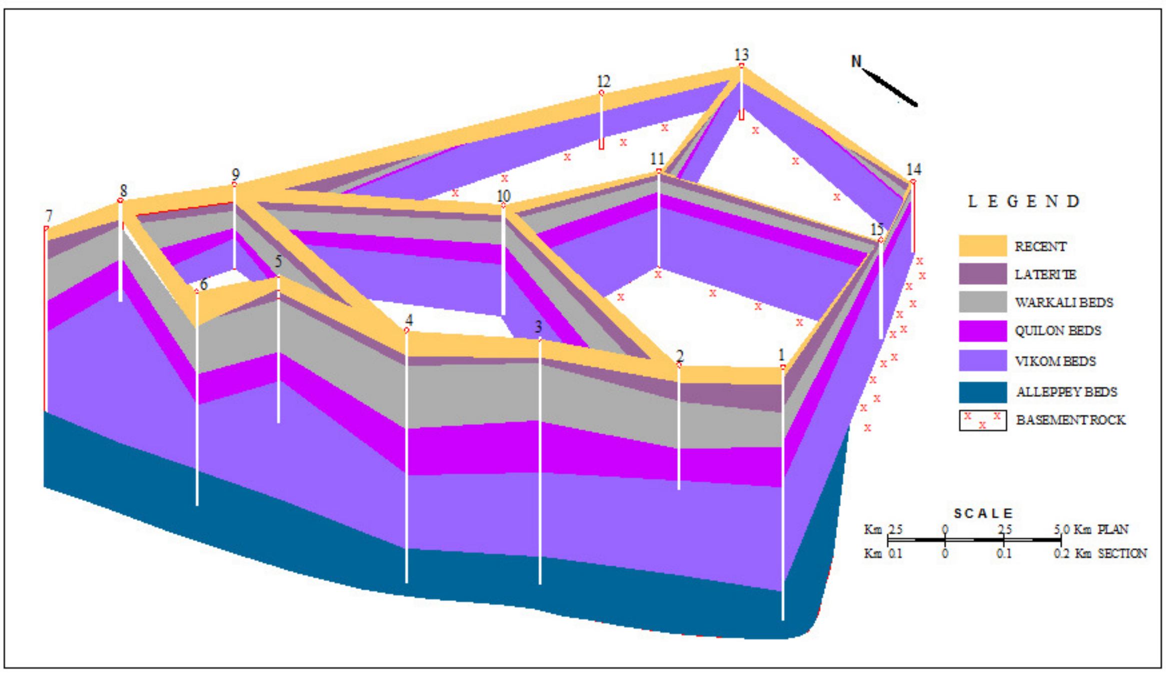


Fig 2.5 Panel diagram of vertical succession of geological formations in the Kuttanad area (present study)

The other formations encountered down to 600 m is given as broad groups under (i) Recent (ii) Laterite (iii) Warkali beds (iv) Quilon beds (v) Vaikom beds (vi) Alleppey beds and (vii) basement rock. The abrupt ending of some formations are noticed and thickening and thinning of formation are also seen. The panel diagram in Figure 2.5 gives overall information about the disposition of various geological formations in the area and its lateral and vertical variations. The bore well data on the thickness of Warkali, Quilon and Vaikom beds used in the preparation of panel diagram (Fig. 2.5) is given in Table 2.3. Each of this formation is comprised of various granular zones acting as multi aquifers. The disposition of sand and clay in the top alluvium and its continuity with the Tertiary aquifer system is to be defined with clarity. To elucidate the disposition of sand and clay in the alluvium and its continuity with the Tertiary beds, cross sections across the study area in E-W direction were prepared (Fig. 2.6) and interpreted.

2.5.1 Disposition of sand and clay in the sedimentary formations

Geological cross sections and panel diagrams are being used to define the aquifer geometry. The study of aquifer geometry is important because it facilitates identification of areas with favourable aquifer disposition involving aquifer boundaries, areal extent, thickness and volume (Samadder et al., 2007). This has implications in lateral groundwater movement, water exchange between adjacent aquifers, seawater intrusions, contaminant transport studies, and studies for artificial groundwater recharge (Srivastava, 2005; Tait et al., 2004).

Five cross sections across the study area have been prepared to bring out the disposition of sand and clay in the sedimentary formations. To highlight the relation of granular zones in the alluvium with that of Tertiary beds the depth of information on lithology in deeper parts of Tertiary beds which do not form fresh water aquifers (Alleppey beds) is avoided. Also, there is insufficient data on deeper Alleppey beds. The cross sections prepared out of the lithological data from wells penetrating partially a clear picture on sub-surface geology of alluvium could be brought. The select section lines are shown in Fig. 2.6 and the cross sections are given in Fig. 2.7-2.11. The cross sections are being made between the locations Nirkunnam and Thalavadi, Kallarkode and Alanthuruthi, Kalavur and Thiruvarapur and finally between Pattanakadu and Mundur.

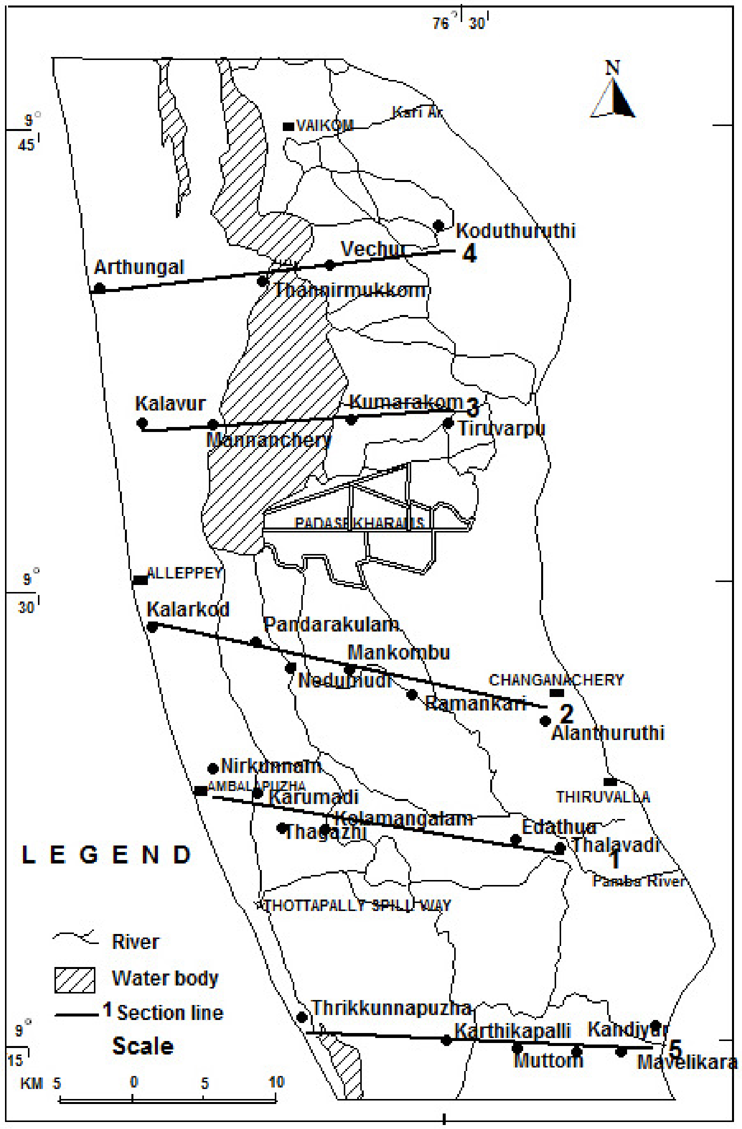


Fig 2.6 The bore hole locations and lithological cross section lines

Vertical thickness of different litho units along Nirkunnam-Thalavadi line

The cross section is drawn with the litho-log data of tube wells at Nirkunnam, Karumadi, Thakazhi, Kelamangalam, Edathua and Thalavadi (Fig.2.7). From this section it can be observed that the sand beds are restricted to coastal area in top and central area in deeper zone in the Recent alluvium thereby giving 3 distinct

Table 2.3. The Top and bottom boundaries and thickness of geological formations in different stratigraphic sequences derived from bore well data

Sl. No	Location name	Depth	Latitude	Longitude	Warkali bed			Quilon bed			Vaikom bed		
					Top of bed m	Bottom of bed m	Thick ness in m	Top of bed m	Bottom of bed m	Thick ness in m	Top of bed m	Bottom of bed m	Thick ness in m
1	Karuvatta	428	9.3167	76.4125	61	165	104	165	229	64	229	468	239
2	Thottapalli	269.44	9.3153	76.3897	85	196	111	196	269	73	_	–	0
3	Nirkunnam	601	9.3917	76.3667	66	203	137	203	318	115	318	510	192
4	Kalarcode	601	9.4583	76.3333	62	217	155	217	323	106	323	494	171
5	Ariyad	400	9.5375	76.3292	57	188	131	188	259	71	259	396	137
6	Kattur	504	9.5750	76.3036	99	202	103	202	271	69	271	418	147
7	Arthungal	445	9.6589	76.2997	60	156	96	156	231	75	_	_	0
8	Cherthala	221	9.7550	76.3194	47	86	39	86	164	78	164	218	54
9	Mannanchery	203	9.5806	76.3653	56	105	49	105	121	16	121	199	78
10	Mankombu	259	9.4417	76.4222	35	92	57	92	140	48	140	258	118
11	Thrikunnapuzha	600	9.2667	76.4083	112	190	78	190	283	93	283	520	237
12	Kidangara	97	9.4194	76.4972	–	_	0	_	_	0	42	97	55
13	Pulikeezhu	70	9.4333	76.5439	_	_	0	_	_	0	38	70	32
14	Kandiyur	133	9.1714	76.5439	12	24	12	24	57	33	57	129	72
15	Muttom	275	9.2486	76.4903	20	68	48	68	102	34	102	248	146

sub-surface geological sections in Recent alluvium. A coarse sand bed in the Tertiary formation is seen below Recent alluvium confined by thick clays. The disposition of laterite is taken as marker bed for demarcating the bottom of Recent alluvium or the top of Tertiary beds. There is a possibility of offset of sediments of strike-slip faults as indicated in section. Whatever may be the tectonic cause, the disposition of three distinct layers in top alluvium is clearly brought out. The first one is sand layer of 1 to 20 m thick which is directly receiving recharge from rainfall. This layer is very tin or absent in eastern side the second layer is 10 to 25 m thick clay with some minor sand bed. The last layer in Recent group is again a thin sand of 5-16 m.

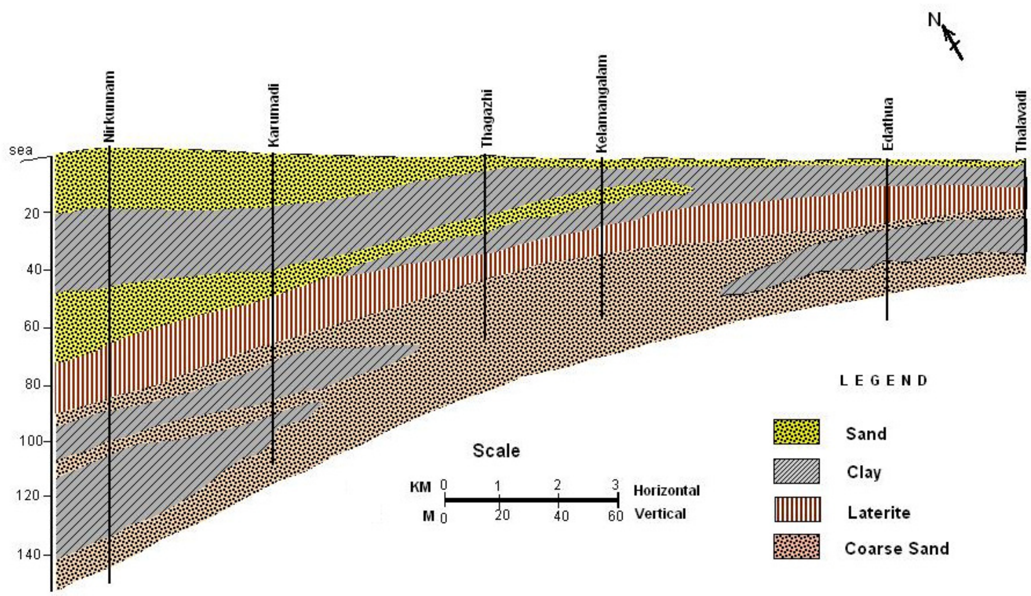


Fig 2.7 Vertical thickness of different litho units showing in a cross section along Nirkunnam – Thalavadi line, which forms part of Kuttanad basin.

The deeper Tertiary sediments also have such individual sand and clay beds which control the groundwater recharge and movement. A coarse sand bed of Warkali formation is seen below the laterite and the clay bed is discontinuous. Recharge to these granular zones from the top aquifers is restricted due to clayey formations and lateritic clays. It is postulated that the lateritic beds are clayey as the hard top portion of laterites originally formed were eroded before the deposition of the Recent alluvium.

Vertical thickness of different litho units along Kallarkod-Alanthuruthu line

The section-2 is drawn between the broewells at Kallarkod and Alathuruthi in E-W direction (Fig. 2.8). The litho logs of bore holes at Pandarakulam, Nedumudi, Mankombu and Ramankari fall in this section. The top sand basin in Recent sediments is thick in coastal line in the order of 22 m while it is 5 to 10 m with clay intercalations in the east. The second clay layer is 30 to 35 m in the line which is very thick at Ramankari.

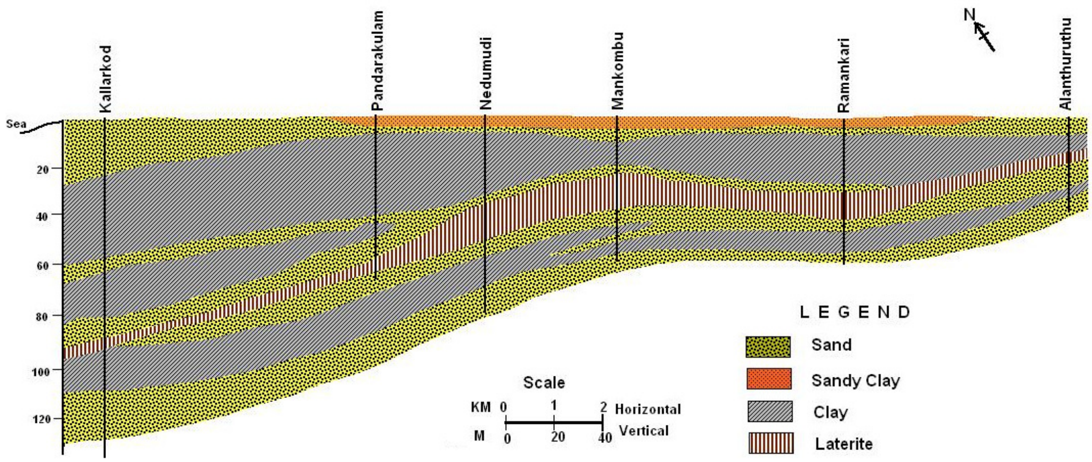


Fig 2.8 Vertical thickness of different litho units showing in a cross section along Kallarkod – Alanthuruthu line, which forms part of Kuttanad basin.

The Tertiary beds in this section are demarcated by well defined laterite bed at the top. Three litho units are mainly observed as two granular zones embedded by a clay bed in the section. However, there may be more beds of Warkali and Vaikom formations below it. The Tertiary beds are confined by very thick clays of Recent alluvium, sealing the scope for any vertical recharge.

Vertical thickness of different litho units along Kalavoor-Thiruvarpu line

It is drawn with the litholog of bore wells at Kalavoor, Mannancherry, and Kumarakom and Thiruvappu. The cross section is cutting across the Vembanad lake and is represented by only two beds in the Recent alluvium above the laterites viz; the granular zone at the top and a thick clay below it. The sand beds at the top near the coast is about 30-35 m thick and pinches out near the western flank of

Vembanad lake. On the eastern side of the lake the thickness of sandy bed is very thin and is less than 6m.

The Tertiary beds in this section can be seen as separated by a thick clay layer of more than 40 m in the west and more than 20 m near the eastern periphery. Thus the Tertiary beds are naturally insulated from any vertical recharge from the top Recent alluvium. The pinching out and discontinuity of sand beds indicates structural disturbances as marked in the section (Fig 2.9).

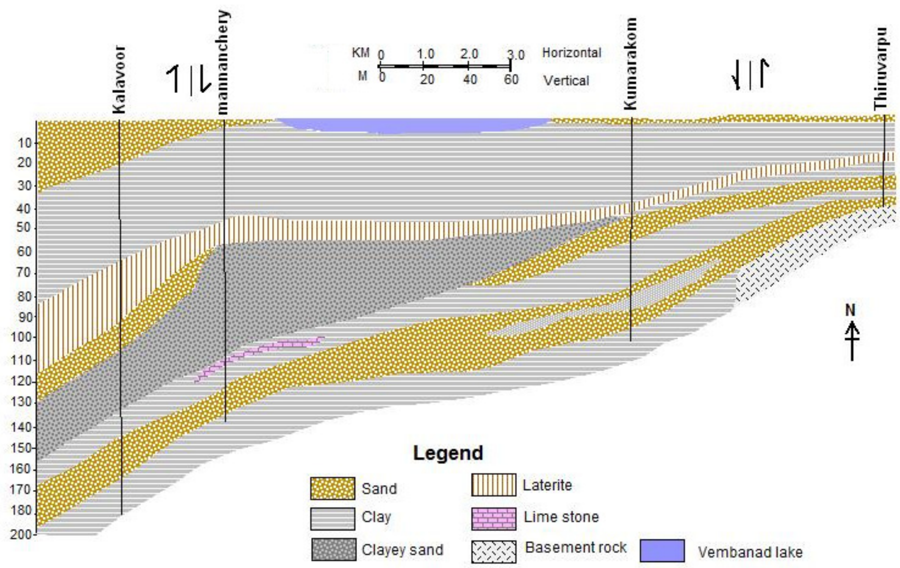


Fig 2.9 Vertical thickness of different litho units showing in a cross section along Kalavoor –Thiruvarpu line, which forms part of Kuttanad basin.

Vertical thickness of different litho units along Arthunkal- Koduthuruthu line

This section is drawn with the lithologs of bore wells at Arthunkal, Mararikulam, Cheruvaranam, Thannermukkom, Vechur, and Koduthuruthu (Fig. 2.10). The thickness of sand layer with clay intercalation is 10-25 m from the coastal tract up to Thanneermukkom and thereafter it is very thin in the eastern side. The second layer is thick clay of 20-25 m seen along the entire section. The bottom sand bed is 4 to 6 m thick and pinches out in the eastern side.

The Tertiary sediments in the section are represented by two prominent litho units of thick clay at the top and a thick sand bed below it. The demarcating laterite bed is seen on the eastern and western parts but totally missing at the central part. The entire Tertiary sediments are confined by the clay beds, sealing it from any vertical recharge.

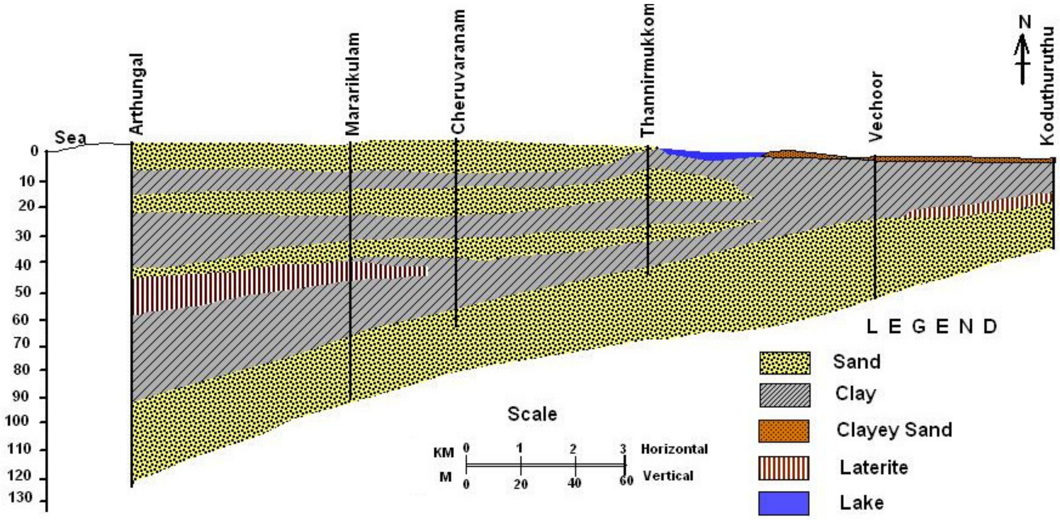


Fig 2.10 Vertical thickness of different litho units showing in a cross section along Nirkunnam – Thalavadi line, which forms part of Kuttanad basin.

Vertical thickness of different litho units along Trikkunnapuzha-Mamprapadom line

The section is drawn with he bore hole lithologs of wells at Thirukunnapuzha, Karthikapalli, Mutotm, Kanidyur, Mavelikara and Mambarapadam (Fig 2.11). Three litho units are identified in the Recent alluvium. The thickness of first sand bed is 5-6 m where as the second clay layer is 25-35 m and the bottom sand bed is 15-20 m thick. The Recent alluvium is mainly restricted to western part of the cross section only.

The Tertiary beds are represented by Warkali and Quilon and Vaikom beds. Here, the limestone bed indicates the Quilon formations and two prominent sand beds are observed viz; one below the Recent alluvium and another one below the limestone (Vaikom bed). The laterites are clayey in nature and are seen all along the section. The Warkali and Vaikom beds in the Tertiary formation are inter connected in the eastern part of the section.

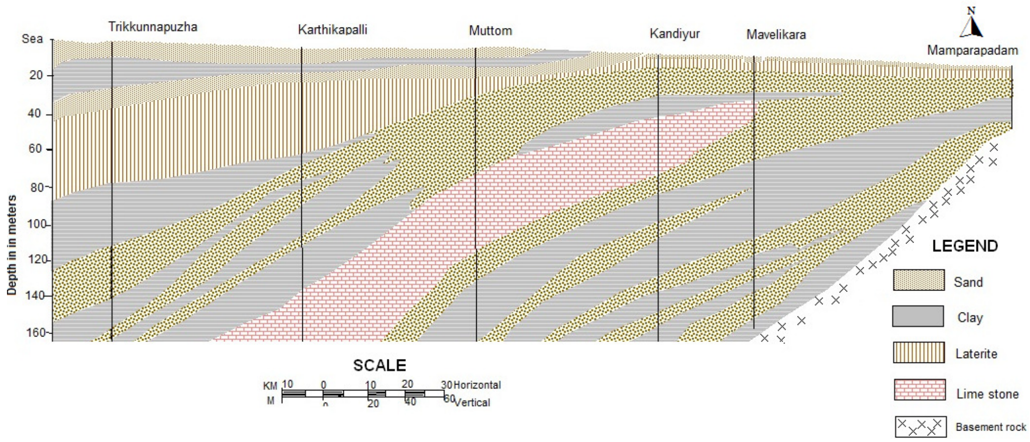


Fig 2.11 Vertical thickness of different litho units showing in a cross section along Trikkunnapuzha – Mamprapadam line, which forms part of Kuttanad basin.

The above five cross sections clearly depicts the disposition of Recent alluvium and Tertiary beds and the lithological continuity/ discontinuity of beds within the Tertiary beds and between Recent alluvium and Tertiary beds.

2.5.2 Disposition of sand and clay in Recent alluvium

It is common to put 20-50 m casing pipe for drilling deep bore holes and construction of deep tube wells. Also, the electrical log signals of S.P., P.R and 16 & 64 Normals are not recordable in the casing section. Hence, detailed information on the shallow zone is missing in such cases. Also, many times the drill cuttings collected in every 3 m from 'drilling mud discharge pipe' are washed of clay particles and only sand particles are obtained thereby giving a chance of missing the realistic sand and clay bed contacts. This is normally obtained by correlation of the electrical logs which is not possible for shallow depths. Hence, there was a generalization of depicting Recent sediments only as sand/silt which is not true in many pockets. Also, the contact of Alluvium and older formations marked at places by laterite is not identified unless the laterite is very thick, due to high speed drilling of rotary rigs of high capacity. This constraint is known to cause an unrealistic picture of the alluvium as seen in all sections prepared for regional correlation of formation. Hence, a panel diagram has been prepared for the northern part of the Kuttanad alluvium with the lithologs from shallow bore wells which are validated by correlating with the electrical logs. This gives a more realistic lateral and vertical distribution of various litho units in the alluvium (Fig. 2.12). The electrical log interpretations are discussed under separate sub- head subsequently.

The panel diagram shows both lateral and vertical variation in aquifer thickness and its distribution. The top and middle granular zones in the panel diagram represent the Recent alluvium and the bottom one represents part of the Tertiary aquifer. The laterite bed demarcating the Recent beds from Tertiary beds is almost eroded and its remnants are seen at Mundur and Koduthuruthy. The granular zones in Recent alluvium pinches out towards east but having continuity towards south and south east direction. Also, the lateral variation in granularity and bed thickness is noticeable. Another important aspect noticeable is that the bottom granular zone in the alluvium is under confined conditions by a thick confining clay layer.

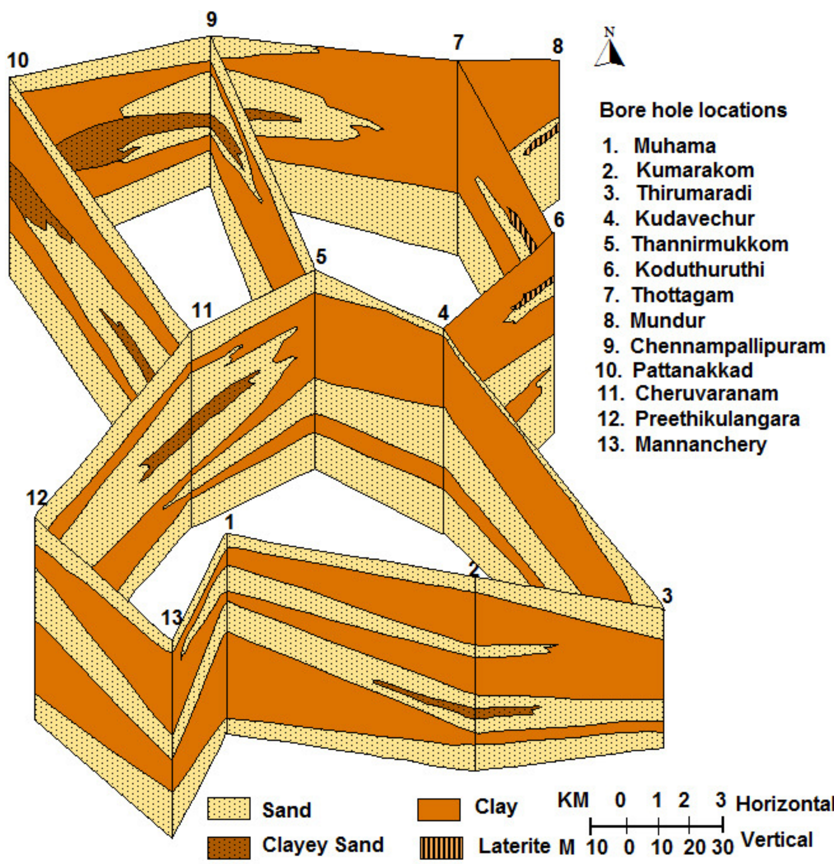


Fig. 2.12 Panel diagram showing aquifer disposition in Kuttanad alluvium

2.5.3 Stratigraphic and lithological inferences from geophysical logs in Recent alluvium

The electrical resistivity, Self Potential (SP) resistivity and this property of the formations or rocks is being utilized in groundwater explorations. The resistivity of formations/ rocks can be determined by sending the electrical current through them. Natural electromagnetic fields also exist in the earth due to diverse physical and electrochemical phenomenon taking place in the earth. The distribution and intensity of the electrical field in the earth depend on the source of excitation as well as upon the electrical properties and geological structure in the region (Patangay and Subnavis, 1984). The different electrical properties that influence electrical fields are, primarily the resistivity, the dielectric permeability and magnetic permeability (Shiffan and Zeev, 1967). While the electrical parameters in different formations vary depending upon the lithology, they are more influenced by the presence, content, and quality of water. Resistivity is defined as the resistance offered by the opposite faces of a unit cube of the material to direct current flowing perpendicular to its faces. The resistivity and resistance are related by the equation $\rho = R(A/L)$ Where, R is resistance, L is the length of the block and A is the cross sectional area of the block. The resistivity (ρ) is the reciprocal of the conductivity and is expressed in ohm-meter (Ω m).Thus the resistivity of a regular block can be determined by measuring its resistance 'R' which is given by V/I where, 'V' is the potential difference or voltage between the two ends of the medium and 'I' is the current (Kaul et al., 1990).

Electrical Logging

Various electrical parameters of the earth could be measured from a bore hole, in a similar way to the operations carried out on the surface. They may be roughly grouped as Natural field or Self Potential (SP) measurements, Electrical resistivity logging, I.P Logging and Special purpose resistivity logs such as focused logs, lateral sounding and electromagnetic techniques of logging. In the present study the Electrical logs and SP logs are subjected to study and a brief description on these logs are given below.

SP Logging

When an electrode moves along the depth of a borehole it encounters various formations along the bore hole via the medium of the borehole mud or groundwater in the borehole. The diffusion and absorption potentials due to difference in salinity and content of borehole fluids and the surrounding formation water are responsible for the development of the Self Potential (SP). Moreover, the oxidation reduction and filtration potentials in the borehole also influence the SP. Thus the SP variation curve from formation to formation along the bore hole is governed by several factors. The shape of the SP curve for formations of limited thickness will be a symmetrical peak or low. When the drilling fluid is more saline than the formation waters SP minima are observed against permeable beds (Sand, sand stone, etc.) and peaks of maxima are observed against low permeable formations such as clay. In case of higher mineralization of formation waters the SP curves will be reversed.

In the present study the SP log are run against Sand – clay sequence of rock formations and is possible to draw straight lines joining all the points of maximum and minimum deflections. The straight line with the maximum deflections is called as clay line or reference line and the other straight line is termed as the sand line. Thus, the SP curve over sand / sandstone formation will touch the sand line and over clay will touch the clay line. With the increase in clay content in sand formation, the amplitude of SP curve decreases. The quality control of SP logs is most important for quantitative interpretation of geophysical logs. In the present study the aquifer zones have been demarcated from the SP logs and the methodology is described below.

Electrical Resistivity Logging

The electrical resistivity of formations is very much affected by the presence and salinity of groundwater. By moving the electrode (sonde) in the bore hole the resistivity of formations are measured from the current variations produced as the electrode traverses different formations. The resistivity curve thus plotted is influenced by the formation resistivity as well as bore hole fluids, more so by the latter. Thus while the resistance curve provides good symmetrically disposed curves against formations, a sufficient degree of demarcation may not be exhibited some times against formations with a minor resistivity contrast (Vinayachandran et al., 2013). When interpreting the results of resistivity logs it is often necessary to know the resistivity of the borehole fluid as well as the mud cake immediately adjacent to the borehole walls. These are measured using resistivity sondes with extremely small separations called as micro sondes or micro logs. The micro logs are also useful in demarcating bed boundaries and indicating their relative permeability. Conventional resistivity logs comprise of the normal and lateral logs.

Normal logs

The shape and amplitude of the curves depend on the resistivity contrast and thickness of the target formation. If the formation is of finite thickness, that is, the spacing of the sonde is very small, the bed boundaries are determined by adding half the sonde length on either side of the inflection point and the resistive bed appears one spacing length thinner than the actual thickness of the bed. The shape of the curve is symmetrical with respect to the centre of the bed boundaries. If the target formation is conductive nature, the actual bed boundaries are located by subtracting half the spacing of the sonde on either side of the inflection point. Thus conductive beds always appear thicker by one electrode spacing than their actual thickness.

The sand and clay are represented by high and low resistivities from a normal log. The resistivity of dry sand is high when compared to saturate sand resistivity. It is also possible to identify sand beds saturated with saline water and fresh water. Similarly gradation in clayeyness in sand beds can be identified as sandy clay or clayey sand.

Lateral logs

Unlike the normal, the lateral device irrespective of bed thickness always shows a positive deflection when passing a resistive bed.

Gamma logs

The natural gamma logs are being used in the present study. The natural radio activity of rocks due to the extremely low content of radioactive material in them is measured in the natural gamma method of logging. Natural gamma logs against formations are usually symmetrical unless successive formations differ in their radioactivity. The nature of formations as well as their thickness can be estimated from gamma logs.

The shape and the amplitude of the natural gamma log curve of a formation depend on the density, thickness, and the intensity with which it is being recorded. If the logger speed is very slow, the curve recorded opposite an infinitely thick layer is symmetrical and the bed boundaries are located at points where the intensity is half of the maximum.

2.5.4 Composite lithologs

The data of bore loggings done by Central Groundwater Board (CGWB) in the exploratory boreholes in the area to decide upon the well assembly has been utilized in the present study for inferring the geoelectric characteristics of various formations, the disposition of granular zones in the alluvium. The presence of monazite with high gamma radiation has given real challenge for the demarcation of beds. The objective of the study on geophysical logs in the Kuttanad area is to understand the hydrostratigraphy of the shallow unconsolidated sediments and variations in the quality of the formation waters within these horizons. In all 21 geophysical logs from bore wells in parts of Alleppey, Kotayam and Pathanamthitta districts were analysed and the locations of these bore wells are shown in Figure 2.13. Most of the wells are penetrated through the Recent alluvium to a maximum depth of 60 m.

Preliminary analysis of the geophysical logs infers that the eastern part of the area around the sites Mundar, Kudavechur, Mulakkanthuruthy (9-11m.), Thalavadi, Podiyadi, Pandanadu (0-6m.), Elanjimale, Mamprapadam and Mavelikara, fresh water zones occur at different depths ranges. However, in the western part of the area in most of the boreholes groundwater as expected to be saline / brackish nature throughout the depth drilled except at Tagazhi (below 30m.) and at Kelamangalam (below 16m.). Below 20 m depth, most of the boreholes are showing high natural gamma radiation at the granular zones indicating the enrichment of radioactive minerals.

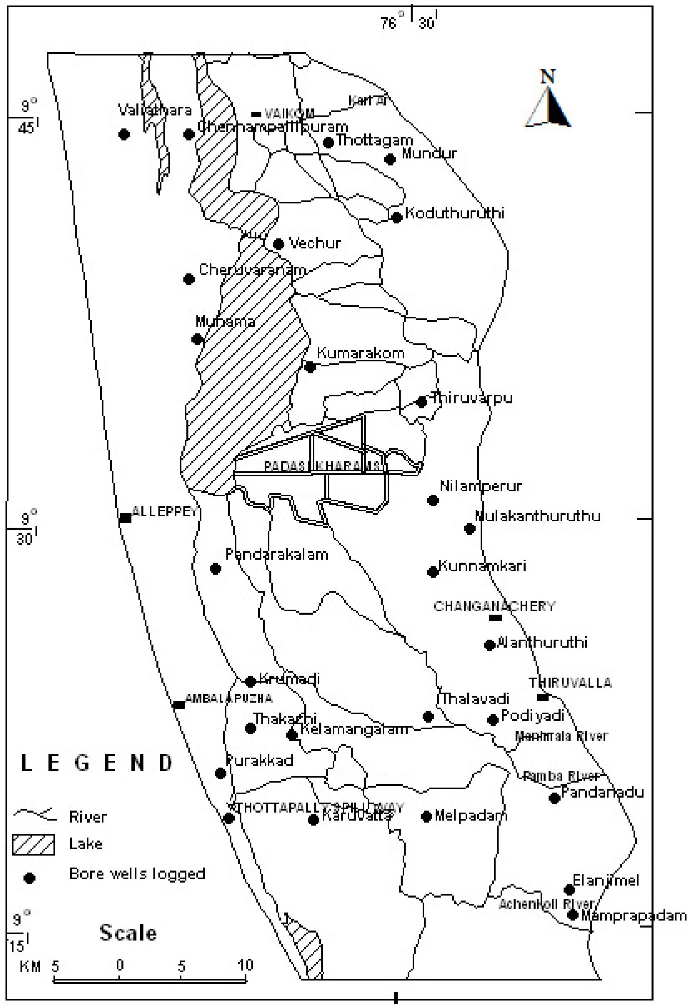


Fig.2.13 Locations of bore holes logged for Electrical and Gamma logs

The composite logs of six bore holes at Valiyathera, Cheruvaranam, Muhama, Thottapally, Karuvatta and Melpadam are given in Figure 2.14 and 2.15. The geoelectrical characteristics of the formation can be inferred from the pattern of SP, resistivity and gamma logs and in comparison with the litholog. . High resistivity, high negative SP and low radiation counts of gamma for the granular zones and vice versa for the clay layers are expected in a formation with fresh water. With quality change in water from fresh to brackish the conductivity of formation increases and is reflected accordingly in the electrical logs but no way affects the gamma log. Hence, gamma logs helps in identifying granular zones irrespective of its water quality. The composite logs in Figure 2.14 and 2.15 show gamma logs except for the bore hole at Cheruvaranam.

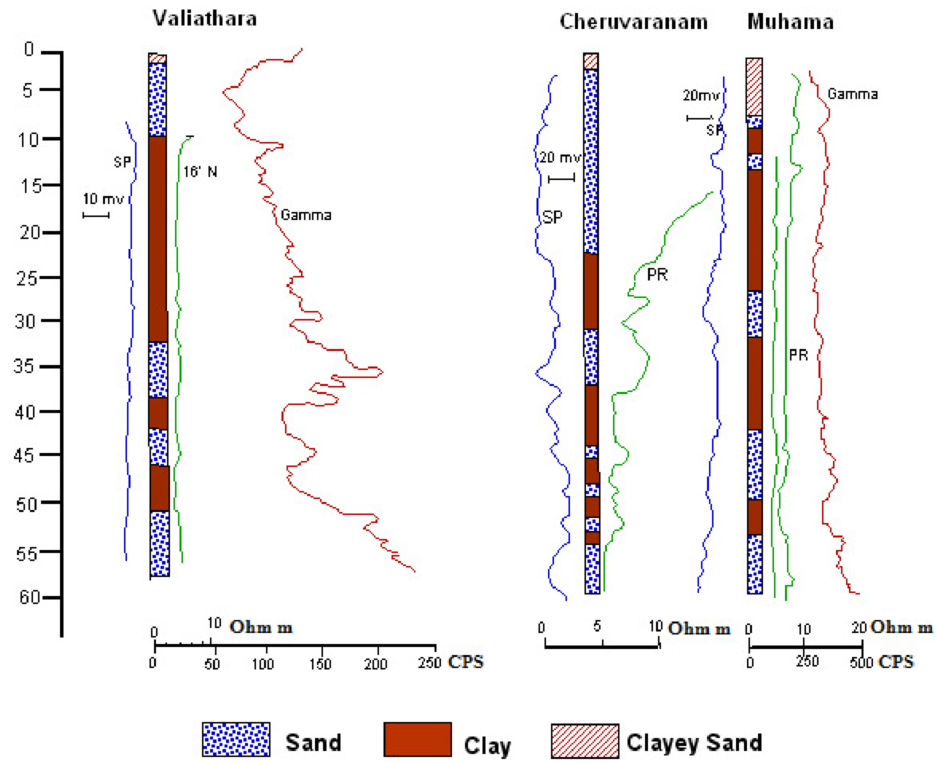


Fig.2.14 Composite logs of Lithology, SP, Resistivity and Natural Gamma

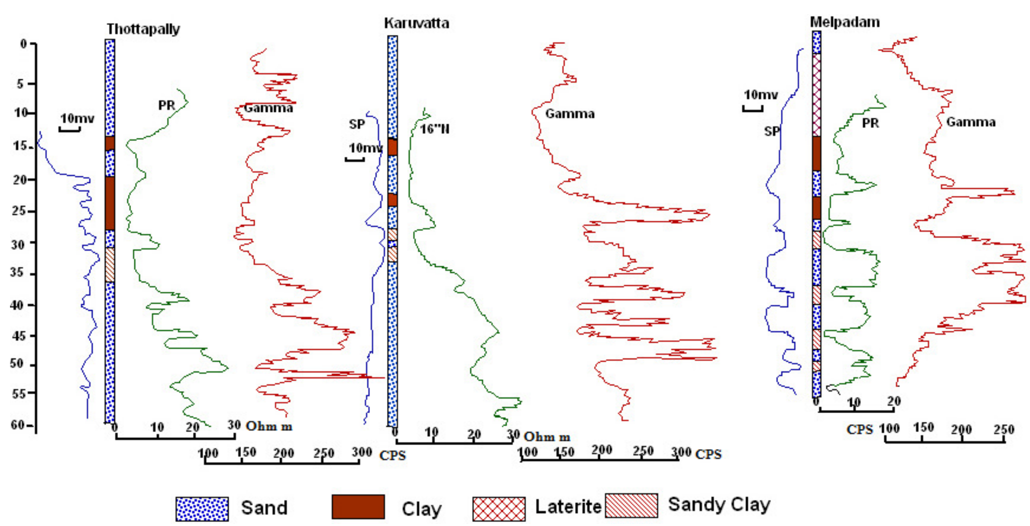


Fig.2.15. Composite logs of lithology, SP, Resistivity and Natural Gamma

From these logs it can be observed that after certain depth the radiation counts are higher for the granular zones compared to that of clay layers, which is an abnormality. The presence of monazite, a mineral of thorium, in the granular zones at certain depth is responsible for this anomaly. It indicates the enrichment of monazite during certain period in the depositional history. It is quite possible that the granular zones may be misinterpreted as clay layers unless it is properly compared and studied with other electrical logs.

The depth of occurrence of high gamma counts in granular zones varies from place to place. For example, at Valiathara and Muhama the depth of occurrence of high gamma counts in granular zones starts at 33 m and 45 m respectively. Similarly for Thottapally, Karuvatta and Melpadam it is at 37 m, 25 m and 20 m respectively. The spatial variation in depth of occurrence of high gamma counts are found out from the gamma logs of 21 wells and is given in Table 2.4. The depth contour map indicating different periods of deposition of radioactive sands is depicted in Figure 2.16. These sands might have deposited at different cycles of marine transgression and regression. The depth of granular zones with radioactive sands varies from 12-45 m and the maximum depth is observed near Vembanad lake.

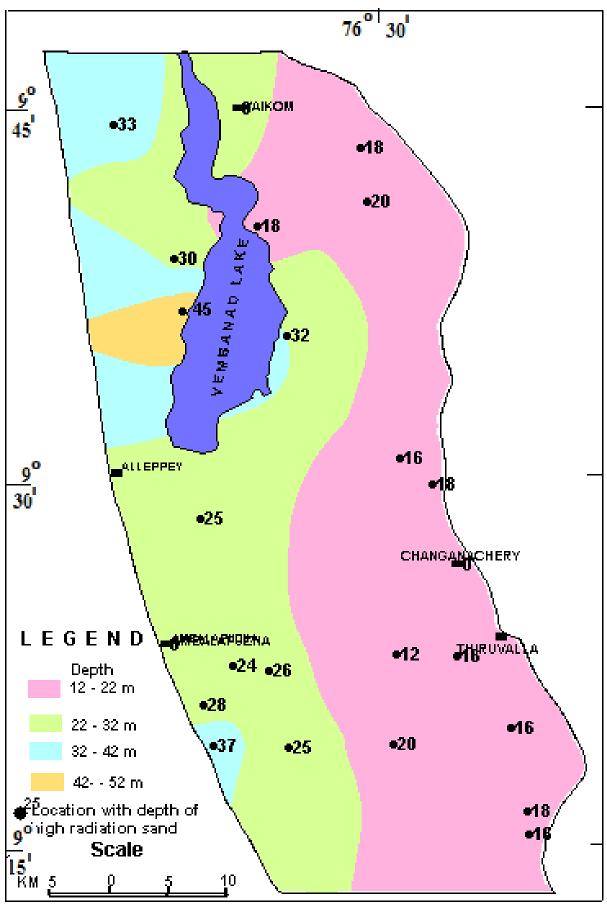


Fig. 2.16. Depth of occurrence of high gamma radiation in granular zone

The use of gamma log in deciphering the granular zones in the bore holes of Kuttanad area may lead to wrong conclusions because of this anomaly.

The lithological correlations have been inferred from Geophysical logs by drawing three cross-sections along AA', BB', and CC' as shown in Fig. 2.17 to 2.19.

Table 2.4 Depth of occurrence of granular zones with high gamma count

Sl.No	Borehole location	Longitude	Latitude	Depth of occurrence of sand beds with high gamma count
1	Valiathara	76.321	9.741	33
2	Mundur	76.488	9.726	18
3	Cheruvaranam	76.362	9.651	30
4	Kudavechur	76.418	9.673	34
5	Koduthuruthi	76.492	9.689	18
6	Muhamma	76.367	9.615	45
7	Kumarakom	76.438	9.598	35
8	Pandarakalam	76.379	9.474	28
9	Neelamperur	76.515	9.515	17
10	Mulakkanthuruthy	76.537	9.498	13
11	Thakazhi	76.402	9.375	16
12	Kelamangalam	76.426	9.371	24
13	Thalavadi	76.512	9.382	12
14	Podiyadi	76.553	9.381	16
15	Purakkad	76.382	9.348	39
16	Thottappalli	76.388	9.32	37
17	Karuvatta	76.439	9.319	25
18	Melpadam	76.51	9.321	20
19	Pandanad	76.59	9.332	16
20	Elanjimel	76.601	9.276	17
21	Mamprapadam	76.602	9.261	15

Section AA' has been prepared between Valiathara and Muhamma in NW-SE direction. It consists of three boreholes at Valiathara, Cheruvaranam and Muhamma little west of Vembanad lake (2.15). The geophysical log correlation has brought out clearly the thickness of sand bed increasing its thickness from 8 m at Valiathara to 23 m at Cheruvaranam and pinching out towards SE of Muhamma. Below this sand layer, a thick clay layer followed by intercalations of sand and clay were also inferred by SP, 16"/64" normal resistivity, PR and gamma logs. Two thin sand beds were also inferred at Cheuvaranam embedded in the thick clay layer. Quality of the formation water has been inferred as saline at all these sites in the section.

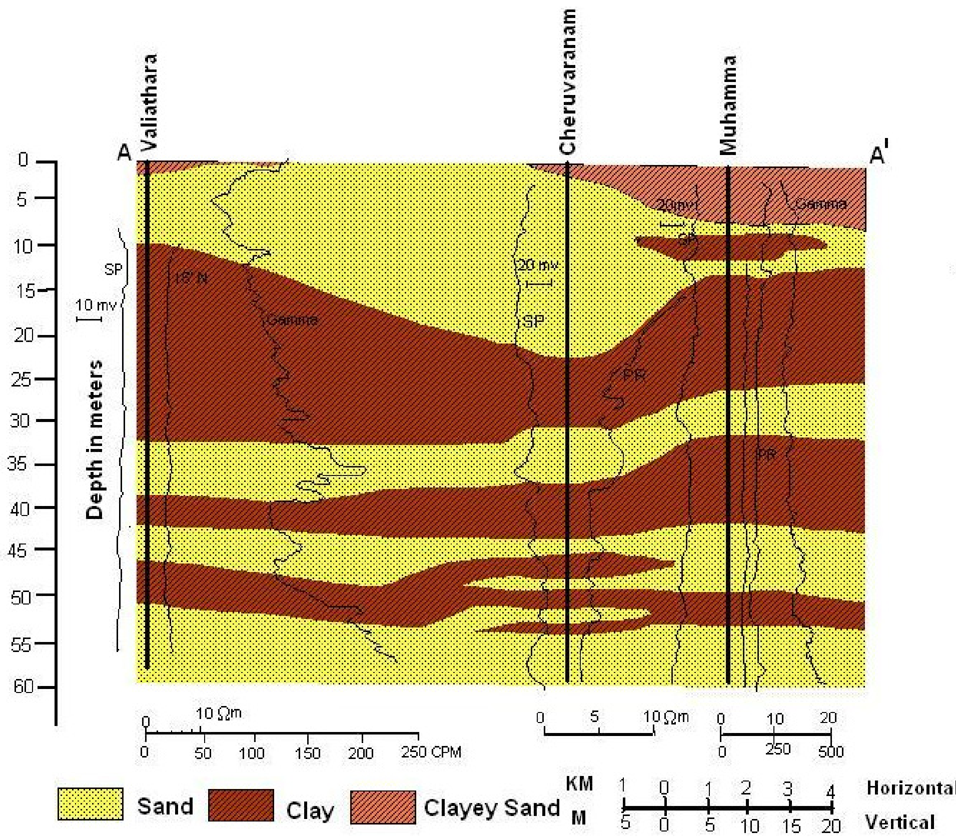


Fig. 2.17 Correlation of Geophysical logs and inferred lithology between Valiathara and Muhamma

South east of section AA', the section BB' has been constructed between Pandarakalam and Karuvatta consisting of three boreholes at Pandarakalam, Kelamangalam and Karuvatta (Fig. 2.18). A thick clay layer has been identified through these logs with thickness ranging between 22 m at Pandarakalam and 2 m at Karuvatta. This vide variation of clay layer may be an indication of transport of sediments and deposition of sands near the coast. But the thick sand lens (17m) at Karuvatta inferred the absence of radioactive minerals since the gamma count from gamma log was recorded as minimum.

Section CC' has been constructed from west to east between Thottapalli and Melpadam transverse to the section BB' consisting of three boreholes at Thottapally, Karuvata and Melpadam (Fig. 2.19). A thick sand layer has been identified at the surface throughout the section to a depth of 15m. But at Melpadam, the surface sand lens of 3 m thickness is underlain by thick laterite which is the marker bed for Warkalai formations.

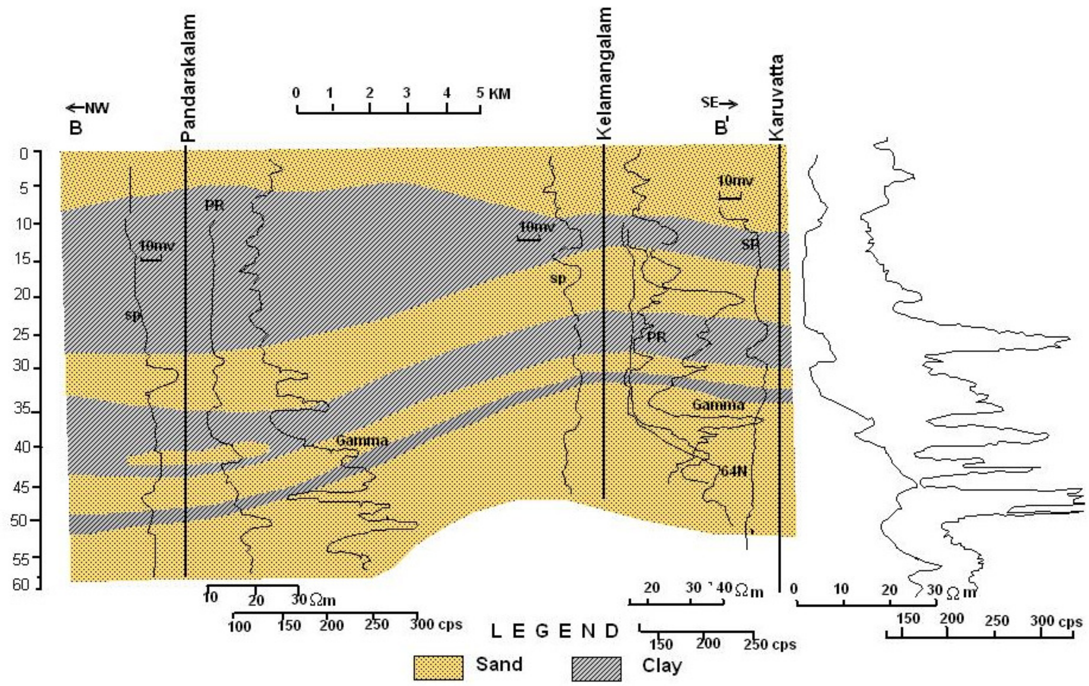


Fig. 2.18 Correlation of Geophysical logs and inferred litholog between Pandarakalam and Karuvatta

Here also the gamma count rate has been recorded minimum against surface sands, indicative of normal radioactivity. Below this thick sand layer, alternate layers of

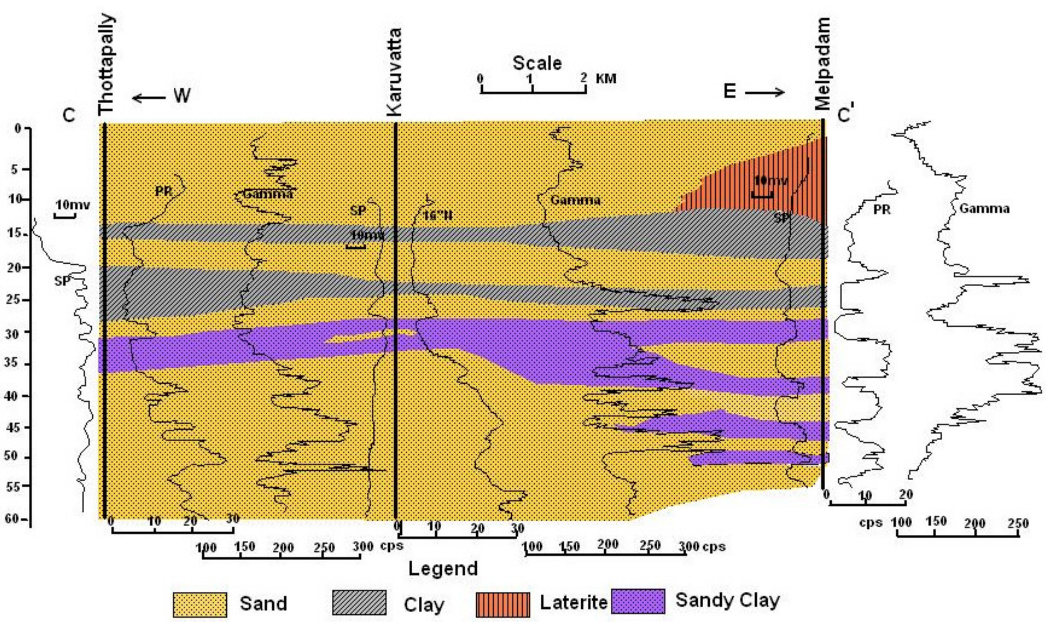


Fig. 2.19 Correlation of Geophysical logs and inferred litholog between Thottapally and Melpadam

clay and sand were identified as different stages of the deposition. Further, below 35 m between Thottapally and Karuvatta, another thick sand bed has been inferred from the geophysical logs while a different picture at Melpadam, where alternate sand and clay intercalations are inferred.

The inferred lithologs gives minute aspects of lithological variations laterally and vertically and throws light on its depositional environment. The thick clay layers demarcated through lithological cross section in fact is intervened by thin granular zones and the high EC values estimated from the electrical logs indicate that they lack regional continuity and contain connate water.

2.6 Geomorphology

Geomorphologically, major part of the area falls under depositional surfaces under marine, fluvio-marine and fluvial environment and is broadly classified as coastal plains. The general elevation of the area is less than 6 m above mean sea level (amsl) with some of the areas below mean sea level (bmsl) in the range of 1-2 m constituting a separate entity as Kuttanad. It is also characterised by typical coastal geomorphic features such as beaches, shore platforms, spits and bars; beach ridges, estuaries, mud flats and tidal flats. The beach ridges are suggestive of marine regression. Unlike other rivers of Kerala, Pamba river has a well developed delta and beach is very narrow and straight. The absence of extensive tidal plain and the intensive coastal erosion may be indicative of neo-tectonic activity. The beach between Purakkad and Trikkunnappuzha is undergoing active erosion.

Land forms

The geomorphic landforms identified in the study area, a part of the coastal lowland, are Beaches, shore platforms, spits and bars, beach ridges, estuaries and lagoons mud flats and tidal flats. The ‘kayals’ are the estuaries, which are submerged river mouths, and a few of them are presently located below sea level. These ‘kayals’ are prone to receive sediments from land. Vembanad lake is the prominent ‘kayal’ in the study area which seems to be the left out part of a much larger lagoon. There has been considerable reclamation of land for cultivation in the past.

The reclaimed area and 'padasekharams' are clearly demarcated in the Imagery. The sub-scenes in part of Cochin coast north of Kuttanad where the Vembanad lake water reaches the sea a turbidity plume is noticed along the coastal tract which extends more than 6 km.

This may be due to the discharge of fresh water with turbidity. The hydrological observations described earlier also presents a similar inference. Being March month, flood discharge is not likely. The shape is not indicative of depth changes. The Imagery of Kuttanad lake shows the Pathiramanal Island with thick vegetation. The Figure 2.20 is part of geocoded image clearly deciphering the strand lines along the coast. The linear red-white-blue colour shades are the beach ridges with or without vegetation and low-lying swale (clay cover) areas.

The southern part of Kuttanad (Fig. 2.21) is showing the reclaimed area and canal alignments with paddy fields. The colour variation is indicative of different ground stages of paddy crop. There are at least 4 distinct strand lines in the coast. The absence of Delta in any river mouth is surprising with a high rainfall rate and heavy sediment transport by rivers flowing in the steep gradients of the hinterland. The slow uplift of the coast and the rate of removal of sediments at the river mouth by waves and currents at a rate exceeding the rate of deposition might have blocked the growth of the delta (Narayana et al., 2001).

It is believed that Vembanad lagoon was a graben. The morphology of the lagoon suggests that en-echelon faulting might have played a role in its evolution. The lagoon at many places cuts across the strandlines suggesting that it might have formed subsequent to the strandline deposits (Narayana et al., 2001). In the recent past, the Vembanad lagoon is undergoing accelerated sedimentation and filling up with the recent sediments. Extensive tidal mudflats are seen on the eastern side of the lagoon and most of the landform is used for aquaculture farming. As the northern part of the lagoon is shallower; the coastal alluvium to the east of this part of the lagoon is inundated during high tide period. The flood plain area further east of these tidal flats is a conspicuous feature as the rivers are unable to discharge

Fig. 2.20. Geocoded image showing strand lines along the coast

Fig. 2.21 Geocoded image showing reclaimed area

directly in to the sea because of the deflection of river courses before debouching in to the lagoon. Nair et al (2009) has reported the occurrence of wooden tree trunks, peat material and skulls of water animals from many locations inland at a depth of one to two meters and presumed that the areas southwest of Alleppey and west of Kottayam with Pamba and Manimala river alluvium are parts of once constituted major delta. Changanacheri area has number of navigation canals with low lying cultivable land. The rain water submerges the low land and those areas are cultivated in the post monsoon period by pumping out the rain water to canals. The geomorphological map of the area modified from the one used by State Ground Water Department is shown in Figure 2.22.

2.7 Sea level rise along Kerala coast and its relation to Kuttanad area

The history of sea level changes in the Pleistocene is partly the geological history of the region. The formation of glaciers in the northern continents by the early Pleistocene had subtracted stupendous quantities of water from the world oceans forcing the sea level to reach a level of about 130 m below the modern sea level. The sea level rise was not gradual; instead it was episodic as the land rebounds due to off loading of ice (Bruckner,1989; Thrivikramji et al, 2003). Curray (1961) published a sea level change curve based on ^{14}C dates of sediment particles depicting the procession of sea level during the last 40.000 yrs Before Present (BP). Two events of sea level rise or transgressions are indicated here. Vaidyanathan (1987) suggested filling up of a series of bays during the Holocene period with mud, which later on got covered by sand sheets moulded into sub-aerial dunes. Contributions of Nair and Hashimi (1980) based on the investigations in western continental shelf (including Kerala offshore), recognized 4 still stands demonstrated by submarine terraces at 92, 85, 75 and 55 m below the modern sea level and ranging in age from 9000-11000 years BP. Nair (2003) suggested that the rocks are of Holocene age and sea level was rising (transgressive phase). Kale and Rajaguru (1985) constructed a sea level rise curve and postulated a rate of 1.8 cm per year and the sea level reached the present day position 6000yrs BP. The lowest stand at 138 m below mean sea level occurred about 12000 years BP.

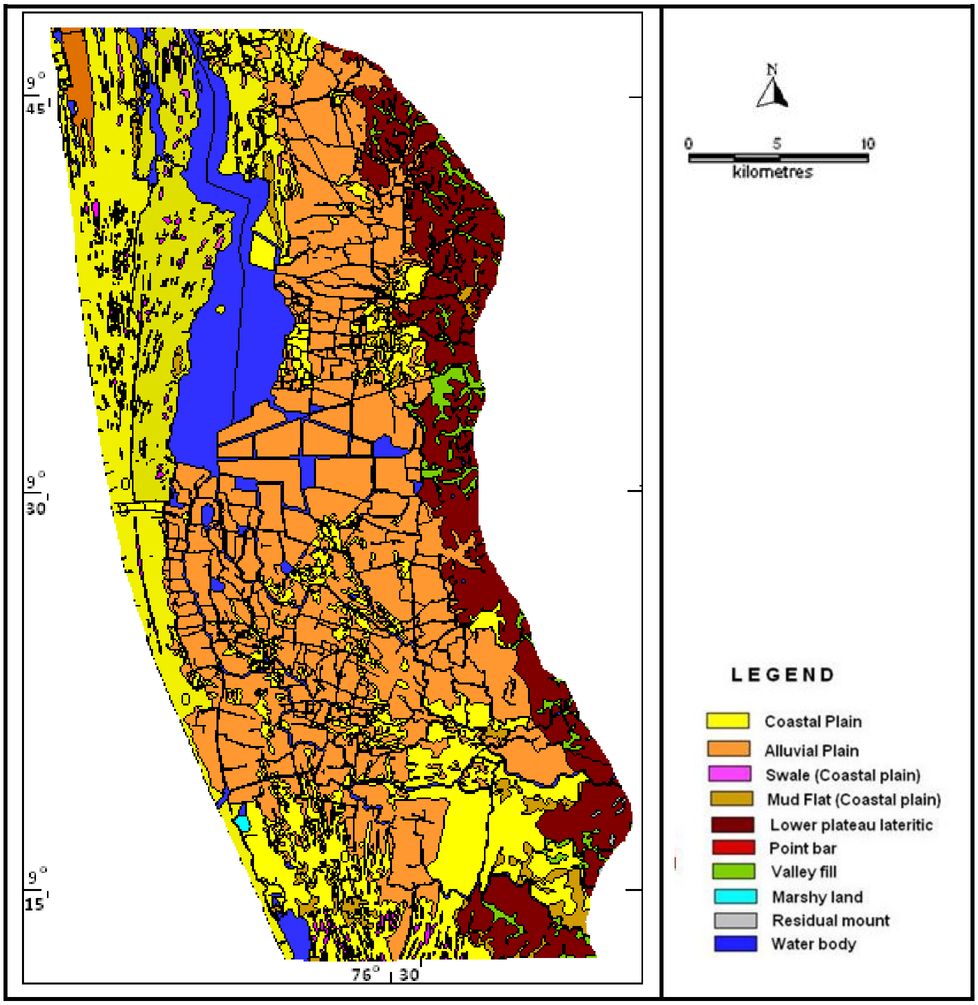


Fig. 2.22 Geomorphology of the study area (Modified after the map of Land Use Board., Kerala)

The implication of sea level changes in the present study is that the sediment deposits along the Kerala coast deposited during these marine transgressions and regressions influenced the evolutionary history of groundwater in the aquifer systems developed in this sedimentary formation.

CHAPTER 3
MATERIALS AND METHODS OF STUDY

3.1 Introduction

Samples collection and data acquisition form the most important activity of the research work as all subsequent analysis and interpretations are being made based on the samples collected and data obtained. Obtaining of data (ie, secondary data) and field sampling forms the two major components of the research work. The methodology and materials used in various aspects of the study such as the hydrometeorology, aquifer geometry and land forms, groundwater flow regime, hydrochemistry and isotope characteristics of groundwater are detailed below.

3.2 Hydrometeorology

The climatic data from the Full Climatic Station (FCS) maintained by State Groundwater Department, Kerala at Alleppey has been used in the present study. The data on temperature, relative humidity and potential Evapo-Transpiration (PET) have been computed and the monthly Potential Evapo-Transpiration was calculated using Thornwaite's (1948) method.

There are 7 rain gauge stations located within the study area, which are maintained by the Central and State Government departments. They are located at Alleppey, Kayamkulam, Mavelikara, Cherthalai, Ambalapuzha, Chengannur, and Haripad (Fig 1.1). The average annual rainfall, seasonal variations and the statistical analysis of the rain fall has been carried out based on 20 years data from 1991-2010.

3.3 Delineation of litho units and aquifer geometry

The information on geology and geomorphology were collected from the reports and maps of Geological survey of India and Land Use board, Kerala. The lithological and electrical log data from the exploratory wells of Central Ground Water Board were collected and used for demarcation of various granular zones for defining the aquifer geometry. The stratigraphic succession and vertical distribution of its lithology were defined based on the lithological data from 35 bore wells. Five cross sections across the study area and one panel diagram were prepared based on the lithology from bore wells to elucidate the lateral and vertical variations in the geology of the area. Lithological logs from fifteen bore wells have been used for the preparation of panel diagram mainly depicting the stratigraphic succession of Tertiary beds.

The lateral and vertical distribution of sand and clay layers in the Recent alluvium has been deciphered from diagrams prepared from 16 shallow bore wells drilled in the area. The data on electrical logs such as, S.P, Point Resistivity, Long Normal and Short Normal and Natural Gamma logs from bore wells were analyzed and interpreted to define the aquifer geometry. The composite lithologs were prepared based on lithology and geophysical logging data from 21 bore wells and the geological cross sections and panel diagrams are being used to define the aquifer geometry in the Recent alluvium (Figs. 2.7 to 2.12 and Figs. 2.14 to 2.19).

In the present study, Indian Remote Sensing Satellite (IRS) 1D, LISS-III imagery acquired in 2002 has been used to identify neo-tectonic features, paleo-channels and strand lines and other features through visual interpretation.

3.4 Groundwater flow regime

Groundwater level data

The water levels from dug wells and piezometric heads from piezometers (tube wells) have been analysed for studying the hydrogeological scenario of the aquifer systems in the area. 82 observation wells (dug wells and tube wells) have been used for water level collection for pre and post monsoon periods during the course of study. This includes the piezometric heads of confined aquifer systems in Recent alluvium and Tertiary beds.

The long term trend in water levels and piezometric heads are derived from the long term data collected over a period of time. The water level trend for the last one decade in the phreatic aquifers and for the last three decades in the tertiary aquifers has been analysed.

Various spatial maps such as the water table elevation contours, depth to water table, water level fluctuation, and water level trends were prepared under GIS platform to elucidate the flow regime existing in the groundwater regime. The spatial maps have been prepared using MapInfo/ Vertical Mapper softwares and represented in figures 4.1 to 4.6.

Evaluation of aquifer parameters

Pump tests were conducted for the evaluation of aquifer parameters such as transmissivity (T) and storage coefficient or storativity (S). Two sets of data viz; time versus drawdown and time versus recovery are normally generated during a pumping test. The water levels recorded during recovery are known as residual draw down. The Theis type curve matching method and the Cooper-Jacob semi-log method (Cooper and Jacob, 1946) are commonly used for estimation of transmissivity and storativity of infinite, homogenous, isotropic, confined aquifers from draw down data of a constant rate pumping test. In the present study all the pumping tests were conducted under transient conditions.

Pump tests were conducted at 6 locations to evaluate the aquifer characteristics (Transmissivity and Storativity) of the Recent confined aquifer systems. The aquifer characteristics of deep confined aquifers in the Tertiary beds were collected from the unpublished reports of Central Ground Water Board.

The aquifer parameters of the aquifer systems in the alluvium were evaluated by conducting pumping tests. The storativity and transmissivity for short duration pumping tests were evaluated from drawdown data and were compared with those obtained from the recovery data. The pump test data has been analysed using Theis, Jacob-Theis methods and Samani methods (2003).

3.5 Hydrochemical studies

Water samples were collected during pre-monsoon and post-monsoon periods of the year 2009 from selected wells and tube wells taping different aquifer systems of the study area and chemical analysis for major ions, physical parametes and minor elements in water samples were analysed. The chemical laboratory facilities of

Central Ground Water Board, Kerala Region and the Chemical Division of Centre for Earth Sciences Studies were used. 252 Water samples were collected from 147 locations representing phreatic and confined aquifers and surface water bodies. During the pre-monsoon period (May 2009) 147 samples and during the post monsoon period (Nov. 2009) 105 water samples were collected and analysed for the above said parameters. The water samples during premonsoon were collected in May immediately after water level monitoring in April. Thus, the premonsoon periods described in hydrogeology and related Chapters are April whereas, in Hydrochemistry and related it is May. The samples were collected in one liter bottles and the sampling bottles were thoroughly washed, rinsed with distilled water before collection of samples and were sealed and labelled properly after the sample collection following the procedures as suggested by American Public Health Association (APHA), (1998). In situ measurements of Electrical Conductivity (EC) and pH were measured using portable conductivity meter and pH meter.

Detailed water samplings from shallow and deep aquifer systems were made and analysed for physical parameters pH and EC, major ions such as Ca, Mg, Na, K, NO_3,CO_3, HCO_3,SO_4,Cl, and minor ions F and Fe. The samples were analysed as per standard protocols (APHA, 1998). Total dissolved solids (TDS) were computed by multiplying the EC by a conversion factor varying from 0.55 to 0.75, depending on the relative concentrations of ions (Hem, 1991). The Total Hardness (TH) as $CaCO_3$ and calcium (Ca^{2+}) were analysed titrimetrically, using standard EDTA. Magnesium (Mg^{2+}) was calculated from the TH and Ca^{2+}. Sodium (Na^+) and Potassium (K^+) were estimated using flame photometer. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) were analysed by standard HCl titration. Chloride (Cl^-) was estimated by standard Silver nitrate ($AgNO_3$) titration. Sulphate (SO_4) and nitrate (NO_3) were analysed using spectrophotometer.

The concentration of dissolved ions are expressed in milligrams per liter (mg/l) and have been checked for ionic balance after converting the ion concentrations into equivalents per million (meq/l). The observed ion balance error computed on each set of complete analysis of water samples is within the range of acceptability ($\pm$ 5%). The Electrical Conductivity values are given in μ mhos/cm at 25^0C.

Historical data on groundwater regime were collected from various State and Central agencies like IMD, Kerala Water Authority, State Groundwater Department, State Irrigation department etc and were used for long term studies and trend analysis.

3.6 Radon activity in groundwater

The spatial distribution of alpha radiation from Radon-222 in groundwater in the area could be established using RAD-7 detector and could be compared with the background radiations from the aquifer materials (gamma radiations) obtained from bore-hole gamma logs. The study mainly involves collection of groundwater samples from select abstraction structures (tube wells) and measurement of radon in them in the field itself within 2 to 3 hrs of sampling. The RAD 7 instrument available with Central Ground Water Board, South Western Region, Bangalore has been used in the present study. The radon present at the time of sampling was calculated as a decay-corrected mean. Specific activity is directly related to the concentration of a particular radionuclide and for simplicity it is referred to as concentration.

The water sampling for radon measurement has been made from tube wells tapping aquifer zones at different depths. Samples were collected carefully without disturbance and after purging for sufficient time in 250 ml bottles without any air bubble. A total of 24 water samples were collected form tube wells tapping sedimentary formations and the samples were analysed using RAD7 instrument.

The concentration of radon gas is not measured directly but rather by the radioactivity it produces. In metric system it is expressed in Becquerel per cubic meter (Bq/m^3). One Becquerel is equivalent to single radioactive disintegration per second. It is also expressed in Pico Curies per litre of air (pCi/L). Curie is a unit of radioactivity equivalent to 1 gram of radium and the prefix ‘pico’ means trillionth. 4pCi/L equals to 148 Bq/m^3. Radon concentration in water is generally expressed in Becquerels per liter (Bq/l).

3.7 Isotope studies

The environment isotopes of oxygen $\delta^{18}O$ and hydrogen $\delta^{2}H$ are excellent tracers for determining the origin of groundwater and widely used in studying the natural water circulation and groundwater movement (Heaton et al., 2012., Wassenaar et al., 2011., Ogrinc et al., 2008., Longinelli et al., 2008., O'Driscoll et al., 2005., Vandenschrick et al., 2002).

Stable isotopes, ^{18}O and ^{2}H occur naturally and form a constituent part of the water molecule. They are considered as isotopically conservative and their concentrations are not affected by the geological settings (Clark and Fritz, 1997). Hence, once reaching the water table, the isotopic signatures of groundwater does not vary until it mixes with isotopically different waters. This signature reflects the history and origin of groundwaters prior to infiltration, and thus it can be used to interpret the mechanism by which recharge occurs. In the present study the isotope data from 47 locations have been analysed and the data is given in Table 6.3. Out of the 47 samples 32 samples are the data collected from Central Ground Water Board and the remaining 15 samples were analysed as part of the present work. The stable isotopes are conservative and do not change with time in deep confined aquifers which are cut off from direct rainfall recharge and the changes in ^{14}C will be negligible in a short span of time. Hence, both the data have been anlysed together and interpreted.

The main objective of isotope study was to evaluate the recharge mechanism in the area, surface and groundwater interaction and sea water ingress along the coast and mixing of groundwater in deeper aquifers. The environmental isotopes, deuterium, Oxygen-18, Tritium and Carbon-14 in groundwater have been subjected to study. The stable isotope (Deuterium and Oxygen-18) were used to study the recharge mechanism and interrelationship between aquifers, surface and groundwater in the area. Whereas, the radioactive Isotopes (Tritium (^{3}H) and Carbon-14 (^{14}C) are used for dating of groundwater.

Water samples were collected during May 2007 from tube wells tapping different aquifers, and surface waters of Pallathuruthy River and Vembanad Lake for environmental isotope analyses. Rain water samples were collected from two stations namely Alleppey and Kottayam. Field parameters like temperature, pH, dissolved oxygen, redox potential and electric conductivity were measured in-situ.

Analysis of stable isotopes like ^{2}H and ^{18}O were carried out by means of Isotope Ratio Mass Spectrometer (IRMS) and are expressed in the delta (δ) notation as follows (Craig, 1961):

$$\delta_{sample}\ (^{0}/_{00}) = [\ (R_{sample} - R_{std})/R_{std}]\ x\ 1000 \ldots\ldots\ldots\ldots \quad (1)$$

where, $\boldsymbol{R_{sample}}$ and $\boldsymbol{R_{std}}$ are the isotope ratios ($^{2}H/^{1}H$ or $^{18}O/^{16}O$) of the sample and the standard respectively.

$\delta^{18}O$ was measured in the form of CO_2 after equilibration with water while δD was measured after reduction of water to H_2 gas using Zinc at 450°C.

The tritium content was determined using electrolytic enrichment and measured by liquid scintillation counting method. It is expressed in terms of Tritium Units (TU). For ^{14}C analysis, carbonate precipitate was extracted from water samples in the field and measured by CO_2 absorption technique using a liquid scintillation counter. I4C values are expressed as percentage Modern Carbon (pMC).

Tritium, Deuterium and Carbon-14 Isotopes in groundwater at selected locations were estimated and could identify the recharge conditions in the multi aquifer system based on aging of groundwater and stable isotope ratio studies.

3.8 Statistical analysis

Statistical tools viz; cluster and factor analysis are employed to study the inter-relationships among various ions and for grouping the samples of similar hydrochemical characteristics based on its degree of similarity. Statistical analyses of the data have been carried out using SPSS software.

Optimal results in multivariate statistical modeling require normal distribution and homoscedasticity. The variances of the parameters need to be compatible so that the interpretation of the final results makes logical sense. Where there are vast differences in the variances of the data of the parameters, the results will be influenced more by the parameters with the highest variances in the distribution of their dataset (Davis, 2002). In this respect, the data for each of the parameters were tested for normal distribution using normal probability plots from SPSS 17.0. Apart from pH whose values were close to normal distribution, all the other parameters strongly deviated from the requirement of normal distribution. There are various methods of transforming data to take the semblance of normal distribution and thus fit the requirements of optimal multivariate analyses. These include differencing, log-transformation, amongst others.

In this study, the parameters were log-transformed to approach normal distribution, and the log transformed data were standardized to their corresponding z-scores using the equation given below.

$$Z = \frac{X - \overline{X}}{SD}$$

where X-$\overline{X}$ and SD are respectively the raw data, the mean, and standard deviation of the data for each parameter. Where the data is highly variable in space, the variance of the data of a parameter can be significantly large. Standardization reduces the variances so that the parameters look similar in the distribution of their data. Data standardization does not affect its distribution. However, it affects the scales and shifts the data in such a way that the variances are brought closer so that the data for all the parameters are assigned equal weight in the ensuing analyses.

Factor analysis makes sense only when the distributions of the data of all the parameters look similar so that no single parameter gains significant advantage over all others due to its high variance. Where the variances are significantly different, the result of factor analysis may be biased and does not reflect a fair contribution of all the parameters in the resulting model which may leads to faulty and unreliable interpretations (Yidana et al., 2012).

The standard z-scores were then subjected to R-mode factor analysis with ‘principal components’ as the extraction method and Kaiser (1960) normalization. In order to achieve maxima in the differentiation of the factors resulting from the factor analysis the factor matrix was varimax rotated (Guler et al., 2002; Cloutier et al., 2008; Ayenew et al., 2009). Varimax rotation is the process of applying an orthogonal matrix to the factor matrix. This will enhance the differences among the resulting factors so that the interpretation of the results will be easy. The factor analysis was carried out repeatedly, each time taking into consideration the contribution of the individual parameters as well as the contribution of each of the factors to the final model. The communality table is one of the results of factor analysis from that the degree to which each parameter contributed to the factor model could be examined. A cut-off was placed at a communality of 0.50, below which a parameter would be regarded as insignificant or inconsequential in the analysis. Such a variable (parameter) has to be dropped so that it does not cloud the results of the analysis. The communality of a variable in factor analysis is the sum of the squares of its loadings on all the factors in the final factor model. In the complete factor model, the communality of each variable is expected to be equal to 1 but not so quite often as the final factor model is not the same as the complete factor model. This is because of the fact that some of the factors in the complete model are redundant and do not usually represent unique processes controlling the distribution of the data of the parameter. In such a case, it is possible that the communalities of some parameters in the selected final factor model may not be equal to 1. Although no single parameter has a communality of exactly 1 in a final factor model of less factors than the complete factor model, it is expected that each parameter in the model contributes significantly to the factor model. In reality, it is possible to produce as many factors as there are variables in the model. A factor model produced in this way would not be of much use as a data dimension reduction methodology. Kaiser (1960) developed a methodology for cutting the number of factors in the final model to size based on merit. The Kaiser criterion requires that a worthy factor in the final model has an eigenvalue of at least 1. The significance of this is that a unique factor should be able to account for the variance not unduly distorted by such parameters. The communality of a parameter thus represents its significance in the factor model.

In this study, the Kaiser (1960) criterion was used to select the factors to be included in the final factor model. Factor analysis was carried out using SPSS 17.0. When the final factor model was determined, factor scores were calculated for each of the factors in the resulting factor model. The factor scores were computed by the method of regression. In addition to the factor scores, key parameters were selected from the factor model to represent each of the factors. The selection of these key parameters was based on their loadings under each factor in the final factor model.

The hydrochemical data have been used to categorize the waters in to different objective water classes on the basis of Q-mode statistical cluster analysis. Statistical classification of geochemical data by Q-mode hierarchical cluster analysis (HCA) has been proven to provide a suitable basis for objective classification of water composition into hydrochemical facies (Meng and Maynard, 2001; Güler et al., 2002, Guler and Thyne, 2003; Kebede et al., 2005; Yidana et al., 2012).

Q-mode HCA was applied to the z-scores of the parameters in order to determine the spatial relationships amongst the various samples or sampled locations. Squared Euclidean distances were used to measure the degree of similarity/dissimilarity amongst the parameters whilst the Ward's agglomeration technique was used to link the initial clusters. Unique clusters were sorted out of the dendrogram, which is the graphical result of the HCA. Statistical summaries of the measures of the parameters under each cluster were computed to assist in the description of the general groundwater flow regime and the general hydrochemical trends in the study area. Factor scores of the members of these clusters were used to plot scatter diagrams against the concentrations of the key parameters identified in the final factor model in order to identify any useful trends in the distribution of the data.

3.9 Hydrochemical facies and spatial analysis

Spatial distribution of various ions has been prepared as iso-concentration maps suing the GIS software Mapinfo 6.5. Rockworks Software has been used for some of the water quality analyses like ion balance and preparation of Trilinear and stiff diagrams. The facies changes and chemical quality of formation waters in time and space were identified and could get a realistic hydrochemical scenario in the aquifer systems.

CHAPTER 4
HYDROGEOLOGY

4.1 Introduction

Kuttanad is the only area in Kerala where water supply is met from groundwater source on a large scale. Requirements for drinking water in this area are mainly met from a large number of tube wells. The major abstraction of groundwater is from Tertiary sedimentary formation and the quality of water in phreatic aquifers is not potable in general. The aquifer systems in Recent alluvium and Tertiary deposits are treated as two separate entities as discussed in chapter 2. A detailed study on the hydrogeology of the deep Tertiary aquifer system is essential to decipher the disposition of these aquifer systems and to identify their inter relation (Kunhambu, 2001). The vertical and horizontal variations of different geological formations and the sub-surface disposition of granular zones described under Chapter 2 have been used to demarcate various aquifer systems in the area.

In the present study two aquifer systems are identified in the Recent alluvium viz; phreatic and confined. The confined aquifer in the Recent alluvium is frequently termed as Recent-confined' or simply as 'Recent aquifer' in this thesis. Similarly, there are two aquifer systems in the Tertiary beds viz; Warkali and Vaikom and they are treated as a single unit in the present study as 'Tertiary aquifers'. The reason for treating these two aquifers as a single unit in the present study is that they are interconnected and lack of sufficient data to describe them separately. In some parts of the thesis mention about Warkali and Vaikom aquifers have been made only to highlight the evidences in the study showing their inter connectivity and similarities.

The five lithological cross sections described in Chapter 2, comprise Recent alluvium and part of Tertiary beds. These cross sections reveal the distribution of granular zones in the Recent alluvium and absence of inter connectivity between Recent and Tertiary aquifer systems. The laterite beds are taken as the demarcation zone for Tertiary beds. From all the five cross sections it can be observed that the Tertiary aquifers are totally cut off from the Recent aquifers by thick clay beds. Further it is recorded that the laterite beds are clayey in nature. The panel diagram shows two major granular zones which act as aquifer in the alluvium.

The study of geophysical logs interpretations shows the presence of intervening granular zones between the clay beds and clay lenses in the aquifer system at places. However, on a regional scale only two aquifer systems are mainly represent the Recent alluvium. The top phreatic aquifer comprising coastal sands and flood plain deposits in interior Kuttanad area form the major phreatic aquifer system. The second granular zone in the alluvium is under semi-confined to confinined conditions as demarcated from the cross sections (Fig 2.7 to 2.12). The hydrogeology of aquifer systems in the area are discussed in the following sections.

4.2. Hydrogeology of alluvial formations

The Recent unconsolidated deposits of Recent age (see section 2.4.2) comprises two aquifer systems. The top phreatic aquifer comprising coastal sands and flood plain deposits in interior Kuttanad area forms the major phreatic aquifer system. The alluvial deposits in interior kuttanad comprise carbonaceous matter. A number of shallow dug wells taps this aquifer for domestic use and in a limited extent for irrigation and industrial purpose. Monitoring of groundwater regime were made from 56 dug wells taping this aquifer system. The locations of these wells and pre-monsoon and post-monsoon water levels are given in Table 4.1. The depth of wells ranges from 2.75 to 10.60 mbgl with shallow water conditions in coastal and high land areas.

In low lying areas and below mean sea level areas the depth of wells are limited up to 4 or 5 m bgl with water levels almost in ground levels and without much seasonal variations. It is observed that there are dug wells of small diameter (<1.2 m) with varying depth of 6-8 m. The wells in the coastal alluvium sustain draft in the range of 1000 liters/day to 3000 liters/day and that in interior kuttanad sustain draft in the range of 200-1000 liters/day. In below mean sea level areas fresh water is floating over the brackish zone and the quality deteriorates upon draft above the optimum.

Table 4.1 Locations of observation wells and water levels in phreatic aquifer during pre-monsoon and post-monsoon seasons.

Sl. No	Location	Latitude	Longitude	RL value m amsl	Water level (April-09) (mbgl)	Water table (April09) m amsl	Water level (Nov-09) (mbgl)	Water table (Nov-09) m amsl	Water level fluctuation (m)
1	Achinagam	9.6542	76.4347	2.11	1.7	0.41	1.58	0.53	0.12
2	Alleppey	9.4920	76.3220	2.526	2.16	0.37	1.9	0.63	0.26
3	Alleppey Town	9.4139	76.3444	1.591	3.09	-1.50	2.81	-1.22	0.28
4	Aranootimangalam	9.2330	76.5760	16.09	10.28	5.81	5.82	11.87	4.46
5	Cheruvaranam	9.6542	76.3583	3.517	1.88	1.64	1.33	2.19	0.55
6	Edathua	9.3780	76.5290	1.17	0.88	0.29	0.74	0.43	0.14
7	Haripad	9.2861	76.4972	1.8	3.66	-1.86	1.84	-0.04	1.82
8	Haripad	9.2870	76.4640	2.41	1.59	0.82	1.2	1.21	0.39
9	Kaidavana	9.4580	76.3420	3.926	1.33	2.60	1.23	2.70	0.1
10	Kakazham	9.3920	76.3540	2.854	1.75	1.10	1.51	1.34	0.24
11	Kalarcode	9.3778	76.3639	4.696	1.68	3.02	0.53	4.17	1.15
12	Kallissery	9.3330	76.6170	5.38	3.56	1.82	3.58	1.80	-0.02
13	Kandiyoor	9.2500	76.5290	5.335	2.9	2.44	2.5	2.84	0.4
14	Karuvatta	9.2903	76.4611	1.89	1.58	0.31	0.2	1.69	1.38
15	Karuvatta	9.3330	76.4170	2.34	1.79	0.55	1.01	1.33	0.78
16	Kattoor	9.5530	76.3140	2.664	1.11	1.55	1.1	1.56	0.01
17	Kumarakom	9.5903	76.4542	0.75	0.72	0.03	0.2	0.55	0.52
18	Mancombu	9.4431	76.4417	0.781	0.56	0.22	0.26	0.52	0.3
19	Mavelikara	9.2500	76.5370	6.65	2.82	3.83	1.76	4.89	1.06
20	Nedumudi (pupalli)	9.4330	76.3830	0.72	0.51	0.21	0.65	0.07	-0.14
21	Neerkunnam	9.4080	76.3480	5.131	1.78	3.35	0.94	4.19	0.84
22	New Vechur	9.7189	76.4278	2.315	2.3	0.02	1.52	0.80	0.78
23	Pacha	9.3620	76.4510	1.11	1.08	0.03	0.5	0.61	0.58
24	Pallipad	9.2860	76.5280	2.63	1.39	1.24	1.07	1.56	0.32
25	Parumala	9.3330	76.5420	7.01	5.83	1.18	5.68	1.33	0.15
26	Pattanakad	9.7330	76.2920	1.518	1.34	0.18	0.96	0.56	0.38
27	Pattiyur	9.2170	76.4830	2.2	1.07	1.13	0.88	1.32	0.19
28	Pulikeezh	9.351	76.546	3.98	3.02	0.96	2.78	1.20	0.24
29	Purakkad	9.3470	76.3670	3.585	2.21	1.38	1.8	1.79	0.41
30	Puthanangadi	9.6444	76.3694	3.962	2.3	1.66	1.79	2.17	0.51
31	Ramankari	9.4250	76.4940	0.75	0.7	0.05	0.96	-0.21	-0.26
32	Sherthalai	9.6833	76.3431	3.911	3.17	0.74	2.42	1.49	0.75
33	Sherthalai	9.7000	76.3500	0.895	0.3	0.60	0.34	0.56	-0.04
34	Thaikattusseri	9.7750	76.3440	2.155	1.72	0.44	1.2	0.96	0.52
35	Thakazhi	9.3764	76.45	1.11	1.66	0.55	1.66	-0.55	0
36	Thannirmukkom	9.6720	76.3717	1.176	0.92	0.26	0.9	0.28	0.02
37	Thevery	9.2330	76.5420	2.4	1.5	0.90	1.4	1.00	0.1
38	Thiruvarpu	9.5833	76.4958	-	1.01	-	0.72	-	0.29
39	Thottapalli	9.3361	76.3739	2.735	1.75	0.99	0.55	2.19	1.2
40	Thuravur	9.6830	76.3000	3.4	2.58	0.82	1.9	1.50	0.68
41	Trikkunnapuzha	9.2830	76.3960	0.85	0.4	0.45	0.95	-0.10	-0.55
42	Vaikom	9.7472	76.4042	5.24	1.2	4.04	0.7	4.54	0.5
43	Valavanad	9.6000	76.3330	5.556	0.92	4.64	0.52	5.04	0.4
44	Vayalar	9.7208	76.3236	-	2.01	-	1.23	-	0.78
45	Venmani(thazhagam)	9.2670	76.6080	7.06	2.17	4.89	1.18	5.88	0.99

The bottom aquifer is generally under confined conditions with brackish water in most parts of low lying areas. The depth of tube wells taping this fresh water aquifer varies from 20 to 60 m with exceptions along the coastal alluvium where it goes up to 80 m. The yield of wells in coastal alluvium is much higher (20-40 thousand litres per hour) than that in the eastern parts of kuttanad (Kunhmbu, 2001; Vinayachandran, 2009). The details of tube wells in this formation used for water level monitoring are given in Table 4.2**.** The discharge from all these wells in the alluvium is poor and is in the range of 0.2-1.5 liters per second.

4.2.1 Water levels in Phreatic Aquifers

Groundwater occurs under phreatic conditions in the top alluvial aquifers lying above the clay beds which acts as the confining layer above the Recent confined aquifer. Depth to water levels in dug wells in the area provides valuable information regarding the groundwater regime in the phreatic zone and is one of the guiding factors for groundwater management in the area.

Table 4.2 Hydrogeological details of tube wells in the area used for water level monitoring in recent confined aquifer.

Sl.No.	Location	Depth drilled (m)	Zone taped (m)	SWL mbgl	Discharge LPS	Aquifer
1	Cheruvaranam	40	32-35	4.35	1.0	confined
2	Thagazhi -1	60	48-51 54-57	5.53	1.5	confined
3	Thagazhi -2	30	16-19	4.12	0.5	confined
4	Purakkad	65	58-64	4.15	1.0	confined
5	Kumarakom-1	60	51-57	0.80	1.0	confined
6	Kumarakom-2	60	54-60	0.85	1.0	confined
7	Thiruvarppu 1	42	32-35	1.38	0.5	confined
8	Thiruvarppu 2	41	33-39	1.40	1.5	confined
9	Alamthurthi	32	25-31	1.30	1.0	confined
10	Podiyadi	60	47-56	2.3	0.5	confined
11	Neelamperoor	21	15-18	4.9	0.2	confined
12	Karumady	30	17-23	1.88	1.1	confined
13	Thannirmukkom	30	17-20	1.84	1.3	confined
14	Chettikulangara	30	24-30	4.74	1.8	confined
15	Haripad (s)	30	17-22	6.20	1.0	confined
16	Kalarkode	40	24-30	2.35	2.1	confined
17	Mannachery	26	9-12	3.38	1.2	unconfined
18	Mudukulam	30	24-30	1.21	0.9	confined
19	Kommady	30	12-14	1.94	3.0	unconfined
20	Preethikulangara	70	59-65	9.30	1.6	confined

The water levels recorded in the observation wells during pre-monsoon (April) and post-monsoon periods (November) are shown in Table 4.3. This data has been used to prepare maps showing the distribution of groundwater levels. The water levels in major part of the area are < 4.0 m bgl during pre-monsoon period and < 2.0 m bgl. during post- monsoon period. A perusal of water level data shows water levels below 2 m in 65% of the monitoring wells in April and 84% of the wells in November 2009. The average water level during pre-monsoon is 1.99 m and that during post-monsoon period is 1.47m. Thus shallow water conditions are prevailing in a major part of the area.

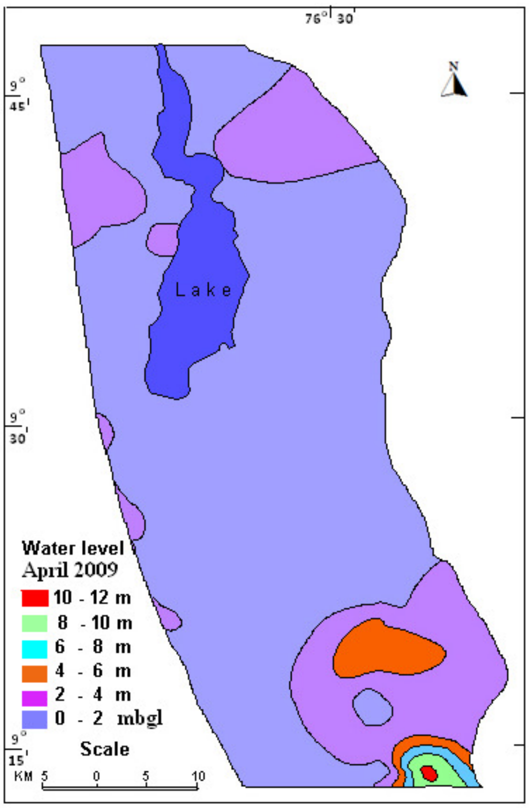


Fig. 4.1 Depth to water level in phreatic aquifer for April 2009

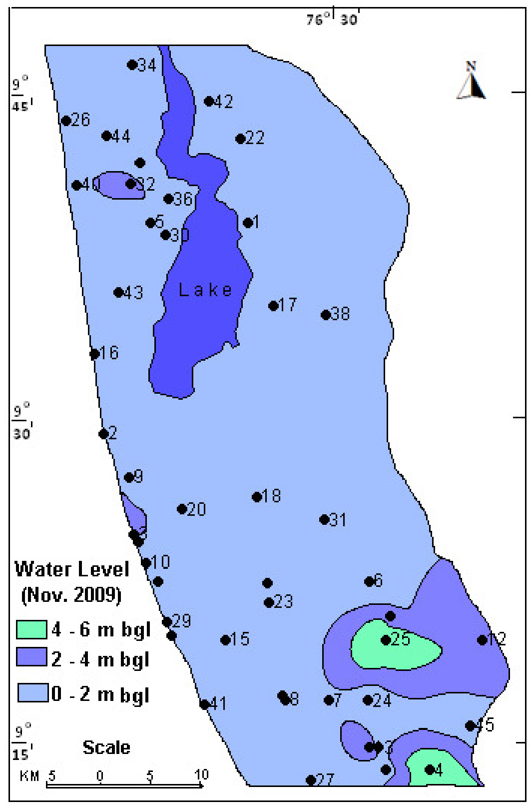


Fig. 4.2 Depth to water level in phreatic aquifer for November 2009

Depth to water level maps gives spatial information on the groundwater levels as different zones. The depth to water level maps prepared for April and November months are given Figure 4.1 and 4.2. These two maps give the groundwater scenario before and after the monsoon recharge. The distribution of water levels during pre- and post-monsoon periods is more or less similar, but for a slight increase in deeper ranges of 2 to 4 m in April. Water table maps of an area give a clear picture of its groundwater flow regime (Freeze and Cherry, 1979; Karanth, 1997; Kompani-Zare et.al, 2005; Najeeb and Vinayachandran, 2012). The water table map of the area based on phreatic water levels during pre- and post-monsoon periods in 2009 is presented in Figure 4.3 and 4.4. The water table maps for both the seasons show very low hydraulic gradients which indicates that the groundwater flow rate is very low in a major part of the area. The water table map shows flow direction towards the sea in the west.

Seasonal Fluctuations during 2009

The effect of base flow, evapo-transpiration and groundwater draft for various purposes and return seepages from different sources affects the water levels in an aquifer system. The water level fluctuation reflects the changes in the groundwater resource

Fluctuation of groundwater levels in the phreatic aquifers is indicative of the status of the groundwater regime in these aquifers. Seasonal fluctuations of water levels reflect the changes in groundwater storage during the period under consideration, whereas long term fluctuations are indicative of the changes in groundwater storage in the aquifers in response to various recharge and discharge parameters over a period of time.

The seasonal water level fluctuations in an area are computed as the difference between the water levels recorded during the pre- and post-monsoon periods. A surplus groundwater recharge is indicated by a rise in water level during post-monsoon period when compared to the pre-monsoon period. Whereas, inadequate compensation of groundwater draft by the monsoon and other recharge components is indicated by a fall in water level. The water level fluctuations in the observation wells, computed as the difference between the pre- and post-monsoon water levels are shown in Table 4.3.

Table 4.3 Water level fluctuations in phreatic aquifer during April and Nov. 2009 (Phreatic aquifer)

S.No	Location	Latitude	Longitude	Water level (April-09) (mbgl)	Water level (Nov-09) (mbgl)	Water level fluctuation (m)
1	Achinagam	9.6542	76.4347	1.7	1.58	0.12
2	Alleppey	9.4920	76.3220	2.16	1.9	0.26
3	Alleppey Town	9.4139	76.3444	3.09	2.81	0.28
4	Aranootimangalam	9.2330	76.5760	10.28	5.82	4.46
5	Cheruvaranam	9.6542	76.3583	1.88	1.33	0.55
6	Edathua	9.3780	76.5290	0.88	0.74	0.14
7	Haripad	9.2861	76.4972	3.66	1.84	1.82
8	Haripad	9.2870	76.4640	1.59	1.2	0.39
9	Kaidavana	9.4580	76.3420	1.33	1.23	0.1
10	Kakazham	9.3920	76.3540	1.75	1.51	0.24
11	Kalarcode	9.3778	76.3639	1.68	0.53	1.15
12	Kallissery	9.3330	76.6170	3.56	3.58	-0.02
13	Kandiyoor	9.2500	76.5290	2.9	2.5	0.4
14	Karuvatta	9.2903	76.4611	1.58	0.2	1.38
15	Karuvatta	9.3330	76.4170	1.79	1.01	0.78
16	Kattoor	9.5530	76.3140	1.11	1.1	0.01
17	Kumarakom	9.5903	76.4542	0.72	0.2	0.52
18	Mancombu	9.4431	76.4417	0.56	0.26	0.3
19	Mavelikara	9.2500	76.5370	2.82	1.76	1.06
20	Nedumudi (pupalli)	9.4330	76.3830	0.51	0.65	-0.14
21	Neerkunnam	9.4080	76.3480	1.78	0.94	0.84
22	New Vechur	9.7189	76.4278	2.3	1.52	0.78
23	Pacha	9.3620	76.4510	1.08	0.5	0.58
24	Pallipad	9.2860	76.5280	1.39	1.07	0.32
25	Parumala	9.3330	76.5420	5.83	5.68	0.15
26	Pattanakad	9.7330	76.2920	1.34	0.96	0.38
27	Pattiyur	9.2170	76.4830	1.07	0.88	0.19
28	Pulikeezh	9.351	76.546	3.02	2.78	0.24
29	Purakkad	9.3470	76.3670	2.21	1.8	0.41
30	Puthanangadi	9.6444	76.3694	2.3	1.79	0.51
31	Ramankari	9.4250	76.4940	0.7	0.96	-0.26
32	Sherthalai	9.6833	76.3431	3.17	2.42	0.75
33	Sherthalai	9.7000	76.3500	0.3	0.34	-0.04
34	Thaikattusseri	9.7750	76.3440	1.72	1.2	0.52
35	Thakazhi	9.3764	76.45	1.66	1.66	0
36	Thannirmukkom	9.6720	76.3717	0.92	0.9	0.02
37	Thevery	9.2330	76.5420	1.5	1.4	0.1
38	Thiruvarpu	9.5833	76.4958	1.01	0.72	0.29
39	Thottapalli	9.3361	76.3739	1.75	0.55	1.2
40	Thuravur	9.6830	76.3000	2.58	1.9	0.68
41	Trikkunnapuzha	9.2830	76.3960	0.4	0.95	-0.55
42	Vaikom	9.7472	76.4042	1.2	0.7	0.5
43	Valavanad	9.6000	76.3330	0.92	0.52	0.4
44	Vayalar	9.7208	76.3236	2.01	1.23	0.78
45	Venmani(thazhagam)	9.2670	76.6080	2.17	1.18	0.99

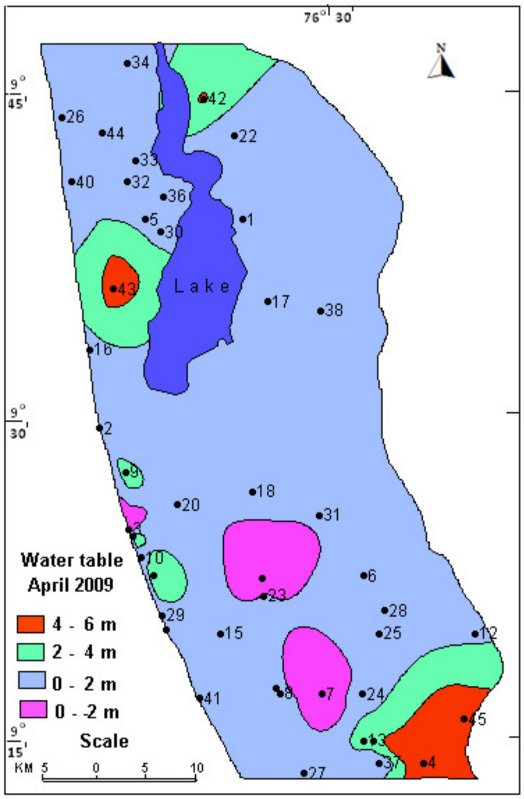


Fig. 4.3 Water table for April 2009 (Phreatic aquifer)

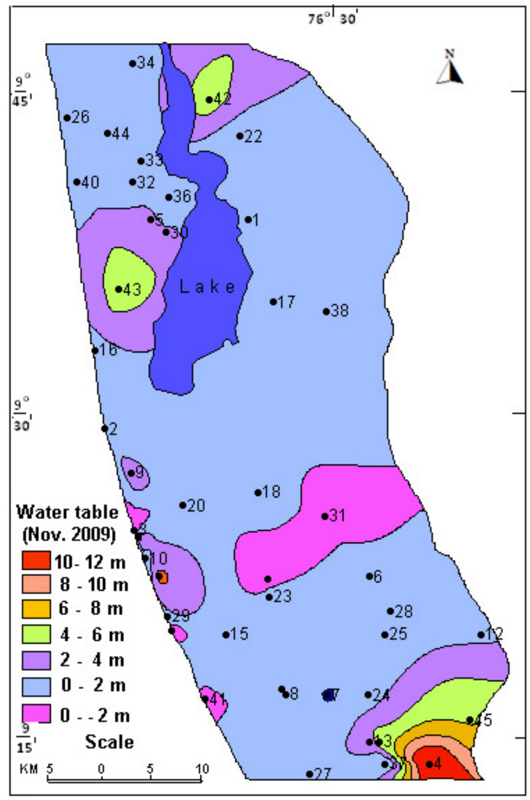


Fig. 4.4 Water table for November 2009 (Phreatic aquifer)

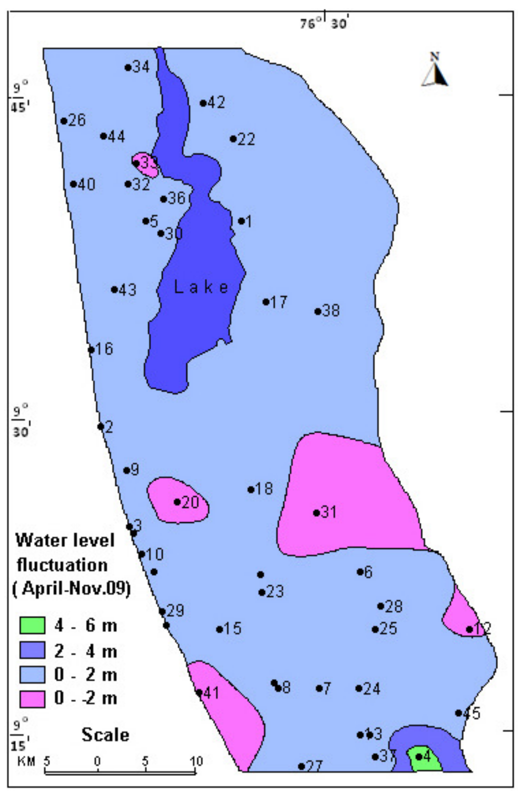


Fig. 4.5 Water level fluctuation between Nov. &April 2009 (Phreatic aquifer)

A perusal of the fluctuation data shows very low groundwater fluctuation with an average fluctuation of about 0.5 m which indicates that most of the rainfall received in the area is being rejected by the phreatic aquifer system. The rise in water levels observed during premonsoon period at Ramankari, Nedumudi, Kallissery, Sherthala and Trikkunnapuzha are mainly due to canal water influences and nothing to do with overdraft normally observed in such a situation. The iso-fluctuation map of the area shown in Fig. 4.5 depicts the extent of the area where water level fluctuation is very low.

Groundwater level fluctuations on a decadal scale (2004-2013)

The variation in water level with reference to time and space is the net result of groundwater development and recharge. The long term change in water level is discernible from the trend of water levels over a period of time and is best reflected in a hydrograph. Salient details of water level trends during pre- and post-monsoon seasons for a period of 10 years are furnished in Table 4.4.

Table. 4.4 Trend of Pre- and Post-monsoon water levels in the phreatic aquifer for the period from 2004 to 2013

Sl No.	Location	Pre-monsoon Trend (m/year)	Post-monsoon Trend (m/year)
1	Alleppey	-0.01	-0.01
2	Aranootimangalam	0.14	-0.10
3	Arukutti	-0.07	0.04
4	Chettikulangara	-0.05	0.01
5	Edathua	-0.08	-0.01
6	Ezhupunna	-0.04	0.01
7	Haripad	-0.08	0.03
8	Idakunnam	-0.18	-0.05
9	Kallissery	-0.02	0.07
10	Kandiyoor	0.00	0.04
11	Karumady	-0.09	-0.02
12	Karuvatta	0.10	0.01
13	Kattanam	-0.02	-0.06
14	Kattoor	-0.07	0.06
15	Kayamkulam	0.03	0.00
16	Kuzhamathu	-0.02	-0.11
17	Mannar	0.07	0.01
18	Mavelikara	0.02	0.03
19	Mudhukulam	0.05	-0.05
20	Muttam	-0.03	0.01
21	Nedumudi	0.09	0.02
22	Nooranad	0.22	-0.14
23	Pacha	0.03	0.01

Sl No.	Location	Pre-monsoon Trend (m/year)	Post-monsoon Trend (m/year)
24	Pallarimangalam	0.02	-0.01
25	Parumala	-0.04	-0.20
26	Pattanakad	0.02	0.03
27	Purakkad	-0.01	-0.06
28	Ramankari	-0.03	-0.01
29	Thakazhi	0.00	-0.05
30	Thamarakulam	-0.10	-0.03
31	Thevery	-0.04	0.04
32	Thuravur	-0.04	0.03
33	Trikkunnapuzha	0.01	-0.01
34	Valavanad	-0.03	0.02
35	Vallikunnam	-0.11	0.27
36	Kumarakom	-0.07	-0.01
37	Tiruvarpu	0.11	0.09
38	Vechur	0.01	0.07

A perusal of the analysed data on water level trends shows no significant decrease in water levels. Water level trend in some of the wells shows a slightly rising trend, perhaps due to the less development of water table aquifer.

The pre-monsoon and post-monsoon water levels for a period varying from 26 to 31 years in four observation wells in the area shows no significant change in water levels as observed from the hydrographs (Fig. 4.6.a-d).

As the changes in water level are closely related to the incidence of rainfall, histograms of average monthly rainfall received during the last decade are plotted against average water levels for the period from 2004 to 2013 (Fig 4.7) and analysed. The average monthly water levels are given in Table 4.5 and a perusal of hydrographs in Fig 4.7 indicates no significant fluctuation in water level with respect to the quantum of rainfall received, indicating a high rejected recharge in the area.

4.2.2 Piezometric heads in confined aquifers

Groundwater occurs under confined conditions in the deeper aquifer system in the Recent alluvium. The thinning and thickening of the confining clay layer observed in the cross sections (Fig.2.15 to 2.17, Chapter 2) also points to restricted vertical leakage at places. The behavior of piezometric heads in bore wells have been studied using the data collected from the bore wells.

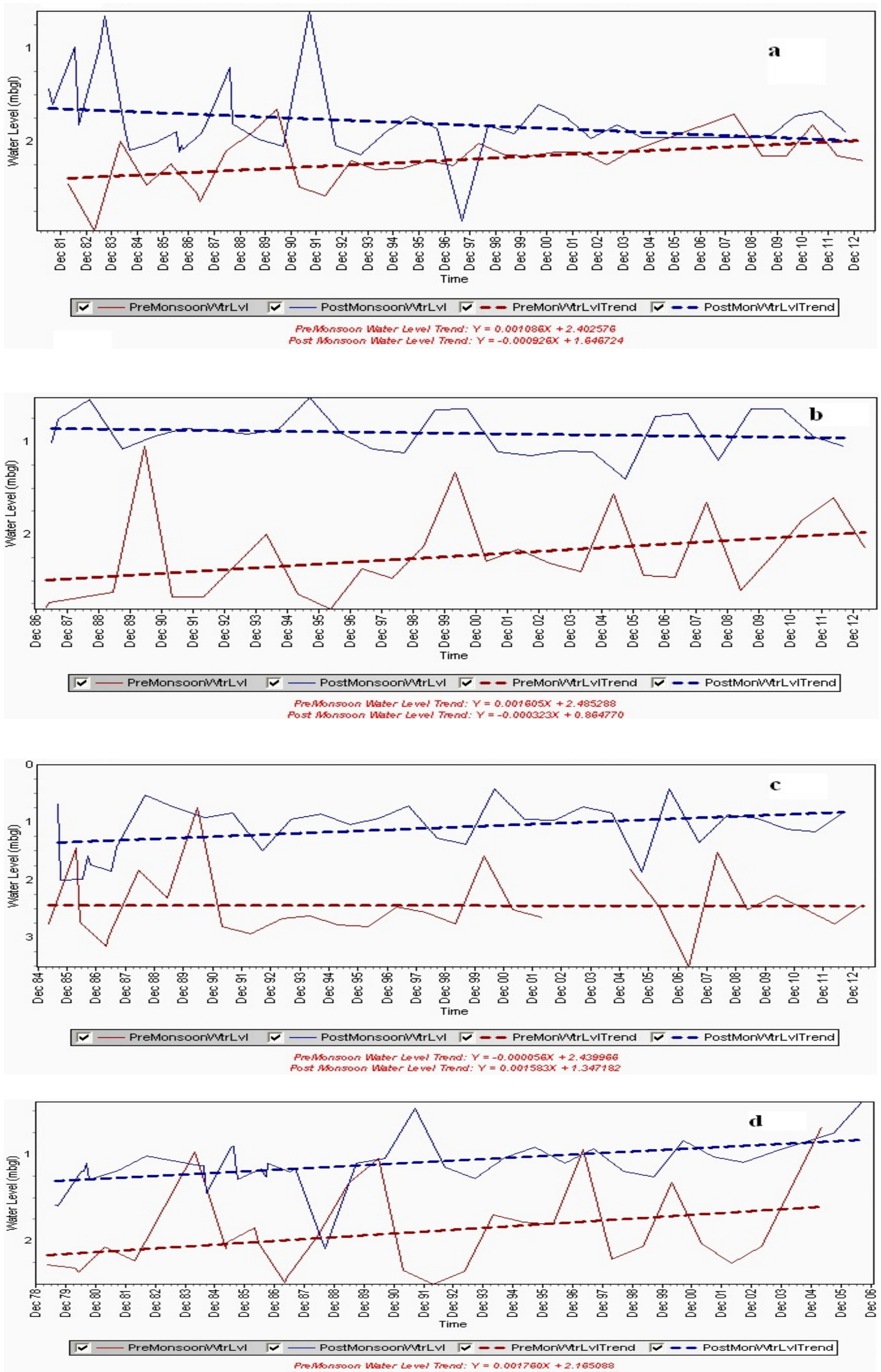


Fig.4.6. Water level fluctuation trends in Phreatic aquifer a) Allissery (1981-2012); b) Chettikulangara (1986-2012); c) Haripad (1984-2012); d) Kaidavana (1978-2006)

The depth to piezometric surface recorded in the bore wells during pre-monsoon (April) and post-monsoon (November) periods are shown in Table 4.6.

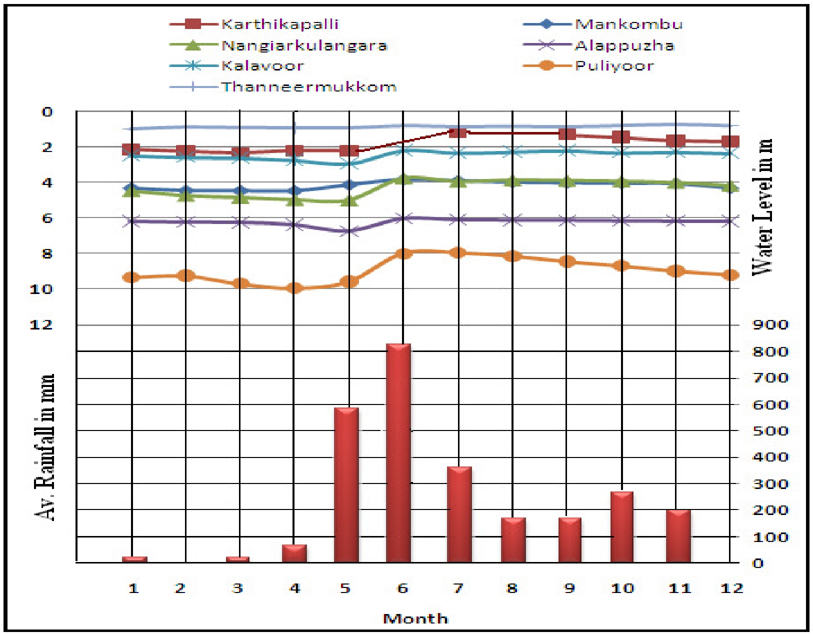


Fig 4.7 Water level response to Rainfall in Phreatic aquifer

Table 4.5 Average monthly Water level variations in phreatic aquifer for the period 2004-2013

month	Mankombu	Karthikapalli	Nangiar-kulangara	Alappuzha	Kalavur	Puliyoor	Thannir-mukkom
	Average water level (mbgl) for the period 2009-2013						
Jan	4.33	2.15	4.47	6.19	2.48	9.38	1.02
Feb	4.47	2.27	4.74	6.24	2.59	9.28	0.89
Mar	4.48	2.35	4.85	6.25	2.62	9.74	0.93
Apr	4.48	2.23	4.97	6.39	2.74	9.98	0.94
May	4.15	2.24	5.00	6.75	2.95	9.62	0.94
Jun	3.85	1.10	3.75	6.02	2.21	8.02	0.82
Jul	3.92	1.20	3.93	6.10	2.34	7.98	0.88
Aug	4.00	1.25	3.85	6.12	2.28	8.18	0.85
Sep	4.03	1.33	3.88	6.13	2.22	8.48	0.88
Oct	4.06	1.49	3.92	6.16	2.33	8.74	0.81
Nov	4.08	1.66	4.00	6.18	2.29	9.02	0.74
Dec	4.33	1.72	4.17	6.18	2.37	9.23	0.82

The piezometers tapping the confined aquifer in Recent alluvium has recorded water level between 0.28 m and 8.01 m bgl during April and between 0.23 and 6.86 during November of 2009. The average piezometric level in this aquifer system is 3.70 m in

April and 3.20 m in November, indicating a stable situation with limited scope for more recharge. Lack of aquifer continuity of Recent sands in the coastal tract with the eastern part of the area, especially in the eastern part of Vembanad Lake, necessitates a good number of piezometers to represent the entire aquifer system for drawing piezometric contour maps.

Table 4.6 The piezometric heads in the Recent-confined aquifer system

Stn. No.	Location Name	Latitude In degrees	Longitude In degrees	Pz head in m April 09	Pz head in m Nov.09	Seasonal Fluctuation in m
1	Cheruvaranam	9.6578	76.3556	4.21	3.60	0.61
2	Haripad	9.2886	76.4636	7.00	5.82	1.18
3	Kakazham	9.3889	76.3508	4.72	4.01	0.71
4	Kakkazham	9.3889	76.3506	4.41	4.17	0.24
5	Kanjikkuzhi	9.6578	76.3556	3.92	3.60	0.32
6	Karumadi	9.3806	76.3886	1.92	1.32	0.60
7	Kumarakom	9.5875	76.4364	0.92	0.82	0.10
8	Mankombu	9.4383	76.4281	2.61	2.65	-0.04
9	Mannanchery	9.5714	76.3475	4.01	2.88	1.13
10	Preethikulangara	9.6058	76.3117	6.48	6.02	0.46
11	Purakkad	9.3492	76.3717	8.01	6.86	1.15
12	Thakazhi	9.3708	76.4117	4.18	3.90	0.28
13	Thannirmukkom	9.6731	76.3925	1.61	1.21	0.40
14	Kalarkode	9.3778	76.3639	1.95	1.62	0.33
15	Kommadi	9.5100	76.3300	1.55	0.68	0.87
16	Mudhukulam	9.2015	76.4500	0.35	0.30	0.05
17	Thiruvarpu	9.5819	76.4883	1.15	0.89	0.26

Fluctuation of piezometric surface

Fluctuations of piezometric surface are indicative of the changes in the groundwater regime. Seasonal fluctuations of piezometric surface reflect the changes between the pre- and post-monsoon seasons in a year, whereas long term fluctuations are indicative of the changes in groundwater storage over a period of time. The fluctuations in piezometric surface in the area, computed as the difference between the piezometric heads measured in observation bore wells during pre- and post-monsoon periods are shown in Table 4.4. The fluctuations of piezometric heads in the area varied from 1.18 m at Haripad to -0.04 m at Mankombu with an average fluctuation of 0.5m.

4.3 Groundwater in Tertiary formations

The Tertiary formations constitute the major aquifer in Kuttanad with total thickness of sediments ranging from 90 to more than 600 m covering extensive area. They are underlain by crystalline basement and overlain by laterite and unconsolidated formations. The tube wells taping the Tertiary aquifer system in the Kuttanad area and their yield are given in **Table 4.7.**

Groundwater in Alleppey beds;

Alleppey beds are the bottom most unit of Tertiary sedimentary formations, comprising of highly carbonaceous clay with intercalations of sand. Alleppey beds were encountered in tube wells at Trikunnapuzha below 522 mbgl and at Kottaram below 299 mbgl. The thickness of Alleppey bed is 70 m at Karumadi and 23 m at Kottaram, whereas at Kalarkode it is more than 106 m and basement was not encountered. The formation water is brackish in quality as revealed by electrical logging.

Groundwater in Vaikom beds;

Vaikom beds overlying the Alleppey bed with thickness varying from 25-238 m is the highly potential aquifer among the Tertiary formations. They comprise of gravel, coarse sand, clay and seams of lignite. They are exposed in south-eastern part of the area in the midlands and are highly lateritised on the surface. The thickness of the granular zones tapped in the tube wells constructed in this aquifer ranges from 5-210 m with discharge in the range of 11-96 m^3/hr. However, the water from Vaikom aquifer in Kuttanad region and in coastal zone west of Vembanad lake is more mineralized. Some of the tube wells with high discharge of 57.6-96.7 m^3/hr have drawdown in the range of 2.23-6.76 m. The tube wells at Karuvatta, Karumadi, Karthikapalli and Kandiyur were having free flow with water level in the range of 1.44 to 4.29 meter above ground level (magl) at the time of

Table 4.7 : Tube wells taping the Tertiary aquifers in Kuttanad area and their yield (CGWB,1992)

Sl. No	Location & toposheet No.	Latitude in degrees	Longitude in degrees	Depth drilled (mbgl)	Depth of well (mbgl)	Zones tapped	Discharge (lps)
1	Alisserey, 58 C/7	9.4861	76.3264	247.56,	122	l-109-119.0, 123-128.(Quilon)	1.5, 0.75
2	Alisserey, 58 C/7	9.4861	76.3264	209	122	158-162, 170-174, 196-200.(Vaikom)	1.5, 0.75
3	Arthungal, 58 C/7.	9.6589	76.2997	444.9	103	91-100(Warkalai)	11.16
4	Aryad, 58 C/6	9.5375	76.3292	400.1	Nil	102-114, 144-156.(Warkalai)	NA
5	Changanacheri, 58 C/11	9.4583	76.5333	35.6	Nil	19.81-22.86, 28.95-32.	NA
6	Edattuva, 58 C/7.	9.3694	76.4764	205.6	109	78-84, 87-90.(Quilon), 99-105.(Vaikom)	45
7	Haripad, 58 C /7	9.2919	76.4625	55	54	38-50	12
8	Kalarkod, 58 C/7.	9.4583	76.3333	601	430	372-393, 408-416, 419-427.	4.98
9	Kallara, 58 C/6.	9.7028	76.4778	37.5	Nil	7.62-12.19, 15.85-24.38.	NA
10	Kandiyur 58 C/12.	9.2481	76.5267	188.9	148	129.86-145.0(Vaikom)	13.71
11	Karthikapalli- 58 C/7.	9.2500	76.4500	450	88	70-76, 80-86.	5
12	Karumadi, 58 C/7.	9.3792	76.3917	437.04	329	247-256, 262-268, 271-280, 283-289, 298-307,310-316,320-326.(Vaikom)	21.98
13	Karuvatta, 58 C/7.	9.3167	76.4125	428.2	368	259-263, 281-296, 354-365.(Vaikom)	26.82
14	Kattoor, 58 C/6.	9.5750	76.3036	504	358	299-308, 319-333.5, 351-355.	Free flowing
15	kidangara, 58 C/7.	9.4194	76.4972	97.14	Nil	39-48, 67-74.4, 84.7-93.2.	NA
16	Kottaram, 58 C/6	9.6972	76.3153	326	172	EW-148-151, 156-160, 162.5-165.5, 167.5-169.50(Quilon)	EW-2.60, OW-2.50
17	Kulashekaramangalam, 58C/6.	9.7917	76.4000	54.86	Nil	13-17, 30-33, 39-48.(Vaikom)	NA
18	Kumarakom, 58 C/6.	9.5861	76.4389	169	127	112-124.(Vaikom)	Free flow 1.8lps
19	Mancombu, 58 C/7	9.4417	76.4222	258.51	70	37-42, 46.5-49.5, 54-68	7.1
20	Mannancherry 58 C/6	9.5806	76.3653	202.73	199	193-196 Vaikom	2.38
21	Muttom, 58C/8.	9.2486	76.4903	274.7	253	163-178, 180-185, 188-193, 201-218, 222-225.	1-free flow 6 lps
22	Nirkunnam, 58 C/7.	9.3917	76.3667	600.79	Nil	between 68 and 266 contains fresh water.	NA
23	North Mararikolam, 58 C/6.	9.6264	76.3333	357.48	Nil	70-74, 78-82, 88-92.	NA
24	Parumala, 58 C/11.	9.3306	76.5403	105.8	82.55	46.33-57.91,70.7-76.2, 78.02-81.07	22.08
25	Pattanakad, 58 C/6.	9.7444	76.3000	274.31	214.3	178-188, 191.4-194.5, 197.4-211.2.	12.61
26	Pulikeezhu, 58 C/11	9.4333	76.5439	I - 88 II - 70	70 62.5	25-28, 44-52, 56-61, 65-67 (Vaikom)	16.75 1.29
27	Ramankari, 58 C/7	9.4217	76.4575	116.9	113	103-110.(Vaikom)	0.9
28	Shertallai, 58C/6	9.6306	76.3278	237	Nil	33-39, 67-73, 83-89, 172-178, 197-203, 215-221.	NA
29	Thakazhi, 58 C/7.	9.3667	76.4264	304	Nil	Nil	NA
30	Thottappalli, 58 C/7.	9.3153	76.3897	269.44	174.14	87-93, 106-120, 130-136, 164-174(Warkalai)	49.26
31	Thrikunnapuzha, 58 C/7.	9.2667	76.4083	600	209.2	111-122, 126-132 (Warkalai)	41.66

construction. At present all the piezometric head have been reduced due to continuous exploitation of groundwater from these aquifers for water supply.

The piezometric surface in respect of Vaikom aquifer is 3 m amsl in the eastern peripheral area and 5 m in south-east, in the midlands and reduces westwards reaching 1 m amsl around Tannirmukkom adjacent to the coast. The general groundwater flow in the aquifer in the area is from south to north.

Groundwater in Quilon beds

Quilon beds are characterized by lime stone deposits and the aquifers in Vaikom and Warkali beds interconnected though this bed (Fig 2.11).

Groundwater in Warkalai beds

The Warkalai bed overlying the Quilon beds is composed of medium to fine grained sand with an effective grain size of 0.21-0.30 mm. This bed bears the most extensively developed aquifer in the district. Groundwater occurs in semi-confined to confined conditions with the cumulative thickness of granular zone varying from 6 to 44 m. The piezometric head of Warkalai beds observed in the tube wells is in the range of 2.8 m amsl in the east (Kandiyur) and 10 m bmsl at Alleppey. The aquifer has attained high degree of development in Alleppey area. The tube wells have depth range of 22-258 m and have discharge in the range of 6-120 m^3/hr.

4.3.1 Piezometric levels in the Tertiary aquifer system

The piezometric surface data of bore wells over a period has been used for the analysis of long term fluctuations of piezometric surface in the area. The piezometric surface in the Vaikom aquifers varied from 1- 10 m amsl during 1985 and at present it is in the range of 2 to 6 m bmsl. Some of the piezometers in this aquifer were under free-flow conditions and now all of them are having piezometric heads below ground level. The piezometric head of Warkali aquifers were in the range of 2.8-10 m bmsl during 1985 and at present it is in the range of 4 to 20 m bmsl.

Table 4.8 Piezometric heads in Tertiary aquifers monitored during April and November 2009

Sl. No	Location	Latitude	Longitude	Aquifer	Drilled Depth (m)	Apr 09 mbgl	Nov 09 mbgl
1	Alissery(east)	9.4861	76.3264	Tertiary-W	247	19.7	17.95
2	Chettikulangara Pz	9.2252	76.5166	Tertiary-W	30	4.46	
3	Haripad	9.2875	76.4639	Tertiary-W	30	2.1	1.66
4	Kakkazham	9.3917	76.3508	Tertiary-W	284	4.47	4.9
5	Kalarkode (74m)	9.4614	76.3315	Tertiary-W	73	3.35	2.88
6	Kandiyur(east)	9.2481	76.5267	Tertiary-V	189	5.27	5.2
7	Kandiyur(west)	9.2481	76.5266	Tertiary-W		3.24	2.2
8	Karthikapally(south)	9.2600	76.4500	Tertiary-W	450	6.83	6.48
9	Karthikappalli(north)	9.2500	76.4500	Tertiary-Q	450		2.87
10	Karumady	9.3834	76.3871	Tertiary-W	30	1.94	1.84
11	Kidangara	9.4194	76.4972	Tertiary-W	38	0.17	0.15
12	Kottaram	9.6972	76.3153	Tertiary-W	179	24.15	22.4
13	Mannancherry (30m)	9.5700	76.3800	Tertiary-W	26	2.9	2.26
14	Mannar	9.2900	76.5600	Tertiary-W	30	5.44	4.67
15	Muttam(north)	9.2600	76.4800	Tertiary-W	75	3.5	3.18
16	Muttam(south)	9.2500	76.4800	Tertiary-V	275	1.71	1.8
17	Pallathuruthy	9.4550	76.3742	Tertiary-W	50	9.52	9.18
18	Preethigulangara-north	9.5812	76.3207	Tertiary-W	70	6.07	6.25
19	Preethigulangara-south	9.5812	76.3207	Tertiary-V	351	1.52	1.55
20	Thaneermukkam	9.6700	76.3900	Tertiary-W	30	1.5	1.41

A perusal of the data indicates rise in piezometric head during post monsoon and fall in piezometric head during pre monsoon periods (Table 4.8). However, an overall decline in piezometric head for both the seasons compared to the previous years is observed, indicating that the recharge and draft patterns are influencing the piezometric heads.

The piezometers taping the Tertiary aquifers at present are insufficient to create a meaningful contour map useful in quantifying the flow in the system. Most of the piezometers constructed earlier are defunct due to corrosion of pipes or destroyed. However, to get general information on the flow of groundwater the wells taping the Warkali strata of the Tertiary aquifer system has been used to plot the piezometer map shown in Fig. 4.8. The piezometers affected by pumping nearby are excluded from the data used for the map preparation. The Fig 4.8 shows a very low hydraulic gradient and the flow pattern seems to be affected by groundwater draft from the aquifer system.

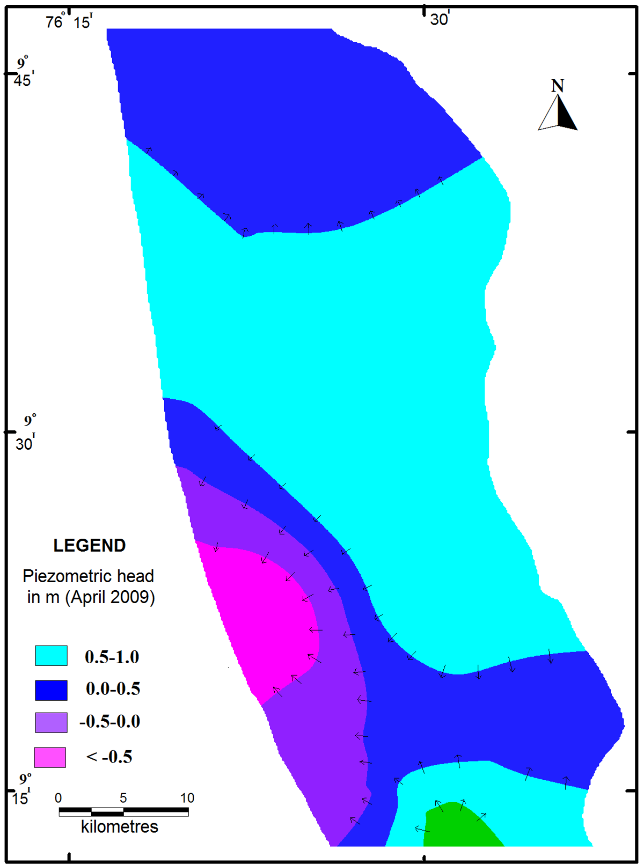


Fig. 4.8 Piezometric head in the Tertiary aquifers (Warkali aquifer)

The piezometric contour map based on 1985 data showed a North to NNW flow direction in the Tertiary aquifers. Because of the heavy draft in Alleppey town area, there the flow is from all the directions as observed in the present map and the general NNW direction of flow is inconspicuous in Kuttanad area.

4.3.2 Trend of piezometric levels

The trend of piezometric heads in bore wells for a period up to 26 years has been analyzed for the long term changes in piezometric surface. Salient details of trend analyses of piezometric heads during pre and post monsoon season form 3 piezometers taping Warkali and Vaikom aquifers are furnished in Table 4.9. All these stations show a steady decline in water levels over a period up to 26 years indicating that the periodical groundwater draft exceeds the recharge. The Hydrographs of bore wells at Kandiyur, Muttom and Karthikapally (Fig 4.9. a to d) shows a gradual decline in piezometric surface in both pre-monsoon and post- monsoon periods. The piezometers at Kandiyur and Muttom are located east of the piezometer at Karthikapalli. The decline in piezometric heads for both the seasons is indicative of an imbalance between the recharge and draft and points to the necessity for restriction on draft from these aquifer systems to avoid adverse effects.

A comparison of the rates of decline of piezometric heads in Warkali aquifer with that of Vaikom aquifer indicates a higher piezometric head for the later one but a similar trend pattern for both the aquifer systems. The similar trend pattern of both Warkali and Vaikom aquifers seems to be an indication of their inter connection through the intermediate Quilon beds.

Table 4.9 Trend of piezometric heads in Warkali and Vaikom aquifers

Particular	Trend of PZ head in Warkali Aquifers (m/year)			Trend of PZ head in Vaikom Aquifers (m/year)		
	Kandiyur	Muttom	Karthikapalli	Kandiyur	Muttom	Karthikapalli
Period (years)	1987-'12	1991-'12	1993-2010	1987-'01	1992-'12	1987-2010
Pre-monsoon trend value	-0.19	-0.03	-0.26	-0.11	-0.22	-0.30
Post-monsoon trend value	-0.18	-0.08	-0.15	-0.05	-0.16	-0.27

4.4 Aquifer characteristics

Pumping tests are commonly used for the evaluation of aquifer parameters, transmissivity (T) and storage coefficient or storativity (S) (Todd, 1980). A pumping test consists of observing rate of change of water level under controled pumping conditions in the discharging well itself and in the adjacent observation wells. Consequent to the well discharge, a pressure gradient is built up in the vicinity of pumped well, resulting in the creation of a cone of depression, which induces the necessary flow of water to sustain the well discharge.

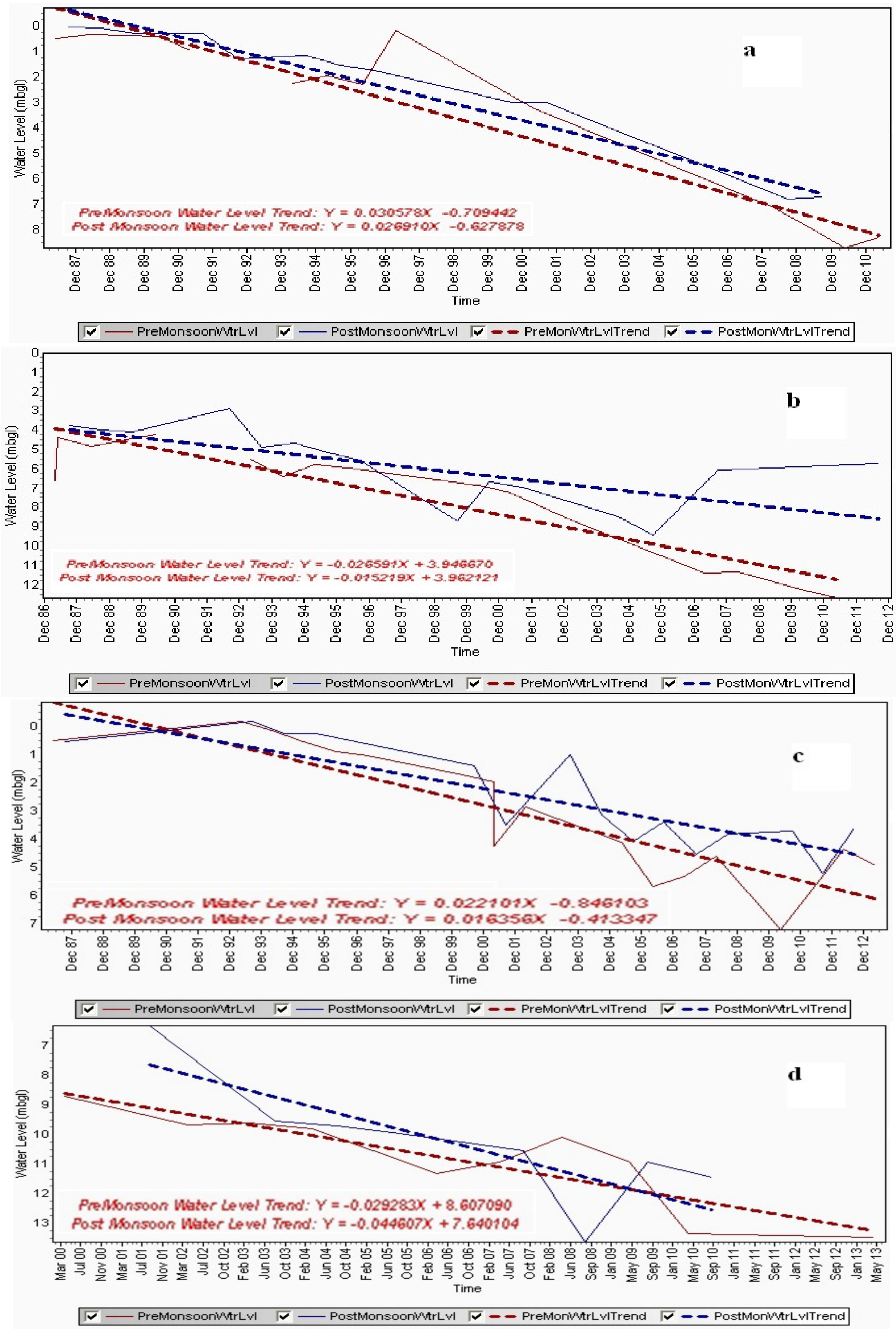


Fig.4.9. The trend in piezometric head of Tertiary aquifers a) Karthikapally (Vaikom-1987-2010); b) Karthikapally (Warkali-1986-‘12); Muttom (Vaikom-1987-‘12); Preethikulangara (Warkali- 2000-‘13)

The spatial and temporal variation in the cone of depression is a function of several factors, such as the aquifer parameters, aquifer geometry, and the rate of well discharge. Conversely if the physical behaviour of the cone of depression is known, as is revealed by time – draw down and distance draw down relationships observed during pumping test, the aquifer parameters could be computed with the help of suitable hydraulic equations. Such equations have been derived for steady state and non steady state or transient flow. The steady state is an equilibrium condition whereby no changes occur with time. It will seldom occur in practice, but it may be approached after prolonged pumping of the well when the water level declines at a very slow rate. Transient flow equations include the time factor and they enable the calculation of the drop in water level or piezometric surface in relation to time since pumping started. In the present study all the pumping tests were conducted under transient conditions.

Two sets of data viz; time versus drawdown and time versus recovery are normally generated during a pumping test. The water levels recorded during recovery are commonly known as residual draw down. The Theis type curve matching method and the Cooper-Jacob semi-log method are commonly used for estimation of transmissivity and storativity of infinite, homogenous, isotropic, confined aquifers from draw down data of a constant rate pumping test.

Recovery data analysis

After pumping has been shut down the water level will stop dropping and instead rise again to its original position. This is being called the recovery of the well. The rise of water level can be measured as residual draw down (s^I), which is the difference between the original water level prior to pumping and the actual water level measured at a certain moment t' since pumping stopped.

The data obtained during recovery permit the calculation of the transmissivity, thus giving a check on the results of the analysis of the data obtained during the pumping period. Moreover, the recovery method has the advantage that the rate of recharge Q is constant and equal to the mean rate of discharge Q during pumping. This means that draw down variations resulting from slight difference in the rate of discharge during pumping do not occur during recovery.

The inflow of water from the aquifer during the recovery can be simulated with imaginary well injecting water into the aquifer (Kruseman et al., 1990). This well has the same pumping rate as the real test well, only with the negative sign. Accordingly, the entire aquifer test can be simulated as a super position of flows at two wells. The resulting drawdown at any time after the actual pumping stops is the algebraic sum of the drawdown from the extraction well and the build up from the introduced imaginary injection well. The resulting residual drawdown can be represented as;

$$s^I = s + s_{rcv} \qquad \text{............................ 4.1}$$

where, s is the draw down from the extraction well and s_{rcv} is the recovery (negative drawdown from the recharge well. When these drawdown components in equation 4.1 are expressed with the Theis equation it follows that;

$$s^I = Q/ 4\pi T\ w(u) + - Q/ 4\pi T\ w(u_{rcv}) \qquad \text{........................... 4.2}$$

The parameters u and u_{rcv} in equation 4.2, which stands for the extraction well and recharge well (imaginary well) are:

$$u = r^2S/4Tt \text{ and} \qquad \text{............................ 4.3}$$

$$u_{rcv} = r^2S/4Tt^I \qquad \text{............................ 4.4}$$

where t^I is the time since actual pumping stopped.

When parameter u is less than 0.05, the Theis equation can be simplified as suggested by Jacob and Cooper and equation 4.2 becomes:

$$s^I = Q/ 4\pi T\ (\text{ In } 2.25Tt/r^2S\ - \text{In } 2.25Tt^I/ r^2S) \text{ ...... 4.5}$$

Equation 4.5 can be simplified as

$$s^I = Q/ 4\pi T \text{ In } t/t^I \qquad \text{................ 4.6}$$

Knowing that In (x) =2.3log(x), equation 4.6 becomes:

$$s^I = 2.3Q/ 4\pi T \log t/t^I \qquad \text{......................... 4.7}$$

As seen from equation 4.7, if residual drawdown s^I is plotted against t/t^I it would form a straight line. The residual drawdown coordinates of any two points on the straight line are:

$$s_1^I = 2.3\ Q/4\pi T\ .\log(t/t^I)_2\ /(t/t^I)_1 \quad ....4.8$$

If the two points are chosen over one log cycle, the equation 4.8 can be solved for the aquifer transmissivity as:

$$T = 2.3\ Q/4\pi\Delta s$$

Residual drawdown method of recovery analysis does not allow calculation of the storage coefficient, neither in the pumping well nor in piezometers. This is obvious from the absence of the storage coefficient in the basic equation describing the method.

The procedure proposed by Goode (1997) for analysis of water-level recovery data employs a plot of log-drawdown as a function of normalized time (time since pumping stopped divided by duration of pumping) and allows estimates of T at the pumped well that are not affected by well loss. This method is similar to the Theis (1935) method for recovery but incorporates early-dimensionless-time response, particularly useful for observation wells. Recovery of observation wells commonly does not satisfy the large-dimensionless-time approximation because dimensionless time is inversely proportional to radial distance squared.

A few more methods have been proposed to evaluate storage coefficient from recovery data including that of Bardsley et al., 1985, 1992; Ballukraya and Sharma, 1991; Banton and Bangoy, 1996. All these methods ignore pumping time effect and as a result the aquifer parameters calculated using them is approximate. Ramey (1980) presented type curves for drawdown during both the pumping and recovery periods on a single log-log plot based on Theis exact solution. This method is limited to cases where the drawdown during the pumping period agrees with that predicted by the Theis equation, which may not be the case, particularly for the pumped well. The estimation of storage coefficient from recovery data where Theis assumptions are not fully satisfied had been proposed by Zdankus, 1974; Fenske, 1977; Rushton and Holt, 1981; Mishra and Chachadi, 1985; Schmitt, 1988 and Tripp and Christian, 1989. Mishra and Chachadi, (1985) present recovery type curves similar to those of Ramey for drawdown during and after pumping, accounting for borehole storage in the pumped well. The possible erratic pumping rates and well loss limit the use of pumping period data in this case. Singh (2001, 2002) proposed simple methods that use the time derivative of drawdown for the evaluation of confined aquifer parameters and identification of boundaries from drawdown measured at an observation well during a constant rate pumping test. Another computationally simple method is proposed by him (Singh, 2003) for the estimation of transmissivity and storage coefficient from only residual drawdown at an observation well. This method does not require the last pumping drawdown, however, duration of pumping is required. Both Chenaf and Chapius (2002) and Samani and Pasandi (2003) used the Cooper Jacob approximation of the Theis solution and gave straight line plots in semilog graphs for estimating T and S from recovery data. Zeng et al. (2005) proposed an improved straight line fitting method for T and S estimation based on transformed recovery data. Another method for the interpretation of recovery tests is proposed (Willmann et al., 2007) based on the Theis recovery method that takes into account the heterogeneity of aquifers. The analytical properties of the solutions of the sensitivity equations for steady-state, two-dimensional shallow water flow was presented by Guinot and Cappelaere (2009)**.** These analytical properties are used to provide guidelines for model calibration and validation.

Samani and Pasandi (2003) introduced a new equivalent time ($\Delta t * t_p/t_p + \Delta t$) for the plot of recovery drawdown versus equivalent time for estimating transmissivity and Storativity. The t_p in the equivalent time represents pumping period and Δt the recovery time. This method uses the recovery data from one observation well only and does not require initial water level. The recovered drawdown data versus equivalent time is plotted on a double log sheet of the scale same as that of the Theis master curve. The field data curve plotted is superimposed with Theis master curve and an arbitrary match point for the best fit is taken and the values from the type curve and field data curve are used to estimate T and S.

In the present study the T and S values are mainly calculated from recovery data analysis employing Nozar Samani method and Jacob-Theis recovery method. Pumping test data (Table.4.10a-f.) for both draw down and recovery collected only from 2 wells due to

Table 4.10 a. Pumping test data of tube well at Kalarcode

Depth
PW-33 m, Distance from 15 m
OW -33 m PW
Screen:PW :24-30m, OW -24-30 m
Duration of Pumping : 1500 min
Pumping Started : 29.4.10 7.40 hrs
Static Water level - Pumping Well : 2.77 m bgl, OW :2.68 m bgl

Aquifer Type Sand (Semi-Confined)
Date of Test 29.4.10
Discharge 518 Cu.m/Day
Pump Stopped at 30.4.10 8.40 hrs

Drawdown Data -PW				Drawdown Data -OW			
Pumping Started (Min)	Draw dowm (m)	Pumping Started (Min)	Pumping Well	Pumping Started (Min)	Draw dowm (m)	Pumping Started (Min)	Draw dowm (m)
1	4.1	470	9.81	1	0.01	440	6.89
2	4.39	500	9.78	2	0.01	470	6.88
3	4.77	560	10.01	3	0.02	500	6.94
4	5.09	620	10.02	4	0.02	560	7.04
5	5.22	680	10.15	5	2.20	620	7.07
7	5.55	740	10.17	6	2.46	680	7.24
8	5.68	800	10.23	7	2.59	740	7.29
10	5.78	860	10.35	8	2.64	800	7.32
12	5.99	980	10.36	9	2.70	860	7.37
14	6.1	1100	10.47	10	2.80	980	7.44
16	6.12	1220	10.5	12	2.96	1100	7.48
18	6.37	1440	10.6	14	3.25	1220	7.66
20	6.47	1500	10.6	16	3.32	1440	7.77
25	6.65	-	-	18	3.46	1500	7.72
30	6.82	-	-	20	3.69	-	-
35	7.13	-	-	25	3.82	-	-
40	7.07	-	-	35	4.34	-	-
50	7.53	-	-	40	4.31	-	-
60	7.77	-	-	50	4.56	-	-
70	7.62	-	-	60	4.75	-	-
80	7.73	-	-	70	4.96	-	-
90	8	-	-	80	5.12	-	-
100	8.03	-	-	90	5.20	-	-
110	8.03	-	-	100	5.33	-	-
120	8.08	-	-	110	5.40	-	-
140	8.38	-	-	120	5.51	-	-
160	8.44	-	-	140	5.67	-	-
180	8.71	-	-	160	5.82	-	-
200	8.67	-	-	180	5.91	-	-
220	8.73	-	-	200	6.01	-	-
240	9.01	-	-	220	6.17	-	-
260	9.06	-	-	240	6.31	-	-
290	9.23	-	-	260	6.27	-	-
320	9.33	-	-	290	6.38	-	-
350	9.69	-	-	320	6.51	-	-
380	9.6	-	-	350	6.66	-	-
410	9.68	-	-	380	6.75	-	-
440	9.82	-	-	410	6.80	-	-

Table 4.10 b. Pumping test data of tube well at Cheruvaranam

Location	Cheruvaranam		
Depth (m)	46	Aquifer Type	Confined
Screen Portion	36.6-39.6 m	Date of Test	26-06-01
Duration (Minutes)	100		
Pump Started at	26/6/01 10.30 hrs	Discharge (Cu.m/Day)	60
	Pump Stopped at	26/6/01 12.10 hrs DrawDown-20.2m	
Pre-pumping Water Level (m.bgl)	3.6 m bgl		

Recovery Data				
Sl.No	**Time SincePumping Stopped (min)**	**Residual Draw down (m)**	**Equivalent time (min)**	**Recovered Draw down (m)**
1	3	17.10	2.9	3.1
2	5	14.40	4.8	5.8
3	10	10.03	9.1	10.17
4	18	9.00	15.3	11.2
5	20	8.02	16.7	12.18
6	30	4.67	23.1	15.53
7	40	3.26	28.6	16.94
8	50	2.73	33.3	17.47
9	60	2.25	37.5	17.95
10	70	1.95	41.2	18.25
11	80	1.73	44.4	18.47
12	90	1.57	47.4	18.63
13	100	1.45	50.0	18.75
14	120	1.26	54.5	18.94
15	140	1.10	58.3	19.1
16	160	1.00	61.5	19.2
17	180	0.91	64.3	19.29

Table 4.10 c. Pumping test data of tube well at Haripad

Location- HARIPAD　　Distance from mainwell (m)- 16.2
Depth (m) : PW :50m, OW :50 m　　Aquifer Type　　Confined
Screen Portion - 38-50 m　　Date of Test　　27/04/2010
Duration - 960　　Discharge (Cu.m/Day) : 69
Pump Started at - 27/4/10 17.00 hrs　　Pump Stopped at　　28/4/10 09.00 hrs
Pre-pumping Water levels (m bgl)　　: PW- 6.72, OW-6.48

Sl. No.	**t (Min)**	**Drawdown (m)**			**t_I (Min)**	**Recovery (Residual Drawdown)**			**Equivalent time**	**Recovered Drawdown (m)**
		Pumping Well	**t (Min)**	**OW (m)**		**Pumping Well**	**t_I (Min)**	**OW (m)**		
1	1	0.57	1	0.01	1	1.52	1	1.61	1.00	0.03
2	2	0.64	2	0.02	2	1.37	2	1.51	2.00	0.13
3	3	0.75	3	0.04	4	1.41	3	1.44	2.99	0.2
4	4	0.81	4	0.05	5	1.41	4	1.4	3.98	0.24
5	5	0.88	5	0.06	6	1.36	5	1.36	4.97	0.28
6	6	0.91	6	0.07	7	1.31	6	1.33	5.96	0.31
7	7	0.91	7	0.08	8	1.29	7	1.29	6.95	0.35
8	8	1.01	8	0.09	9	1.28	8	1.22	7.93	0.42
9	9	1.01	10	0.11	11	1.38	9	1.25	8.92	0.39
10	10	1	12	0.13	13	1.33	10	1.23	9.90	0.41
11	12	1.07	16	0.14	14	1.2	12	1.18	11.85	0.46
12	14	1.09	18	0.16	16	1.14	14	1.15	13.80	0.49
13	16	1.1	20	0.18	18	1.2	16	1.12	15.74	0.52
14	18	1.14	25	0.2	20	1.07	18	1.09	17.67	0.55
15	20	1.17	30	0.25	25	1.15	20	1.06	19.59	0.58
16	25	1.21	35	0.3	30	1.09	25	1.01	24.37	0.63
17	30	1.36	40	0.35	35	0.94	30	0.96	29.09	0.68
18	35	1.39	50	0.4	40	0.93	35	0.92	33.77	0.72
19	40	1.41	60	0.5	50	0.84	40	0.88	38.40	0.76
20	50	1.42	70	0.6	60	0.86	50	0.81	47.52	0.83
21	60	1.44	80	0.8	80	0.77	70	0.72	65.24	0.92
22	70	1.49	90	0.9	90	0.69	80	0.68	73.85	0.96
23	80	1.53	100	1	100	0.74	90	0.65	82.29	0.99
24	90	1.57	110	1.2	120	0.54	100	0.62	90.57	1.02
25	100	1.59	120	1.4	140	0.49	120	0.58	106.67	1.06
26	110	1.67	140	1.6	160	0.53	140	0.53	122.18	1.11
27	120	1.69	160	1.8	180	0.49	180	0.47	151.58	1.17
28	140	1.75	180	2	200	0.46	220	0.42	178.98	1.22
29	160	1.74	200	2.2	220	0.47	300	0.36	228.57	1.28
30	180	1.92	220	2.4	240	0.43	360	0.32	261.82	1.32
31	200	1.86	240	2.7	270	0.4	-	-		
32	220	1.97	270	3	300	0.44	-	-		
33	240	1.86	300	3.6	360	0.34	-	-		
34	260	1.84	330	1.44	-	-	-	-		
35	300	1.98	360	1.46	-	-	-	-		
36	330	1.97	420	1.49	-	-	-	-		
37	360	2.01	480	1.52	-	-	-	-		
38	420	2.04	600	1.57	-	-	-	-		
39	480	2.15	720	1.61	-	-	-	-		
40	600	2.14	855	1.62	-	-	-	-		
41	855	2.15	900	1.63	-	-	-	-		
42	900	2.18	960	1.64	-	-	-	-		
43	960	2.15			-	-	-	-		

t = time since pumping started

t_I= time since pumping stopped

OW = Observation well

Table 4.10 d. Pumping test data of tube well at Kommadi

Location	Kommadi	Well No.	
Depth (m)	17.5	Aquifer Type	Unconfined
Screen Portion	8.5-11.5 m	Date of Test	30/4/2010
Duration (Minutes)	100 min.	Discharge	259 Cu.m/Day
Pump Started at	30/4/10 10.00hr	Pump Stopped at	30/4/10 11.40 hrs
Pre-pumping Water Level	2.3 (m bgl)		

Drawdown Data			**Recovery Data**		
Sl.No	**Time Since Pumping Started (Min)**	**Draw down (m)**	**Sl.No**	**Time Since Pumping Stopped (Min)**	**Residual Draw down (m)**
1	1	0.10	1	10	3.70
2	2	0.20	2	20	3.52
3	3	0.45	3	30	3.51
4	4	0.75	4	40	3.51
5	5	1.22	5	50	3.50
6	6	1.50	6	60	3.49
7	7	1.70	7	240	3.30
8	8	2.16	8	300	3.20
9	9	2.30	9	360	3.10
10	10	2.60	10	420	3.05
11	12	3.02	-	-	-
12	14	3.03	-	-	-
13	16	3.07	-	-	-
14	20	3.10	-	-	-
15	25	3.15	-	-	-
16	30	3.20	-	-	-
17	35	3.29	-	-	-
18	40	3.34	-	-	-
19	45	3.40	-	-	-
20	50	3.47	-	-	-
21	60	3.51	-	-	-
22	70	3.51	-	-	-
23	80	3.51	-	-	-
24	90	3.51	-	-	-
25	100	3.50	-	-	-

Table 4.10 e. Pumping test data of tube well at Pallathuruthy

Location	Pallathuruthy
Depth (m)	60
Screen Portion	51.5-57.5
Duration (Minutes)	100 min.
Pump Started at	7/8/01 14.00 hrs
Pre-pumping Water level	8,72 m bgl
Aquifer Type	Confined
Date of Test	7/8/2001
Discharge (Cu.m/Day)	69
Pump Stopped at	7/8/01 15.40 hrs, DD- 44

Recovery data (Residual Draw down)			**Equivalent time (min)**	**Recovered Drawdown (m)**
Sl. No.	**Time since PumpingStopped (min)**	**Residual Draw down(m)**		
1	1	37	1	7
2	2	28	2	16
3	3	23	3	21
4	4	20	4	24
5	6	19	6	25
6	8	18	7	26
7	10	17	9	27
8	15	14	13	30
9	20	12	17	32
10	25	10	20	34
11	30	9	23	35
12	40	7	29	37
13	50	5	33	39
14	60	4	38	40

Table 4.10 f. Pumping test data of tube well at Thakazhi

LocatioN	Thakazi	Distance of OW from main well - 10 m	
Depth (m)	60	Aquifer Type	Sand
Screen portion	48-51, 54-57 m	Date of Test	4/5/2010
Duration	250	Discharge	52 Cu.m/Day
Pump Started at	04/5/2010 07.00 hrs	Pump Stopped at	04/5/2010 11.10 hrs
Pre-pumping Water Level		Pumping Well	4.26 mbgl
		Obs. Well	4.2 m bgl

Drawdown Data			**Recovery Data**						
Sl. No.	**Time since Pumping Started (Min)**	**Draw down in Obs. Well (m)**	**Sl.No.**	**Time Since Pumping Stopped (Min)**	**Residual Draw down in Puming Well (m)**	**Time Since Pumping Stopped (Min)**	**Residual Draw down in m Obs.Well**	**Equivalent time (min)**	**Recovered Draw down**
1	1	0.01	1	7	24.16	1	7.4	1	0.00
2	2	0.02	2	10	20.61	2	7.39	2	0.01
3	3	0.06	3	12	18.72	3	7.38	3	0.02
4	4	0.10	4	14	16.72	4	7.37	4	0.03
5	5	0.20	5	16	15.39	5	7.36	5	0.04
6	6	0.30	6	18	13.71	6	7.34	6	0.06
7	7	0.40	7	20	12.92	7	7.31	7	0.09
8	8	0.50	8	25	10.84	8	7.28	8	0.12
9	10	0.60	9	30	9.44	9	7.23	9	0.17
10	12	0.80	10	35	8.15	10	7.16	10	0.24
11	14	1.01	11	40	7.58	12	7.1	11	0.30
12	16	1.20	12	50	6.18	14	7.05	13	0.35
13	18	1.40	13	60	5.56	16	6.83	15	0.57
14	20	1.55	14	70	4.97	18	6.62	17	0.78
15	25	2.35	15	80	4.68	20	6.5	19	0.90
16	30	2.60	16	90	4.31	25	5.4	23	2.00
17	35	3.00	17	100	3.9	40	5.27	34	2.13
18	40	3.30	18	110	3.73	50	4.6	42	2.80
19	45	3.60	19	120	3.52	60	4.3	48	3.10
20	50	3.80	20	140	3.11	70	4.06	55	3.34
21	60	4.30	21	170	2.79	80	3.79	61	3.61
22	70	4.70	22	180	2.69	90	3.58	66	3.82
23	80	5.00	23	-	-	100	3.36	71	4.04
24	90	5.30	24	-	-	110	3.18	76	4.22
25	100	5.55	25	-	-	120	3.01	81	4.39
26	110	5.75	26	-	-	140	2.74	90	4.66
27	120	5.95	27	-	-	170	2.4	101	5.00
28	130	6.10	28	-	-	180	2.32	105	5.08
29	140	6.32	29	-	-	200	2.19	111	5.21
30	160	6.40	30	-	-	220	2.06	117	5.34
31	170	6.55	31	-	-	240	1.94	122	5.46
32	180	6.65	32	-	-	280	1.74	132	5.66
33	190	6.85	33	-	-	-	-	-	-
34	200	6.95	34	-	-	-	-	-	-
35	220	7.15	35	-	-	-	-	-	-
36	240	7.24	36	-	-	-	-	-	-
37	250	7.40	37	-	-	-	-	-	-

4.4.1 Aquifer parameters in Recent Alluvium

Pumping test has been carried out in 6 shallow tube wells taping the confined aquifers. The tube wells maintained by CGWB for monitoring have been used for conducting pumping tests. The pumping tests with constant discharge were conducted with 1HP submersible pump as the yields from the wells were poor .

Time – Draw down graphs

The draw down data of each well is plotted against the corresponding time and the residual drawdown data is plotted against the time (t/t^i) values on a semi logarithmic paper. The time-draw down curves are used to delineate the type of aquifer taped. The time- draw down curves also indicate the effect of well storage and boundary conditions from the trend of observed data plots. The data are analysed using Jacobs, Theis and Nozar Samani and Pasandi methods and the aquifer characteristics are given in Table 4.11.

Table 4.11. Aquifer parameters in the confined aquifer system of Recent alluvium

Sl. No	Location	Depth of well	Transmissivity in m^2/day			Storativity		
			Jacob	Theis	Samani and Pasandi	Jacobs	Theis	Samani and Pasandi
1	Haripad (distance to OW-16.2m)	50	20	19	20.38	2.3E-04	2.6E-04	4.74E-04
2	Kalarkode-(distance to OW-15m)	33	47.4	-	-	3.4E-03	-	-
3	Pallathuruthi	50	0.65	-	0.43	-	-	-
4	Kommadi	17.5	395	-	431	-	-	-
5	Cheruvaranam	46	0.75		0.78	-	-	-
6	Thakazhi-(distance to OW-19.6m)	46	1.59	20	1.56	2.6E-04	3.1E-04	4.17E-05

The pumping test results show low transmissivity values in the eastern part of the area and relatively high values in the coastal area. The transmissivity in coastal tract got a maximum value of 431 m^2/day at Kommadi. As the recovery data could not be collected only the draw down data was analyzed in the case of well at Kallarkode and the time draw down plots in semi-log sheet for Kallarkode is given in Fig 4.10

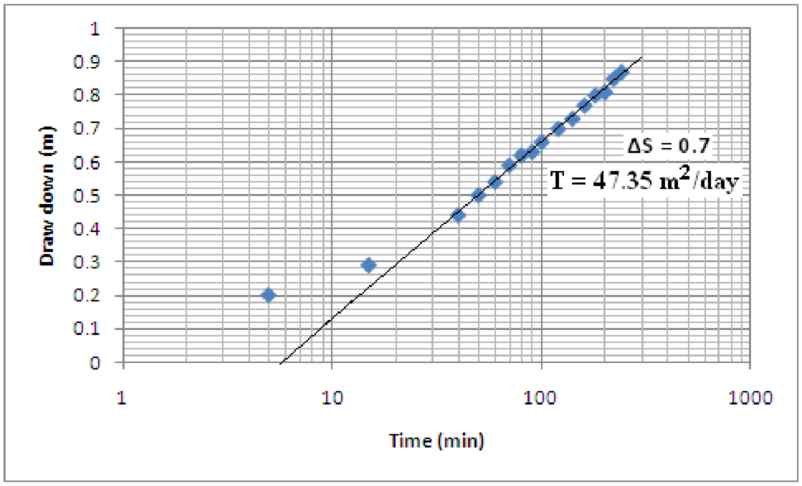


Fig 4. 10. Time vs Drawdown graph of the well at Kalarkode

The aquifer parameters estimated by Jacob, Theis, and Nozar Samani and Pasandi methods are comparable and the analysis of recovery data by Theis method and Samani's method gives similar T values and the Samani's method can be effectively used for determining the T and S values from recovery data. The recovery data plotting in semi-log sheets for six pumping tests as t/t^I vs Residual drawdown and Equivalent time vs Recovered Drawdown are shown in Fig.4.11 as a-e and a^I to e^I respectively. It could be seen from the plotting that some of the data are not falling in the straight line, indicating the deviation from the assumptions of the pumping test. However, the data is analysed here by avoiding the portion of the data affected by storage effect. The most important aspect in the use of the Nozar Samani and Pasandi method is that it does not require the initial water level or the static water level. Getting the actual static water levels is a real issue in the field many a times. Results from the present study indicate that in such situations this method can effectively be used.

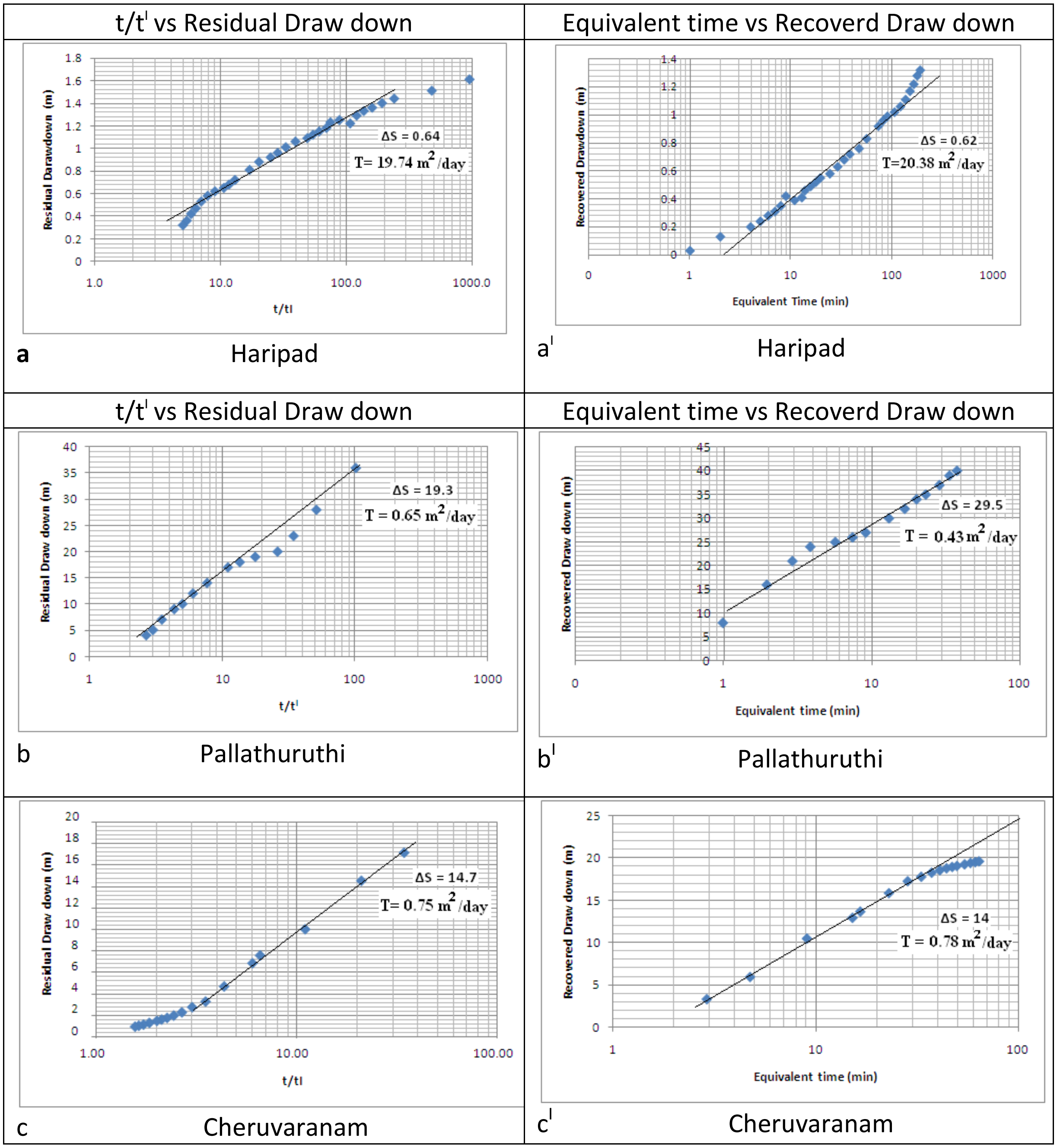


Fig 4.11. Semi-log plottigs of t/t' vs Residual Drawdown (a to c) and Equivalent time vs Recovered Drawdown (a' to c').

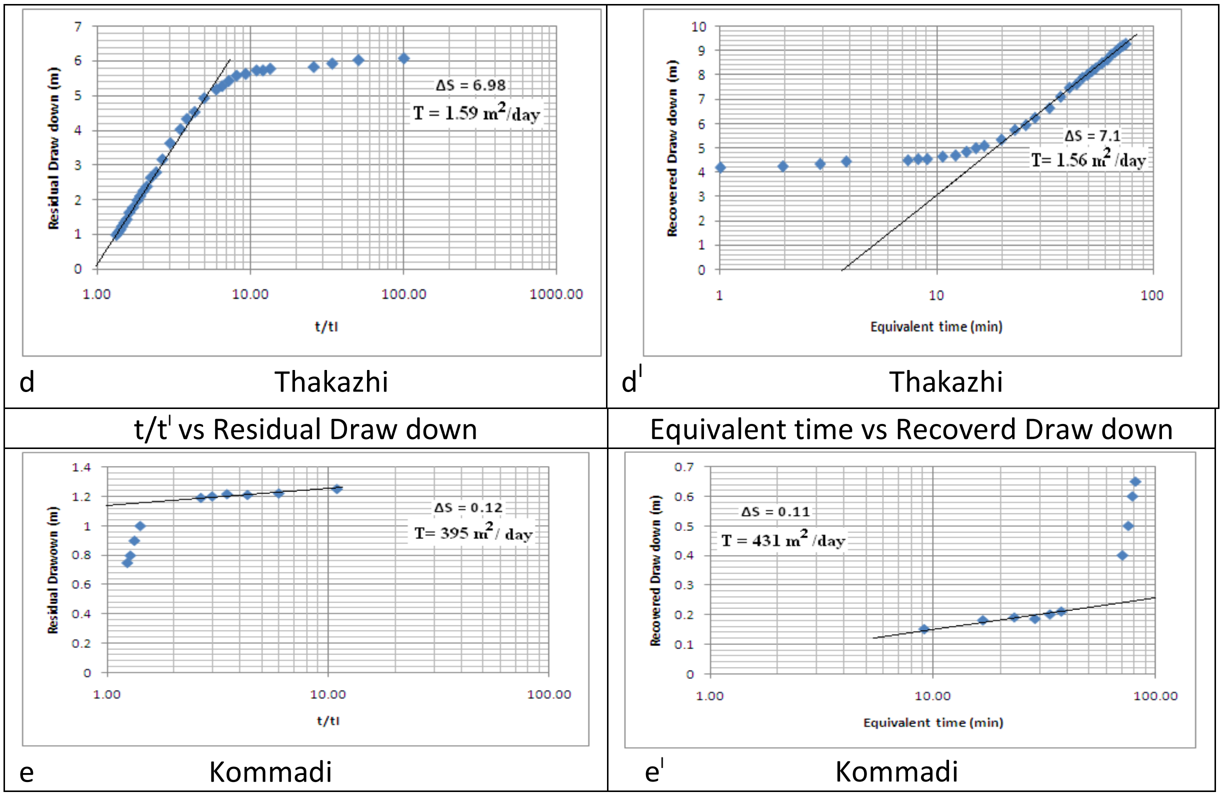


Fig 4.11. Semi-log plottigs of t/t' vs Residual Drawdown (a to e) and Equivalent time vs Recovered Drawdown (a' to e').

4.4.2 Aquifer parameters of Tertiary aquifers

The aquifer parameters estimated for the aquifer systems in the Tertiary beds are shown in Table 4.12. The data shows that there is wide variation in the yield of wells and the depth at which the aquifers are encountered. This is because of the spatial variations in the formation of sand and clay beds as described in Chapter 2. Similar to yield variations, considerable variation in the specific capacities of wells and transmissivity of the aquifers are observed. The wells taping the Warkali aquifer has transmissivity values ranging from 28 to 659 m^2/day, whereas in the Vaikom aquifer it is in the range of 6 to 530 m^2/day. However, the average Transmissivity and specific capacity are higher in the Vaikom aquifer and the details are shown in Table 4.13. The specific capacities of wells and the Transmissivity computed from pumping tests shows good correlation and are reflected in the Fig. 4.13.

Table 4.12 Aquifer parameters evaluated for the aquifer systems in the Tertiary beds

Well No	Location/ toposheet	Latitude in degrees	Longitude in degrees	Depth of well (mbgl)	Zones tapped	Discharge (lps)	SP capacity lpm/m	T m^2/day	Static WL mbgl	Remarks
1	Arthungal, 58 C/7.	9.6589	76.2997	103	91-100(Warkalai)	11.16	118.93	220.69	1.88	-
2	Haripad, 58 C /7	9.2919	76.4625	54	38-50(Warkalai)	12	53.8	27.6	3.17	-
3	Kandiyur 58 C/12.	9.2481	76.5267	148	129.86-145.0(Vaikom)	13.71	145.33	197.18	1.20	-
4	Karthikapalli- 58 C/7.	9.2500	76.4500	88	70-76, 80-86.	5	38.75	28.23	1.4	-
5	Karumadi, 58 C/7.	9.3792	76.3917	329	247-256, 262-268, 271-280, 283-289, 298-307,310-316,320-326.(Vaikom)	21.98	275.98	347.6	3.85 magl	Brackish Free flow.
6	Karuvatta, 58 C/7.	9.3167	76.4125	368	259-263, 281-296, 354-365.(Vaikom)	26.82	238.04	385.6	4.29 magl.	Free flow Brackish.
7	Mancombu, 58 C/7	9.4417	76.4222	70	37-42, 46.5-49.5, 54-68	7.1	168	278.9	2.66	Brackish.
8	Muttom, 58C/8.	9.2486	76.4903	253	163-178, 180-185, 188-193, 201-218, 222-225.(Vaikom)	6 lps	207.85	296.5	0.75magl	free flow
9	Parumala, 58 C/11.	9.3306	76.5403	82.55	46.33-57.91,70.7-76.2, 78.02-81.07(Vaikom)	22.08	198	125	4.95	-
10	Pattanakad, 58 C/6.	9.7444	76.3000	214.3	178-188, 191.4-194.5, 197.4-211.2. (Warkalai)	12.61	28.5	97.5	3.43	Brackish
11	Pulikeezhu, 58 C/11	9.4333	76.5439	70 62.5	25-28, 44-52, 56-61, 65-67 (Vaikom)	16.75	326.45	530	4.65	-
12	Ramankari, 58 C/7	9.4217	76.4575	113	103-110.(Vaikom)	0.9	4.34	6.07	0.80 magl.	Brackish
13	Thottappalli, 58 C/7.	9.3153	76.3897	174.14	87-93, 106-120, 130-136, 164-174(Warkalai)	49.26	141.57	413	1.24	-
14	Thrikunnapuzha, 58 C/7.	9.2667	76.4083	209.2	111-122, 126-132 (Warkalai)	41.66	405.2	659	0.95	-
15	Edattuva, 58 C/7.	9.3694	76.4764	109	78-84, 87-90.(Quilon), 99-105.(Vaikom)	45	309.55	NA	0.69 magl	Free flow

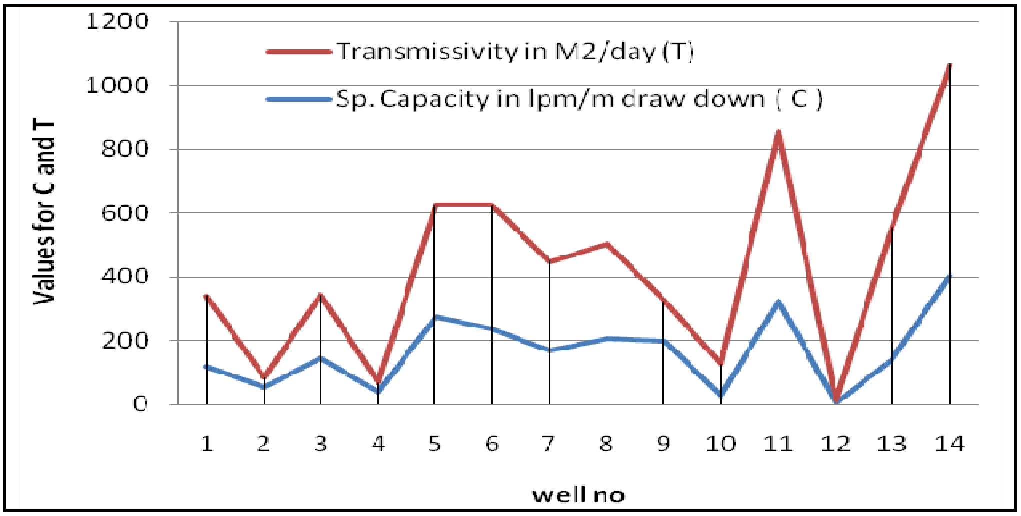


Fig. 4.12 The relation between Transmissivity and Specific Capacity

Table 4.13 Transmissivity and Specific Capacity in Warkali and Vaikom aquifers

Particulars	Warkali aquifer			Vaikom aquifer		
	Average	**max.**	**min.**	**Average**	**max.**	**min.**
Discharge in LPS	20	49	5	15	27	1
Specific Capacity in lpm/mdd	136	405	29	199	326	4
Transmissivity in Sq. m/day	246	659	28	270	530	6

4.5 Groundwater flow and resources in Tertiary aquifers

The tertiary strata are dipping gently towards the west and are intersected by a number of faults (Nair et al., 2009). The tertiary strata are outcropping east of Vembanad lake, along their eastern periphery. The tertiary aquifers are confined by thicker clays as could be seen from the cross sections and panel diagrams given in chapter 2. Towards the south east they are capped by laterites and along the coast overlain by recent sands.

Groundwater in the Tertiary aquifers is at high pressure heads as observed from the piezometric levels in the area. However, the hydraulic gradients are small and in the order of 10^{-4}. Combined with hydraulic conductivities of about $5x10^{-3}$ m/s the flow rates will be less than a meter per year. The Vaikom beds have lower pressure heads, indicating a leakage upwards through the Quilon beds. The above mentioned faults do not seem to have created direct hydraulic contacts.

The largely unconsolidated sediments are likely to have "healed and sealed" after the faulting. In parts of the Warkali aquifer where no pumping takes place the gradients are of the same order as in the Vaikom beds. With slightly higher hydraulic conductivities the movements of water would be slow also here. However there is at places, especially near Alleppey considerable extraction creating cones of depression in the pressure heads. In undisturbed conditions the flow rates seem to be very small in both Vaikom and Warkali aquifers. Recharge may occur along the SSE part of the area where the tertiary beds are overlain by laterites. The ground is also somewhat higher here creating gradients.

The flow in the confined aquifer system is estimated based on the transmissivity, hydraulic gradient and length of the aquifer system. The rate of groundwater flow in the aquifer system is generally expressed as;

Q= TIL, where

T is transmissivity which is generally estimated from pumping test data.

I is the hydraulic gradient which is computed from the flow net and

L is the length of the aquifer.

Groundwater flow in the Warkali aquifer system was estimated at 36 MCM and that in the Vaikom aquifers as 11 MCM. as per the 1992 estimation by CGWB. The total groundwater draft from the Warkali aquifer was 25 MCM and from the Vaikom aquifer was 4 MCM. Thus a balance resource of 17 MCM was available for future development.

Over the years, the groundwater draft from these aquifers gradually increased and no criteria is being followed in the case of draft from individual wells as well as from the aquifer as a whole. Many of the flowing wells in these aquifers have stopped auto-flow because of the impact of increased draft. This indicates that the groundwater draft from these aquifers is to be restricted to make it sustainable. The piezometer network representing the Tertiary aquifers are insufficient to work out the flow in the aquifer system at present.

CHAPTER 5
HYDROCHEMISTRY

5.1 Introduction

The suitability of groundwater for domestic, agriculture and industry is normally ascertained based on the concentration of various dissolved ionic species. The hydrochemistry in a geological terrain unaffected by pollution or contamination can better be interpreted from major ion studies alone. However, in complex hydrogeological environments water analysis for other relevant minor and trace elements also have to be analysed for better interpretation of the hydrochemical scenario existing in aquifer systems. Groundwater and surface water geochemical studies can provide a better understanding of potential water quality variations due to various factors (Stumm and Morgan, 1996; Appelo and Postma, 2005; Stutter et al., 2006). The chemical composition of water and its mineralization processes are imperative in classifying and assessing drinking water quality (WHO, 2004; Kozisek, 2005; Sadashivaiah et al., 2008) while irrigation water quality criteria can be used as a guideline by farmers for selecting appropriate management practice to overcome potential problems arise out of salinity (Gupta et al., 2009; Ramesh and Elango, 2012).

Water analysis gives information on regional distribution of water quality and their suitability for various uses. Such information can be depicted as graphs and maps for easy and better comprehension. More than that, the hydrochemistry can be effectively used for tracing the origin and history of water. In a groundwater flow regime water chemistry constantly undergoes changes/ modification due to various processes such as dissolution of minerals, precipitation of dissolved ions under unstable conditions, cation exchange etc. The hydrochemical evolution along the flow paths are significantly altered under anthropogenic interferences and consequent pollution of aquifer systems (Drever, 1982; Langmuir, 1997; Abu-Jabeer, 2001; Singh et al, 2007). The effects of pollution in the flow system can easily be identified through comparison of dissolved ions and ion ratio studies in simple terms (Hem, 1985).

Tremendous work has been reported on the water quality and its relation to the geology, environment and health. The water quality standards have been formulated by World Health Organization and many countries on drinking water, irrigation and Industrial uses (WHO, 1993; BIS 1991). The studies on various agro-climatic regions in India shows the influence of climate on the enrichment of ions in groundwater (Lawrence et al, 2000; Umar and Sami Ahmed, 2000; Ahmed et al., 2002; Rajesh and Murthy, 2004). Suitability of water for irrigation has been assessed using various properties or ionic ratios. These include EC, Sodium Adsorption Ratio (SAR), Kelley's Ration (KR) and Residual Sodium Carbonate (RSC) (Gupta et al., 2009; Ramesh and Elango, 2012).

In this chapter, the data pertaining to various hydrochemical parameters viz., TDS, EC, TH, pH and the concentration of the ions Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO_3^{2-}, F^{-} and Fe^{2+} are discussed.

5.2 Hydrochemical parameters in the surface waters

Surface water samples were collected from 20 locations during May 2009 from the area, which include canals, lake, and ponds. They were analysed for major ions viz; ions Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO_3^{2-} and physical parameters pH, EC and temperature. The range in concentration of dissolved ions and physical parameters are given in Table 5.1 and the chemical data of surface water samples are given in Table-5.2.

The surface water drainages like canals and back water are affected by tides and seasonal changes in the river flows in the area. The distribution of cations, anions and EC depicted in Fig. 5.9 clearly reflect some of the samples undergone sea water mixing in canals and in lake waters. The high EC values are mainly contributed by Na and Cl ions. In most of the samples with high EC values are having high Mg concentrations than Ca concentrations indicative of sea water mixing with the fresh water in the affected part of the canals and rivers.

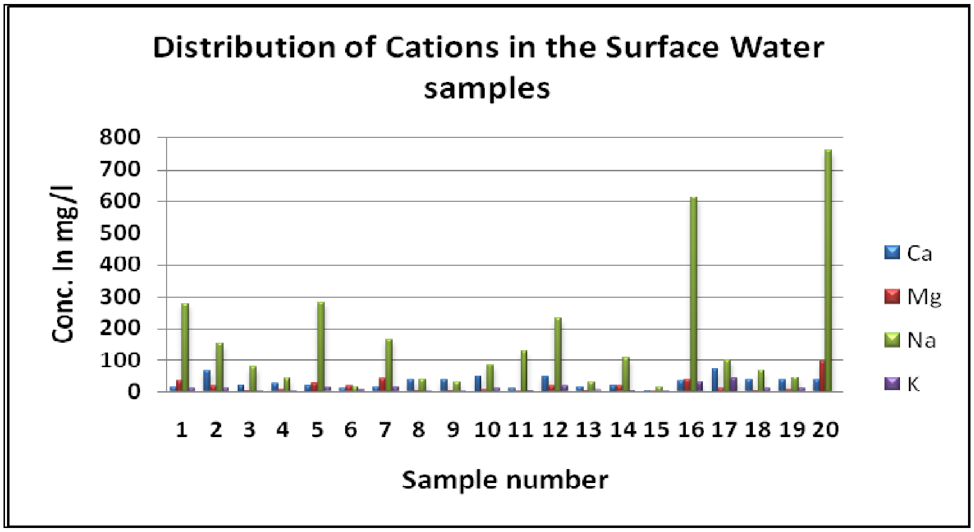
Table 5.1. Range in concentration of dissolved ions in surface water

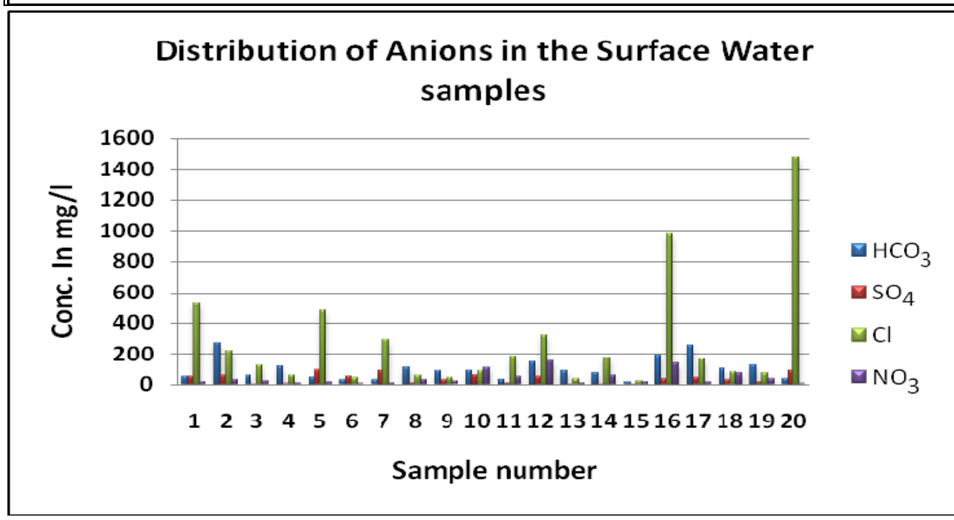
Major ions in mg/l & Physical Properties	Average	Max	Min	SD
pH	7.38	8.18	6.56	0.51
EC (μs/cm at 25°C)	1032	4440	51	1138
Ca	30	68	4	17
Mg	18	95	2	21
Na	162	756	14	198
K	11	41	1	10
HCO_3	98	268	19	72
SO_4	37	92	2	31
Cl	271	1475	21	365
NO_3	41	154	5	44

The surface water bodies in the form of rivers canals and ponds in this area are essentially part of the shallow waters in the phreatic aquifer system and they do interact each other and modify the groundwater chemistry and vice versa. The surface water chemistry may help in explaining the spatial variations in the geohydrochemistry, especially that in the phreatic aquifer system in this area.

5.3 Hydrochemical parameters in the groundwater

The study area comprises multi aquifer system existing under confined and unconfined conditions representing different geological horizons. The hydrochemistry of these aquifers differs significantly in composition and concentration of dissolved ions. The hydrochemistry of phreatic aquifer system has been studied from the water quality data of 46 water samples analysed during pre monsoon and 32 water samples during the post monsoon. The shallow confined/semiconfined aquifer system has been studied from the water quality data of 30 water samples analysed during pre monsoon and 32 water samples during the post monsoon.





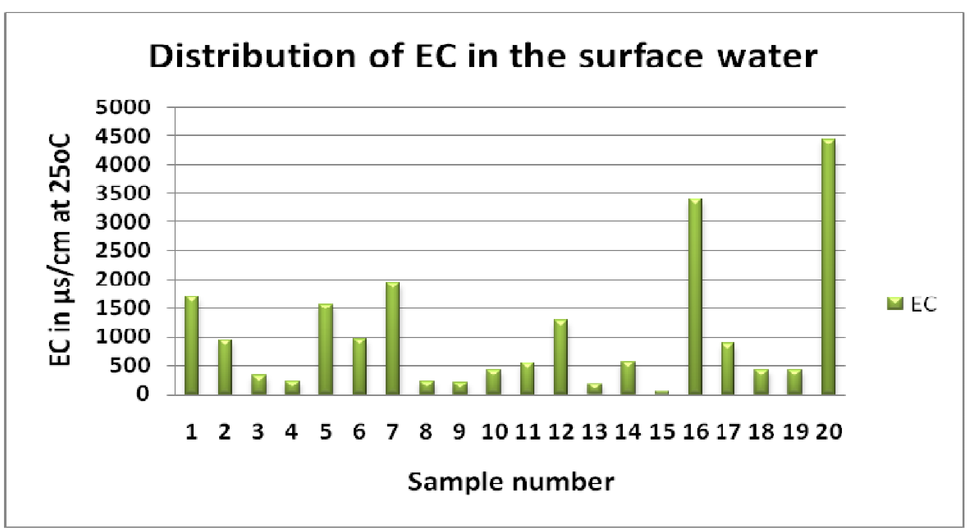


Fig.5.1. Cations, anions and EC distribution in the surface water samples

Table 5.2. Analytical Results of Surface water Samples from Kuttanad area (May 2009)

Sample No.	Location	Latitude in degrees	Longitude in degrees	WT	pH	EC	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3
				°C		µS/cm at 25°C	mg/l							
1	Thottapalli Canal -Bridge	9.3169	76.3878	28	7	1707	16	32	276	12	52	53	523	14
2	Fly over bridge (in front of Corporation office) - Alleppey-Canal	9.4936	76.3400	27	8	941	64	17	151	12	268	56	222	30
3	Kanjikkuzhi pond water-Cherthala	9.6222	76.3317	31	7	317	20	5	77	3	56	3	121	21
4	Alleppey-Cherthala Highway Canal	9.6794	76.3389	28	7	228	24	7	39	4	118	5	60	11
5	Attachira Palam- Canal	9.6772	76.3781	29	7	1549	20	27	280	13	47	92	481	17
6	Vembanad-Thanneermukkam Bund-Canal	9.6753	76.3969	29	7	951	12	17	14	8	28	52	41	5
7	Thanneermukkam Bund (Sea side - North)	9.6753	76.3969	30	7	1945	16	39	164	14	28	89	288	10
8	Vaikkom Boat Jetty (near to KTDC restaurant)	9.7492	76.3889	30	7	221	36	5	38	1	110	11	60	30
9	Attarapalam-Canal	9.7383	76.4033	28	8	208	36	5	28	1	85	33	45	19
10	Kalchira Bridge-Achinakam-Canal	9.6550	76.4264	27	8	415	48	7	83	12	88	62	85	107
11	Koduthuruthil Canal (Adj. To Puthankari Pada Shekaram, Near cattle shed)	9.6819	76.4433	29	7	547	12	2	128	5	33	10	182	49
12	Koduthuruthil Bridge-Canal	9.6833	76.4625	28	7	1279	48	17	228	19	148	50	321	154
13	Pathiramanal Island - Pond	9.6167	76.3856	30	8	183	16	5	28	7	88	4	36	10
14	Pallathuruthy River	9.4633	76.3619	29	8	555	20	17	106	6	75	2	176	55
15	Mankompu Canal	9.4383	76.4281	29	7	51	4	2	16	2	19	2	21	15
16	Kidangara Bridge- River	9.4208	76.4925	27	7	3390	32	37	612	28	188	35	973	137
17	Kumarakom-Kavalakkal Palam- Canal	9.5931	76.4353	30	8	872	68	12	97	41	259	45	165	18
18	Thiruvarpu Canal	9.5789	76.4722	30	8	417	36	5	64	12	102	31	78	74
19	Edathva Bridge- Canal	9.3642	76.4778	30	7	418	36	7	45	10	124	16	74	35
20	Karumadi Canal (near to Co-op. Bank)	9.3806	76.3886	27	8	4440	36	95	756	Nil	38	89	1475	6

The hydrochemistry of Warkali and Vaikom aquifers in the Tertiary beds are studied from the water quality data of 51 water samples analysed during pre monsoon and 41 water samples during the post monsoon. The water quality of surface water from 20 locations has been analysed only for the pre monsoon period. The spatial distribution of sampling sites in phreatic aquifer, confined aquifer of Recent alluvium and Tertiary aquifers is shown in Figure 5.2.

The chemical analysis results of water samples from phreatic aquifer for pre- and post-monsoon periods are shown in Table 5.3a and 5.3b respectively. The analytical results for confined aquifer in Recent alluvium for pre- and post-monsoon seasons are given in Table 5.4a and 5.4b and for Tertiary aquifers the analytical results are given in Table 5.5a and 5.5b.

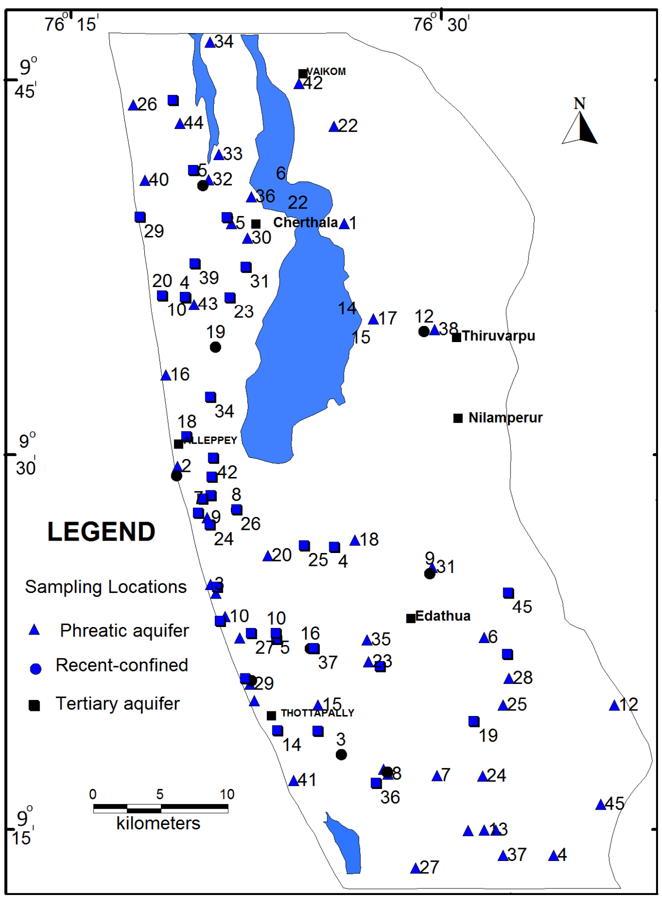


Fig 5.2 Water sampling sites in phreatic, confined (Recent alluvium) and Tertiary aquifers

Table 5.3a. Analytical Results of Groundwater Samples from Phreatic Aquifers in Kuttanad area (May 2009)

Sample No.	Location	Lat.	Long.	WT	pH	EC	T.H.	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F
						µS/cm at 25°C	(As Ca CO_3)	---------------mg/l---------------									
1	Achinagam	9.6542	76.4347	30	6.85	345	96	30	5	13	7	1	78	18	50	4	0.00
2	Alleppey	9.4920	76.3220	26	7.57	313	170	66	5	5	1	4	186	5	38	8	0.00
3	Alleppey Town	9.4139	76.3444	27	8	318	110	40	2	22	4	2	151	20	7	12	0.26
4	Aranootimangalam	9.2330	76.5760	28	8.00	126	26	10	1	11	1	0	17	16	12	6	0.00
5	Cheruvaranam	9.6542	76.3583	27	8.01	207	80	31	1	11	7	2	90	12	28	2	0.21
6	Edathua	9.3780	76.5290	27	7.69	325	106	26	10	20	3	0	132	28	16	0	0.30
7	Haripad-1	9.2861	76.4972	27	6.46	326	110	32	7	27	5	1	94	22	68	14	0.00
8	Haripad-2	9.2870	76.4640	27	6.36	212	80	20	7	14	3	2	47	17	49	9	0.18
9	Kaidavana	9.4580	76.3420	27	8.03	391	140	40	10	27	12	2	108	33	87	5	0.13
10	Kakazham	9.3920	76.3540	27	6.33	638	140	37	12	80	16	2	149	132	34	3	0.16
11	Kalarcode	9.3778	76.3639	26.8	8.25	314	140	52	2	10	4	3	137	19	29	5	0.26
12	Kallissery	9.3330	76.6170	28	7.22	55	14	5	1	8	1	1	12	7	9	1	0.18
13	Kandiyoor	9.2500	76.5290	27	9.22	140	42	14	2	7	4	12	12	13	12	0	0.10
14	Karuvatta-1	9.2903	76.4611	27	7.86	263	163	56	5	26	7	2	153	34	63	3	0.31
15	Karuvatta-2	9.3330	76.4170	28	8.67	664	170	60	5	47	45	5	200	85	43	35	0.34
16	Kattoor	9.5530	76.3140	27	8.19	138	60	23	1	2	1	0	71	6	1	2	0.18
17	Kumarakom	9.5903	76.4542	27	7.75	947	340	112	15	40	44	5	479	33	73	2	0.00
18	Mancombu	9.4431	76.4417	26	6.7	48.9	20	4	2	38	1	1	25	39	31	2	0.22
19	Mavelikara	9.2500	76.5370	27.5	7.96	261	160	56	5	26	7	2	153	34	50	3	0.31
20	Nedumudi (pupalli)	9.4330	76.3830	27	8.55	1037	250	52	29	96	8	7	177	188	76	7	0.56
21	Neerkunnam	9.4080	76.3480	27	7.83	173	54	17	3	11	3	0	34	18	27	8	0.29
22	New Vechur	9.7189	76.4278	30	7	220	104	35	4	4	1	1	93	4	31	4	0.00
23	Pacha	9.3620	76.4510	27	6.87	402	140	48	5	30	14	2	129	32	42	6	0.21

Continued

Sample No.	Location	Lat.	Long.	WT	pH	EC	T.H.	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F
				^oC		µS/cm at 25^oC	(As Ca CO_3)	----------mg/l----------									
24	Pallipad	9.2860	76.5280	29.5	7.89	382	160	56	5	21	42	4	238	36	23	8	0.31
25	Parumala	9.3330	76.5420	28	7.8	62	12	4	1	4	0	3	8	6	1	1	0.07
26	Pattanakad	9.7330	76.2920	27	8.59	427	202	74	4	8	4	7	220	10	4	6	0.15
27	Pattiyur	9.2248	76.4830	27	8.07	157	42	16	1	11	1	0	22	28	9	7	0.20
28	Pulikeezh	9.351	76.546	27.5	7.96	261	160	56	5	26	7	3	152	34	51	3	0.31
29	Purakkad	9.3470	76.3710	28	8.41	365	102	28	8	24	12	0	112	34	23	5	0.18
30	Puthanangadi	9.6444	76.3694	27	6.33	638	140	37	12	80	16	3	150	20	178	3	0.16
31	Ramankari	9.4250	76.4940	27	8.47	355	104	32	6	26	6	5	115	40	5	3	0.17
32	Sherthalai	9.6833	76.3431	26	7.79	378	180	56	10	15	5	2	129	28	77	2	0.03
33	Sherthalai	9.7000	76.3500	28	8.56	1130	180	62	6	142	5	7	165	231	36	4	0.44
34	Thaikattusseri	9.7750	76.3440	27	8.16	142	52	18	2	7	3	0	46	10	16	3	0.22
35	Thakazhi	9.3764	76.45	27	8.8	950	240	58	23	92	8	24	195	135	63	4	0.42
36	Thannirmukkom	9.6720	76.3717	26	7.77	152	60	20	5	7	6	6	62	7	26	4	0.19
37	Thevery	9.2330	76.5420	27	8.89	286	86	11	14	16	6	12	63	30	22	1	0.09
38	Thiruvarpu	9.5833	76.4958	29	7.1	362	108	34	6	14	6	3	144	7	24	2	0.22
39	Thottapalli	9.3361	76.3739	27	7.99	1012	210	52	19	94	67	5	401	79	60	16	0.00
40	Thuravur	9.6830	76.3000	27	8.69	288	112	42	2	9	5	7	100	16	19	7	0.36
41	Trikkunnapuzha	9.2830	76.4004	28	8.6	385	164	55	6	13	3	7	171	27	4	3	0.06
42	Vaikom	9.7472	76.4042	29	7.3	178	84	29	3	12	1	4	84	24	7	4	0.06
43	Valavanad	9.6000	76.3330	27	8.79	293	134	51	2	4	3	12	144	9	3	1	0.12
44	Vayalar	9.7208	76.3236	28	7.01	178	70	24	2	15	5	1	75	24	19	5	0.27
45	Venmani(thazhagam)	9.2670	76.6080	28	9.14	228	46	9	6	21	2	19	15	31	14	1	0.38
46	Chettikulangara	9.2497	76.5183	28	7.72	117	30	10	2	8	2	0	7	24	11	3	0.34

Table 5.3b. Analytical Results of Groundwater Samples from Phreatic Aquifers in Kuttanad area (November 2009)

Sample No.	Location	Latitude	Longitude	WT	pH	EC	Total Hardness (As $CaCO_3$)	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F
				^oC		µS/cm at 25^oC		------------------------------------Mg/l---------------------------------------									
1	Haripad-1	9.2861	76.4972	24	8.16	425	375	93	47	37	7	3	117	32	352	2	0.17
2	Haripad-2	9.2864	76.4975	24.5	8.28	175	69	23	3	19	1	6	37	36	33	6	0.28
3	Thottapalli	9.3361	76.3739	26.5	8.41	385	291	78	24	24	4	12	233	18	152	2	0.15
4	Kalargode	9.3778	76.3639	27	8.36	287	214	77	5	6	3	10	178	16	78	4	0.08
5	Alleppey (Light house)	9.4917	76.3333	26	8.39	300	335	99	21	7	1	8	233	35	135	2	0.06
6	Alleppey (front of Coir Board)	9.5458	76.3375	25	7.85	207	287	36	33	6	2	0	114	20	115	4	0.12
7	Cherthala	9.6833	76.3431	26.5	7.46	306	182	59	8	17	10	0	42	36	158	2	0.16
8	Vayalar Jn.-	9.7208	76.3236	27	7.45	129	159	31	20	6	6	0	123	45	23	4	0.08
9	Thanneermukkam	9.6750	76.3833	25	7.4	104	88	16	12	5	3	0	31	12	54	8	0.11
10	Vaikkom Jn.	9.7472	76.4042	27.5	7.67	84	37	9	3	9	1	0	20	23	10	3	0.08
11	Vechoor	9.7189	76.4278	27	7.13	236	102	37	2	24	3	0	68	31	59	16	0.24
12	Achinakam	9.6542	76.4347	30	6.85	345	96	30	5	13	7	0	84	18	48	4	0.00
13	Puthenangadi	9.6444	76.3694	28	7.5	1176	170	44	15	92	9	0	134	32	229	4	0.12
14	Pathiramanal Island	9.6189	76.3872	29	7.04	161	30	6	4	10	12	0	22	28	8	10	0.00
15	Mankompu	9.4431	76.4417	31	7.69	518	140	38	11	33	3	0	113	35	72	20	0.29
16	Kumarakom	9.5903	76.4542	26.5	7.94	683	300	72	29	44	37	0	147	5	302	2	0.21
17	Thiruvarpu	9.5833	76.4958	26	8.03	50	46	15	2	31	1	0	20	45	32	4	0.07
18	Edathva	9.3642	76.4775	27	7.35	429	136	40	9	16	7	0	112	12	84	3	0.13
19	Bunglow Parambu	9.4153	76.3514	26	8.2	378	184	61	8	11	4	0	137	7	102	2	0.19
20	Ramankary	9.4389	76.4597	27	6.6	264	88	18	11	15	2	0	89	15	35	3	0.18
21	Kommady	9.5158	76.3306	26	7.23	358	116	43	2	17	6	0	107	35	33	4	0.15
22	Devaswom parambil -	9.5156	76.3308	27	6.48	139	48	13	4	7	2	0	38	18	8	6	0.06
23	Kanniparambil	9.5157	76.3310	28	7.75	418	120	37	7	22	9	0	91	43	46	6	0.13
24	Cheriyakalam	9.5157	76.3312	27	7.33	424	128	40	7	24	7	0	103	12	98	2	0.09
25	Noorani Masjid	9.4928	76.3258	26	8.05	258	132	51	1	5	1	0	102	13	42	1	0.09
26	Alleppey (Rotary Comm.hall)	9.4928	76.3333	27	7.25	178	60	22	1	34	4	0	24	29	78	2	0.11
27	Kozhikuttungal	9.4928	76.3367	26.5	8.4	727	220	79	6	40	4	0	259	3	120	2	0.24
28	Chungam	9.4922	76.3475	27	7.8	443	152	58	2	23	2	0	125	44	56	2	0.11
29	Cheruvaranam	9.6542	76.3583	27	7.10	233	80	24	5	17	5	0	76	38	13	2	0.13
30	Alleppey beach	9.4861	76.3139	27.5	8.33	353	152	53	5	12	3	0	148	19	42	3	0.41
31	Thundiyil	9.4811	76.3375	27.5	8.11	461	108	34	6	128	9	0	181	13	255	3	1.03
32	Kunnapuzha	9.4808	76.3422	28	8.03	286	100	32	5	19	5	0	108	20	45	1	0.22

Table 5.4a. Analytical Results of Groundwater Samples from confined Aquifers of Recent alluvium (May 2009)

Sample no	Location	Latitude	Longitude	Depth in m	WT	pH	EC	Total Hardness	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	NO_3	F	Fe^{2+}
					°C		µS/cm at 25°C	(As Ca CO_3)	mg/l										
1	Haripad PZ-1	9.2886	76.4636	30	29	6.70	141	52	14	4	18	3	0	41	27	25	6	0.04	1.07
2	Haripad PZ-2	9.2886	76.4637	30	29	8.20	749	128	19	19	91	3	4	134	4	128	52	0.21	1.26
3	Karuvata	9.3000	76.4325	27	27.5	6.17	109	60	16	5	13	2	0	28	18	21	29	0.02	2.18
4	Kanjikuzhi	9.6044	76.3272	27	27.5	7.3	92	32	10	2	12	0	0	24	10	10	20	0.00	0.41
5	Thnnirmukkom-1	9.6794	76.3389	25	28	7.69	167	44	13	3	28	3	0	44	10	42	13	0.02	1.95
6	Thannirmukkom 2	9.6775	76.3922	27	27	7.8	100	40	14	1	25	1	0	40	10	31	15	0.07	0.80
7	Kallarcode	9.4611	76.3361	35	31.5	8.1	160	56	14	5	5	3	0	55	11	10	3	0.00	0.18
8	Pallathuruthy pz	9.4633	76.3617	50	28.5	7.67	4404	500	40	97	620	23	0	378	30	1095	124	1.76	8.37
9	Kidangara	9.4208	76.4925	38	27	7.01	2990	220	56	19	605	9	0	141	7	990	157	0.74	4.91
10	Karumadi PZ	9.3806	76.3886	30	30	8.14	3621	412	72	56	626	26	0	24	106	1309	13	0.32	0.33
11	Thannirmukkom PZ	9.6775	76.3922	30	28	7.01	469	100	32	5	50	58	0	79	42	122	39	0.06	1.70
12	Thiruvarpu PZ-1	9.5819	76.4883	42	29	5.5	939	130	29	14	20	9	0	88	21	50	23	0.11	2.10
13	Thiruvarpu PZ-2	9.5819	76.4884	41	29	4.25	13500	1800	301	255	2250	32	0	325	5	4550	5	0.00	4.06
14	Kumarakom PZ-1	9.5875	76.4364	60	30	6.96	564	96	19	12	42	34	0	32	116	72	4	0.64	0.28
15	Kumarakom PZ-2	9.5876	76.4364	40	30	7.21	1691	236	36	35	270	9	0	30	111	527	5	0.13	0.27
16	Thakazhi deep PZ	9.3708	76.4117	60	27	7.85	813	350	61	48	40	5	0	218	2	186	18	0.34	0.60
17	Thakazhi PZ	9.3708	76.4118	46	29	8.16	1761	240	80	10	366	182	0	290	253	458	32	0.08	1.41
18	Kommady- PZ	9.5119	76.3282	30	26	7.5	353	60	28	14	58	3	0	63	6	93	103	0.03	1.60
19	Mannanchery PZ	9.5714	76.3475	26	27	7.34	165	60	16	5	21	7	0	37	7	30	54	0.66	0.91
20	Preethikulangara PZ	9.6058	76.3117	70	30.5	8.39	4500	80	26	20	934	34	0	122	16	1538	18	1.75	8.90
21	Kanjikuzhi- PZ-1	9.6578	76.3556	46	27	7.18	386	160	48	15	18	9	0	181	6	31	56	0.80	8.45
22	Kanjikuzhi- PZ-2	9.6579	76.3556	60	28	7.44	413	80	24	5	54	5	0	110	5	74	23	0.22	0.56
23	Kanjikuzhi- PZ-3	9.6578	76.3557	60	29	6.92	298	120	40	5	29	7	0	129	6	43	48	0.24	2.45
24	Pazhaveedu	9.4861	76.3214	18	27	8.30	573	160	45	16	48	6	5	180	5	72	55	0.17	3.69
25	Kakkazham	9.3889	76.3508	18	29.5	8.39	908	20	40	12	148	7	12	179	3	230	41	1.56	4.57
26	Purakkad- PZ-1	9.3492	76.3717	65	29	7.26	1803	360	88	34	284	18	0	296	13	496	141	0.41	7.86
27	Purakkad- PZ-2	9.3493	76.3717	65	28	7.20	2991	600	98	87	480	21	0	482	85	817	238	0.26	0.20
28	Kumarakom PZ 3	9.5877	76.4364	60	30.5	6.28	13520	3050	385	508	1350	52	0	114	294	4137	250	0.00	0.05
29	Kanjikuzhi- PZ-4	9.6579	76.3557	40	27.5	7.84	15160	1650	228	262	2980	75	0	116	121	6167	123	2.23	5.97
30	Purakkad PZ 3	9.3492	76.3718	69	29	7.47	4764	690	102	106	840	16	0	201	253	1606	139	0.36	0.13

Table 5.4b. Analytical Results of Groundwater Samples from confined Aquifers of Recent alluvium (Nov.2009)

Sample No	Location	Latitude	Longit ude	Depth in m	WT	pH	EC	TH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	F	Fe^{2+}
					°C		µS/cm at 25°C	(As Ca CO_3)	------------------------------mg/l------------------------------									
1	Haripad - PZ1	9.2886	76.4636	30	24.5	8.36	310	204	71	7	23	2	171	44	13	27	0.19	0.16
2	Haripad - PZ2	9.2886	76.4636	30	24	8.36	462	169	57	7	40	4	161	86	14	7	0.22	1.68
3	Haripad - PZ3	9.2886	76.4636	30	24.5	8.41	212	135	39	9	15	3	95	40	9	17	0.23	0.68
4	Karuvatta	9.3000	76.4325	27	25.5	8.19	124	92	31	4	8	1	81	27	5	7	0.05	0.78
5	Cherthala	9.6044	76.3272	27	27.5	7.83	64	59	12	7	3	1	28	11	2	28	0.05	1.24
6	Alleppey l	9.6794	76.3389	25	27	7.55	115	76	25	4	9	4	72	23	3	20	0.07	1.26
7	Thanneermukkam-1	9.6775	76.3922	27	26	7.66	95	132	24	18	5	1	73	20	25	40	0.01	0.57
8	Thannirmukkom-PZ	9.6775	76.3939	30	25	6.73	106	48	15	3	16	2	71	18	2	2	0	0.12
9	Kalargode	9.4611	76.3361	35	31.5	8.1	160	66	18	5	5	3	64	10	11	3	0.02	0.18
10	Pallathuruthy pz	9.4633	76.3617	50	30	6.89	4500	709	67	132	942	48	975	1498	2	59	0.77	1.23
11	Kidangara	9.4208	76.4925	38	26	6.78	3031	240	34	38	788	26	284	1235	9	61	1	0.65
12	Thannirmukkom PZ	9.6775	76.3922	30	28	7.01	469	100	32	5	78	58	79	142	42	50	0.06	1.7
13	Thiruvarpu	9.5819	76.4883	42	27	5.45	412	70	16	7	46	3	29	24	2	141	0.13	2.03
14	Thiruvarpu	9.5819	76.4883	41	27.5	4.24	13240	1801	273	272	3300	48	76	6436	8	54	0.94	5.84
15	Kumarakom -PZ2	9.5875	76.4364	60	29	6.14	495	140	24	19	148	6	47	259	41	72	0.16	0.06
16	Kumarokam PZ -3	9.5875	76.4364	65	29	8.01	14040	2500	313	418	3434	64	281	7562	49	207	1.49	1.68
17	Thakazhi PZ1	9.3708	76.4117	60	28	8.13	778	420	75	56	244	8	273	447	28	168	0.68	0.51
18	Thakazhi PZ2	9.3708	76.4117	46	28	7.47	757.5	400	77	51	180	8	287	391	1	119	0.54	0.72
19	Thakazhi PZ3	9.3708	76.4114	30	28	8.5	1722	140	48	5	582	9	196	873	36	118	0.54	1.24
20	Thakazhi PZ4	9.3708	76.4117	28	29	8.08	2369	480	92	61	682	24	335	1196	47	126	0.44	5.26
21	Kommady - PZ	9.5119	76.3281	30	30	6.22	332	121	18	19	38	4	84	49	16	55	0.11	2.11
22	Mannanchery PZ	9.5714	76.3475	26	29	6.59	288	166	39	17	15	10	53	83	18	57	0.21	0.11
23	Kanjikuzhy PZ-1	9.6578	76.3556	46	28	7.96	389	180	32	24	115	12	183	192	4	78	0.27	0.45
24	Kanjikuzhi-PZ-2	9.6579	76.3556	60	29	6.95	289	80	19	8	104	14	79	139	3	108	0.22	0.62
25	Kanjikuzhy PZ-3	9.6578	76.3556	60	29	6.95	160	84	14	12	8	0	31	26	27	11	1.1	1.67
26	Pazhaveedu Jn.	9.4728	76.3500	18	27.5	7.53	240	147	18	25	9	0	101	4	35	44	0.15	3.40
27	Kakkazham	9.3889	76.3508	18	31	8.55	40	112	8	22	7	2	34	21	35	60	0.45	3.84
28	Purakkad- PZ-1	9.3492	76.3717	65	29.5	7.04	350	189	39	22	18	0	198	11	37	20	1.89	5.86
29	Purakkad - PZ -2	9.3492	76.3717	65	29	7.04	320	215	45	25	17	0	185	11	38	63	0.63	2.53
30	Alleppey -2	9.4861	76.3214	25	26.5	7.08	152	80	16	10	6	0	59	11	19	13	0.12	2.49
31	Kanjikuzhy PZ-4	9.6578	76.3556	40.00	27.5	7.39	80	51	10	6	5	0	32	10	11	13	0.76	0.46
32	Purakkad PZ -3	9.3492	76.3719	65.00	29.5	7.7	350	194	36	25	31	0	144	88	13	15	0.13	2.46

Table 5.5a. Analytical Results of Groundwater Samples from Tertiary Aquifers (May 2009)

Sample no.	Location	Latitude	Longitude	Depth in m	Aquifer	WT	pH	EC	TH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	F	Fe^{2+}
						°C		µS/cm at 25°C	As $CaCO_3$	mg/l									
1	Kakkazham- PZ	9.3889	76.3508	284	W	30	7.7	12600	2020	233	350	4500	25	375	7239	625	243	1.30	0.43
2	Kanjikuzhi -KWA well	9.6044	76.3274	140	W	29	7.2	3174	668	124	87	670	14	180	1217	54	441	0.23	1.20
3	Kallarcode-PZ	9.4611	76.3361	74	W	31.5	8.4	456	28	6	3	110	12	62	145	23	27	0.50	0.09
4	Mankombu KARI(RRI)	9.4383	76.4281	72	W	30	7.6	492	96	18	13	98	3	47	197	15	5	1.50	1.09
5	Karumadi PZ	9.3806	76.3886	30	W	30	8.1	3621	412	72	56	686	26	24	1396	126	13	0.32	0.33
6	Pattanakkad	9.7361	76.3189	140	W	30	8.1	1829	140	29	17	324	8	224	486	56	9	1.49	0.25
7	Karumadi Old PZ	9.3769	76.3889	437	V	30	8.8	3628	380	72	49	590	16	17	1241	86	3	0.17	0.09
8	Kommady-KWA well	9.5119	76.3281	120	R+W	29	7.2	605	120	24	15	56	9	157	87	4	27	2.32	0.36
9	Kommady- PZ	9.5119	76.3281	30	R	26	7.5	353	84.9	28	4	58	3	43	93	6	53	0.03	1.60
10	Preethikulangara- PZ 1	9.6058	76.3117	339	V	29	6.9	982	244	26	43	104	14	8	329	4	63	0.07	1.81
11	Preethikulangara- PZ 2	9.6058	76.3117	351	V	29.5	7.3	1165	40	8	5	224	9	56	348	6	52	1.91	2.20
12	Kottaram- PZ	9.6893	76.3328	120	W	30	8.1	3187	80.1	24	5	680	34	95	1111	20	47	1.50	5.98
13	Kottaram- KWA well	9.6894	76.3328	179	V	27.5	8.4	2975	186	42	20	510	9	143	827	77	58	0.97	0.21
14	Thottapally- KWA well	9.3161	76.3897	76	R	31	7.3	393	156	37	16	14	4	125	21	1	73	0.51	0.83
15	Chandanakavu KWA	9.4850	76.3453	146	W	30	7.1	1320	200	24	34	240	12	240	362	1	125	0.22	0.22
16	Pazhaveedu-KWA well	9.4728	76.3447	144	R+W	28	8.3	729	190	34	26	160	7	217	155	72	113	1.90	1.11
17	Mannar- PZ-1	9.3222	76.5222	30	W	30	6.60	147	80.9	29	2	12	5	47	19	19	23	0.24	0.03
18	Mannar- PZ-2	9.3221	76.5222	58	W	30	7.1	160	56	14	5	18	2	51	41	2	8	0.70	0.04
19	Velliyakulam Tube well	9.6811	76.3833	120	R+W	31	7.9	1531	110	24	12	262	5	109	424	59	0	0.18	1.07
20	Thanneermukkam KWA	9.6775	76.3939	150	V	31	7.9	1090	130	28	15	156	5	126	222	97	0	0.09	1.10
21	Muhamma-KWA well	9.6044	76.3575	168	V	29.6	7.2	2368	270	24	51	358	18	375	581	13	0	1.06	0.14

W= Warkali aquifer, V= Vaikom aquifer R= Recent confined aquifer

Continued

Sample no.	Location	Lat-itude	Long-itude	Depth in m	Aqui-fer	WT	pH	EC	TH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	F	Fe^{2+}
						°C		µS/cm at 25°C	As $CaCO_3$	Mg/l									
22	Thookkulam KWA well	9.4533	76.3439	202	W	31.5	8.2	518	96	18	13	65	6	141	104	1	0	0.51	0.88
23	Nedumudy KWA Well	9.4394	76.4078	62	W	31	6.8	714	156	37	16	138	16	49	296	43	0	4.04	0.02
24	Pallathuruthy KWA Well	9.4633	76.3619	113	W	30.9	7.6	1448	208	44	24	182	8	206	272	87	0	0.48	1.48
25	Ambalapuzha KWA well	9.3806	76.3717	132	W	31	7.7	358	100	18	14	24	6	139	30	12	0	0.78	1.45
26	Purakkad-KWA well	9.3506	76.3678	154	W	31	8.1	649	144	27	18	61	5	103	134	1	0	0.51	0.70
27	Aruthungal-KWA Well	9.6583	76.2967	100	W+R	27	7.3	808	210	48	22	74	3	187	166	2	0	1.51	0.19
28	Cherthala-KWA well	9.6050	76.3272	120	W	29	7.2	4174	668	124	87	570	14	188	1317	54	0	1.20	0.23
29	Kaipuram-KWA well	9.6250	76.3683	160	V	28	6.8	122	40	10	4	22	2	50	31	7	0	0.35	0.16
30	Pazhaveedu-KWA well	9.4728	76.3447	140	W	28	8.3	729	190	34	26	140	7	217	155	72	0	1.11	1.10
31	Viyapuram-KWA well	9.3586	76.4589	120	W	29	7.2	553	180	40	19	40	4	148	83	16	0	0.23	0.42
32	Komalapuram KWA well	9.5381	76.3444	102	W	26	7.1	1260	300	56	39	120	9	182	321	1	0	0.19	0.99
33	Karuvatta-KWA Well	9.3156	76.4167	112	W	29	7.1	353	148	35	15	120	3	190	210	1	0	0.58	0.80
34	Haripad-KWA well	9.2811	76.4561	90	W	29	6.8	426	188	53	14	10	2	152	72	1	0	5.03	0.43
35	Thakazhi-KWA well	9.3706	76.4142	67	W	29	6.7	361	112	22	14	19	7	169	22	1	0	0.95	0.83
36	Neerkunnam-KWA well	9.4117	76.3489	140	R+W	30	7.5	375	88	16	12	30	6	163	22	2	0	2.42	1.11
37	Mararikulam-KWA well	9.6272	76.3339	140	R+W	30	7.3	2088	600	140	61	220	14	140	641	101	0	0.39	0.47
38	Kommady-PZ	9.5119	76.3281	150	R+V	26	7.5	353	60	18	4	58	3	63	93	6	0	1.60	0.03
39	Chandhanakavu2 KWA	9.4850	76.3453	135	W	29	7.8	1287	146	28	18	210	12	205	354	5	0	0.25	1.83
40	Pazhavangadi-2-KWA	9.4975	76.3464	144	R+W	30	7	898	140	26	18	96	10	153	192	1	0	0.41	1.62
41	Chudukadu pump-KWA	9.4706	76.3389	150	W	29	8.2	419	72.7	21	5	14	2	55	31	0	12	0.21	1.98
42	Karumadi-PZ	9.3806	76.3886	30	W	30	8.1	3621	412	72	56	586	0	24	1286	0	4	4.86	1.2
43	Alamthuruthy-PZ	9.4078	76.5456	32	V	29	6.6	1880	140	26	19	348	3	174	565	1	57	1.54	0.03
44	Podiyadi-PZ	9.3667	76.5450	60	V	29	7.10	1245	104	18	15	138	18	171	217	2	26	1.28	0.04

W= Warkali aquifer, V= Vaikom aquifer R= Recent confined aquifer

Table 5.5b. Analytical Results of Groundwater Samples from Tertiary Aquifers (November 2009)

Sample No.	Location	Latit-ude	Longitude	Depth in m	Aqu-ifer	WT	pH	EC	T.H.	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	F	Fe^{2+}
						°C		µS/cm at 25°C	As $CaCO_3$	mg/l									
1	Kakkazham- PZ	9.3889	76.3508	284	W	28	8.72	16970	1294	274	149	4233	48	726	469	7377	21	1.26	0.00
2	Kanjikuzhi KWA well	9.6044	76.3274	140	W	29	7.21	3174	668	124	87	570	14	180	54	1217	141	0.23	1.20
3	Kalargode- PZ deep	9.4611	76.3361	74	W	28.5	8.1	373	151	24	22	76	12	172	0	151	8	0.49	0.00
4	Chudukadu KWA	9.4706	76.3389	150	W	26	8.6	440	79.6	18	9	70	7	190	0	23	65	1.74	0.00
5	Mankompu	9.4383	76.4281	72	W	27.5	7.1	482	100	19	13	158	5	74	6	227	30	0.10	1.30
6	Karumadi PZ	9.3805	76.3886	30	W	29	8.92	3725	420	63	64	792	28	55	50	1601	29	0.34	0.17
7	Pattanakad	9.7361	76.3189	140	W	28.5	8.39	1730	154	44	11	365	10	300	14	511	60	1.60	0.00
8	Karumadi - old PZ	9.3769	76.3889	437	V	30	7.59	3396	360	67	47	683	46	161	46	1301	102	1.20	0.21
9	Kommady - KWA	9.5119	76.3281	120	R+W	30.5	7.58	441.2	120	24	15	98	9	126	2	150	70	1.47	0.19
10	Preethikulangara -PZ2	9.6058	76.3117		W	33	7.66	975	300	56	39	166	14	35	10	408	125	0.27	4.32
11	Preethikulanagara PZ1	9.6058	76.3117	339	V	30.5	7.73	1148	40	38	40	182	10	106	0	426	63	1.60	4.12
12	Preethikulangara PZ 3	9.6058	76.3117	351	V	30	8.63	4587	90	36	38	1028	17	87	4	1898	18	1.52	2.09
13	Kottaram, - PZ1	9.6894	76.3328	120	W	29	8.6	3022	70	80	6	862	36	127	2	1580	34	0.53	2.10
14	Kottaram-PZ2	9.6894	76.3328	179	V	33	7.76	2163	190	40	40	712	14	316	9	1178	27	1.30	0.16
15	Thottappally KWA	9.3161	76.3897	76	W	30	7.95	160	48	10	23	7	0	83	46	21	26	0.15	0.92
16	Kumarakom PZ-1	9.5875	76.4361	48	W+R	28	7.46	240	48	29	66	14	0	251	51	83	40	0.30	1.09
17	Chandhanakavu KWA	9.485	76.3453	146	W	25.5	8.1	160	48	10	29	14	2	109	67	11	20	0.45	0.22
18	Pazhaveedu KWA	9.4728	76.3447	144	R+W	25.5	7.92	280	34	15	10	0	42	21	77	12	0	1.90	0.99
19	Mannar -PZ1	9.3222	76.5222	30	W	27	6.6	56	19	2	22	12	0	22	53	29	22	0.06	0.03
20	Mannar -PZ2	9.3222	76.5222	58	W	28	7.05	56	14	5	30	8	1	48	28	33	33	0.05	0.04
21	Velliyakulam	9.6811	76.3833	140	W	31	7.28	1746	98	31	5	296	12	108	33	503	3	1.54	0.07

W= Warkali aquifer, V= Vaikom aquifer R= Recent confined aquifer

Continued

Sample No.	Location	Latitude	Longitude	Depth in m	Aquifer	WT	pH	EC	T.H.	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	F	Fe^{2+}
						°C		µS/cm at 25°C	(As $CaCO_3$)	mg/l									
22	ThannirmukkomKWA	9.6775	76.3939	150	V	25	7.06	1569	159	38	16	263	22	107	37	455	39	1.36	0.05
23	Muhama KWA well	9.6044	76.3575	168	V	28	7.25	3060	368	67	49	504	34	264	7	999	34	0.59	0.27
24	KarumadyKWA well	9.3769	76.3889	90	W	28.5	6.65	3900	333	72	34	685	33	223	52	1253	3	1.41	0.05
25	Thookkulam KWA	9.4533	76.3439	202	W	28	7.27	750	119	41	10	108	22	147	0	200	41	1.17	0.04
26	Nedumudi KWA	9.4394	76.4078	62	W	29	6.68	735	143	36	13	88	12	159	2	169	9	4.81	0.04
27	Pallathuruthy KWA	9.4633	76.3619	113	W	29	7.2	1600	202	53	17	222	32	150	65	406	38	2.90	0.04
28	Ambalapuzha KWA	9.3805	76.3717	132	W	28	7.33	431	96	18	13	18	4	109	1	36	14	1.32	0.20
29	Purakkad KWA well	9.3505	76.3678	154	W	29	7.15	760	136	33	13	98	11	170	0	178	14	1.52	0.42
30	Aathungal KWA well	9.6583	76.2966	100	W	25.5	7	885	269	74	21	109	12	223	2	215	45	0.32	0.20
31	Pazhaveedu KWA	9.4727	76.3447	140	W	28	7.40	690	126	25	16	68	18	140	22	109	33	1.64	1.06
32	Viyapuram KWA	9.3586	76.4588	120	W	29	6.95	650	214	59	16	54	4	170	0	111	52	0.74	0.00
33	Komalapuram KWA	9.5380	76.3444	102	W	28	7.09	1463	295	53	40	216	14	247	0	445	10	1.63	0.05
34	Haripad KWA well	9.2811	76.4561	90	W	27.5	7.15	406	153	35	16	12	2	182	5	27	6	1.28	0.00
35	Thakazhi KWA well	9.3705	76.4141	67	W	28	7.33	497	199	53	16	50	2	185	5	98	34	0.72	0.00
36	Nirkunnam KWA	9.4116	76.3488	140	R+W	28.5	7.02	455	106	24	11	23	3	127	1	39	14	1.04	0.00
37	Mararikulam KWA	9.6272	76.3338	140	R+W	28	7.25	1415	144	33	15	233	22	253	0	350	15	2.62	0.03
38	Chandanakavu KWA	9.4705	76.3388	135	W	28	7.08	449	81	28	19	228	33	250	1	365	19	1.58	0.50
39	Pazhavangadi-2-KWA	9.4975	76.3464	144	R+W	26	7.67	160	32	19	26	12	1	334	231	13	128	0.30	0.19
40	Alamthuruthi-PZ	9.4078	76.5456	32	V	29	6.55	140	18	15	11	2	66	27	30	11	0	0.03	-
41	Podiyadi -PZ	9.3667	76.5450	60	V	29	7.1	104	18	15	32	8	1	155	56	20	12	0.05	0.04

W= Warkali aquifer, V= Vaikom aquifer R= Recent confined aquifer

5.3.1 Hydrogen ion concentration (pH)

The pH value of water is an indicator of the solvent power of water and is expressed as the negative logarithm of hydrogen ion concentration in water. A solution with pH less than 7 is acidic and greater than 7 is alkaline. The pH of water changes with the production of hydrogen or hydroxyl ion during different chemical reactions. The pH in combination with oxidation-reduction potential, temperature and pressure determine, which mineral will dissolve, which compound will precipitate and which ion will remain on the groundwater regime. Isolated higher pH values in an area can be related to absorption of CO_2 in water by plants. Similarly in clayey formations low pH water of acidic nature is encountered because of high concentration of uncombined CO_2. The measured pH is a very important piece of information in many types of geochemical equilibrium or solubility calculations (Gibbs, 1970).

The average pH in all the aquifer systems indicates alkaline nature of water in general. The pH in the phreatic zone varies from 6.33 to 9.22 with an average value of 7.85 during premonsoon and from 6.48 to 8.41 with an average value of 7.68 during Post monsoon. A significant change in pH is not observed during the two seasons except a minor lowering of pH after the rains. The seasonal changes in pH in the confined aquifer systems of Recent alluvium and Tertiary sediments are negligible as can be observed from the Table 5.6.

Table 5.6. Seasonal changes in pH in different aquifer systems

Aquifer system	**Min**		**Max**		**Average**	
	May	**October**	**May**	**October**	**May**	**October**
Phreatic (dug wells)	6.33	6.48	9.22	8.41	7.85	7.68
Confined (Recent alluvium)	4.25	4.24	8.39	8.58	7.31	7.37
Confined (Tertiary sediments)	6.28	6.55	8.83	8.92	7.49	7.49

Sporadic high pH values in an area are generally related to absorption of CO_2 in water by plants. In the present case it is mainly due to the consumption of hydrogen ions by the decaying organic matter in the soil.

According to BIS standards (1991), the acceptable limit of pH is 6.5 and the maximum allowable limit is 8.5. Except a few cases the pH values in the study area fall within the allowable limit.

5.3.2 Electrical conductivity (EC)

Electrical conductivity is a measure of the ability of water to conduct electricity and is measured in µ mhos/cm at 25^{o}C.The conductance of groundwater is a function of the concentration of ions and temperature. Hence, it is considered as an index of mineralization of the water. In the study area, the EC ranges widely in all the aquifer systems and a simple statistics of the data is presented in Table 5.7. A few wells taping the saline zones in the confined aquifers give high standard deviations and for any statistical analysis which requires a normal distribution of data have to discard such anomalous values. For getting a realistic picture of the freshwater aquifer system the data from saline zones are to be treated separately especially in the studies on hydrochemical evolution of the aquifer systems.

Table 5.7 Electrical Conductivity (EC) of groundwater in different aquifer systems

Aquifer system	**Month**	**EC in µ mhos/cm at 25^{o}C**			**SD**
		Average	**Max**	**Min**	
Phreatic aquifer	May-09	361	1130	49	270
	Oct.-09	341	1176	50	219
Recent –confined aquifer	May-09	2603	15160	92	4146
	Oct.-09	1452	14040	40	3342
Confined aquifer - Tertiary aquifer system	May-09	2090	15160	122	3313
	Oct.-09	1596	16970	56	2744

Classification of the water quality based on the EC values of water samples from different aquifer system given in Table 5.8 indicates that most of the water samples in these aquifer systems are suitable for domestic and irrigation purposes.

Table 5.8 Classification of water quality for drinking based on the EC values

Range of EC in µ mhos/cm at 25°C	Quality	Number of samples and percentage					
		Phreatic aquifer		Confined/ semi confined aquifer in Recent alluvium		Confined aquifers in Tertiary beds	
		May '09	Oct.'09	May '09	Oct.'09	May '09	Oct.'09
0 - 333	Excellent	28 (61%)	27 (85%)	8 (27%)	17 (53%)	3 (6%)	9 (22%)
333-500	Good	10 (22%)	1 (3%)	4 (13%)	7 (22%)	11 (24%)	9 (22%)
500-1000	Permissible	5 (11%)	3 (9%)	6 (20%)	3 (9%)	10 (22%)	7 (17%)
1000-1500	Brackish	3 (6%)	1 (3%)	nil	nil	7 (15%)	6 (7%)
>1500	Brackish to Saline	nil	nil	12 (40%)	5 (16%)	15 (33%)	13 (32%)
Total no. of samples		46	32	30	32	46	41

As per BIS (1991) specifications EC up to 1500 µ mhos/cm at 25 °C is desirable for drinking purpose. The quality of 94% of the water samples during premonsoon (May) and 97% during the postmonsoon (October) periods from the phreatic aquifers are within the permissible limit. An improvement in water quality due to dilution of water is observed during post monsoon period. The EC variation in the confined/ semi-confined aquifer system in Recent alluvium is conspicuous with an improvement in water quality in the excellent category from 27 to 53 % after the rains. Highest percentage of water samples in brackish to saline category is also observed in this aquifer system (Recent). Forty percentages of the samples which are brackish to saline during pre monsoon period improved its quality after the rains as can be observed from the Table 5.8. The immediate improvement in water quality after the rains indicates the semi confined nature of this aquifer system. The scenario is somewhat different in the case of Tertiary aquifer system where the EC variations are not prominent. An immediate impact in EC after the rains is not significant. Even, the small changes in percentage in different EC categories can also be attributed to the changes in sampling locations during pre and post monsoon seasons, in some of the cases. The isoelectrical conductivity maps for the pre-monsoon season in the Phreatic, Recent-confined and Tertiary aquifer systems indicate EC values < 1000 µ mhos/cm at 25°C in major part of aquifer in phreatic and Tertiary aquifers (Figs.5.3, 5.4 and 5.5).

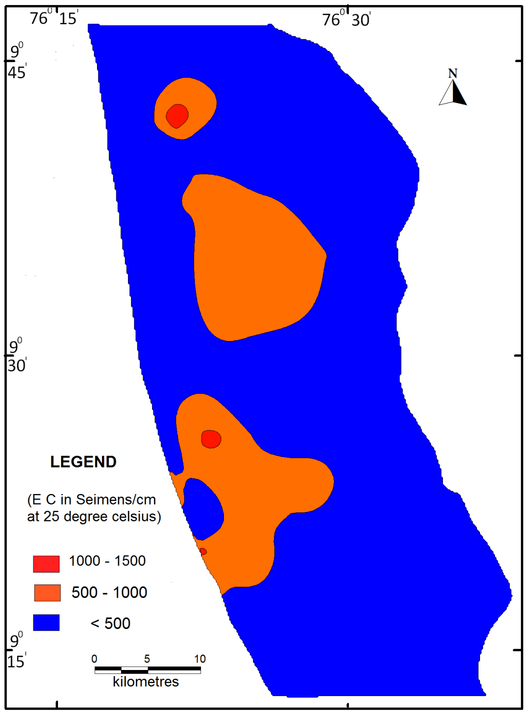


Fig. 5.3 Spatial distribution of EC for May 2009 in Phreatic aquifer

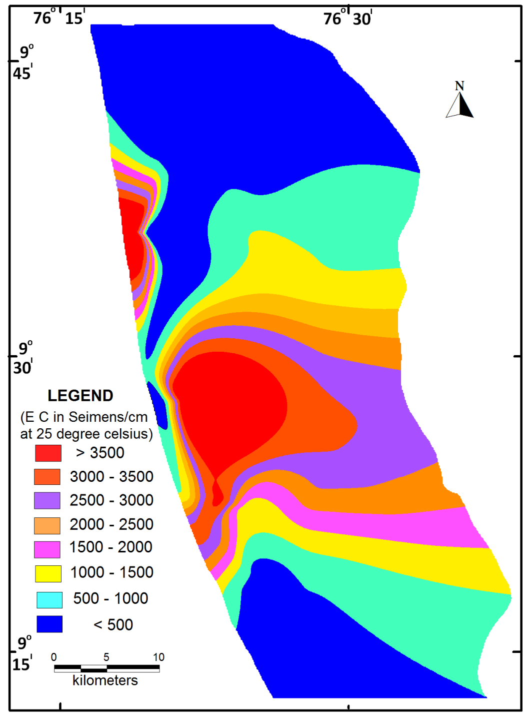


Fig. 5.4 Spatial distribution of EC for May 2009 in Recent-confined aquifer

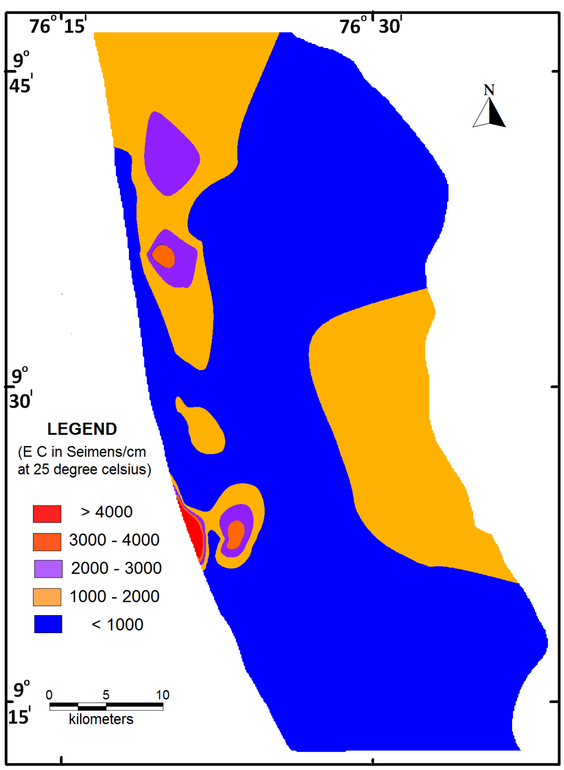


Fig. 5.5 Spatial distribution of EC for May 2009 in Tertiary aquifers

5.3.3 Major ion chemistry of groundwaters in aquifer systems in the area

Calcium (Ca)

Calcium is found in almost all the waters, essentially dissolved from the soils and rocks. It is one of the most abundant cations in the surface and groundwater environments and is present in minerals like feldspar, amphibolites, pyroxene group of minerals, apatite and \wollastonite. Presence of potassium and sodium influence the solubility of calcium in the aquifers. The desirable limit of Ca^{2+} as per drinking water standards is 75 mg/l. and the permissible limit is Ca < 200 mg/l. Calcium enrichment of water causes permanent hardness and more than any health hazard the aesthetic issues related to high calcium content is the primary concern. In water delivery systems and utensils hard water forms encrustations.

Table 5.9. Concentration of Ca^{2+} in the waters of different aquifer systems

Aquifer system	Month	Con. of Calcium in mg/l			SD	Ca>200 mg/l	
		Average	Max	Min		No. of samples	Percentage (%)
Phreatic aquifer	May-09	36.94	112.20	3.64	22.09	nil	0
	Oct.-09	42.77	98.90	6.01	24.46	nil	0
Recent –confined aquifer	May-09	66.51	384.80	9.62	87.22	3.00	10
	Oct.-09	50.92	312.60	4.86	67.28	2.00	6
Confined Tertiary aquifer system	May-09	52.46	384.80	6.41	70.56	3.00	7
	Oct.-09	44.38	273.80	1.94	43.85	1.00	2

Different aquifer systems in the area have varying ranges in calcium ion concentration and are presented in Table 5.9. Groundwater in the phreatic aquifer has Ca^{2+} concentrations within in the permissible limit for both pre and post monsoon seasons. The water samples from confined aquifers of Recent alluvium have shown a maximum of 10% of the total samples with Ca^{2+} above the permissible limit. Similarly, the water samples from Tertiary aquifers have high Ca^{2+} concentration in 7% of the samples with calcium ion concentration above the permissible limit. It can be observed that the calcium ion concentration in below the desirable limit in most of the samples representing all the aquifer systems.

Magnesium (Mg)

Magnesium is a common constituent of natural water and makeup the total hardness of water in combination with calcium. Because of its low dissolution, it causes temporary hardness. The common sources of magnesium are dolomite, amphibolites, olivine, chlorite, mica, montmorillonite and serpentinite (Hem, 1985). As per BIS (1991) standards magnesium in drinking water should not exceed 30mg/l if there is 250 mg/l sulphate. In the presence of lower concentrations of sulphate, magnesium may be acceptable up to a level of 150mg/l. The problem at this level of magnesium may be the palatability and hardness of water.

Table 5.10. Concentration of Magnesium in the waters of different aquifer systems (mg/l)

Aquifer system	Month	Magnesium in mg/l			SD
		Average	Max	Min	
Phreatic aquifer	May-09	6.16	29.00	0.50	5.98
	Oct.-09	9.99	46.90	0.97	10.62
Recent –confined aquifer	May-09	55.94	507.80	0.97	107.71
	Oct.-09	64.06	417.90	2.53	93.77
Confined Tertiary aquifer system	May-09	30.80	349.90	1.94	53.59
	Oct.-09	35.26	152.00	4.90	36.92

Perusal of table 5.10 shows that all the samples from the phreatic aquifers are having low Mg^{2+} values with range in concentration from 0.5 to 29 mg/l during premonsoon and from 0.97 to 46.9 mg/l during postmonsoon period. The average Mg^{2+} values are above 30 mg/l in all the Recent alluvial and Tertiary aquifer systems. It is observed that the seasonal changes in magnesium ion concentration is conspicuous in the phreatic and semi-confined aquifer systems of Recent alluvium.

Sodium (Na)

Sodium is one of the most important and abundant alkali metals in natural waters. Sodium gets released in to the natural water during the chemical weathering of the minerals plagioclase feldspar, nephiline, sodalite, glaucophine, clay minerals and soda bearing pyroxene and amphibolites (Hem, 1985). In sedimentary aquifer systems clay and clay minerals play significant role in the contribution of sodium ions. Through Base Exchange reactions with clays under favourable conditions can increase sodium in groundwater. Natural waters normally contain sodium in the range of 1-60 mg/l. and very high concentrations are observed under brackish environments.

Table 5.11. Concentration of Sodium in the waters of different aquifer systems (mg/l)

Aquifer system	Month	Sodium in mg/l			SD
		Average	Max	Min	
Phreatic aquifer	May-09	27.0	142	2.3	30
	Oct.-09	23.3	128	4.1	25
Recent –confined aquifer	May-09	411	2980	5.4	694
	Oct.-09	341	3434	3.3	831
Confined Tertiary aquifer system	May-09	298	4500	9.8	680
	Oct.-09	325	4233	0.488	683

High range in the concentrations of dissolved sodium is seen in all the aquifer systems in the area and high values correspond to brackish environments. However, most of the samples have low sodium ion concentrations as can be observed from the Table 5.11. High sodium values in phreatic aquifers are mainly due to interaction with brackish eaters in back waters. Whereas, leaching of salts from clay layers and ion exchange play a significant role in the confined aquifers.

Potassium (K)

Potassium is one of the important alkalis present in natural water and it is released to groundwater during the process of weathering of rocks rich in orthoclase, microcline, leucite and biotite (Hem, 1992). Even though, the earth crust constitutes about 2.5 percent of potassium (Drever, 1997; Langmuir, 1997) most potable groundwater contain less than 10 mg/l with a common range of 1 to 5 mg/l due to adsorption of K^+ along the flow path by clay minerals. High concentration of Potassium in groundwater are reported from fertilizers and other sources (Naik and Purohit, 2001; Sahu and Sikdar, 2008). In agricultural lands, brackish environments and water logged areas high potassium in groundwater is common (Shaji et al., 2009, Subba Rao et al., 2002).

The distribution of potassium in various aquifer systems in the area is given in Table 5.12. High level of dissolved potassium is recorded mainly from the brackish water samples collected from the confined aquifers.

Table 5.12. Concentration of Potassium in the waters of different aquifer systems (mg/l)

Aquifer system	Month	Potassium in mg/l			SD
		Average	Max	Min	
Phreatic aquifer	May-09	8.97	67.00	0.20	13.52
	Oct.-09	5.62	37.00	0.90	6.43
Recent –confined aquifer	May-09	22.02	182.00	0.40	35.41
	Oct.-09	11.45	64.00	0.04	17.86
Confined Tertiary aquifer system	May-09	9.01	34.00	0.32	7.14
	Oct.-09	16.47	66.34	0.19	15.66

Carbonate and Bicarbonate (CO_3 and HCO_3)

Carbonates and bicarbonates along with hydroxides contribute the alkalinity or acid neutralizing power of water. The relative amounts of these two anions depend on the pH of the water and other factors. Carbonates are seldom found in significant levels in groundwater. However, high values of carbonates are expected at high pH levels (pH.8.2) by the dissociation of HCO_3^- to CO_3^{2-} (Hem, 1992). An increase in HCO_3^- with a decrease in pH is normally found in groundwater. Higher content of bicarbonate in groundwater system is indicative of a sulphate reducing environment. The desirable limits of carbonates and bicarbonates in drinking water are 100mg/l and 400 mg/l respectively. The range in concentration of bicarbonate ions in different aquifer systems in the study area is given in Table 5.13.The average concentration of bicarbonate in all the aquifer systems is far below the desirable limit set for drinking water. However, bicarbonates above the desirable limit are present at some locations in all the aquifer systems.

Table 5.13. Concentration of Bicarbonate in the waters of different aquifer systems (mg/l)

Aquifer system	Month	Bicarbonate in mg/l			SD
		Average	Max	Min	
Phreatic aquifer	May-09	120.55	479.00	7.30	92.82
	Oct.-09	107.92	259.13	19.74	63.09
Recent –confined aquifer	May-09	139.43	481.75	24.30	116.59
	Oct.-09	151.85	975.25	28.20	174.74
Confined Tertiary aquifer system	May-09	136.20	375.06	7.99	83.95
	Oct.-09	168.72	726.48	20.50	120.13

The bicarbonate variations are significant during the two seasons in phreatic and Recent alluvial aquifers compared to the variations in the Tertiary aquifers. In the Tertiary aquifer system sample no 1, which in the proximity of sea shows high variation during both seasons.

It could be noticed that the bicarbonate in the confined aquifer systems are much higher than that in the phreatic aquifer systems which supposed to have more HCO_3^- content as it forms the recharge water for the deeper aquifer systems.

Normally carbon dioxide is added to the water in the soil zone as result of the elevated levels of CO_2 in the soil air due to organic matter decay. Through weathering reactions part of the carbon dioxide in the soil zone is converted to bicarbonate. Deeper down the reminder is consumed without further addition. This will result in decreasing carbon dioxide content (partial pressure of CO_2) towards depth. As the bicarbonate increases towards depth there must be some strong sources of carbon dioxide in the aquifers system.

The presence of peat and lignite is observed in Tertiary beds. Oxidation of organic matter has to go along with the reduction of some other specie. Dissolved oxygen is usually low even in shallow groundwater. Due to the higher temperature the solubility of oxygen in groundwater is usually very low. After the depletion of oxygen in a confined aquifer system the high valency ions like Mn^{4+} and Fe^{3+} may be reduced to Mn^{2+} and Fe^{2+}. As a matter of fact the iron content in the waters of the Tertiary aquifers is often high.

Where the environment becomes even more reducing sulphate may be reduced to sulphide. Reduction means uptake of electrons. In this case the electrons come from organic matter oxidation;

$$C_6H_{12}O_6 + SO_4^{2-} \rightarrow 6\ HCO_3 + 3H_2S$$

This reaction is verified by smell of hydrogen sulphide (H_2S) observed in several wells. H_2S in measurable quantities have also been found in water samples. In such a reducing environment any Fe present would be precipitated as FeS. However both the smell of H_2S and presence of iron have been found in some waters. This is a good indication of the heterogeneous character of the aquifers. The pumping sucks water from both more and less reduced environments and mixing occurs only in the borehole. The presence of shells constitutes an easily weatherable component which can consume the carbonic acid formed in oxidation of organic matter.

Chloride (Cl)

Chloride is found in significant quantities in all natural waters. Normally, it will not take part in ion exchange or other chemical reactions along its course of movement in aquifers. Hence, it is considered as a conservative ion and is being used in many hydrogeological investigations as tracers. It is present as sodium chloride in groundwater, but chloride content may exceed the sodium due to base exchange reactions. Chloride bearing minerals like orthoclase, sodalite etc. are minor rock forming minerals and their contribution of chloride to the natural water is insignificant when compared to the total chloride concentrations in any water. Most of the chloride in water comes from sea via atmosphere as part of the hydrologic cycle. Abnormal concentrations of chloride in groundwater may result from anthropogenic pollutions caused be sewage, leaching of salts residue in the soil, and land use changes (Brink et al., 2007). The permissible limit of chloride in drinking water is 250 mg/l and most of the samples have chloride below this level in all the aquifer systems in the area. The range in concentration of chloride in various aquifer systems in the area are given in Table 5.14.

Table 5.14. Concentration of Chloride in the waters of different aquifer systems (mg/l)

Aquifer system	**Month**	**Chloride in mg/l**			**SD**	**samples with Cl<250 mg/l**	
		Average	**Max**	**Min**		**No.**	**%**
Phreatic aquifer	May-09	37.06	231.00	4.42	46.54	46	100
	Oct.-09	25	45.2	2.9	12	32	100
Recent –confined aquifer	May-09	832	6167	10	1503	26	87
	Oct.-09	656	7562	4	1716	23	71
Confined Tertiary aquifer system	May-09	526	7239	19	1111	24	55
	Oct.-09	591	7377	11	1203	23	56

In the phreatic aquifers all the samples are having chloride within the permissible limit. Whereas, in the confined and semi-confined Recent aquifer system 87% of the samples during premonsoon and 71% during postmonsoon are having chloride within the permissible limit. In the case of Tertiary aquifer system it is 55 and 56 percentages respectively. The spatial distribution of chloride in the phreatic, Recent-confined and Tertiary aquifer systems are shown in Fig 5.6, 5.7 and 5.8 respectively. The high Chloride values during pre-monsoom period in phreatic aquifers is mainly due to mixing of brackish waters from backwaters. The confined aquifer system is not affected by backwaters except in some of the wells in Recent confined, which are linked to phreatic aquifer. The whole process involned in ion enrichment is explained under the paragraphs 5.7, 5.8, 5.9 and 5.10.

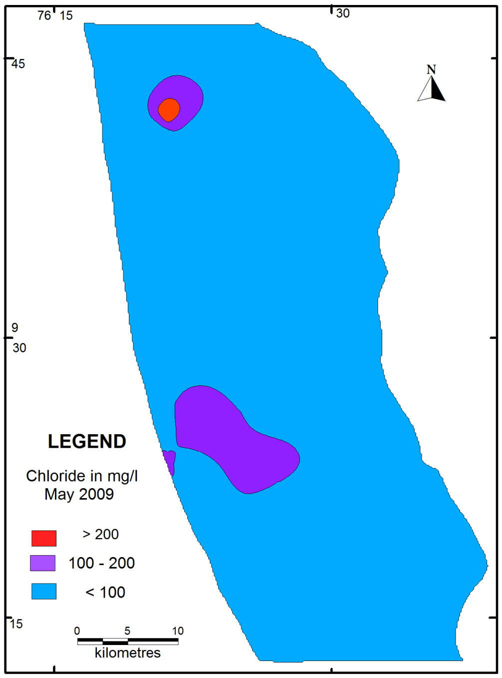


Fig. 5.6 Spatial distribution of Chloride in Phreatic aquifer during May 2009

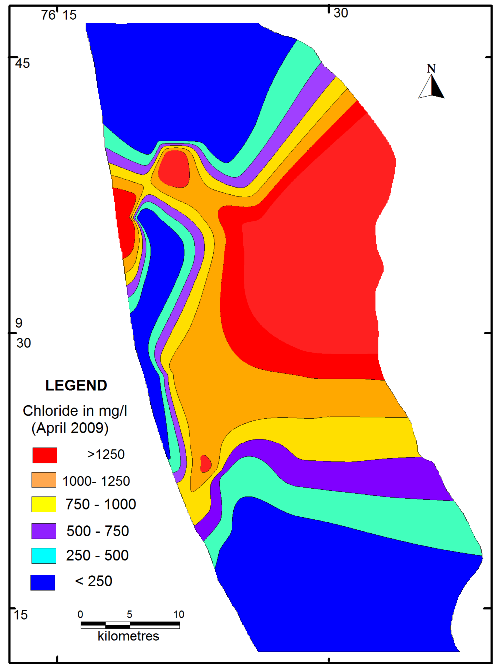


Fig. 5.7 Spatial distribution of Chloride in Recent-confined aquifer during May 2009

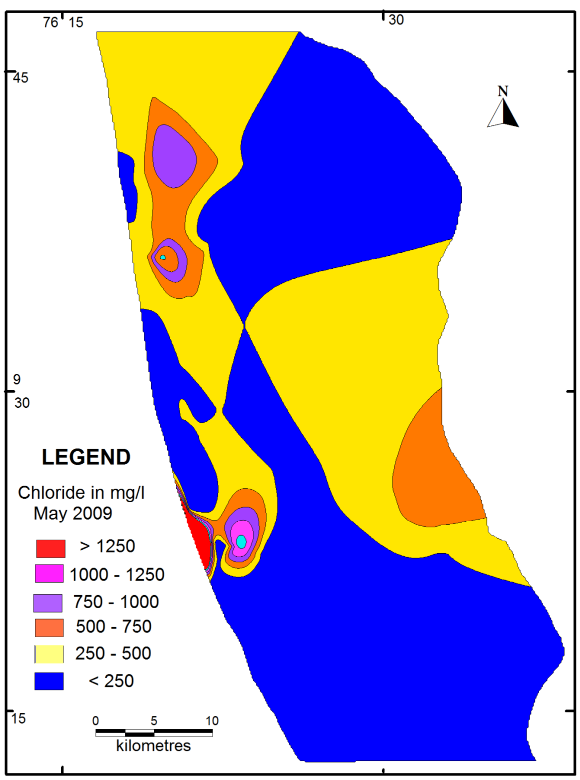


Fig. 5.8 Spatial distribution of Chloride in Recent-confined aquifer during May 2009

Sulphate (SO_4)

Sulphate in groundwater is derived from the sulphides of heavy metals which is usually present in igneous and metamorphic rocks, anhydrite and gypsum. The sulphates of calcium, magnesium and sodium are soluble in water in most environments in which it occurs and due to this, high sulphate concentrations are commonly observed in groundwater. Sulphates usually get reduced in aquifer systems by bacteria under reducing environments. Very low concentrations of sulphates in groundwater are expected under such a situation. Sulphate concentration below 200 mg/l is desirable in drinking water as per BIS (1991) specifications. Concentration between 200 and 400mg/l is the permissible limit and above that it is not suitable for drinking. The range in concentration of sulphates in various aquifer systems in the area is given Table 5.15.

Table 5.15. Concentration of sulphate in the waters of different aquifer systems (mg/l)

Aquifer system	Month	Sulphate in mg/l			SD	samples with SO_4>200 mg/l	
		Average	Max	Min			
Phreatic aquifer	May-09	34	178	4	32	0	0
	Oct.-09	91	352	8	86	4	12
Recent –confined aquifer	May-09	53	294	2	82	3	10
	Oct.-09	19	49	1	15	0	0
Confined Tertiary aquifer system	May-09	40	625	0	97	1	2
	Oct.-09	38	469	0	80	1	2

High sulphate values obtained only from a few samples and all the samples except one in the Tertiary aquifer falls within the permissible limit of 400 mg/l. From the Table 5.15 it can be seen that most of the samples fall under desirable category of BIS specifications for drinking water. The seasonal variation in sulphur is conspicuous in phreatic aquifers than in the confined/ semi-confined aquifers of Recent alluvium.

Nitrate (NO_3)

Nitrogen is a major constituent of the earth's atmosphere and occurs in many different gaseous forms such as elemental nitrogen, nitrate and ammonia. Natural reactions of atmospheric forms of nitrogen with rainwater result in the formation of nitrate and ammonium ions. While nitrate is a common nitrogenous compound due to natural processes of the nitrogen cycle, anthropogenic sources have greatly increased the nitrate concentration, particularly in groundwater. Nitrogen is present in very small quantities in common rocks and minerals, but an important constituent of organic materials which on dissolution gives nitrate to groundwater. The largest anthropogenic sources are septic tanks, application of nitrogen-rich fertilizers and food processing industries. In densely populated areas, sewerage systems can represent a major local source of nitrate to the groundwater. However in less populated areas sewerage systems do not really pose much of a threat to groundwater contamination.

High nitrate concentration in groundwater has harmful biological effects and may cause methemoglobinemia in infants (Comly, 1987). High nitrate concentrations are often associated with high bacterial contamination and it depends on the source of nitrate contamination.

Nitrate compounds are highly soluble in water and a concentration of 600 mg/l could be expected in groundwater. The desirable concentration of nitrate in drinking water is 45mg/l as per Bureau of Indian Standards (BIS, 1991). The nitrate concentrations in various aquifer systems in the study area are given in Table 5.16.

The nitrate content in all the samples from phreatic aquifer is below the desirable limits specified by BIS. In forty three percentage of the water samples from Recent aquifers and 25% of the samples from Tertiary aquifers during pre-monsoon period have nitrates above the desirable limits. Similarly, for the post-monsoon season 53 and 27 percentages of the water samples from Recent and Tertiary aquifers respectively are above desirable limits.

Table 5.16. Concentration of Nitrate in the waters of different aquifer systems (mg/l)

Aquifer system	Month	Nitrate in mg/l			SD	samples with NO_3>45 mg/l	
		Average	Max	Min		No.	%
Phreatic aquifer	May-09	5	35	0	6	0	0
	Oct.-09	4	20	1	4	0	0
Recent –confined aquifer	May-09	61	250	3	68	13	43
	Oct.-09	58	207	2	52	17	53
Confined Tertiary aquifer system	May-09	34	441	0	78	11	25
	Oct.-09	37	141	0	34	11	27

5.3.4 Minor elements in groundwater

Fluoride and iron are the minor ions analysed and interpreted in the present study.

Fluoride (F)

Fluoride (F^-) is an essential element for higher forms of life as it has a significant role in the formation of bones and teeth. Its concentration in groundwater is very low (generally less than 1 ppm). Fluoride ion have the same charge and the same radius of hydroxide (OH^-) ions, thus the ions may replace each other in mineral structures. It forms strong solute complexes with many cations. Because of this reason its presence in aqueous environment is very low. Here, it will be interesting to note that the presence of Fluoride in the rock forming minerals in the land is higher than chloride (Cl^-), which is very abundant in aqueous environment.

The common minerals of fluoride are fluorite (CaF_2), apatite [$(Ca_5Cl,F,OH)(PO_4)_3$], and hornblende. Some of the micas may contain fluoride which has replaced part of the hydroxide from its atomic structure. The minerals cryolite ($Na_3\ AlF_6$) and ralstonite [$Na\ Mg\ Al\ (F, OH)_6.H_2O$ or $Al_2\ (F,OH)_6\ H_2O$], are rare but could become sources of fluoride during weathering.

Fluoride is normally present in water as F^- ion. It may also exist in the form of HF^0, $Si\ F_6^{2-}$ or $Si\ F_4^0$ under very low pH (<3.5) conditions (Hem, 1992). In water containing sufficient concentration of calcium, the concentration of F^- ions will be low due to the precipitation of fluoride as calcium fluoride. Hence high concentration of F^- ion is expected in water low in calcium concentration.

The desirable and permissible limits for fluoride in drinking water are 1.0 mg/l and 1.5 mg/l respectively as per the BIS specifications. Very low concentration as well as high concentration of fluoride may lead to various health hazards in humans as given below :

F <0.8 mg/l	Dental caries	F >5 mg/l	Affects bones
F 1-2 mg/l	Dental Fluorosis	F 10-40 mg/l	Crippling fluorosis
F >2 mg/l	Discolouration of teeth		

The fluoride levels in the aquifer systems in the area are given in Table 5.17. Fluoride in all the water samples from the phreatic aquifer system is below the permissible limit and most of the samples are below the desirable limit. In the Recent alluvial aquifers (confined/semi-confined) the 13% of the water samples have fluoride above permissible limit during pre-monsoon and fluoride in all the samples are below permissible limit during post-monsoon probably due to rainwater dilution effect. Tertiary aquifers have fluoride above the permissible limit in 20 and 24 percentages of the water samples during pre and post-monsoon seasons respectively.

Table 5.17. Concentration of Fluoride in the waters of different aquifer systems (mg/l)

Aquifer system	Month	Fluoride in mg/l			SD	samples with F>1.5 mg/l	
		Average	Max	Min		No.	%
Phreatic aquifer	May-09	0.19	0.56	0.00	0.13	0	0
	Oct.-09	0.17	1.03	0.00	0.18	0	0
Recent –confined aquifer	May-09	0.47	2.23	0.00	0.61	4	13
	Oct.-09	0.44	1.89	0.00	0.46	0	0
Confined Tertiary aquifer system	May-09	1.08	5.03	0.03	1.17	9	20
	Oct.-09	1.10	4.81	0.03	0.93	10	24

The spatial distribution of fluoride does not show a regular pattern as observed from the locations the water sampling sites and the fluoride enrichment seems to be in situ. The rate of pumping, constitution of litho units and the presence of brackish water in the confining clay layers as well as in the inter beds play a significant role (Cairneross and Feachem, 1993) in the enrichment of fluoride in groundwater. The possible reason for the fluoride enrichment in Tertiary aquifers could be physical and chemical changes taking place in and around the pumping well which creates a low pressure zone around the well resulting in the vertical leakage of brackish water from the confining clay layers enriched with fluoride ions. Thus, Tertiary aquifer system has enrichment of fluoride at favourable locations only.

Iron (Fe^{2+})

Iron is present in acidic groundwater characterized by low pH values. The permissible limit of iron in drinking water is 1mg/l. Rather than health concerns the aesthetic issues like staining of utensils and cloths are the major issues associated with high Fe content in water. The concentration of iron in various aquifer systems in the area is given in Table 5.18. Analysis was not carried out for iron in phreatic aquifers and the values for the other aquifer systems are given Table 5.18.

Table 5.18. Concentration of Iron in the waters of different aquifer systems (mg/l)

Aquifer system	Month	Iron in mg/l			SD	samples with Fe>1 mg/l	
		Average	Max	Min		No.	%
Phreatic aquifer	May-09	ND	-	-	-	0	0
	Oct.-09	ND	-	-	-	0	0
Recent –confined aquifer	May-09	2.57	8.90	0.05	2.79	18	60
	Oct.-09	1.67	5.86	0.06	1.62	17	55
Confined Tertiary aquifer system	May-09	0.86	5.98	0.02	1.01	16	36
	Oct.-09	0.56	4.32	0.00	1.01	8	20

Iron content in more than 50% of the samples in Recent aquifers are having iron content above the permissible limit for both the seasons. In the Tertiary aquifers, 36% of the samples during pre-monsoon and 20% during post-monsoon are having iron content above permissible limits. Ferruginous clays are present in Recent and Tertiary aquifer systems. The ferruginous clays consumes hydroxyl ions (OH^-) to form iron hydroxide ($Fe(OH)_2$) and subsequent oxidation of $Fe(OH)_2$ to FeO_2 releases hydrogen ion in to the water. Both the reactions results in enrichment of H^+ concentration and consequent low pH of groundwater.

$$Fe\,(OH)_2 \longrightarrow FeO_2 + 2H^+$$

Under low pH conditions $Fe(OH)_2$ dissociates and Fe ions are released. The tube wells at Thiruvarpu shows very low pH values (pH<5) and high Fe content. (see Table 5.4.).

5.4 Hardness

Hardness of water is a major aesthetic aspect in domestic use of water and most commonly associated with the ability of water to precipitate soap. Chemically, hardness is often defined as the sum of polyvalent cation concentrations dissolved in the water. The most common polyvalent cations in fresh water are calcium (Ca^{++}) and magnesium (Mg^{++}). Hardness below 300mg/l is desirable in drinking water as per BIS (1991) specifications.

Hardness of water in the aquifer systems of the area shows wide variation and is given in Table 5.19. Most of the water samples in the phreatic aquifer have total hardness (TH) within the desirable limit and 30% of the samples during pre-monsoon and 18% during post-monsoon periods in the Recent alluvium (confined/ semi-confined aquifers) are having TH above the desirable limit. Around 15% of the samples from Tertiary aquifers are having TH above the desirable limit during both the seasons.

Table 5.19.Total Hardness of water in different aquifer systems (mg/l)

Aquifer system	Month	Total Hardness in mg/l			SD	samples with TH>300 mg/l	
		Average	Max	Min		No.	%
Phreatic aquifer	May-09	117	340	12	68	1	2
	Oct.-09	148	375	30	89	3	9
Recent –confined aquifer	May-09	386	3050	20	659	9	30
	Oct.-09	300	2500	48	514	6	18
Confined Tertiary aquifer system	May-09	232	2020	28	316	7	16
	Oct.-09	184	1294	14	222	6	15

5.5 Index of Base Exchange (Chloro-Alkaline Indices-CAI)

The ion exchange between the groundwater and the aquifer material during the residence or travel can be understood by studying the chloro-alkaline indices (Schoeller, 1967). Ion exchange and reverse ion exchange occurring in a region can be confirmed by the two chloro alkaline indices $CAI_1$and CAI_2 and these two indices can be expressed as:

$$CAI_1 = [Cl-(Na+K)] / Cl$$

$$CAI_2 = [Cl-(Na+K)] / (SO_4+NO_3+HCO_3+CO_3)$$

All values in the above equation are expressed in meq/l.

When there is an exchange between Na or K in groundwater with Mg or Ca in the aquifer material, both of the indices are positive, indicating direct ion exchange. If the exchange takes place between the Ca or Mg in groundwater with Na or K in the aquifer material, the indices will be negative, indicating reverse ion exchange. The Base Exchange characteristics of water in all the aquifer systems in the area is presented in Table 5.20. The hydrochemical data of all the aquifer systems in meq/l are given in Table 5.21, 5.22 and 5.23.

Table 5.20. Base exchange characteristic of water in different aquifer systems

Aquifer system	Month	Chloro-Alkaline Indices				
		Total	No. of	No. of	% of	% of
Phreatic aquifer	May-09	46	9	37	20	80
	Oct.-09	32	15	17	47	53
Recent –confined aquifer	May-09	30	15	15	50	50
	Oct.-09	32	21	11	66	34
Confined aquifer - Tertiary aquifer system	May-09	44	27	17	61	39
	Oct.-09	41	30	11	73	27

The value of both the indices in the phreatic aquifer is negative in 80% of the samples and this indicates lack of long residence time in the aquifers (Freeze and Cherry, 1979). Whereas, the significant percentage of negative values in the confined aquifer systems indicate reverse exchange in the system under evolution of water along its flow path.

Table 5.21 : Hydrochemical data of phreatic aquifer and percentage of error for May. 2009

Sample No	pH	Ca meq/l	Mg meq/l	Na meq/l	K meq/l	CO_3 meq/l	HCO_3 meq/l	SO_4 meq/l	Cl meq/l	F meq/l	NO_3 meq/l	Total cation	Total Anion	Ion balance	% error
1	6.85	1.52	0.40	0.57	0.18	0.04	1.28	1.03	0.50	0.00	0.07	2.68	2.92	-0.04	-4.26
2	7.57	3.31	0.40	0.21	0.04	0.12	3.05	0.80	0.14	0.00	0.13	3.96	4.24	-0.03	-3.39
3	8	2.00	0.20	0.96	0.11	0.08	2.48	0.15	0.56	0.01	0.20	3.26	3.46	-0.03	-2.89
4	8.00	0.48	0.04	0.48	0.02	0.00	0.28	0.25	0.45	0.00	0.09	1.02	1.07	-0.02	-2.26
5	8.01	1.53	0.08	0.48	0.17	0.07	1.48	0.58	0.35	0.01	0.04	2.25	2.50	-0.05	-5.28
6	7.69	1.30	0.80	0.87	0.08	0.00	2.16	0.34	0.79	0.02	0.00	3.05	3.30	-0.04	-3.88
7	6.46	1.60	0.60	1.17	0.14	0.05	1.54	1.41	0.63	0.00	0.22	3.51	3.84	-0.04	-4.43
8	6.36	1.00	0.60	0.61	0.07	0.08	0.77	1.02	0.49	0.01	0.14	2.28	2.50	-0.05	-4.50
9	8.03	2.00	0.80	1.17	0.31	0.06	1.77	1.81	0.94	0.01	0.07	4.28	4.65	-0.04	-4.10
10	6.33	1.84	0.96	3.48	0.41	0.08	2.44	0.71	3.72	0.01	0.05	6.69	7.00	-0.02	-2.24
11	8.25	2.61	0.20	0.43	0.10	0.10	2.25	0.60	0.54	0.01	0.07	3.34	3.56	-0.03	-3.13
12	7.22	0.24	0.04	0.35	0.02	0.03	0.20	0.18	0.20	0.01	0.01	0.65	0.62	0.02	2.44
13	9.22	0.70	0.12	0.31	0.10	0.40	0.20	0.25	0.37	0.01	0.00	1.23	1.22	0.01	0.55
14	7.86	2.80	0.40	1.13	0.18	0.08	2.51	1.32	0.94	0.02	0.05	4.51	4.89	-0.04	-4.09
15	8.67	3.00	0.40	2.04	1.15	0.16	3.28	0.89	2.39	0.02	0.56	6.60	7.29	-0.05	-4.95
16	8.19	1.15	0.04	0.10	0.03	0.00	1.16	0.03	0.16	0.01	0.04	1.32	1.39	-0.02	-2.39
17	7.75	5.61	1.20	1.74	1.12	0.18	7.85	1.51	0.93	0.00	0.04	9.66	10.51	-0.04	-4.20
18	6.7	0.20	0.20	1.65	0.04	0.04	0.41	0.65	1.11	0.01	0.03	2.09	2.24	-0.04	-3.54
19	7.96	2.81	0.40	1.13	0.18	0.08	2.51	1.04	0.94	0.02	0.05	4.51	4.61	-0.01	-1.06
20	8.55	2.60	2.38	4.17	0.21	0.24	2.90	1.58	5.30	0.03	0.12	9.37	10.14	-0.04	-3.93
21	7.83	0.85	0.24	0.48	0.08	0.00	0.56	0.57	0.51	0.02	0.13	1.65	1.76	-0.03	-3.28
22	7	1.76	0.32	0.18	0.02	0.05	1.52	0.65	0.12	0.00	0.06	2.28	2.41	-0.03	-2.77
23	6.87	2.40	0.40	1.32	0.35	0.07	2.11	0.88	0.91	0.01	0.10	4.47	4.07	0.05	4.74
24	7.89	2.81	0.40	0.92	1.08	0.12	3.90	0.48	1.01	0.02	0.13	5.20	5.63	-0.04	-4.01
25	7.6	0.18	0.04	0.19	0.01	0.10	0.14	0.02	0.18	0.00	0.02	0.42	0.46	-0.05	-4.80
26	8.59	3.70	0.32	0.33	0.11	0.24	3.61	0.08	0.28	0.01	0.09	4.46	4.29	0.02	1.92
27	8.07	0.80	0.04	0.48	0.03	0.00	0.36	0.19	0.79	0.01	0.11	1.35	1.45	-0.04	-3.65
28	7.96	2.81	0.40	1.13	0.18	0.10	2.49	1.05	0.94	0.02	0.05	4.51	4.63	-0.01	-1.31
29	8.41	1.40	0.64	1.04	0.31	0.00	1.84	0.48	0.96	0.01	0.07	3.39	3.35	0.01	0.67
30	6.33	1.84	0.96	3.48	0.41	0.10	2.46	3.71	0.57	0.01	0.05	6.69	6.89	-0.01	-1.47
31	8.47	1.60	0.48	1.13	0.14	0.16	1.89	0.10	1.13	0.01	0.05	3.35	3.33	0.00	0.39
32	7.79	2.81	0.80	0.65	0.12	0.07	2.11	1.61	0.79	0.00	0.04	4.38	4.62	-0.03	-2.71
33	8.56	3.10	0.50	6.17	0.12	0.24	2.70	0.75	6.51	0.02	0.06	9.89	10.27	-0.02	-1.85
34	8.16	0.90	0.16	0.28	0.09	0.00	0.75	0.33	0.28	0.01	0.05	1.43	1.42	0.00	0.29
35	8.8	2.90	1.89	4.00	0.21	0.80	3.20	1.31	3.80	0.02	0.06	9.00	9.18	-0.01	-0.95
36	7.77	1.00	0.40	0.29	0.15	0.20	1.01	0.54	0.20	0.01	0.07	1.84	2.02	-0.05	-4.81
37	8.89	0.55	1.15	0.70	0.15	0.40	1.03	0.46	0.85	0.00	0.01	2.55	2.75	-0.04	-3.78
38	7.1	1.68	0.48	0.59	0.16	0.11	2.36	0.50	0.21	0.01	0.03	2.91	3.20	-0.05	-4.76
39	7.99	2.61	1.60	4.09	1.72	0.17	6.57	1.25	2.23	0.00	0.26	10.01	10.48	-0.02	-2.30
40	8.69	2.10	0.16	0.37	0.12	0.24	1.64	0.40	0.45	0.02	0.11	2.74	2.83	-0.02	-1.54
41	8.6	2.75	0.52	0.57	0.07	0.24	2.80	0.08	0.76	0.00	0.05	3.90	3.93	0.00	-0.43
42	7.3	1.44	0.24	0.50	0.02	0.13	1.37	0.16	0.66	0.00	0.06	2.21	2.39	-0.04	-3.99
43	8.79	2.55	0.12	0.19	0.09	0.40	2.36	0.05	0.24	0.01	0.02	2.95	3.07	-0.02	-1.96
44	7.01	1.20	0.20	0.67	0.13	0.04	1.23	0.40	0.67	0.01	0.08	2.19	2.42	-0.05	-4.94
45	9.14	0.44	0.48	0.91	0.05	0.63	0.25	0.29	0.87	0.02	0.02	1.88	2.07	-0.05	-4.83
46	7.72	0.48	0.12	0.33	0.04	0.00	0.12	0.23	0.68	0.02	0.04	0.98	1.07	-0.04	-4.21

Table 5.22 : Hydrochemical data of confined aquifer (Alluvium) and percentage of error for May. 2009

Sample No	pH	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	NO_3	Total Cation	Total Anion	% Error
		Values in meq/l											
1	6.70	0.72	0.32	0.79	0.08	0.00	0.66	0.56	0.70	0.09	1.92	2.01	-2.47
2	8.20	0.96	1.60	3.96	0.08	0.13	2.19	0.08	3.61	0.84	6.60	6.86	-1.94
3	6.17	0.80	0.40	0.55	0.04	0.00	0.46	0.38	0.60	0.46	1.79	1.90	-2.97
4	7.3	0.48	0.16	0.50	0.01	0.00	0.40	0.22	0.29	0.32	1.16	1.22	-2.90
5	7.69	0.64	0.24	1.24	0.08	0.00	0.72	0.21	1.17	0.20	2.20	2.32	-2.59
6	7.8	0.72	0.08	1.07	0.02	0.00	0.66	0.21	0.87	0.24	1.89	1.99	-2.51
7	8.1	0.72	0.40	0.23	0.08	0.00	0.90	0.23	0.29	0.05	1.44	1.48	-1.42
8	7.67	2.00	7.99	26.96	0.58	0.00	6.20	0.62	30.83	2.00	37.53	39.66	-2.76
9	7.01	2.81	1.60	26.30	0.22	0.00	2.31	0.15	27.90	2.54	30.92	32.90	-3.10
10	8.14	3.61	4.64	27.22	0.65	0.00	0.40	2.22	36.87	0.21	36.11	39.70	-4.73
11	7.01	1.61	0.40	2.17	1.49	0.00	1.29	0.87	3.44	0.63	5.67	6.23	-4.75
12	5.5	1.44	1.16	0.87	0.23	0.00	1.45	0.44	1.42	0.37	3.70	3.68	0.29
13	4.25	15.03	20.98	97.83	0.82	0.00	5.33	0.11	128.17	0.08	134.66	133.69	0.36
14	6.96	0.96	0.95	1.83	0.86	0.00	0.52	2.41	2.04	0.06	4.60	5.03	-4.48
15	7.21	1.80	2.92	11.74	0.24	0.00	0.49	2.30	14.85	0.08	16.70	17.73	-3.00
16	7.85	3.05	3.96	1.74	0.13	0.00	3.58	0.04	5.24	0.29	8.87	9.15	-1.56
17	8.16	4.01	0.80	15.91	4.67	0.00	4.75	5.28	12.90	0.51	25.39	23.44	3.99
18	7.5	1.38	1.14	2.50	0.08	0.00	1.04	0.12	2.62	1.65	5.10	5.43	-3.13
19	7.34	0.80	0.40	0.93	0.17	0.00	0.60	0.14	0.85	0.87	2.30	2.46	-3.30
20	8.39	1.30	1.62	40.61	0.00	0.00	2.00	0.33	43.32	0.29	43.53	45.95	-2.70
21	7.18	2.40	1.21	0.78	0.23	0.00	2.96	0.13	0.87	0.90	4.63	4.86	-2.43
22	7.44	1.20	0.40	2.35	0.12	0.00	1.80	0.10	2.10	0.37	4.07	4.36	-3.45
23	6.92	2.00	0.40	1.25	0.19	0.00	2.11	0.13	1.22	0.77	3.84	4.24	-4.89
24	8.30	2.24	1.29	2.09	0.14	0.17	2.95	0.10	2.04	0.89	5.76	6.14	-3.19
25	8.39	2.00	1.02	6.43	0.18	0.40	2.94	0.07	6.47	0.66	9.64	10.54	-4.46
26	7.26	4.41	2.80	12.35	0.47	0.00	4.85	0.27	13.98	2.27	20.03	21.38	-3.28
27	7.20	4.89	7.11	20.87	0.54	0.00	7.90	1.78	23.01	3.84	33.41	36.52	-4.45
28	6.28	19.24	41.76	58.70	1.33	0.00	1.87	6.13	116.52	4.03	121.03	128.55	-3.01
29	7.84	11.42	21.58	129.6	1.92	0.00	1.90	2.52	173.73	1.98	164.49	180.13	-4.54
30	7.47	5.11	8.69	36.52	0.41	0.00	3.30	5.28	45.25	2.24	50.73	56.06	-4.99

Table 5.23 : Hydrochemical data of Tertiary aquifers and percentage of error for May. 2009

Sample no	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	Total Cation	Total anion	% Error
		Values in meq/l										
1	7.69	11.63	28.77	195.65	0.64	6.15	203.91	13.03	3.92	236.69	227.00	2.09
2	7.21	6.21	7.15	29.13	0.36	2.96	34.27	1.12	7.11	42.85	45.46	-2.95
3	8.37	0.32	0.24	4.78	0.31	1.02	4.08	0.48	0.44	5.65	6.01	-3.08
4	7.6	0.88	1.04	4.26	0.06	0.77	5.54	0.32	0.08	6.25	6.70	-3.52
5	8.14	3.61	4.64	29.83	0.65	0.40	39.32	2.63	0.21	38.72	42.57	-4.73
6	8.05	1.44	1.36	14.09	0.22	3.67	13.69	1.16	0.14	17.10	18.65	-4.33
7	8.83	3.61	4.00	25.65	0.41	0.29	34.96	1.80	0.04	33.67	37.08	-4.83
8	7.16	1.20	1.20	2.43	0.23	2.58	2.45	0.09	0.43	5.07	5.54	-4.50
9	7.5	1.38	0.32	2.50	0.08	0.71	2.62	0.12	0.85	4.28	4.30	-0.21
10	6.87	1.30	3.57	4.52	0.36	0.13	9.26	0.08	1.01	9.76	10.49	-3.64
11	7.27	0.40	0.40	9.74	0.24	0.92	9.79	0.13	0.84	10.78	11.69	-4.03
12	8.1	1.20	0.40	29.57	0.87	1.56	31.29	0.42	0.76	32.04	34.03	-3.01
13	8.41	2.10	1.62	22.17	0.22	2.34	23.30	1.61	0.94	26.12	28.19	-3.81
14	7.3	1.84	1.28	0.62	0.09	2.06	0.58	0.02	1.18	3.83	3.84	-0.08
15	7.11	1.20	2.80	10.43	0.31	3.94	10.19	0.02	2.01	14.74	16.17	-4.61
16	8.31	1.68	2.12	6.96	0.18	3.56	4.37	1.50	1.82	10.94	11.24	-1.35
17	6.60	1.46	0.16	0.52	0.13	0.77	0.54	0.39	0.37	2.27	2.06	4.75
18	7.05	0.72	0.40	0.78	0.05	0.83	1.15	0.04	0.13	1.95	2.15	-4.81
19	7.93	1.20	1.00	11.39	0.14	1.78	11.94	1.23	0.00	13.73	14.95	-4.26
20	7.87	1.40	1.20	6.78	0.13	2.06	6.26	2.01	0.00	9.52	10.34	-4.13
21	7.16	1.20	4.20	15.57	0.46	6.15	16.36	0.26	0.00	21.43	22.78	-3.06
22	8.15	0.88	1.04	2.83	0.14	2.31	2.93	0.02	0.00	4.89	5.26	-3.69
23	6.84	1.84	1.28	6.00	0.40	0.81	8.35	0.89	0.00	9.52	10.05	-2.71
24	7.57	2.20	1.96	7.91	0.19	3.37	7.67	1.80	0.00	12.27	12.85	-2.31
25	7.69	0.88	1.12	1.04	0.14	2.27	0.85	0.25	0.00	3.19	3.39	-3.06
26	8.05	1.36	1.52	2.65	0.13	1.69	3.79	0.03	0.00	5.66	5.50	1.37
27	7.26	2.40	1.80	3.21	0.07	3.06	4.66	0.03	0.00	7.48	7.76	-1.82
28	7.21	6.21	7.15	24.78	0.36	3.09	37.09	1.12	0.01	38.51	41.31	-3.51
29	6.83	0.48	0.32	0.96	0.04	0.83	0.87	0.14	0.00	1.80	1.85	-1.22
30	8.31	1.68	2.12	6.09	0.18	3.56	4.37	1.50	0.00	10.07	9.43	3.31
31	7.15	2.00	1.60	1.73	0.10	2.43	2.33	0.33	0.00	5.43	5.09	3.22
32	7.08	2.81	3.20	5.22	0.24	2.98	9.03	0.02	0.00	11.46	12.03	-2.45
33	7.05	1.76	1.20	5.22	0.08	3.11	5.93	0.02	0.00	8.26	9.06	-4.58
34	6.79	2.65	1.12	0.43	0.06	2.50	2.04	0.03	0.00	4.25	4.56	-3.54
35	6.72	1.12	1.12	0.81	0.19	2.77	0.62	0.02	0.00	3.24	3.42	-2.77
36	7.53	0.80	0.96	1.30	0.15	2.68	0.62	0.03	0.00	3.21	3.34	-1.90
37	7.26	7.02	5.00	9.57	0.35	2.30	18.06	2.10	0.00	21.92	22.46	-1.21
38	7.5	0.88	0.32	0.52	0.08	1.04	2.62	0.12	0.00	3.78	3.78	-0.01
39	7.81	1.40	1.52	9.13	0.29	3.36	9.96	0.10	0.00	12.35	13.43	-4.21
40	6.99	1.28	1.52	4.17	0.25	2.51	5.42	0.03	0.00	7.22	7.96	-4.89
41	8.18	1.06	0.39	0.62	0.04	0.90	0.87	0.00	0.19	2.12	1.96	3.79
42	8.14	3.61	4.64	25.46	0.01	0.40	36.23	0.01	0.07	33.71	36.70	-4.25
43	6.55	1.28	1.52	15.13	0.08	2.85	15.90	0.01	0.92	18.01	19.68	-4.44
44	7.10	0.88	1.20	6.00	0.46	2.81	6.12	0.04	0.42	8.54	9.39	-4.72

5.6 Corrosivity Ratio (CR)

The magnitude of corrosiveness of water can be assessed by using a parameter known as corrosivity ratio which can be determined using the following formula.

$CR= [(Cl/35.5) + (SO_4/48)] / [(HCO_3 +CO_3)/50]$, where all the ions are expressed in mg/l.

Corrosiveness denotes the potential of groundwater to corrode metals. Continuous use of corrosive water damages the distribution systems made of metallic pipes for irrigation and the metallic fillings of water supply systems. CR has been effectively used to evaluate corrosive tendency of groundwater on metallic pipes of various regions (Raman, 1985; Aravindan et al., 2004). Water having CR less than 1 is safe and non-corrosive. The rate at which corrosion proceeds depends upon certain physical parameters like temperature, pressure and velocity of flow of water in the pipes. In the absence of carbonate minerals and in the presence of Cl and SO_4 the water becomes more corrosive. Based on the CR calculated for the waters of different aquifer systems the percentage of corrosive samples in the area are presented in Table 5.24.

Table 5.24.Corrosive Ratio of water in different aquifer systems

Aquifer system	Month	Number and percentage of corrosive samples		
		Total no. of samples	CR > 1	% of samples with CR>1
Phreatic aquifer	May-09	46	4	8.7
	Oct.-09	32	16	50
Recent –confined aquifer	May-09	30	25	83
	Oct.-09	32	17	53
Confined aquifer - Tertiary aquifer system	May-09	44	34	77
	Oct.-09	41	30	73

Most of the samples in all the aquifer systems are corrosive in nature. Seasonal variations in the percentage of corrosive samples are observed in the case of phreatic aquifer and Recent alluvial aquifer under confined/ semi-confined conditions. Almost stable situation is seen in the case of Tertiary aquifer without much seasonal changes in the percentage of corrosive samples. Use of Mild Steel pipes (MS pipes) for tube well construction in the area will reduce the life of wells. Hence, PVC blank and slotted pipes are suitable for tube well construction in this area.

5.7 Inter relationships of ions

The observations made through chemical analysis needs to be interpreted in a rational manner to decipher the spatial and temporal variation in the hydrochemical data. In addition, water quality depends on a variety of physico-chemical parameters and meaningful prediction, ranking analysis or pattern recognition of the quality of water requires multivariate projection methods (Subba Rao et al.,2013; Ayoko et al, 2007) for simultaneous and systematic interpretation. Taking this into consideration the multivariate statistical techniques are used to interpret the water quality of the study area and to give meaningful results that were not possible while assessing the data at a glance.

The descriptive statistical analysis was done for the major ion species in the groundwater of the phreatic and confined aquifer systems in Recent alluvium and for the Tertiary aquifers. The muli-variate analysis carried out include Pearson correlation, Factor analysis and Cluster analysis. All these are synthesized here to decipher the dynamics involved in the hydrochemistry of the aquifer systems in the area.

Correlation coefficient is used to measure the strength of association between two continuous variables. The correlation measures the observed co-variation and the most commonly used measure of correlation is Pearson's r. It is also called the linear correlation coefficient because r measures the linear association between two variables (Helsel and Hirsch, 2002).

The inter-relationships of various chemical constituents in the groundwaters of phreatic and confined aquifer systems of Recent alluvium and the Tertiary aquifers have been studied from a correlation matrix of major chemical constituents. Normal distribution of the variables and homoscedacity (equal varience) are necessary pre-requisites for application of parametric statistical techniques (Yidana, 2012). Hence, the variables were first transformed to their natural logarithms to make their distribution normal and then the data set was standardized to have a mean of 0 and standard deviation of 1 by deducting the mean of each variable from individual values and then dividing them with their standard deviation. This transformed data set has been used for the determination of correlation coefficients. The matrix of correlation coefficients of Ca, Mg, Na, K, CO_3, HCO_3, SO_4, Cl, F, and NO_3 for the samples collected during pre-monsoon period from phreatic and confined aquifers in the Recent alluvium is shown in Table 5.25and 5.26 and the matrix of correlation for the Tertiary aquifer is shown in Table 5.27.

The correlation matrix of phreatic aquifer indicates that significant positive correlation (at 0.01 confidence level) are shown by Ca with Mg, K, HCO_3, SO_4 and NO_3; by Na with K, HCO_3, SO_4, and Cl; by HCO_3 with SO_4 and NO_3 and SO_4 with Cl (Table 5.25). Chloride shows good correlation with Na indicating leaching of secondary salts and the influence of marine aerosols. The significant correlation of HCO_3 with Ca, Mg, K, SO_4, and Cl indicates anthropogenic influence on characteristic recharge area type water. Fluoride shows poor correlation with all other ions. The good positive correlation of NO3- with Cl- suggests their anthropogenic origin (Demlie et al., 2007). Main potential sources of NO3- in the aquifer system are numerous shallow pit toilets and oxidation of organic matter and agricultural practices. The positive correlation of Cl with Na suggests the Cl- contribution from atmospheric inputs. The strong positive correlations of HCO_3 with Ca, Mg, Na and K indicate similar origin of ions. The low concentrations of F- in groundwater of the phreatic aquifer may be due to its acidic nature which renders F- immobile (Hem, 1992; Edmunds and Smedley, 2000).

Table 5.25 Matrix of Correlation Coefficients of Major Ions in Groundwater from Phreatic Aquifers (May 2009)

	Ca	**Mg**	**Na**	**K**	**CO_3**	**HCO_3**	**SO4**	**Cl**	**F**	**NO_3**
Ca	1									
Mg	.549**	1								
Na	.348*	.697**	1							
K	.632**	.652**	.650**	1						
CO_3	-0.137	-0.123	-0.149	-0.125	1					
HCO_3	.912**	.654**	.463**	.696**	-0.224	1				
SO_4	.391**	.662**	.633**	.594**	-.338*	.404**	1			
Cl	.310*	.588**	.897**	.547**	0.056	.352*	.447**	1		
F	0.189	0.14	0.091	0.12	-0.098	0.191	.335*	-0.041	1	
NO_3	.408**	0.173	0.276	.332*	-0.166	.381**	.295*	0.255	.338*	1

**. Correlation is significant at the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed).

Table 5.26 Matrix of Correlation Coefficients of Major Ions in Groundwater from Recent-Confined Aquifers (May 2009)

	Ca	**Mg**	**Na**	**K**	**HCO_3**	**SO_4**	**Cl**	**NO_3**	**F**	**Fe**
Ca	1									
Mg	.881**	1								
Na	.808**	.826**	1							
K	.698**	.632**	.709**	1						
HCO_3	.611**	.534**	.504**	.473**	1					
SO_4	.394*	.407*	.467**	.599**	-0.068	1				
Cl	.848**	.876**	.988**	.734**	.514**	.465**	1			
NO_3	.449*	.402*	.398*	0.231	.534**	0.115	.388*	1		
F	.419*	.482**	.574**	.397*	.390*	0.046	.555**	.415*	1	
Fe	-0.02	-0.074	0.081	0.085	0.334	-.460*	0.049	0.153	0.335	1

**. Correlation is significant at the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed).

Table 5.27 Matrix of Correlation Coefficients of Major Ions in Groundwater from Tertiary Aquifers (May 2009)

	Ca	**Mg**	**Na**	**K**	**HCO_3**	**Cl**	**SO_4**	**NO_3**	**F**	**Fe**
Ca	1									
Mg	.801**	1								
Na	.511**	.655**	1							
K	0.212	.355*	.509**	1						
HCO_3	0.179	0.27	0.128	0.209	1					
Cl	.598**	.693**	.966**	.468**	0.056	1				
SO_4	.375*	.328*	.543**	.569**	0.083	.489**	1			
NO_3	0.054	0.054	0.281	0.177	-0.184	0.237	0.084	1		
F	-0.02	0.158	0.141	-0.035	0.268	0.085	0.083	0.056	1	
Fe	0.169	0.18	0.075	0.059	0.106	0.102	0.013	0.045	-0.238	1

**. Correlation is significant at the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed).

The correlation matrix of major ions in the confined aquifer of Recent alluvium (Table 5.26) indicates significant positive correlation (at 0.01 confidence level) by Ca with Mg, K, HCO_3, SO_4 and by Na with Cl, K and SO_4. The HCO_3 shows significant correlation with Cl and NO_3. Chloride shows a positive correlation with F indicative of fluoride enrichment and leaching of salts in the aquifer. Similarly the correlation of HCO_3 with Cl and NO_3 indicates the influence of organic matter decay and leaching of salts in the flow system.

The correlation matrix in Table 5.26 indicates that significant positive correlation (at 0.01 confidence level) are shown by Ca with Mg, Na, and Cl; by Na with K, SO_4, and Cl; by K with SO_4 and Cl; by Cl with SO_4. The good correlation by chloride with Na and the significant correlation of SO_4 with Na, K, and Cl indicate leaching of salts. NO_3, F and Fe show no significant correlation with any other ion, indicative of their enrichment in some of the samples as site specific and not influenced by the regional flow system.

5.8 Factor and Cluster models for Phreatic aquifers

R-mode Factor analysis, which is a statistical technique for reducing a large number of original variables into a few factors using linear combinations (Davis, 2002), was used to gain a better insight into the hydrochemical characteristics of groundwater from the phreatic aquifer systems. The factors thus generated have been used to interpret the hydrochemical characteristics. Q-mode HCA was applied to the z-scores of the parameters in order to determine the spatial relationships amongst the various samples or sampled locations (Ayenew et al., 2009).

5.8.1 Factor results

The Principal Component approach with Varimax rotation was adopted in the present study and the final factor model has four factors which account for 81% of the total variance in the hydrochemistry. The Factor loadings matrix is shown in Table. 5.28 and the percentage of varience explained by various factors in groundwater is shown in Table 5.29

Factor 1 explains 45% of the total variance and has high positive loadings for most of the major ions (Na^{+}, Mg^{2+}, Cl^{-} and SO_4^{2-}). The loadings of Na+ and Cl− under factor 1 are compatible and suggest a similar source for them. It has a positive loading with K ion and the loadings of ions in factor 1 indicate anthropogenic interferences. Factor 1 is a mixed factor representing the contribution of the dissolution of chlorides and sulfates of the major cations.

Table 5.28. Factor loadings matrix from R-mode factor

	Component			
	1	2	3	4
Ca	.182	.933	.125	-.035
mg	.711	.469	.022	-.135
Na	.935	.174	.119	-.074
K	.601	.606	.104	-.067
CO3	-.022	-.098	-.001	.955
HCO3	.276	.914	.089	-.115
SO4	.651	.197	.346	-.438
Cl	.904	.131	.026	.170
F	-.042	.087	.892	-.126
NO3	.091	.426	.514	-.090
Fe	.234	.013	.884	.141

The Mg^{2+} ion probably resulted from the dissolution as well as mixing brackish water interactions from the tidal inlets and canals. The Na+ ion has the highest loading with factor 1and was identified as the key and representative parameter for the chemical reactions in the aquifer system. The dendrogram of R-mode factor analysis in Fig. 5.8 shows the relations among the ions.

Factor scores usually indicate the degree to which the processes represented by the factor affect groundwater quality in the area. Where the factor score is higher than 0, the contribution of factor 1 at the location is high (Jiang et al., 2009; Kim et al., 2009). The converse is true for negative factor scores. The more positive the factor score, the higher the effect of the factor in question at the location.

Table 5.29 Percentage of Variance explained by various factors in groundwater from phreatic aquifer.

	Initial Eigenvalues			**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loadings**		
Factors	**Total**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	4.902	44.565	44.565	4.902	44.565	44.565	3.155	28.686	28.686
2	1.686	15.323	59.888	1.686	15.323	59.888	2.578	23.432	52.118
3	1.320	11.999	71.887	1.320	11.999	71.887	2.010	18.277	70.395
4	1.055	9.593	81.479	1.055	9.593	81.479	1.219	11.084	81.479
5	.752	6.837	88.316						
6	.397	3.608	91.924						
7	.354	3.218	95.142						
8	.247	2.248	97.389						
9	.173	1.571	98.961						
10	.078	.712	99.673						
11	.036	.327	100.000						

Factor 2 in the final factor model has high positive loadings for Ca^{2+} and HCO_3^- and represents the effects of carbonate mineral weathering on the hydrochemistry of groundwater in the study area. It accounts for 15% of the total variance in the hydrochemistry (Table 5.28) and therefore represents the second most important process in the hydrochemistry of groundwater in the study area. Factor 2 loads positively with K^+, Mg^{2+} and NO_3^- although these loadings are relatively weak at 0.606, 0.469, and 0.426 respectively (Table 5.28).

The third factor in the model accounts for about 12% of the total variance in the hydrochemistry and has a high positive loading for loading for F^- and Fe^{2+}. It loads positively with NO_3^- and SO_4^{2-} with a relatively weak loading of .514 and .346 respectively.

The fourth factor in the model accounts for about 10% of the total variance in the hydrochemistry and has a positive loading for CO_3^-.

A perusal of the rotated component matrices computed from the analysis (Table 5.28) indicates that rock water interaction could be the major factor determining the hydrochemical characteristics of groundwater in the phreatic aquifers, with anthropogenic sources modifying the chemistry through contributions of ions such as Chloride and sodium.

5.8.2 Hierarchical Cluster Analysis results

The multivariate statistical method of R mode cluster analysis (Davis, 2002) was applied to the standardized data groundwater samples collected from both the aquifers to understand the inherent variations in their chemical compositions. The dendrograms generated from the data pertaining to the phreatic aquifer is shown in Fig. 5.9.

At a linkage distance of 10 in the dendrogram the hydrochemistry of phreatic aquifer is mainly explained by two clusters, one with a strong Ca-HCO_3 relationship and the second with a strong Na-Cl relationship. The clusters shown in the dendrogram corroborates with the Factor analysis results.

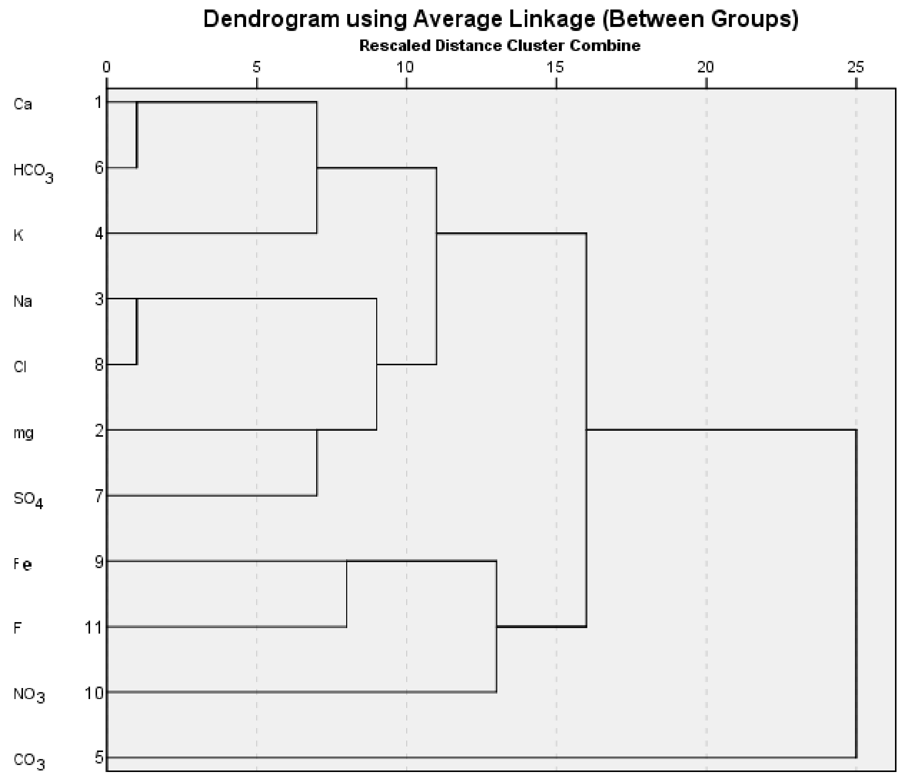


Fig. 5.9. Dendrogram of R-mode Cluster Analysis of groundwater samples from phreatic aquifers

Q-Mode Hierarchical Cluster Analysis (HCA)

Q-mode HCA was applied to the z-scores of the parameters in order to determine the spatial relationships amongst the various samples or sampled locations. Squared Euclidean distances were used to measure the degree of similarity/dissimilarity amongst the parameters whilst the Ward's agglomeration technique was used to link the initial clusters. Unique clusters were sorted out of the dendrogram, which is the graphical result of the HCA (Ayenew et al., 2009). Statistical summaries of the measures of the parameters under each cluster were computed to assist in the description of the general groundwater flow regime and the general hydrochemical trends in the study area. Factor scores of the members of these clusters were used to plot scatter diagrams against the concentrations of the key parameters identified in the final factor model in order to identify any useful trends in the distribution of the data.

Results of the Q-mode HCA are presented in Fig. 5.10 in which four spatial groundwater associations have been distinguished. The phenon line was drawn across the dendrogram at a linkage distance of 10. The four spatial groundwater associations represented by the four clusters at this linkage distance (Fig. 5.10). The first cluster represents the biggest group with sixteen samples followed by 9 samples in the second association. The third and fourth groups have 5 and 6 groundwater associations respectively.

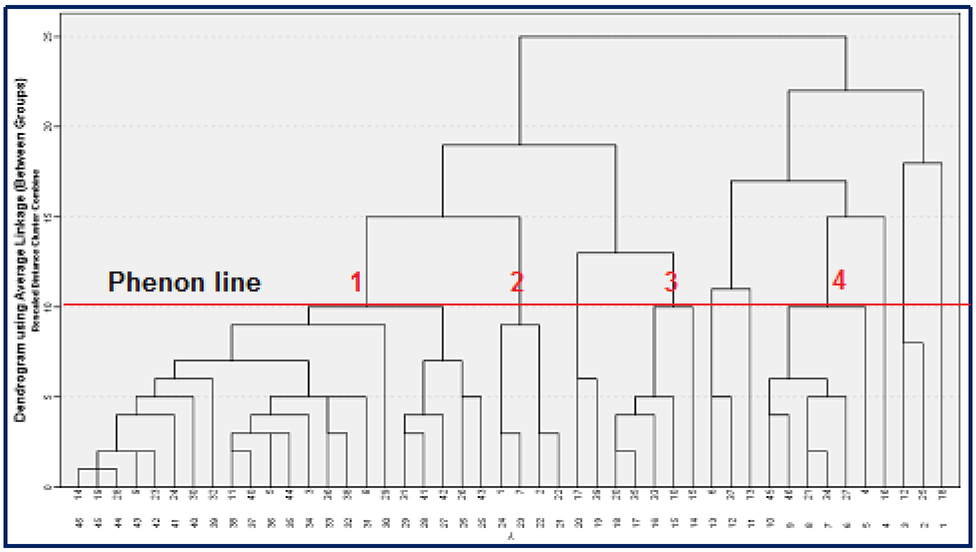


Fig.5.10 Dendrogram of Q-mode Cluster Analysis of groundwater samples from phreatic aquifers

Stiff diagrams for the arithmetic averages of the measures of the chemical constituent for each group were prepared (Fig. 5.11) to identify the water type representing each group. The group 1 (Fig. 5.11) represents intermediate type, Na–HCO_3 fresh groundwater types in the flow regime; group 2 represents fresh Ca–HCO_3 groundwater types which are characteristic of groundwater recharge areas in the general flow regime; group 3 represents Na–Cl groundwater type which is characteristic of groundwater in discharge areas of the flow regime or areas affected by salinity. Group four is characterized by a mixed category with an order of dominance of Mg, Na+K, and Cl indicating the anthropogenic influence on the groundwater chemistry. Although clusters 1 and 2 represent intermediate and recharge type groundwaters respectively, they might have evolved from the interaction between the aquifer material and groundwater and other intervening factors in the area.

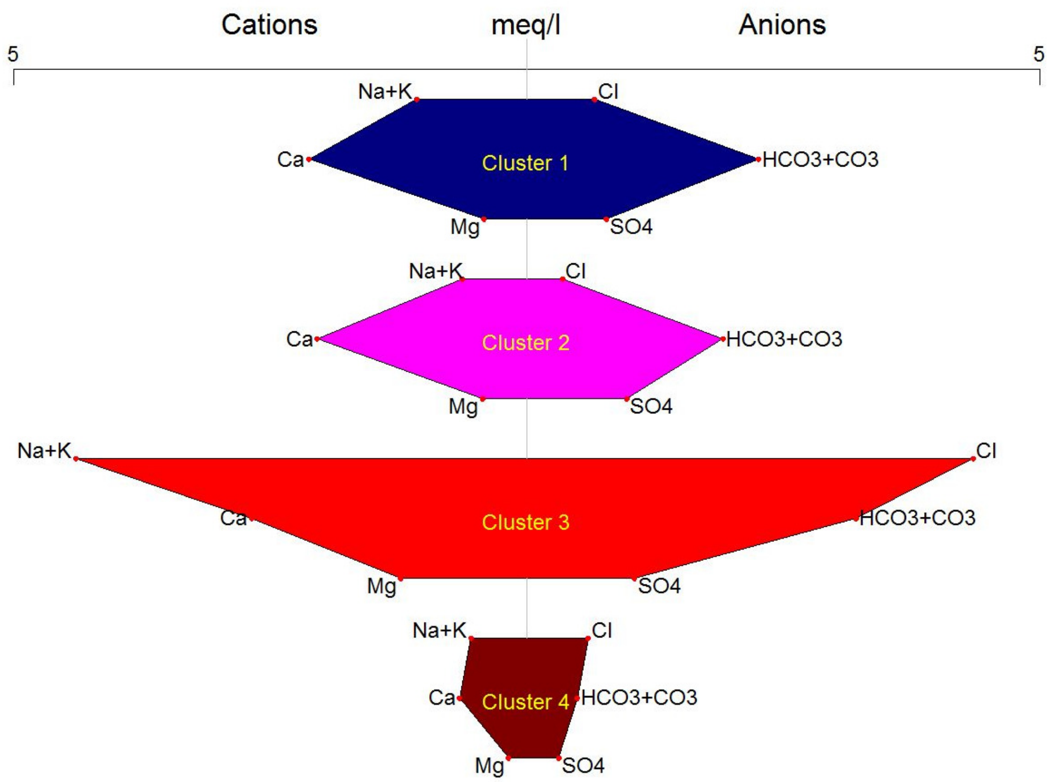


Fig 5.11. Stiff diagram showing average chemical characteristic of Cluster groups in the Phreatic aquifers.

Each cluster (group) represents the position of its members in the groundwater flow regime and/or the key processes influencing groundwater hydrochemistry in the areas where the membership of these clusters are presented. The spatial location of the membership of these clusters has been compared with the water table surfaces of groundwater in the study area (Fig 4.4). Due to low hydraulic gradients, the flow in the aquifer system is very slow with shallow water table conditions and groundwater is almost stagnant over a large area. The different groundwater types in the area are therefore more influenced by the surface water quality and anthropogenic interferences.

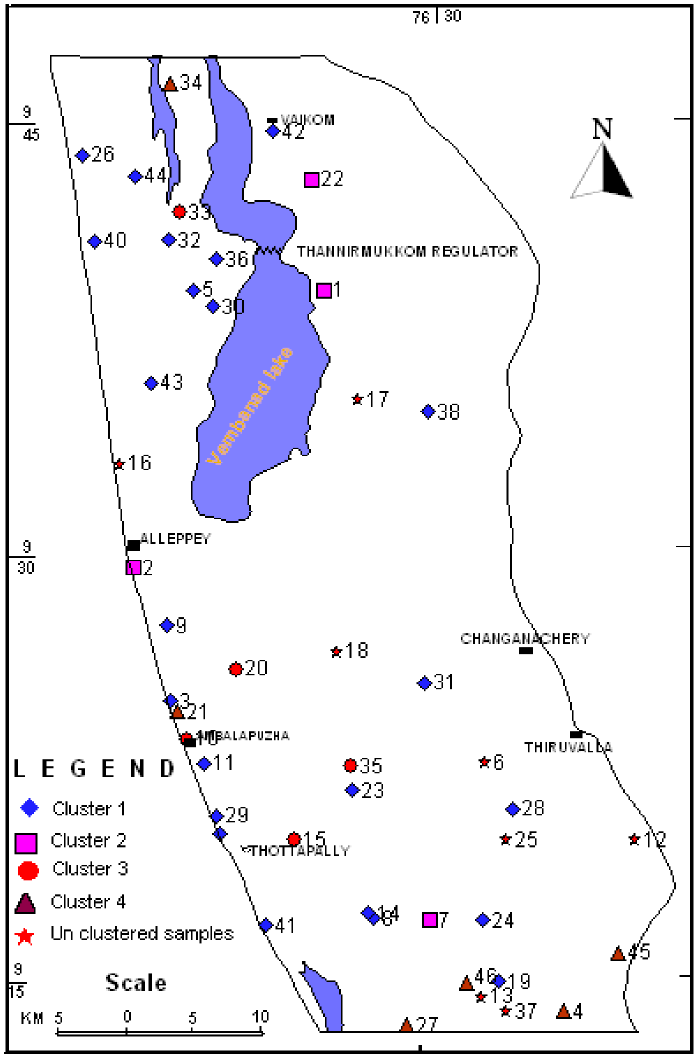


Fig 5.12 Spatial representation of the members of the Clusters in Phreatic aquifer

The spatial representation of the cluster members shown in Fig 5.12 indicates that the members of the cluster-3, which is Na-Cl dominant water type are located either near to brackish water bodies or canals influenced by tidal effects. The members of the other three clusters are essentially Ca-HCO_3 type water with compositional differences. The members of cluster 4 reperesent the recharge type water with low ionic concentrations and are mainly located in the south-eastern part and sand dunes. It is inferred that the members of cluster 1and 2 are modified by chemical reactions and influenced by anthropogenic activities.

5.9 Factor and Cluster models for Recent-confined aquifer

5.9.1. Factor analysis

Chemical analysis data of 30 water samples have been subjected to factor analysis. The final factor model has three factors which account for 78% of the total variance in the hydrochemistry. Table 5.30 and 5.31 presents the factor loadings matrix and the variance explained by various factors. Factor 1 explains 53% of the total variance and has high positive loadings for the major ions ($Ca^{2,+}Na^{+}$, Mg^{2+}, K^{+}, Cl^{-} , HCO_3^{-} and F^{-}) and EC. The loadings of most of major ions in factor 1 suggest the influence of a brackish environment. It has a positive loading with K ion and the loadings of ions in factor 1 indicate anthropogenic sources of contamination or influence of a brackish environment. Factor 1 is a mixed factor representing the contribution of the dissolution of chlorides and sulfates of the major cations. The Mg^{2+} and K^{+} ions probably resulted from ion exchange and mixing of brackish water within the confining clay layers. The Cl^{-}, Na+, K^{+}, Ca^{2+}, Mg^{2+} and EC are having high loading with factor1 and are identified as the key and representative parameters.

The factor 2 in the final factor model of Recent confined aquifers have positive loadings for Fe^{2+} and relatively weak loadings for HCO_3^{-} and F^{-}. It accounts for 15% of the total variance in the hydrochemistry (Table 5.31) and therefore represents the second most important process in the hydrochemistry of groundwater in this aquifer system. Factor 2 loads positively with Fe^{2+}, HCO_3^{-} and F^{-} and negatively with SO_4^{2-} with the loadings 0.842, 0.536, 0.407 and -0.730 respectively. The negative loading of factor 2 with SO_4^{2-} suggests that the processes it represent go contrary to the processes that generate SO_4^{-} in the system.

Table 5.30. Factor loadings matrix from R-mode factor

	Component		
	1	2	3
pH	-.213	-.082	.908
EC	.978	.022	-.007
Ca	.922	.044	-.126
mg	.922	-.010	-.078
Na	.939	.017	.091
K	.810	-.109	.050
HCO3	.600	.536	.110
SO4	.526	-.730	.107
Cl	.961	.001	.049
NO3	.453	.304	.506
F	.561	.407	.315
Fe	.018	.842	.028

Table. 5.31 Percentage of Variance explained by various factors in groundwater from Recent-confined aquifer.

Factors	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	6.365	53.043	53.043	6.365	53.043	53.043	6.322	52.682	52.682
2	1.838	15.319	68.362	1.838	15.319	68.362	1.808	15.069	67.751
3	1.165	9.707	78.069	1.165	9.707	78.069	1.238	10.318	78.069
4	.815	6.790	84.859						
5	.608	5.069	89.928						
6	.490	4.084	94.012						
7	.326	2.714	96.726						
8	.164	1.365	98.090						
9	.120	.999	99.089						
10	.087	.726	99.815						
11	.017	.140	99.956						
12	.005	.044	100.000						

The factor 3 in the final factor model accounts for 10% of the total variance in the hydrochemistry (Table 5.31) in Recent confined aquifers. The factor 3 has positive loadings for pH and NO_3^- and F^-. The factor loadings for NO_3^- and F^- are weak with loading 0.506 and 0.315 respectively.

It is inferred that the major reactions in the Recent aquifers are dissolution of salts and reverse cation exchange as indicated by factors 1 and the factor 2 shows weak negative relation with pH indicative of release of hydrogen ions from the ferruginous clays which consumes hydroxyl ions (OH^-) to form iron hydroxide ($Fe(OH)_2$ and subsequent oxidation of $Fe(OH)_2$ to FeO_2 and releases hydrogen ion in to the water. Both the reactions results in enrichment of H^+ concentration and consequent low pH of groundwater. However, this relation is controlled by another reaction in the aquifer system where consumption of hydrogen ion results from the decay of organic matter with the aquifer system as observed from the significant loading of NO_3 and pH in factor 3.

5.9.2 Hierarchical Cluster Analysis

The inherent variations in the chemical compositions of the groundwater in the Recent confined aquifer system analysed using R-Mode Hierarchical Cluster classification.

R-Mode Hierarchical Cluster Results of Recent aquifers.

The dendrograms generated from the data pertaining to the Recent confined aquifers are shown in Fig 5.13.

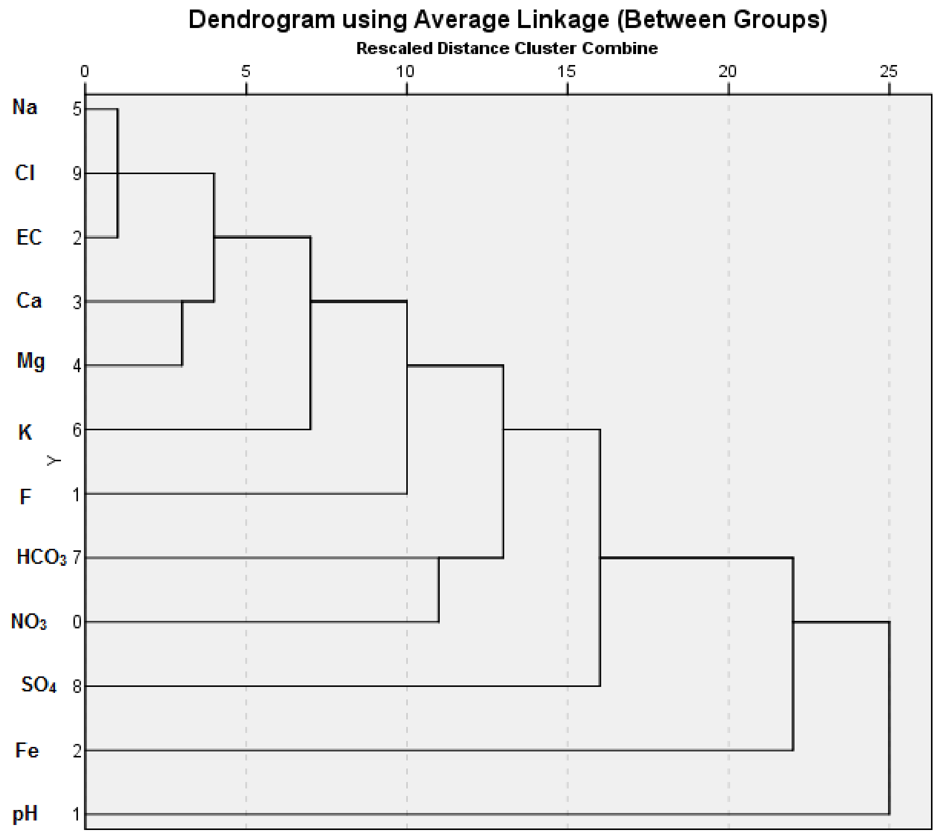


Fig 5.13 Dendrogram of R-mode Cluster Analysis of groundwater samples from Recent-confined aquifer system

Within a linkage distance of 10 strong relation among Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, and Cl^{-} ions are observed from the dendrogram. Weak relations of HCO_3^- and SO_4^{2-} with other ions reflected from high linkage distance indicate influence of chemical processes in addition to mineral dissolution in the contribution of these ions to the groundwater. The strong relation between Na and Cl observed indicates dissolution of salts the major process in this aquifer system.

Q-Mode Hierarchical Cluster Analysis

Results of the Q-mode HCA are presented in Fig. 5.14 in which three spatial groundwater associations have been distinguished. The phenon line was drawn across the dendrogram at a linkage distance of 10 and three spatial groundwater associations represented by the three clusters could be identified in Fig. 5.14.

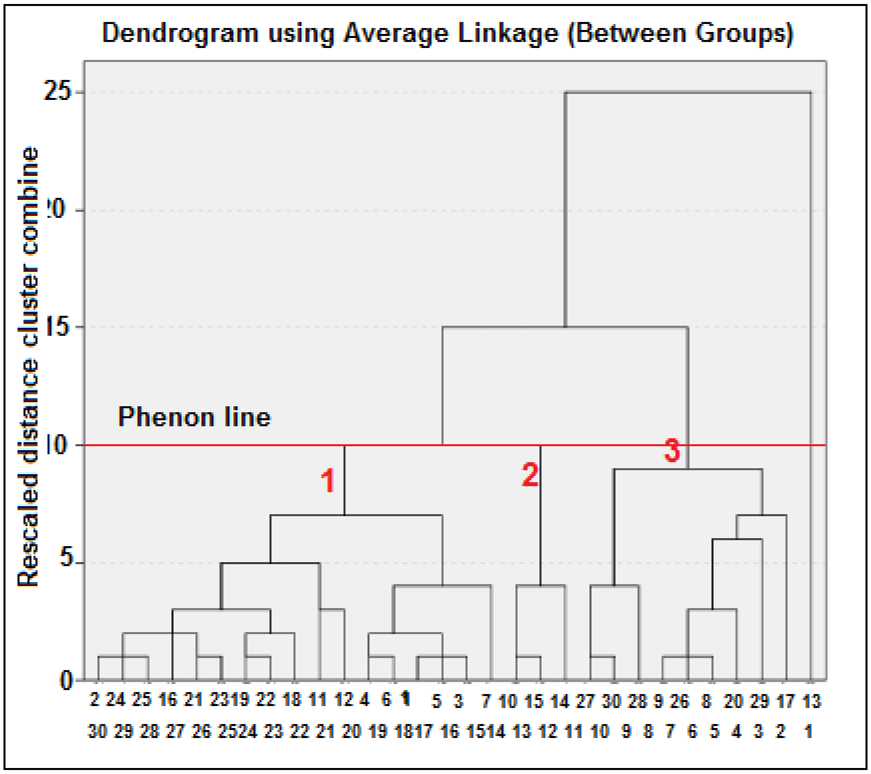


Fig.5.14 Dendrogram of Q-mode Cluster Analysis of groundwater samples from Recent-Confined aquifer**.**

Stiff diagrams were generated for the arithmetic averages of the measures of the chemical parameters used in this study. Figure 5.15 presents the stiff diagrams and the spatial distribution of all the three clusters (groups) in the study area is shown in Fig.5.16. Each cluster (group) represents the position of its members in the groundwater flow regime and/or the key processes influencing groundwater hydrochemistry in the areas where the membership of these clusters are presented.

The Stiff diagrams presented in Fig. 5.15 represent Na-Cl type water of three groundwater associations. The group one represents fresh groundwater of Na-Cl-Ca-HCO_3 dominant type in the flow regime; group 2 represents Na-Cl type groundwater of brackish nature in the general flow regime; group 3 represents Na–Cl groundwater type which is characteristic of groundwater in flow regime or areas affected by salinity.

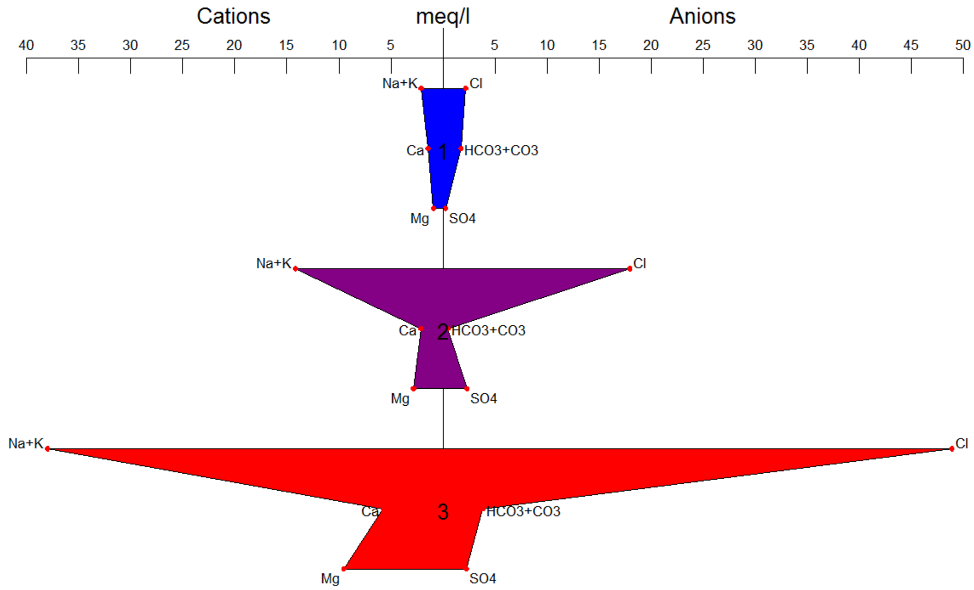


Fig 5.15. Stiff diagram showing average chemical characteristic of Cluster groups in the Recent-confined aquifers.

The spatial representation of the members of the three clusters shown in Fig. 5.16 indicates that most of the members of cluster 1 with comparatively low ion concentration are located all along the coast. The members of cluster 1 and 2 seem to be modified by leaching of salts from the clay layers and the members of cluster 3 represents brackish zones within the Recent alluvium.

5.10 Factor and Cluster models for Tertiary aquifer system

5.10.1 Factor analysis

Chemical analysis data from 46 locations have been subjected to factor analysis. The final factor model has four factors which account for 72% of the total variance in the hydrochemistry. Table 5.32 and 5.33 presents the factor loadings matrix and the variance explained by various Factors. Factor 1 explains 40% of the total variance and has high positive loadings for the major ions ($Ca^{2,+}Na^{+}$, Mg^{2+}, and Cl^{-}). The loadings of most of major ions in factor 1 suggest the influence of a brackish environment. Factor 1 is a mixed factor representing the contribution from the dissolution of salts in the aquifer system or the confining clay layers of marine origin as Mg^{2+} has the highest loading. The Mg^{2+} ions probably resulted from ion exchange also. The Mg^{2+} ion has the highest loading with factor1and was identified as the key and representative parameter for the latter.

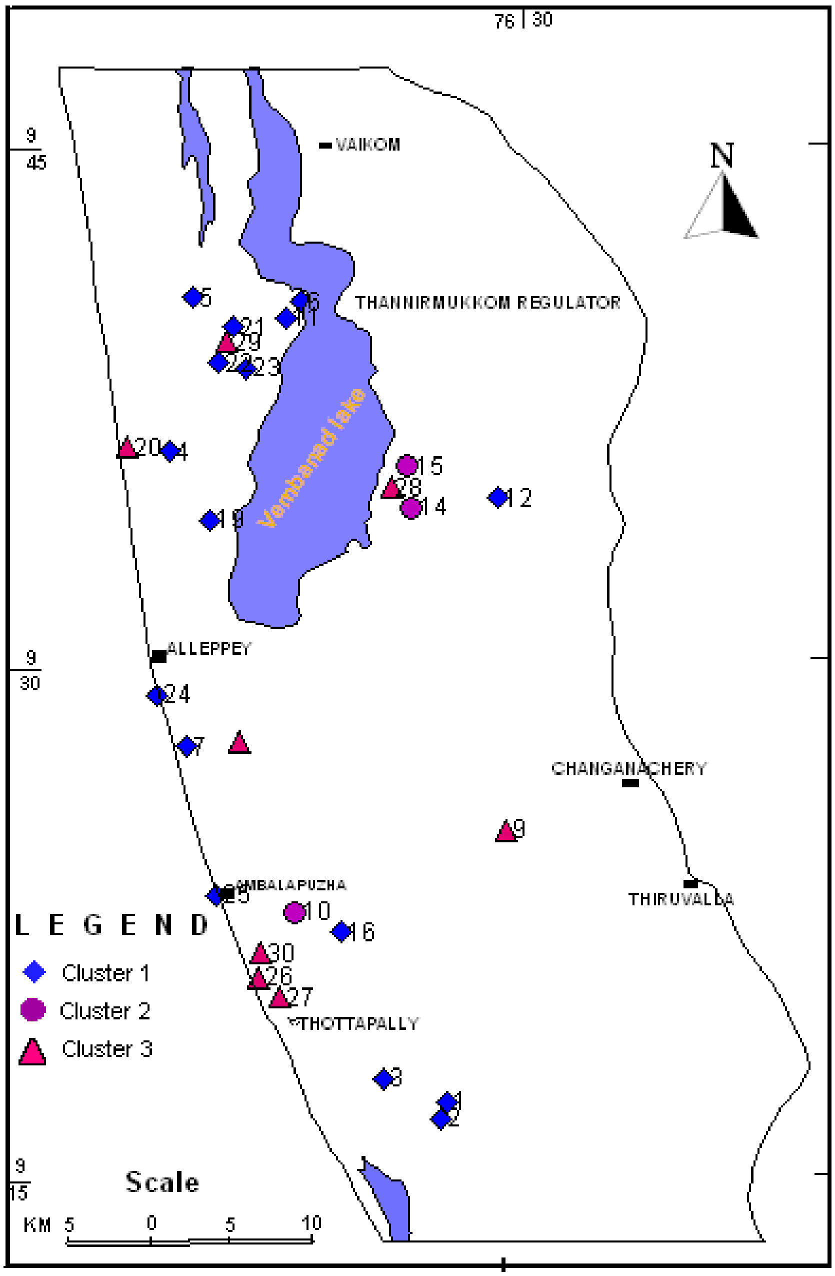


Fig. 5.16 Spatial representation of the members of the Clusters in Recent-confined aquifer

Table 5.32. Factor loadings matrix from R-mode factor

	Component			
	1	2	3	4
pH	.057	.504	.375	-.177
EC	.857	.412	.140	-.016
Ca	.845	.025	-.120	-.140
Mg	.907	.108	-.161	-.001
Na	.752	.530	.213	.108
K	.238	.771	-.141	.004
HCO_3	.227	.129	-.768	.170
Cl	.813	.430	.220	.043
SO_4	.239	.807	-.043	.053
NO_3	.206	.072	.657	.155
F	.161	-.032	-.148	.810
Fe	.237	-.009	-.120	-.724

The factor 2 in the final factor model of Tertiary aquifers has highest positive loadings for K^+ and SO_4^{2-} and relatively weak loadings for Na^+, Cl^- and pH with the loadings 0.530, 0.430, .504 respectively (Table 5.32). It accounts for 12% of the total variance in the hydrochemistry (Table 5.33) and therefore represents the second most important process in the hydrochemistry of groundwater in the Tertiary aquifer system.

Table 5.33 Variance Explained by various Factors

Factors	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.843	40.359	40.359	4.843	40.359	40.359	3.791	31.594	31.594
2	1.468	12.232	52.591	1.468	12.232	52.591	2.171	18.089	49.683
3	1.286	10.719	63.310	1.286	10.719	63.310	1.374	11.449	61.132
4	1.039	8.661	71.971	1.039	8.661	71.971	1.301	10.840	71.971
5	.925	7.711	79.682						
6	.894	7.452	87.134						
7	.564	4.703	91.837						
8	.478	3.983	95.820						
9	.313	2.606	98.426						
10	.127	1.054	99.480						
11	.046	.381	99.861						
12	.017	.139	100.000						

The factor 3 in the final factor model of Tertiary aquifers has highest positive loading for NO_3^{2-} and negative loadings for HCO_3^-. It accounts for 11% of the variance in the hydrochemistry. The negative loading of factor 3 with HCO_3^- suggests the involvement of other processes than that normally generates HCO_3^- in the system. The positive loadings of NO_3^{2-} indicate contamination from organic matter and lignite in the tertiary aquifer system. The reaction involving decomposition of organic matter generate bicarbonate and NO_3 in the system.

The factor 4 in the final factor model of Tertiary aquifers has highest positive loading for F^- and negative loading for Fe^{2+} and accounts for 9% of the variance in the hydrochemistry. This indicates that the reactions which release F and Fe in the aquifer system are contrary to each other.

5.10.2 Hierarchical Cluster Analysis

R-Mode Hierarchical Cluster Analysis for tertiary aquifers

The inherent variations in the chemical compositions of the groundwater in the Tertiary aquifer system analysed using R-Mode Hierarchical Cluster classification. The dendrograms generated from the data pertaining to the Tertiary aquifers are shown in Fig. 5.17. Within a linkage distance of 10 strong relation among Ca^{2+},Na^+, Mg^{2+}, K^+, and Cl^- ions are observed from the dendrogram. Weak relations of HCO_3^- and SO_4^{2-} with other ions reflected from high linkage distance and indicate chemical processes in addition to mineral dissolution in the contribution of ions to the groundwater.

Q-Mode Hierarchical Cluster Analysis for tertiary aquifers

Results of the Q-mode HCA are presented in Fig. 5.18 in which four spatial groundwater associations have been distinguished. The phenon line was drawn across the dendrogram at a linkage distance of 5. This resulted in five spatial groundwater associations represented by the five clusters in Fig. 5.18. Each cluster (group) represents the position of its members in the groundwater flow regime and/or the key processes

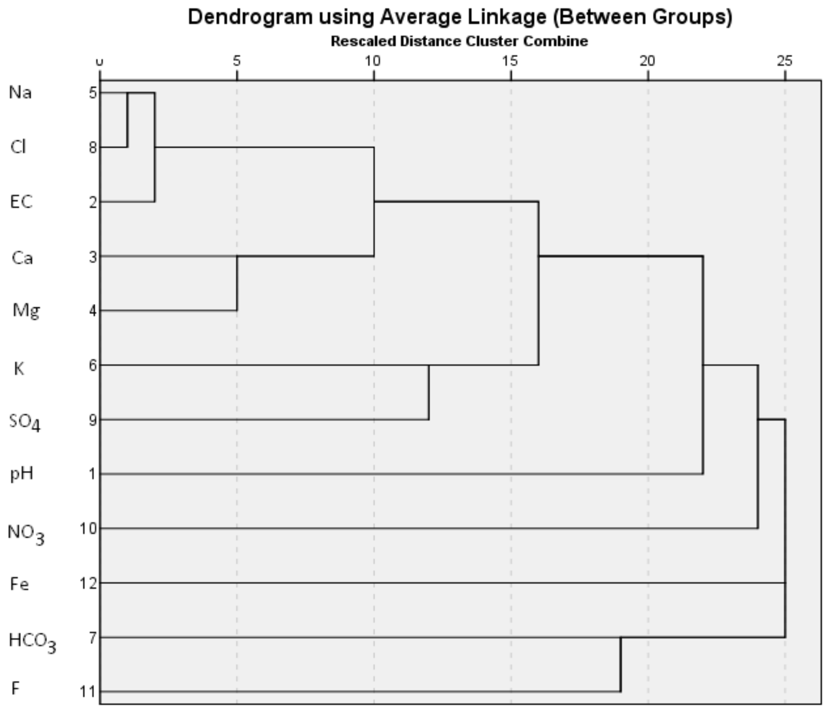


Fig 5.17 Dendrogram of R-mode Cluster Analysis of groundwater samples from Tertiary aquifers

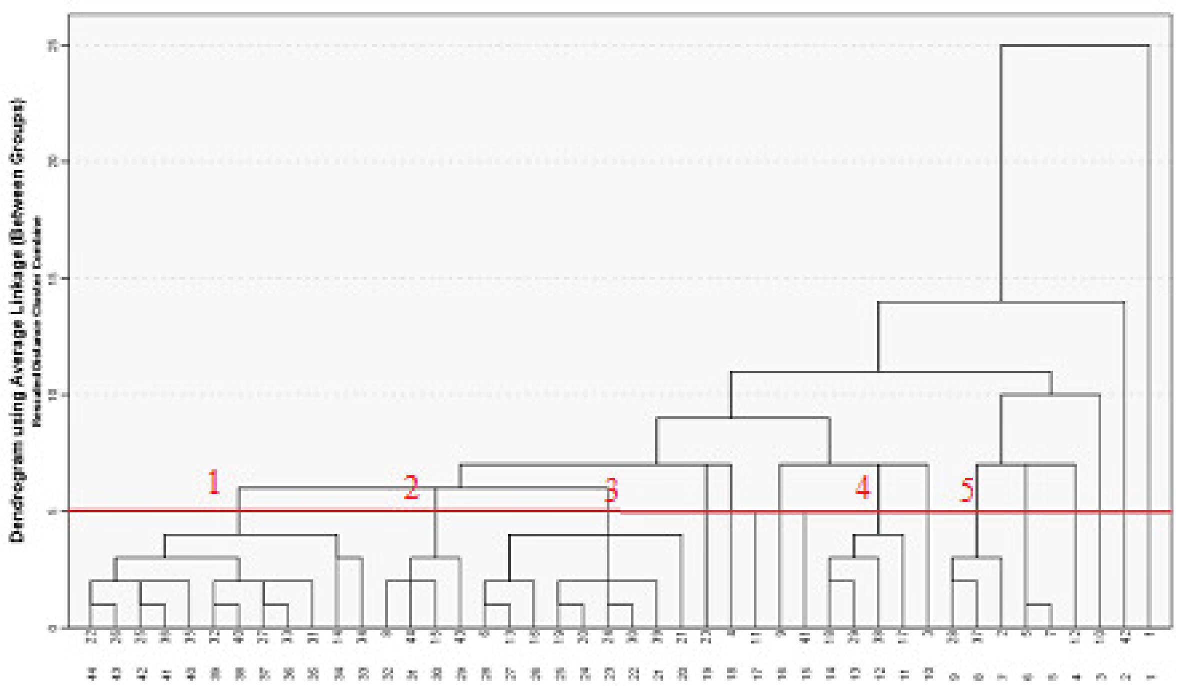


Fig.5.18 Dendrogram of Q-mode Cluster Analysis of groundwater samples from Tertiary aquifers

influencing groundwater hydrochemistry in the areas where the membership of these clusters are presented. Strong relation or similarity exists among the samples in this aquifer system. At linkage distance of 10 only two groups exists and five groups are identified at a linkage distance of 5.

Stiff diagrams for the arithmetic averages of the measures of the chemical constituent for each group were prepared to identify the water type representing each group. The Stiff diagrams presented in Fig. 5.19 represents Na-Cl dominant water of different groundwater associations.

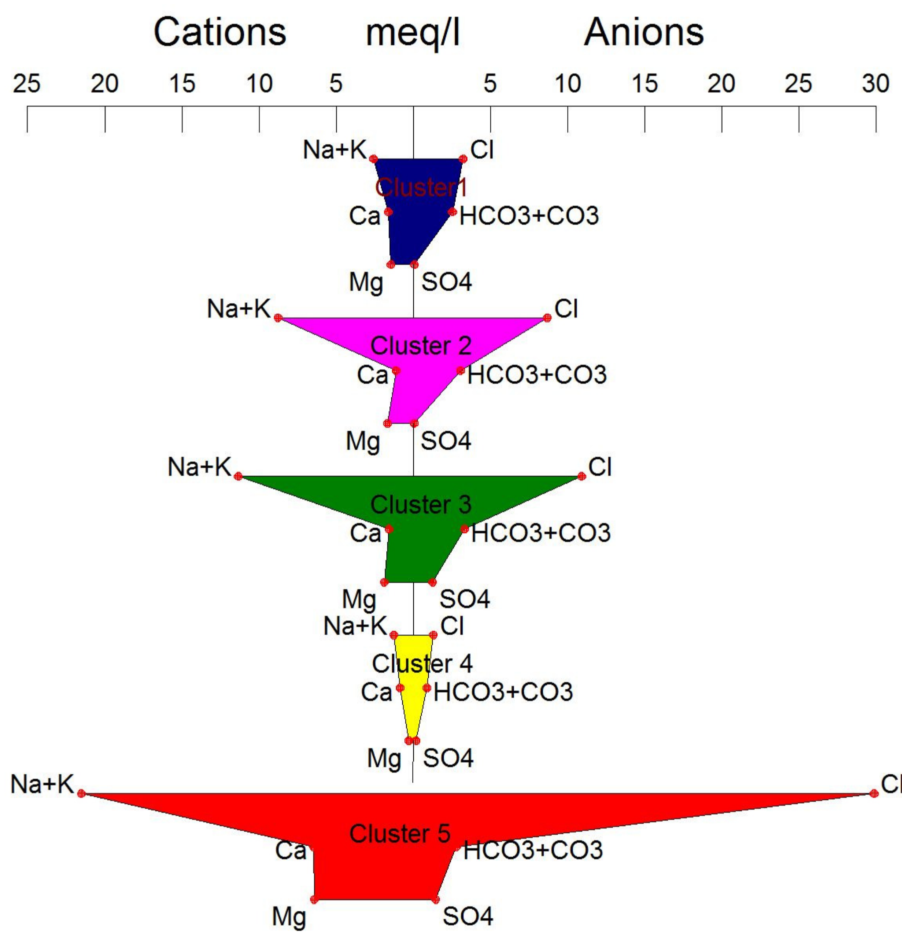


Fig 5.19. Stiff diagram showing average chemical characteristic of Cluster groups in the Tertiary aquifers.

The spatial distribution of all the five clusters (groups) in the tertiary aquifer system is shown in Fig. 5.20. The cluster group 1 shows fresh groundwater association of Na-Cl-

HCO_3 type in the flow regime and has undergone considerable ion exchange. Groundwater of similar nature with comparatively high mineralization is observed in group 2, where the very low sulphate values indicate a reducing environment. The dominance of ions in the order Na-Cl-HCO_3-Mg-Ca in group 3 with high mineralization of water indicates water association of a brackish environment. The fourth group represents fresh water environment with anthropogenic influence. The fifth group is Na-Cl type water affected by salinity.

The samples representing each cluster in the phreatic, Recent-confined and Tertiary aquifers are shown in Table 5.34 and various groundwater types identified from the clusters formed in this three aquifer systems are shown in Table 5.35 for an easy comparison. The cluster averages calculated for Phreatic, Recent-confined and Tertiary aquifers are given in Table 5.36.

The spatial representation of the members of the five clusters shown if Fig 5.19 indicates a clear cut hydrochemical variation tallying with the general direction of groundwater flow in the tertiary aquifer system. South of the area is mainly represented by members of cluster 1 characterized by fresh water of relatively low ionic concentration of mixed type. In this part of the aquifer system the recharge type water (Ca-HCO_3 or Ca-Na-HCO_3 type) modified to mixed type by leaching of salts from the confining clay layers and ion exchange processes. The northern part of the area is mainly represented by members of the clusters 3 and 5 characterised by brackish waters of Na-Cl type.

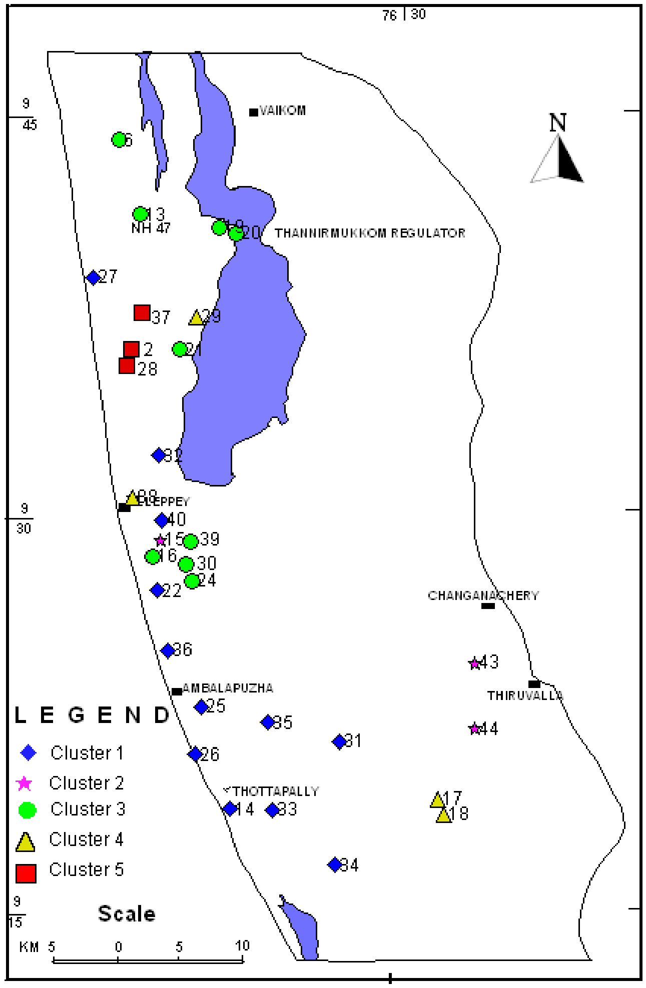


Fig. 5.20 Spatial representation of the members of the Clusters in Tertiary aquifers

Table 5.34 Samples representing each Cluster in the Phreatic, Recent-confined and Tertiary aquifers

Aquifer	**CLUSTER MEMBERS**				
	1	**2**	**3**	**4**	**5**
Phreatic aquifer	3,5,8,9,11,14,19,23 ,24,26,28,29,30,31, 32,36,38,40,41,42, 43,44	1,2,7,22	10,15,20,33,35	4,21,27,34,45, 46	NA
Recent-confined aquifer	1,2,3,4,5,6,7,11,12, 16,18,19,21,22,23, 24,25	10,14,15	8,9,17,20,26,27, 28,29,30	NA	NA
Tertiary aquifers	22,26,25,36,35,32, 40,27,33,31,14,34.	8,15,43,44	6,13,16,19,20, 21,24,30,39	17,18,29,38	2,28,37

Table 5.35 Groundwater types in the phreatic, Recent-confined and Tertiary aquifers identified from Cluster analysis

Aquifer	FACTOR ANALYSIS			Q-MODE CLUSTER ANALYSIS			
	Major Factors	loadings In the Factor	% of variance	No of clusters	Cluster No	Water type	Water Quality
Phreatic	1	$Na\text{-}Cl\text{-}Mg\text{-}SO_4\text{-}K$	45	4	1	$Ca\text{–}Na\text{-}Cl\text{-}HCO_3$	Fresh
	2	$Ca\text{-}HCO_3\text{-}K\text{-}Mg\text{-}NO_3$	15		2	$Ca\text{–}Na\text{-}SO_4\text{-}HCO_3$	Fresh
	3	$F\text{-}Fe\text{-}NO_3$	12		3	Na–Mg-Cl	Brackish
	4	CO_3	10		4	$Mg\text{-}Ca\text{-}Na\text{-}Cl\text{-}HCO_3$	Fresh (mix)
Recent-confined	1	Na-Cl-Ca-Mg-K-	53	3	1	$Na\text{- }Ca\text{- }Cl\text{-}HCO_3$	Fresh
	2	$Fe\text{- }HCO_3\text{-}F$	15		2	$Na\text{- }Mg\text{-}Ca\text{- }Cl\text{-}SO_4$	Brackish
	3	NO_3	9		3	$Na\text{- }Mg\text{-}Ca\text{- }Cl\text{-}HCO_3$	Brackish
Tertiary	1	Mg-Ca-Cl	40	5	1	$Na\text{- }Mg\text{-}Ca\text{ -}Cl\text{-}HCO_3$	Fresh (mix)
	2	$SO_4\text{-}K\text{-}Na$	12		2	$Na\text{- }Mg\text{- }Cl\text{-}HCO_3$	Brackish
	3	NO_3	11		3	$Na\text{- }Mg\text{- }Cl\text{-}HCO_3\text{-}SO_4$	Brackish
	4	F	9		4	$Na\text{- }Ca\text{- }Cl\text{-}HCO_3$	Fresh
	-	-	-		5	Na- Ca -Mg -Cl	Brackish

Table 5.36 Cluster averages in meq/l for major ions in Phreatic, Recent-confined, and Tertiary aquifers

Aquifer	Clusters	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl
Phreatic	1	2.13	0.42	0.87	0.21	0.12	2.13	0.78	0.66
	2	2.05	0.43	0.54	0.09	0.06	1.85	0.97	0.35
	3	2.69	1.23	3.97	0.42	0.30	2.90	1.05	4.34
	4	0.66	0.18	0.49	0.05	0.11	0.39	0.31	0.60
Recent -confined	1	1.40	1.26	3.17	0.23	0.04	1.88	0.27	3.65
	2	2.12	2.84	13.59	0.58	0.00	0.47	2.31	17.92
	3	6.40	11.64	43.98	0.68	0.00	3.79	2.13	59.32
Tertiary	1	1.65	1.46	2.44	0.14	0.00	2.53	0.07	3.23
	2	1.14	1.68	8.50	0.27	0.00	3.04	0..4	8.67
	3	1.59	1.90	11.12	0.22	0.00	3.32	1.24	10.88
	4	0.89	0.30	1.19	0.08	0.00	0.87	0.17	1.30
	5	6.48	6.43	21.16	0.36	0.00	2.78	1.45	29.81

The application of multivariate statistical techniques helped in identifying the relationship between the variables that is otherwise difficult to get at first glance. The Pearson correlation coefficient and R-mode cluster analysis could simplify the complexity of hydrochemical data each of the aquifer system and show the extent of dependence of one variable on the other. The Factor analysis of the hydrochemical data reduced the original data matrix into a fewer components that explains a major percentage of the total variance. The Q-mode cluster analysis could bring out the sample groups with identical hydrochemical characteristics. These results further substantiate the usefulness of the multivariate analysis in hydrochemical studies of the groundwater.

5.11 Hydrochemical impact of groundwater draft from Tertiary aquifers

The implications of over exploitation of any coastal aquifer are manifested in the form of seawater intrusion and consequent deterioration of water quality in the aquifer. The freshwater-seawater interface position in the study area is expected far away in the off shore. With the present knowledge it is difficult to say whether this means a totally safe situation from sea water intrusion in the foreseeable time. If there is deterioration in water quality this will be a slow process giving an early warning. From hydrochemical studies it could be seen that the quality variations observed at Thannirmukkom, Mararikulam and in some places in Alleppey town are due to leaching of salts from clay layers and mixing of water from the brackish pockets within the aquifers established hydraulic connectivity during pumping for a long period. The electrical conductivity values given in Table 5.37 are for some of the pumping wells taping the Tertiary aquifers. Over a period of time of 15 years or more they do not show any significant change in quality indicating a stable situation.

Table 5.37 Change in EC values of pumping wells taping Tertiary aquifers over a period of time (>15years)

Location	Aquifer	1985-94	2009
		EC	EC
Mankombu	Tertiary	398	492
Thottapalli	Tertiary	378	393
Kandiyur	Tertiary	222	194
-do-	Tertiary	670	283*
Muttom	Tertiary	710	635
Muttom	Tertiary	560	405
Thakazhi	Tertiary	490	455
Purakkad	Tertiary	418	406
Chudukad	Tertiary	460	419
Mararikulam	Tertiary	362	1415
Thannirmukkam	Tertiary	1450	106*
Pazhavangadi	Tertiary	728	898

* New Well taping the same aquifer

From the above observations, the falling trend in piezometric head can be considered as an overdraft situation and points to the need for proper aquifer management for preventing the possible seawater intrusion in future.

5.12 Radioactivity of Groundwater

Radon activity of groundwater

Coastal sands of Kerala are well known for the presence of Thorium bearing mineral Monazite and in the study area relatively high gamma radiations in the sand beds compared to clay layers has been observed in the geophysical logging studies (see chapter 2). The background radioactive emissions in the coastal areas of southern Kerala have been studied by many agencies and institutions (Kumar et al., 2007). However, much attention has not so far been paid on the distribution of Radon in groundwater, known to have serious implications for human health. Literature on the radon measurements made in different terrains of the country is available (Choubey et al., 1997, 2001; Sonkawade et al., 2004; Ramola et al., 1999, 2008; Hunse et al., 2010) and most of them are pioneering work reporting the concentration levels of Radon in air, soil and groundwater and its application as a tool in hydrogeological studies are very limited in the country.

The most important radioactive series in the lithosphere are those of uranium and thorium. The first members of these series and their decay products are leached out of the rocks and dissolved in groundwater to varying degrees. There are three different isotopes of Radon (Rn), but only ^{222}Rn, with a half life of 3.8 days is of interest in the context of the present study as the other isotopes are very short lived with half-life of less than a minute. ^{222}Rn is the gaseous radioactive member of the uranium series, which is easily dissolvable and is enriched in water in relation to other members of the series. Radioactivity of groundwater is contributed mainly by radon. Radon-222 and Radon-220 (Thoron), the gaseous daughter products of U-238 and Thorium respectively accounts for more than 50% of the human exposure due to natural radiation. In the present study the term ‘radon’ refers solely to ^{222}Rn and ‘radium’ to ^{226}Ra, which are members of the ^{238}U decay series.

Other than the health concerns, radon in groundwater is effectively being used in hydrogeological investigations like water infiltration, sub surface discharge etc. While radon has been used to assess infiltration of surface waters into aquifers (Hamada and Komae, 1998), it is more powerful as a tracer of groundwater discharge into surface receiving bodies of water (Ellins et al., 1990; Cook et al., 2003, 2006; Mullinger et al., 2007). The much higher concentration (by 2 to 4 orders of magnitude) of radon in most groundwaters compared to surface waters provides the source strength that makes it an excellent tracer.

Radon activity of groundwater samples from the aquifers

Twenty four water samples were collected form tube wells tapping Recent and Tertiary aquifers for radon measurement. The samples were analysed using RAD7 instrument and the results are tabulated in Table 5.38.

Water sampling for radon

Radon measurement with RAD 7 instrument

The concentration of radon gas is not measured directly but rather by the radioactivity it produces. In metric system it is expressed in Becquerel per cubic meter (Bq/m^3). One Becquerel is equivalent to one radioactive disintegration per second. It is also expressed in Pico Curies per litre of air (pCi/L). Curie is a unit of radioactivity equivalent to 1 gram of radium and the prefix 'pico' means trillionth. 4pCi/L equals to 148 Bq/m3. Radon concentration in water is generally expressed in Becquerels per liter (Bq/l).

The presence of radium in the host rock and the groundwater movement in the aquifer system decides the extent of its enrichment in groundwater. Normally, when radon enters the flow system, concentrations do not increase considerably along flow paths due to its fast decay rate relative to groundwater flow rates (Choubey and Ramola, 1999). In hard rock area, the scenario is different as the flow in fracture systems is normally much faster than that in the matrix. Radon has been considered as an effective tool in locating fracture systems because of this differential flow behaviour in the aquifer system.

Table: 5.38 Radon activity and sampling locations in the area

Sl. No	Location	Latitude in Decimal degrees	Longitude in Decimal degrees	Well Type*	Depth (m)	Radon activity (Bq/l)	Aquifer
1	Thottapally	9.3158	77.3894	TW	300	3.15	Tertiary
2	Thookulam	9.4592	76.3406	TW	148	2.71	Tertiary
3	Kommady	9.5183	76.3275	TW	150	3.26	Tertiary
4	Kommady	9.5186	76.3275	FW	6	4.21	Recent
5	Cherthala	9.6222	76.3325	FW	6	1.39	Recent
6	Velliyakulam	9.6831	76.3606	FW	6	0.88	Recent
7	Thannirmukka	9.6642	76.3847	FW	6	1.83	Recent
8	Chandanakavu	9.4889	76.3431	TW	140	3.77	Tertiary
9	Kozhimukku	9.3619	76.4669	TW	90	1.94	Tertiary
10	Karumadi	9.3833	76.3872	TW	90	2.05	Tertiary
11	Punthala	9.3367	76.3722	TW	140	2.16	Tertiary
12	Ambalapuzha -	9.3819	76.3697	TW	121	1.83	Tertiary
13	Desathinakom	9.1842	76.5319	TW	120	5.03	Tertiary
14	Muttom	9.2500	76.4969	TW	120	4.11	Tertiary
15	Mannar	9.3078	76.5478	TW	120	2.42	Tertiary
16	Haripad	9.2886	76.4636	TW	30	2.42	Recent
17	Muhamma	9.6044	76.3575	TW	168	3.92	Tertiary
18	Nedumudy	9.4394	76.4078	TW	62	7.39	Tertiary
19	Pallathuruthy	9.4633	76.3619	TW	113	2.89	Tertiary
20	Komalapuram	9.5381	76.3444	TW	102	5.14	Tertiary
21	Thannirmukko	9.6775	76.3922	TW	27	8.24	Recent
22	Karumadi	9.3806	76.3886	TW	30	25.8	Recent
23	Thakazhi	9.3708	76.4118	TW	46	5.6	Recent
24	Mannanchery	9.5714	76.3475	TW	26	7.46	Recent

*** TW-Tube well, FW- Filter point well**

In sedimentary as well as hard rock environment the radioactive minerals like uranium (^{238}U) and radium (^{226}Ra) present in the host rock mainly contribute radon to groundwater. Groundwater in crystalline rocks often has an elevated radon concentration along fractures in relation to the radon concentration of the surrounding rock. It can be due to the fact that uranium is leached out of the rock and precipitated together with its decay products, especially radium, on the surfaces of the fractures in the rock. Radon emanate from the radium enriched coatings directly to the groundwater in the fracture system (Akerblom and Lindgren 1997). Thus, high spatial variations of radon in groundwater are observed in the same geological terrain or rock type.

The radon levels in the water samples analysed are low and a comparison of the activity in Recent aquifers with that of Tertiary aquifers are shown in Table 5.39. and do not pose any threat to health. Only two samples have radon levels slightly above the permissible limits specified (11 Bq/l) for water supply by United States Geological Society.

Table 5.39 Range in concentration of radon in the area

Particulars	**Radon in Bq/l**	
	Recent sediments	**Tertiary aquifers**
No of samples	15	9
Average	6.42	3.45
Maximum	25.8	7.39
Minimum	0.88	1.83

The average radon concentration is high in the Recent coastal sediments when compared to the Tertiary aquifers.

No specific trend is observed between the depth of wells and dissolved radon in groundwater as can be seen from the Fig. 5.21. This is probably due to the fact that rather than depth the concentration of radioactive minerals in the host rock plays the most significant role in the dissolution of radon in groundwater. Groundwater in the tube wells tapping the Recent coastal aquifers in the area show radon levels in the range of 0.88 to 25.80 Beq/l and in the tube wells tapping the tertiary aquifers in the area has radon in the range of 1.83 to 7.39 Beq/l. The water samples from both shallow and deeper zones have low radon levels and do not pose any health threat to the local populace. The radon activity in the groundwater does not have any significant correlation with depth of tube sampled. The radon distribution does not show any relation to the spatial distribution of gamma radiation in the area.

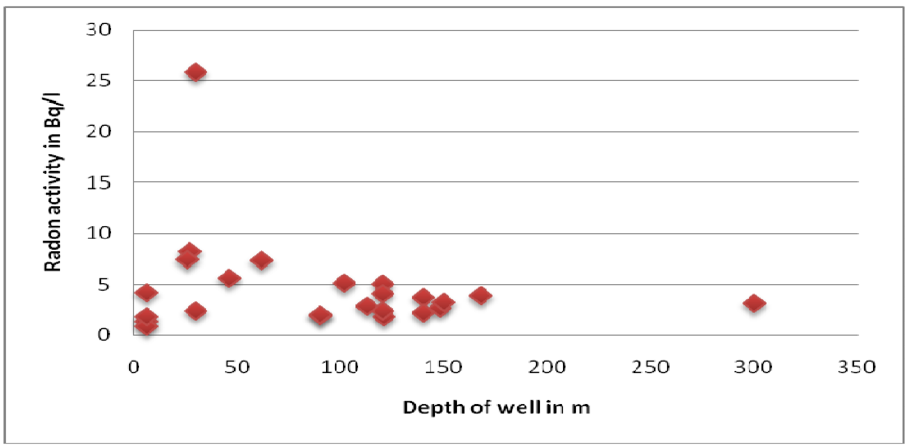


Fig. 5.21 Depth of bore wells VS radon in groundwater

Radon activity of approximately 400Bq/l in water would result in a concentration of about 150 Bq/m^3 in the air above the water. Dunduli et al., (1984) suggested that even water borne radon levels up to 400 Bq/l do not increase the risk of stomach or intestinal cancer by direct ingestion. The US Environmental Protection Agency in 1982 recommended remedial action at an activity level of 400 Bq/l. The values of radon activity of groundwater in the present study area is very low compared to these activity levels mentioned above.

CHAPTER 6

HYDROCHEMICAL FACIES AND EVOLUTION OF GROUNDWATERS

6.1 Introduction

The major ion chemistry of groundwater is a powerful tool for determining solute sources and for describing groundwater evolution (Edmunds and Smedley 2000; Petrides and Cartwright 2006; Thilagavathi et al., 2012). The major ion chemistry of groundwater and compositional relations among ionic species can reveal the origin of solutes and processes that generated an observed water composition (Demlie et al., 2007; Cendon et al., 2011; Rajmohan et al., 2000). The hydro-chemical facies and its evolution in the aquifer systems are being brought out in the present study through chemical facies studies, ion ratios and other related factors from the previous chapters.

Chemical composition of water varies in time and space due to changes in recharge conditions and flow patterns, and the chemical reactions between the water and the porous material. In general, a gradual increase of the mineralization of ground- water and shift from the dominant anion HCO_3 via SO_4 to Cl^- are observed in waters moving from shallow to greater depth, due to decreasing groundwater circulation and increasing water-rock interaction. Such variations in chemical character are used to subdivide formation water into characteristic zones, or 'hydrochemical facies', a term introduced by Back (1960). Hydrochemical facies evaluation are extremely useful in providing a preliminary idea about the complex hydrochemical processes in the subsurface (Sajil Kumar, 2013). Determination of hydrochemical facies was extensively used in the chemical assessment of groundwater and surface water for several decades. The first attempt in this direction was made by Piper (1944) and Durov (1948). A simple modified piper diagram was introduced by Chadha (1999). Groundwater types were used by many researchers in their studies to understand the controlling factors of the water chemistry (Sanchez-Martos et al., 2002; Aris et al., 2009; Karmegam et al., 2010; Mondal 2010; Prasanna et al., 2010, 2011;); In the present study water types were assessed using Piper and Chadha's approaches for the pre-monsoon samples from

Phreatic and confined aquifers of Recent alluvium and Tertiary aquifers. As the changes in water quality between pre- and post-monsoon periods are not significant, the hydrochemical interpretations in this chapter have been made based on the chemical analysis data of pre-monsoon period.

6.2 Hydrochemical facies

For demarcating the hydrochemical facies existing in the phreatic and confined aquifer systems Piper (1953) and the modified Piper diagram by Chadha (1999) were used. The sample plotting falls in different areas in these diagrams (Table 6.1 and 6.2) characterizes the different facies (Karanth, 1987).

6.2.1 Phreatic aquifer system

The plotting on the Piper diagram (Fig. 6.1) for the samples from the phreatic aquifer shows no particular cation dominance (>50%) in about 37 percent of the samples analysed. About 45 percent of samples are of calcium type, whereas about 17 percent belong to sodium+potassium type. No sample is representing the magnesium type water. On the other hand, bicarbonate is the major anionic species in about 52 percent of the samples, followed by chloride in about 18 percent and sulphate in about 2 percent. No particular anion is dominant in about 28 percent samples.

Table 6.1 Characteristics of groundwater samples in different zones derived from Piper's Trilinear diagram.

Sub-	Groundwater Type	Percentage
1	Alkaline earths exceeds alkalis	85
2	Alkalis exceed alkaline earths	15
3	Weak acids exceeds strong acids	52
4	Strong acids exceeds weak acids	41
5	Carbonate hardness exceeds 50%. ie. chemical properties are dominated by	50
6	Non-carbonate hardness exceeds 50% (Ca-Cl type)	0
7	Non- carbonate alkali exceeds 50%. ie. chemical properties are dominated by	13
8	Carbonate alkali exceeds 50% (Na-HCO_3 type)	0
9	No single cation-anion pair exceeds 50% (mixed Ca-Na-HCO3 type) or (mixed	28

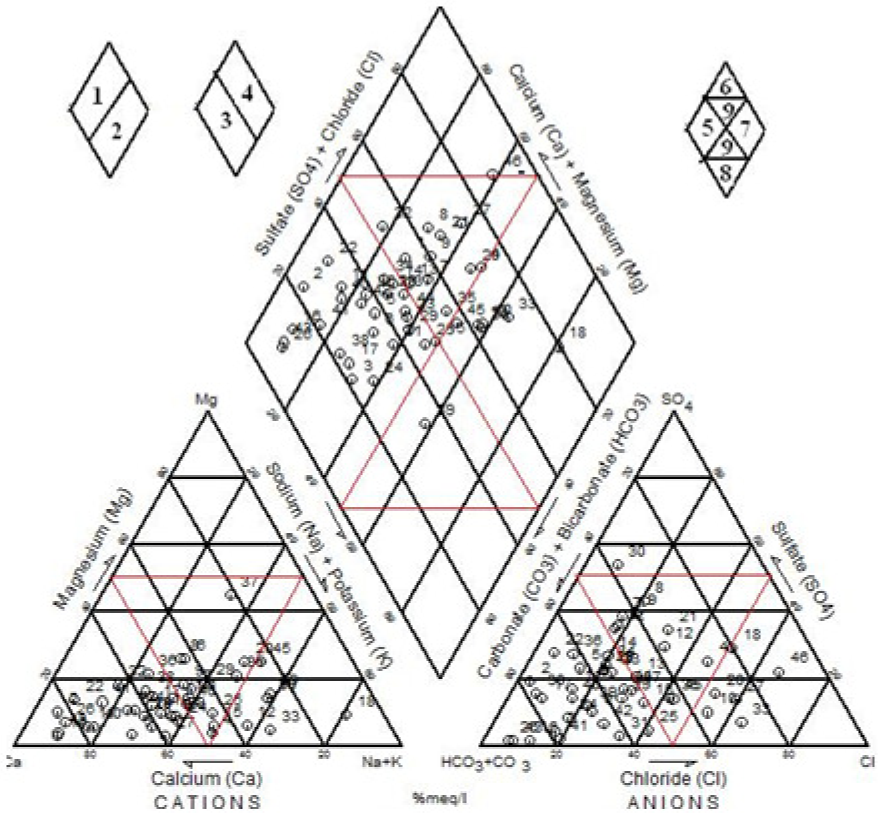


Fig 6.1 Groundwater samples plotting in different sub areas of Piper's Trilinear diagram–Phreatic aquifer (May 2009)

For better understanding the hydrochemistry and comparing the water types Chadha's diagram (1999) was plotted, which represents eight distinct hydrochemical fields (Fig 6.2).

In Chadha's diagram, the difference in milliequivalent percentage between alkaline earths (calcium plus magnesium) and alkali metals (sodium plus potassium), expressed as percentage reacting values, is plotted on the X axis, and the difference in milliequivalent percentage between weak acidic anions (carbonate plus bicarbonate) and strong acidic anions (chloride plus sulphate) is plotted on the Y axis. The resulting field of study is a square or rectangle, depending upon the size of the scales chosen for X and Y co-ordinates. The milliequivalent percentage differences between alkaline earths and alkali metals, and between weak acidic anions and strong acidic anions, would plot in one of the four possible sub-fields.

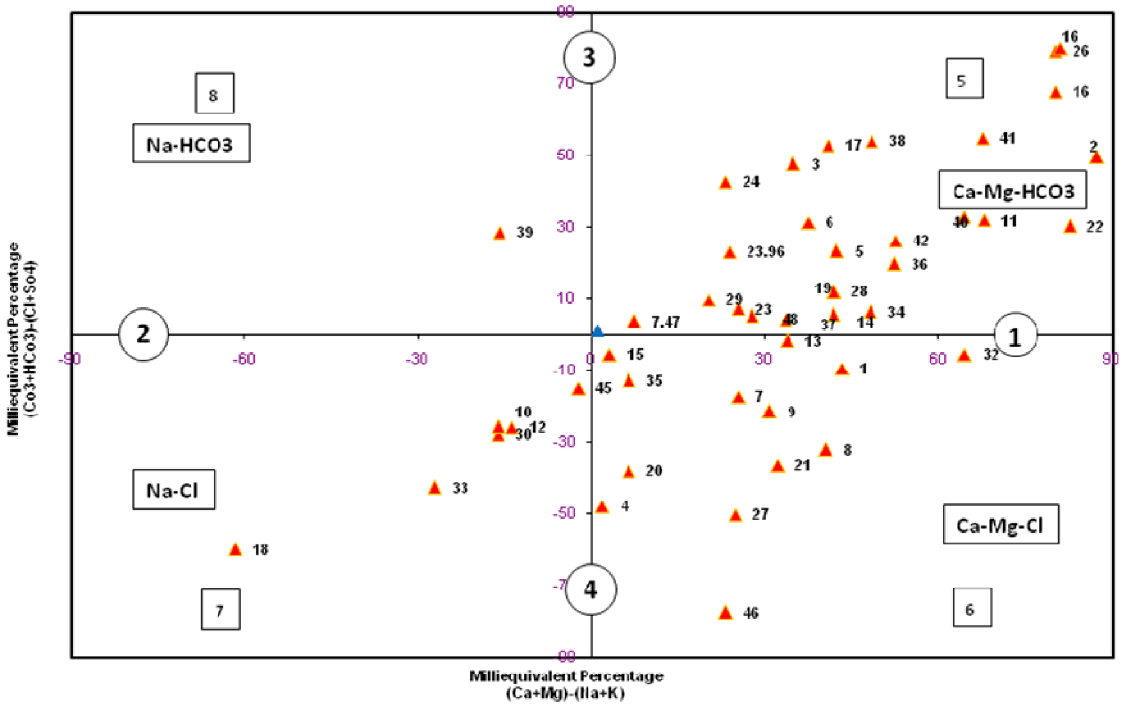


Fig. 6.2 Groundwater samples from Phreatic aquifers of Kuttanad area (May 2009) plotted on modified Piper diagram (Chadha,1999)

1.Alkaline earths exceed alkali metals, 2. Alkali metals exceed alkaline earths, 3. Weak acidic anions exceed strong acidic anions, 4. Strong acidic anions exceed weak acidic anions, 5. Alkaline earths and weak acidic anions exceed alkali metals and strong acidic anions, respectively, 6. Alkaline earths exceed alkali metals and strong acidic anions exceed weak acidic anions, 7. Alkali metals exceed alkaline earths and strong acidic anions exceed weak acidic anions, 8. Alkali metals exceed alkaline earths and weak acidic anions exceed strong acidic anions

The hydrochemical processes and the chemical facies suggested by Chadha (1999) are indicated in each of the four quadrants of the graph (Table 6.2).

Table 6.2 Characteristics of groundwater samples in different zones derived from Chadha's diagram.

Field	**Chemical facies**	**Characteristics**
5	Ca-Mg-HCO_3 type of recharge waters	water type with temporary hardness
6	Ca-Mg-Cl Type of reverse ion-exchange waters	water type with temporary hardness
7	Na-Cl type of end-member waters (seawater)	water type with permanent hardness
8	Na-HCO3 type of base ion-exchange waters	water type which causes foaming

A majority of the samples (57%) fall in the 5th field representing Ca-Mg-HCO3 type waters 28% of the samples are plotted in the 6th field, representing Ca-Mg-Cl type and 13% plotted in the 7th field representing Na-Cl type and 2% plotted in the 8th field representing Na-HCO3 type waters. This is exactly similar to the results obtained from the piper plot.

The above analysis indicates that the hydrochemical characteristics of groundwater in the phreatic aquifers show considerable variations, which could be attributed to various factors such as the composition of the lithounits, soil type and even water contamination. The Na-Cl type water indicates interaction of brackish surface water bodies with the groundwater system at water mixing zones.

6.2.2 Confined aquifers of Recent alluvium

The hydrogeology of Recent-confined aquifer indicates high residence time for groundwater in the flow system, giving sufficient scope for rock water interaction. The hydrochemical facies studies have revealed higher mineralization and different hydrochemical environment in the aquifer system. The sample plotting in Chadha's diagram (Fig. 6.3) shows a Na-Cl dominant facies as explained by the variance from factor analysis and Q-mode cluster analysis under chapter 5. Ninety percent of the samples from this aquifer plots in the fields 6 and 7 representing Ca-Mg-Cl and Na-Cl type waters respectively. About 10% of the samples plot in Ca-Mg-HCO_3 field representing typical recharge type water.

6.2.3 Tertiary aquifers

The plots of water samples from the Tertiary aquifers in the Chadha's diagram represents all the fields but, dominate by the chemical facies of Na-Cl and Ca-Mg-Cl. About 65% of the samples represent the Na-Cl facies, 18 % the Ca-Mg-Cl facies, 15% Ca-Mg-HCO_3, and 2% of the samples represent Na-HCO_3 facies of groundwater.

A comparison of the chemical facies identified with the classification of samples made based on factor and cluster analysis in chapter 5 shows significant relation but more sample groups of identical hydrochemical characteristics could be identified by the statistical approach.

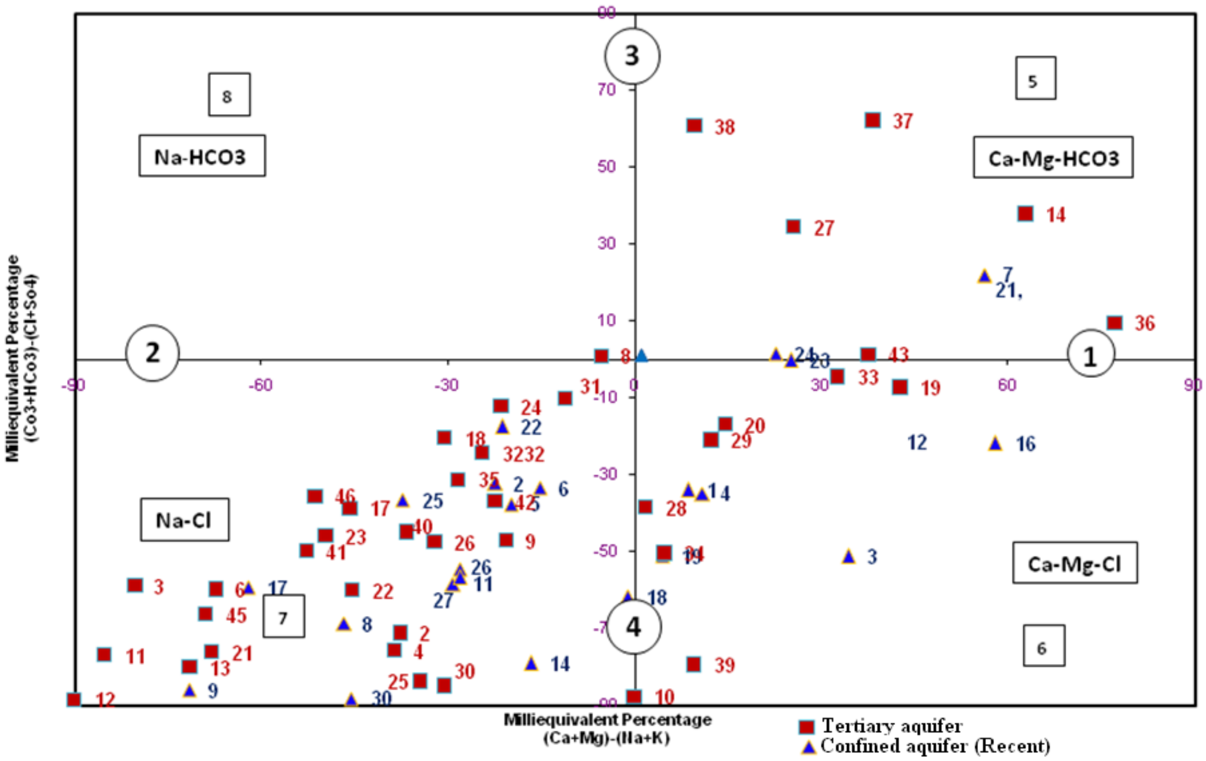


Fig. 6.3 Groundwater samples from Recent confined and Tertiary aquifers of Kuttanad area (May 2009) plotted on modified Piper diagram

6.3 Inferences from Ion ratio studies

The groundwater during its course of movement undergo chemical changes because of minerals in the aquifer and solutes entrapped in the aquifer and clay layers in a sedimentary formation. Ionic ratio studies have been carried out to infer information on some of these reactions. A few samples in the aquifer systems with ionic concentrations above 50 meq/l have been excluded from the analysis as it obscure the overall scenario in the aquifer system.

Table 6.3 Percentage of groundwater samples with higher ionic ratios in Phreatic, Recent-confined and Tertiary aquifers

Aquifer	No. of samples	Na/Cl	Mg/Ca	SO_4/Cl	K/Cl
		>1	>1	>.05	>.019
Phreatic	46	61%	4 %	100 %	98 %
Recent -confined	30	67 %	37 %	60 %	70 %
Tertiary	46	59 %	50 %	43 %	67 %

Seawater has distinct ionic ratios, as reported in many publications (Vengosh et al., 2002; Mondal et al., 2010; Thilagavathi et al., 2012) and such ionic ratios are effectively used in identifying salinization processes in freshwater environments. The probable source of salinization is characterized by a distinguishable chemistry and well-known ionic ratios. Modification of the geochemical characteristics of these saline waters is caused by the major factors; base- exchange reactions with clay minerals (Martinez. 2002); adsorption onto clay minerals; and carbonate dissolution-precipitation (Lakshmanen et al., 2003).

The dissolution of salts or halite leads to a Na/Cl mole ratio of about 1 and in normal marine environment the ratio is about 0.85 (Petrides and Cartwright,2006). A higher Na/Cl ratio (more than one) indicates additional Na contribution to the groundwater involving different processes depending upon the hydrogeological environment in which the aquifer exists. The Na/Cl ratio having values greater than one is represented by more than 50% of the groundwater samples representing all the aquifer systems (Table 6.3) indicating halide dissolution or mixing of salt water. A comparison of Na-Cl relationships among these three aquifer systems, phreatic aquifer shows a relatively weaker correlation (Fig 6.4). This indicates the influence of more than one process including anthropogenic contribution in the release of more Na or Cl in to the water in the phreatic aquifers. The leaching of salts seems to be the major process in the Recent confined and Tertiary aquifers. The spread of plots around the trend line indicates influence of other factors such as reverse ion exchange (Najeeb, 2012).

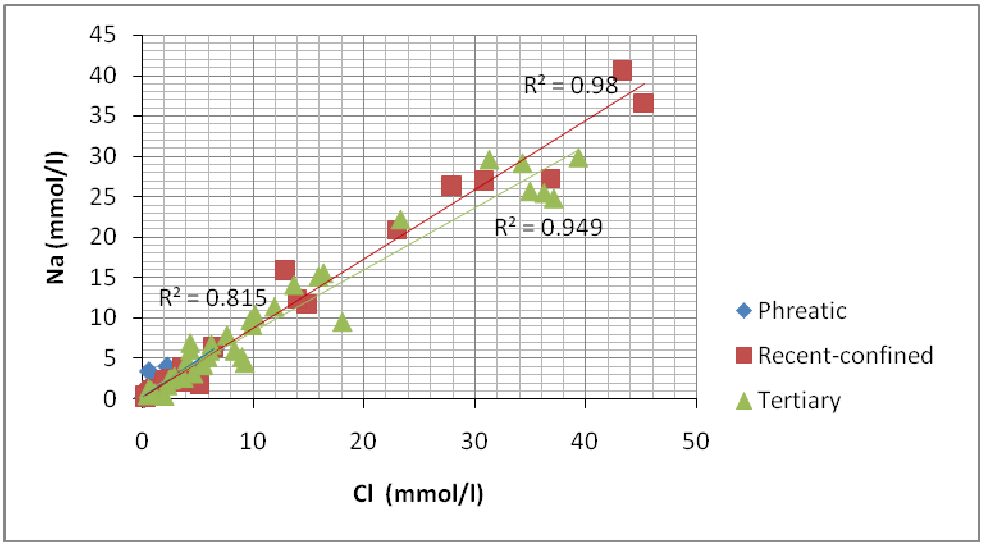


Fig 6.4 Relation between sodium and chloride in groundwaters of phreatic, Recent-confined and Tertiary quifer systems

The relation between Na/Cl ratio and Cl indicates a decrease in the ratio with increase in chloride (Fig 6.5). Chloride, a conservative ion in groundwater, is an indicator of water salinity. It is observed from Fig 6.5 that strong influence of factors other than dissolution of salts influencing Na/Cl ratios at the sampling locations where the water samples having higher Cl values. The relation between (Ca+Mg) with Cl indicates a general increase in Ca+Mg with increase in salinity (Fig 6.6). These two relations clearly indicate locations of reverse ion exchange process where Ca and Mg adsorbed in clay layers are exchanged for Na in water.

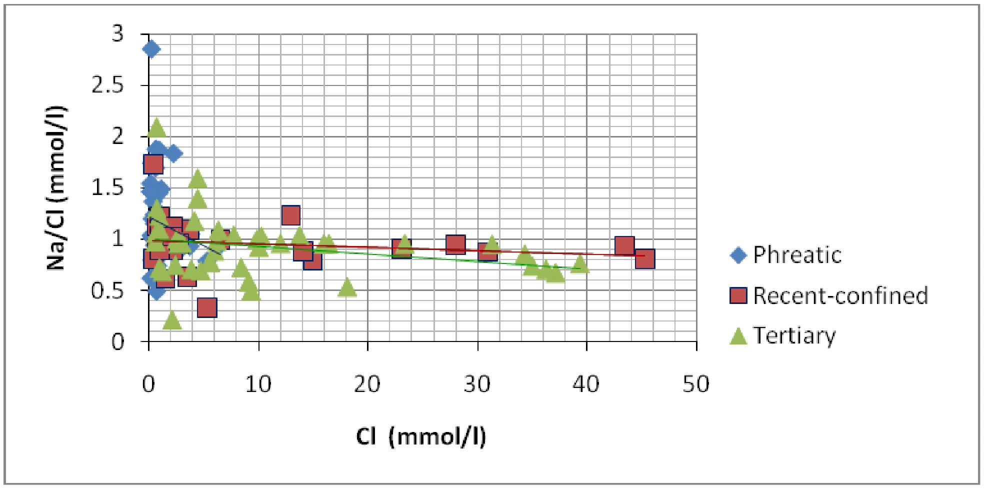


Fig 6.5 Plot of Na/Cl vs Cl in groundwaters of phreatic, Recent confined and Tertiary aquifer systems

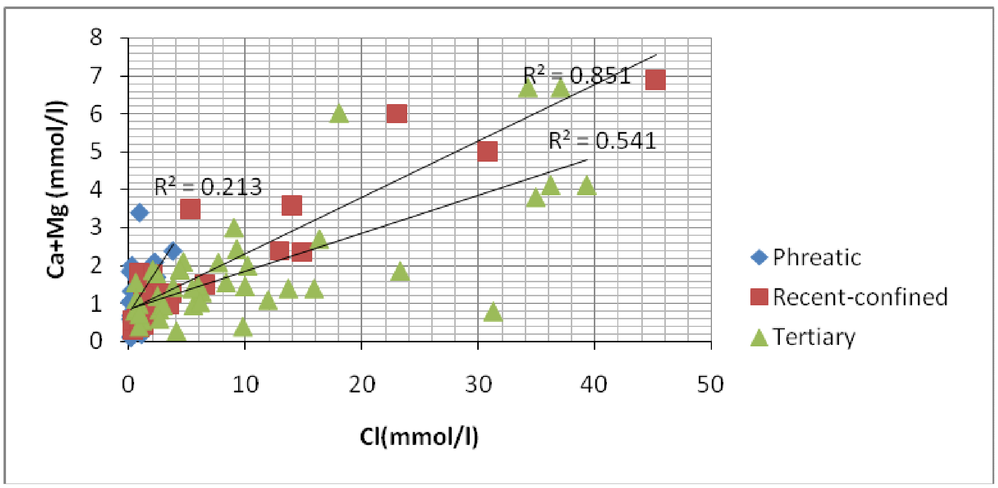


Fig 6.6 Plot of Ca+Mg vs Cl in groundwaters of phreatic, Recent-confined and Tertiary aquifer systems

The mole ratio of (Ca+Mg)/HCO_3 and Cl has been used (Fig 6.7) to undestand the source of Ca and Mg in the aquifer sytems. The mole ratio in Fig 6.7 shows an increase in the ratio with increse in salinity in Recent-confined and Tertiary aquifers and a reverse relation in phreatic aquifer. The increase in (Ca+Mg)/HCO_3 ratio with salinity in the confined aquifer systems indicates that Ca and Mg are added to the solution at a greater rate than HCO_3 (Rajmohan and Elango, 2004.). Whereas, the reverse is the case with the groundwater in phreatic aquifers. If the source of Ca and Mg are mainly from the carbonate minerals the ratio should be around 0.5 (Rajmohan and Elango, 2004).

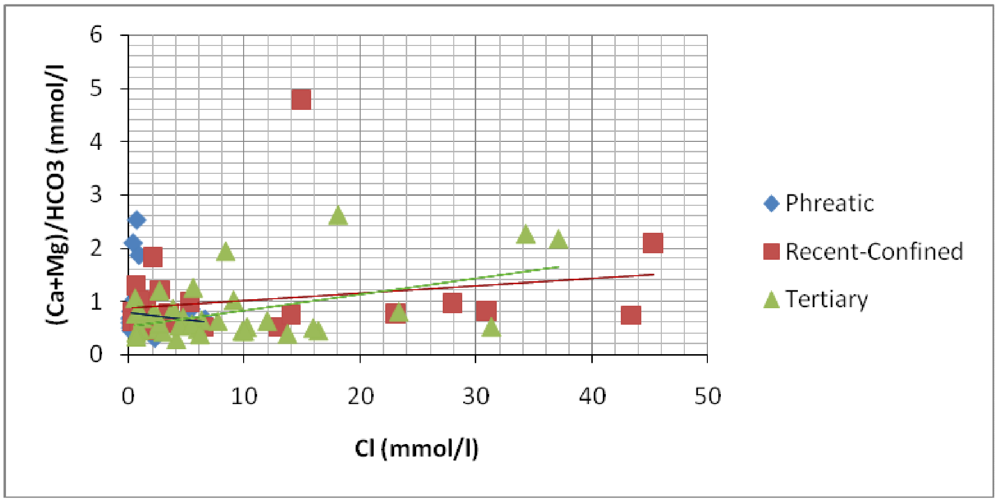


Fig 6.7 Plot of (Ca+Mg)/HCO_3 vs Cl in groundwaters of phreatic, Recent-confined and Tertiary aquifer systems

The governing equations for calcite and dolomite dissolution in the aquifer systems would be;

$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^-$ ………………………… 6.1

$CaMg(CO_3)_2 + 2CO_2 + 2H_2O \leftrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-$ …………6.2

Majority of the samples of all the aquifer systems fall above the ratios 0.5 as seen in Fig 6.7, and this can be attributed to addition of Ca and Mg or depletion of HCO_3 in the aquifer systems. The increase in the ratio with salinity increase in the Recent confined and Tertiary aquifers indicate Ca and Mg addtion to the waters through a reverse ion exchange process. Bicarbonate addition to the waters in confined aquifers (see section 5.2.3) at favourable sites where organic matters are present leads to a low ratio. Whereas, in the phreatic aquifer the ratio decreases with increase in salinity indicating a combined effect of HCO_3 addition from the dissolution of carbonate minerals and cation exchange.

In sea water the Mg/Ca ration is higher. This is because of the higher consumption of Ca by marine organisms (Hem, 1992). The Mg /Ca ratio is usually less than one in a groundwater flow regime. However, higher ratios are seen in dolometic terrains and reverse cation exchange sites and sea water mixing zones. Only 4% of the samples are having ratios above one in phreatic aquifer whereas, it is 37% and 50% respectively in Recent and Tertiary aquifers (table 6.3), indicating significant reverse cation exchange sites in both the confined aquifers. The theory of sea water mixing as a source for higher ratios can be dismissed as Mg /Ca ratios are less than 2 in these aquifers (Petrides and Cartwright, 2006). The high SO_4/Cl and K/Cl ratios in the phreatic aquifer indicate additional sources of SO_4 and K from fertilizer application and other anthropogenic activities.

The plot of (SO_4+HCO_3) versus (Ca+Mg) will be close to the 1:1 line if the dissolutions of calcite, dolomite and gypsum are dominant reactions in a system (Fisher and Mulican, 1997; Thilagavathi et al., 2012). Ion exchange tends to shift the points to the right due to an excess of (Ca + Mg) governed by the equation 6.3 given below.

Na^+ -Water + Ca^{2+}(Mg^{2+})-Clay $\leftrightarrow$ Na^+-Clay + Ca^{2+}(Mg^{2+}) -Water………….6.3

The points shift to the left due to an excess of (SO_4+HCO_3) over (Ca + Mg) derived from reverse cation exchange process. The plot of (Ca + Mg) versus (SO_4+HCO_3) in Fig 6.8 shows that most of the groundwater samples from the phreatic aquifer are clustered around and above the 1:1 line indicating an excess of (SO_4+HCO_3) in the system. In the Recent confined and Tertiary aquifers most of the samples are clustered around and below the 1:1 line indicating an excess of (Ca + Mg) over (SO_4+HCO_3). This again indicates reverse cation exchange sites in the aquifer as observed from other ion ratios.

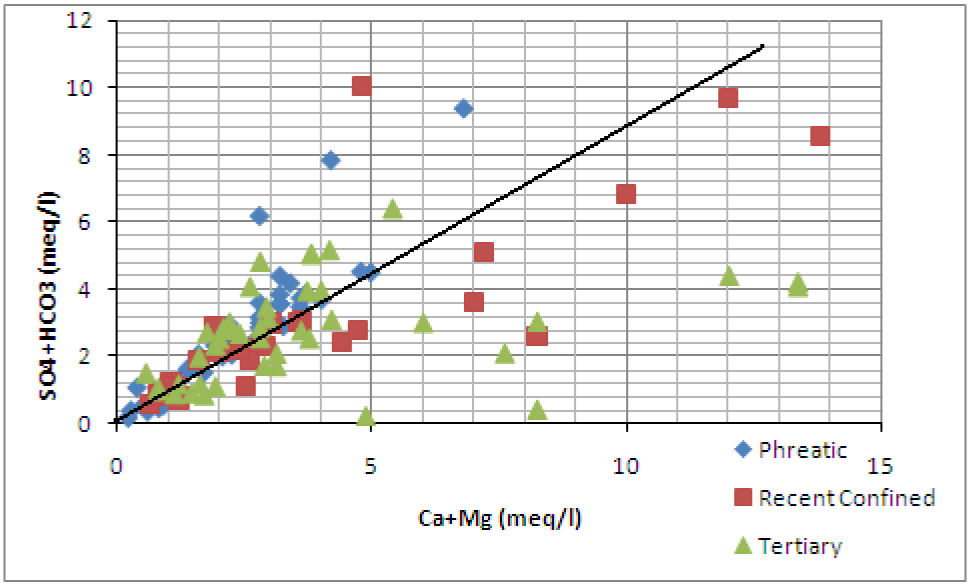


Fig 6.8 Plot of (Ca+Mg) vs (SO_4+HCO_3) in groundwaters of phreatic, Recent and Tertiary quifer systems

6.4 Characterization of hydrochemical processes

The environmental isotopes $\delta^{18}O$ and $\delta^{2}H$ are excellent tracers for determining the origin of groundwater and widely used in studying the natural water circulation, groundwater movement and salinisation of groundwater systems. (Walter D'Alessandro, et al.,2004.; O'Driscoll et al.,2005.; Tim et al., 2012.; Wassenaar,et al., 2011., Nives Ogrinc et al.,2008., Longinelli et al.,2008., Vandenschrick et al. 2002).

The stable and radioactive isotopes were effectively used to evaluate the recharge mechanism in the area, surface and groundwater interaction, sea water ingress, and mixing of groundwater in aquifer systems. In the present study the environmental isotopes, deuterium, Oxygen-18, Tritium and Carbon-14 have been employed to understand the evolution of groundwater. The stable isotope (Deuterium and Oxygen-18) are useful in understanding the recharge mechanism and interrelationship between aquifers, surface and groundwater in the area, whereas, the radioactive Isotopes (Tritium (^{3}H) and Carbon-14 (^{14}C) are used to know the age of groundwater.

Stable Isotopes

Stable isotope content of groundwaters from the Recent alluvial aquifer varies between -3.8‰ to -2.7‰ for $\delta^{18}O$ and between -18.2‰ to -8.8‰ for $\delta^{2}H$, where as corresponding values for Tertiary aquifer is -3.4‰ to -0.4‰ and -13.7‰ to +5.1‰ respectively. The $\delta^{2}H$ - $\delta^{18}O$ relationships are shown in Fig 6.9 along with Global Meteoric Water Line (GMWL). The sampling locations and Isotope data are given in Table6.3.

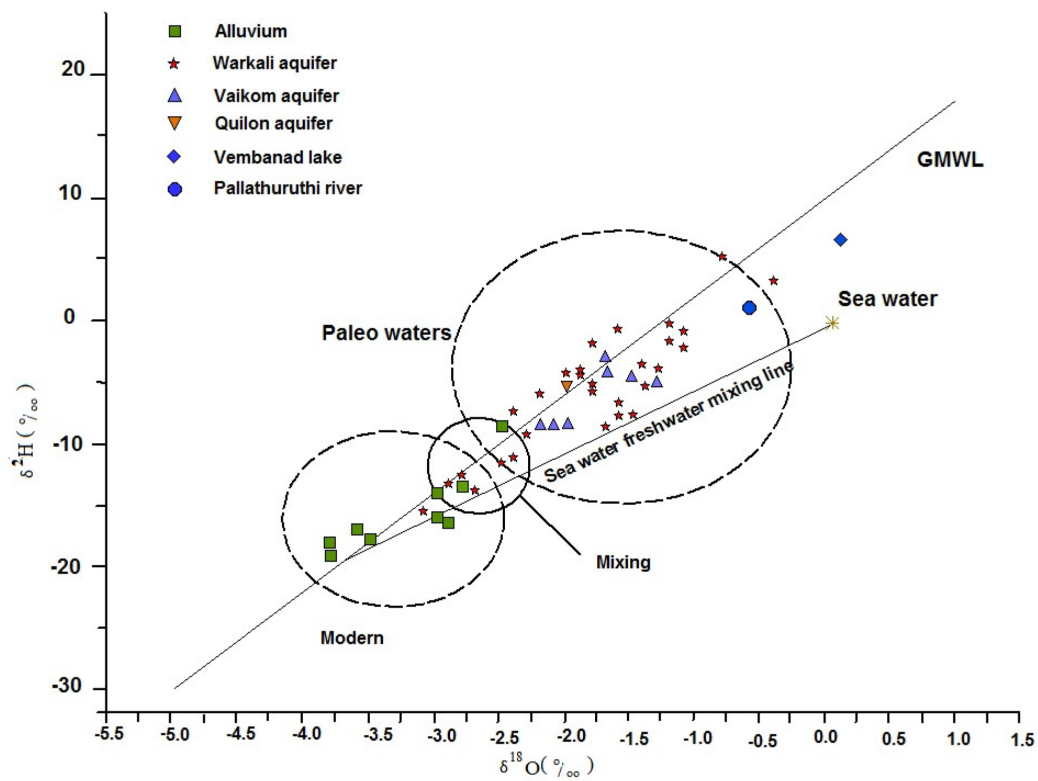


Fig. 6.9 ($\delta^{2}H$ - $\delta^{18}O$) relationships in groundwaters of the area

Most of the groundwater samples from alluvial and Tertiary aquifers fall on or close to the GMWL indicating that these waters are of meteoric origin and are not affected by secondary isotope effects such as evaporation or isotope exchange.

Table 6.4 Isotope sampling locations and data of ^{18}O, ^{2}H, ^{3}H and ^{14}C

Sam ple	Location	Source	Well depth	Aquifer	EC (μS/c	Temp ^{O}C	pH	δD (‰)	δ^{18} O	^{3}H (TU)	^{14}C (pMC)
1	Kommady	TW	145	Tertiary (W)	598	29.4	8.44	-5.8	-1.8	0.2	1.6±0.5
2	Kalavur	FTW	12	Alluvium	127	26.5	7.69	-16	-3	4.1	
3	Kanjikuzhy	FTW	12	Alluvium	92	27.5	7.3	-16.4	-2.9	3.5	
4	Cherthala	FTW	12	Alluvium	167	28	7.69	-17.7	-3.5	-	
5	Kottaram	TW	165	Tertiary (Q)	2975	32	8.41	-5.2	-2	0.9	
6	Pattanakkad	TW	126	Tertiary (W)	1829	32.5	8.05	-5	-2.3	1	
7	Velliyakulam	TW	140	Tertiary (W)	1531	31	7.93	-5	-1.8	0.2	
8	Thanneermukkom	FTW	12	Alluvium	100	27	7.8	-8.6	-2.5	-	
9	Thanneermukkom	TW	150	Tertiary (V)	1090	31	7.87	-8.4	-2.2	0.7	
10	Thanneermukkom Bund	SW		Surface water	7408	28.5	8.27	6.6	0.1	3.2	
11	Muhamma	DW	5	Alluvium	2368	29.6	7.16	-11.3	-2.4	-	
12	Karumady	TW	326	Tertiary (V)	3628	30	8.83	-4.6	-1.5	1	0.2±0.5
13	Thookkulam	TW	155	Tertiary (W)	518	31.5	8.15	-0.8	-1.1	0.1	0.1±0.5
14	Nedumudi	TW	61	Tertiary (W)	714	31	6.84	-11.7	-2.5	1.6	2.4±0.5
15	Pallathuruthy (River)	SW		Surface water	495	28.5	7.65	1.1	-0.6	3.6	
16	Pallathurthy	TW	174	Tertiary (W)	1448	30.9	7.57	-6.7	-2.2	0.9	
17	Ambalapuzha	TW	130	Tertiary (W)	358	31	7.69	-2.1	-1.8	0.7	
18	Purakkad	TW	90	Tertiary (W)	649	31	8.05	-2.2	-1.1	0.5	
19	Thottappally	TW	175	Tertiary (W)	393	31	7.3	5.1	-0.8	0.8	
20	Arathungal	TW		Tertiary (W)+	908	27	7.26	-14.9	-2.2	2.5	
21	Cherthala	TW		Tertiary (W)	4174	29	7.21	-4	-1.3	0.5	
22	Kaipuram	TW	160	Tertiary (V)	122	28	6.83	-13.7	-3.1	3.9	
23	Pazhaveedu	TW		Tertiary (W)	729	28	8.31	-1.6	-1.2	0.8	
24	Viyapuram	TW		Tertiary (W)	553	29	7.15	-5.1	-1.4	0.6	
25	Komalapuram	TW	100	Tertiary (W)	1260	26	7.08	-6.6	-1.6	0.7	
26	Karuvatta	DW	4	Tertiary (V)	107	30	6.92	-3.8	-1.7	3.8	
27	Karuvatta	TW	81	Tertiary (W)	353	29	7.05	-3.2	-2.3	0.6	
28	Haripad	TW		Tertiary (W)	426	29	6.79	-0.44	-1.2	0.6	
29	Thakazhi	TW	66	Tertiary (W)	361	29	6.72	-0.6	-1.6	0.6	
30	Neerkunnam	TW	140	Tertiary (W)	375	30	7.53	3.3	-0.4	0.5	
31	Chandanakavu	TW	145	Tertiary	1320	30	7.11	-3.4	-1.4	-	
32	Mararikulam	TW	92	Tertiary (W)	2088	30	7.26	-8.6	-1.7	0.8	
33	Preethikulangara	TW		Tertiary (W)	1320		7.5	-4.2	-1.9	4.2	1.52±0.5
34	Preethikulangara	TW		phreatic	4260		8.5	-2.9	-1.7	4.5	4.6±0.5
35	Alamthuruthy	TW	31	Tertiary (W)	1855	29	7.25	-2.9	-7.3	0.7	11.9±0.5
36	Mararikkulam	TW		Tertiary (W)	2370	30.7	6.97	-5.4	-2.6	2.8	10.9±0.5
37	Ramankari	TW	57	Tertiary (W)	2230	30.2	6.86	-7.91	-2.5	2.3	45.9±0.9
38	Muttom	TW	68	Tertiary (W)	635	28.9	7.46	-12.4	-2.8		21.3±1.0
39	Kandiyur	TW	20	Tertiary (W)	194	28.8	6.85	-8.2	-2.9	3.2	55.9±1.3
40	Kandiyur	TW	145	Tertiary (V)	283	28.8	6.74	-8.6	-3.4	3.3	80.6±1.2
41	Kanjikuzhy PZ1	TW	45	Alluvium	475	29.2	7.53	-10.9	-3	2.6	
42	Kanjikuzhy PZ4	TW	35	Alluvium	13580	31.6	7.22	-18.2	-3.8	3.7	
43	Preethikulangara	TW	218	Tertiary (V)	5060	31.2	9.03	-4.8	-2.6	1.3	
44	Podiyadi	TW	56	Warkali	1234	28.1	7.48	-2.9	-6.4	0.3	98±1.2
44	Vallikkavu	TW	30	Warkali	267	28.5	6.79	-12.4	-2.8	2.2	
45	Thakazhi PZ2	TW	44	Alluvium	957	29.7	7.82	-10.8	-3.8	-	
46	Thakazhi PZ3	TW	20	Alluvium	2820	29.7	7.7	-13.8	-3.6	-	

W- Warkali, V-Vaikom, Q-Quilon , DW –dugwell TW-Tube well, FTW- Filter point Tube well, SW-surface water

The stable isotopic composition of groundwater from the unconfined aquifer is slightly depleted compared to the mean annual precipitation. The depletion in stable isotopes indicates that the recharge to this aquifer occurs mainly during intense storm events, which are quite common in the monsoon season. In large rain events, isotopic depletion is caused by the preferential rainout of heavier isotopes.

In δ^2H - $\delta\ ^{18}O$ plot, most of the samples from the alluvial and Tertiary aquifers form distinct clusters showing that these two aquifers are not interconnected while samples from Vaikom and Warkali aquifers form a single group indicating that they are interconnected at few places through Quilon beds, which is a limestone aquifer.

6.4.1 Salinisation mechanism and evolution of groundwater.

Water samples from the Tertiary aquifers are in general Na-Cl type in the central part of the study area. Reduction in hardness is seen along the flow path in the groundwaters of Warkali aquifer, i.e., natural freshening is taking place in this aquifer. Trends in Chadha's diagram show that subsequent increment of Na+ in waters of Warkali along the flow path is caused by exchange of both Ca and Mg (cation exchange).

Isotopes are recognized as an essential tool in understanding salinisation processes, especially when chemistry of waters undergo secondary changes such as ion exchange, precipitation etc. Generally, stable isotopic composition of groundwater will not change during dissolution and flushing of dry salts. However, salinity derived from mixing of saline solutions eg. seawater with fresh water, give rise to waters of different salinity and isotopic concentration and fall in a mixing line between these components in δD - $\delta^{18}O$ plot. If salinity is because of evaporative concentration, the samples may fall in an evaporation line, which will be typical of an evaporation process.

Few groundwater samples from the unconfined alluvial aquifer in the coastal regions are brackish. They have measurable tritium and fall in the seawater freshwater mixing line in the δ D - $\delta\ ^{18}O$ plot. Hence the brackishness could be due to modern seawater intrusion.

Stable isotopes are effective tools in reconstructing the palaeo climate from the study of marine–continental sediment deposits of glacial- interglacial periods (Leigh et al., 1995; Cook et al., 2004; Levin et al., 2006; Lindsey et al., 2013). Continental aridity on a glacial- interglacial time scale increased as a result of changes in the latitudinal positions of global wind movement and rainfall distribution (Lindsey et al., 2013).

As mentioned earlier, the quality of groundwater in the Tertiary aquifers changes from fresh to brackish as it moves from south to central part of the study area. The progressive increase in brackishness could be due to leaching of salts from the clay, as shown in the Chloride versus $\delta^{18}O$ plot (Fig.6.10). However, the variation (enrichment) in $\delta^{18}O$ without appreciable increase in Chloride is not due to evaporation as could be observed from Fig. 6.9, but can be explained by the paleo-aridity.

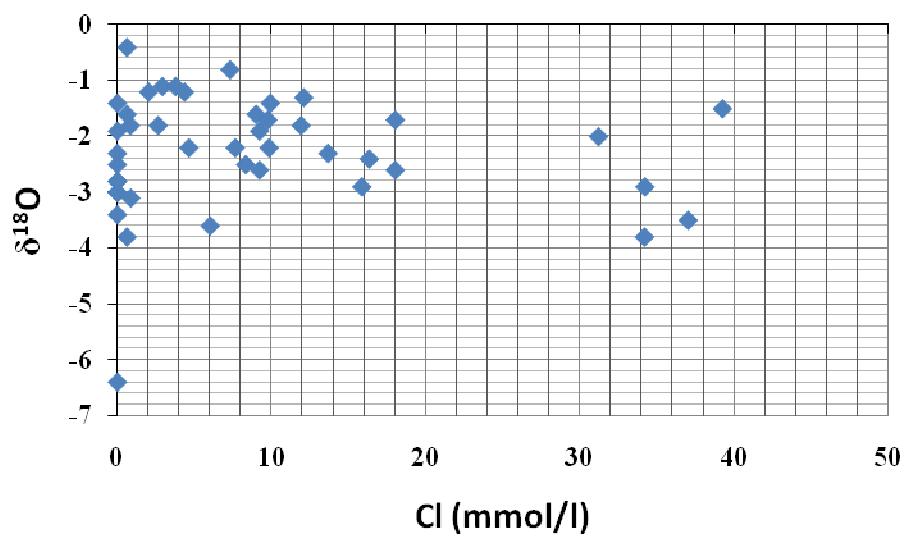


Fig. 6.10 Plot of Chloride versus $\delta^{18}O$ in the Tertiary aquifers

6.4.2 Radioactive Isotopes (^3H and ^{14}C)

Tritium content of groundwater from the alluvial aquifer varies from 3-4 TU, which is similar to the present day precipitation values indicating modern recharge. Tertiary aquifers contain negligible tritium except at the southeastern parts of the study area and their ^{14}C values are in the range of <1 to 98 pMC. Using Pearson's model (Pearson and White, 1967), corrections were applied for the initial activity of ^{14}C and the groundwater ages estimated for these Tertiary aquifers were in the range of 9,000 to

30,000 years Before Present (B.P). It indicates that these are paleowaters recharged in a distant past.

In general, it has been found that ^{18}O and ^{2}H concentrations in precipitation are temperature dependent, and hence rains occurring in cooler climatic conditions are more isotopically depleted than at warmer conditions (Dansgaard, 1954). This temperature dependence along with the dating techniques can be used for the reconstruction of paleoclimate.

The samples representing tertiary aquifers are low in Tritium content and the plottings of $\delta^{18}O$ versus ^{14}C in Fig 6.11 shows decrease in ^{14}C content (or increase in groundwater ages) with an increase in $\delta^{18}O$. This indicates that these groundwaters might be recharged during arid and humid phases in a span of 9,000 to 30,000 years B.P.

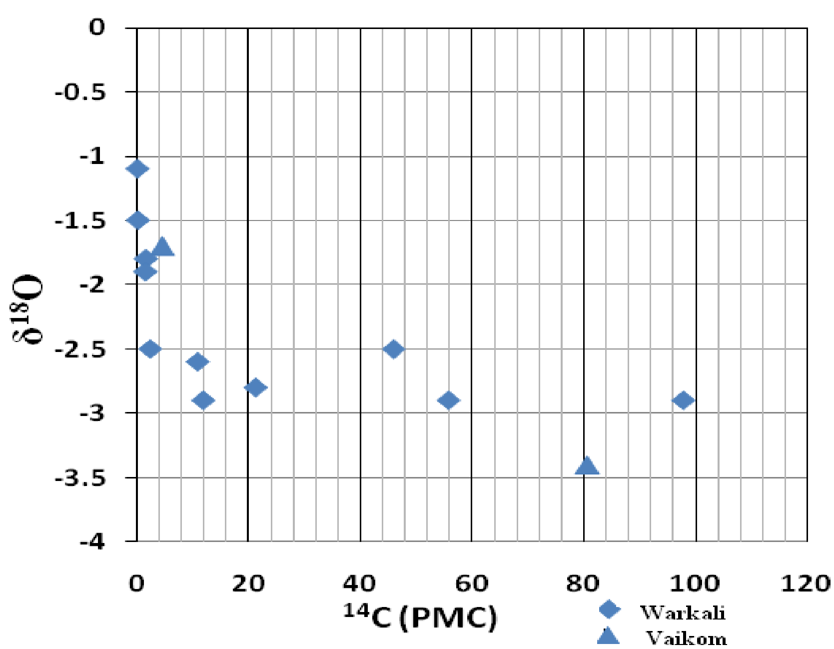


Fig. 6.11 Variation of $\delta^{18}O$ with ^{14}C in the Tertiary aquifers

Groundwater samples from Tertiary formations in the southeastern parts of the study area have measurable tritium. ^{14}C content of these samples ranges from 45 to 98 pMC.

They fall in a mixing zone in the $\delta^2H - \delta^{18}O$ diagram. It means that the Tertiary aquifers are getting some modern recharge from this area. It is further confirmed with the local hydrogeology that some parts of the Vaikom aquifer are outcropped in this area. However, this contribution seems to be small, as observed from the hydrogeological studies and piezometric level changes over the years.

Based on the existing isotope data and their analysis it is inferred that the groundwaters in the alluvial aquifer are of meteoric origin and are replenished periodically by modern precipitation. The very low tritium values in the Tertiary aquifers indicate lack of vertical recharge from the phreatic aquifer system due to the presence of thick clay layers below surface waters and wetlands as established from the study of bore well litholog under chapter 2. However, small amount of modern recharge takes place to the Tertiary aquifers from the southeastern parts of the study area. Similar isotopic characteristics of Warkali and Vaikom aquifers of Tertiary aquifer system and the similarity of water level response reflected in hydrographs suggest their interconnection through the Quilon limestone aquifer in many places. Deep groundwaters in Kuttanad area are paleowaters which might have recharged during arid and humid phases in the past. Brackishness in the unconfined aquifer along the coastal regions and adjacent to brackish water bodies are due to mixing of modern seawater / brackish water with the fresh water in the aquifer system. The hydrochemistry in Tertiary aquifers are not modified by seawater intrusion and salinity in this aquifer system is mainly caused by leaching of salts and cation exchange processes. This could be established from hydrochemical studies and supported by the oxygen-18 versus Cl and oxygen-18 versus carbon-14 plottings.

6.5 Evolution of groundwater in different aquifer systems

Recent alluvium

The groundwater in the phreatic aquifer has low mineralization with electrical conductivity less than 700µs/cm in general with a few exceptions in the wells adjoining the sea or backwaters. Such higher electrical conductivities observed at Sherthala, Nedumudi, Thottapalli etc. are spot specific and spatially located very near to backwaters or canals having brackish water. The spatial variations in ionic concentrations are depicted in the electrical conductivity map (Fig 5.2) and the chloride distribution map (Fig 5.5) in Chapter 5. Seasonal variation in water quality in this aquifer system is mainly due to mixing of waters and anthropogenic interferences.

The mineralization of water in the phreatic aquifer is very low and some of the samples show very high CO3- values, which is rare in natural conditions. The low mineralisation is due to low dissolution of minerals in the aquifers system. The restricted hydraulic continuity of the coastal aquifer with the regional groundwater flow system, depicted in the lithological cross sections given under chapter 2, limits the scope for any significant chemical evolution of groundwater along the flow path. Also, the rainwater recharging the aquifer reaches the sea fast, giving limited residence time for chemical reactions.

The results of factor and cluster analysis and facies studies clearly indicates that the waters in the phreatic aquifer is predominantly Ca-HCO_3 type. This type of water is characteristic of water of a recharge area. The groundwater in phreatic aquifer is being modified by surface water mixing and other anthropogenic interventions as revealed by the results of clusters and factor analysis.

The hydrogeological studies show low hydraulic gradient and water logging conditions in the phreatic aquifer which are unfavourable for natural cleansing of aquifer.

The mineralogy of the coastal aquifers and the marine aerosol play a significant role in the hydrochemistry of this aquifer system. In the coastal tract the aquifer is comprised of sand (SiO_2) with some minor quantities of calcareous materials and heavy minerals. The deposits of pure silica sand in certain parts of coastal tracts (in and around Sherthalai) which are depleted in calcium carbonate lead to a situation where the water charged with CO_2 infiltrates down to the saturated zone without much CO_2

consumption. The CO_2 exists in solution as H_2CO_3. The marine aerosol contribution to the soil in these areas makes the infiltrating water Sodium bicarbonate type. The sites at which the pH attains a higher value (>8.2) the HCO_3^- ion partially dissociates in to CO_3 ions. The samples located along the coast falls in the Na-Cl facies even though such samples have very low EC values. High correlation of sodium with Cl also points to the marine aerosol contribution. All these factors clearly indicate the role of aerosols in modifying the water chemistry in the coastal tract.

The confined aquifer system in Recent alluvium is well developed only along the coastal part in the west and forms poor aquifers in rest of the area as revealed from hydrogeological studies. Chemical facies and isotope study clearly indicates the existence of different hydrochemical facies dominantly influenced by the hydrogeological controls rather than a gradual evolution of hydrochemistry along the flow path in these aquifers because no lateral discontinuity is observed from hydrogeological studies. Cation exchange also plays an equally significant role in the evolution of water as revealed from ion ratio studies.

Tertiary aquifers

The sediments of tertiary beds are formed under the influence of a series of sea transgressions and regressions. The sediments are deposited under protected marginal marine environments like lagoons or estuaries or even under lacustrine conditions. The almost ubiquitous presence of shells in the clay layers and abundance of organic remains like peat and lignite in Warkali and Vaikom aquifers plays a significant role in the hydro chemical evolution of groundwater in these aquifer systems.

A strong correlation among the samples of Tertiary aquifers obtained from Q-mode cluster analysis indicates similar source of water which has undergone hydrochemical reactions within the aquifer at later stages. Different clusters of samples of specific hydrochemical characteristics evolved out of the interaction between water and minerals within the aquifer system or the existing geochemical environment. There is a clear clustering of groundwater types in the aquifers noticed from the hydrochemical studies and such clusters do not show any spatial zoning or evidence of hydrochemical evolution along flow directions. All the water samples from this aquifer system represent Na-Cl dominant water of different groundwater associations. The long residence time of groundwater in this aquifer system provided ample time for hydrochemical reactions such as leaching of salts and ion exchange.

In a steady state system there is no change in dissolved constituents with time as the ions on exchange sites are in equilibrium with those in the water. The transient effects are reflected by compositional changes in water chemistry. If the aquifer material has a high ion exchange capacity the extent of its effects on water chemistry may be considerable.

Ion exchange processes are described in connection with sea water intrusion (Thilagavathi et.al. 2012) and in connection with refreshening after a previous saline episode (Bruno Capaccioni 2005). These processes have been modelled by Ortega-Guerrero (2003) and Beatrice et al. (2007) and many others.

In the Tertiary aquifer systems the ion exchangers are likely to be clay minerals and organic matter. The affinity to most ion exchange sites of the common major cations is the following.

$$Ca^{2+} > Mg^{2+} = K^{+} >> Na^{+}$$

The aquifer material bearing freshwater of $Ca\text{-}HCO_3$ type will be predominantly Ca-saturated. Some of the sites in such aquifers may have Mg^{2+} and K^+ predominance.

In the case of seawater intrusion the Na concentration is high enough to displace some of the Ca^{2+} adsorbed in the aquifer material and water get enriched in Ca^{2+}. The changes in Mg^{2+} and K^+ will be moderate. Aquifer material having high sodium exchange sites easily replace Na^+ for Ca^{2+} in the $Ca\text{-}HCO_3$ type water leading to a situation of reverse ion exchange leading to the formation of $Na\text{-}HCO_3^-$ type water. When the easily replaced Na^+ is pushed out from the exchange sites, the turn comes to Mg^{2+} and K^+ which are abundant in seawater than Ca^{2+} and thus over represented on exchange sites relative to Ca^{2+}. This will result in a mixed cation-HCO_3 type of water in which all the four major cations (Ca, Mg, Na and K) are rather equally represented.

The mixed cation-HCO_3 water and mixed cation-Cl- HCO_3 type waters in the Tertiary aquifers are resulted from the ion exchange process explained above and from leaching of salts entrapped in clay layers. Ion exchange is a faster process than $CaCO_3^-$ dissolution constituting a sink for Ca^{2+}. The shells of aragonite composition contribute additional Mg in groundwater when it gets metamorphosed to a more stable calcite structure (Najeeb, 2012).

During the last glaciations (about 10000 years before present) the sea level was likely to be much lower (Thrivikramjii, 2003). Thus in the past a few thousand years ago there might have been considerably faster flow than today. With the transgression of the sea the flow has become gradually lesser and lesser leading to a stagnant situation of water in the aquifer systems. The sea level was higher at 3000 years BP along this coast. In the western coast of India, the sea level reached its maximum at 4000-6000 years BP (Kale and Rajaguru, 1985: Hashimi et al., 1995). According to Bruckner (1989), the modern sea level was attained around 2000-2800 years BP off the Konkan coast, further north of the study area. The distribution of water types in the Tertiary aquifer system is a "frozen" image of a past time flow pattern. What has happened during more recent time is the diffusion of Na-Cl from the clay layers. In some places this diffusion was strong enough to imitate a seawater intrusion effect, causing low Na/Cl ratios.

CHAPTER 7
SUMMARY AND CONCLUSIONS

The present study has been carried out to understand the aquifer systems, their inter relationships and evolution in the Kuttanad area of Kerala. The multi aquifer systems in the Kuttanad basin were formed from the sediments deposited under fluvio-marine and fluvial depositional environments and the marine transgressions and regressions in the geological past and palaeo climatic conditions influenced the hydrochemical environment in these aquifers. The evolution of groundwater and the hydrochemical processes involved in the formation of the present day water quality are elucidated from hydrochemical studies and the information derived from the aquifer geometry and hydraulic properties.

There are three major aquifer systems in the study area viz; the phreatic aquifer, Recent confined aquifer system and the Tertiary aquifers. They have distinct hydrogeological and hydrochemical characteristics. The coastal sands and flood plain deposits of interior Kuttanad form the major phreatic aquifer system in the study area. The granular zone which lies below the phreatic aquifer forms the Recent confined aquifer system. The Tertiary aquifers lie below the Recent aquifers and exists under confined conditions.

The aquifer disposition and geometry of sand deposits in Recent alluvium and Tertiary sedimentary beds are established from the analysis of lithologs from 35 deep and 15 shallow tube wells. The three aquifer systems are separated by thick clay layers which act as confining layers preventing vertical leakage from the phreatic aquifer system.

The hydraulic behavior of the aquifer systems was studied from the groundwater levels and piezometric heads observed from 76 dugwells and 37 piezometers. The phreatic aquifer receives direct rainfall recharge and the water levels are shallow. Groundwater level fluctuation between pre- and post-monsoon seasons in the phreatic aquifers is low and has high rejected recharge. The phreatic aquifers have low hydraulic gradients and the general flow direction is towards the sea in the west. Decadal change in water level is insignificant in the phreatic aquifer system. The confined aquifer in Recent alluvium has low water level fluctuations and has low groundwater potential.

The piezometric heads are high in the Tertiary aquifers. However, the hydraulic gradients are low and are in the order of 10^{-4}. The flow in the Tertiary aquifers is converging towards the central part of the study area as a result of heavy groundwater draft in an around Alleppey town. The pumping test results show low transmissivity values in the eastern part of the area and relatively high values in the coastal areas. The decline in piezometric heads for both the seasons is indicative of an imbalance between the recharge and draft and points to the necessity for restriction on draft from these aquifer systems to avoid adverse effects.

Evaluation of the chemical quality of groundwater in time and space were made from the analysis of 252 water samples representing the aquifer systems. More than 50% of the water samples in the aquifers of Recent alluvium are unsuitable for domestic use. The freshwater in the Tertiary aquifers forms the main source of drinking water. The high nitrate sites in phreatic aquifer system indicate anthropogenic contamination as well as decomposition of organic matter present in the aquifer, whereas, in the Recent confined aquifers the organic matter present in the aquifer system are the major nitrate sources. Tertiary aquifers have high fluoride levels (>1.5mg/l) and Iron contamination in certain pockets.

The hydrochemical facies and evolution trends were deciphered from various studies such as correlation matrix, ion ratios, factor and cluster analysis and isotope studies. These studies revealed rock-water interaction as the major factor contributing the hydrochemical characteristics of groundwater in the phreatic aquifers.

Two significant chemical reactions modifying the hydrochemistry in the Recent aquifer identified in the present study are the release of hydrogen ions from oxidation of iron from ferruginous clays and consumption of hydrogen ions in the process of decomposition of organic matter within the aquifer system. These two reactions give contrary results and are site specific in nature. Leaching of salts from the clay layers which were deposited under marine environment releases fluoride in to the groundwater in Recent aquifer.

In the Tertiary aquifers the water is evolved out of chemical reactions along the flow path and subsequently modified through leaching of salts in confining clay layers and cation exchange processes. The peat and lignite observed in Tertiary beds form the sources of carbon dioxide within the Tertiary aquifer system. A highly reducing environment exists in the Tertiary aquifers where sulphate is reduced to sulphide. Leaching of salts from the clays and reverse ion exchange processes are responsible for the enrichment of fluoride in this aquifer system. Fluoride contamination in this aquifer system lacks a regional pattern and is more or less site specific in nature.

The radioactive contamination of groundwater in the aquifer systems in Kuttanad area was evaluated from the radon activity of groundwater studied from 24 samples. The groundwaters in all the aquifer systems have low radon activity and do not show any correlation with the areas having high gamma counts recorded from the aquifer zones.

Environmental isotope ($\delta^{2}H$, $\delta^{18}O$,^{3}H and ^{14}C) studies were carried out in 46 groundwater samples collected from the study area to understand the mixing of waters in the aquifer systems vis-à-vis the age of water. The $\delta^{2}H$ - $\delta^{18}0$ relationships in most of the groundwater samples of Recent confined and Tertiary aquifers fall on or close to the GMWL indicating that these waters are of meteoric origin and are not affected by secondary isotope effects such as evaporation or isotope exchange. The salinity observed in the Tertiary aquifers is derived from leaching of salts from the confining clay beds.

The ion ratio studies also proved that the groundwater in the Tertiary aquifers were evolved out of ion exchange processes along the flow path and subsequently modified through leaching of salts present in confining clay layers. These studies clearly shows that the salinity of water observed in the tertiary aquifer system were not due to mixing of sea water.

From the hydrochemical studies and the hydrochemical facies identified it was inferred that the hydrochemistry of groundwater in various aquifer systems of Kuttanad are controlled and influenced by different hydochemical processes. Mixing of waters and anthropogenic interferences are the dominant processes modifying the hydrochemistry in phreatic aquifers, whereas, leaching of salts and cation exchange are the dominant processes modifying the hydrochemistry in the confined aquifer system of Recent alluvium. The hydrochemical environment is entirely different in the Tertiary aquifers as the groundwater in this aquifer system are palaeo waters evolved during various periods of marine transgressions and regressions and these waters are being modified by processes of leaching of salts and cation exchange and chemical reactions under strong reducing environment. Salinity of water observed in the groundwaters of Tertiary aquifers are due to dissolution of salts from the clay formations. The studies proved that ion exchange process is one of the major factors in the evolution of groundwaters in Tertiary aquifers.

CONCLUSIONS:

Kuttanad area comprises of three types of aquifer systems namely phreatic aquifer underlain by Recent confined aquifer followed by Tertiary confined aquifers. These systems were formed by the deposition of sediments under fluvio-marine and fluvial environment.

The study of the hydrochemical and hydraulic properties of the three aquifer systems proved that these three systems are separate entities. The phreatic aquifers in the area have low hydraulic gradients and high rejected recharge.

The Recent confined aquifer has very poor hydraulic characteristics and recharge to this aquifer is very low. The Tertiary aquifer system is the most potential fresh water aquifer system in the area and the groundwater flow in the aquifer is converging towards the central part of the study area (Alleppey town) due to large scale pumping of water for water supply from this aquifer system.

Mixing of waters and anthropogenic interferences are the dominant processes modifying the hydrochemistry in phreatic aquifers. Whereas, leaching of salts and cation exchange are the dominant processes modifying the hydrochemistry of groundwater in the confined aquifer system of Recent alluvium. Two significant chemical reactions modifying the hydrochemistry in the Recent aquifers are oxidation of iron in ferruginous clays which contributes hydrogen ions and the decomposition of organic matter in the aquifer system which consumes hydrogen ions.

The hydrochemical environment is entirely different in the Tertiary aquifers as the groundwater in this aquifer system are palaeo waters evolved during various marine transgressions and regressions and these waters are being modified by processes of leaching of salts, cation exchange and chemical reactions under strong reducing environment. It is proved that the salinity observed in the groundwaters of Tertiary aquifers are not due to seawater mixing or intrusion, but due to dissolution of salts from the clay formations and ion exchange processes. Fluoride contamination in this aquifer system lacks a regional pattern and is more or less site specific in nature.

The lowering of piezometric heads in the Tertiary aquifer system has developed as consequence of large scale pumping over a long period. Hence, puping from this aquifer system is to be regulated as a groundwater management strategy. Pumping from the Tertiary aquifers with high capacity pumps leads to well failures and mixing of saline water from the brackish zones. Such mixing zones are noticed from the hydrochemical studies. This is the major aquifer contamination in the Tertiary aquifer system which requires immediate attention. Usage of pumps above 10 HP capacities in wells taping Tertiary aquifers should be discouraged for sustainable development of these aquifers. The recharge areas need to be identified precisely for recharging the aquifer systems through artificial means.

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