GROUND WATER RESOURCES MODELLING OF A WATERSHED USING MODFLOW

SAJEENA S
(2012-28-101)

Faculty of Agricultural Engineering and Technology

Kerala Agricultural University

DEPARTMENT OF LAND AND WATER RESOURCES & CONSERVATION ENGINEERING

KELAPPAJI COLLEGE OF AGRICULTURAL ENGINEERING & TECHNOLOGY

TAVANUR P.O. MALAPPURAM-679573

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By

SAJEENA S

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THESIS

Submitted in partial fulfillment of the requirement for the degree of

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KELAPPAJI COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY

TAVANUR P.O., MALAPPURAM-679573

KERALA, INDIA

2015

DECLARATION

I, hereby declare that this thesis entitled **"GROUND WATER RESOURCES MODELLING OF A WATERSHED USING MODFLOW"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Tavanur **Sajeena, S**

Date: 05/03/2016 **2012-28-101**

CERTIFICATE

Certified that this thesis entitled **"GROUND WATER RESOURCES MODELLING OF A WATERSHED USING MODFLOW"** is a bonafide record of research work done independently by **Mrs. Sajeena, S (2012-28-101)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

Tavanur
Date: 05/03/2016

Dr. Kurien, E. K.
(Major Advisor, Advisory Committee)
Special Officer
Academy of Climate Change Education and Research
Vellanikkara, Thrissur

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1	Identification of groundwater prospective zones using geoelectrical and electromagnetic surveys (Review article)	Sajeena, S, Kurien, E. K. Abdul Hakkim, V.M.	2014	*Int. J. of Eng Inventions..* 3(6): 17-21
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CERTIFICATE

We, the undersigned members of the advisory committee of **Mrs. Sajeena, S., (2012-28-101),** a candidate for the degree of Doctor of Philosophy in Agricultural Engineering with major in Soil and Water Engineering, agree that the thesis entitled **"GROUND WATER RESOURCES MODELLING OF A WATERSHED USING MODFLOW"** may be submitted by **Mrs. Sajeena, S.,** in partial fulfillment of the requirement for the degree

Dr. E. K. Kurien
(Chairman, Advisory Committee)
Special Officer
ACCER
Vellanikkara, Thrissur.

Dr. Hajilal, M. S
(Member, Advisory Committee)
Dean, KCAET
Tavanur.

Dr. K.K Sathian
(Member, Advisory Committee)
Associate Professor
Department of Land and Water Resources and Conservation Engineering
KCAET, Tavanur.

Dr. Rema, K.P.
(Member, Advisory Committee)
Associate Professor
Department of Irrigation and Drainage Engineering,
KCAET, Tavanur.

Dr. Jayan P.R.
(Member, Advisory Committee)
Associate Professor
Department of Farm Power Machinery and
KCAET, Tavanur.

Dr. Sudheer, K.P.
(Member, Advisory Committee)
Associate Professor
Department of Civil Engineering, Energy,
IIT, Madras.

EXTERNAL EXAMINER
(Name and Address)

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Sajeena, S

ABBREVIATIONS USED

AMSL	-	Above Mean Sea Level
Assoc.	-	Association
CGWB	-	Central Ground Water Board
cm	-	Centimeter
CWRDM	-	Centre for Water Resources Development and Management
Eng.	-	Engineering
et al.	-	and others
Fig.	-	Figure
GIS	-	Geographical Information System
GPS	-	Global Positioning System
J.	-	Journal
Int.	-	International
lph	-	litre per hour
m	-	metre
MCM	-	Million Cubic Metre
md^{-1}	-	metre per day
ms^{-1}	-	metre per second
Natl.	-	National
r	-	Coefficient of Correlation
RH	-	Relative Humidity
RMSE	-	Root Mean Square Error
viz.	-	namely
vs	-	Versus
%	-	Percentage

CHAPTER 1

INTRODUCTION

Ground water is one of the most valuable natural resources, which supports human health, economic development and ecological diversity. Ground water is considered as an underground reservoir and is usually held in porous soils or rock materials. Exploration of ground water as a viable source for domestic, agricultural and industrial use has assumed top priority in recent years. Ground water is safer and economical than surface water, as it is generally uncontaminated. Because of the over exploitation of ground water for domestic, industrial and agricultural purposes, people all around the world face serious water shortage. Around 7 x 10^6 million people out of the projected 9.3 x 10^6 million in the entire world is estimated to face water shortage and out of these, 40 per cent will suffer acute water crisis (Ashwanikumar, 2011). The threat of freshwater scarcity looming large over the horizon and government has taken several initiatives to make people aware about the need to conserve and augment this precious resource. The annual replenishable ground water resources in India is estimated to be 432 x 10^6 MCM out of which 398 x 10^6 MCM is available for utilization, leaving aside 34 x 10^6 MCM for natural discharge. Ground water contributes to 60 per cent of the total irrigated area of the country and plays a significant role in irrigation development. Presently the overall stage of ground water development is 58 per cent, however there exists a significant regional variation in its development. Ground water exploitation is more than its sustainable level in the states like Delhi (170%), Punjab (145%), Haryana (109%) and Pondicherry (105%). Average ground water development in western arid zone comprising of Gujarat, Rajasthan and Daman and Diu is 96 per cent and it is followed by southern states of Andhra Pradesh, Karnataka, Kerala, Tamil Nadu and Pondicherry with 61 per cent. Ground water development in Bihar, Orissa, Eastern Uttar Pradesh and West Bengal is quite low and it has an annual maximum potential of 102.5 x 10^6 MCM of the total ground water resources in India (Ashwanikumar, 2011).

Ground water is the most essential and necessary substitute to surface water and is a hidden, replenishable resource whose occurrence and distribution greatly varies according to the local as well as regional geology, hydrogeologic setting and to a great extent, the nature of human activities on the land (Mondal *et al.,* 2010). A saturated formation of earth material which not only stores water but also yields it in sufficient quantity is called aquifer. Aquifers also feed streams and rivers and livens them during dry season. Stream flows fed by ground water are called base flow. Aquifers may occur at relatively shallow depths below the ground surface, ground water surface in such aquifers can be said to be at atmospheric pressure. Such aquifers are called as unconfined aquifers. Aquifers may be present at much greater depth below ground surface; ground water present in such aquifers has pressure more than atmospheric pressure due to overlying and underlying rocks. Such aquifers are called confined aquifers. The type of rock, its structure and its openings decides how much water the rock will store and how quickly it will allow water to flow from one point to another. Therefore we can say that rocks have both high porosity to hold water and permeability to allow water to flow (Todd, 1980).

The ground water storage is generally controlled by the thickness and hydro-geological properties of the weathered zone and the aquifer geometry. Over exploitation of ground water, beyond the safe yield limit, may cause continuous reduction in ground water levels, reduction in river flows, reduction in wetland surface, degradation of ground water quality and many other environmental problems like drought and famine.

Geophysical electrical resistivity methods have been extensively used for ground water investigation by many researchers throughout the world, which were developed in early nineties. It is the most suitable method of ground water investigation in most geological formations due to simplicity. Among various geophysical studies, Vertical Electrical Sounding (VES) is a depth sounding galvanic method and has proved very useful in ground water studies due to simplicity and reliability of the method.

The electrical resistivity of rock depends on lithology and fluid contents. The resistivity of coarse- grained, well consolidated sandstone saturated with fresh water will be higher than that of unconsolidated silt of the same porosity, saturated with the same water. Similarly, the resistivities of identical porous rock samples may vary with respect to the salinity of the saturated water. The instrumentation for this method is simple as the field logistics are easy and straight forward and the analysis of data is less tedious and economical (Ekine and Osobonye, 1996). By using this method, depth and thickness of various subsurface layers and their water yielding capabilities can be inferred. These measurements have been used to solve ground water and its related problems; notably in determining suitable site for drilling of boreholes and in studying ground water contamination. This can also be used for the estimation of dynamic as well as static ground water reserves (Paliwal and Khilnani, 2001)

Use of ground water models have been applied to investigate a wide variety of hydro-geologic conditions. Ground water models describe the ground water flow and transport processes using mathematical equations based on certain assumptions. The objectives of ground water modelling in India are mainly for ground water recharge studies, study of dynamic behaviour of the water table, stream-aquifer interaction studies and sea-water intrusion studies. It is important to understand the general aspects of both ground water flow and transport models, so that application or evaluation of these models may be performed correctly.

MODFLOW, a U.S. Geological Survey modular finite-difference flow model, which is a set of computer programs that solves the ground water flow equation (Harbaugh, 2005). The program is used by hydro-geologists to simulate the ground water flow through aquifers. The code of this software is written primarily in FORTRAN and can compile and run on Microsoft Windows or Unix-like operating systems.

Visual MODFLOW is a complete and user-friendly, modelling environment for three dimensional ground water flow and contaminant transport simulation. It is a fully integrated package which combines MODFLOW, MODPATH, MT3D and PEST with the most intuitive and powerful graphical interface available. The model grid, input parameters and results can be visualized in 2D (cross-section or plan view) or 3D at any time during the model development or the result display. For complete three-dimensional ground water flow and contaminant transport modelling, Visual MODFLOW software package could be used effectively.

In Kerala, most of the people depend on ground water as the source for drinking water supply. Kerala has a unique hydro-geological and climatic condition and the surface and ground water resources of the state play a vital role in the development of activities like irrigation, industrial and domestic uses. The State experiences wide variation in the rainfall pattern from eastern hilly areas to the western coastal regions and most of the rainfall leaves as surface run off particularly during monsoon season. The base flow from the ground water emerges as surface run off during the non-monsoon periods. A realistic estimation of ground water and related information for each watershed are needed to mitigate water scarcity, water pollution and ecological problems in the state.

Malappuram is the most populous district of Kerala with highest decadal population growth rate. With the ever increasing population growth and to meet the demand of water for various purposes, there is a growing stress on the ground water resources. Management of ground water has become a great concern for the scientists, planners and administrators alike. Sustainable management of available ground water resources has thus become vital for the prevention of over exploitation and contamination of ground water.

Though the district is endowed with an average annual rainfall of about 3000 mm spread over both the southwest and northeast monsoons, the ground water availability during the peak requirement period (Dec – May) has been found to be meagre for domestic and agricultural purposes. This is mainly on account of the large dependence on ground water in rural areas and the resultant high well density. Further, as the major part of the district is characterised by crystalline rocks with very thin unconsolidated phreatic aquifer with steep hydraulic gradient from east to west, the ground water runoff from the phreatic aquifer is appreciable on account of the unique geomorphic and hydro-geological set up of the area . A strong ground water legislation with strict regulation and control along with mandatory registration of all new pumping ground water extraction structures with the State Ground Water Authority would aid in proper governance and ensure sustainability of this precious resource.

The demand for ground water is increasing year by year in the district due to recurring drought, growing population, urbanisation and increased agricultural and industrial activities. To meet this increasing demand, proper understanding of the ground water potential of the district, both in terms of availability and distribution is important. Before taking up any ground water developmental activity, basic data required are the principal hydro-geologic units and their distribution, recharge and discharge areas, knowledge on water table fluctuation and general ground water potential. These data will help in establishing the framework for future planning and development.

Major rivers of Malappuram district are Kadalundi River, Chaliyar River and Bharathapuzha (locally known as Ponnani River). Major portion of the catchment of Chaliyar river falls in Kozhikode and Wayanad districts and that of Bharathapuzha falls in Palakkad and Thrissur districts. Kadalundi river has a total length of 130 km with a drainage area of 1122 km^2 and major portion of the catchment falls within Malappuram district and a small portion in Palakkad district of Kerala. Kadalundi river originates from the Western Ghats at the western extreme of the Silent Valley and cut across the district of Malappuram. Kadalundi river basin covers major geographical area of Malappuram district comprising of 34 per cent of the total area of the district and this river basin can be considered as a general representation of the district. Hence Kadalundi river basin is selected as study area of this research work.

Water resources studies should be carried out with drainage basin or watersheds, as it is the unit for better understanding of the hydrologic system and for accurate quantitative estimation of the resources. River basin is a natural integrator of all hydrological processes pertaining to its boundaries, and therefore, may be considered as the physical unit for planning optimum development of land and water. Therefore, an integrated planning for development and management of a river basin is found to be necessary. Keeping view of the above aspects, the present study is carried out to make a ground water resources flow modelling and mapping of Kadalundi river basin using MODFLOW.

The specific objectives of the research are:

1. To study the aquifer characteristics of the study area
2. To study the spatial and temporal ground water variations in the study area
3. To identify the potential ground water zones within the study area using earth resistivity studies.
4. To develop a ground water flow model for the river basin using Visual MODFLOW and to map the ground water resources of the study area.

CHAPTER 2

REVIEW OF LITERATURE

The chapter reviews the concepts and literatures available on ground water flow, geophysical methods of ground water investigations, recharge estimation methods, details of MODFLOW and finally the case studies of Kadalundi River Basin.

2.1 Ground water flow

Ground water is usually held in porous soils or rock materials. The area where water fills these spaces is called the saturated zone, top of this zone is called water table. The water table may be shallow or it may be deep extending to several meters down and may rise or fall depending on many factors. Heavy rains may cause the water table to rise while an extended period of drought may cause the water table to fall.

The nature of ground water flow depends on the size of the pores in the rock or within the soil particles and how well the spaces are interconnected. Aquifers typically consist of gravels, porous sedimentary rocks and fractured crystalline rocks. Water in aquifers at times reaches the surface of the earth naturally through springs. Ground water can also be extracted from a well manually or can be pumped out. Artesian wells do not need a pump because of natural pressures that force the water up and out of the well.

Ground water theory starts with discussion of the basic law which governs the ground water flow by a French hydraulic engineer Henry Darcy. The result of his experiment is to analyze the flow of water which is generalized as an empirical law known as Darcy‘s law (Freeze, 1979).

2.1.1 Hydraulic head and gradient

Every physical process which involves flow usually requires the presence of potential and its flow occurs in the direction of higher to lower potential. It is also true in case of ground water flow. Ground water potential at a given point is the energy required to transport a unit mass of water from a standard reference state to that point. It concludes that potential term in the ground water flow system is basically head term in Darcy experiment. Hydraulic head is explained in terms of two components, elevation head z and pressure head ψ (Deller, 1999).

$$\text{Hydraulic head, } h = z + \psi \qquad \text{(Eq. 2.1)}$$

2.1.2 Hydraulic conductivity

It is the property of material which describes the ease with which a fluid (usually water) can move through pore spaces or fractures. The constant of proportionality involved in Darcy‘s law is hydraulic conductivity. It depends on the size and arrangements of porous medium and on dynamic characteristics of fluid such as dynamic viscosity, density and strength of gravitational field. Hence, hydraulic conductivity is a function of not only the porous medium but also of fluid (Todd, 1980). Hydraulic conductivity can be obtained using laboratory studies.

The most reliable method for estimating aquifer hydraulic conductivity is pumping tests of wells. Based on observations of water levels near pumping wells, an integrated hydraulic conductivity (K) value over a sizable aquifer section can be obtained (Todd, 1980).

Bhosle and Kumar (2000) determined the best suited values from a wide range of model parameters and the horizontal hydraulic conductivity (K_h) value of different substrata obtained through calibration are given in Table 1.

Collection of water-level recovery data is a common practice for pumping test. The resulting data can provide some of the most useful information from the test, but are rarely used to their full value. A general method that uses recovery data to extent the effective duration of pumping.

Table 1. Horizontal hydraulic conductivities of different substrata

Substrata	Range (md^{-1})	Best Suited (md^{-1})
Sand	30 – 85	45
Laterite	25 – 70	40
Lateritic clay	10 – 50	25

The method is easy to implement and applicable for simple or complex hydrogeologic settings. The only assumption involved is that the response remains linear such that the principle of superposition can be applied and no other assumptions about the properties of the aquifer are required. The method can greatly increase the value of pumping tests by extending the effective duration of the tests for as long as significant residual drawdown is observed (Neville and Kamp, 2012).

2.1.3 Unsaturated flow and the water table

It is assumed that when a well is drilled it strikes water once it reaches below the water table. Underground water occurs in two different zones, one zone occurs immediately below the land surface which contains both air and water is known as unsaturated zone. Below this unsaturated zone, there is a zone in which all interconnected openings are full of water, known as saturated zone. Water table is known as the surface on which the fluid pressure p in the pores of porous medium is exactly atmospheric, this surface reveals when we dig a well up to a depth just enough to encounter standing water. If p is measured then on the water table $p = 0$ and then the hydraulic head, h equals to the elevation z of the water table at that point (www.clas.ufl.edu/users/screaton/06fall/ Unsaturated Zone.doc).

In saturated zones, the hydraulic conductivity K, which is constant, is not a function of the pressure head. But in case of unsaturated zones, both hydraulic conductivity K and the moisture content are functions of the pressure head. The sandy soil with larger pore spaces has a lower moisture content for a given pressure head than clayey soil. At low moisture contents, only the smallest pore spaces, with the highest surface tension, will hold water and at higher moisture contents, larger pores with lower surface tension will be filled. The relationship between pressure head and water content depends on the pore size distribution and the shape of the curve depends on whether the soil is wetting or drying out. This occurs because drainage is controlled by the size of the smallest pore spaces, whereas wetting is controlled by the size of the largest pore spaces. As moisture content decreases, hydraulic conductivity decreases, which has been determined by flow measurements at varying moisture contents. It occurs because the water fills only part of the pore space (remaining portion with air) and so effectively the flow takes place through smaller, more poorly-connected channels. As the moisture content approaches porosity, the hydraulic conductivity will approach the saturated hydraulic conductivity. Unsaturated zone flow equations are developed similarly to those for the saturated zone, using Darcy‘s law and the conservation of mass. Solution of the flow equations is more complex than for the saturated zone because of the dependence of pressure head and hydraulic conductivity on the moisture content (www.clas.ufl.edu/users/screaton/06fall/ Unsaturated Zone.doc.).

2.2 Spatial and temporal changes of ground water

Ground water is a dynamic resource, which may be expressed as the quantity of water measured by the difference between optimum and minimum water table within the aquifer. This annual fluctuation of water table mainly depends on rainfall and other factors such as climate, geomorphology, topography, soil and subsurface geology. Charon *et al***.** (1974) stated that drainage pattern is one of the most important indicators of hydrogeological features, because drainage pattern and density are controlled in a fundamental way by the underlying lithology. The influence of landforms on well yields is also demonstrated by Perumal (1990) from a study of granite-gneiss and charnockite formations in the Athur valley of Tamil Nadu. Fault-controlled buried pediments, where the weathered horizon is thicker, will also give higher water yield as compared to other landforms (Perumal, 1990).

The topography and landforms have strong influence on well yield, especially of shallow wells, as they influence the thickness of weathered zone (Henriksen, 1995). Wells located in valleys have greater yield than that of those located on steep slopes, sharp ridges and interfluvial areas. Therefore, to a certain extent the well yields can be predicted using the topographic considerations. The concept of optimum depth of wells holds good in crystalline fractured rocks as the permeability usually decreases with depth. An overall decrease in well yield with depth is reported from various crystalline rock terrains in different parts of the world (Henrisken, 1995).

Harinarayana *et al.* (2000) stated that the lineaments are the main conduits of the ground water in impermeable rocks worldwide. The aperture, the spacing, the interconnection, and the orientation of fracture planes play a significant role in the occurrence and the movement of ground water resources in aquifer. Most of the lineaments in the area are aligned with the trend of stream courses and high porosity and hydraulic conductivity zones are associated with the lineaments.

Ramalingam and Santhakumar (2002) reported that in the hard rock areas, geomorphology (land forms) plays the very important role in ground water recharge. Hence, highest factor weightage has been assigned. Similar studies conducted at Tamil Nadu assigned highest weightage to the same factor. Further, among the various classes of morphology, valley fills plains followed by the pediments are the most favourable geomorphological classes, because they check the velocity of surface runoff and provide more chance for water accumulation.

Scanlon *et al*. (2002) concluded that mapping topographic attributes through satellite-based digital elevation models (DEMs), Stereo-satellite image and SAR interferometry technique can be used to generate DEMs. While the absolute accuracy of satellite- based DEMs is of the order of few meters, relative accuracy is quite good for obtaining certain topographic attributes which when combined with other remote sensing and ground observations provide further insights into understanding hydrogeological processes, e.g. ground water flow patterns, runoff-recharge processes, etc. One major limitation of satellite- based DEM is that they provide digital surface model (DSM) rather than digital terrain model (DTM). Laser Altimetry (or Lidar) has the capability to overcome this problem. The SRTM (Shuttle Radar Topographic Mission) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEMs having 90 m and 30 m spatial resolutions, respectively, are available in public domain and can be used to map the runoff and recharge areas.

Shaban *et al*. (2006) stated that land cover and land use also affect evapotraspiration, volume, timing and recharge of the ground water system. Land cover/ land use play a significant role in the development of ground water resources.

Ettazarini (2007) reported that geological fractures (e.g. faults, joints, bedding plains and fissures) are the main conduits of fluids in non-permeable rocks worldwide. In fact, the geological fracture plane constitutes the useful void volume corresponding to the potential space able to be occupied by the water in such medium. The aperture, the spacing, the connection and the orientation of fracture plans, play a significant role in the occurrence and movement of ground water resources in fractured aquifers.

Arunkumar and Joseph (2009) evaluated the ground water quality in the coastal zone of Thiruvanathapuram District, Kerala, India and the analysis of ground water samples from the study area indicate that the ground water is more or less deteriorated. Except pH, TDS, chloride and Na, most of the other parameters analyzed are within the permissible limits of World Health Organization (WHO). Based on the Hill Piper trilinear diagram, it is confirmed that majority of the dug wells are characterized by high amount of Na and chloride, indicating the influence of saline water intrusion. Correlation analysis of hydrochemical attributes showed perfect correction between electrical conductivity (EC) and total dissolved solids (TDS), which indicates that EC is a measure of dissolved solids in ground water. The study further raises points for the need of action towards sustainable utilization of precious resources.

The long-term behaviour of water table in the state of Punjab for the period 1998-2006 using GIS indicated that water table has declined at the rate of 52 cm per annum due to large scale adoption of rice-wheat rotation. Area under water table depth of 3 –10 m has reduced from 75 to 40 percent, whereas the area with the critical depth (10- 20 m) has increased from 20 to 58 per cent, indicating additional cost on replacement of centrifugal pump by submersible pump and additional cost of pumping (ICAR, 2010).

A study on ground water balance to assess the quantity of water available for development in the Parambikulam - Aliyar basin was conducted and both increasing and decreasing trends have been noted over the period of 21 years in almost all the wells of the basin. This clearly indicating that the water level fluctuation is mainly controlled by the intensity of the rainfall as well as abstraction (ICAR, 2010).

Muhammed *et al.* (2012) conducted a study on ground water fluctuation at Barind area, Rajshahi. They reported that ground water level shows a seasonal pattern of fluctuation and the magnitude of fluctuation depends upon the quantities of water recharge and discharge.

Subin (2012) stated that drainage density is the prime indicator of identification of potential ground water zone. Higher the drainage density the lesser the infiltration capacity i.e., low void ratio of the terrain leads to lesser ground water potentiality. This is because much of water coming as rainfall goes as runoff. In general drainage density is the most important parameter that control ground water occurrence and distribution.

Venkataramanan *et al.* (2013) reported that the ground water occurrence in a geological formation and the scope for its exploitation primarily depends on the porosity of formation. High relief and steep slopes impart higher runoff, while topographical depressions increase infiltration. An area of high drainage density also increase surface runoff compared to a low drainage density area. Surface water bodies like rivers, ponds, etc., can act as recharge zones, enhancing the ground water potential in the neighbourhood.

Rajaveni *et al.* (2014) conducted a study on spatial and temporal variation of ground water level and its relation to drainage and intrusive rocks in a part of Nalgonda District, Andra Pradesh. The region predominantly comprise of granites and gneisses. Observed groundwater levels were compared with drainage and dyke density. Groundwater level fluctuation in low drainage density region is generally greater than those in moderate and high drainage density regions. The dykes do not act as barriers for groundwater flow as they are highly weathered. The quantity and flow of groundwater in this region is predominantly controlled by drainage density, intensity of weathering and presence of fractures. Thus the study indicated that the drainage density play a major role in groundwater level fluctuation and as the dykes are weathered, they do not affect the groundwater flow in this shallow unconfined aquifer. This may be the case in most of the other regions comprising of crystalline rocks where ground water occur at shallow depth of less than 15 m.

Senthilkumar and Shankar (2014) stated that drainage density expressed in terms of km/km^2 indicates closeness of spacing of channels as well as the nature of surface material. More the drainage density, higher would be runoff. Thus drainage density characterizes the runoff in an area or in other words, the quantum of relative rainwater that could have infiltrated. Hence lesser the drainage density, higher is the probability of recharge.

2.3 Geophysical methods for ground water investigations

The role of geophysical methods in ground water exploration is vital and are used to obtain more accurate and adequate information about subsurface conditions, such as type and depth of consolidated or unconsolidated materials, depth of weathered or fractured zone, depth to ground water, depth to bedrock and salt content of ground water (Bouwer, 1978).

In geophysical investigations for water exploration, depth to bedrock determinations, sand and gravel exploration etc, the Electrical Resistivity Meter (ERM) method can be used to obtain, quickly and economically, details about the location, depth and resistivity of subsurface formations. Emenike (2001) studied about the ground water potential and a correlation of the curves with the lithologic log from a nearby borehole and suggested that the major lithologic units penetrated by the sounding curves were laterite clay, sandstone and clay. The sandstone unit, which was the aquiferous zone had a resistivity range between 500 ohm-m and 960 ohm-m and thickness in excess of 200 m

The Electrical resistivity method has the widest adoption in ground water exploration among the various geophysical methods of ground water investigation studies (Ariyo, 2007). This is due to the fact that the equipment is portable, the field operation is easy, less pressure is required for greater depth of penetration and it is accessible to modern communication systems. The Electrical resistivity method is very useful in the identification and better understanding of aquifer dimensions (Ariyo and Adeyemi, 2009).

The basis of any geophysical method is measuring a contrast between physical properties of the target and the environs. The better the contrast or anomaly, the better the geophysical response and hence the identification. So, the efficacy of any geophysical technique lies in its ability to sense and resolve the hidden subsurface hydrogeological heterogeneities or variation. Hence for ground water exploration, a judicious application or integration of techniques is most essential for success in exploration, technologically as well as economically (Rosli *et. al.,*2012).

2.3.1 Electrical resistivity methods

Electrical Resistivity Method is one of the geophysical techniques used to investigate the nature of the subsurface formations. ERM uses an artificial source of energy and rather the source detector can be altered to achieve the optimum separation, which effectively controls the depth of measurement. ERM is easy for operate, speedy and accurate and water exploration survey can be done at a low cost using ERM. Liu (2004) used ERM method to study the imaging changes of moisture content in the vadose zone and the ability of the integrative approach was tested by directly estimating moisture distributions in three-dimensional, heterogeneous vadose zones. ERM is generally employed for ground water studies, such as quality, quantity, mapping fresh water lenses, investigation of salt water intrusion and determination of the extent of contaminants.

2.3.2 2-D Electrical resistivity tomography

2-D electrical resistivity tomography (ERT) has been widely used for many years for ground water exploration. The technique is used together with drilling for determination of resistivity value of alluvium and the effect of ground water. 2-D electrical resistivity tomography (ERT) is now mainly carried out with a multi-electrode resistivity meter system. Such surveys use a number (usually 25 to 100) of electrodes laid out in a straight line with a constant spacing. A computer-controlled system is then used to automatically select the active electrodes for each measure (Griffith and Barker, 1993).

The resistivity method mainly measures the resistivity distribution of the subsurface materials. The resistivity of hard rock is mainly dependent on the degree of fracturing. The greater the fracturing, the resistivity value of the rock is lower. A study was conducted in areas which have thick alluvium and the result shows that ground water will lower the resistivity value and silt will bring down the resistivity value more than the ground water effect. Ground water reservoirs are found in saturated sand, saturated sandy clay and saturated silt, clay and sand. Each and every material has got its own resistance. Similarly resistivity values of each layer of the earth also vary. Resistivity values of some commonly seen earth materials are as shown in Table 2.

Table 2. Resistivity values of earth materials

Composition	**Resistivity (ohm-m)**
Top soil	5-50
Peat and clay	8-50
Clay sand and gravel mixture	90-250
Saturated sand and gravel	40-100
Moist to dry sand and gravel	100-3000
Mud stone and shale	8-100
Sandstone and limestone	100-1000
Crystalline rock	200-10000
Quartz	100
Calcite	500
Dense granite	1000000
Metamorphic rock	100-100000000
Unconsolidated sedimentary rock	10-10000
Gravel and sand with water	100
Fresh water	100
Shale and clay	10
Brine	0.05

(Source: Kurien, et al., 2013)

Based on these resistivity values it is possible to distinguish water bearing materials from the others. Resistivity values of different types of water also differ from each other. Some of these values are shown in Table 3.

Table 3. Resistivity values of different types of water

Different types of water	Resistivity(ohm-m)
Meteoric water (derived from precipitation)	30-1000
Surface water (in districts of sedimentary rocks)	10-100
Ground water (in areas of igneous rocks)	30-150
Sea water	0.2
Ground water (in areas of sedimentary rocks)	More than 1

(Source: Kurien, et al., 2013)

2.3.3 Direct-current (DC) resistivity method

The direct-current (DC) resistivity method for conducting a vertical electrical sounding (i.e. Schlumberger sounding) is effectively used for ground water studies due to the simplicity of the technique, easy interpretation and rugged nature of the associated instrumentation (Ebraheem et al., 1997). Direct-current (DC) resistivity method is used to determine the electrical resistivity structure of the subsurface. The resistivity of a soil or rock is dependent on several factors that include amount of interconnected pore water, porosity, amount of total dissolved solids such as salts and mineral composition (clays) (Rosli *et. al.,*2012).

2.3.4 VLF Electromagnetic method

The VLF(Very Low Frequency) method is applied successfully to map the resistivity contrast at boundaries of fractured zones having a high degree of connectivity. The VLF method yields a higher depth of penetration in hard rock areas because of their high resistivity (McNeill et al., 1991).

VLF data are also useful in determining the appropriate strike direction to perform resistivity soundings (parallel to strike), again improving the likelihood of success.

2.3.5 Resistivity observation methods

Resistivity surveying is the technique used to investigate variations of electrical resistance by causing an electrical current to flow through the ground using wires connected to it (Mussett & Khan, 2000). The various electrical measurements usually measure electrical conductivity or resistivity, the ability of a material to conduct electricity (Schwartz & Zhang, 2003).

There are two types of procedures for making resistivity observations. They are:

1. Resistivity Sounding / Vertical Electrical Sounding(VES)
2. Resistivity Profiling / Horizontal Electrical Profiling.

Resistivity soundings are used to determine the depth to bedrock, while resistivity profiling is to locate the boundaries of a deposit. In resistivity profiling, the location of the spread is changed while maintaining a fixed electrode interval. As the depth of investigation remain unchanged, it is possible to detect the resistivity variation in a horizontal direction.

2.3.5.1 Vertical electrical sounding (VES):

The Vertical Electrical Sounding is common type of investigation in resistivity surveys, which indicates how resistivity varies with depth. A series of potential differences are acquired at successively greater electrode spacings while maintaining a fixed central reference point. The induced current passes through progressively deeper layers at greater electrode spacing. The potential difference measurements are directly proportional to the changes in the deeper subsurface. Apparent resistivity values calculated from measured potential differences can be interpreted in terms of overburden thickness, water table depth, and the depths and thicknesses of subsurface strata.

2.3.5.1.1 Disadvantages of VES

The resistivity sounding technique has the following inherent disadvantages:

1. The resolving power of this method is poor and is particularly true for deeper boundaries.
2. Due to the principle of suppression, a middle layer with resistivity intermediate between enclosing beds will have practically no influence on the resistivity curve as long as its thickness is small in comparison to its depth. Hence the layers with small thickness cannot be recognized.
3. Due to principle of equivalence, conductive layer sandwiched between two layers of higher resistivities will have the same influence on the curve as long as the ratio of its thickness to resistivity (h/p) remains the same.

A resistive layer sandwiched between two conducting layers will have the same influence on the curve as long as the product of its resistivity and thickness. Hence the thicknesses and resistivities of sandwiched layers of small thickness cannot be determined uniquely.

2.3.5.2 Configuration of electrodes

In electrical resistivity method, current is sent into the ground through a pair of electrodes, called current electrodes, and resulting potential difference across the ground is measured with the help of another pair of electrodes, called potential electrodes. There are several types of electrode arrangements (configurations) of which the most popular and commonly used are Wenner Configuration and Schlumberger Configurations

2.3.5.2.1 Wenner Configuration

In the Wenner configuration, potential electrodes are nested within the current electrodes with a equal lateral distance between adjacent electrodes called the electrode spacing ‘a’ (Fig.1). The electrodes in a Wenner array are expanded about a centre point by equally incrementing the spacing ‘a’. The current therefore progressively passes into deeper layers, with the nominal depth of investigation being equal to the spacing ‘a’. This procedure provides apparent resistivity values that are dependent upon vertical conductivity variations of the subsurface.

The geometric factor for the Wenner array is $G(r) = 2\pi a$ and this simplicity of algebraic form as well as in field set up is the merits of this array. The Wenner array generally provides for high signal-to-noise ratios, good resolution of horizontal layers and good depth sensitivity. On the other hand, the Wenner array is not good at determining the lateral location of deep in homogeneities because the large electrode spacing degrades lateral resolution, and the potential electrodes are located within the spread of the current electrodes(Ward, 1990). It is possible to perform limited profiling with the Wenner array by keeping the spacing constant and moving the entire array laterally between resistivity readings. However, investigation depth and resolution are limited for the profiling Wenner array if the *a*-spacing is held constant throughout the entire survey.

The resistance is multiplied by the geometric factor $G(r) = 2\pi a$ to get the value of apparent resistivity (ρ_a)

$$\rho_a = 2\,\pi a\,R, \qquad \text{(Eq. 2.2)}$$

where, Resistivity, $R = \Delta V / I$, ΔV is potential difference and I is the current applied.

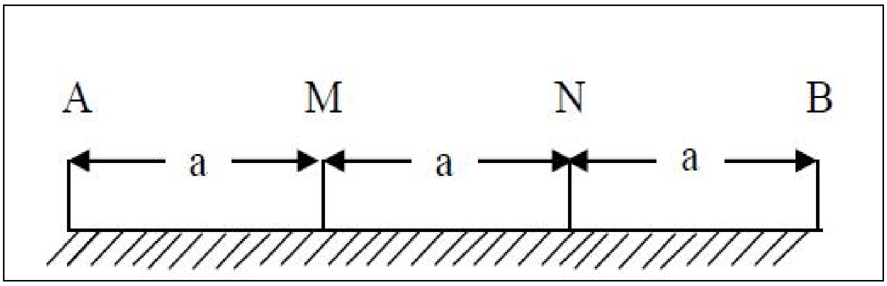


Fig.1. Wenner electrode configuration

2.3.5.2.2 Schlumberger configuration

The Schlumberger array (Fig.2) is similar to the Wenner array having a nested electrode configuration except that the potential electrodes have an internal spacing of *a* and the current electrodes are spaced at an increased distance of *na* from the potential electrodes, where the integer value *n* varies dependent upon target size and depth. The geometric factor is G(r) = $\pi n(n+1)a$, which can be shown to be just a modification of the Wenner array result. The Schlumberger array of electrodes provides for high signal-to-noise ratios, good resolution of horizontal layers, and good depth sensitivity (Ward, 1990).

The apparent resistivity for this configuration is computed with the formula;

$$\rho_a = \frac{\pi\,[(AB/2)^2 - (MN/2)^2]R}{MN} \qquad \text{(Eq. 2.3)}$$

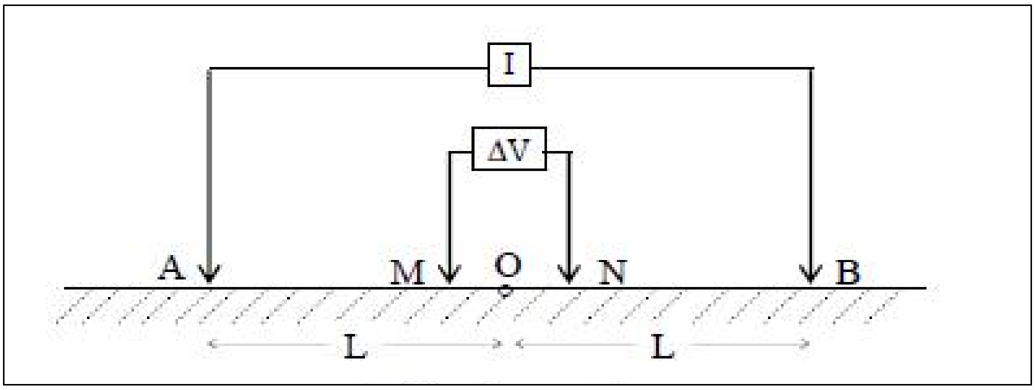


Fig. 2. Schlumberger electrode configuration

Ojelabi *et al.* (2002) have shown that the Schlumberger electrode array provides greater depth of investigation than the Wenner electrode array. The Schlumberger technique is easier to use more than the Wenner technique because only two of the four electrodes are moved between successive readings. A Schlumberger VES survey can be conducted bykeeping the potential electrodes fixed at one location while the current electrodes are extended about a centre point. Only when the current electrodes become relatively far does the potential electrode spacing need to be extended in order to have measurable potentials.

Arshad *et al.* (2007) carried out resistivity survey to study the ground water conditions along the Jhang Branch canal, such as depth, thickness and location of the aquifer and the type of water. Vertical electrical soundings by Schlumberger array were conducted out at 9 locations up to a depth of 200m. The resistivity data confirm that the aquifer consists of an alluvial aquifer. These data were used to determine the lithology and the ground water quality of the aquifer. Interpretation of the VES tests indicates the presence of an alluvial aquifer that mainly consists of sand and clay. The resistivity of the aquifer between 30 to 140 m showed the increasing value, which indicated the existence of fresh ground water. The after 140m and up to 200 m possesses marginally fit quality having larger TDS values than the upper zone.

Ground water exploration in hard rock terrain due to the restricted movement or occurrence of water, remains a challenging task. Resistivity of rock formation gives an indication of ground water occurrence with an established inverse relationship. Gopalan (2011) carried out resistivity surveys in Rajapuram and Balal areas of Kasargod district and have proven successful in demarcating water resources of potential zones and barren zones in the study area. The resistivity values in Balal areas varies from 133 ohm-m to 265 ohm-m and it has a water bearing formation with yield of 3 litre per second. Ground water occurs here in fractures, joints, fissures and weathered zones of massive crystalline rocks. The resistivity values ranging from 621.5 ohm-m to 1795 ohm-m in laterite terrain of Rajapuram area is not having water bearing formation due to the presence of massive bedrock without any fracture zone. Here, all the formations are dry and this site cannot be recommended for bore wells.

Rao *et al.* (2011) studied about the problems and prospects of geophysical methods in identifying ground water potential zones of hard rocks. The case studies of success and failed wells are taken up to identify the efficacy of the various geophysical techniques to identify the aquifers in the khondalitic formation, granitic formation and basaltic formation. Geophysical surveys were conducted at pairs of successful and failed wells covering all the three formations in such a way that the failed well and successful wells are only few meters apart and are in similar hydrogeologic settings. The comparison of geophysical signals at successful and failed wells has revealed that studying of anisotropy by conducting radial vertical sounding is the better strategy to identify the fracture distribution. To produce a good well yield, fracture system must extend in all the four directions which is identified with high values of coefficient of anisotropy or more rounded nature of apparent resistivity polygons while the unidirectional fracture system may not produce the good well yield which is identified with less value of coefficient of anisotropy and less rounded nature of the polygons. Shallow Seismic Refraction method could not be of much help to find the fracture zones. Similarly Very Low Frequency Electromagnetic method is of some use where inclined and nearly vertical fractures present in the granitic terrain and found that this method may not provide much help in the case of khondalitic terrain and Deccan trap terrain where most of the times the terrain is horizontally stratified.

Raut (2012) conducted a study on geoelectrical investigations for shallow water in Balipatna canal command area of Orissa. In this study, sixteen Vertical Electrical Soundings (VES) of Schlumberger configuration and two Wenner configurations were laid out in three villages covering an area of 410 ha. There are five geoelectric layers were found within a depth of 40 m below ground level and data from two points were compared with litholog data of bore holes to assign resistivity values of different strata. Using resistivity fence diagram, the quantity of ground water under shallow aquifer was computed to be around 12.2 ha-m. It was also showed that the quality of ground water was good with low salinity and low alkali hazard by chemical analysis and could be grouped as C_1S_1 under USDA irrigation water quality classification.

Selvam (2012) carried out a study with the aim of demonstrating the application of vertical electrical sounding method of investigation in the exploration for ground water in Pachipenta Mandal and environs. The results of geoelectric investigation carried out over hard rock environment, VES has proved to be very reliable for ground water studies. This method can excellently be used for shallow and deep ground water geophysical resistivity investigations. In this study this method has helped to identify the aquiferous units and has provided an understanding of aquifer dimensions, depth to bed rock and fractured zones which are required for locating points with high potential for ground water occurrence.

Selvam and Sivasubramanian (2012) carried out a geo-electrical resistivity survey using Vertical Electrical Sounding (VES) in Medak District, Andhra Pradesh, India, in order to assess the subsurface geology and ground water potential zones. Twenty six vertical electrical soundings were recorded with Schlumberger electrode configuration with current electrode spacing (AB/2) half ranging from 1 to 150m. The field data has been primarily interpreted using curve matching and electrical imaging software IP2WIN. The curves are prominently of A and H type indicating the presence of three layers followed by combination of curves AK, Ha, KH, HK, AH indicating the presence of five layer subsurface layers. Interpretation reveals the number of subsurface layers, their thickness and their water bearing capacity within the study area. The best layer which acts as the good aquifer of Medak district is the second layer which consist the fracture/ weathered rock formations at the depth between 5 to 15m.

Kumar *et al.* (2013) conducted electrical resistivity surveys in the form of spot Vertical Electrical Soundings (VES) in Manthada landslide area of Nilgiri district, Tamil Nadu, to estimate the thickness of overburden/depth to bed rock. Twenty seven VES using Schlumberger array have been carried out over the study area. Interpretation of the field data suggests three and four layer earth section to exist with thickness varying from 1 m to more than 30 m. The bed rock has resistivity higher than 500 ohm.m. Resistivity lows and highs of the order of a few hundred ohm.m to a few thousands of ohm.m correspond to highly jointed to massive Charnockite rocks respectively. Depth to the bed rock or overburden thickness map reveals that the depth to bed rock is shallow in the western and north western portions whereas it is deep in the southeastern part varying from 2.5 meter to more than 30 meters in the surveyed area. Apparent Resistivity, resistivity pseudo-section and depth to basement rock maps were prepared. The apparent resistivity maps bring out resistivity lows of order 200 ohm.m to 400 ohm.m disposed in NNE-SSW direction indicative of a weak zone which may be prone to landslides. On the other hand, high resistivity trends may indicate a stable land mass of massive charnockite rocks.

Kurien *et al.* (2013) carried out hydro-geophysical investigation of ground water resources in KCAET campus so as to discover a sustainable source of water, to cater the various requirements of the campus. By this study, all possible sites in the campus were explored for the presence of ground water. The project could come to a positive conclusion, whereby potential areas for sustainable water supply were delineated. From the six locations under consideration, three of the locations revealed potential ground water reserves which could be a good source of water to be explored. In one site, near to the Bharathapuzha River filter-point wells may be a possibility. The sites where appreciable discharge can be expected and where tube wells can be installed for ground water extraction are namely: near to the workshop, near to the volleyball court and near to the canteen. So the present project has succeeded in fulfilling its primary objectives and therefore, drilling of tube wells is suggested in the potential sites located.

Brijesh and Balasubramanian (2014) conducted hydro-geological studies and ground water modelling of Bharathapuzha River Basin, Kerala. In this study VES have been conducted at 39 locations in the Kerala part and resistivity survey data collected from Ground water division of Public Work Department of Tamil Nadu State. The results of interpretation of the geophysical data from the basin showed that among the total fifty six VES locations, there are six 5-layer cases, thirty six 4-layer cases and fourteen 3-layer cases. The 3-layer case is representing the laterite, the weathered zone and the basement rock. The 4-layer case might be resulting from the above said three layers overlying by veneer of top soil. The predominance of H-type (central low) curve may be due to the presence of clay layer, the resistivity of which is comparatively low. The results of geophysical data interpretation have been made use of in identifying the ground water zones.

Kurien *et al*. (2016) conducted a hydro-geophysical investigation of ground water resources in coconut garden of College of Horticulture, Vellanikkara to identify potential source of water, to meet the various requirements of the campus. A special technique called 'Resistivity Scanning' is found to successfully delineate the fractured geometry of formation. From the eight locations under consideration, none of the locations could serve as potential ground water sources. Major portion of area was occupied by a continuous layer of crystalline rock formation which extended up to 80m depth. Beyond crystalline rock, there was a layer of continuous metamorphic formation which could not provide sufficient water. By this study, all possible sites in the coconut garden were explored for the presence of ground water. The project could come to a conclusion that, potential areas for sustainable water supply were not available in the coconut garden.

2.4 Estimation of ground water recharge

Viswanathan (1984) developed a model for the estimation of recharge levels of unconfined aquifers which recharged entirely by rainfall at Tomago Sandbeds, Newcastle, Austria. Model that estimates the water table levels from the history of rainfall observations and past water table levels. From the field tests, it was observed that the assumption of variable rates of time dependency of recharge parameters produced better estimates of water table levels compared to that with constant recharge pearameters. It was also observed that considerable recharge due to rainfall occurred on the very same day of rainfall. The increase in water table level was insignificant for subsequent days of rainfall.

Richard and Ken (1996) studied the timing and magnitude of recharge determined by soil moisture balance approach supported by stable isotope data and ground water flow modelling at catchment area of the Victoria Nile basin in central Uganda. The soil moisture balance study, it was observed that the average recharge was 20 mm/yr and was more dependent upon heavy rainfall than total annual volume of rainfall. Stable isotope data suggested that the recharge occurred during the heaviest rainfall of the monsoon and further established that recharge stems entirely from direct infiltration of rainfall. Aquifer flow modelling supported the recharge estimates but demonstrated that vast majority (about 99 %) of recharging water must be transmitted by the aquifer in the regolith rather than underlying bed rock fractures, which has traditionally been developed for rural water supplies.

Cherkauer and Ansari (2005) developed an empirical relation between normalized recharge and readily available climate, topographic and land measures for small watershed in the glaciated terrain of southern Wisconsin. The method is providing a reasonable, but conservative, first approximation of recharge. Stream base flow was measured as a surrogate for recharge in small watersheds in southern Wisconsin. It was equated to recharge (R) and then normalized to observed annual precipitation (P). The empirical relationship for predicting R/P developed for the study watersheds was shown to be statically viable and was then tested outside the study area and against other methods of calculating recharge. The method produces values that were in agreement with base flow separation from stream flow hydrographs.

Israil *et al.* (2006), presents a new approach for the estimation of ground water recharge in the area of a known geological formation. In this study, the ground water recharge estimated using the tritium tagging technique shows that the recharge in the study area varies between 3 and 13%. Conceptually, the vertical recharge depends on the infiltration characteristic of the unsaturated topsoil layer. The physics of the electrical current flow in an unsaturated soil depends upon soil type and its infiltration characteristics. Resistivity of low permeability soil is very low compared with the resistivity of high permeability soil. The average resistivities of the unsaturated topsoil layer were calculated for each site from interpretation of the resistivity data collected in and around the site of interest. A linear relationship was obtained between the resistivity of the unsaturated topsoil layer and the estimated recharge per cent using tritium tagging techniques. This relationship is extremely useful for ground water-resources evaluation and recharges estimation in a particular area of interest and is valid for areas of similar geology.

Kannan (2007) estimated natural ground water recharge of a degraded Western Ghat -terrain using Thornthwaite - Mather water balance method by preparing spatiotemporal distribution of ground water recharge. Penman method and NRCS curve number methods were employed for generating the water balance parameters. Monthly natural recharge varies from 0 to 44 Mm^3, the total annual natural recharge was found as 158 Mm^3. By analysing the infiltration rate, geology, geomorphology, rechargeable depth, slope and drainage density, land use, relative relief, soil depth etc., hydrogeologically potential areas for ground water recharge systems and land slide prone areas were delineated through GIS weighted overlay analysis. Land slide prone areas were excluded from potential recharge areas. 46.78% of total area was found to be favourable for artificial recharge. The most suitable recharge structures suitable for the hard rock hilly terrain viz, check dams, subsurface dykes, recharge wells, runoff harvesting structures are suggested and suitable locations for the specific recharge measures were delineated.

Wang *et al.* (2008), Tritium and bromide were used as applied tracers to determine ground water recharge in Hebei Plain, North China, to evaluate the impacts of different soil types, land use, irrigation, and crop cultivation practice on recharge. Temporal variability of recharge and the effect on results of the particular tracer used is also evaluated. Average recharge rates and recharge coefficient determined by tritium and bromide tracing for different sites were 0.00 to1.05 mm/day and 0.0 to 42.5 per cent respectively. The results showed relative recharge rates for the following paired influences (items within each pair are listed with the influence producing greater recharge first): flood irrigated cropland and non irrigated non cultivation land, flood irrigation (0.42 to

0.58mm/day) and sprinkling irrigation (0.17 to 0.23 mm/day), no stalk mulch (0.56 to 0.80 mm/day) and stalk mulch (0.44 to 0.60 mm/day), vegetable such as Chinese cabbage and garlic (0.70 mm/day) and wheat–maize (0.38 mm/day), peanut (0.51 mm/day) and peach (0.43 mm/day). The results also showed greater recharge for the first year of tracer travel than for the second due to fact that the total precipitation and irrigation were greater in the first year than in the second and this may reflect temporal variability of recharge. The method may not be applicable where the water table is shallow (less than 3 m). A comparison of the near-ideal tritium tracer with the more common but less ideal bromide showed that bromide moved approximately 23 per cent faster than tritiated water, perhaps because of anion exclusion.

Unsaturated flow modelling is increasingly being used to estimate the potential ground water recharge. Review of previous studies found that unit-gradient and fixed water table lower boundary conditions have been applied to models of both constant and variable vertical grid spacing (discretization). Hernandez *et al.* (2012) studied the effect of both discretization and boundary conditions on simulation times and estimated fluxes on the water table, using one dimensional models of 2,4,6 and 12m comprised of sand, sandy loam, loamy sand, and loam. Climatological data from the Boreal plain of North Alberta, Canada is used for this study. Because of the long term water deficit and the thick unconsolidated glacial deposits, unsaturated flow is expected to be vertical, both downward and upward and inter-annual changes in water storage will be more important. Long term simulations (1919-2007) comprised both wet and dry cycles, reveal that when a variable vertical discretization at both the top and bottom of the columns varying from 0.1 to 10 cm is utilized, a balance between simulation accuracy and running time can be achieved.

It is also found that whenever the unsaturated flow modelling approach is used to estimate the potential ground water recharge, a fixed head lower boundary conditions should be selected because it also allows upward flux from the water table during dry periods, a situation that prevails on both sub-humid and semi-arid areas, where accurate ground water recharge estimates are needed the most,. However, it should be kept in mind that the use of fixed water table is a simple representation of the regional water table, which in reality interacts with the regional ground water flux and surface water like lakes and wetlands.

Walter *et al.* (2012) reported that recharge through the intermittent and ephemeral stream channels is believed to be a primary aquifer recharge process in arid and semiarid environments. The intermittent nature of precipitation and flow events in these channels, and their often remote locations, makes direct flow and loss measurements difficult and expensive. Airbone and satellite optical images were interpreted to evaluate aquifer recharge due to stream loss on the Frio river in south-central Texas. Losses in the Frio river are believed to be a major contributor to recharge to the Edwards Aquifer. The results of this work indicate that interpretation of readily available remote sensing optical images can offer important insights into the spatial distribution of aquifer recharge from losing streams. In case of upstream gauging data are available, simple visual analysis of length of the flowing reach downstream from the gauging station can be used to estimate channel losses. In case of the Frio River, the rate of channel loss estimated from the length of flowing reach at low flows was about half of the loss rate calculated from in-stream gain-loss experiments. Analysis based on water surface width and channel slope indicated that losses were mainly in a reach downstream of the mapped recharge zone. The analysis based on water-surface width, however, did not indicate that this method could yield accurate estimates of actual flow in pool and riffle streams, such as Frio River and similar rivers draining the Edward plateau.

2.5 Ground water flow modelling

The use of ground water models is prevalent in the field of environmental science. Models have been applied to investigate a wide variety of hydro-geologic conditions. More recently, ground water models are being applied to predict the transport of contaminants for risk evaluation.

Models are conceptual descriptions or approximations that describe physical systems using mathematical equations. They are not exact descriptions of physical systems or processes. By mathematically representing a simplified version of a hydro-geological system, reasonable alternative scenarios can be predicted, tested, and compared. The applicability or usefulness of a model depends on how closely the mathematical equations approximate the physical system being modelled. In order to evaluate the applicability or usefulness of a model, it is necessary to have a thorough understanding of the physical system and the assumptions embedded in the derivation of the mathematical equations (Kumar, 2015).

Ground water models describe the ground water flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties in the values of data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions. Ground water models, however, even as approximations, are a useful investigation tool that ground water hydrologists may use for a number of applications.

Application of existing ground water models include water balance (in terms of water quantity), gaining knowledge about the quantitative aspects of the unsaturated zone, simulating of water flow and chemical migration in the saturated zone including river-ground water relations, assessing the impact of changes of the ground water regime on the environment, setting up/optimising monitoring networks, and setting up ground water protection zones.

2.5.1 Model development

A groundwater model application can be considered to be two distinct processes. The first process is model development resulting in a software product, and the second process is application of that product for a specific purpose. Groundwater models are most efficiently developed in a logical sequence (http://www.angelfire.com/nh/cpkumar/hydrology.html)

2.5.1.1 Model objectives

Model objectives should be defined which explain the purpose of using a groundwater model. The modelling objectives will profoundly impact the modelling effort required.

2.5.1.2 Hydro-geological characterization

Proper characterization of the hydro-geological conditions at a site is necessary in order to understand the importance of relevant flow or solute transport processes. Without proper site characterization, it is not possible to select an appropriate model or develop a reliably calibrated model.

2.5.1.3 Model conceptualization

Model conceptualization is the process in which data describing field conditions are assembled in a systematic way to describe groundwater flow and contaminant transport processes at a site. The model conceptualization aids in determining the modelling approach and which model software to use.

2.5.1.4 Modelling software selection

After hydro-geological characterization of the site has been completed and the conceptual model developed, a computer model software is selected. The selected model should be capable of simulating conditions encountered at a site. For example, analytical models can be used where field data show that groundwater flow or transport processes are relatively simple. Similarly, one-dimensional/ two-dimensional/ three-dimensional groundwater flow and transport models should be selected based upon the hydro-geological characterization and model conceptualization. (http://www.angelfire.com/nh/cpkumar/hydrology.html).

2.5.1.5 Model design (input parameters)

Model design includes all parameters that are used to develop a calibrated model. The input parameters include model grid size and spacing, layer elevations, boundary conditions, hydraulic conductivity/transmissivity, recharge, any additional model input, transient or steady state modelling, dispersion coefficients, degradation rate coefficients etc.

2.5.1.6 Model calibration

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. Model calibration requires that field conditions at a site be properly characterized. Lack of proper site characterization may result in a model calibrated to a set of conditions that are not representative of actual field conditions.

2.5.1.7 Sensitivity analysis

A sensitivity analysis is the process of varying model input parameters over a reasonable range and observing the relative change in model response. Typically, the observed change in hydraulic head, flow rate or contaminant transport are noted. Data for which the model is relatively sensitive would require future characterization.

2.5.1.8 Model validation

A calibrated model uses selected values of hydro-geologic parameters, sources and sinks and boundary conditions to match historical field conditions. The process of model verification may result in further calibration or refinement of the model. After the model has successfully reproduced measured changes in field conditions, it is ready for predictive simulations.

2.5.1.9 Predictive simulations

A model may be used to predict some future groundwater flow or contaminant transport condition. The model may also be used to evaluate different remediation alternatives. However, errors and uncertainties in a groundwater flow analysis and solute transport analysis make any model prediction no better than an approximation. For this reason, all model predictions should be expressed as a range of possible outcomes that reflect the assumptions involved and uncertainty in model input data and parameter values.

Jain (1998) conducted a study to locate ground water potential zones in Upper Urmil River Basin, Chhatarpur district, Madhya Pradesh using IRS-LISS-II data. Hydro morphological, lineament, lineament density and ground water prospect maps were prepared through visual interpretation of geocoded images on 1:50,000 scale and Survey of India topographical maps of the same scale. The resulting base line information was integrated for evaluating ground water potential of mapping units. The alluvial plain, flood plain, infilled valley and deeply buried pediplain were shown as the prospective zones of ground water exploration and development. Fractures and faults parallel to drainage courses constituted priority zones for ground water targeting.

Kharad *et al.* (1999) developed a GIS based Ground water Assessment Model (GWAM) for ground water assessment. They employed water table fluctuation method and calculated ground water recharge based on norms recommended by the National Ground water Estimation Committee. The parameters they selected include normal monsoon and yearly rainfall data for 20 years, depth to water table for pre and post monsoon, specific yield for zone of water table, geomorphology map, and canal map, irrigation and well data, land use map, water body and other conservation structures and slope map. The data base for the above parameters (spatial and non spatial) was created in ARC INFO. The model GWAM developed in ARC INFO selected the recharge of individual component. Finally, the results of individual components were summed up to arrive at the ground water balance. They concluded that the GWAM model allows engineers and planners to assess the ground water more efficiently and accurately.

Thangarajan *et al.* (1999) developed a model for an inland Delta aquifer system to evolve pre-development management schemes in Upper Thamalakane River valley, Botswana, southern Africa. In this work a preliminary multilayer model was developed for this aquifer system by making use of available data. The hydrodynamic behaviour was studied under two prediction scenarios to evolve appropriate management decisions for locating the well field (large diameter wells) in the upper aquifer by making use of induced river infiltration during the flood season. The aquifer response for variable river-flow conditions was studied in this and the induced river infiltration was quantified.

Reddy *et al.* (2000) evaluated the ground water potential zones in Gaimukh watershed, Bhadra district, Maharashtra using IRS-1C LISS- III geo coded data on 1:50,000 scale. The analysis revealed that the deep valley fills with thick alluvium have excellent, shallow valley fills and deeply weathered pediplains with thin alluvium have very good and moderately weathered pediplains in the geological formations of Tirodi Gneiss and Sausar Groups have good ground water potential and these units are highly favourable for ground water exploration and development. The good inter relationship was found among the geological units, geomorphological units, lineaments density, hydro-geomophological zones and ground water yield data.

Rao *et al.* (2001) identified the ground water potential zones using remote sensing techniques in and around Guntur town, Andra Pradesh. The identified units and features with the integration of conventional information and limited ground truths are shallow weatherd pediplains (PPD), residual hill(RH) and lineaments (L). The results showed that the PPD, PPM and PPS are good, moderate to good and poor to moderate promising zones, respectively for ground water prospecting.

Gawande *et al.* (2002) carried out a detailed study on geology, hydrogeology foe the Kamthi and adjoining areas of district Nagpur by visual interpretation method of remote sensing data of IRS LISS III, FCC of bands 2,3 and 4. They delineated the area with reference to ground water projects into excellent, very good to good, moderate and poor ground water prospect zones. It was observed that the sandstone litho- units form excellent aquifers while the basalt and shale form moderate to poor aquifers respectively.

Sankar (2002) evaluated the ground water potential zones in Upper Vaigai river basin, Tamil Nadu using IRS-ID LISS III geocoded data on 1:50,000 scale. The geology, geomorphology, lineament tectonic maps were generated and integrated to evaluate the hydro geomorphological characteristics of the basin. A number of geomorphic units were observed. Out of this the more ground water prospective units are buried pediment medium, buried pediment deep, flood plain, bajada and lineament and intersection of lineaments. Non-potential areas like pediment, pediment inselberg, shallow pediment and pediplain were identified.

Kinzelbach *et al.* (2003) reported on the sustainability of ground water, they discussed the sustainable related factors such as falling water tables, drying wetlands, increasing sea water intrusion and general deterioration of water quality. They discussed several scientific tools to maintain sustainability in the ground water. They include methods for the determination of ground water recharge, ground water modelling including the estimation of its uncertainity, and the interfacing to the socio-economic field. They also highlighted that the quality of water management work could be largely enhanced with new tools available, including remote sensing, digital terrain models, differential GPS, GIS, environmental tracers, automatic data collection, modelling and the coupling of models from different disciplines.

Kumar and Singh (2003) developed an integrated water management model by combining an unsaturated flow model and a ground water simulation model. The combined model was used as a tool for decision making in irrigation water management to maintain water tables at a safe depth. It was applied to Sirsa Irrigation Circle in the northwestern part of Haryana, India, which is facing the serious waterlogging and salinity problems. The model was used to study the long-term impact of two water management interventions related to the canal irrigation system, namely, (i) the change in pricing system of irrigation water, and (ii) the water supply according to demand on the extent of waterlogging risk. It was found that the water supply according to demand strategy was slightly more effective in reducing aquifer recharge than the water pricing intervention. They claimed that the implementation of the proposed water pricing policy would pose no problem in fitting into the existing irrigation system, and thus it would be easier to implement, compared to the water supply according to demand strategy, when taking technical, financial, and social considerations into account.

Don *et al.* (2004) conducted a study at the Shiroshi site in Japan to simulate ground water hydraulics, land subsidence and solute transport in alluvial low land plain. The study was conducted keeping in mind of various alarming factors like increased water demand on a limited water resource, declining ground water levels, land subsidence and saltwater encroachment. The model combines the ground water flow and solute transport to simultaneously simulate water level and investigate the mechanisms of land subsidence due to ground water overdraft as well as predict transient solute transport. By calibrating the model with ground water level, land subsidence and chloride concentration observed data; the aquifer parameters of the system were estimated. The model outputs agreed well with the observed results. The river package is applied to account for this feature. In addition, the drain package is used to take into account the features of drained agricultural areas. The average recharge amount from paddy fields to ground water was estimated to be 7.0 mm/day during the growing season of crops from June to September as a result of a surface water balance model which balance the available amount of surface water supply to irrigation from rainfall, ground water, river, pond and creek, and the consumed amount by evapotranspiration, runoff, and infiltration.

Ezzy *et al.* (2006) modelled ground water flow within a coastal alluvial plain setting using a high-resolution hydrofacies approach in Bells Creek plain, Australia. In this study Ground . penetrating radar (GPR) has been used in conjunction with direct geological data, to develop a model of aquifer. Finite difference ground water modelling conducted in this study not only enabled determination of the dominant ground water flow paths for the plain, but has also quantified the effects of within-facies and between-facies sedimentary heterogeneity on those flow paths.

Gates *et al.* (2006) developed a finite difference model using Ground water Modelling System (GMS) software package to analyze and predict water table elevations and salinity, flow of water and salts in and between the shallow aquifer, the river and the irrigation-drainage system. The model was applied in the salinity threatened lower Arkansas river basin of Colorado. They simulated seven scenarios viz., base-line conditions (average conditions measured), increase pumping rates by 20 per cent and 33per cent, reduce recharge rate by 20per cent and 33per cent, increase pumping rate by 20 per cent and reduce recharge rate by 20 per cent and increase pumping rate by 33 per cent and reduce recharge rate by 33 per cent. Preliminary steady-state modelling indicates that only limited improvement can be expected from vertical drainage derived from increased pumping or from decreased recharge.

Uddameri *et al.* (2007) used Simulation-optimization approach to assess ground water availability in Refugio County. A simulation model characterizing ground water flow in the shallower unconfined and the deeper semi-confined formations of the Gulf coast aquifer was calibrated and evaluated in this study.

The model results were used in conjunction with a mathematical programming scheme to estimate maximum available ground water in the county. The model results from the study indicate that roughly 4.93 - 107 m^3 of water can be extracted in a typical year and the management model was noted to be very sensitive' to the imposed saltwater intrusion constraint.

Reta (2011) calibrated a 3-D transient ground water model to simulate the long term ground water and lake water balance of Naivasha basin that could be utilized to evaluate the effects of changes in system flux over time. The analysis starts with GPS measurement to accurately estimate height of surface water and ground water levels. Time series data were analyzed on a monthly basis which includes Lake water level, surface water inflow, evaporation and precipitation. Recharge was estimated by analyzing monthly changes in ground water level and average recharge measured in the area. The model design spans over 79 years (1932-2010) with a total of 942 stress periods and a single time step. A long term water budget is calculated reflecting all water flow in to or out of the regional aquifer. The inflow component include recharge 2.8x 10^6 m^3/month, river seepage in 1.4x10^5 m^3/month and lake seepage in 5.56x10^6 m^3/month. The outflow includes well abstraction 7.5 x 10^5 m^3/month, river leakage out 2x 10^4 m^3/month lake seepage out 1.1x10^6 m^3/month. The overall results indicate that Naivaisha basin is in equilibrium with a net outflow which is greater by 1% than the inflow.

Dong *et al.* (2012) conducted a case study of regional ground water flow in the Pinggu basin, Beijing, China. It is demonstrated that the ARD (areal recharge and discharge) method can efficiently simulate really distributed precipitation recharge, multilayer pumping wells discharge and irrigation infiltration recharge to the ground water system simultaneously. The basin, comprised of one unconfined and three confined aquifers according to the hydrogeological data and which has a good ground water supply capacity due to large precipitation recharge and lateral runoff recharge from surrounded mountains. There are 1209 pumping wells in the agricultural irrigation regions, accounting for over 80 percent of the total study area. The discharge of average extracted ground water volume of $25x10^8$ m^3 per year for agricultural purpose, while the irrigation return coefficient, defined as the ratio of the return recharge to the total discharge, is 0.14–0.18 according to different soil types and hydrological conditions. The average precipitation is 624.7 mm/year and the effective infiltration coefficient ranges from 0.18 to 0.25. With the benefit of the ARD method, water budgets of precipitation recharge, irrigation return recharge, agricultural pumping, industrial and domestic pumping were calculated easily.

2.5.2 MODFLOW

MODFLOW is a modular finite-difference ground water flow model developed by the U.S. Geological Survey (USGS) and also a computer program for simulating common features in ground-water systems (McDonald and Harbaugh,1988). The program was constructed in the early 1980's and is continuously used for the development of many new packages and related programs for ground water studies and most widely used program in the world for simulating ground water flow. The popularity of the program is attributed to the following factors:

- The finite-difference method used by MODFLOW is relatively easy to understand and apply to a wide variety of real- world conditions.
- MODFLOW works on many different computer systems ranging from personal computers to super computers.
- MODFLOW can be applied as a one dimensional, two dimensional, or quasi- or full three - dimensional model.
- Each simulation feature of MODFLOW has been extensively tested.
- Data input instructions and theory are well documented.
- The modular program design of MODFLOW allows for new simulation features to be added with relative ease.
- A wide variety of computer programs written by the USGS, other federal agencies, and private companies are available to analyze field data and

construct input data sets for MODFLOW.

- A wide variety of programs are avail- able to read output from MODFLOW and graphically present model results in ways that are easily understood.
- MODFLOW has been accepted in many court cases in the United States as a legitimate approach to analysis of ground-water systems.

MODFLOW is to simulate saturated flow through a layered porous media. The partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad \text{(Eq. 2.4)}$$

Where, K_{xx}, K_{yy} and K_{zz} are defined as the hydraulic conductivity along the X, Y and Z coordinate axis, h represents the potentiometric head, W is the volumetric flux per unit volume being pumped, S_s is the specific storage of the porous material and t is time.

MODFLOW is designed to simulate aquifer systems in which

1. Saturated - flow conditions exist
2. Darcy's law applies
3. The density of ground water is constant, and
4. The principal directions of horizontal hydraulic conductivity or transmissivity do not vary within the system.

These conditions are met for many aquifer systems for which there is an interest in analysis of ground water flow and contaminant movement. For these systems, MODFLOW can simulate a wide variety of hydrologic features and processes. Steady state and transient flow can be simulated in unconfined aquifers, confined aquifers, and confining units. A variety of features and processes such as rivers, streams, drains, springs, reservoirs, wells, evapotranspiration, and recharge from precipitation and irrigation also can be simulated. At least four different solution methods have been implemented for solving the finite-difference equations that MODFLOW constructs. The availability of different solution approaches allows model users to select the most efficient method for their problem (Leake, 1997).

The most widely-used ground water flow model in the world, MODFLOW can simulate external flow stresses such as wells, areal recharge, evapotranspiration, drains and rivers with a set of stress packages (Harbaugh, 2005). According to the different characteristics, these packages can be classified into three categories, point, line and area features. The well (WEL) package can simulate specified recharge or discharge point feature such as wells. The general head boundary (GHB) package, the river (RIV) package and the drain (DRN) package usually represent line features of inflows and outflows to a ground water system. Area features such as precipitation, plant transpiration and direct evaporation can be simulated with the recharge (RCH) package and the evapotranspiration (ET) package, respectively.

2.5.2.1 Application of MODFLOW

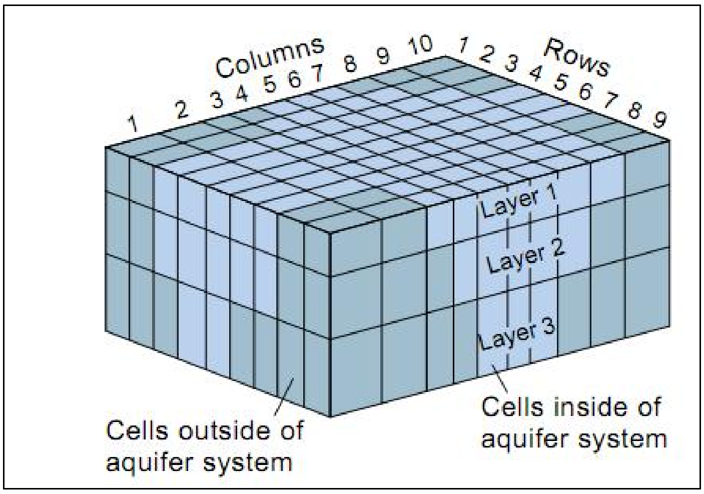
MODFLOW simulates ground water flow in aquifer systems using the finite difference method. In this method, an aquifer system is divided into rectangular blocks by a grid (Fig.3). The grid of blocks is organized by rows, columns and layers and each block is commonly called a “cell” (Leake, 1997).

2.5.1.2 Model input

For each cell within the volume of the aquifer system, the user must specify aquifer properties, information relating to wells, rivers and other inflow and outflow features for cells corresponding to the location. For example, if the interaction between a river and an aquifer system is simulated, then for each cell traversed by the river, input information includes layer, row and column indices, river stage and hydraulic properties of the river bed (Leake, 1997).

2.5.1.3 Model output

MODFLOW uses the input to construct and solve equations of ground-water flow in the aquifer system. The solution consists of head (ground-water level) at every cell in the aquifer system (except for cells where head was specified as known in the input data sets) at intervals called "time steps." The head can be printed and (or) saved on a computer storage device for any time step. Hydrologists commonly use water levels from a model layer to construct contour maps for comparison with similar maps drawn from field data. They also compare computed water levels at individual cells with measured water levels from wells at corresponding locations to determine model error. The process of adjusting the model input values to reduce the model error is referred to as model calibration(Leake, 1997).



Source: (Leake, 1997).

Fig. 3. Model grid for simulating three- dimensional ground water flow.

In addition to water levels, MODFLOW prints a water budget for the entire aquifer system. The budgets lists inflow to and outflow from the aquifer system for all hydrologic features that add or remove water. Other program output consists of flow rates for each model cell. MODFLOW can write the flow rates onto a computer storage device for any hydrologic feature in a simulation (Leake, 1997).

2.5.3 Visual MODFLOW

Visual MODFLOW is the proven standard for professional 3-D ground water flow and contaminant transport modelling. Visual MODFLOW combines the most powerful and intuitive interface available with the latest versions of MODFLOW, MODPATH, Zone Budget and MT3D. Visual MODFLOW can be applied to evaluate ground water remediation systems, delineate well capture zones, simulate natural attenuation of contaminated ground water, estimate the reductive dechlorination of Trichloroethylene and Polychloroethylene in ground water, design and optimize pumping well locations for dewatering projects and determine contaminant fate and exposure pathways for risk assessment. The Visual MODFLOW interface has been specifically designed to increase modelling productivity and decrease the complexities typically associated with building three-dimensional ground water flow and contaminant transport models. The interface is divided into three separate modules viz.., Input Module, Run Module and Output Module

The ground water flow in the aquifer adjacent to the lower River Sieg, a tributary of the River Rhine, is located on the northern bound of the Rheinische Schiefergebirge, Germany, could be successfully simulated for steady-state and transient conditions using the finite difference model MODFLOW and MODPATH (Michl, 1996). The derivation of the conceptual model was obtained combining the raster-based GIS IDRISI with PROCESSING MODFLOW and MODFLOW. The GIS based data model permits fast presentation and improved interpretation of the models input and output. In a second step, the MODFLOW modules RIV and STR1 were applied to delineate areas of different river bank seepage and the results were compared to existing data. The applied methodology enabled a fast evaluation of a really distributed grid-based infiltration rates.

Asghar *et al.* (2002) used two ground water models namely, MODFLOW and MT 3D to model the interface movement in an unconfined aquifer of Punjab, Pakistan. The results indicated that skimming wells of 10-18 L/s can be installed and operated successfully with 60-70% well penetration ratio for an operating time of 8-24 h/day from an unconfined aquifer having 15-18 m thick relatively fresh ground water lens. Extraction of water with skimming wells from inappropriate depths and rates will cause upcoming of the interface between the relatively fresh ground water lens and salty ground water.

Osman and Bruen (2002) studied seepage from a stream, which partially penetrates an unconfined alluvial aquifer when the water table falls below the stream bed level. A simple and improved method of incorporating seepage into ground water models was presented. They considered the effect on seepage flow of suction in the unsaturated part of the aquifer below a disconnected stream and allowed for the variation of seepage with water table fluctuations. The technique was incorporated into the MODFLOW and was tested by comparing its predictions with those of a widely-used.variably saturated model, SWMS_2D, (model for simulating water flow and solute transport in two-dimensional variably saturated media). Comparisons were made for both seepage flows and local mounding of the water table. It was concluded that the suggested, technique compares very well with the results of SWMS_2D.

Bakker (2003) presented a formulation for the modelling of seawater intrusion in coastal multi-aquifer systems starting from a specified salinity distribution. The Dupuit approximation was adopted, and diffusion and dispersion were not taken into account. The formulation was based on a vertical discretization of the ground water into zones of either constant density (stratified flow) or continuously varying density (piecewise linear in the vertical direction). The zones were separated from each other by curved surfaces, representing interfaces for stratified flow and iso-surfaces of the density for variable density flow. During simulation both the change of the elevations of the surfaces and the change in head were computed through consistent application of continuity of flow; a simple tip and toe tracking algorithm was applied to simulate the horizontal movement of the surfaces. The resulting differential equations were equivalent to the differential equation for single-density flow. The density effects were incorporated through the addition of pseudo-source terms. This makes it easy to implement the formulation in existing numerical ground water codes. The main advantage of the formulation is the tremendous reduction of the number of cells needed for a simulation because every aquifer may be represented by a single layer of cells. The accuracy of the formulation was demonstrated through comparison with existing exact solutions and a numerical solution.

Lin and Medina (2003) incorporated the transient storage concept in modelling solute transport in the conjunctive stream-aquifer model. Three well-documented and widely-used USGS models were coupled to form the core of this conjunctive model: (i) MODFLOW for simulating ground water flow in the aquifer, (ii) DAFLOW for computing unsteady stream flow and for simulating stream-aquifer exchange, and (iii) MOC3D for simulating solute transport in the ground water zone. In addition, an explicit finite difference package was developed to incorporate one-dimensional transient storage equations for solute transport in streams. The quadratic upstream interpolation algorithm was employed to improve the accuracy of spatial differencing. An adaptive stepsize control algorithm for the Runge-Kutta method was used to increase overall model efficiency. The modelling results indicated that the conjunctive stream-aquifer model with a transient storage can effectively handle the bank storage effect during flooding event.

Mohan *et al.* (2003) presented combined simulation-optimization approach for saltwater intrusion control. In this study an attempt has been made to solve a problem associated with the intrusion of saltwater in the Thiruvanmiyur-Kovalam aquifer along the Chennai coast by developing a combined simulation optimization methodology. As a result of continuing pumping for domestic purpose, saltwater from sea has intruded into the aquifer, which has made the ground water in some part of aquifer getting polluted and thus becomes useless for domestic purpose. In order to prevent further spreading of the saltwater into the aquifer, a simulated annealing optimization method is combined with a numerical simulation model, to obtain an optimal pumping strategy. The Visual MODFLOW is used for flow simulation. The optimization coding and interfacing program has been written in Matlab. The results proved that the combined approach offer a better and viable solution for ground water management problems

Kumar and Elango (2004) developed a ground water model MODFLOW to assess the effect of a subsurface barrier on ground water flow in the Palar river basin, Tamil Nadu. In order to meet the ever-increasing demand for ground water since the nearby nuclear power station is using significant quantity of ground water therefore a subsurface barrier/dam was proposed across Palar river to improve the ground water potential. It predicted the ground water levels would increase by 0.1-0.3 m at a distance of about 1.5 – 2 km from upstream side and a decline of 0.1 -0.2 m on the downstream side.

Sivakumar *et al.* (2006) developed a numerical model for South Chennai coastal aquifer to understand the behavior of systems with changes in hydrological stresses. It simulated the effect of increase in pumping and changes in rainfall pattern. This study was carried out to develop a numerical model for the area in order to understand the behavior of the system with the changes in hydrological stresses. The conceptual model of the hydro geologic system was derived from geology, borehole lithology and water level fluctuations in wells. Ground water of the study area was found to occur in both alluvial formations and in the underlying weathered rocks was conceptualized as an unconfined single layered system. The finite difference computer code MODFLOW (Modular 3-d finite difference flow) with Ground water Modelling System (GMS) as pre and post processor was used to simulate the ground water flow in this study. Simulation was carried out from the year 2000 assuming the initial ground water level measured from about 28 wells located in the area. Aquifer parameters were estimated from about five pumping tests carried out by the government agencies. The K and S values determined from these tests ranged from 25 to 75m/day and 0.17 to 0.23 respectively. The model developed was initially calibrated with steady state run and later by transient state. The model input parameters namely the K and S values were varied by about 10 per cent during calibration. The simulated ground water head values compare reasonably with the observed trends. The model was later used to simulate the effect of increase in pumping and the changes in the rainfall pattern.

Arshad *et al.* (2007) carried out a study to measure and assesses the recharge contribution of a distributory of canal in Pakistan for crop irrigation using ground water flow model. This study was carried out because of increasing ground water demand by various crops specially wheat and rice, which consume the maximum quantity of water. With the increase in consumption of these crops and to cater the necessity of water by these crops heavy pumping is being carried out. Therefore assessment of recharge through distributary was carried out using a ground water flow MODFLOW model, which utilized the observed water table, climatic, crop and soil for a period of about 1 year in addition to hydraulic conductivity, evapotranspiration and aquifer characteristics data. The requisite primary data for MODFLOW were collected from field and secondary data from public sector organizations dealing with water. Model calibration involved changing input parameters within reasonable limits until acceptable matches were obtained between the observed and simulated water levels for all observed hydrographs. The external inputs such as, recharge through irrigation, precipitation, stresses due to evaporation, lateral flow and stream were simulated to calculate the monthly water budget of aquifer. As concluded, recharge contribution was 16.5 per cent of the inflow rate of the distributary. Using predicted results of the model a relationship between recharge (R) and discharge (Q) was also developed.

Rejani *et al.* (2008) developed a 2 D ground water flow and transport model of the Balasore coastal ground water basin in Orissa using the Visual MODFLOW package for analyzing the aquifer response to various pumping strategies. This region of orissa is under a serious threat of overdraft and seawater intrusion. The overexploitation resulted in abandoning many shallow tube wells in the basin. The main intent of this study is the development of a 2-D ground water flow and transport model of the basin. A model was simulated to assess, the ground water response to five pumping scenarios under existing cropping conditions. The results of the sensitivity analysis indicated that the Balasore aquifer system is more susceptible to the river seepage, recharge from rainfall and interflow than the horizontal and vertical hydraulic conductivities and specific storage. The final results comes up with wise management strategy saying that if the reduction in the pumpage from the second aquifer by 50 per cent in the downstream region and an increase in the pumpage to 150 per cent from the first and second aquifer at potential locations.

Wang *et al.* (2008) carried out a study at North China plain (NCP) for estimating water budget and recharge rate by using MODFLOW and geographic information system. The aim of the study is to check the ground water usage pattern based on recharge and discharge quantity. Therefore study area was generalized to a conceptual hydrologic model which was three layers, heterogeneous, horizontal isotropy, and three dimensional, transient. On the basis of the conception model, a numeric model was set up. The model was calibrated through fitting calculated value with observed value. The results of model were in accordance with the practical hydro geologic conditions. And the water budgets of North China Plain showed that the total recharge was 49,374 x 10^6 m^3 and the total discharge was 56,530 x 10^6 m^3 during the simulation period, the difference was -7,156 9 106 m^3. This verified that the ground water in the NCP was over-exploited and the water crisis is serious. For the shallow aquifer of the NCP the precipitation recharge was the main recharge source and it was 34,220 x 10^6 m^3 accounting for 75.15 per cent of all recharge in 2002 and 2003. And the evaporation is the main discharge of shallow aquifer accounting for 24.71% of all discharge in 2002 and 2003. For the deep aquifers of the NCP artificial pumping is the major discharge. That was the main reason led to series of water environment problems.

Zume and Tarhule (2008) used a visual MODFLOW, numerical ground water flow model to evaluate the impacts of ground water exploitation on stream flow depletion in the Alluvium and Terrace aquifer of the Beaver-North Canadian

River (BNCR) in Oklahoma, USA. Using MODFLOW's stream flow routing package, pumping-induced changes in base flow and stream leakage were analyzed to estimate stream flow depletion in the BNCR system. Simulation results indicates that ground water pumping has reduced base flow to streams by approximately 29 per cent and has also increased stream leakage into the aquifer by 18 per cent for a net stream flow loss of 47 per cent. The magnitude and intensity of stream flow depletion, however, varies for different stream segments, ranging from 0 to 20,804 m^3d^{-1}.

Kushwaha *et al.* (2009) presents the results of a mathematical ground water model developed for the northern part of mendha sub-basin in the semi arid region of northeastern Rajasthan, employing conceptual ground water modelling approach. For this purpose, Ground water Modelling Software (GMS) was used which supports the MODFLOW-2000 code. For the purpose of modelling the Source/Sink Coverage, Recharge Coverage, Extraction Coverage, Return Flow Coverage and soil Coverage were considered. The model was calibrated against the historical and observed water level data for periods 1998 to 2003 and 2003 to 2005 respectively. The model was calibrated using observed water level data collected during the study period, so that model is capable of producing field measured heads and flow. The model was run to generate ground water scenario for a 15 year period from 2006 to 2020 considering the existing rate of ground water draft and recharge. The water budget predictions indicate a decrease from 349.50 to 222.90 MCM in the ground water storage system, whereas ground water abstraction shows an increase from 258.69 to 358.74 MCM per annum. The predicted water table contour map for the years 2007, 2015 and 2020 have also been generated.

Nimmer *et al.* (2010) worked on contaminant transport beneath an infiltration basin by using MT3D model simulation of tracer transport. This simulation model showed mound formation to cause more rapid tracer movement away from the basin compared to the natural gradient, and advection was shown to be the dominant transport process in the flow direction. This study used a combination of the numerical one-dimensional HYDRUS model and the three-dimensional MODFLOW model to predict water table mound formation, and the numerical model MT3D to assess the potential for contaminant transport beneath a storm-water infiltration basin. Results from this study indicate that although the unsaturated zone was thin and comprised of coarse material, an attenuation of recharge by approximately two hours justified the need to couple an unsaturated model HYDRUS-1D with MODFLOW. Mounding caused more rapid spreading of contamination added to the basin. Mounding decreased the arrival time of peak contaminant concentration by approximately 14 and 7.5 h at 10 and 20 m, respectively, down gradient of the basin center, and by approximately 158 h at 20-m side gradient of the basin. Dispersion influenced contaminant transport in the transverse direction, while advection was the dominant transport process in the direction of flow.

Rajamanickan and Nagan (2010) conducted a study on ground water quality modelling of Amaravati river basin of Karur District, Tamil Nadu, using visual MODFLOW. This study area is severely polluted with discharge of partially treated effluent by the texti1 bleaching and dying units. About 14600 m^3 of coloured effluent with total dissolved solids (TDS) of 5000 to 10000 mg/l is let into the river daily. This study concluded that the discharge of untreated or partially treated effluent had severely affected the ground water quality and this practice continues it will create further deterioration of the ground water quality. There will be an improvement in the quality of ground water over a period of 15 years when the units go for zero discharge to the river. There is no comparable improvement in the quality of ground water if the effluent is treated to 2100 mg/l.

Post (2011) presented a new package, periodic boundary condition (PBC) package into MODFLOW to overcome the difficulties encountered with tidal boundaries in modelling coastal ground water system. It highlights the boundary condition for head and concentration during simulations and allows for development of seepage face. This new package was developed for MODFLOW and SEAWAT. This package is primarily designed for handling dynamic boundary conditions due to tides, but other types of water level fluctuations, like sea level rise, can also be incorporated. Boundary conditions are assigned to the nodes at the sediment air or sediment water interface depending on a user-defined tidal signal. Any number of tidal constituents can be included.

Saghravani and Mustapha (2011) investigated the movement of phosphorous pollution which is leachate to ground water in Seri Petalling Landfill. Visual MODFLOW was used to predict subsurface and surface migration of pollution within 10 years. The results of sample analyzing of phosphorous has shown its concentration in place of landfill was 2.38 mg/l since the National Water Quality Standard for Malaysia defined the maximum value of phosphorous in ground water for Class IIA/IIB and III at 0.1 and 0.2 mg/l respectively. The prediction show phosphorous migrated widely to further places such as river and it has adverse effect on environment, animal and human.

Kambhammettu *et al.* (2012) conducted a study on Effect of Elevation Resolution on Evapotranspiraion Simulations using MODFLOW and which aims at utilizing the increasingly available high resolution DEMs for effective simulation of evapotranspiration (ET) in MODFLOW as an alternative to grid refinement techniques. The source code of the evapotranspiration package of the modified by considering for a fixed MODFLOW grid resolution and for different DEM resolutions, the effect of variability in elevation data on ET estimates. Piezometric head at each Dem cell location is corrected by considering the gradient along row and column directions. Applicability of the research is tested for the lower Rio Grande (LRG) basin in southern New Mexico. The DEM at 10 m resolution is aggregated to resample DEM grid resolutions which are integer multiples of MODFLOW grid resolution. Cumulative outflows and ET rates are compared at different coarse resolution grids. Results of the analysis conclude that variability in depth-to-ground water within the MODFLOW cell is a major contributing parameter to ET outflows in shallow ground water regions. DEM aggregation methods for the LRG Basin have resulted in decreased volumetric outflow due to the formation of a smoothing error, which lowered the position of water table to a level below the extinction depth.

Lachaal *et al.* (2012) developed an integral methodology to investigate hydrological and ground water properties, in ZeramdineBeni Hassan Miocene aquifer system in East- central Tunisia in a semi-arid region, from geological, geophysical and hydro chemical studies in the region using MODFLOW 2000 with GIS tools. A 3D ground water flow model was developed using available geological and hydrological data. The model was calibrated and validated with data sets of 1980–2007 periods. Results of the ground water dynamics simulation of the study aquifer show that calculated water levels are close to the observed values. The hydraulic conductivity and the aquifer water balance are deduced from the steady state. The porosity, specific storage, and ground water reserve evolution are deduced from the transient simulations.

Malik *et al.* (2012) carried out a study in Gurgaon district which is about 32 km from New Delhi, the national capital of India. The study area is divided into 102 column and 66 rows wherein each grid has 570.03 m in length and 570.03 m in width. Using the information of 75 observation wells and input of model parameters viz. storage coefficient (0.011) and effective porosity (0.16) were given and transmissivity was specified as the model calculated value. MODFLOW model was calibrated to match the observed draw downs with model calculated draw downs using different values of aquifer parameters. Using this calibrated model and water balance inputs of 35 years averaged over five year period, recharge, pumping, balanced water as well as horizontal exchange at various time developmental stages and potential were estimated. Calibrated and validated model was used to find out 1974 to 2008 period as well as for future predictions at 2025 and 2050. Existing water was analyzed to understand different component of water pumping, recharge and change in water levels. Various scenarios viz. normal rainfall and no-pumping, roof top water harvesting with recharge and water conservation structure recharge were formulated for sustainable planning and management.

Kelson (2012) conducted a study on Predicting Collector Well Yields with MODFLOW and this study demonstrated that it is possible to predict the yield for radial collector wells given the operating drawdown in the well, using a MODFLOW model based on the dupuit assumption. The solution presented here is appropriate for estimating the yield of collector wells, and may be extended in a similar manner to angled wells, horizontal wells, drains or galleries. In addition, this method is suitable for the implementation of discharge- specified wells, including the effects of head losses due to friction within the laterals as flow moves to the caisson.

Lakshmipriya and Narayanan (2015) conducted a study on groundwater modelling of aquifers using Visual MODFLOW to reveals the suitability of MODFLOW software under various hydrogeologic conditions. They concluded that the Visual MODFLOW software is suitable to simulate and predict the aquifer conditions and to represent the natural groundwater flow in the environment, to forecast the outcome of future groundwater behavior, to simulate hydraulic heads and ground water flow rates within and across the boundaries of the system and to simulate the concentrations of substance dissolved in ground water.

Niranjana (2015) conducted a study on effect of land use / land cover change on groundwater contamination in the coastal area of Ernakulam District, Kerala. This study suggested that the AHP-DRASTIC model was used for prioritization of vulnerable areas in order to prevent the further pollution to already more polluted areas. Water quality data collected from different localities are used in conjunction with multivariate statistical technique (factor analysis) to identify key variables. Spatial variation map was prepared using Q-mode analysis in SPSS and Arc GIS software. During post monsoon season, areas of Munambam, Njarakkal, Malipuram, Edavanakkad, Vyppin, Palluruthy and Chellanam areas are highly vulnerable to pollution. But during Pre monsoon season more areas in the coastal areas other than the above areas are extremely highly vulnerable to pollution. It was found that Chellanam area is mostly affected by contamination during pre monsoon and post monsoon. A numerical model for groundwater flow and contaminant transport was developed in transient state using MODFLOW2000 and SEAWAT. Parameters of these models were estimated. The water table contour map and flow direction map showed that at certain locations of the study area such as Munambam, the chance of salt water intrusion is high. The extent of saltwater intrusion is up to a limit of 1.7 km from the coast of the study area during the years 2015, 2020 and 2025. The wells beyond this limit are not affected by saltwater intrusion. Groundwater in this zone is already contaminated due to saline water and any groundwater development activity in the region needs to be carefully planned with remedial measures in order to reduce the further intrusion of seawater.

2.6 Studies on Kadalundi river basin

Prasad *et al.* (2007) evaluated the ground water development prospects in Kadalundi river basin. In their study, the pattern of water level fluctuation in different physiographic regions, the depth to water level and saturated thickness in different seasons, the hydrogeological properties of the rocks within the basin, the ground water assessment, the ground water quality, etc were studied. The annual ground water availability has been estimated as 108 MCM and the gross annual ground water draft has been estimated as 44.7 MCM for the Kadalundi Basin. The stage of ground water development has been computed as 41%. There is no significant rise or fall of water levels during both the pre-monsoon and post-monsoon intervals in the basin. Considering the stage of development and the trend of water levels, it has been categorised that the Kadalundi Basin is 'SAFE' for future ground water development.

They also reported that in coastal low land region no serious saline water intrusion problem with in the basin. However, since there is a possibility of saline water intrusion especially during peak summer, future ground water development in the coastal region should be taken up with caution. Consequently, a well planned programme of ground water development to meet both drinking and irrigation water requirements (with the former being given greater priority) can be safely initiated in Kadalundi river basin to optimally utilize the ground water potential and at the same time ensure that the ground water development is both sustainable and has no adverse environment impacts.

Harikumar and Kokkal (2010) conducted an environmental monitoring programme on water quality of Kadalundi river basin. From the seasonal monitoring of water quality of Kadalundi river basin, the following salient features can be drawn:

- Water quality problems of Kadalundy basin was mainly associated with pH, conductivity, colour, turbidity, chloride, hardness, sulphate, iron, dissolved oxygen and faecal contamination.
- One of the hot spot identified was Kottakkadavu; the reason can be attributed to waste dumping, lime shell trade and increased human activities.
- One of the major problems faced by both surface and ground water sources of the basin was seawater intrusion, mainly in the downstream stretch of the river.
- Excess iron was found to be a major problem in surface water samples.
- Sulphate problem was observed in the retting areas of the basin (Kadalundi estuary & Kottakkadavu)
- The ground water sample collected from Melattor is found to be highly contaminated.

Anitha *et al.* (2012) conducted hydrological studies of Kadalundi wetland in relation to the drainage basin. The Basin- wide Holistic Integrated Water Assessment (BHIWA) model developed by International Commission on Irrigation and Drainage (ICID) was made use of to simulate the water balance of the Kadalundi basin, as well as to analyse the impacts of land and water use on return flows of this basin. Four water situation indicators were propounded in the model to depict the level of water use (withdrawals) and potential risks (due to return flows) to water quality. The model has been conceived mainly to address the issues of water use under the three sectors namely water for nature, water for people and water for food. The following are the major conclusions:

- The annual total input to the surface water system is 896.05MCM in which surface water runoff due to rainfall contributing 673.96 (75.2 per cent of the total). It is also seen that, the annual total yield from the surface water system is 896. 05(same as the input) with surface water withdrawal to meet irrigation use accounting for 14.98 MCM (about 1.7 per cent of the total).
- The annual total input to the ground water system is 258.81 MCM with ground water recharge due to rainfall contributing 224.65 MCM (87 per cent of the total), and the return flow from ground water supplied to meet irrigation use is 34.16 MCM (13.2 per cent of the total).
- The total evapotranspiration from the watershed is 470.48 MCM, in which 176.86 MCM (37.6 per cent of the total), 293.63 MCM (62.4 per cent of the total) are the evapotranspiration losses for the nature and food sectors respectively. There is no evapotranspiration loss for the people sector.
- For the present and past situation the Indicator 1 (for surface water withdrawal) is 0.01 and 0.02 respectively which is less than 0.2 (limiting value) which in turn indicates that the basin is not stressed at all in present and past. A value of 0.41 in the future foresees a highly stresses basin. Indicator 2 for the past and present situations shows that the basin is under low stress. Future seems to be highly stressed. The past and present are low stressed as far as indicator three is concerned; future is highly stressed with a value of 0.54. As per indicator 4, which pertains to ground water quality, past and present are low stressed and future is moderately stressed with a value of 0.36.

CHAPTER 3

MATERIALS AND METHODS

Ground water is a vital natural resources and the availability as well as its quality are very critical to the existence of life. The demand for ground water is increasing every year and in order to meet this increasing demand, proper understanding of the ground water condition, in terms of availability and distribution is very important. The objective of the present research was to model the ground water resources flow processes of Kadalundi river basin and to map the basin using Visual MODFLOW. A river basin is a natural integrator of all hydrological processes pertaining to its boundaries and may be considered as the physical unit for planning optimum development of land and water resources. Kadalundi river basin is taken as study area for this research work and the materials and methods adopted for the study are briefly discussed in this chapter.

3.1 General features of the study area

3.1.1 Location

Kadalundi river originates from the Western Ghats at the western boundary of Silent Valley and flows through the district of Malappuram. Location map of the Kadalundi River basin is shown in Fig. 4. It is formed by the confluence of its two main tributaries, Olipuzha and Veliyar (Plate 2). The Olipuzha takes its origin from the Cherakkomban mala at an elevation of 1160 m above MSL and Veliyar originates from the forests of Erattakomban mala at an elevation of 1190 m above MSL. The length of the main stream is 130 km with a drainage area of 1122 sq.km and lies between 10^0 51' 42" to $11^0$10' 42" N and 75^0 48' 21" to 76^0 24' 30" east longitudes. The downstream stretch of the river falls into Arabian Sea (Plate 3) and most part of the basin falls within the Malappuram district and a small portion in Palakkad district of Kerala State.

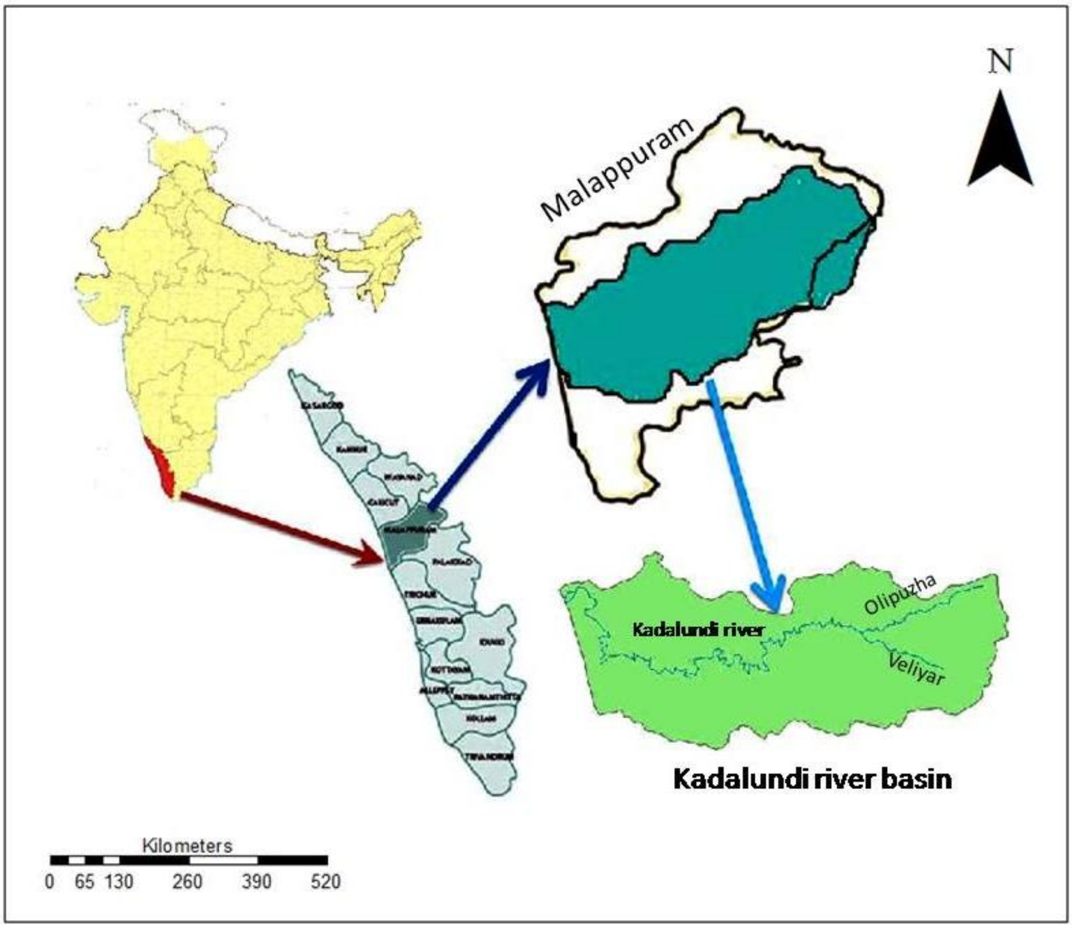


Fig. 4. Location map of the study area – Kadalundi river basin

Plate 1. Origin of Kadalundi river

Plate 2. Kadalundi river joining to Arabian Sea at Kadalundi

3.1.2 Physiography

The Kadalundi river basin can be broadly classified into three physiographic zones as follows

- The coastal belt or lowland in the west (between MSL and 7.5 m above MSL)
- The midland region in the central portion (between 7.5 m and 75 m above MSL)
- The highland in the east comprising the foot hill and hill ranges of western ghats (more than 75 m above MSL) (Anitha, *et al*., 2012)

Fig. 5 shows the physiographic map of the river basin with different altitudes.

3.1.3 Rainfall

The average annual rainfall of the Kadalundi river basin is 2700 mm. Out of this, major contribution is from South-West monsoon (June to September) and the remaining from North-East monsoon (October to December) and summer showers. The South-West monsoon is usually very heavy and nearly 73.5 per cent of the rainfall is received during this season. North-East monsoon contributes nearly 16.4 per cent and summer rain from March to May contributes nearly 9.9 per cent. The balance 0.2 per cent is accounted for during January and February months.

3.1.4 Temperature and humidity

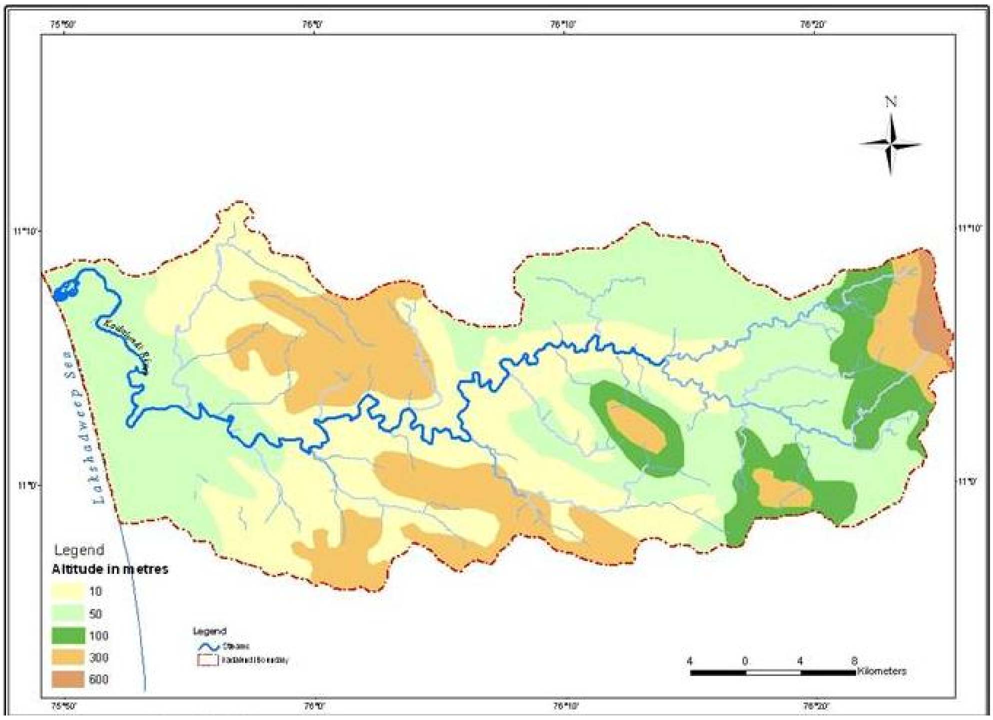
The average daily maximum temperature (between March and May) is 32^{O}C and the average daily minimum temperature (between December and February) is 21^{O}C. The air is highly humid throughout the year and the relative humidity generally varies from 60 to 88 per cent in the basin. Winds are generally light to moderate and they strengthen in the monsoon season.

3.1.5 Drainage

The drainage patterns have a complex arrangement in the basin with considerable variation in spatial arrangements controlled by topography, slope, rock type and structural deformations. The basin is characterized by dendritic type of drainage pattern with varying density. The densest dendritic pattern is developed on the hard charnockite and gneissic rocks. In some areas the drainage pattern is subdendritic reflecting structural control. The Kadalundi river basin is a fifth order stream and the drainage density varies between 0.65 to 3.15 km/km^2 depending on the geological and geomorphological characteristics(Prasad *et al.,* 2007). Figure 6 shows the drainage map of the basin .

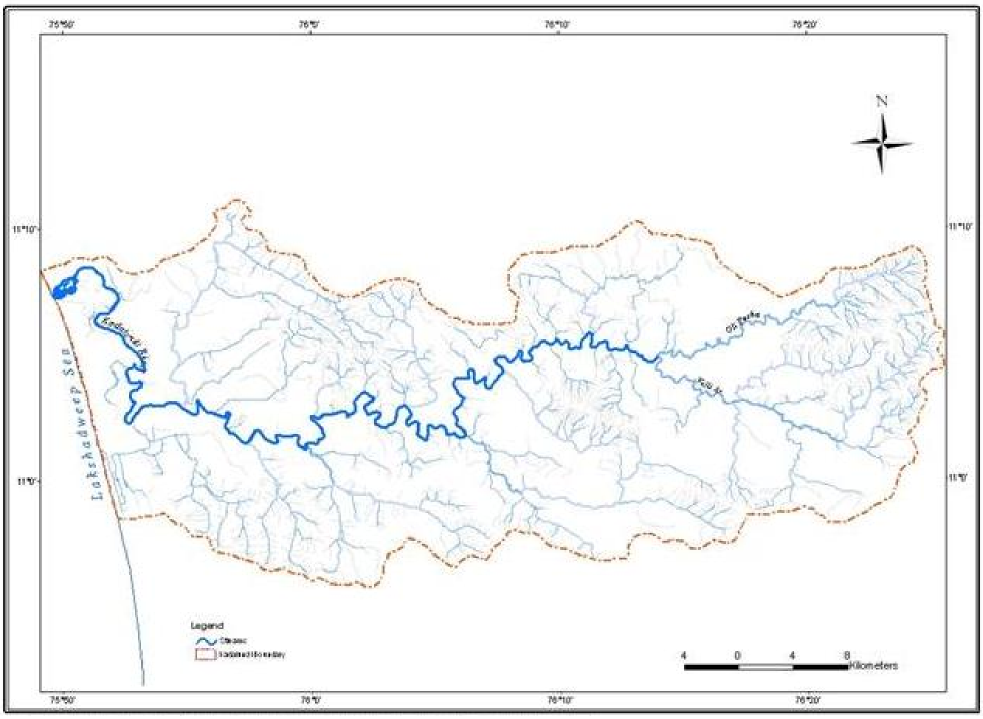
3.1.6 Land use and cropping pattern

The various types of land use seen in this basin are water bodies, river and streams, wastelands, plantations, arable land and forest land. With different agro climatic conditions experienced in different physiographic zones, a large variety of crops such as paddy, coconut, arecanut, tapioca, pepper, rubber, cashew are grown in the basin. The highlands are mostly covered by dense forests with patches of tea estates in higher reaches and coffee estates in the lower reaches. Coconut farming system is followed in the coastal and midland regions including number of intercrops such as pepper, arecanut and banana. Rice based farming system is followed in the valley regions of the midland depending on the availability of water one to three crops are grown. Annual crops like vegetables, pulses and oil seeds are grown in the fallows, as summer crops. Plantation crops like rubber, pepper and cashew are grown in the elevated areas of midland and highland region (Prasad *et al.,* 2007). Land use pattern details are given in Table 4 and land use classification of Kadalundi river basin is given in Fig. 7.



Source: Anitha, *et al.(*2012)

Fig. 5. Physiographic map of Kadalundi river basin



Source: Anitha, *et al.* (2012)

Fig. 6. Drainage map of Kadalundi river basin

Table 4. Land use pattern of Kadalundi river basin

Sl. No.	Land use	Area (km^2)
1	Mixed Trees	187.0
2	Rubber	49.0
3	Coconut	416.0
4	Arecanut	229.0
5	Teak	62.0
6	Paddy	95.24
7	Dense Forest	119.09
8	Coffee/Tea	0.83

Source: Anitha, *et al.* (2012)

3.1.7 Geology of the area

Geologically the Kadalundi river basin is characterized by charnockites and hornblende gneiss of Precambrian age, laterites of Pliestocene age and alluvial formations of recent to sub recent age. Laterite occur as residual formation formed due to tropical weathering of crystalline rocks and occur as capping over these rocks. Laterite occur as both primary/ insitu as well as secondary/ transported material. They are exposed as irregular patches with varying thickness from one geomorphic unit to other. The recent alluvial formation includes coastal sand, river alluvium and valley fill. These are composed of fine to medium grained sand(Prasad *et al.,* 2007).

Available data on existing observation wells in the study area have been used to analyse the subsurface lithological details. In the coastal region, fine to medium grained alluvial deposit of 5 to 15 m thickness is seen. This alluvial deposit is followed by laterites, lithomargic clay, weathered and/or hard rocks. In the midland region, lateritic soil of 0.5 to 2.0 m thickness is seen overlying the laterites of 5 to 20 m thickness followed by lithomaergic clay of less than 2m thickness. This clay is overlying weathered rock of 0.5 to 2 m thickness followed by hard rock with or without fractures. In highland region, the area is covered by brown soil of 1 to 3 m thickness followed by laterites, weathered rock and rock with or without fractures. The thickness of laterites in the highland varies between 2 to 10 m. Clay layer is absent in the highland region and the depth to the bedrock varies between 5 m to

27 m below ground level(Prasad *et al.,* 2007). The geology map of Kadalundi river basin is given in Fig. 8.

3.1.8 Soils

The different types of soils which occur in this river basin are coastal alluvium, riverine alluvium, lateritic soil, brown hypodermic soil and forest loam (Prasad *et al.,* 2007). The soil map of Kadalundi river basin is shown in Fig. 9.

3.1.8.1 Coastal alluvium

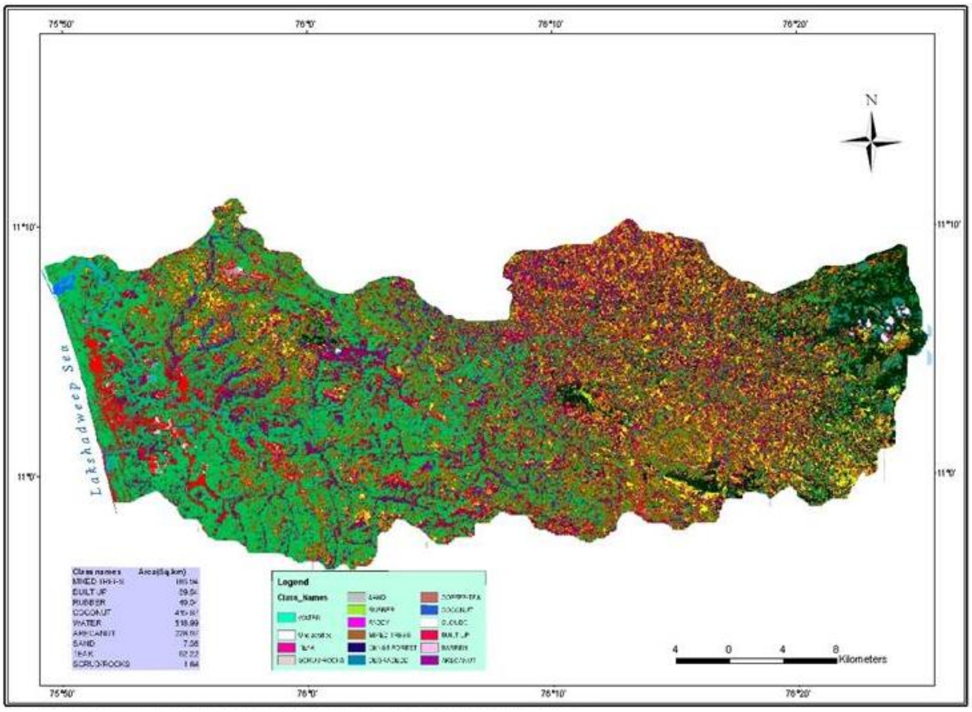
This soil has originated from recent deposits and is predominantly of marine origin, with some fluvial sediments along the coast. This soil is immature with high sand content and is highly porous with very low water retention capacity. pH value is less than 6.5 in most of the areas.

3.1.8.2 Riverine alluvium

This soil is seen along the river valleys, cutting across the extensive lateritic soils and is very deep with surface texture ranging from sandy loam to clay. It is very fertile having high water holding capacity and plant nutrients which regularly get replenished during flood. This supports cultivation of paddy, arecanut, pepper, tapioca and a wide variety of vegetables.

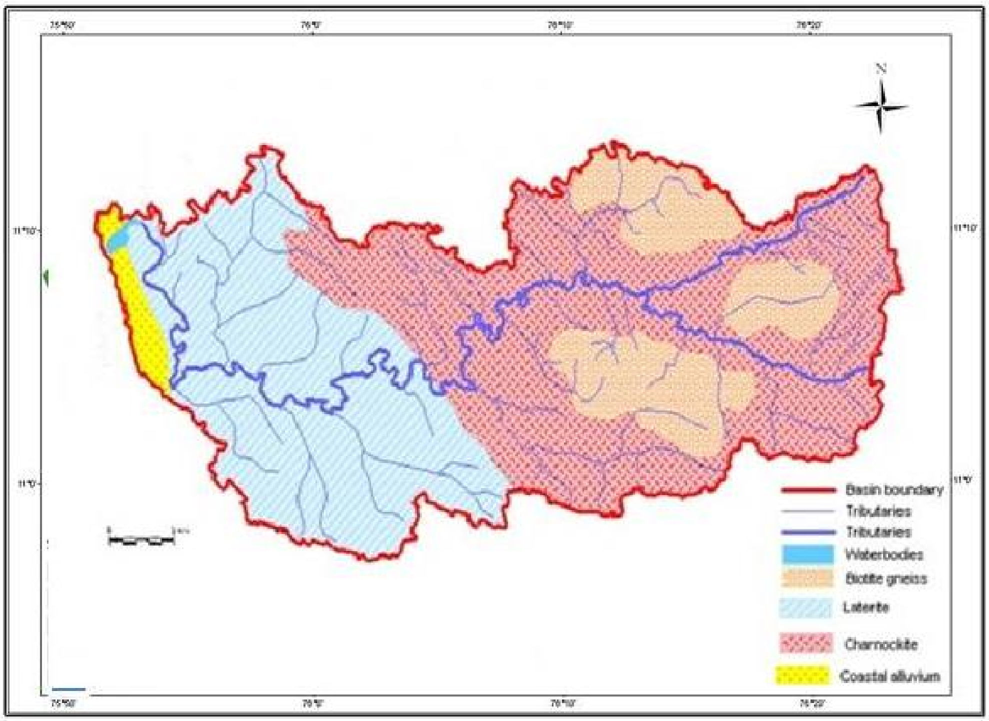
3.1.8.3 Lateritic soil

The lateritic soil is the predominant soil type in the basin, which occurs in the midland and highland regions. The lateritic soil is a weathered product derived under humid tropical conditions. In most areas this soil is developed with abundant ferrugeneous and quartz gravels. This soil is acidic and poor in nitrogen, phosphorous, potash and organic matter. It is well drained, widely cultivated and responds to agricultural management practices. The pH of the soil ranges from 5 to 6



Source: Anitha, *et al.* (2012)

Fig. 7. Land use map of Kadalundi river basin



Source: Anitha, *et al.* (2012)

Fig. 8. Geology map of Kadalundi river basin

and a variety of crops like coconut, tapioca, arecanut, cashew, pepper etc are grown in this soil.

3.1.8.4 Hydromorphic soil

The brown hydromorphic soil is the second predominant soil type found in the basin. This occurs mostly in the valleys between undulating topography in the midland and in the low lying areas of the coastal strip. This soil is formed as a result of transportation of materials from adjoining hill slopes and deposition by the river. The forest loam is developed in the hilly and forest areas. The upper layer is highly enriched with organic matter derived from the decomposed leaves, nitrogen and potash and deficient in lime and phosphate. Due to organic matter, the soil is dark reddish brown to black in colour. This soil is acidic in some places. Provision for drainage is essential for poorly drained areas,.

3.1.8.5 Forest loam

This soil is seen in the hilly and forest areas of the basin. The upper layer is highly enriched with organic matter and rich in nitrogen but poor in bases due to heavy leaching. This soil is generally acidic with pH ranging from 5.5 to 6.3.

3.1.9 Lineaments

A detailed estimate of the lineaments of Kadalundi river basin have been reported by Prasad *et al.* (2007). According to them,

1. The lineaments are dominant in the midland region with almost negligible intensity of lineaments in the highland and in the coastal region
2. Most of these lineaments are found to follow linearly arranged valleys and hence are potential zones for ground water exploration
3. The major direction of the lineaments are NW-SE and NE-SW and
4. In some places the lineaments intersect each other and such areas are expected to be more favourable for ground water exploration.

3.1.10 Geomorphology and slope

The Kadalundi basin exhibits undulating topography with steep slopes. The basin has been classified as low land representing the coastal belts, midland comprising mostly of laterites and highland by hard rocks. However there are small intermittent hillocks of 100 to 500 m AMSL in the midland region. These small hillocks of midland region are covered by hard laterites with sparse vegetation. In Kadalundi river basin the ground elevation ranges between 0 to 1200 meters AMSL with in the basin length of 60 km. It has been reported that about 85 per cent of the area falls within the ground elevation of 100 m AMSL. Slope map of Kadalundi river basin is shown in Fig. 10.

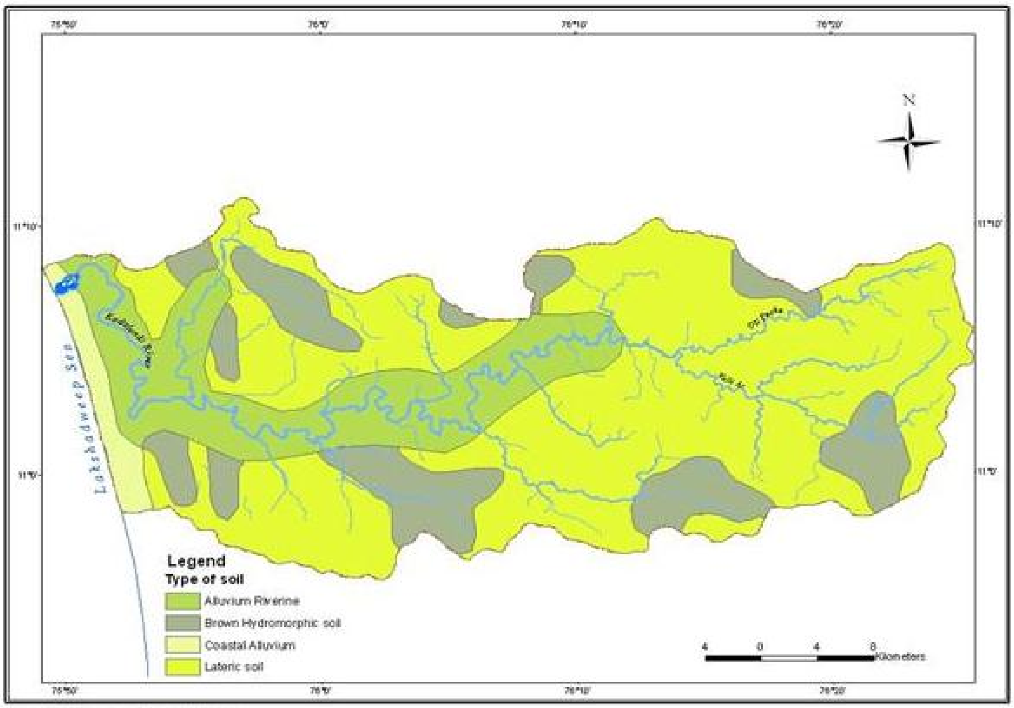
Based on the relationship between topography, lithology and drainage, the study area has been classified into different hydro-geomorphological units such as lateritic uplands, buried pediments, alluvial plain, flood plains, beach and coastal plains (Prasad *et al*., 2007).

3.2 Ground water scenario

Hydrogeologically, the aquifer system in the river basin can be broadly divided into crystalline aquifers (fractured basement rock aquifers), laterite aquifers, lateralized sedimentary (tertiary) aquifers and alluvial aquifers. Crystalline and laterite aquifers constitute major part (85 per cent) of the basin (CGWB, 2013).

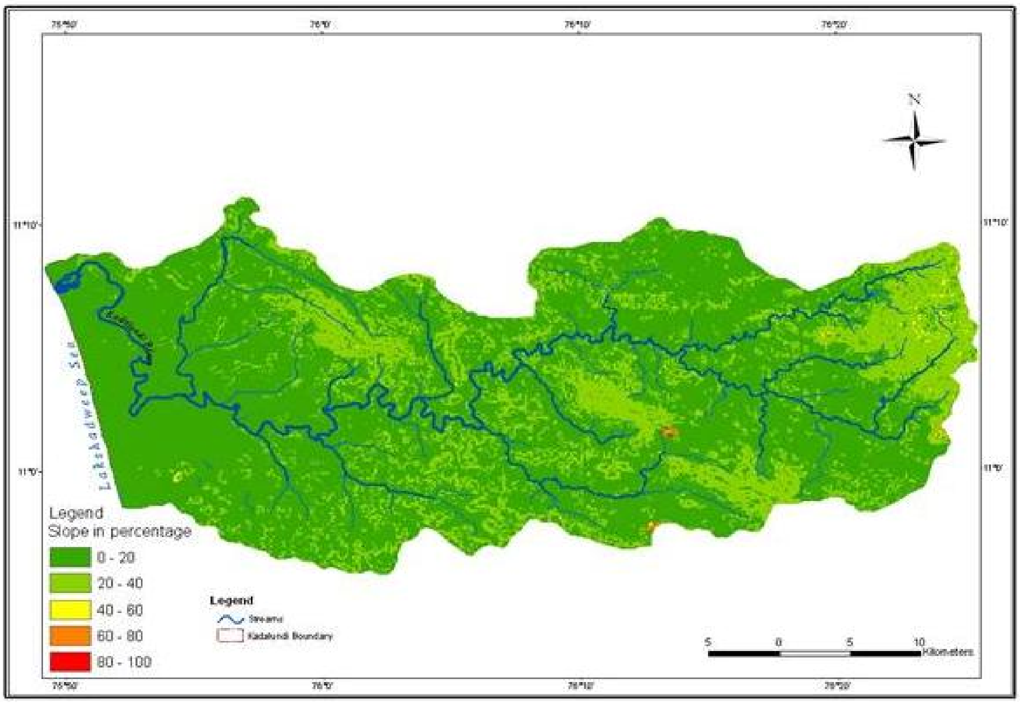
3.2.1 Ground water in crystalline formations

The crystalline formation of the study area comprises of Charnockite, Biotite gneiss and Migmatite rock. In these areas, the occurrence and movement of ground water are dominantly controlled by the nature and extent of weathering and the presence of structural features. Under unconfined conditions, ground water occurs in the secondary intergranular pores and voids of shallow weathered and fractured rocks whereas under semi-confined to confined conditions ground water occurs in the deeper fractured zones.



Source: Anitha, *et al.* (2012)

Fig.9 Soil map of Kadalundi river basin



Source: Anitha, *et al.* (2012)

Fig.10. Slope map of Kadalundi river basin

Weathered rock forms potential aquifers and the thickness of weathered rock ranges from 4 to 12 m below ground level. Along the valley portions of the area ground water is developed mostly by means of dug wells and their depth varies from 3.5 m to 21 m below ground level. The yields of these wells are of the order of 6 to 12 m^3h^{-1} and the specific yield values ranges from 1-3 per cent. The depth of wells located in the hornblende gneiss varying from 6 to 15 m below ground level and their yield ranges from 4 to 5 m^3h^{-1}. They can sustain pumping for only few hours and recuperation rate is very poor. The studies and explorations conducted in the study area indicate that the intersections of exploratory well fractures are highly potential zones followed by NE – SW fractures and ground water is extracted by means of bore wells. In the case of deep crystalline aquifers the fractures are fairly deep and inter connected (CGWB, 2013).

3.2.2 Ground water in laterites

This is the most widely distributed aquifer system in the mid land region of the river basin and constitutes the potential aquifer because of its highly porous and permeable nature. Once the rain recedes, the stored water escapes as sub-surface run-off from the elevated hills and slopes due to the high porosity. The laterite is resulting from both the tertiary formation and also from the crystallines and mainly occupy the hill top areas as laterite capping and also in low land areas where thickness is very meager. Dug wells are the main water abstraction structures in the aquifer and the depth of these wells range from less than 5.0 m to 15 m below ground level. Majority of the wells tapping laterites dry up during summer months. The bottom part of the wells are mainly of lithomargic clay and becomes low yielding during peak summer periods. In valley portions, the water table is shallow and appreciable thickness of saturated zone is available for ground water development. Aquifer yield ranges from 8 to 10 m^3h^{-1} and the specific yield values ranges from 2-5 per cent(CGWB, 2013).

3.2.3 Ground water in alluvial formations

Alluvial formations are the most potential aquifers in the study area and the coastal alluvium is essentially composed of sand, silt and clay. Ground water occurs under water table conditions and large number of dug wells and filter point wells tap this aquifer to meet the domestic and agricultural needs. Riverine alluvium of considerable thickness is seen in and around the central portion of Kadalundi river. Open dug wells and shallow tube wells are feasible in this stretch. The alluvial deposits are tapped by dug wells and these wells often meet entire needs of minor irrigation schemes. Shallow dug wells piercing alluvium over laying the lateritic horizon vary in depth from 15 to 20 m below ground level. The specific yield of these formations range from 10 to 20 per cent (CGWB, 2013).

3.3 Spatial and temporal variations of ground water level

Ground Water Department, Government of Kerala is having 30 ground water monitoring wells (GWMW) in Kadalundi river basin consisting of 14 dug wells and 16 piezometers. The dug wells are established in the laterite aquifers (Phreatic aquifers) and piezometers are established in the fractured basement rock aquifers (confined/semi confined). These wells are monitored for ground water level and data for the period from 2008 to 2013 were collected from ground water department. The trend of pre-monsoon and post-monsoon water levels of dug wells and bore wells for the period from 2008 and 2013 were mapped separately using Arc GIS 10.1. Spatial and temporal variations of ground water level of dug wells and bore wells were analyzed separately for evaluating the aquifer characteristics. In order to check the hydraulic continuity, variations of ground water levels of dug wells and bore wells in the same location of the different areas were compared.

3.4 Electrical resistivity methods of ground water investigation

3.4.1 Interpretation of VES Data

In Kadalundi river basin, Vertical Electrical Sounding (VES) method was applied using Signal Stacking Resistivity Meter (MODEL-SSR-MP-ATS) (Plate 3). VES survey was carried out in 22 locations as shown in Fig.11. Schlumberger electrode configuration for 9 locations and Wenner electrode configuration for 13 locations were carried out for finding out the resistivity of the underground substrata. The schlumberger soundings were carried out with current electrode spacing (AB) ranging from 3 to 200 m(AB/2=1.5 to 100 m). The spacing of potential electrode (MN) ranged from 1 to 40 m (MN/2=0.5 to 20 m). In the case of Wenner electrode configuration, current electrode spacing (AB) ranged from 6 m to 120 m (AB/2= 3 to 60 m) and potential electrode spacing (MN) ranged from 2 to 40 m (MN/2=1 to 20 m). At each VES station, electrodes were placed in a straight line and the inter electrode spreads were gradually increased about a fixed centre (Plate 4). Current was applied into the ground and the potential difference (V) due to this current (I) was measured and recorded against the electrode spacing. As the electrode spacing increases, the penetration of current also increases. The penetration of current below the surface is proportional to half of the distance between two current electrodes. With these values of currents (I) and potential (V) of the electrode configuration adopted one can get the apparent resistivities (ρ_a). The resistivity value decreases with fractures, joints, water content etc of the formation.

3.4.1.1 Computer inversion techniques

In order to avoid the chance of error in the interpretation and judgement of manual curve matching procedure, computer inversion program IPI2WIN version 2.1, developed by the Moscow State University (2001) was used in the study.

The input data given for execution includes

1. Field measurements as spacings and apparent resistivities
2. Type of electrode arrangement used (Wenner, Schlumberger or Dipole)
3. Number of layers and
4. Assumed layer resistivities (ρ) and thickness (h)

This procedure is iterative. A starting resistivity model is chosen based on a prior information from ground truth or averaged geophysical measurements and apparent resistivity data are modeled for the type of field survey geometry used.

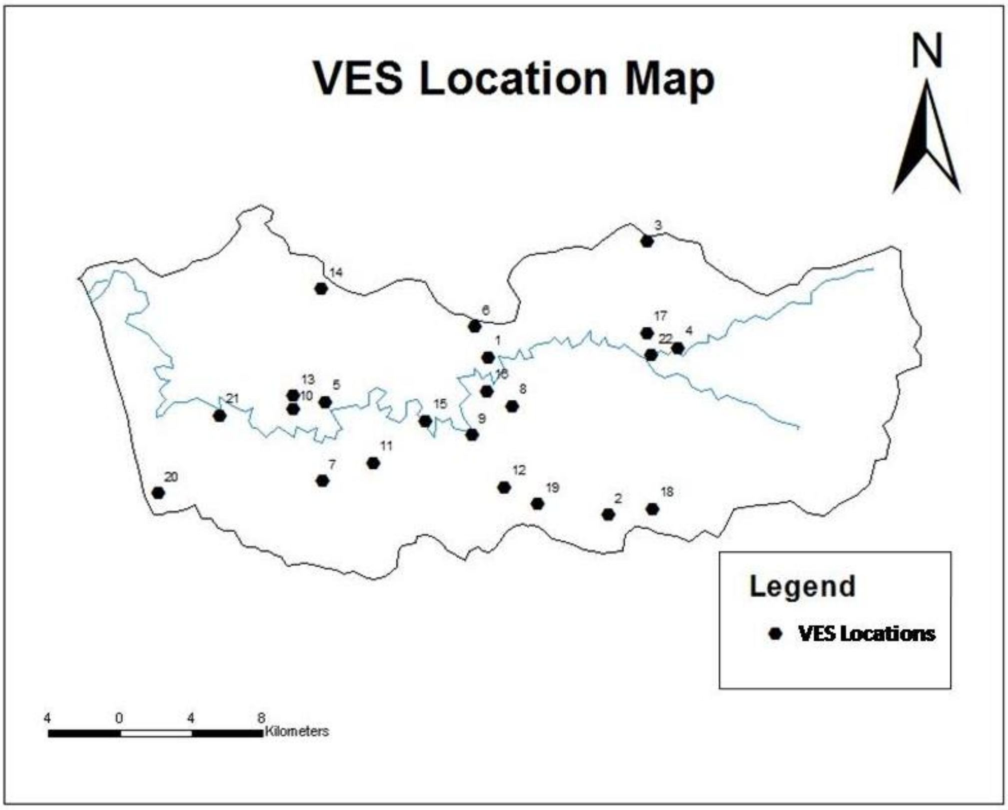


Fig. 11. VES locations in the study area

Plate 3. Signal Stacking Resistivity Meter (MODEL-SSR-MP-ATS)

Plate 4. VES survey using SSR meter

These calculated data were compared with the actual data and the resistivity model was updated based on the difference between observed and calculated data. This procedure was continued until the calculated data matched the actual measurements within an interpreter- defined level of error.

3.4.1.2 Types of sounding curves

Depending upon the geological and hydrogeological settings and the maximum electrode spread employed, various combinations of sounding curves were produced. The simplest sounding curves are the ascending and descending types of two layer cases, where the ground has a two-layer structure, with loose topsoil or a weathered and a compact basement (highly resistive) and the curve is ascending type. If the top layer is highly resistive and the bottom layer is conductive due to saline water or some other saturated condition, then a descending curve is obtained (Brijesh and Balasubrahmanian, 2014).

Four types of sounding curves are possible in a three layered geology of ground substrata. If $\rho1$, $\rho2$ and $\rho3$ are the resistivities of three successive layers, a sounding curve with a low resistivity at centre ($\rho1 > \rho2 < \rho3$) is said to be H type curve. This type of curves are obtained generally in hard rock terrains which consists of dry top soil of high resistivity as the first layer, water saturated weathered layer of low resistivity as the second layer and compact hard rock of very high resistivity as the last layer (Brijesh and Balasubrahmanian, 2014).

If the resistivities of the layers are continuously increasing ($\rho1 < \rho2 < \rho3$), the curve is called as A- type, which occurs in the hard rock with conductive soil. Sounding curve showing a maximum hump flanked by low resistivity values ($\rho1 < \rho2 > \rho3$) are called K-type curves. In coastal areas, these curves will be encountered due to freshwater aquifer underlying a clayey layer and overlying a saline water layer (Brijesh and Balasubrahmanian, 2014). A sounding data which has a continuously decreasing resistivity ($\rho1 > \rho2 > \rho3$) will form a Q- type curve. In coastal areas, where saline water is present, such curves are obtained

Four layer curves (HK, HA, KH, KQ, AA, AK, QQ, QH) of eight possible combinations are available and complicated sounding curves representing multilayer situations like HKHK, KHKH, HAA etc. are available for interpretation. (Brijesh and Balasubrahmanian, 2014).

Based on these concepts, the resistivity values of different subsurface layers and their corresponding thickness obtained from the IPI2WIN software were interpreted and processed qualitatively and quantitatively.

3.5 Ground water flow modelling

Modelling is one of the many tools that can be used to determine remedial options. Models range from simple mathematical equations to complex computer generated models. A mathematical equation or computer generated model does not provide a unique solution to an environmental problem. It provides a scenario based on specific assumptions and specific input values. The model should be calibrated with existing site conditions. Once calibrated, the model can be run in predictive mode to generate results for a range of sensitive parameters and the results should be evaluated and summarized with conclusions and recommendations. In this study, Visual MODFLOW software version 2.8.1 developed by Waterloo Hydrogeologic Inc. was used.

3.5.1 MODFLOW model development process

A general flow chart for modelling methodologies of an aquifer is given in the schematic block diagram (Fig. 12). In this study, Visual MODFLOW model was developed and calibrated with 4 years data (2008 to 2011) and validated with 2 years data (2012 & 2013). After the development of a validated MODFLOW model, the model was used to predict the ground water scenario of next 15 years.

3.5.2 MODFLOW input

3.5.2.1 Conceptual model of the Kadalundi river basin

Visual MODFLOW supports the use of base maps in all modules of the program. Raster map of Kadalundi river basin obtained from CWRDM was used to prepare the base map using Arc GIS (Arc Map10.1) and was converted into BMP format. Base map was imported into the model screen as shown in Fig. 13 and it was geo referenced using geo referencing option of MODFLOW software .

The conceptual model for the study area was developed based on the topo sheet of the area, well logs at 30 sites and the data obtained from the geophysical studies conducted in the study area. An important tool to characterize the aquifer is hydrogeological profile. The geological profile revealed that there were no distinct separation of layers and the profile consists of fine to coarse laterites, followed by weathered rock in some areas. In between these layers lithomargic clay was present in some areas. The study of hydraulic continuity of the aquifer revealed that hydraulic continuity was existing in almost all parts of the study area. Hence the aquifer system of the study area for the modelling purpose was assumed as homogeneous, isotropic, single layer and unconfined aquifer, exploited by dug wells for domestic as well as irrigation purposes. More than 80 per cent of the ground water extraction was from the first aquifer. The aquifers were recharged mainly by rainfall and the study area was hydraulically bounded in the west by the Arabian sea.

3.5.2.2 Discretization of the Basin

After the conceptual model was developed, the study area was discretized by dividing it into 62 rows and 136 columns with a grid spacing of 500 m x 500 m. Thus the area was discretized into 8432 cells and the cells outside the boundary of the study area were made as inactive. The grid formation of the study area is shown in Fig. 14. Based on the ground water level data availability, a time step of month was chosen within which all hydrological stresses can be assumed to be constant.

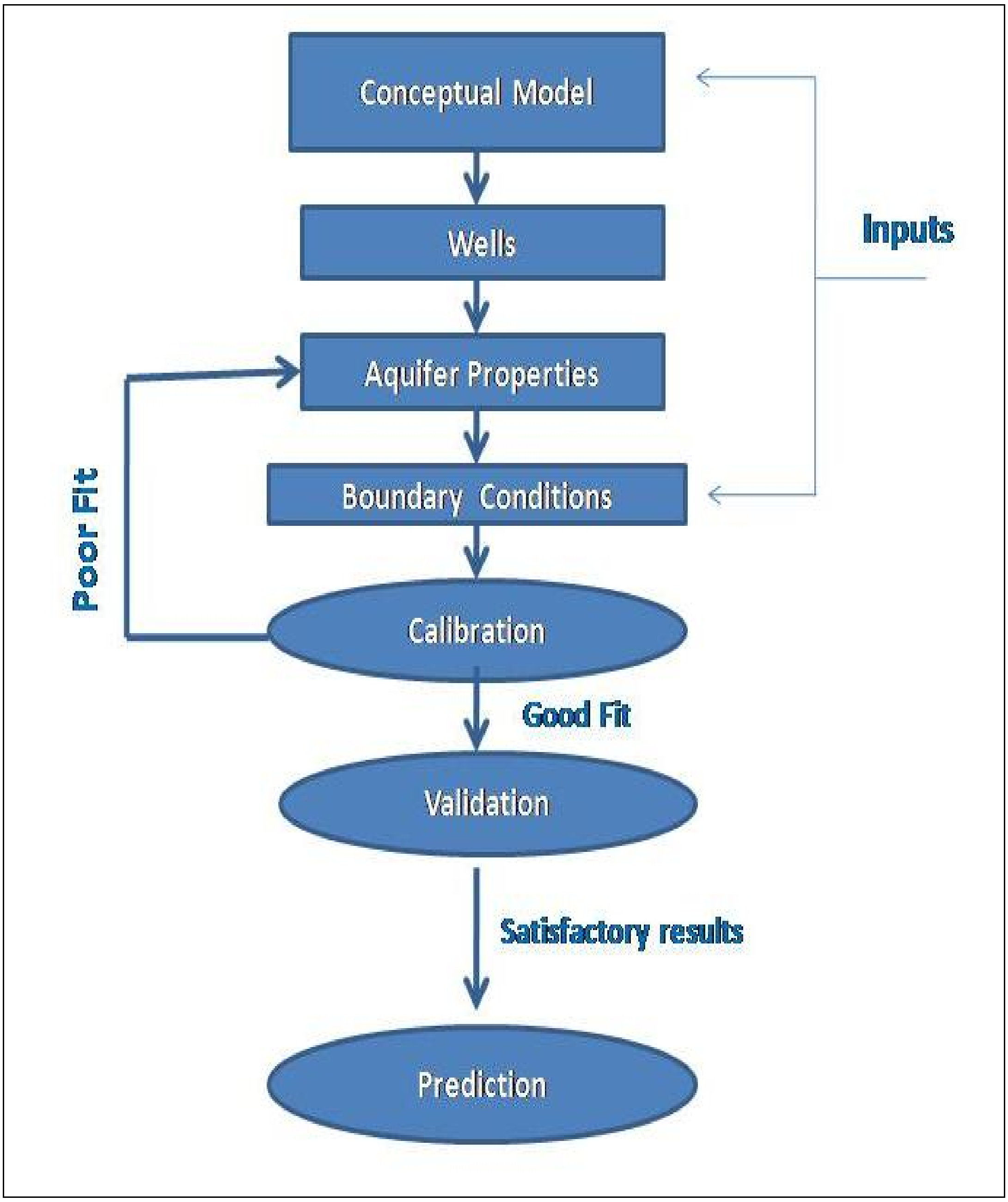


Fig. 12. Flow chart of MODFLOW model development process

Visual MODFLOW imports the data files of format ASCII or text file (*.TXT) or sufer.grd. Hence, the data on surface elevation and bottom elevation (Appendix I) were made in text format and fed as input. Minimum layer thickness assigned was 1 m. In Visual MODFLOW, the upper layer will not move to accommodate the imported layer.

3.5.2.3 Wells

Visual MODFLOW permits to input field observations of pumping rate and water table observations from observation wells to get model output values. From the well drop-down menu of the software we can choose to graphically add, delete, move or edit pumping wells and head observation wells.

3.5.2.3.1 Pumping wells

Well inventory was carried out in the entire study area and their pumping rate and usage were calculated. Dug wells are mainly used for ground water abstraction in most part of the study area.

Total 35 numbers of major pumping wells of Kerala Water Authority and Jalanidi Malappuram were selected for this study. By carrying out field observations and using the available data from Ground Water Department and CWRDM, the ground water abstraction for irrigation and domestic purposes in the study area were calculated. The pumping wells were located in the grids and the pumping rates were entered as .txt files. For pumping rate negative sign was used and positive sign was used for injection. In this study area no injection wells are used. Regardless of the screening interval assigned, MODFLOW consider a well to be screened across the entire layer. The pumping rate must be specified continuously for all stress periods. The pumping wells are turned off if the pumping rate is not specified for the later stress periods in a transient simulation. If a well cell goes dry during a simulation, the pumping rate of the well at that location will automatically be reduced. Pumping well edit screen is shown in Fig. 15.

3.5.2.3.2 Observation wells

The Visual MODFLOW saves the calculated heads at the locations of specified observation wells for every time steps in a *.HVT (Head versus Time) file. This helps the user to compare simulated heads with observed heads during calibration and produce hydrographs at observation wells without saving the entire MODFLOW solution at every time step. Observation well information is needed for the calibration and model saves hydraulic head and drawdown at every time step. Ground Water Department (GWD), Government of Kerala is having 30 ground water monitoring wells (GWMW) in Kadalundi river basin consisting of 14 dug wells and 16 piezometers. (Appendix II). The GWD monitoring wells were located in the grid using head observation wells menu and the water levels from year 2008 to 2011 were entered through edit screen of observation well as shown in Fig.16.

3.5.2.4 Hydrogeological properties

Visual MODFLOW model input includes hydrogeological parameters such as hydraulic conductivity, specific storage, specific yield, porosity and initial head values.

3.5.2.4.1 Hydraulic conductivity

From the literature available and the study reports of Central Ground Water Board, it is observed that the hydraulic conductivity of the lateritic terrain is about 20-35 md^{-1}. In this study hydraulic conductivity of longitudinal and lateral directions were selected as 30 md^{-1} and vertical hydraulic conductivity was selected as 10 percent of longitudinal hydraulic conductivity, 3 md^{-1} (CGWB,2013).

3.5.2.4.2 Storage

Visual MODFLOW requires four parameters such as Specific storage (S_S) in m^{-1}, Specific yield (S_Y), Effective porosity (Eff. Por.) and Total porosity (Tot. Por) as input in the storage menu. The model determines primary storage coefficient (sf1)

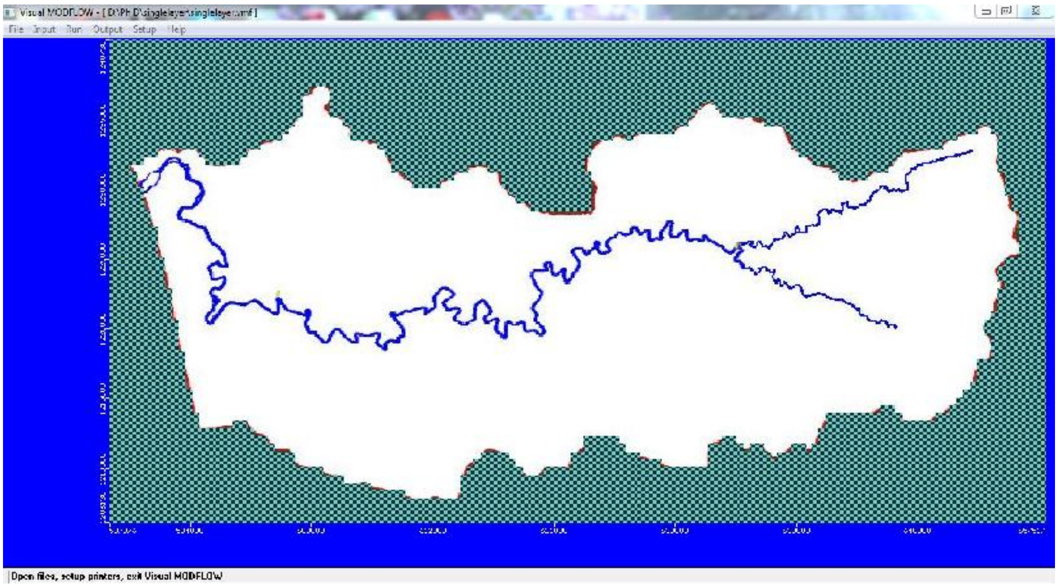


Fig. 13. Base map of the model

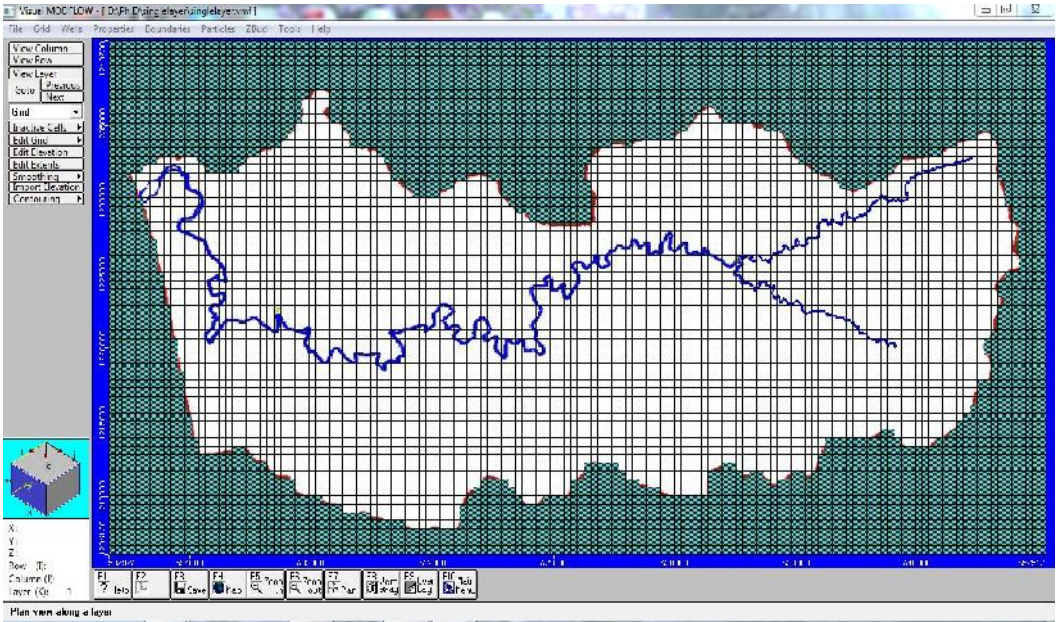


Fig. 14. Grid formation of the study area

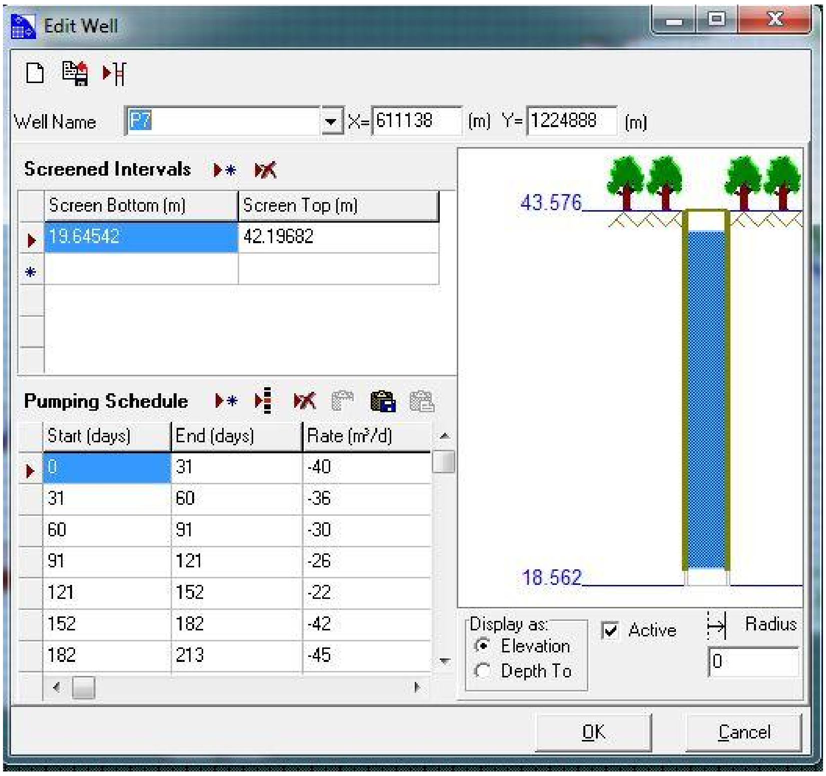


Fig. 15. Edit screen of pumping well

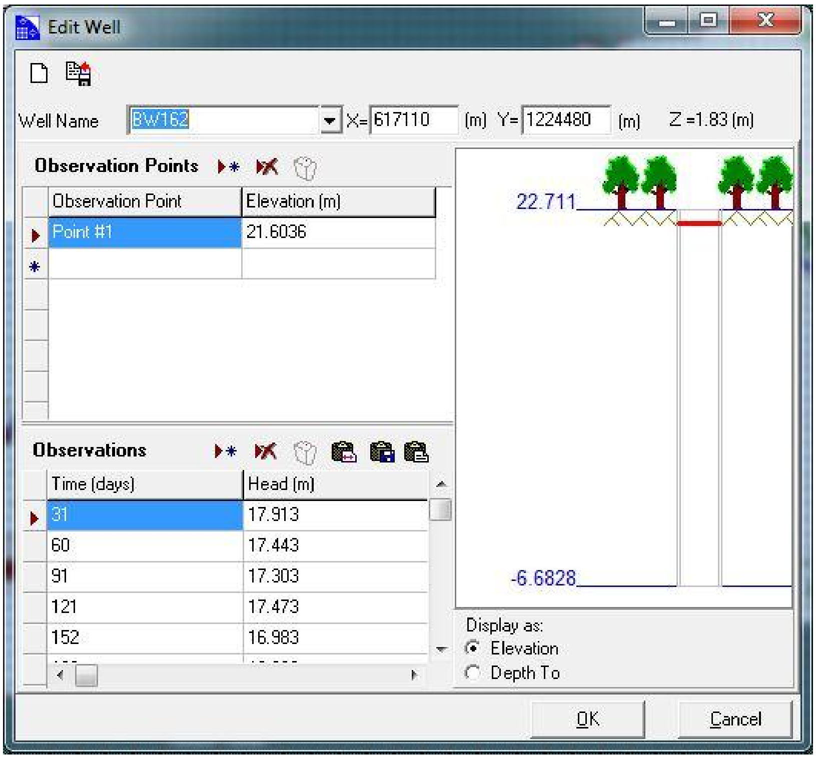


Fig.16. Edit screen of observation well

by multiplying specific storage (S_S) with the layer thickness. The storage term of unconfined aquifer is known as the specific yield. Storage properties used in this study were collected from different literature and from Central Ground Water Board. Hydraulic properties of the aquifer is given in Table 5 and data base of properties are shown in Fig. 17.

Table 5. Hydraulic properties of the layer

S.No.	Model Properties	Layer I Laterite
1	Hydraulic conductivity in longitudinal direction K_X, md^{-1}	30
2	Hydraulic conductivity in lateral direction K_y, md^{-1}	30
3	Hydraulic conductivity in vertical direction K_Z, md^{-1}	3
4	Specific storage, S_S (m^{-1})	0.00035
5	Specific Yield, S_y	0.20
6	Effective Porosity	0.35
7	Total Porosity	0.40

3.5.2.4.3 Initial head

MODFLOW requires an initial value for the head distribution for steady state simulation and a starting head distribution for a transient simulation. The drawdown is also calculated from the initial head and which is assigned based on the water level data obtained from Ground Water Department, which is given in Appendix III and also shown in Fig. 18.

3.5.2.5 Boundaries

MODFLOW model needs boundary conditions of the model domain which includes constant head, rivers, general head, drains, walls (horizontal flow boundaries), recharge and evapotranspiration.

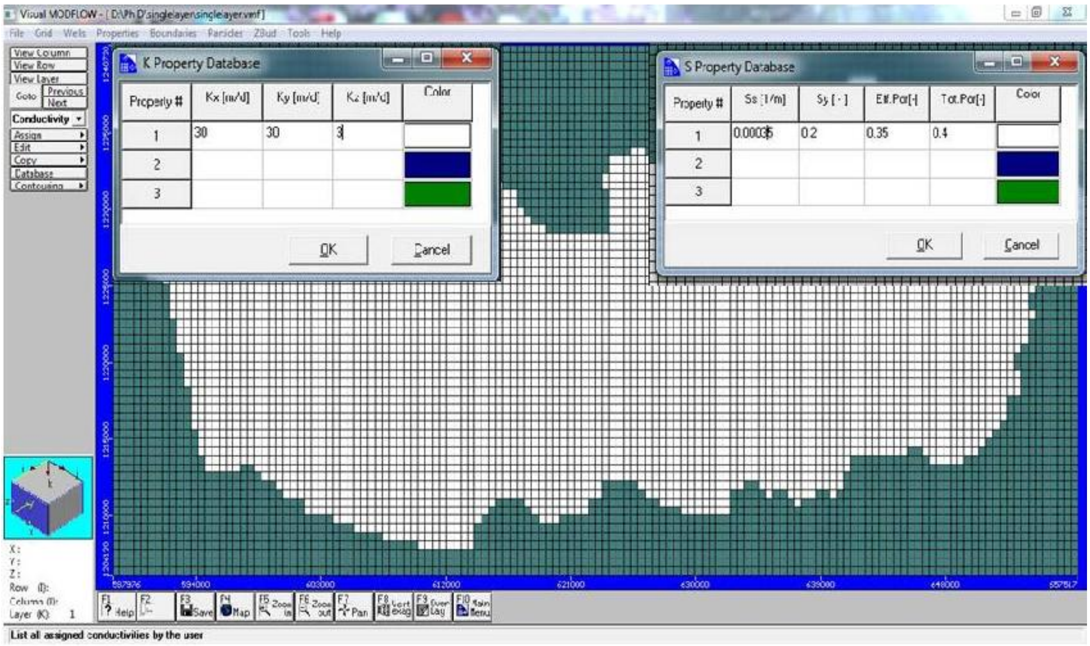


Fig. 17. Database window of hydraulic properties of the model

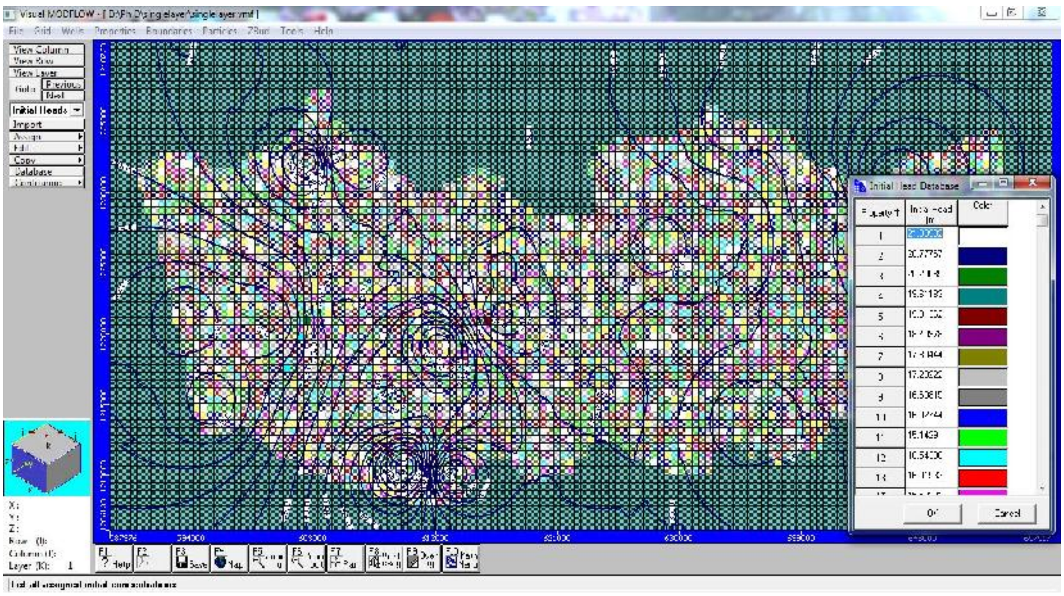


Fig. 18. Initial head screen of the model with database

3.5.2.5.1 Minimum boundary conditions

At least one head boundary must be specified for a steady-state simulation and the head boundary acts as a reference head for all calculations. Specified initial heads are sufficient for a determinant solution of the transient simulation.

In general, transient conditions remain constant over a stress period and change abruptly between stress periods. A stress period can be defined as the time period during which all the stress on the system are constant. The constant heads are never constant unless the heads at the beginning and at the end of the stress periods are the same. In this study, the western side of study area is Arabian Sea and hence the boundary of the system is fixed as constant head of 'zero' as shown in Fig. 19.

3.5.2.5.2 River head

The river boundary condition is used to simulate the influence of a surface water body on the ground water flow. The effect of flow between the rivers and aquifer was simulated by dividing the rivers into reaches containing single cells. The MODFLOW river package input file requires the following information for each grid cell containing a river boundary. The schematic diagram of river boundary is shown in Fig. 20.

River Stage: The free water surface elevation of the surface water body. This elevation may change with time.

Riverbed Bottom: The elevation of the bottom of the seepage layer (bedding material) of the surface water body.

Conductance: A numerical parameter representing the resistance to flow between the surface water body and the ground water caused by the seepage layer (riverbed).

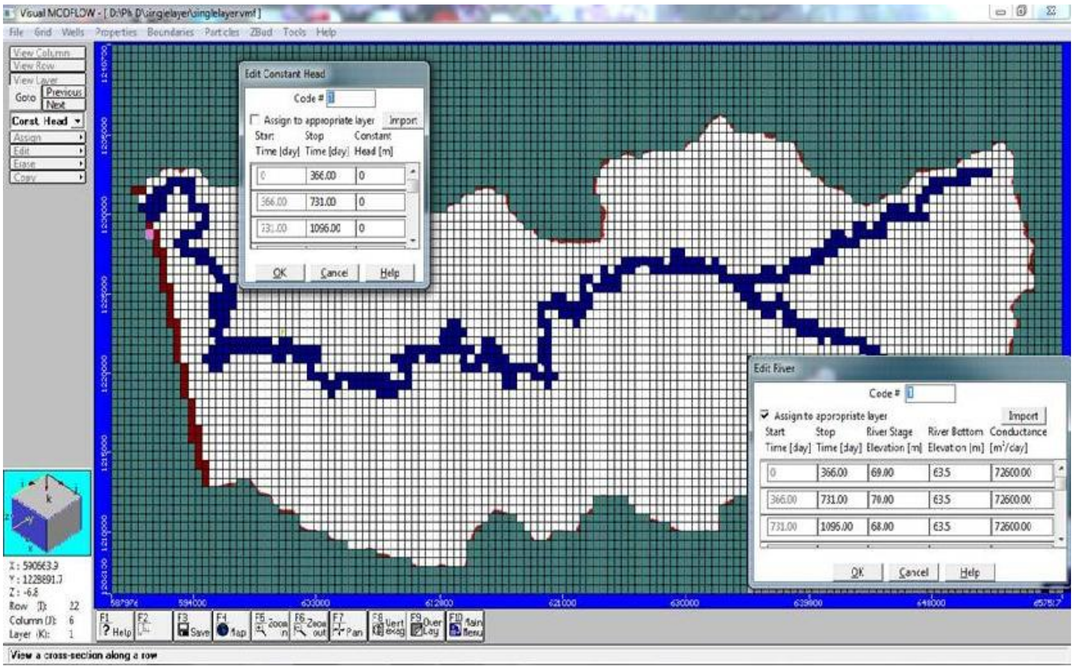
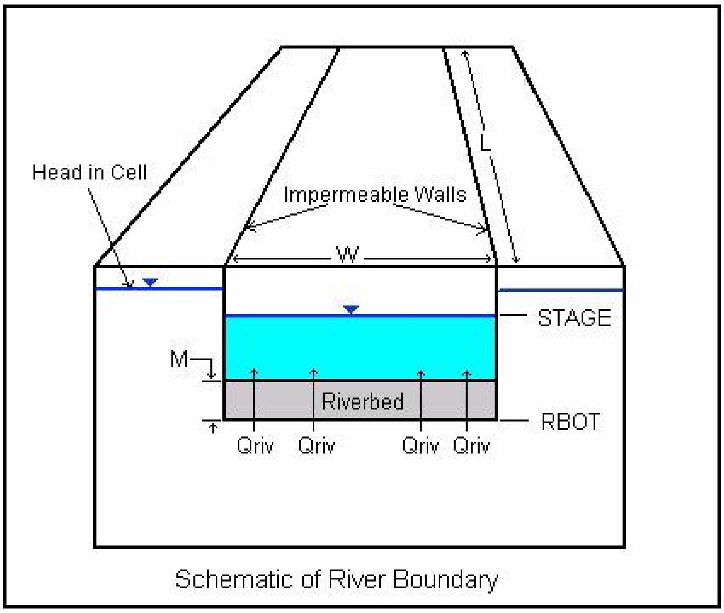


Fig.19. Edit screen of constant head and river package



Source: Visual MODFLOW user's manual

Fig. 20. Schematic diagram of river boundary

The conductance value (C) can be calculated using the following equation,

$$C = \frac{K \times L \times W}{M} \qquad \text{(Eq. 3.1)}$$

where C = Conductance, m^2d^{-1}, K = Hydraulic conductivity, $md^{-1,}$ L = Length of a reach through a cell, m, W = Width of the river in the cell, m and M= Thickness of the river, m

3.5.2.5.3 Drains

Visual MODFLOW is designed to simulate the effects of agricultural drains which remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head or elevation of the drain. It is assumed that the drain has no effect on head of flow if the head in the aquifer falls below the fixed head of the drain and in this study area, there is no significant effect on drains.

3.5.2.5.4 Recharge

Visual MODFLOW is designed to simulate aerial distribution of recharge to the ground water system. Generally, aerial recharge occurs as a result of rainfall, seepage flow from adjoining areas, deep percolation from irrigated rice and other irrigated areas to the ground water system and also from the sources like artificial recharge structures. Recharge can only be the input for the top layer, ie, layer 1. There is no need to allow recharge to occur simultaneously at multiple depths in the same vertical column because natural recharge enters the ground water system at the ground surface. To compute the recharge from rainfall, 6 years of rainfall data from 2008 to 2013 were collected and the recharge was calculated using the equation Eq. 3.2 (Chandra and Saxena, 1975) and it was found to be about 20 to 25 per cent of average annual rainfall. Hence the monthly recharge was taken as 23 per cent of monthly rainfall of the study area and which is given in Appendix IV.

$$R = 3.984\,(R_{av} - 40.64)^{0.5} \qquad \text{(Eq. 3.2)}$$

where, R = areal recharge in cm and R_{av} = the average annual rainfall in cm.

Recharge from irrigated fields, including the losses in field channels was estimated using the guidelines suggested by the Ground Water Estimation Committee (1984) as

1. Recharge from irrigated rice area is about 35-64 per cent of total draft for irrigation

2. Recharge from irrigated non-rice area is about 25- 35 per cent of total draft for irrigation.

Annual Rain fall data from 2008 to 2013 were collected from the rainfall station at Perinthalmannna in Kadalundi River Basin. Recharge of the entire area due to rainfall and also the recharge through irrigation were calculated and entered in to the model as input as shown in Fig. 21.

3.5.2.5.5 Evapotranspiration

Visual MODFLOW requires Evapotranspiration (ET) to simulate the effect of plant transpiration through capillary rise from the saturated zone. Evapotranspiration rate was assumed as 10 per cent of the rainfall uniformly for the entire study area and the values are entered as input as shown in Fig. 22.

3.5.3 Visual MODFLOW run

After completing the uploading of input parameters, run model [Run] is selected from the main menu and selected 'Run Type' dialogue box appears. Steady state and transient state run types are available in the model (Fig. 23). First, the model was run for steady state condition. After that the model was run under transient condition. WHS solver was selected. The WHS solver works on a two-tier approach to a solution at one time step.

Initial head options, recharge options, WHS solver parameters, anisotropy factor, layer type, rewetting options, and output control options are shown in Fig. 24. The wetting of a cell is controlled by either the head in the cell directly beneath or by the heads in the four adjacent horizontal cells, plus the one beneath. The first method is generally more stable and is particularly good when the adjacent horizontal cells are poor indicators of whether a cell should become wet. Horizontal anisotropy is the ratio of transmissivity or hydraulic conductivity along a column to its component value along each row. The anisotropy factor can be assigned by layer or remain as specified in the hydraulic conductivity. The model was run with all the above inputs for steady and transient conditions using WHS solver. Steady state run was done with the data during the period of 2008. Transient run was done for 4 years stress period with the data during 2008 to 2011 (Fig. 25). The simulations were compared with observed data.

3.5.3.1 Model calibration

The model was calibrated using observed water level data collected, so that model is capable of producing field measured heads and flow. The monthly water level data collected from Ground Water Department, Govt. of Kerala for the period from 2008 to 2011 were used for the calibration purpose (Appendix V). The study involves transient state simulation which includes the length and time span of steps. In this study, 48 stress periods were defined for the calibration purpose having length of 30 days (one month). The model was calibrated by systematically adjusting values of selected parameters like hydraulic conductivity, specific yield and specific storage to achieve an acceptable match between observed values of water table elevation with corresponding computed values by the model. For the calibration, Root Mean Square (RMS) has been chosen as the calibration criteria and calibration process was continued till no further reduction in RMS values was possible.

3.5.3.2 Model validation

The model was validated with the calibrated values of various parameters and using the observed data of ground water level for the period of 2012 and 2013 (Appendix V). The model was verified for its accuracy and predictive capability within acceptable limits of errors, independent of the calibration data. The model was then considered as validated and useful for predicting aquifer response for various water resource management strategies.

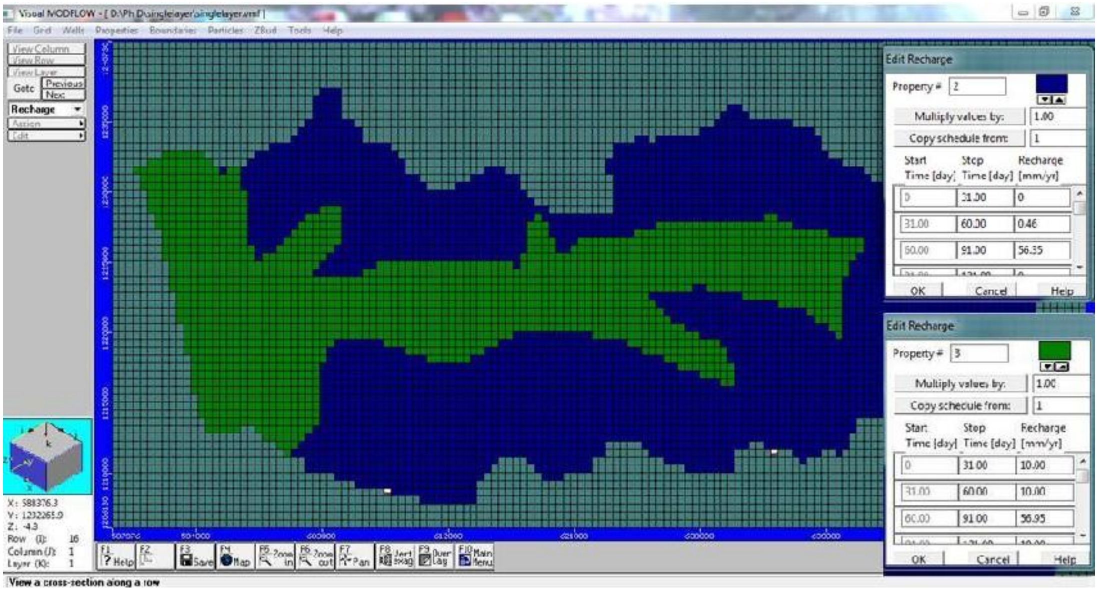


Fig. 21. Assigned recharge rate to the model domain

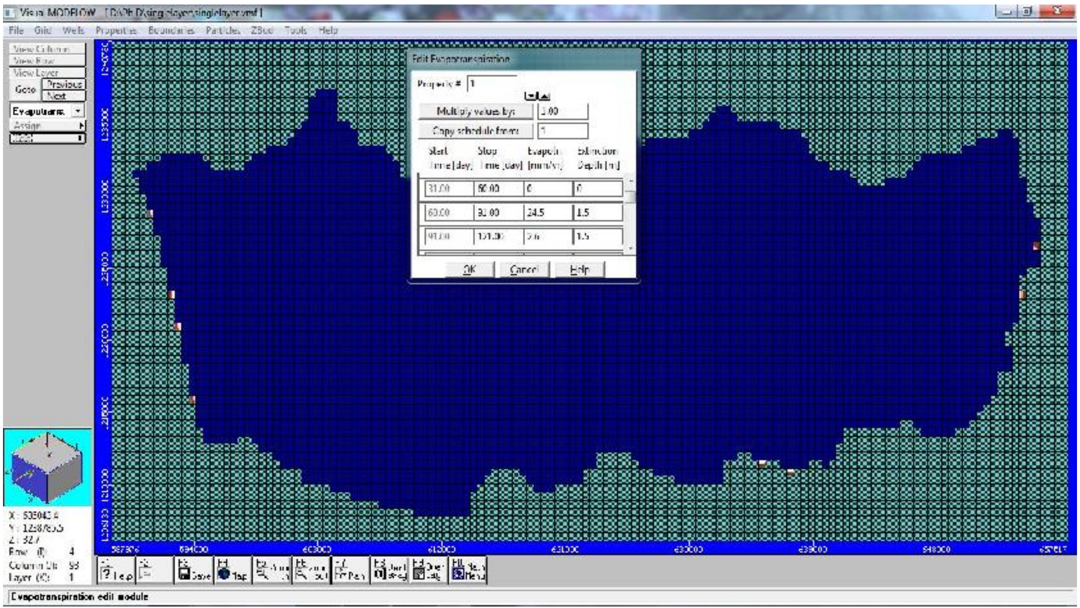


Fig. 22. Assigned evapo-transpiration rate to the model domain

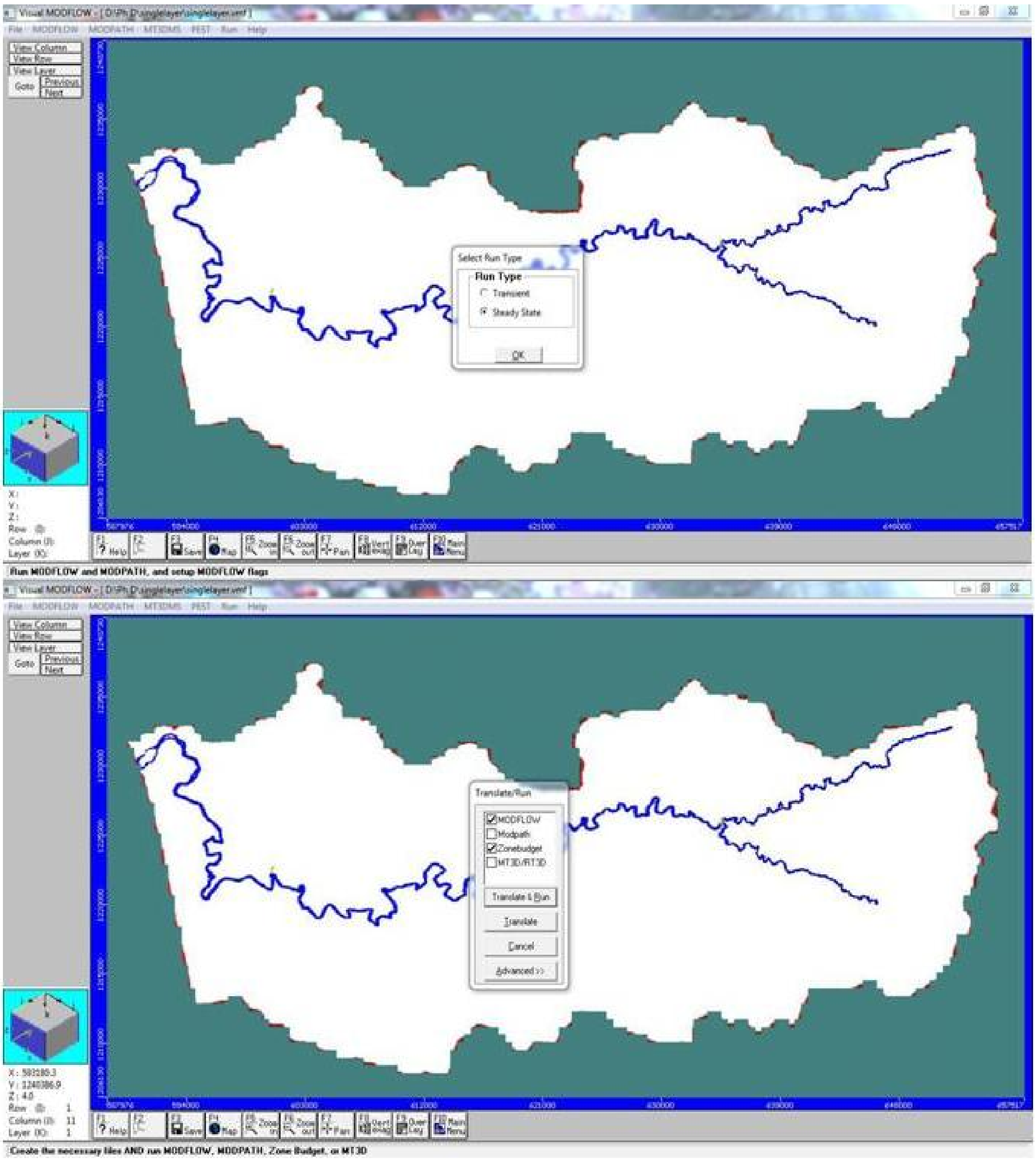


Fig. 23. Run options of Visual MODFLOW

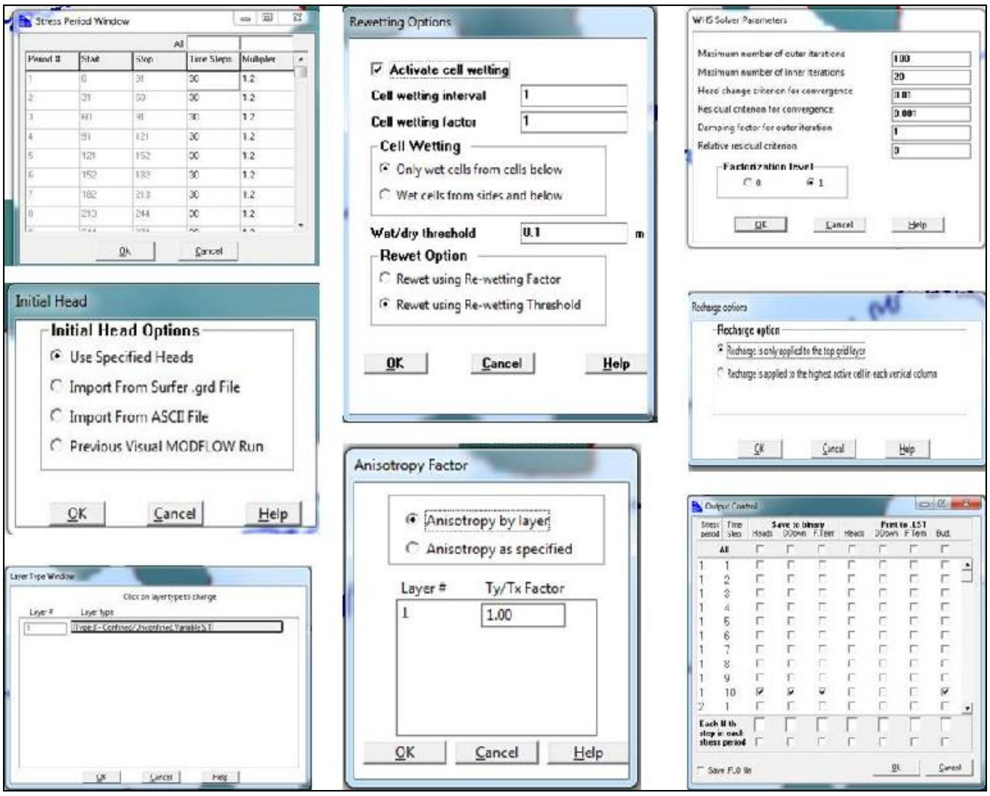


Fig. 24. Different run parameters of Visual MODFLOW

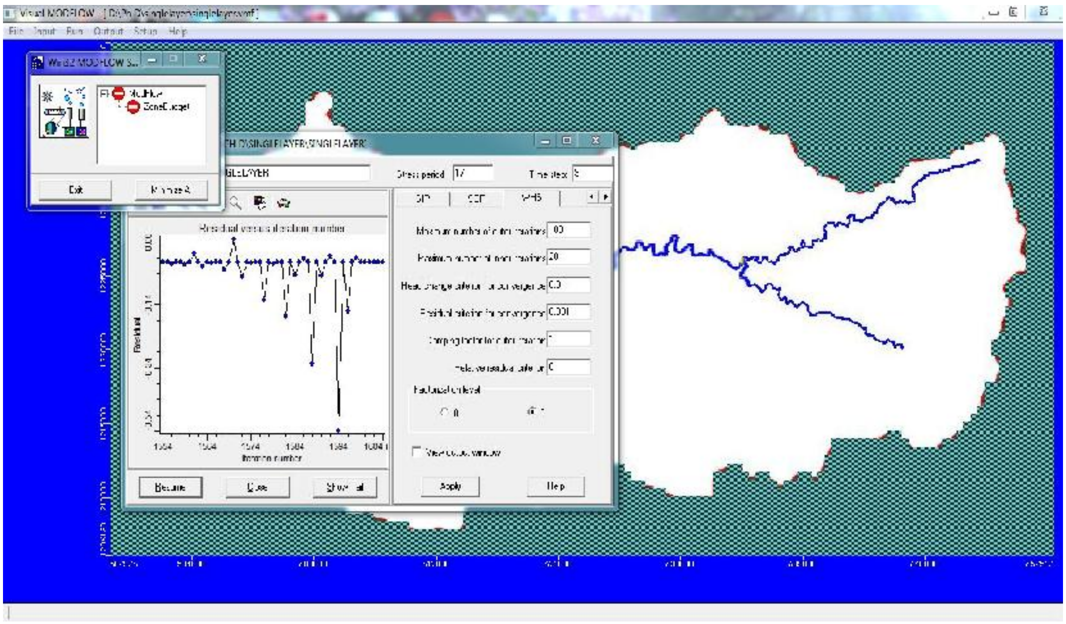


Fig.25. Visual MODFLOW model run under transient condition

3.5.3.3 Model prediction

The validated model was used for predicting the flow head for the next 5, 10 and 15 years with five per cent decrease in recharge for every year and also predict the ground water condition after 15 years by increasing the pumping rate by 10, 25 and 50 percent of pumping rate of the validated period (2013).

CHAPTER 4

RESULTS AND DISCUSSIONS

Ground water level fluctuations in an area mainly depend on several factors like precipitation, topographical features, soil properties, land use pattern, geology, geomorphology and river hydraulics. Results of the analysis of spatial and temporal variations of ground water levels, interpretation of Vertical Electrical Sounding (VES) data, calibration, validation and prediction of ground water flow of the study area using Visual MODFLOW are discussed in detail in this chapter.

4.1 Aquifer characteristics and ground water scenario of the study area

Evaluation of aquifer characteristics is an important component of all ground water resource assessment. Spatial and temporal variations of ground water table of the study area were analyzed with the help of ground water level data collected from dug wells and piezometric level from bore wells separately for evaluating the aquifer characteristics. Monthly water level data from 16 bore wells and 14 dug wells during the period from 2008 to 2013 were used for the analysis. The locations of these observation wells are shown in Fig. 26.

4.1.1 Spatial and temporal variations of ground water table

Ground water can be considered as a dynamic resource and can be expressed as the quantity of water represented by the difference between maximum and minimum water table within the aquifer. The density of dug wells in the study area is high due to small size of holdings and the concept of one well per family. About 80 per cent of the dug wells are used for domestic use and 20 per cent are used for both domestic use and irrigation. The analysis were carried out with two conditions of ground water table variations.

4.1.1.1 Pre and post monsoon variations

Ground water table for the month of April and October months were monitored to study the pre- monsoon and post monsoon fluctuations. The ground water table during pre and post monsoon in 14 dug wells located at different physiographic locations were observed and the difference between pre and post monsoon water table (water table fluctuations) noted are given in Table 6. It was observed that the water table fluctuations in all the wells were almost similar and ranged from 1.31 m to 4.31 m, except the maximum water table fluctuation of 7.98 m noted in well OW24. This well is located at Marakkara at an elevation 98.54 m. The variation of water table fluctuation between pre and post monsoon indicates the replenishment for groundwater resources in the study area by recharge through rainfall. The lesser the difference between pre and post monsoon water levels, more the area is having ground water potential.

Ground water table maps were prepared for both pre-monsoon and post monsoon periods for six consecutive years using Arc GIS (10.1) and are shown in Fig. 27 and 28 respectively. From Fig. 27, it could be seen that pre-monsoon variation was similar for all six years from 2008 to 2013. At Malappuram, Kondotty, Mankada, Manjeri, Waodoor, part of Perinthalmanna and Palakkad, comprising of more than 60 per cent of the study area, depth to water table during pre- monsoon periods from 2008 to 2013 ranged from 5.1 m to 8.1 m (light violet). In some parts of Thirurangadi, Vengara and Kuttippuram blocks, the average depth to water table varied from 7.0 m to 10.2 m (Yellowish green) whereas, at elevated parts of Thirurangadi and Vengara, it varied from 8.9 m to 12.5 m (light green). In small pockets of the river basin, pre-monsoon average depth to water table varied from 3.0 m to 6.2 m and 10.8 m to 14.9 m as influenced by the elevation and aquifer properties of the area.

Similar trends were observed in post monsoon water table maps of the study period from 2008 to 2013 as shown in Fig. 28. The post monsoon depth to water table varied from 2.5 m to 5.8 m (light violet) and 4.3 to 8.0 m (Yellowish green) in major parts of the study area. The fluctuation between pre- monsoon and post monsoon is more important than the annual water table fluctuation for ground water development and management activities, as these values reflect the effective ground water recharge due to rainfall (Prasad *et al*., 2007). The magnitude of fluctuation depends up on the quantity of water recharge and discharge (Muhammad, *et al*., 2012).

Fig. 29 shows the average ground water fluctuation map between pre monsoon and post monsoon period during 2008 to 2013. From the figure, it was observed that the ground water fluctuation is almost similar along the central and eastern part of the study area and ranged from1.31 m to 2.65 m. In coastal region and some part of Kondotty, Thirurangadi, Tanur and Wandoor, ground water fluctuation was 2.65 m to 3.98 m, due to the remarkable recharge from rainfall. This indicated that the aquifer formation in this area has high porosity and permeability. Coastal alluvium and laterite constitute potential aquifer because of its high porosity and permeability and the area other than coastal region are mostly occupied with laterite aquifer. Report of CGWB (2013) and Prasad *et al*., (2007) are also supported this results. However, the groundwater drains off easily from such aquifer in certain locations after the monsoon due to the over exploitation of ground water for agriculture and domestic purposes and along the hills and slopes, high fluctuation is due to the faster natural discharge (Prasad *et al*., 2007). This was proved by the maximum fluctuation (7.98 m) of water level noted from the well OW24, located at Marakara, high elevated (98.54m) area of the study basin.

Fig. 30 shows the pre-monsoon and post monsoon ground water level AMSL against average annual ground water level AMSL at different physiographical regions during the study period from 2008 to 2013. From the figure, it could be seen that the depth of water table was low and varied from 2008 to 2013 in low land area when compared to mid land and high land area. This indicated that the depth of water table

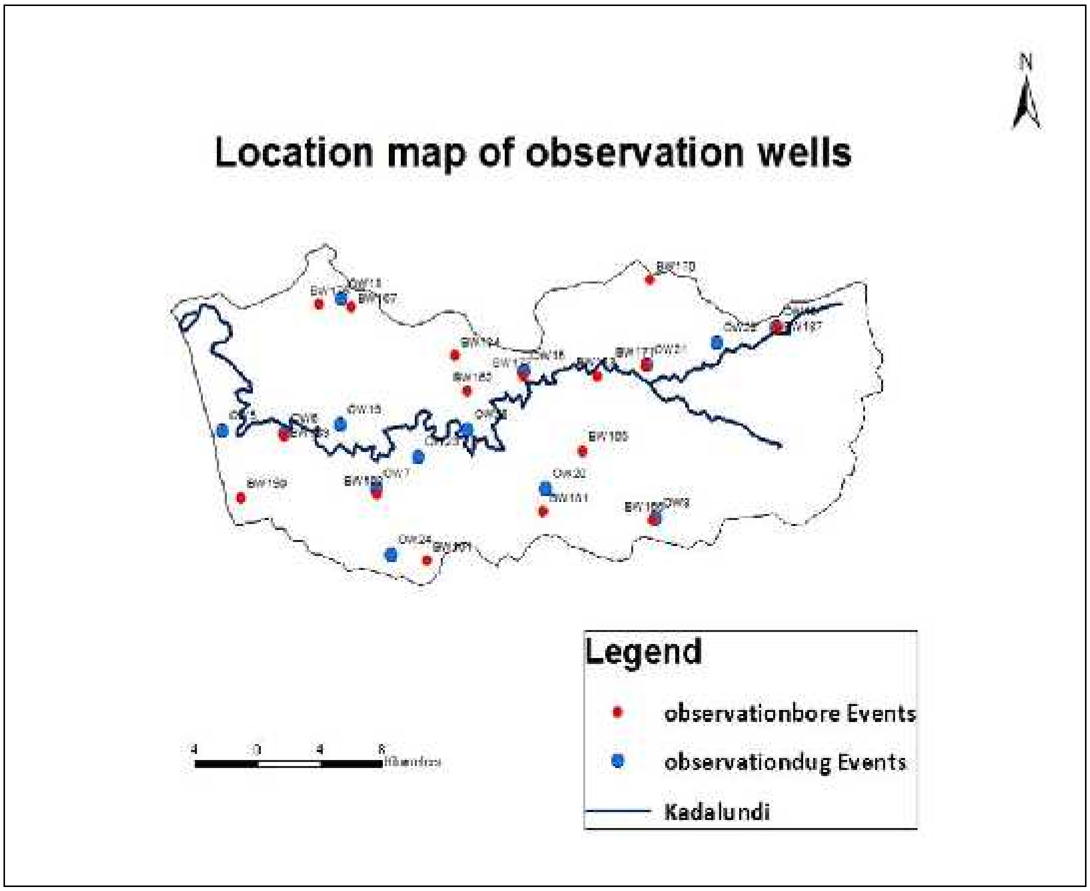


Fig. 26. Location map of observation wells

Table 6. Pre and post monsoon variations of water level in dug wells

Well Name	Pre Monsoon water table, m							Post Monsoon water table, m							Fluctuations, m
	2008	2009	2010	2011	2012	2013	Average	2008	2009	2010	2011	2012	2013	Aver-age	
OW18	3.21	5.81	5.91	4.77	4.76	6.48	5.16	0.82	0.57	0.69	0.74	1.3	0.95	0.85	4.31
OW15	6.07	6.24	6.32	5.98	6.42	6.97	6.33	5.21	5.26	4	5.17	5.53	4.95	5.02	1.31
OW7	9.6	9.75	9.71	10.28	9.42	10.37	9.86	7.71	7.55	7.35	7.82	7.39	7.63	7.58	2.28
OW28	3.57	3.52	3.18	3.41	3.18	4.29	3.53	2.5	1.74	2	2.16	1.56	1.86	1.97	1.56
OW5	3.04	4.69	4.68	3.63	4.7	5.11	4.31	0.98	1.17	1.06	1.9	1.87	0.72	1.28	3.03
OW6	9.64	11.82	11.01	12.61	10.71	10.44	11.04	8.7	8.68	8.43	8.47	8.68	8.61	8.60	2.44
OW9	6.96	7.7	6.64	6.79	6.93	7.83	7.14	5.99	5.39	4.56	4.89	6.05	6.01	5.48	1.66
OW19	11.14	11.95	12.34	11.92	12.65	13.01	12.17	10.15	9.85	9.32	9.8	10.07	10.08	9.88	2.29
OW23	13.53	14.31	12.85	12.48	14.86	13.85	13.65	10.91	11.36	9.75	11.85	12.52	11.88	11.38	2.27
OW10	4.27	4.29	4.88	3.49	4.19	4.61	4.29	1.53	2.04	1.49	2.27	1.87	2.08	1.88	2.41
OW21	5.68	4.49	4.61	3.31	4.14	5.22	4.58	1.23	1.75	1.85	1.76	2	1.79	1.73	2.85
OW22	11.37	10.67	10.98	10.33	11.32	11.09	10.96	6.43	7.28	7.84	7.06	7.7	8.84	7.53	3.44
OW20	6.14	6.19	5.56	6.64	6.46	7.12	6.35	3.96	4.99	4.18	4.74	4.63	4.62	4.52	1.83
OW24	13.55	13.34	13.1	8.23	12.28	12.35	12.14	4.17	4.31	3.52	4.00	4.38	4.58	4.16	7.98

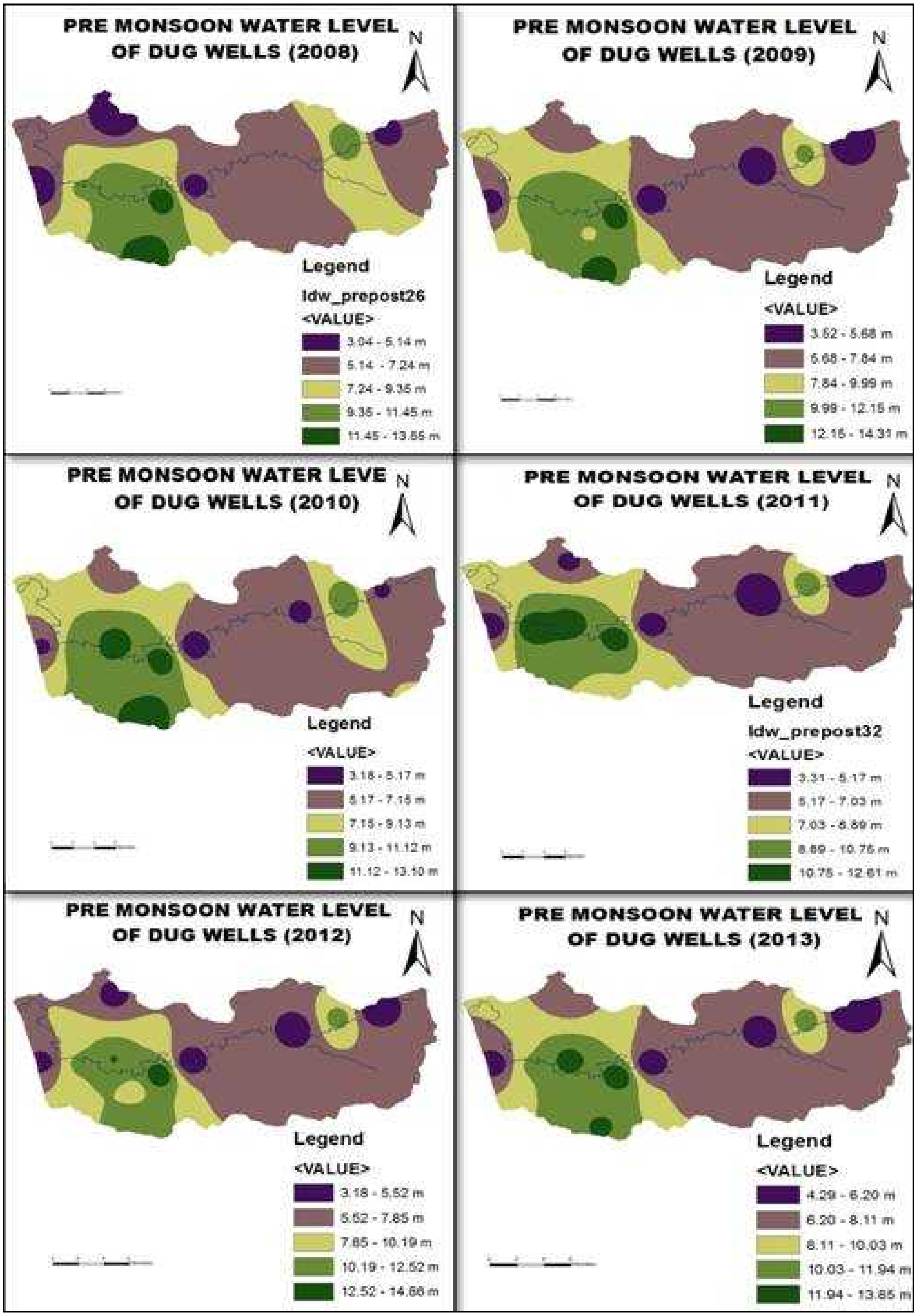


Fig. 27. Pre- monsoon water level map of dug wells during 2008 to 2013

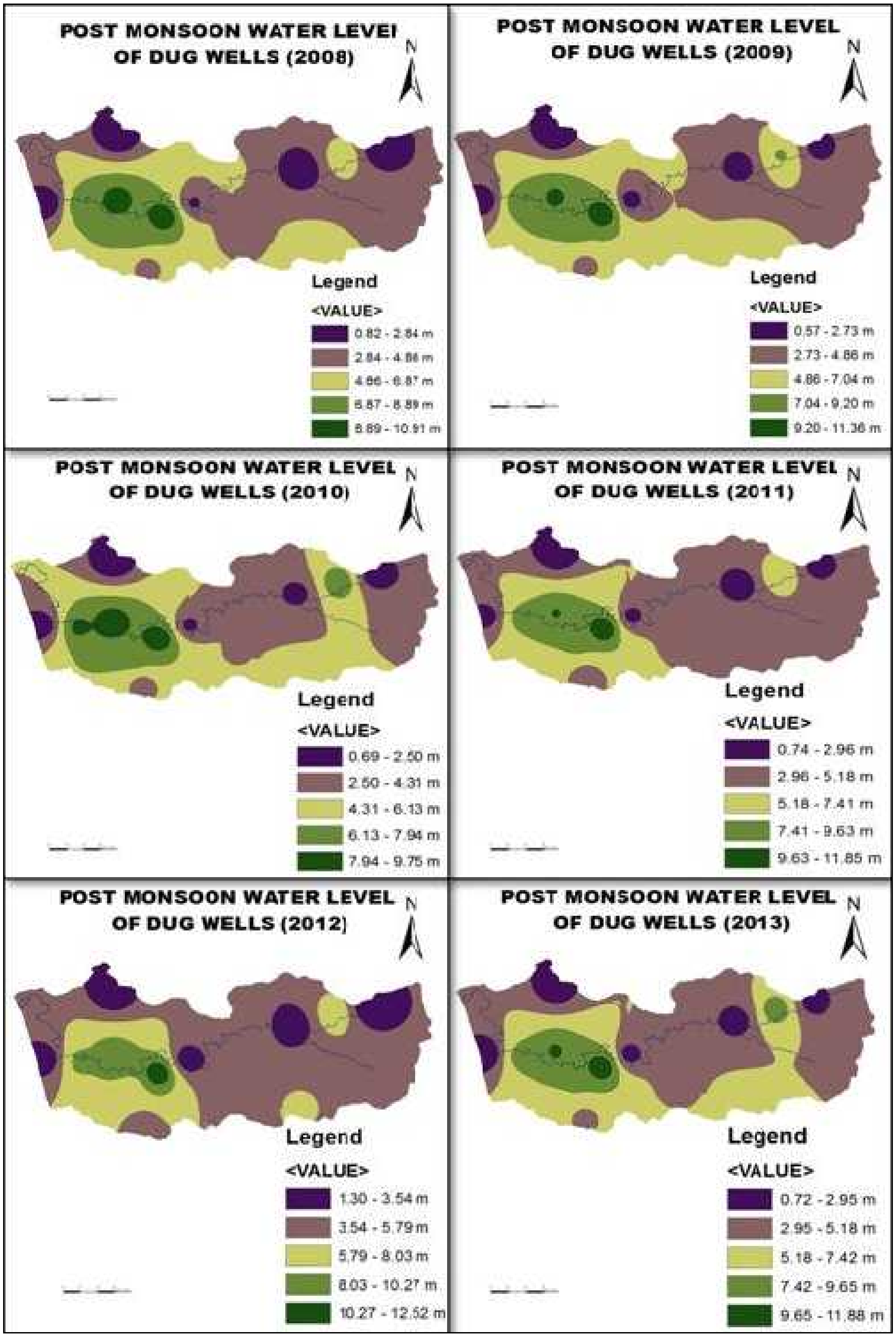


Fig. 28. Post monsoon water level map of dug wells during 2008 to 2013

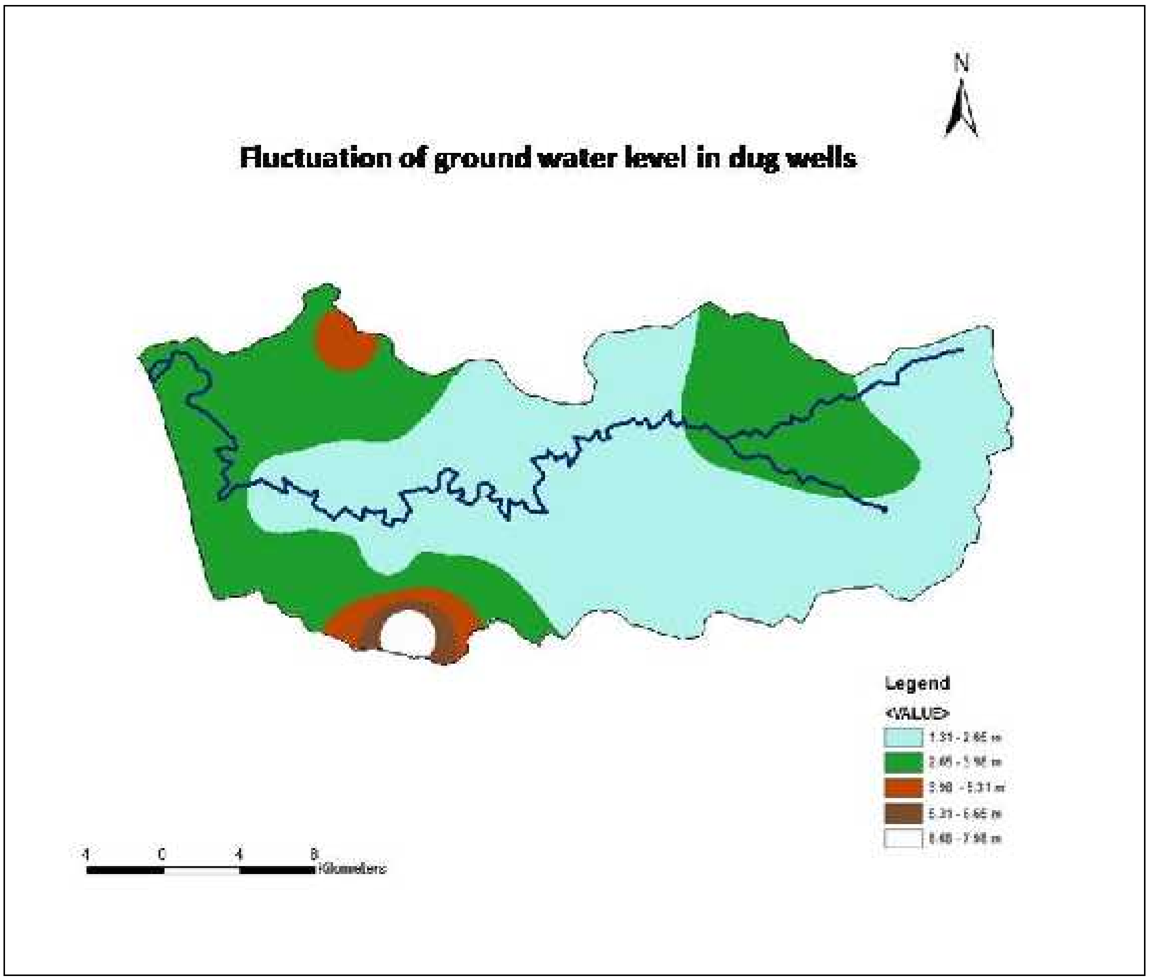
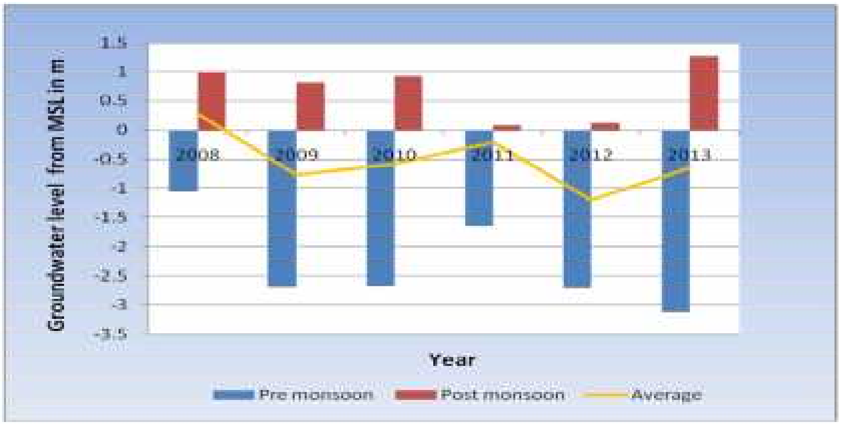
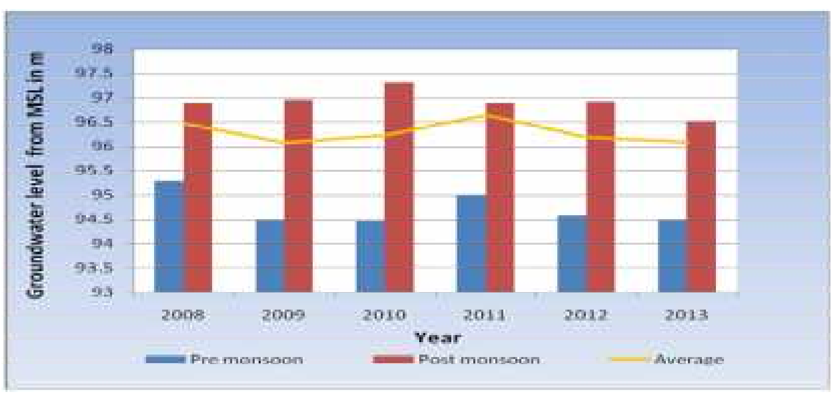


Fig. 29. Ground water recharge map of dug wells



Low land

Mid land



High land

Fig. 30. Pre and post monsoon ground water table of dug wells in different pysiographical region

and its temporal variation in the area is closely related to topography and aquifer properties of the area. Pichaiah *et al*., (2013) also support this findings that the depth to water level is closely related to topography, extraction bodies and rainfall.

4.1.1.2 Groundwater table hydrograph

Variations in the ground water table primarily reflects the relationship between recharge, discharge, land slope and the influence of aquifer properties. The depth of ground water table recorded from the dug wells located at different physiographic regions such as low land, mid land and high land areas were used to prepare the water table hydrographs corresponding to the variation of rainfall in the study area. The different physiographical regions identified for this study are shown in Fig. 31.

The magnitude of annual ground water table fluctuation in an observation well is considered as the difference between maximum and minimum depth to water level during that year. The maximum and minimum depth to water table and annual fluctuations of water table during six consecutive years in low land, mid land and high land area are given in Table 7, 8 and 9 respectively. The minimum and maximum values reflected the response of rainfall on the ground water table in the area.

Dug wells located at Parappanagadi (OW5) and Thirurangadi (OW6) were selected in the low land region for water table fluctuation study . From Table 7, it was noted that in dug well OW5, the minimum and maximum depth to water table was recorded during 2013 and it was found to be 0.19 m and 5.11 m respectively. In dug well OW6, the minimum and maximum depth to water table was recorded during 2011 and it was found to be 6.45 m and 12.61 m respectively. The depth to water table was more in well OW6, because this well is situated in a more elevated area (11.06 m) than OW5 well (2.45 m). The water level is more deeper in topographically elevated region and shallower in plain surface. Hence it can be said that the thickness of aquifer formation is more in Thirurangadi area.

Annual fluctuations of water table in OW5 during the study period were similar except for 2013. In OW6, annual water table fluctuations were varying year by year depending on the rainfall as well as the aquifer properties. This also in agreement with the data obtained from Fig. 32 (a). The fluctuations of water table in OW6 was found to be more correlated with rainfall variations (coefficient of correlation, r = 0.55) than fluctuations of water table in OW5, r = 0.18 (Fig.33a). Well OW5 located at Parappanagadi, is more closer to Arabian sea and hence the influence of sea water may be a reason for low correlation of water table with rainfall.

Temporal variations of water table from 2008 to 2013 were analyzed using ANOVA (F- test) and the results are given in Table 10 and also in Appendix VI. From the table, it could be seen that $F_{calculated}$ value of wells OW5 and OW6 were less than $F_{critical}$ value, which indicated that there was no temporal variation of water table in both the wells during the period from 2008 to 2013.

In mid land region, dug wells located at Kondotty (OW18), Anakayam (OW15) and Malappuram (OW28) were selected for the study. From Table 8, it could be seen that the minimum and maximum depth to water table were found to be 1.71 m and 6.97 m in well OW15, 0.12 m and 6.48 m in OW18 and 0.98 m and 4.29 m in OW28 respectively. It was also seen that the minimum and maximum depth to water table and maximum fluctuations were observed during 2013 for all wells.

The temporal variation of depth to water table in mid land region is shown in Fig.32 (b). From the figure, it was noted that the water level in all the three wells are similar and the trend of variations was also similar in nature. This is in agreement with the results of F- test, $F_{calculated}$ values of all three wells were less than $F_{critical}$ values (Table 10), which indicated that there was no temporal variations of water table in both the wells during the period from 2008 to 2013.

Statistical analysis were carried out to check the correlation of variation between water table and rainfall and the results are shown in Fig. 33(b). The correlation of water table with rainfall for wells OW15, OW18 and OW28 are found to be 0.53, 0.43 and 0.57 respectively. Fluctuations of ground water table of all three wells are on par with variations of rainfall. The correlation coefficient also indicated that the ground water level fluctuation in a region depends not only on rainfall but also several factors like topography, infiltration, geology, geomorphology, ground water gradient, weathering, presence of fractures etc (Rajaveni, *et al.*, 2014).

Dug wells at Thuvvur (OW22), Othukkungal (OW23) and Marakara (OW24) were selected for analysis in the high land region. From Table 9, it was seen that the minimum and maximum depth to water table were 10.71m and 14.42 m in OW24, 5.28 m and 12.04 m in OW22 and 8.14m and 14.86 m in OW23 respectively. It was also observed that the minimum and maximum values of depth to ground water table were almost same during every year from 2008 to 2013 for all wells. This indicated that spatial variations exist in high land region but no temporal variation during the study period from 2008 to 2013 and this is in agreement with the results of F- test (Table 10).

The annual fluctuation ranged from 2.12 m to 3.35 m in OW 24, 3.48 to 6.62 m in OW22 and 3.86 to 5.99 m in OW 23 and the fluctuations in OW24 was almost constant for every year when compared to other two wells, which is evident from Fig. 32(c). It could be seen that the depth to water table was almost similar for all wells during the study period. Statistical analysis were carried out to check the correlation of variation between water table and rainfall and the results are shown in Fig. 33(c). The correlation coefficient (r) of water table with rainfall in wells OW24, OW22 and OW23 are found to be 0.26, 0.52 and 0.61 respectively. Fluctuations of ground water table in wells OW22 and OW23 were highly correlated with variations of rainfall whereas in the case of OW24 located at high elevated area (98.54 m),

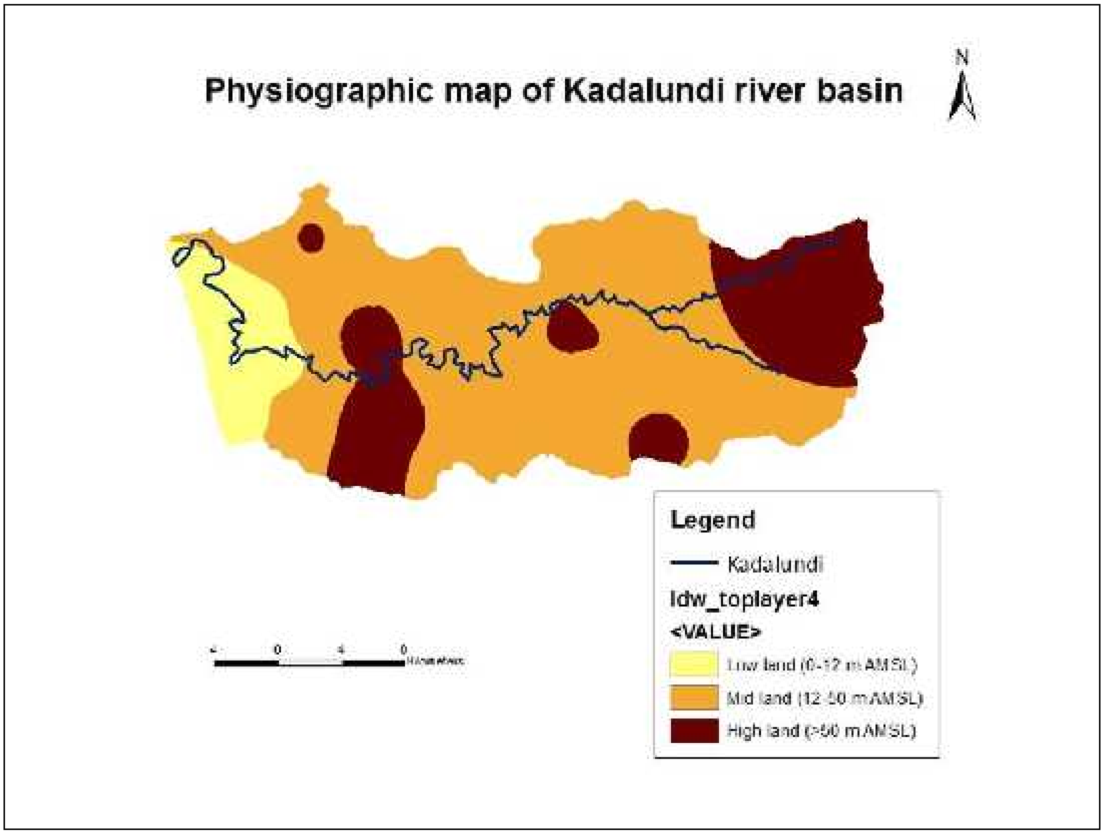


Fig.31. Different physiographical regions identified for the study

Table 7. Depth to ground water level in dug well of low land area

Year	Maximum depth, m		Minimum depth, m		Annual fluctuations, m	
	OW5	OW6	OW5	OW6	OW5	OW6
2008	3.04	10.02	0.47	8.32	2.57	1.70
2009	4.69	11.82	0.90	7.08	3.79	4.74
2010	4.68	11.01	0.89	8.33	3.79	2.68
2011	3.66	12.61	0.73	6.45	2.93	6.16
2012	4.70	12.58	0.85	7.39	3.85	5.19
2013	5.11	10.44	0.19	7.11	4.92	3.33

Table 8. Depth to ground water level in dug well of mid land area

Year	Maximum depth, m			Minimum depth, m			Annual fluctuations, m		
	OW15	OW18	OW28	OW15	OW18	OW28	OW15	OW18	OW28
2008	6.07	4.31	4.03	1.87	0.77	1.97	4.20	3.54	2.06
2009	6.39	6.40	4.21	1.86	0.35	1.59	4.53	6.05	2.62
2010	6.35	5.91	4.08	2.96	0.54	1.67	3.39	5.37	2.41
2011	6.25	4.77	3.72	2.92	0.12	1.08	3.33	4.65	2.64
2012	6.42	5.36	3.89	3.86	0.39	1.56	2.56	4.97	2.33
2013	6.97	6.48	4.29	1.71	0.37	0.98	5.26	6.11	3.31

Table 9. Depth to ground water level in dug well of high land area

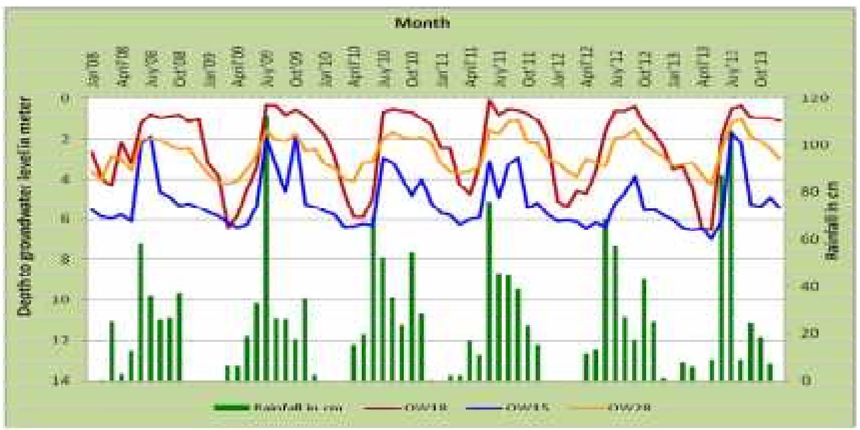
Year	Maximum depth, m			Minimum depth, m			Annual fluctuations, m		
	OW24	OW22	OW23	OW24	OW22	OW23	OW24	OW22	OW23
2008	13.62	11.37	13.53	11.5	6.43	9.67	2.12	4.94	3.86
2009	14.41	12.04	14.31	11.4	6.06	8.32	3.01	5.98	5.99
2010	14.43	10.98	14.21	11.53	7.50	9.70	2.90	3.48	4.51
2011	13.9	11.63	13.81	10.71	6.51	8.14	3.19	5.12	5.67
2012	14.31	11.42	14.86	11.27	7.56	9.82	3.04	3.86	5.04
2013	14.42	11.9	13.85	11.07	5.28	8.28	3.35	6.62	5.57

the fluctuations of water table was poorly correlated with variations of rainfall. This indicated that the ground water level fluctuation in a region depends not only on rainfall but also several other factors like topography, infiltration, geology, geomorphology, ground water gradient, weathering, presence of fractures etc (Rajaveni, *et al.*, 2014). This results is also supported by the findings of Deller, (1999) who stated that recharge to an aquifer is controlled by the elevation difference between discharge and recharge area.

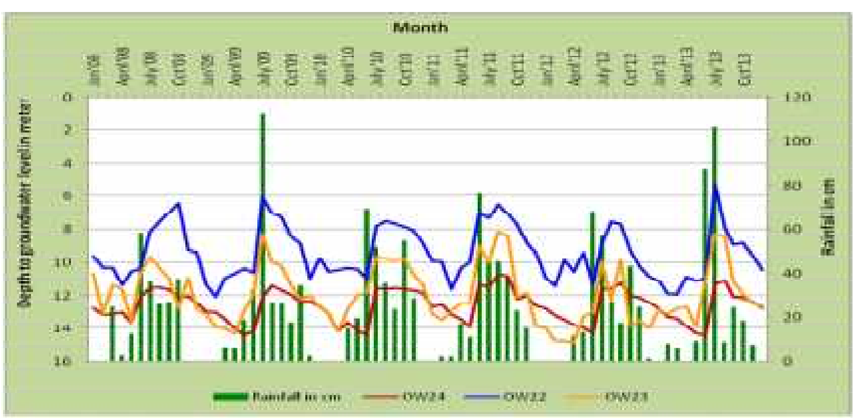
Table 10. Results of analysis of variance (F –test) for the water table

Sl. No.	Physiographic regions	Well Name	F calculated	F - critical
1	Low land	OW5	1.66	2.35
		OW6	0.60	2.35
2	Mid land	OW18	0.42	2.35
		OW15	0.60	2.35
		OW28	0.25	2.35
3	High land	OW24	0.63	2.35
		OW22	0.79	2.35
		OW23	1.73	2.35

a. Low land

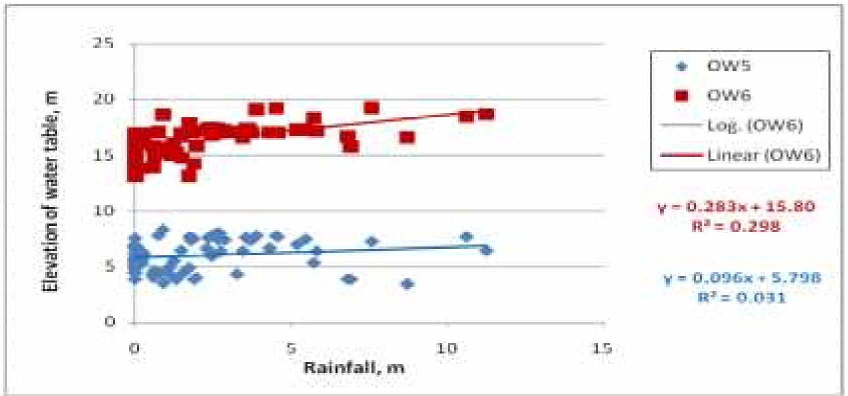


b. Mid land

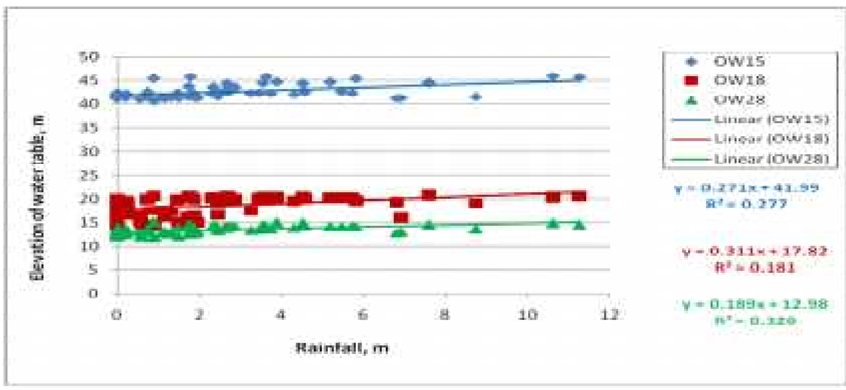


c. High land

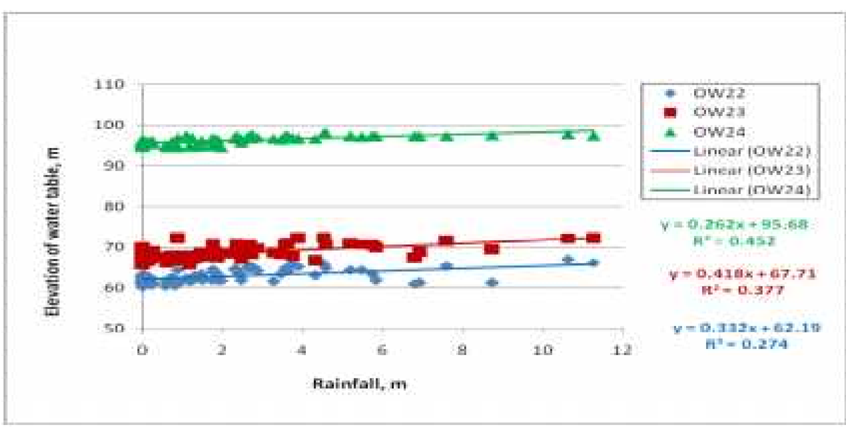
Fig. 32. Variation of ground water level in dug wells from different physiographical regions



a. Low land



b. Mid land



c. High land

Fig. 33. Plot of linear regression and correlation between ground water table and rainfall

A general observation of water level data from the dug wells indicated that water table tends to rise during June to September, reaching the peak in September and started to decline from October to the end of May in every year. The rise and fall depend upon the amount, duration and intensity of rainfall, thickness of weathered zone, specific yield of the formation and general slope of the aquifer bottom towards the drainage channel. It was also observed that the water table fluctuation in low land, mid land and high land area is correlated with rainfall except few locations. This indicated that the major part of the basin occupies laterite formations having porous and highly permeable in nature. Hence it is presumed that the potential aquifer of the basin and dug wells are the suitable abstraction structure in the aquifer as report by CGWB (2013) and (Prasad *et al*., 2007).

4.1.2 Spatial and temporal variations of piezometric water levels

Spatial and temporal variations of piezometric water level reveal the geological and geo-morphological characteristics of subsurface formations from which the bore wells draw water and can be considered as the prime tool of ground water resources assessment. Piezometric water level from sixteen bore wells located at different physiographical regions were analyzed using pre and post monsoon variations and piezometric water level hydrographs.

4.1.2.1 Pre and post monsoon variations

Ground water table for the months of April and October months were monitored to study the pre- monsoon and post monsoon fluctuations. The peizometric water levels during pre- monsoon and post monsoon were observed and the difference in piezometric water levels between pre and post monsoon are given in Table 11. The variation of piezometric water level between pre and post monsoon indicates groundwater resources replenishment in the study area. From the table it is revealed that the maximum fluctuation was 8.64 m in BW 166 located at Perinthalmanna at a highly elevated area of 53.98 m and minimum was 0.30 m in BW190 located at Tanur, coastal region with an elevation of 3.80 m. Most of the bore wells are located in mid land region, where the piezometric water level fluctuation between pre and post monsoon is ranged from 0.78 m to 3.48 m.

Piezometric water level maps were prepared for both pre and post monsoon for the bore wells during six consecutive years using Arc GIS (10.1) and are shown in Fig. 34 and 35 respectively. The Fig. 34 indicated that the pre-monsoon variation was same during all the six years. Major part comprising of more than 75 per cent of the total study area, depth to piezometric water level in pre- monsoon period was ranged from 2.6 m to 9.5 m (red) and 7.6 m to 15.4 m (yellow) during the study period. Higher depth to piezometric water levels were seen in some part of Thirurangadi, Tanur, Vengara, Malappuram and Kuttippuram blocks which ranged from 12.5 m to 32.9 m (bluish green, blue and navy blue).

From Fig. 35, it could be seen that the post monsoon piezometric water level maps follow similar trend during all the six years of the study (2008 to 2013). It was also observed that the increase in piezometric water level is directly proportional to the rainfall in major part of the study area. This may be due to the fact that the bore wells in that area is mainly abstract water from fractured aquifers in the crystalline formations and ground water occurs under semi- confined to shallow confined aquifers.

Fig. 36 shows the average ground water fluctuation map between pre- monsoon and post monsoon in bore wells during 2008 to 2013. From the figure, it could be seen that major portion of the study area, the piezometric water fluctuation is almost similar and is 1.97 to 3.68 m. This indicated that in major part of the study area, the laterite formation overlying the weathered crystalline rock, are the potential aquifer for bore wells. This is in agreement with the findings of Prasad, *et al*.,(2007) who stated that " in coastal region, alluvial deposits is followed by laterites, lithomargic clay, weathered

Table 11. Pre and post monsoon variations of piezometric water level in bore wells

Well Name	Pre Monsoon piezometric water level, m							Post Monsoon piezometric water level, m							Fluctuations, m
	2008	2009	2010	2011	2012	2013	Average	2008	2009	2010	2011	2012	2013	Average	
BW167	7.79	8.09	8.39	7.54	7.55	8.85	8.04	6.55	6.18	5.02	5.93	6.4	5.71	5.97	2.07
BW175	8.01	8.7	10.4	9.47	10.18	14.13	10.1	3.94	6.57	1.95	6.66	7.12	6.01	5.38	4.77
BW163	29.1	28.2	27.6	27.1	25.56	27.18	27.5	27.83	27.5	26.54	25.42	24.15	25.38	26.14	1.31
BW162	4.57	4.27	6.65	4.66	4.37	6.05	5.1	3.08	2.23	2.61	3.23	3.39	3.17	2.95	2.14
BW177	2.77	2.55	2.6	2.59	2.65	3.7	2.8	1.72	2	0.97	1.39	2.1	0.82	1.5	1.31
BW183	6.75	8.32	8.44	6.8	8.35	9.3	7.99	2.63	4.89	4.17	4.79	5.86	5.28	4.60	3.39
BW184	6.65	7.41	6.97	5.55	6.8	8.28	6.94	4.86	2.44	2.56	3.88	3.78	3.26	3.46	3.48
BW166	19.0	26.3	22.6	21.48	25.89	32.87	24.7	12.96	13.5	15.12	9.18	22.43	23.24	16.07	8.64
BW189	22.8	20.6	30.6	27.38	28.34	18.66	24.7	26.04	18.8	20.3	25.08	27.13	13.32	21.77	2.94
BW187	4.06	3.35	3.67	2.94	3.7	5.16	3.81	1.69	1.77	1.76	1.89	2.71	1.99	1.97	1.85
BW170	5.08	4.95	5.17	5.05	5.05	5.43	5.12	3.41	4.79	4.73	4.88	4.86	4.81	4.58	0.54
BW171	8.59	8.86	8.76	10.37	10.31	9.63	9.42	6.4	7.86	7.22	7.26	8.4	8.15	7.55	1.87
BW165	3.86	4.51	5.95	3.72	4.03	4.56	4.43	2.5	1.65	2.45	1.97	2.91	3.19	2.45	1.99
BW181	5.81	5.95	5.82	5.9	5.92	6.22	5.93	5.48	5.68	3.73	5.12	5.4	5.51	5.15	0.78
BW190	3.28	3.44	3.47	3.34	3.53	3.82	3.48	3	3.09	3.34	3.06	3.23	3.35	3.18	0.30
BW161	13.6	14.4	14.4	13.9	14.31	14.42	14.2	12.02	11.9	11.6	12.01	11.99	12.39	11.99	2.19

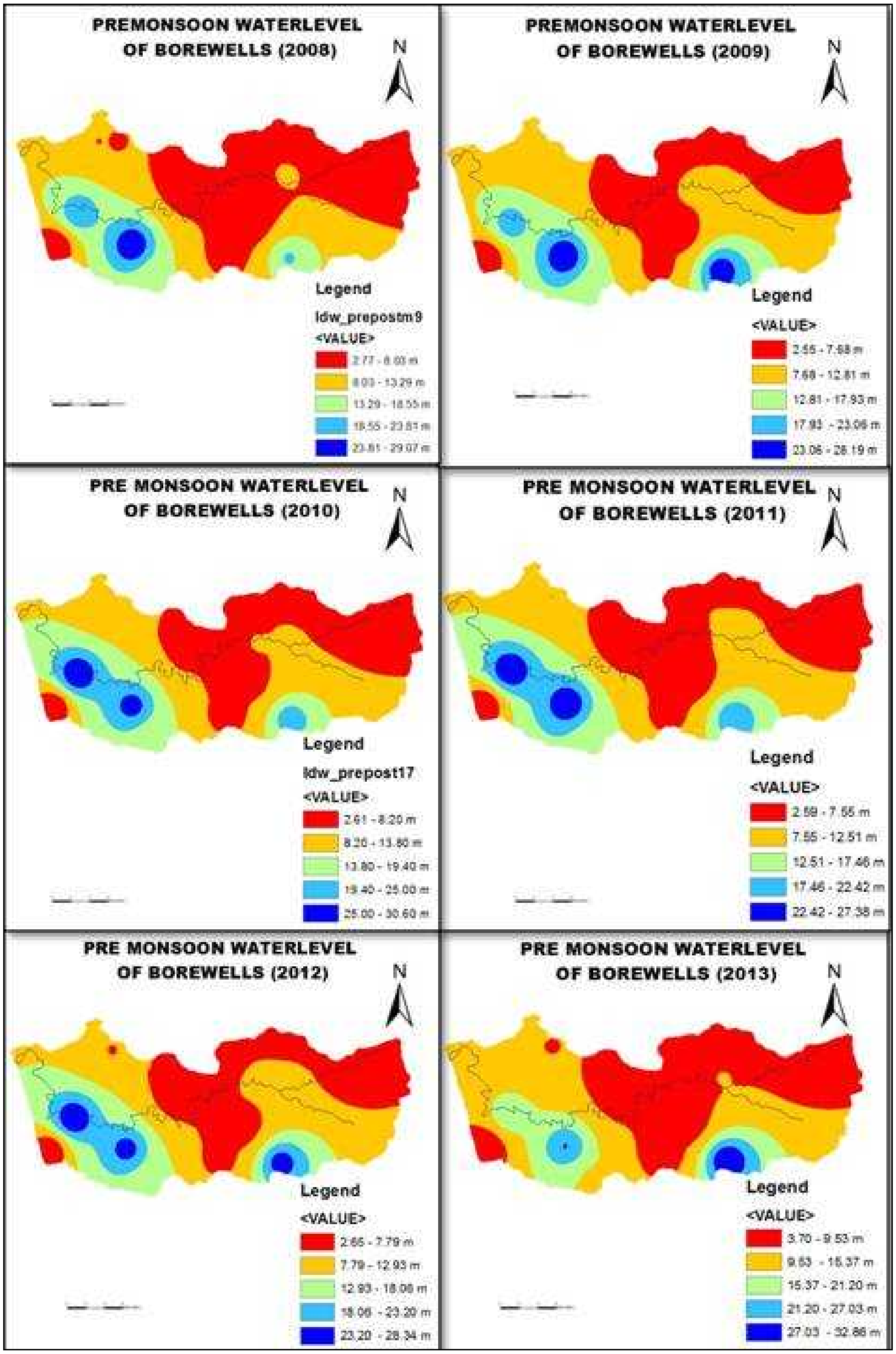


Fig. 34. Pre- monsoon water level map of bore wells during 2008 to 2013

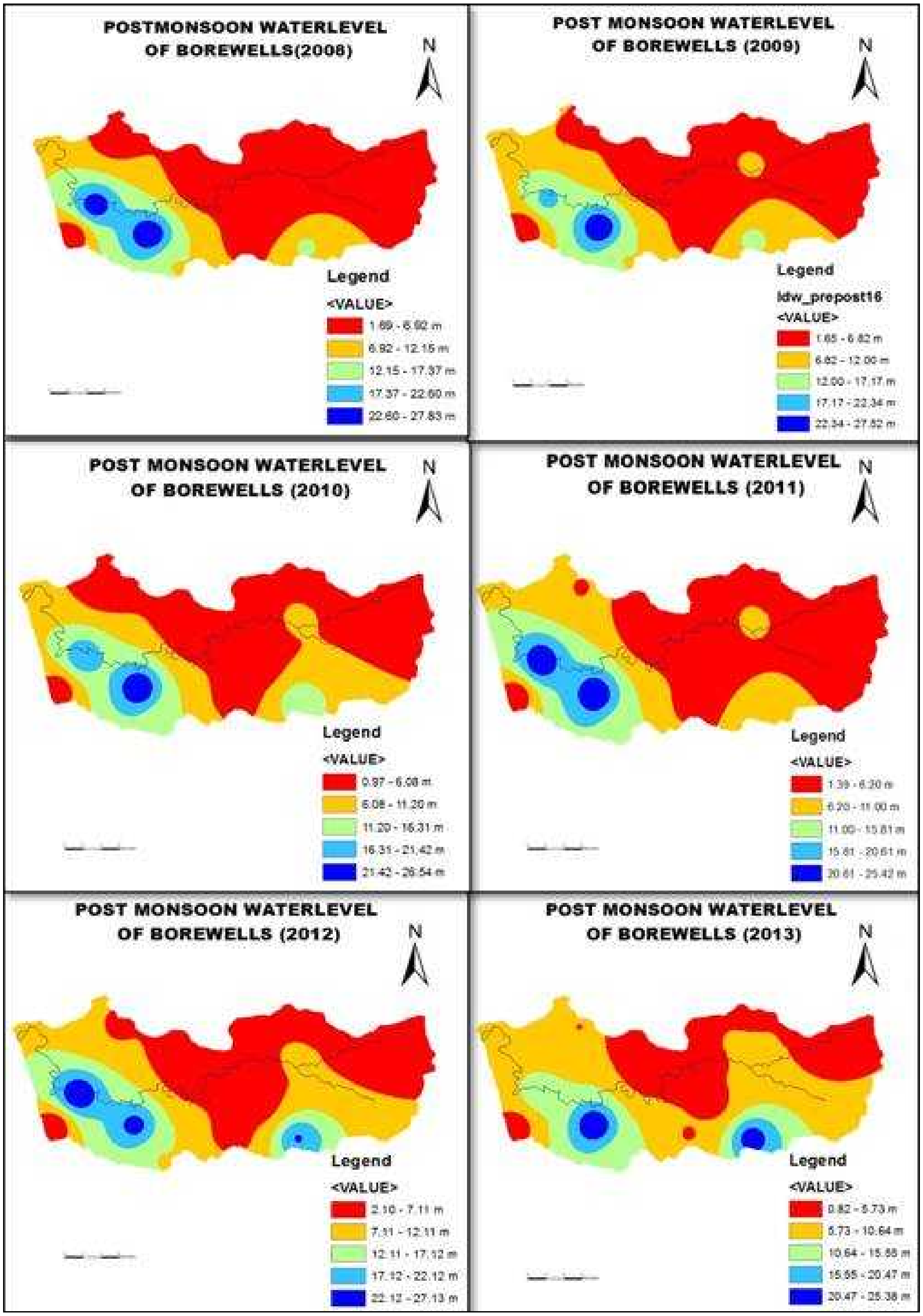


Fig.35. Post monsoon water level map of bore wells during 2008 to 2013

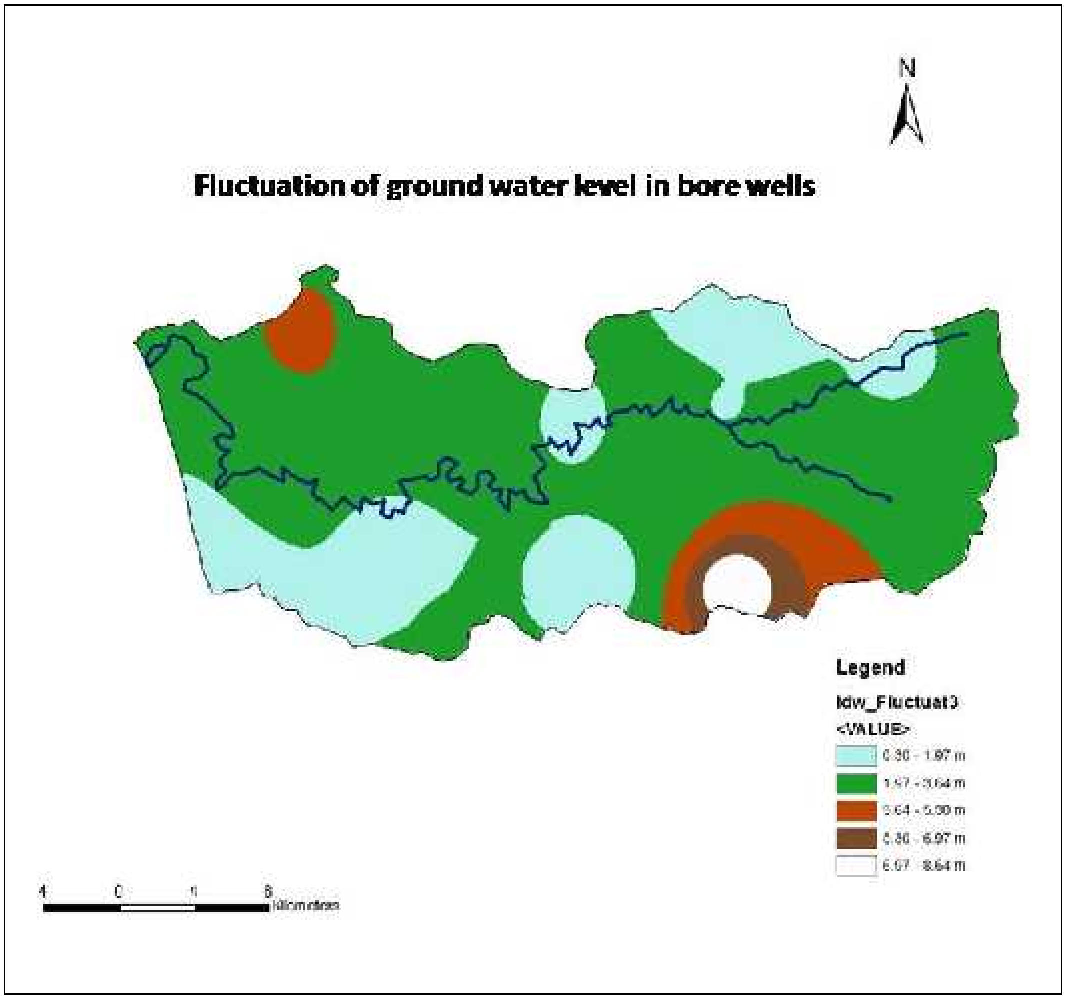


Fig. 36. Ground water recharge map of bore wells

and hard rock. In mid land region, laterites of 5 to 20 m overlying lithomargic clay and followed by weathered rock/ hard rock with fractures. In high land region the area is covered by brown soil of 1 to 3 m thickness followed by laterites, weathered rock and hard rock with or without fractures."

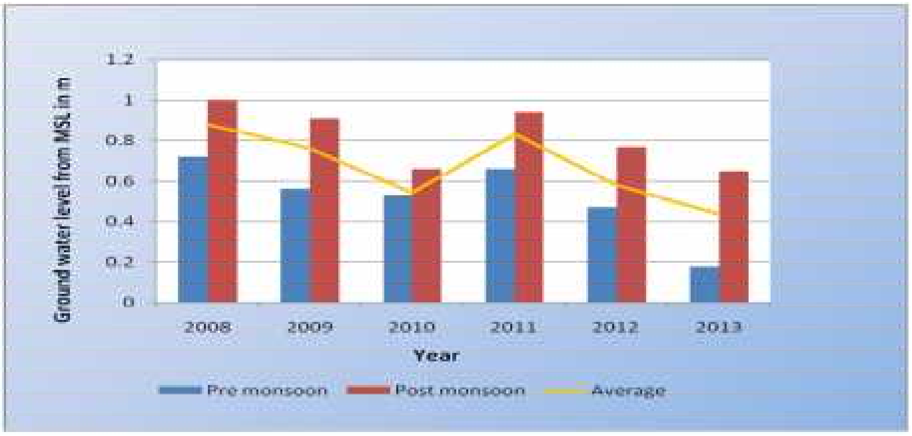
Fig. 37 shows the pre-monsoon and post monsoon piezometric head against average annual piezometric water level above mean sea level of bore wells during six consecutive years from 2008 to 2013 for different physiographical regions. From the figure, it can be seen that the average elevation of piezometric level was almost same during the every year of study in all physiographical region.

4.1.2.2 Piezometric water level hydrograph

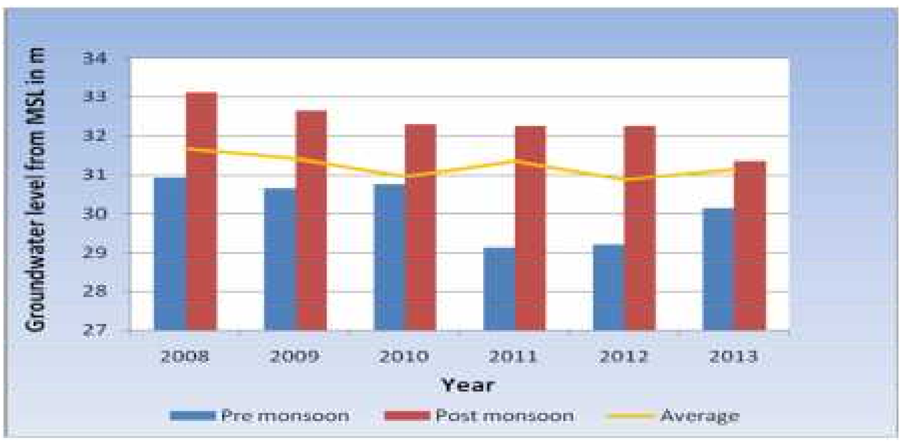
The piezometric water level recorded from sixteen bore wells located at different physiographic regions such as low land, mid land and high land areas (Fig. 26) were used to prepare the piezometric water level hydrographs corresponding to the variation of rainfall in the study area.

The minimum, maximum and annual fluctuations of piezometric water levels in bore wells during six consecutive years in low land, mid land and high land area are given in Tables 12, 13 and 14 respectively. The minimum and maximum values reflect the response of properties of aquifer on ground water levels in that area

In low land region, bore wells located at Thirurangadi (BW189), Kuttippuram (BW161) and Tanur (BW 190) were selected for the analysis. From the Table 12, it could be seen that the minimum depth to water level ranged from 3 m to 3.35 m and maximum from 3.28 m to 4.34 m in BW190 and it was ranged from 2.17 m to 3.53 m and 6.8 m to 7.6 m respectively in BW 161. This indicated that there was no temporal variations in piezometric levels in BW190 and BW161 during the period from 2008 to 2013. Hence the annual fluctuations were almost similar from 2008 to 2013 in both the wells BW190 and BW 161, whereas in BW189, the minimum and maximum.



Low land



Mid land

High land

Fig. 37. Pre and post monsoon ground water levels of bore wells in different physiographical region

depth to water level ranged from 12.06 m to 23.36 m and 20.10 m to 30.60 m respectively and annual fluctuation varied from 16.24 m to 26.75 m. This indicated that temporal variations existed in Thirurangadi region. This was in agreement with the results of analysis of variance (F- test) given in Table 15 and Appendix VII (F value of BW 189 is 14.09, which was much greater than $F_{critical}$, 2.35). From the table it can be seen that temporal variation existed during 2008 to 2013 in OW 190 located at Tanur, nearer to the coastal region. In the case of OW 161, there was no temporal variation of piezometric water level during 2008 to 2013.

The depth to piezometric water table was more in the case of BW189 than BW190 and BW161 was observed from the Fig. 38 (a). This indicated that BW189 abstract ground water from deep confined aquifer, whereas BW161 and BW190 abstract ground water from shallow semi-confined aquifer and this also indicated the presence of lithomargic clay with varying depth as confining layer of shallow bore wells. This is in agreement with the findings of Prasad, *et al*., (2007) and litholog data available from Ground water Department, Malappuram, Govt. of Kerala.

Statistical analysis was carried out to check the correlation between fluctuations of piezometric water level and rainfall and the results are shown in Fig. 39(a). From the figure, it could be seen that the correlation between piezometric water level with rainfall for the wells BW190, BW189 and BW161 were found to be 0.03, 0.22 and 0.55 respectively. Fluctuation of ground water table in well BW161 was highly correlated with variation of rainfall than that for BW189. In the case of BW190, the fluctuation of water table was very poorly correlated with variation of rainfall. The well BW190 is located very near to sea shore and abstracted water from shallow sandy aquifer, hence the influence of sea water may be a reason for low correlation of water table with rainfall. Litholog data of this region available from Ground water Department, Govt. of Kerala is supporting this results.

In mid land region, bore wells located at Pandikkad (BW171), Mankada (BW165) and Anakkayam (BW177) were selected for the analysis. From Table 13, it could be seen that the annual fluctuation of piezometric water level ranged from 3.19 m to 4.38 m in BW171 and it ranged from 1.78 m to 5.52 in BW165, whereas in BW177, the annual fluctuation of water level ranged from 1.03 m to 4.03 m during the study period. This indicated that the annual fluctuation was slightly more in BW165 when compared with BW171 and BW177. This was also supported by the analysis of variance (F- test) given in Table 15. From the table it could be seen that the F value of well BW165 was slightly higher than the $F_{critical}$ value, which indicated that a small temporal variation of piezometric water level existed during 2008 to 2013, whereas in the case of BW171 and BW 177, there was no temporal variation.

From Figure 38 (b) it could be observed that the depth to piezometric water level was more in the well BW171 compared to BW 177 and BW 165, although the elevation of all the wells are same (32.74, 31.33 and 38 respectively). It was also observed that the variations of all wells are similar and correlated with variations of rainfall. This was also proved from the results of the statistical analysis and the resulting graph is shown in Fig. 39(b). From the figure, it was observed that the BW171 was more correlated ($r = 0.64$) with rainfall variations than BW177($r = 0.52$) and BW165 ($r = 0.34$). This is proved that a regional confined aquifer is directly recharged by rainfall in the area where the aquifer crops out, having the same characteristics as an unconfined aquifer (http://echo2.epfl.ch/VICAIRE/mod_3/chapt_9/main.htm).

Bore wells located at Malappuram (BW175), Kottakkal (BW163) and Karuvarakundu (BW187) were selected for the analysis of high land region. From Table 14, it could be seen that the minimum and maximum depth to piezometric water level ranged from 0.21 m to 3.44 and 8.51 m to 14.13 m respectively in BW175 and it ranged from 0.65 m to 1.69 m and 3.38 m to 5.16 m respectively in BW187.

This indicated that the depth to piezometric water levels in wells BW175 and BW187 were very low when compared to depth to piezometric level in BW163, where the minimum and maximum depth to water level ranged from 23.71 m to 27.83 m and 25.56 m to 29.52 m respectively. It was also observed that the annual fluctuation is minimum in BW163, ranged from 1.35 m to 3.30 m when compared to BW175and BW187 where it ranged from 5.07 m to 13.15 m and 2.05 m to 4.49 m respectively. This is clearly depicted in Fig. 38 (c).

From the results of F-test (Table 15) it was observed that there was no temporal variation of piezometric water level in wells BW175 and BW187 during 2008 to 2013, whereas in the case of BW163, there was notable variation during 2008 to 2013 (F value is 47.09). It can also be noted that piezometric water level of BW163 was poorly correlated with rainfall (r value of 0.13) as shown in Fig. 39(c). This indicated that the bore well BW163 is located in hard rock terrain of Kottakkal, originating from deep confined aquifer . From the Fig. 39(c), it was observed that the piezometric water level fluctuation in BW187 (r value of 0.51) and BW175 (r value of 0.48) were well correlated with rainfall.

A general observation of piezometric water level data from the bore wells indicated that the occurrence and movement of ground water in crystalline formations (from which bore wells abstract water) dominantly controlled by the nature and occurrence of weathering and presence of structural features like fractures, joints and shear zones which generally varies from place to place (CGWB,2013).

It was also observed that the piezometric water level fluctuation in some locations of Malappuram, Wondoor, Thirurangadi and Mankada blocks were well correlated with rainfall variations which indicates that the bore wells in these areas abstract water from semi- confined or shallow confined aquifer with lithomargic clay as upper confining layer. This is in agreement with the findings of Prasad *et al*., (2007).

Table 12. Depth to ground water level in bore wells of low land area

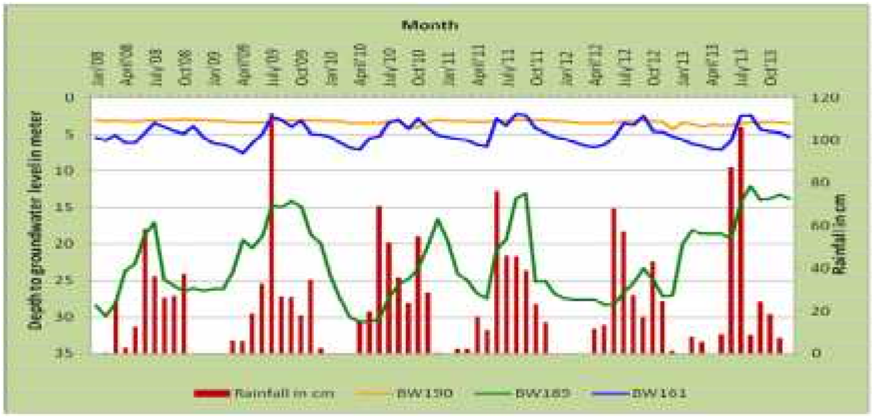
Year	Maximum depth, m			Minimum depth, m			Annual fluctuations, m		
	BW190	BW189	BW161	BW190	BW189	BW161	BW190	BW189	BW161
2008	3.28	29.79	6.14	3.00	17.08	3.53	0.28	12.71	2.61
2009	3.44	26.15	7.60	3.09	14.14	2.61	0.35	12.01	4.99
2010	4.17	30.60	7.08	3.09	16.65	2.93	1.08	13.95	4.15
2011	3.35	27.38	6.64	3.04	13.15	2.17	0.31	14.23	4.47
2012	4.34	28.34	6.80	3.14	13.36	2.49	1.20	14.98	4.31
2013	4.02	24.10	7.12	3.35	12.06	2.36	0.67	12.04	4.76

Table 13. Depth to ground water level in bore well of mid land area

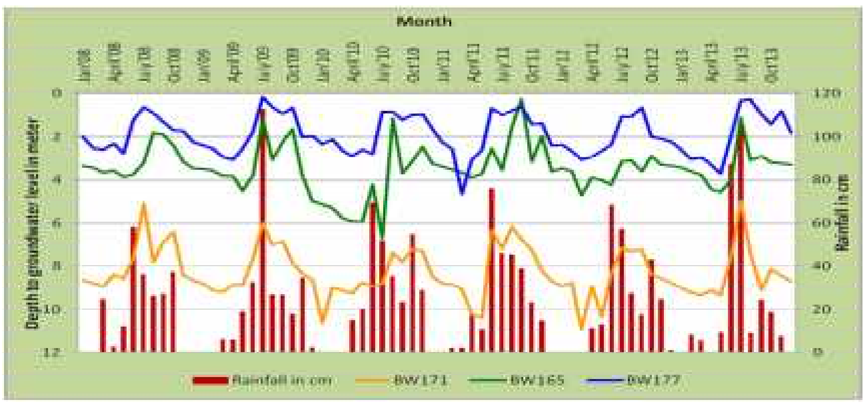
Year	Maximum depth, m			Minimum depth, m			Annual fluctuations, m		
	BW171	BW165	BW177	BW171	BW165	BW177	BW171	BW165	BW177
2008	8.95	3.86	2.77	5.12	1.80	0.64	3.83	2.06	2.13
2009	9.2	5.01	3.06	6.01	1.17	0.16	3.19	3.84	2.90
2010	10.64	6.68	2.89	7.22	1.16	0.86	3.42	5.52	1.03
2011	10.37	3.88	4.65	6.19	0.27	0.62	4.18	3.61	4.03
2012	10.9	4.69	3.06	7.16	2.91	0.67	3.74	1.78	2.39
2013	9.36	4.56	3.7	4.98	1.15	0.27	4.38	3.41	3.43

Table 14. Depth to ground water level in bore well of high land area

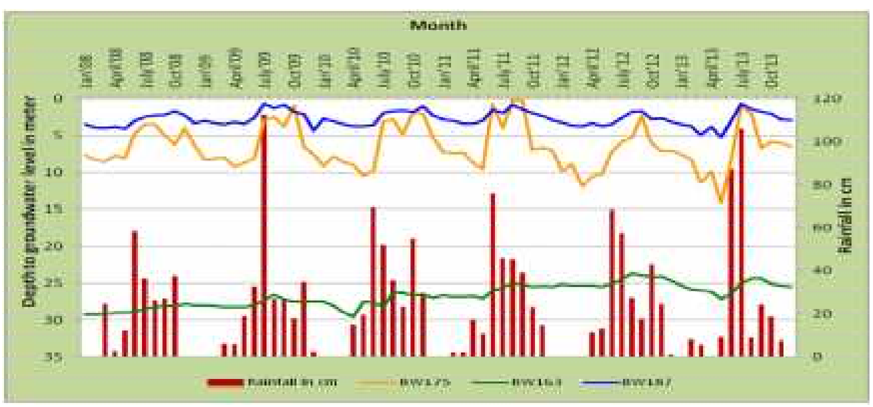
Year	Maximum depth, m			Minimum depth, m			Annual fluctuations, m		
	BW175	BW163	BW187	BW175	BW163	BW187	BW175	BW163	BW187
2008	8.51	29.18	4.06	3.44	27.83	1.69	5.07	1.35	2.37
2009	9.16	28.19	4.24	0.94	26.59	0.65	8.22	1.60	3.59
2010	10.4	29.52	3.68	1.86	26.22	1.00	8.54	3.30	2.68
2011	9.47	27.1	3.38	0.21	25.01	0.81	9.26	2.09	2.57
2012	11.87	25.56	3.7	2.29	23.71	1.65	9.58	1.85	2.05
2013	14.13	27.18	5.16	1.98	24.36	0.67	12.15	2.82	4.49



a. Low land

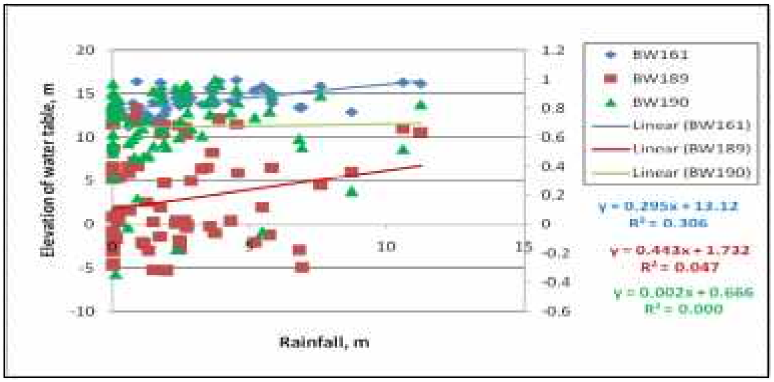


b. Mid land

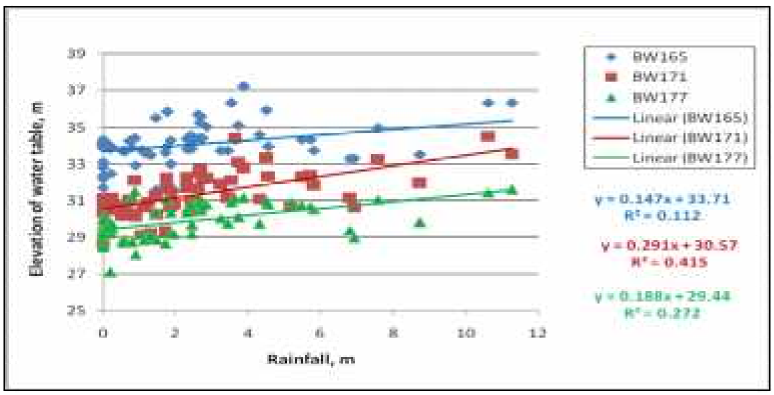


c. High land

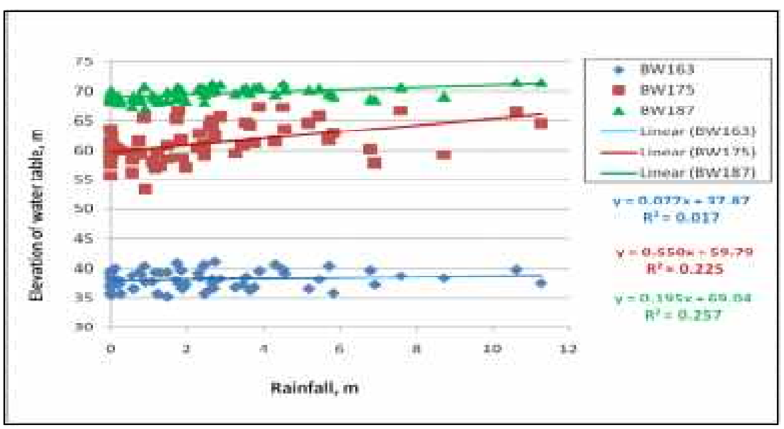
Fig. 38. Variation of groundwater level of bore wells in different physiographical regions



a. Low land



b. Mid land



c. High land

Fig.39. Plot of linear regression and correlation between ground water table and rainfall

4.1.5 Hydraulic continuity of aquifer formations in the study area

Hydraulic continuity refers that "the interconnection between ground water aquifers and surface water resources". Hydraulic continuity exists when an aquifer is being recharged by these surface water resources (www.kpud.org/downloads/**hyd**rcont.pdf). In order to check the hydraulic continuity of different layers of a particular area, variations of ground water table in dug wells and bore wells in that particular area to be analyzed with the rainfall variations. Hydraulic continuity analysis was carried out at eight locations of Kadalundi river basin viz. Kondotty, Thirurangadi, Karuvarakundu, Anakayam, Pandikkad, Kottakkal, Perinthalmanna and Kuttippuram comprising all physiographical regions. The correlation coefficient was calculated to check the correlation between water table variation and rainfall variation in these locations and is given in Table 16. The variations of ground water table and piezometric level with rainfall of each location are shown in Fig. 40 to 47.

From the Table, it could be seen that in Kondotty, Karuvarakundu, Anakayam, Pandikkad and Kuttippuram, variations of ground water table and piezometric water level were correlated with rainfall variations. This indicated that hydraulic continuity of ground water and surface water exists between aquifers of dug well and bore well in these areas. It is also proved that natural recharge occurs mainly by downward percolation through the unsaturated layers under the ground surface or/and by vertical fluxes (leakage) through the saturated semi-pervious layers from over lying or underlying aquifers with a higher hydraulic head. (http://echo2.epfl.ch/VICAIRE/mod_3/chapt_9/main.htm).

In locations like Thirurangadi (Fig. 41) and Kottakkal (45), variations of piezometric water level were poorly correlated with rainfall variations than the correlation between water table and rainfall, this indicated that there was no hydraulic continuity between upper unconfining and lower confining layers. In the case of wells at Perinthalmanna (Fig. 46), negative correlation was observed plausibly due to the delayed recharge occurring in that aquifer due to the absence of fractures and joints in the confining layers of the confined aquifer.

Table 15. Results of analysis of variance (F –test) for the piezometric water level

Sl. No.	Physiographic regions	Well Name	F calculated	F - critical
1	Low land	BW190	07.87	2.35
		BW189	14.09	2.35
		BW161	00.24	2.35
2	Mid land	BW171	00.76	2.35
		BW165	02.82	2.35
		BW177	00.17	2.35
3	High land	BW175	00.89	2.35
		BW163	02.22	2.35
		BW187	01.06	2.35

Table 16. Correlation coefficient between water table and rainfall

Sl. No.	Locatioons	Correlation coefficient	
		Dug well	**Bore well**
1	Kondotty	0.426	0.549
2	Thiruraangadi	0.546	0.217
3	Karuvarakundu	0.449	0.507
4	Anakayam	0.526	0.522
5	Pandikkad	0.369	0.644
6	Kottakkal	0.543	0.132
7	Perinthalmanna	0.426	-0.447
8	Kuttippuram	0.193	0.586

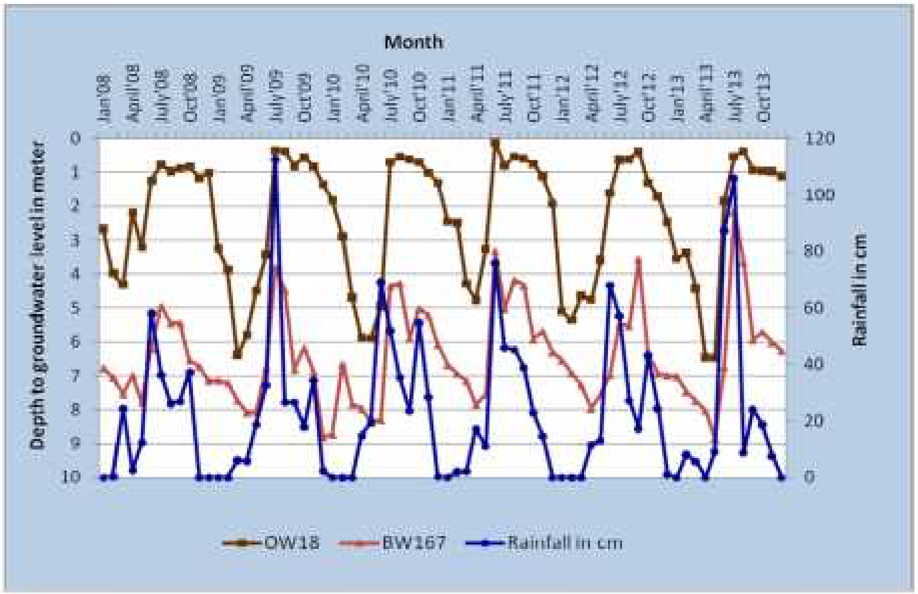


Fig. 40. Comparison of ground water levels in bore and dug well with rainfall at Kondotty

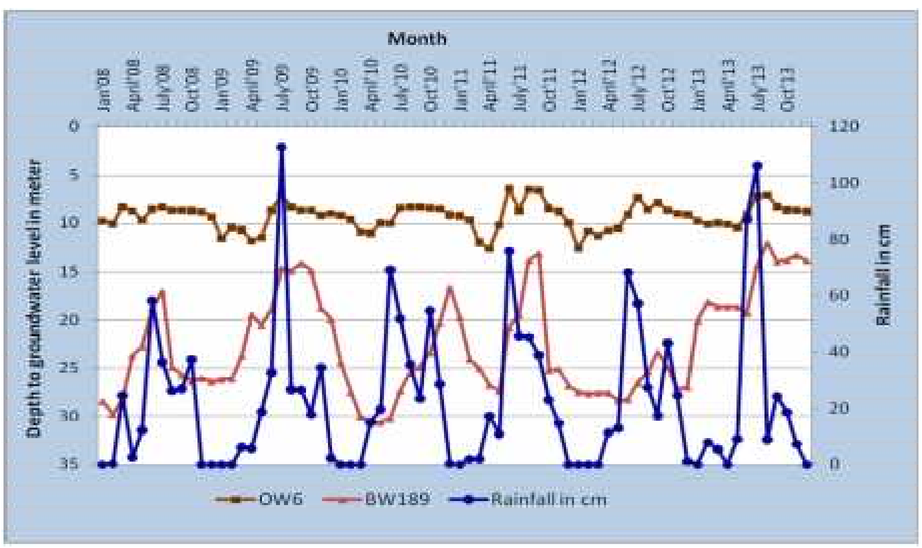


Fig. 41. Comparison of ground water levels in bore and dug well with rainfall at Thirurangadi

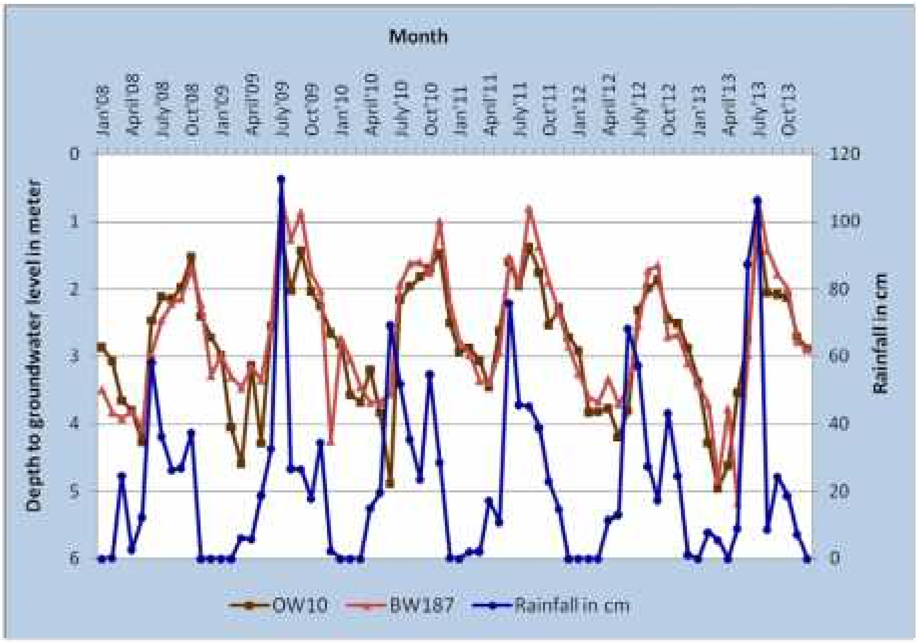


Fig.42. Comparison of ground water levels in bore and dug well with rainfall at Karuvarakundu

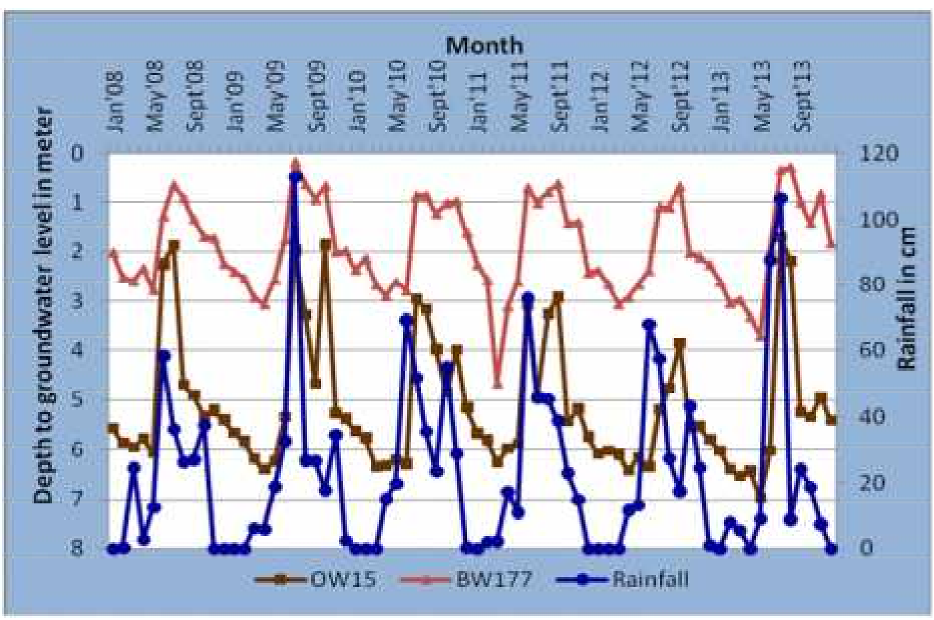


Fig.43. Comparison of ground water levels in bore and dug well with rainfall at Anakayam

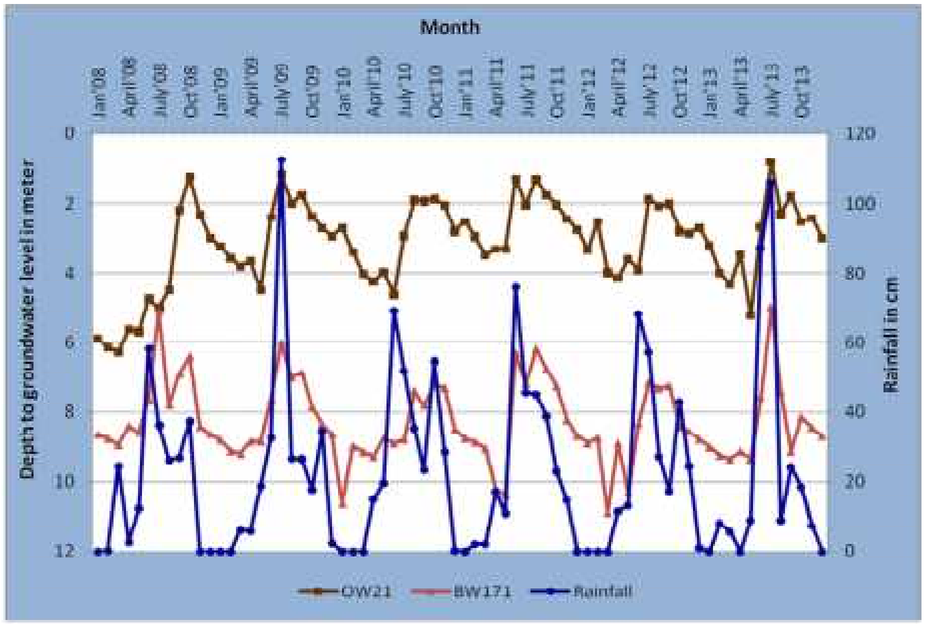


Fig. 44. Comparison of ground water levels in bore and dug well with rainfall at Pandikkad

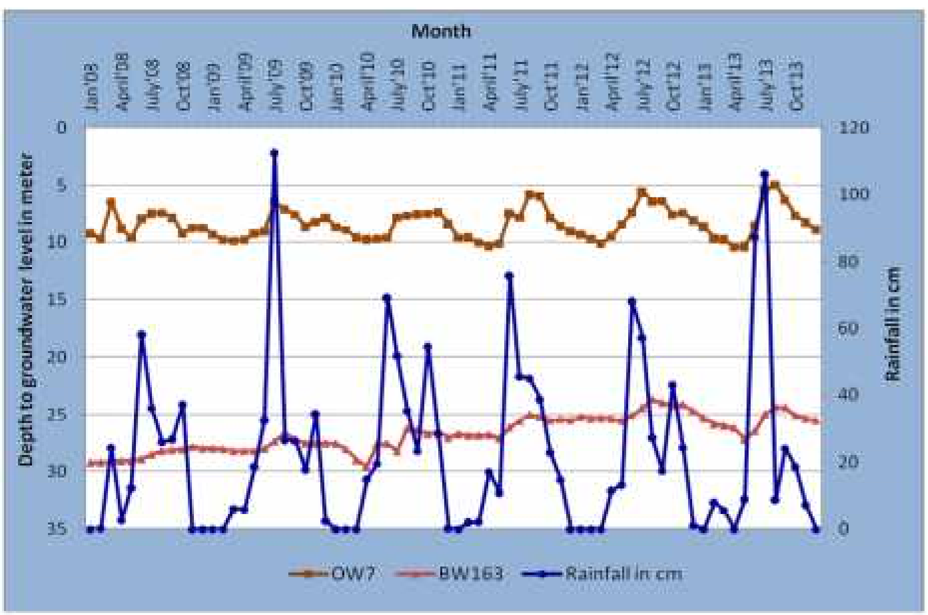


Fig. 45. Comparison of ground water levels in bore and dug well with rainfall at Kottakkal

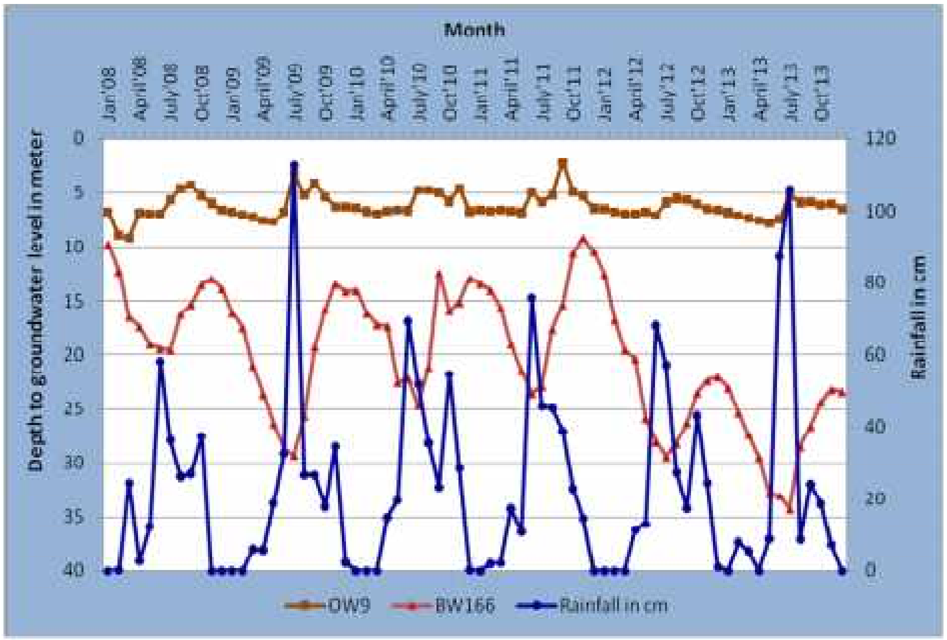


Fig. 46. Comparison of ground water levels in bore and dug well with rainfall at Perinthalmanna

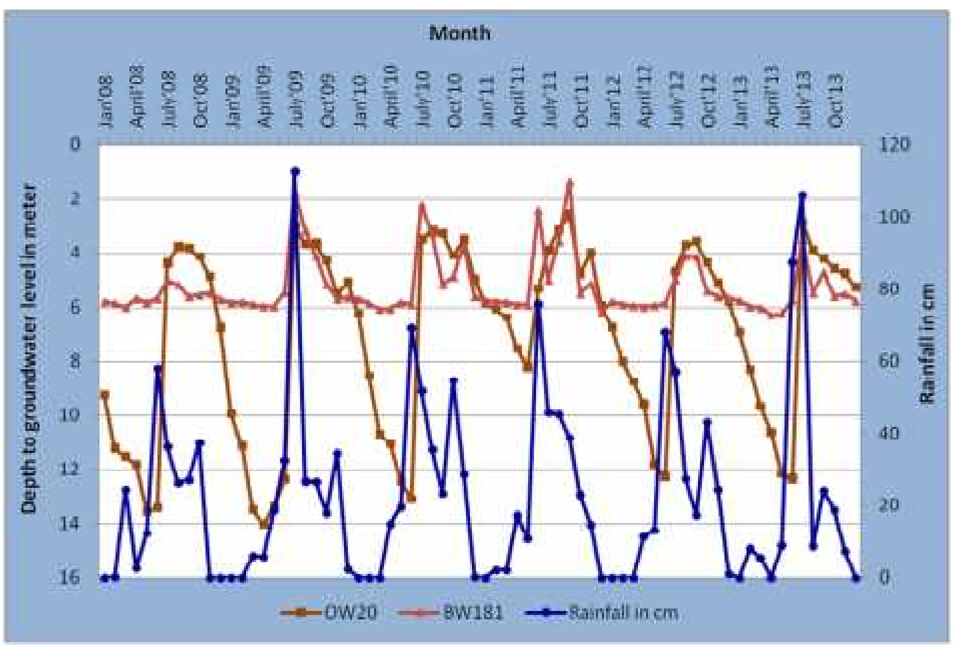


Fig. 47. Comparison of ground water levels in bore and dug well with rainfall at Kuttippuram

4.2 Identification of ground water potential zones

Electrical Resistivity Meter (ERM) method can be used to obtain details about the ground water potential zones quickly and economically. In electrical resistivity methods, resistivity surveying is the technique used to investigate variations of electrical resistance by causing an electrical current to flow through the ground using wires connected to it. Two basic types of field procedures are commonly used, Vertical Electrical Sounding(VES) and Horizontal Electrical Profiling (HEP). In this study VES was carried out in 22 locations using Signal Stacking Resistivity Meter (MODEL-SSR-MP-ATS).

4.2.1 Interpretation of VES Data

Field data obtained from VES survey were processed and interpreted qualitatively and quantitatively using IPI2WIN software to obtain the resistivity values of different subsurface layers and their corresponding thickness and is given in Table 17. From the interpretation of VES curves, 3 to 4 subsurface layers where identified within the study area. The sounding curves were of A,H,K,Q,HK and KH types reulting in 3-4 layer sequence. The curves were prominently of H, Q, K and A type indicated the presence of three layer substrata and combination of curves like HK and KH indicate the four layer sub strata. From the table it could be seen that among the total 22 VES location there are five 4 layer cases and seventeen 3 layer cases.

The resistivity value of first layer obtained from VES data interpretation was used to prepare the map of resistivity of the study area using Arc GIS(10.1) and is shown in Fig. 48. From the figure it could be seen that major part of river basin having same range of resistivity, 101-500 ohm-m. It indicated that the formation of the first layer in these areas are lateritic soil or brown soil and this is in agreement with the report of CGWB and CWRDM. In some pockets like Wandoor and Vengara blocks, hard rock with greater resistivity is exposed and this is in agreement with the results of site visits as shown in plate 5 and 6 and contour map of the depth to bed rock.

The map of depth to bed rock was prepared using Arc GIS (10.1) and shown in Fig. 49. From this figure it could be seen that almost all part of study area have same range of depth to bed rock, 10 -20 m. In some part of Wandoor, Vengara and Malappuram blocks shallow bed rock was seen, 0-10 m. A small part of Mankada block has deep bed rock with 20 – 60 m.

4.2.1.1 H type curve

Soundings from Anakayam (VES1), Karuvarakundu (VES4), Keezhmuri (VES5), Nooradi (VES15), Pandikkad (VES17) and Thirurangasi (VES21) indicated three layer model ($\rho_{1>}$ $\rho_{2<}$ ρ_3) with predominance of H type curves (Fig. 50). This type of curves are obtained generally in hard rock terrains which consists of dry top soil having high resistivity as the first layer, saturated weathered layer of low resistivity as the second layer and compact hard rock of very high resistivity as the last layer. In this case, resistivity of first layer ranged between 140 to 2026 ohm-m and thickness ranged from 1 m to 9.38 m, indicating that the presence of lateritic formation which is suitable for dug wells. Second layer has resistivity ranging from 56.5 to 189 ohm-m, representing the presence of clay to clayey laterite and weathered zone of thickness 4.22 to 16.3 m. The third layer bears resistivity ranging from 1021 to 18548 ohm-m indicating the presence of hard laterite and massive charnokite /gneiss. At Nooradi (VES15), the third layer showed weathered zone with comparatively low resistivity of 201ohm-m and it was observed that this area has high potential for groundwater.

Table 17. Resistivity data interpretation and corresponding thickness

Sl. No	Locations	ρ1 (ohm-m)	ρ2 (ohm-m)	ρ3 (ohm-m)	ρ4 (ohm-m)	h1 (m)	h2 (m)	h3 (m)	Depth to bed rock (m)
1	Anakayam	298	166	18548	-	1.00	16.3	-	17.3
2	Angadippuram	1495	417	110	-	4.30	9.95	-	14.3
3	Cherukodu	109	24003	166	-	3.55	4.67	-	8.22
4	Karuvarakundu	491	181	8330	-	1.00	4.22	-	5.22
5	Keezhumuri	2026	189	1031	-	9.38	5.48	-	14.9
6	Kolarakunnu Manjeri	1364	3695	4.11	-	7.29	8.55	-	15.8
7	Kottakal	897	1744	239	-	2.47	3.95	-	6.42
8	Kulapparambu	1621	1574	316	-	2.05	6.83	-	8.88
9	Kuruva Kunnumpadam	349	1447	877	-	1.65	1.89	-	3.54
10	Kuruvapadam Vengara	123	382	73148	-	1.00	13.5	-	14.5
11	Kuruvikundu Othukkungal	1943	1161	4062	726	0.75	4.79	3.89	9.43
12	Mannathikuzhi	972	2784	344	83513	0.87	1.11	53.0	54.98
13	Mannathiparambu	2934	894	148	-	1.41	21.4	-	22.8
14	Nediyiruppu	64.1	396	45950	-	1.00	14.3	-	15.3
15	Nooradi	743	111	201	-	1.14	5.82	-	6.96
16	Padinjattumuri	244	1120	260	79601	2.89	20.6	32.7	56.2
17	Pandikkad	230	66	8175	-	1.00	7.84	-	8.84
18	Perinthalmanna	92.5	174	623	-	1.00	13.2	-	14.2
19	Puzhakattiri	394	130	1336	11.8	1.17	9.99	21	32.17
20	Tanur	281	59.4	1.19	-	1.53	21.7	-	23.2
21	Tirurangadi	140	56.5	10073	-	1.70	9.75	-	11.4
22	Valarad	2557	854	2257	199	1.00	3.66	17.1	21.76

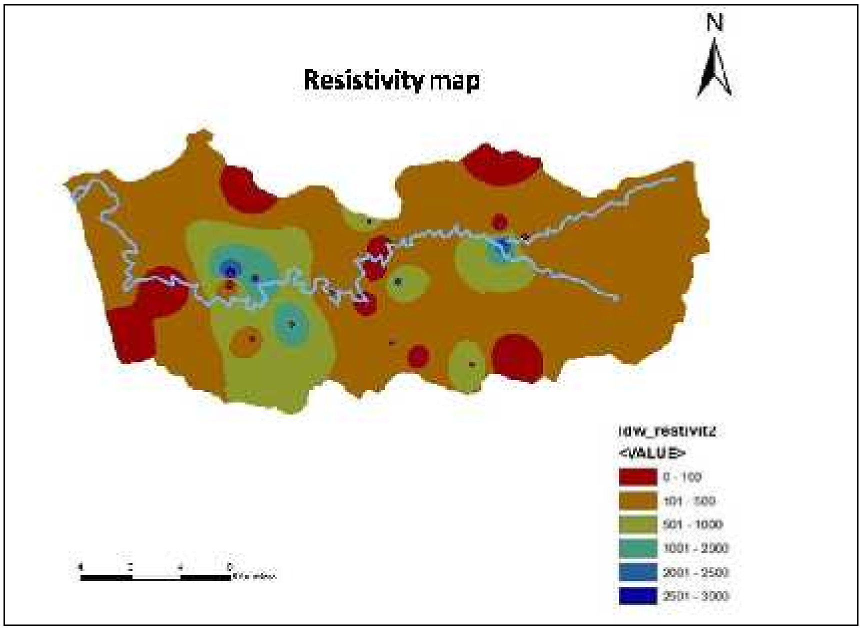


Fig. 48. Resistivity map of Kadalundy river basin

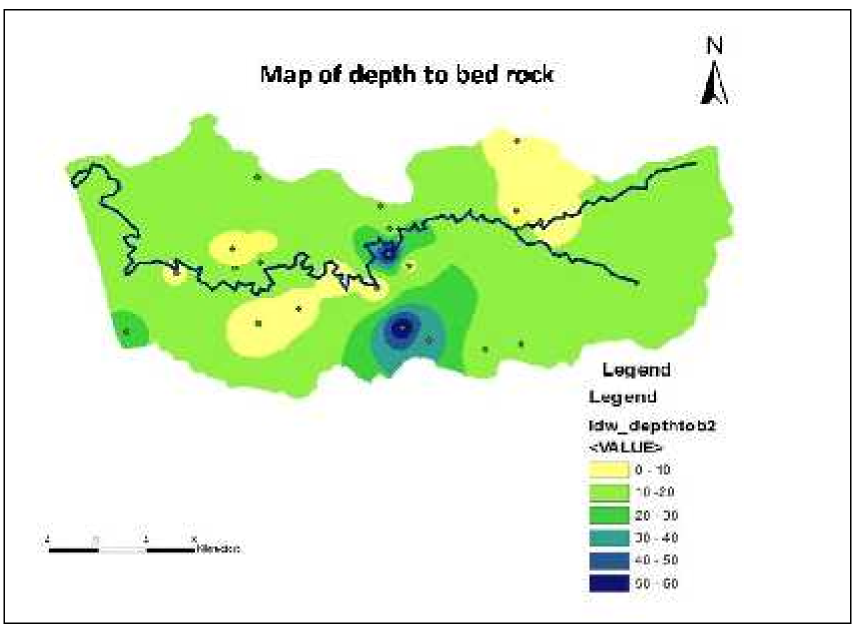


Fig. 49. Map of depth to bed rock of Kadalundy river basin

Plate 5. Hard rock exposed at Cherukode area

Plate 6. Hard rock exposed at Valarad area

Hard laterite with resistivity ranging from 500-1000 ohm-m was seen in the central mid land and high land part of the study area. At Thirurangadi, Tanur and some other small pockets, low resistivity of 0-100 ohm.m was seen and these area falls under low land area and the litholog data obtained from the Ground water Department Malappuram and analysis of ground water level agreed with this condition.

4.2.1.2 Q type curve

Soundings from Angadippuram (VES2), Kulapparambu (VES8) and Tanur (VES20) have continuously decreasing resistivity ($\rho_{1>}$ $\rho_{2>}$ ρ_3) forming a 'Q'- type curve (Fig. 51). In coastal area, where saline water is present, these type curves are obtained (Brijesh and Balasubramanian., 2014). In the present study, at Tanur (VES20) this type of Q curve is seen as it is the coastal region. Other three locations have hard laterite at the top layer having resistivity ranged from 1495 to 1621 ohm-m, for a thickness of 2 m to 4.3 m, decreasing towards the basement which indicate that the hardness of laterite is also decreasing. The third layer resistivity was further decreasing, indicating the presence of highly weathered zone having resistivity ranging from 110 to 360 ohm-m at a depth of 9 to 14 m and it correlates with the litho log data obtained from Kerala State Ground Water Department, Govt. of Kerala.

4.2.1.3 K type curve

Curves with a maximum hump flanked by low resistivity values ($\rho_{1<}$ $\rho_{2>}$ ρ_3) are called 'K'- type curves as given by soundings from Cherukode (VES3), Kolarakunnu (VES6), Keezhumuri (VES7) and Kuruva Kunnumpadam (VES9) as showm in (Fig. 52). In lateritic area, a hard and massive trap of laterite exists between a top brown hydromorphic/ lateritic soil as the first layer and below that a saturated weathered rock. The resistivity of the first layer (top soil) ranged betweeen 109 ohm-m to 1364ohm-m with a thickness of 1.65 m to 7.29 m, indicated the presence of lateritic/hydomorphic topsoil and moderately hard laterites.

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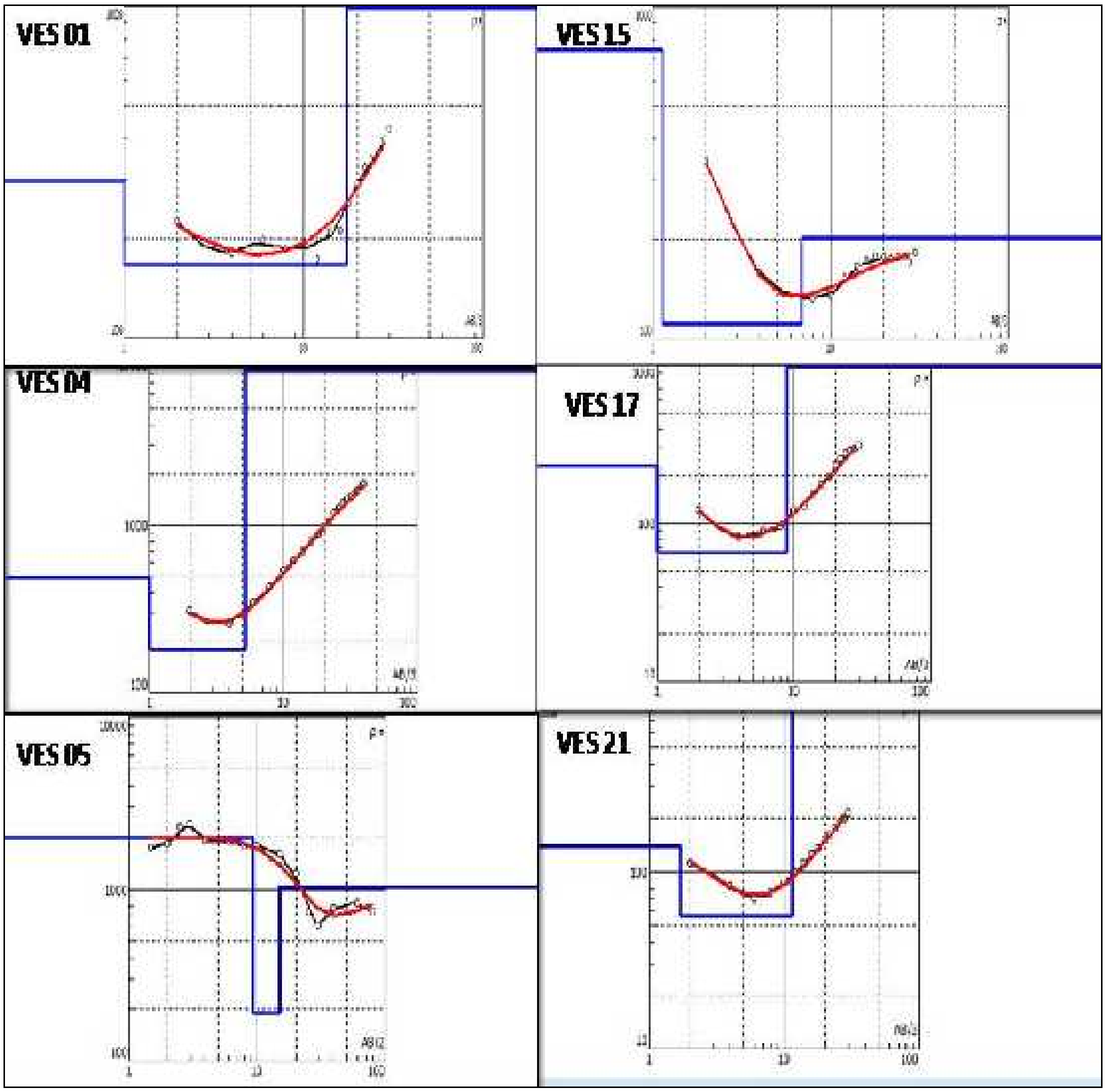


Fig. 50. Resistivity sounding curves (H type)

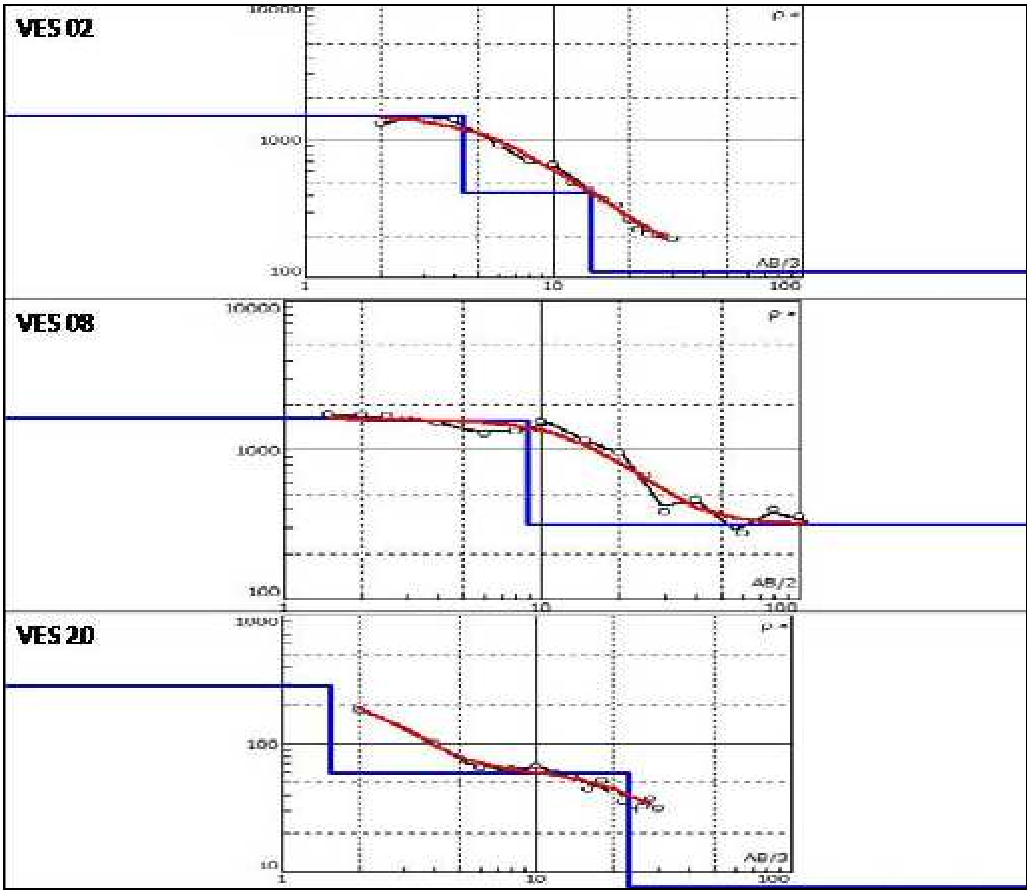


Fig. 51. Resistivity sounding curves (Q type)

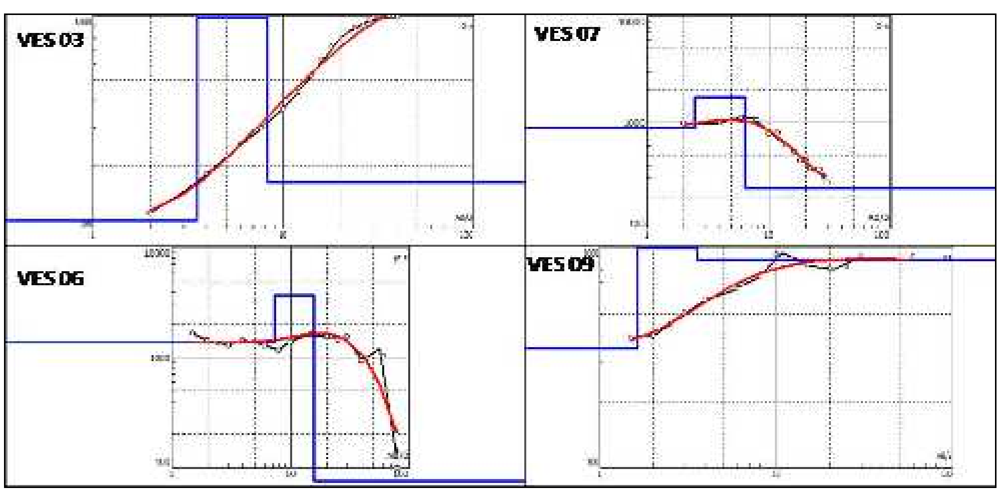


Fig. 52. Resistivity sounding curves (K type)

The second layer comprises of hard and compact laterites/ gneiss with high resistivity values ranged from 1447 to 24003 ohm-m and thickness of 1.89 to 8.55 m. The third layer has resistivity ranged from 4.11 to 877 ohm-m which could be due to the presence of water in the weathered rock. From the inferred nature of the lithounits, these areas seems to be ideal for borewells.

4.2.1.4 A type curve

Soundings from Kuruvapadam (VES10), Nediyiruppu (VES14) and Perinthalmanna (VES18) can be explained by the three layer model ($\rho_{1<}\ \rho_{2<}\ \rho_3$) with the presence of 'A' type curve (Fig. 53). The first layer was the top soil having resistivity ranged from 64 to 123 ohm-m with a thickness of one meter. The second layer was a weathered zone/ laterite having resistivity ranged between 174 to 396 ohm-m and a thickness of around 14 m, followed by hard and massive rock type having resistivity ranging from 623 to 73148 ohm-m. These locations are also suitable for dug wells. Inferred data from the sounding curves are matching with the litholog data obtained from Kerala State Ground Water Department.

4.2.1.5 HK type curve

Soundings from Othukkungal (VES11), Puzhakattiri (VES19) and Valarad (VES22) can be explained by the four layer model ($\rho_{1>}\ \rho_{2<}\ \rho_{3>}\ \rho_4$) with 'HK' type curve (Fig. 54). HK curve indicated the presence of lateritic soil / moderate laterites followed by weathered laterite with a depth from 4.66 m to 11.16 m. The third layer has resistivty ranging from 1336 to 4062 ohm-m which indicated the presence of hard laterite/ charnokite followed by clay/weathered zone which could be identifed with resistivity ranging from 11.8 to 726 ohm-m.

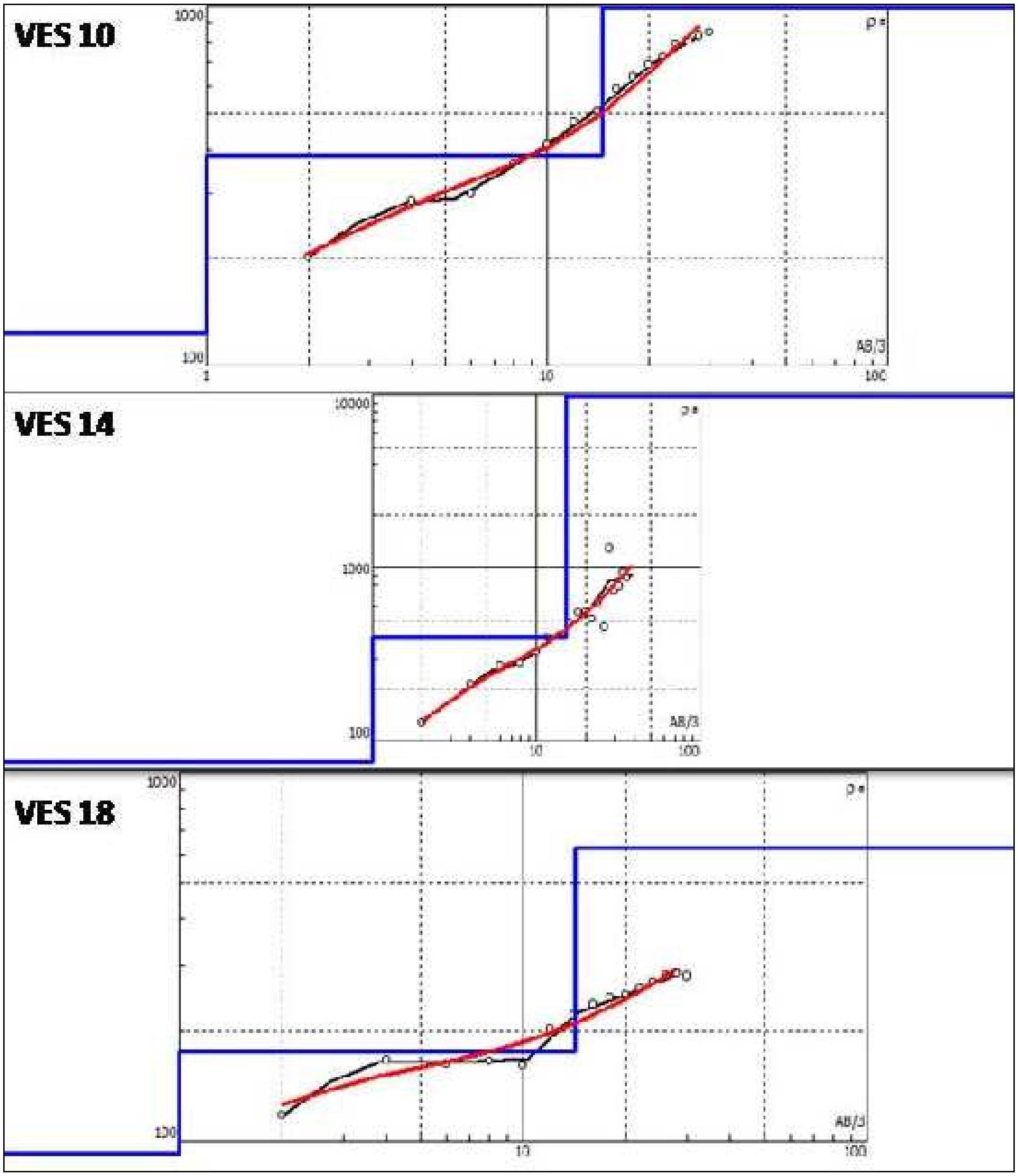


Fig. 53. Resistivity sounding curves (A type)

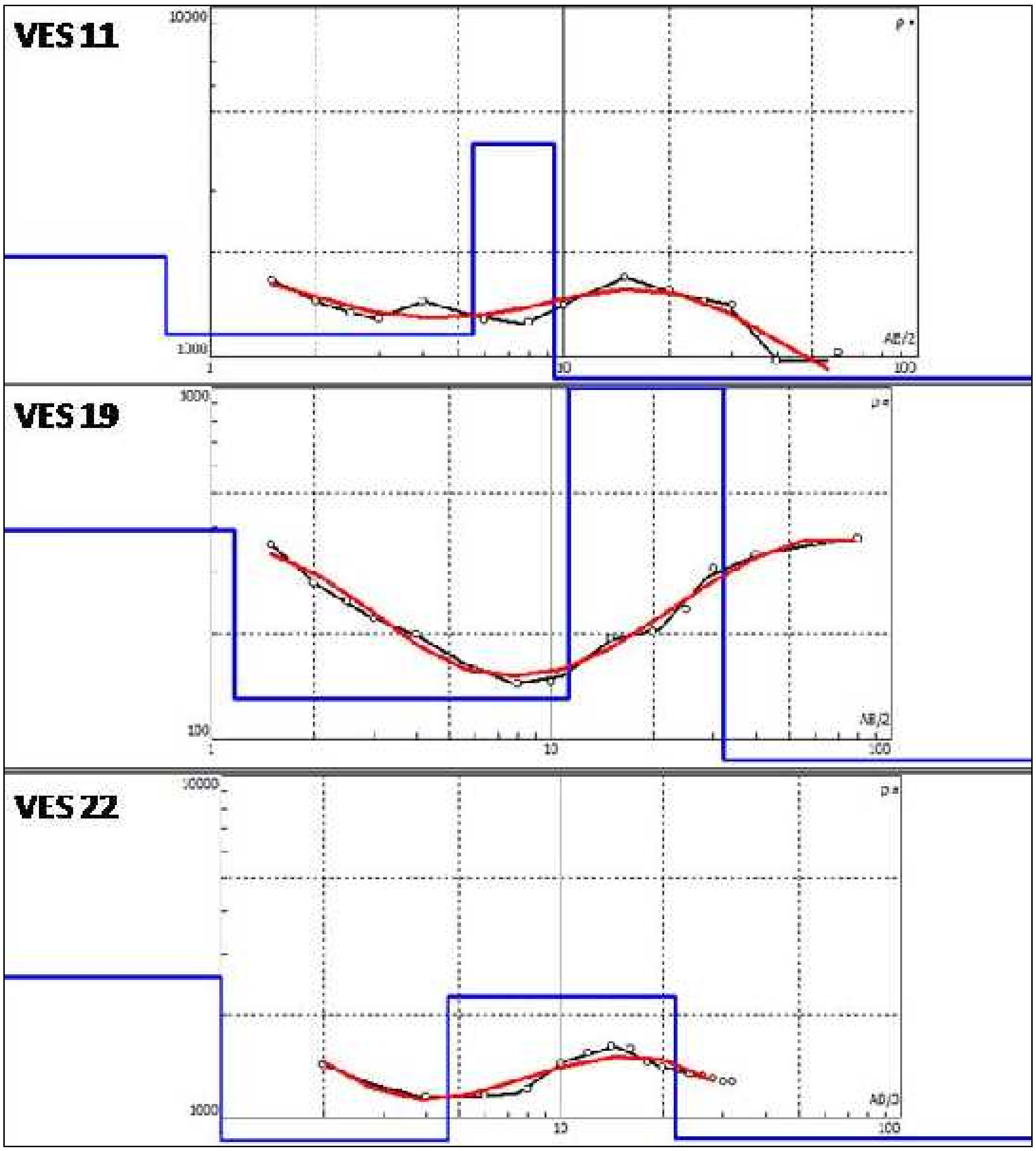


Fig. 54. Resistivity sounding curves (HK type)

4.2.1.6 KH type curve

Soundings form Mannathikizhu (VES12) and Padinjattumuri (VES16) could be explained by the four layer model ($\rho_{1<} \rho_{2>} \rho_{3<} \rho_4$) with 'KH' type curve (Fig. 55). In the case of locations 12 and 16, third layer shows low resistivity of 260 to 344 ohm-m for a higher depth of 32.7 m to 52 m, indicated the weathered zone at greater depths,which is suitable for bore wells.

4.2.2 Resistivity and pseudo cross sections

Resistivity and pseudo cross sections along AA', BB', CC' and DD' were prepared using true and apparent resistivity values (Fig.56). The pseudo cross section reflects the observed values vertically along selected profiles in logarithmic scale.

Resistivity cross section shows the vertical true resitivity variation by using the interpreted parameters of the soundings along the profile in a linear scale. The sections show shape, vertical variation of resistivity and layer sequence along selected profile which help in understanding the subsurface geology.

4.2.2.1 Section AA'

This section was plotted with the soundings VES7,VES15,VES1 and VES3 in SW-NE direction (Fig. 57) and the length of the section is 24 km. A low resistivity zone of less than 250 ohm-m was observed throughout Nooradi (VES15) and Anakayam(VES1) area indicated the presence of river in that area, which continues towards Cherukode (VES03) area. These areas have high potential for dug wells. In Kottakal (VES07) area, hard laterites were seen on upper layers and resistivity was gradually deceasing, which indicated that this area is suitable for bore wells. In Cherukode (VES03) area, lateriteic zone is present below the low resistivity zone at a depth of 6 m to 20 m and below that hard laterite/rock of high resistivity is present.

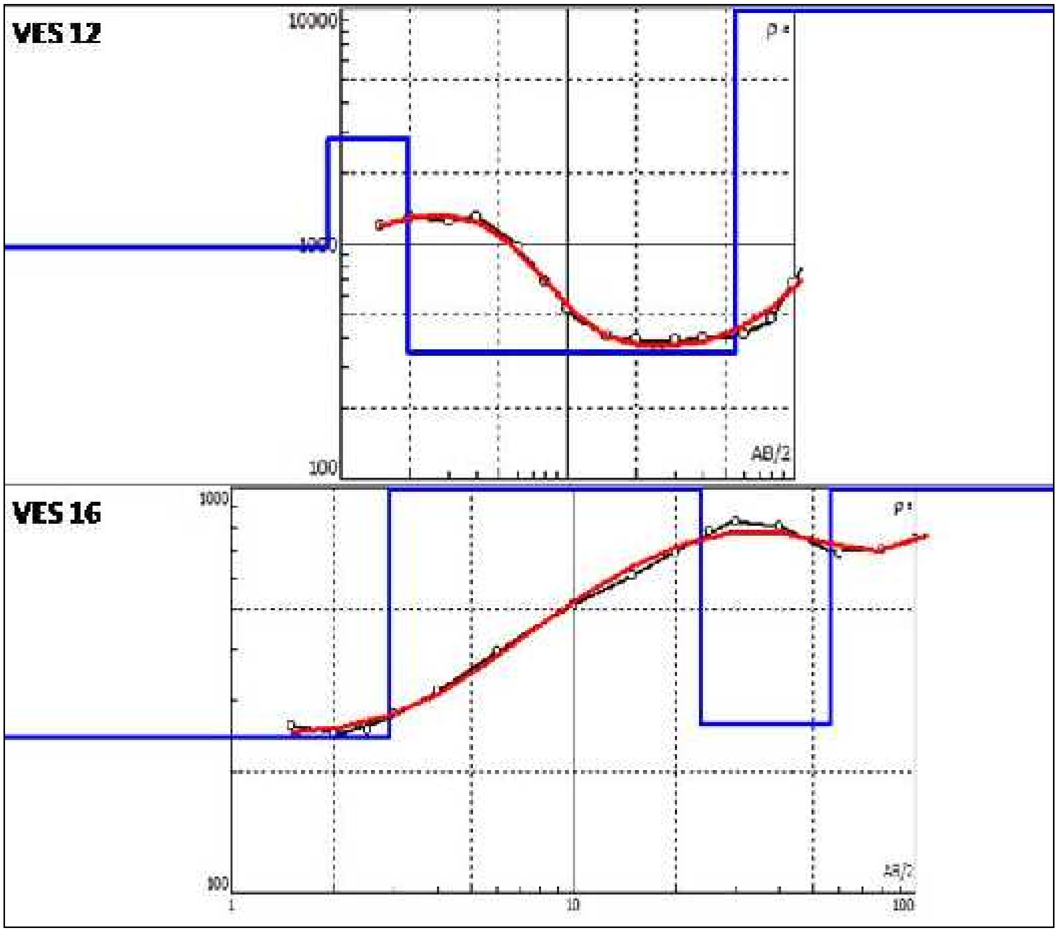


Fig. 55. Resistivity sounding curves (KH type)

4.2.2.2 Section BB'

This section was plotted with the soundings VES3,VES17,VES22 and VES18 in N-S direction (Fig. 58). A low resistivity zone was observed in Pandikkad (VES17) region upto a depth of 10 m below ground level and which continues towards Cherukode (VES03) area with a decreasing depth. From this results we could say that these are high potential areas for dug well and it matches with data obtained from Dept. of Groundwater, Malappuram.

4.2.2.3 Section CC'

This section was plotted with the soundings VES 6, VES 16 and VES 12 in N-E direction and is shown in Fig. 59. The length of section was around 2.5 Km and low resistivity zone of less than 100 ohm in loction VES 16 indicated the presence of clay at the top and it continues towards the location VES 12 at lower depth. Laterites and weathered zones were observed throughout the section with resistivity ranging from 100 to 1000 ohm-m. A patch of high resistivity zone of more than 1000 ohm-m was observed in Kolarkunnu (VES06) location from the depth of 10 m to 30 m which indicate the presence of massive charnokite. A weathered zone was obsevrved below this hard rock up to a depth of 70 m and hence we can suggest this area for bore wells.

4.2.2.4 Section DD'

This section was plotted with the sounding of VES14, VES20 and VES 21 in NE-SW direction (Fig. 60) and length of the section is 13 km. A low resistivity zone of less than 100 ohm-m was observed in the central part of VES 21(Tanur) and it continued upto VES20. This zone continues to a depth of more than 20 m which indicated the presence of clayey soil and is matching with the data obtained from localised survey and litholog of that area obtained from Dept of Groundwater, Malappuram.

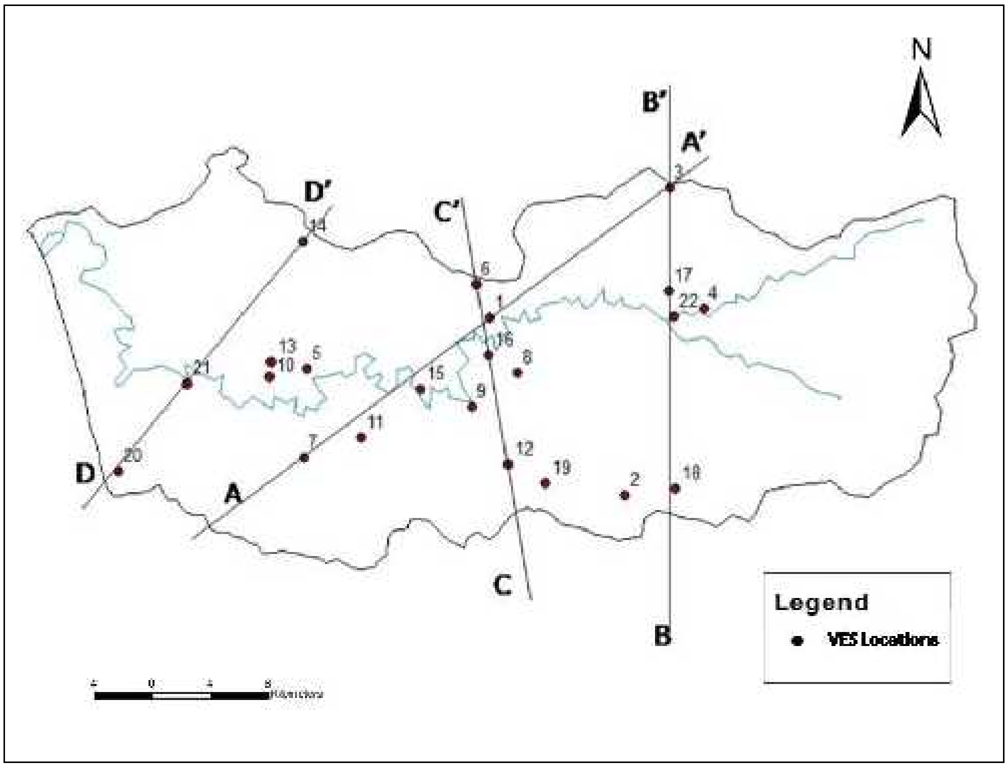


Fig.56. Sections of resistivity and pseudo cross sections

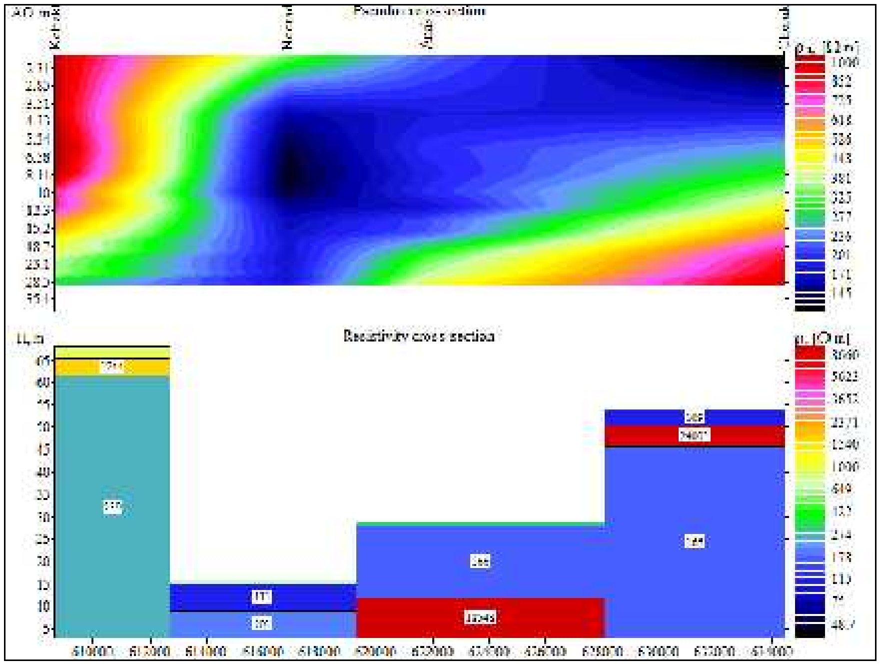


Fig. 57. Pseudo and Resistivity cross sections along section AA'

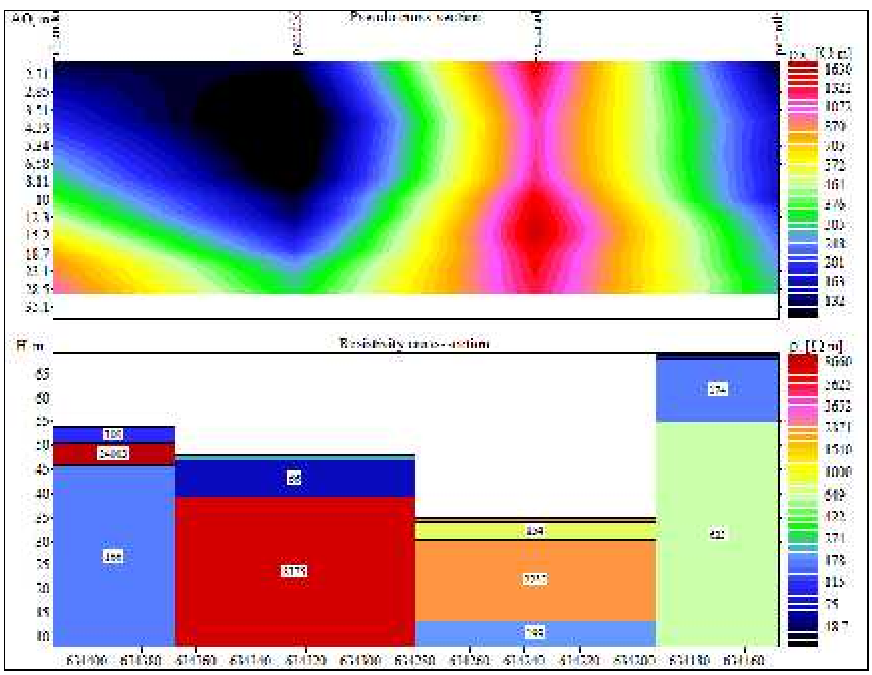


Fig. 58. Pseudo and Resistivity cross sections along section BB'

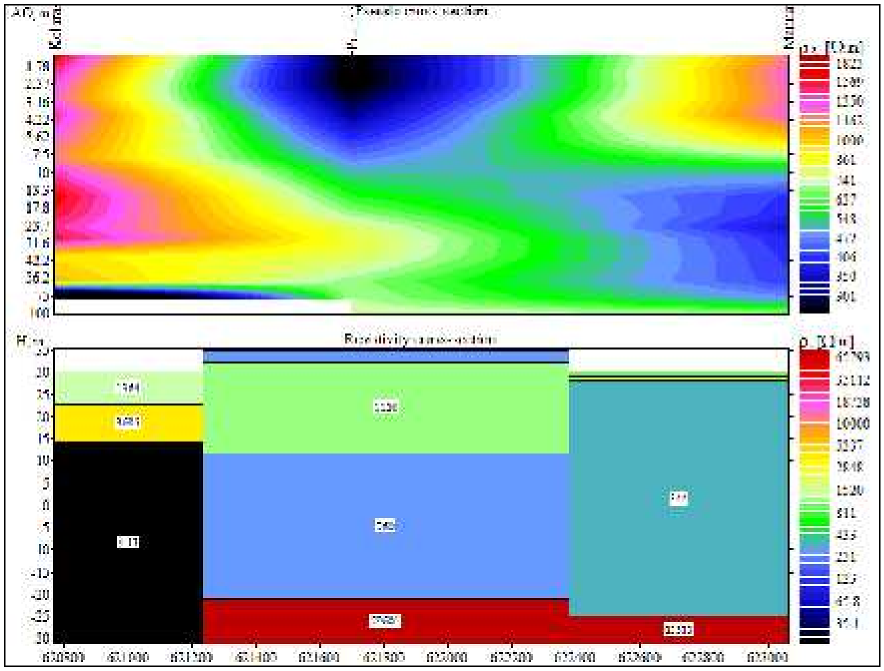


Fig. 59. Pseudo and Resistivity cross sections along section CC’

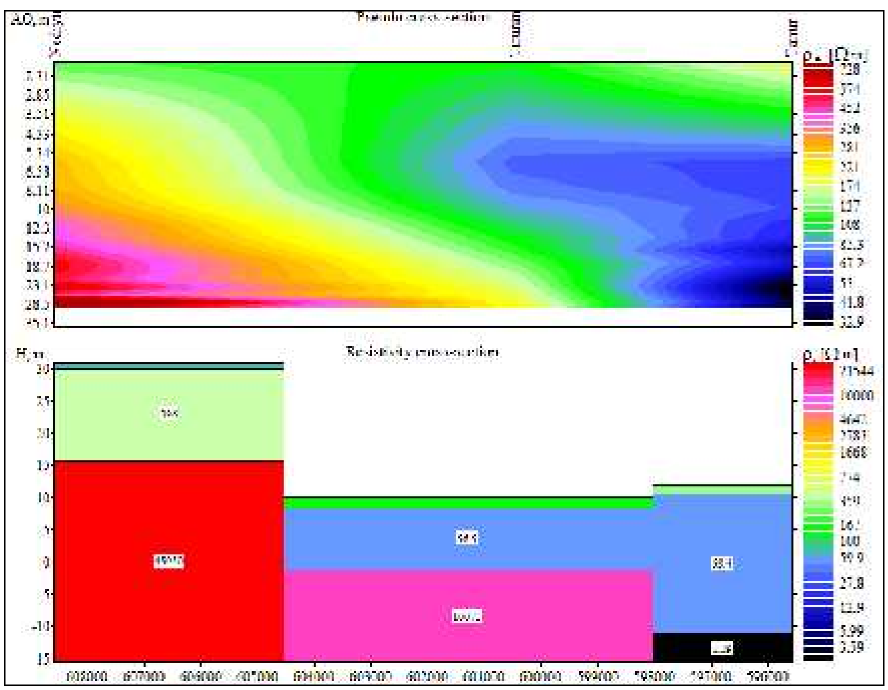


Fig. 60. Pseudo and Resistivity cross sections along section DD’

4.3 Ground water flow modeling

The process of ground water modeling has a number of stages and hence the modeling needs to have a combination of skills, a broad or general knowledge of hydro geology, the process of ground water flow and the methods for checking and testing the reliabilities of models. In this study Visual MODFLOW is used for the flow modeling of the study area.

4.3.1 Visual MODFLOW output

Visual MODFLOW output provides contours of head equipotentials, head difference, drawdown, elevation, net recharge and water table. It also provides graphs of calculated Vs. observed heads, calibration of residual histogram, head Vs. time, normalized RMS Vs. time and drawdown Vs. time. The model output also provides velocity vectors with direction of flow. By using the input and output screen the model is calibrated.

4. 3.1.1 Steady state calibration

The model was calibrated for steady state conditions. The aquifer condition of year 2008 is assumed to be the initial condition for the steady state model calibration. The steady state model calibration started by minimizing the difference between the computed and the field water level for each observation well. The hydraulic conductivity values of the aquifers varied iteratively so that root mean squire (RMS) error could be kept below 10 m. The scatter plot for computed vs. observed head for 30 selected observation wells are shown in Fig. 61. From the figure it could be seen that there was a very good agreement between the calculated and observed water levels in most of the wells.

4.3.1.2 Transient state calibration

The hydraulic conductivity values, boundary conditions and the water levels obtained from the steady state model calibration were used as the initial condition in the transient model calibration. The above values are used along with the specific storage and specific yield distribution, time variable recharge and dumping distribution. The transient (dynamic) calibration was carried out for the time period from year 2008 to year 2011 (1461 days). The storage coefficient values varied iteratively so that a reasonably good match was obtained between computed and observed water levels. The hydraulic properties of the layer obtained after calibration for both steady state and transient states are shown in Table 18.

The graph of calculated head vs. observed head for 15 days and 1461 days (4 years) are shown in Fig. 62 and 63 respectively. From the figures, it could be seen that the calculated heads are well matching with observed heads at 95 % confidence level.

Table 18. Hydraulic properties of the layer after calibration

S.No.	Model Properties	Layer I Laterite
1	Hydraulic conductivity in longitudinal direction K_x, m d^{-1}	20
2	Hydraulic conductivity in lateral direction K_y, m d^{-1}	20
3	Hydraulic conductivity In vertical direction K_z, m d^{-1}	2
4	Specific storage S_s, m^{-1}	0.0005
5	Specific Yield, S_y	0.20
6	Effective Porosity	0.35
7	Total Porosity	0.40

The computed and observed ground water level hydrographs for the selected observation wells (bore wells at Porur, Morkanad and Karuvarakundu and dug wells at Karuvarakundu Perinthalmanna and Puzhakattiri) are shown in Fig. 64 and it could be seen that the computed water table hydrographs were comparable with the observed values. Computed water table contour map of the study area obtained from the model is shown in Fig. 65. From this figure it could be seen that in the coastal region the water elevation was very low ranging from zero to 15 m. At extreme west side, it is zero because of Arabian Sea as boundary.

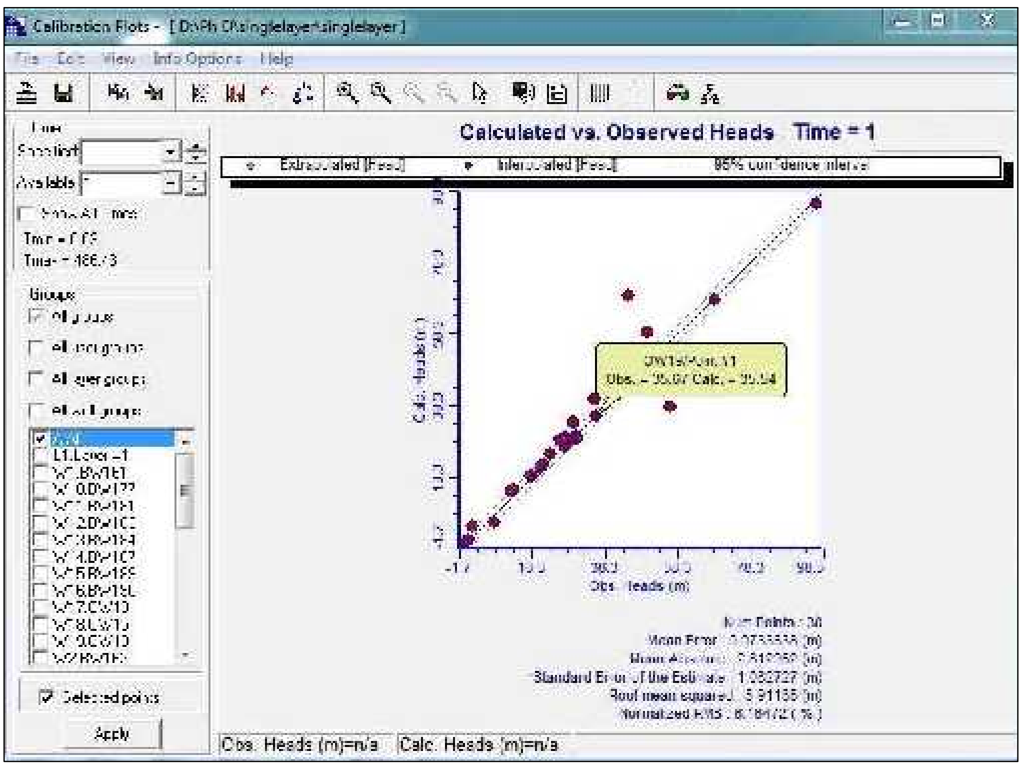


Fig. 61. Model computed vs observed water level of the year 2008 (Steady State)

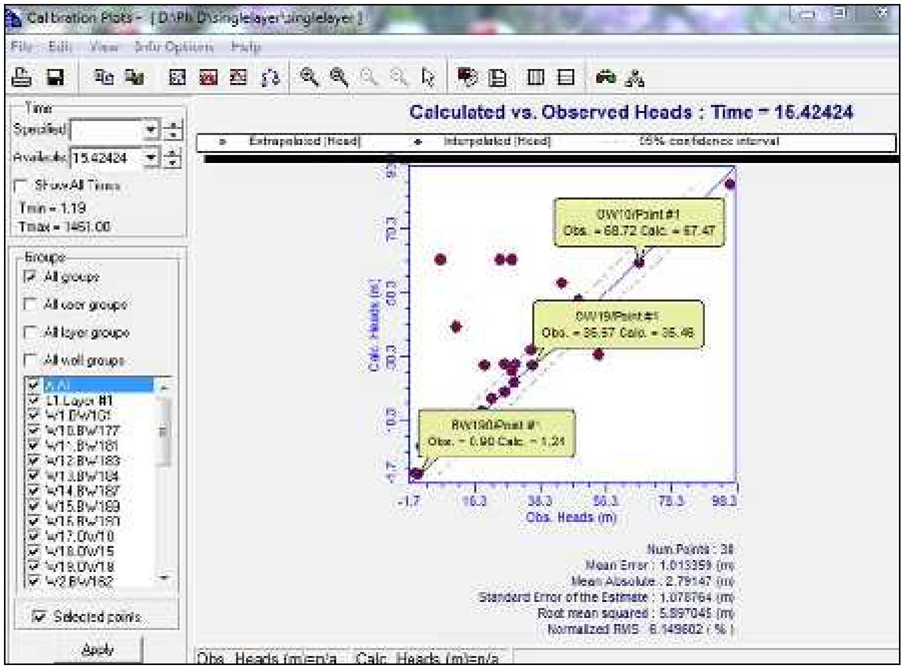


Fig. 62. Model computed vs observed water level at 15 days (Transient state)

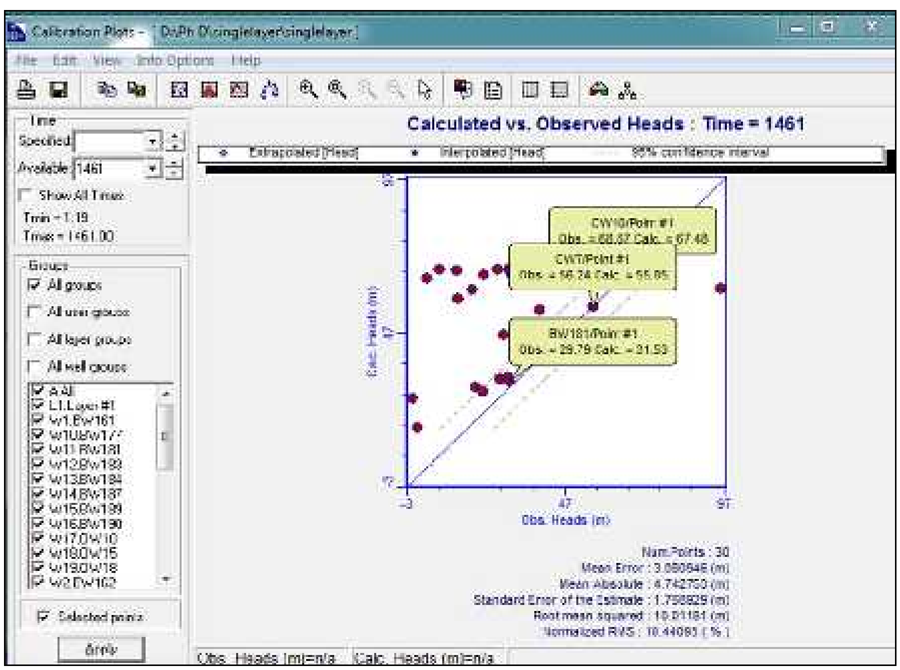
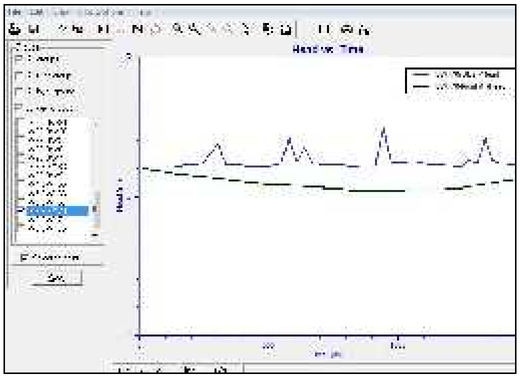
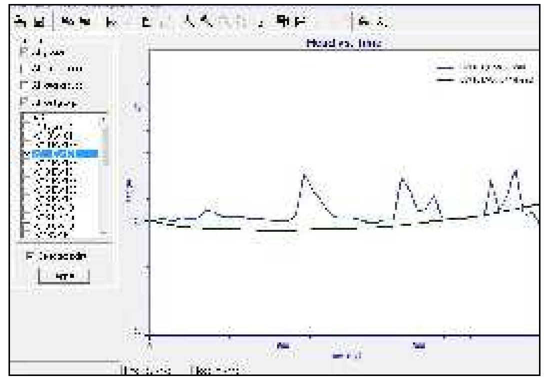


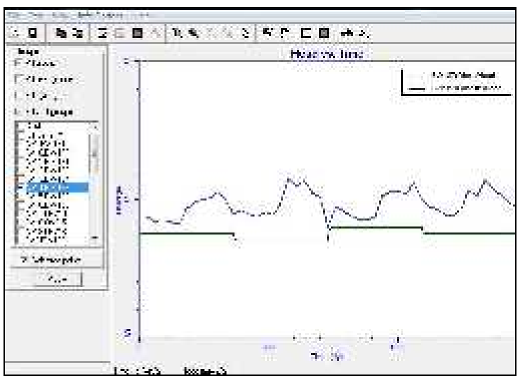
Fig.63. Model computed vs observed water level at 1461 days (Transient state)



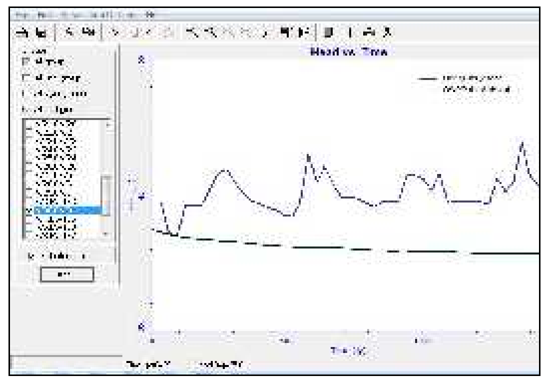
BW170 at Porur



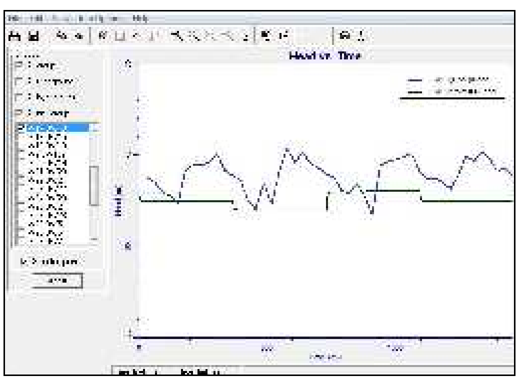
BW181 at Morkanad



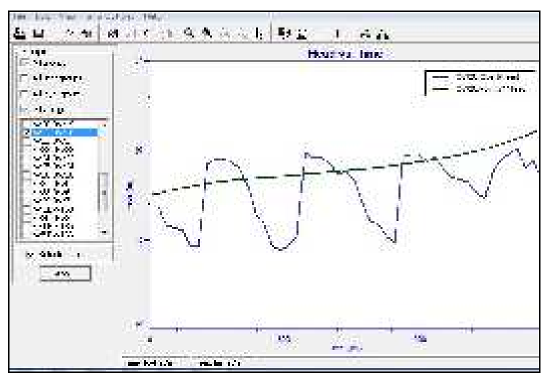
BW187 at Karuvarakundu



OW9 at Perinthalmanna



OW10 at Karuvarakundu



OW20 at Puzhakattiri

Fig. 64. Computed and observed ground water level hydrographs for the selected observation wells

In the central part of the study area comprising of Malappuram, Mankada and Manjery blocks, the water table elevation ranged from15 m to 32 m (bluish green shade) and 32 m to 40 m (green shade), indicating that major part of study area was under same range of water table elevation. From the Fig.48 and 49, it was also seen that this area have same range of resistivity and depth to bed rock. At some pockets of Wondoor and Kuttippuram blocks, the water table elevation was found to be high, ranged from 66 m to 85 m and this may due to high elevation of that area. Some part of Vengara and Malappuram blocks, it ranged from 40 m to 57 m.

The perusal of model run revealed that some dried cells has been seen in the Vengara and Perinthalmanna block comprising an area of 6.75 and 8.5 sq. km respectively. This indicated that this area comprising of hard rock and it is supported by the results of earth resistivity studies (Table 17). The velocity vectors of ground water flow in the aquifer formation after calibration is given in Fig. 64. Velocity vectors shows that the ground water flow is towards the direction of river flow (i.e) northeast to southwest. This also proves that the input parameters of the model are correct and model can be used for validation and prediction.

4.3.3 Model validation

The model was validated with the water level data and the scatter plot for computed vs. observed heads for 24 selected observation wells as shown in Fig. 67. The observed and calculated water levels above mean sea level is given in Table 19. From this table, it can be seen that the root mean square error (RMSE) for almost all the wells during validation are reasonably low and are within acceptable limit except for dug well OW28 located at Malappuram and bore wells BW163, BW165 and BW 189 located at Kottakal, Mankada and Thirurangadi respectively. Wells OW28 and BW189 are very close to the river and is most likely to be influenced by the interflow of river.

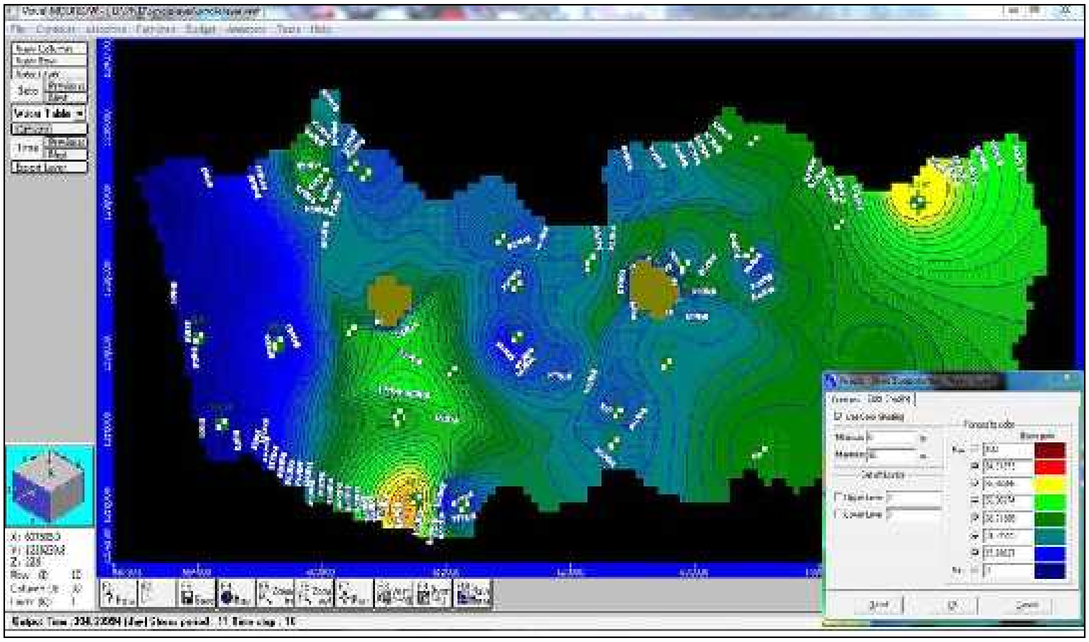


Fig. 65. Computed water table contour map after calibration

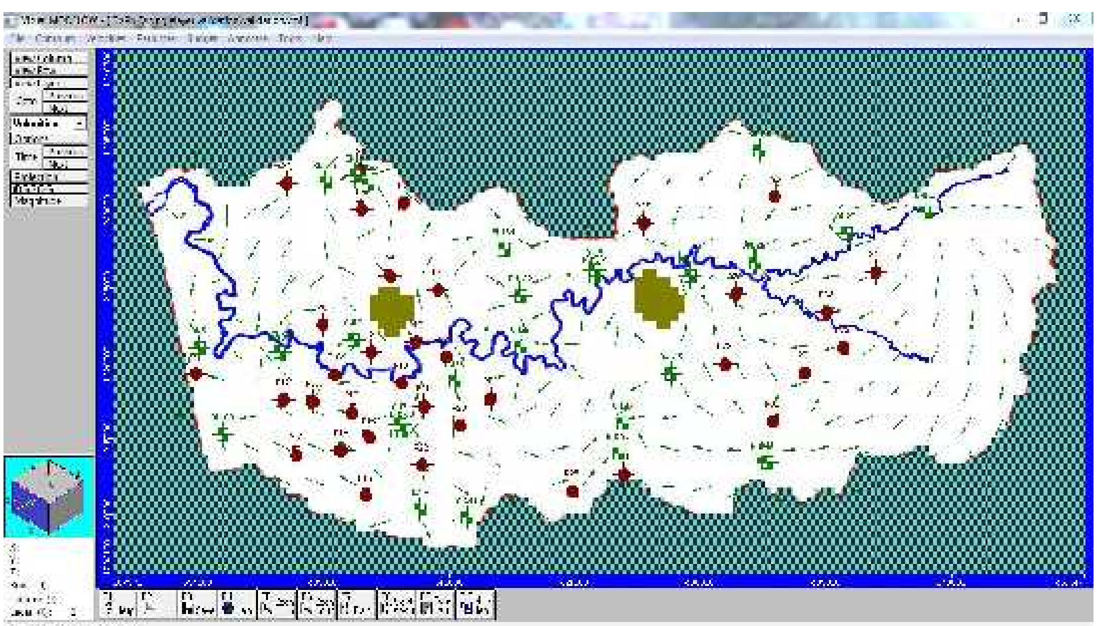


Fig. 66. Velocity vector of ground water flow in the study area

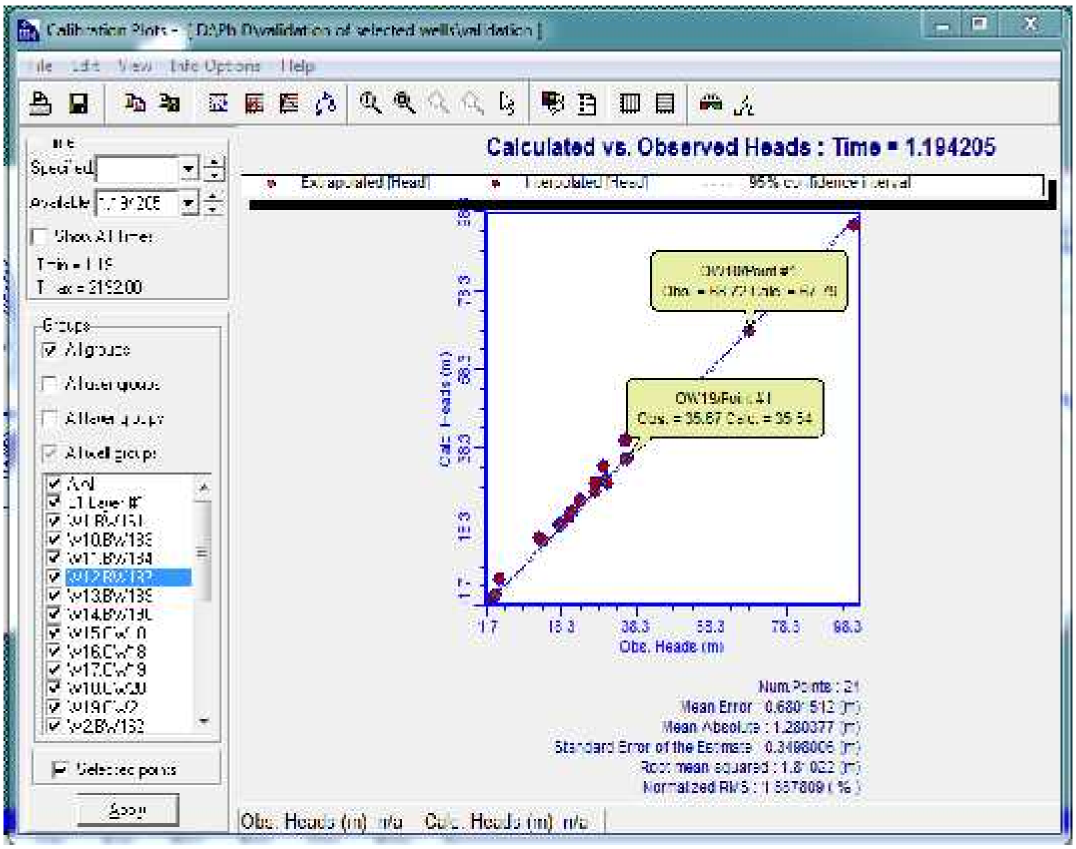


Fig.67. Model computed vs observed water level after validation

Table 19. Validated values of observed and calculated heads of selected wells

Sl.No	Well Name	Average value of observed Head	Average value of calculated Head	RMSE value
1	BW161	13.29	14.69	1.401401
2	BW162	17.91	18.62	0.708065
3	BW163	35.58	40.13	4.556236
4	BW165	29.49	33.79	4.300787
5	BW166	40.26	41.54	1.282049
6	BW167	20.65	20.80	0.210940
7	BW170	42.23	42.08	0.158069
8	BW171	30.87	29.39	1.483471
9	BW181	30.18	30.09	0.093467
10	BW183	21.31	21.84	0.533027
11	BW184	27.36	27.20	0.158656
12	BW187	68.71	67.79	0.914344
13	BW189	01.87	04.91	3.042180
14	BW190	00.90	01.02	0.121072
15	OW5	00.24	00.30	0.061290
16	OW9	44.42	42.51	1.915585
17	OW10	68.72	67.79	0.929344
18	OW18	18.25	18.65	0.929344
19	OW19	35.67	35.54	0.129372
20	OW20	23.54	24.94	1.402215
21	OW21	27.32	29.39	2.063529
22	OW22	40.74	41.10	0.359464
23	OW24	96.13	94.71	1.420428
24	OW28	12.52	15.60	3.082307

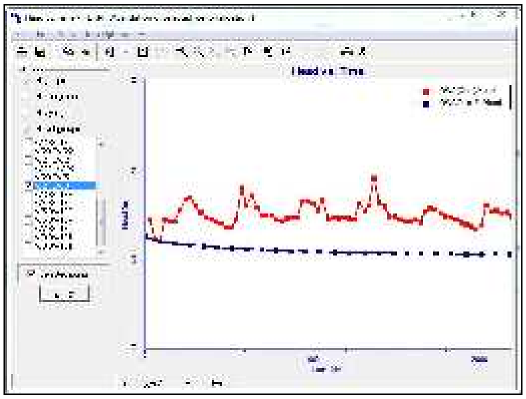
Bore wells BW163 and BW165 are located in hard laterite zone and the variations of piezometric water level in BW163 was not correlated with variations of rainfall. As a result, the average difference between observed and calculated ground water levels were relatively high. The hydrographs of computed and observed water levels for the selected observation wells after validation are shown in Fig. 68. The computed well hydrographs for bore wells at Porur (BW170), Moorkanad (BW181) and Mankada (BW165) and dug wells at Karuvarakundu (OW10), Perinthalmanna (OW9) and Puzhakattiri (OW20) showed fairly good agreement with observed values of head.

The ground water flow direction during pre monsoon and post monsoon are shown in Fig. 69 and 70. From this figures, it could be seen that flow was more active and towards the river and Arabian sea during post monsoon than pre- monsoon period. It was also noted that there was no reverse flow from Arabian sea even during pre monsoon period.

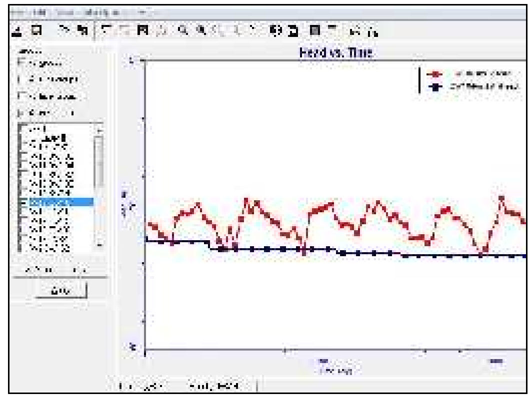
The drawdown vs time curve of selected observation wells are shown in Fig. 71. It could be seen that the drawdown vs. time curve of dug well as well as bore well for a particular areas like Kondotty, Pandikkad and Kuttippuram showed similar nature, indicated that there is no significant demarcation between unconfined and confined aquifers. This results are also in agreement with the results of hydraulic continuity analysis of the study area

4.3.4 Model prediction

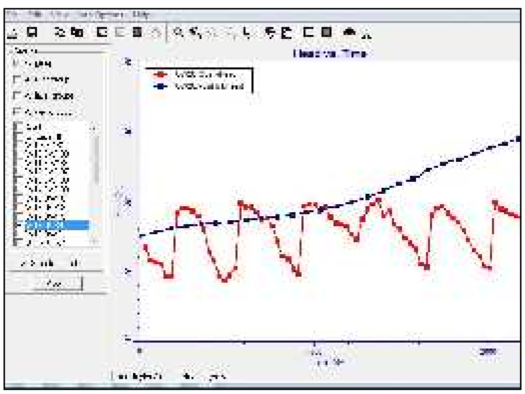
The validated model was run for predicting the trend of water level for next 5 years (4018 days), 10 years (5844 days) and 15 years (7668 days) from 2014 to 2018, 2023and 2028 in order to evaluate the decline of ground water table by assuming that the recharge of the study area will be reduced 5 per cent every year.



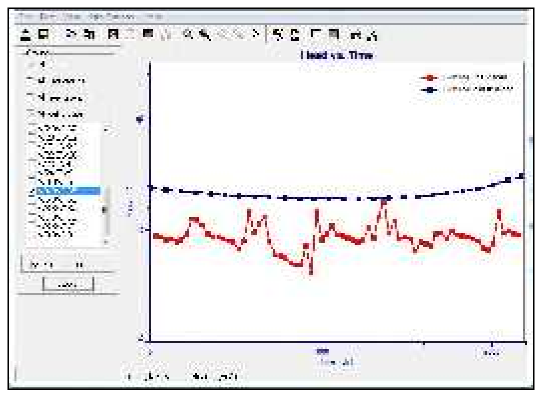
OW9 at Perinthalmanna



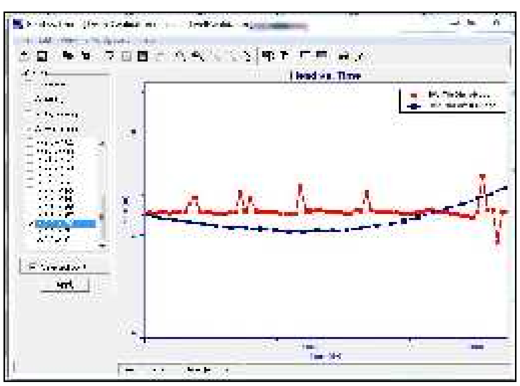
OW10 at Karuvarakundu



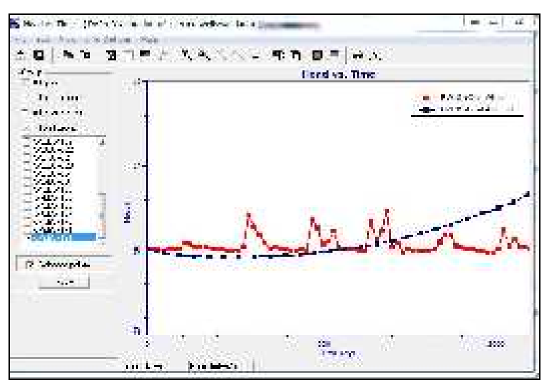
OW20 at Puzhakattiri



BW165 at Mankada



BW170 at Porur



BW181 at Moorkanad

Fig. 68. Computed and observed ground water level hydrographs for the selected observation wells after validation

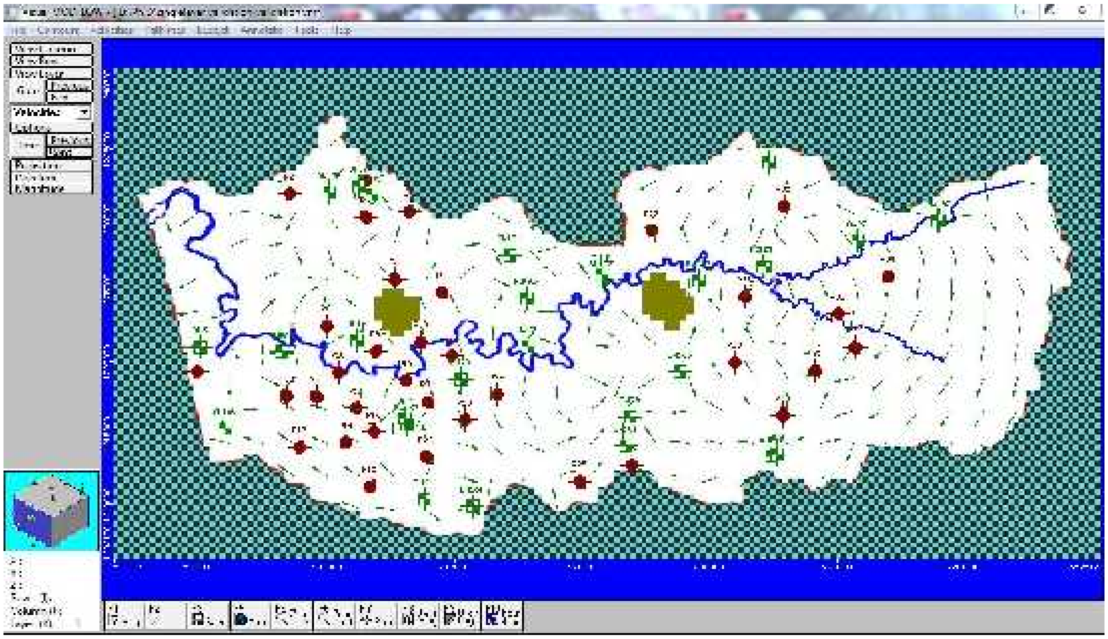


Fig. 69. Velocity vector of ground water flow during pre- monsoon period

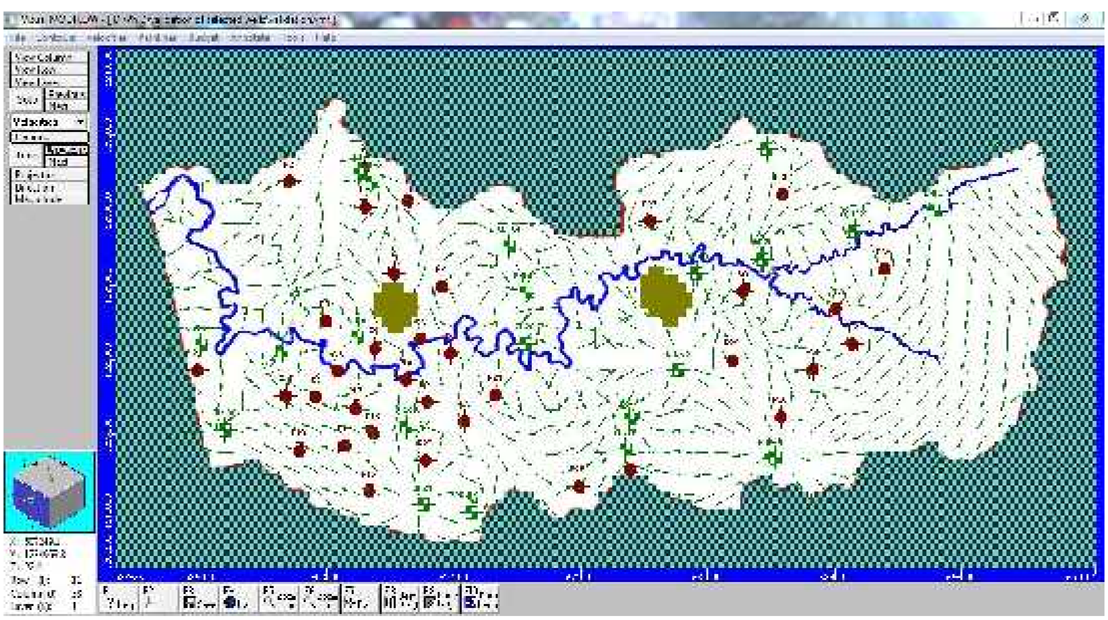
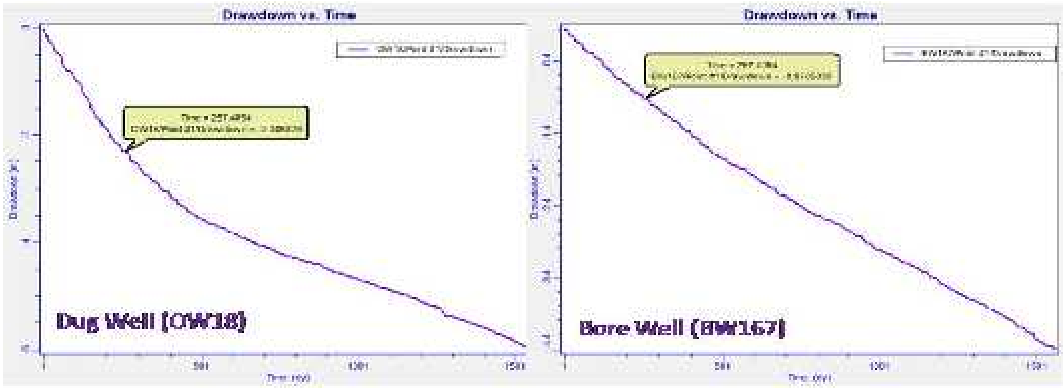
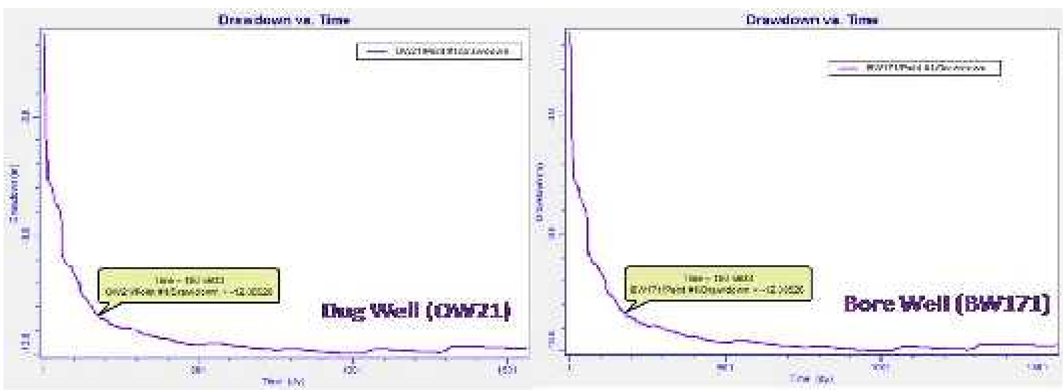


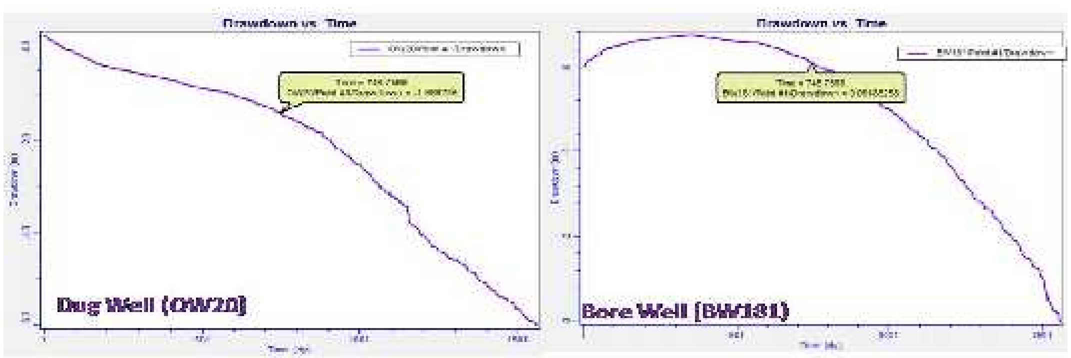
Fig. 70. Velocity vector of ground water flow during post monsoon period



Kondotty



Pandikkad



Kuttippuram

Fig. 71. Drawdown Vs. Time curve of dug wells and bore wells at different locations

Prediction was also made by assuming that the increase of pumping rate by 10, 25 and 50 per cent after 15 years to identify the area susceptible to ground water stress or the ground water deficit zones. The predictive simulation was done for 180 stress periods using the data for 48 stress periods for calibration and 24 stress periods for validation.

Decline of water table in the observation wells for a next 15 years from 2014 to 2028 was simulated using visual MODFLOW and the simulated water table hydrograph for the selected wells are shown in Fig. 72 and 73. Predicted water table for dug wells at Karuvarakundu, Marakara and Malappuram are shown in Fig. 72. From the figure, it could be see that there can be a fast decline of water table during the first five years with the decrease of recharge. In the case of well at Karuvarakundu, the reduction of water table predicted was found to be from 66.49 m to 63.6 m and in the subsequent years it will be very meager from 63.6 m to 63.21 m. This is because of the reason that the ground water table reaches the level of bed rock in that area.

Similar trend was observed in the case of dug wells OW24 and OW28 as shown in Fig.72. In the case of OW24, the water table decline was about 68.1 m to 53.8m during the first five years and then attains a more or less constant level. High decline of water table predicted in this well may be due to the reason that this well is located at high elevated area and also shows high fluctuation in the water table fluctuation study.

Fig. 73 shows the simulated piezometric level hydrograph for the selected bore wells located at Mankada, Pandalur and Karuvarakundu and it was observed that the decline of piezometric level was very low (1.5 m for the next 15 years) in BW165 when compared to BW 183 and BW187. It was also noted that, BW187 showed

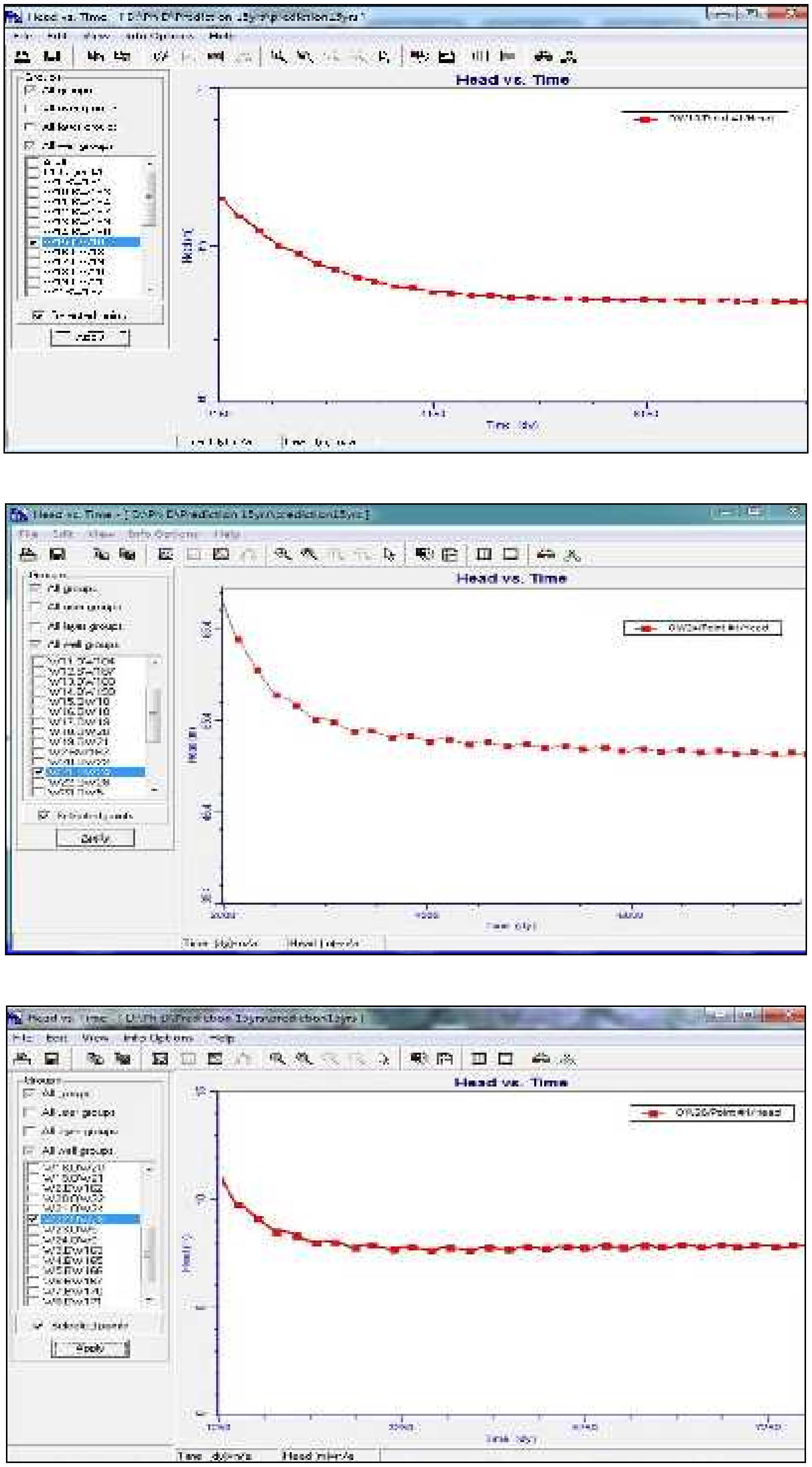
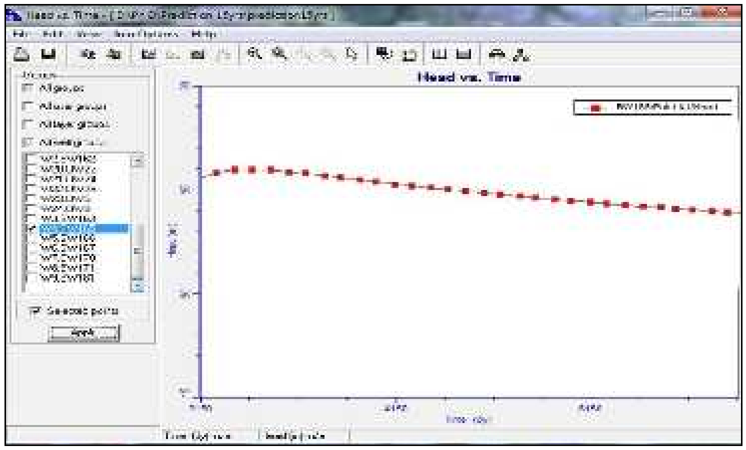
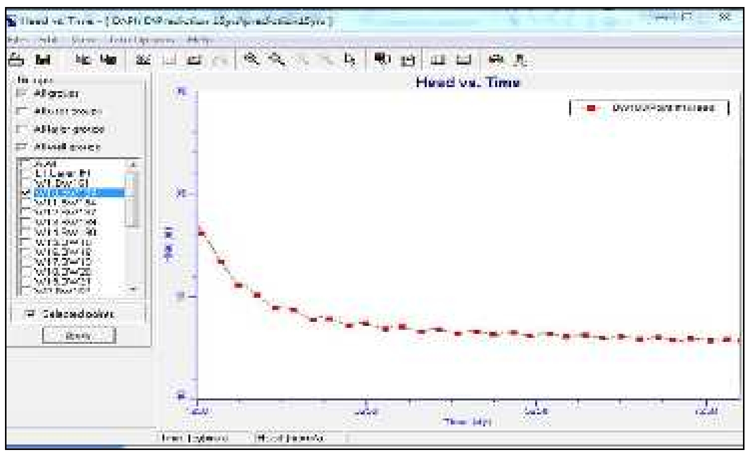


Fig. 72. Simulated water table hydrograph of selected dug wells





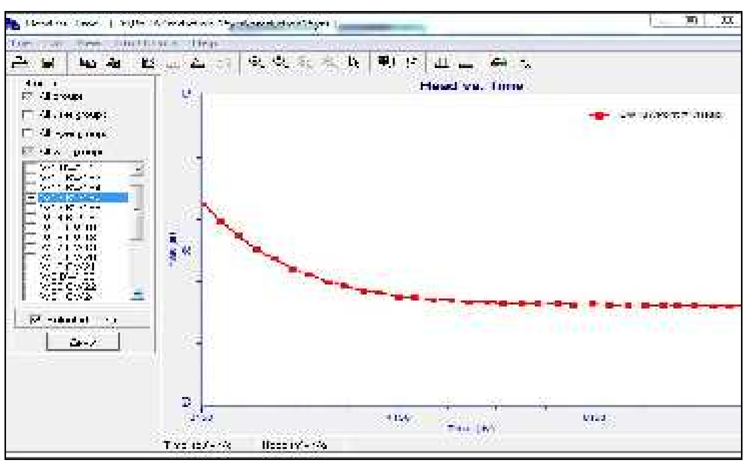


Fig. 73. Simulated piezometric water level hydrograph of selected bore wells

similar trend of decline in piezometric level as that of water table in that area and this is in agreement with the results of hydraulic continuity studies in that area.

Predicted water table contour map of Kadalundi river basin for the next 5,10 and 15 years are shown in Fig.74. From the figure, it is presumed that there could be a significant reduction in water table during the first 5 years and after that it will be more or less constant.

Considering the above observations it may be predicted that there is significant reduction of water table during first five years (from 2 m to 14.3 m) and subsequently there is no further reduction. This is because of the reason that the ground water table reaches the level of bed rock in many areas and this indicate the necessity of artificial ground water recharge techniques in the study area to increase the recharge of rainfall to the ground water.

Ground water deficit or vulnerable zones were predicted using visual MODFLOW assuming increased pumping rate by 10, 25 and 50 percent with the existing recharge and other aquifer properties. From the figures, it could be seen that there will not be any further increase of existing deficit zone in the study area due to increase in the pumping of ground water draft by 10 per cent. The vulnerable zone, would increase from 15.25 sq. km to 18.5 sq. km when pumping rate is increased by 25 per cent and the area would further increase to 23 sq. km with 50 per cent increase of pumping as shown in Fig.75, which infers that the thickness of aquifer formation of the area is very less when compared to other areas of the Kadalundi river basin.

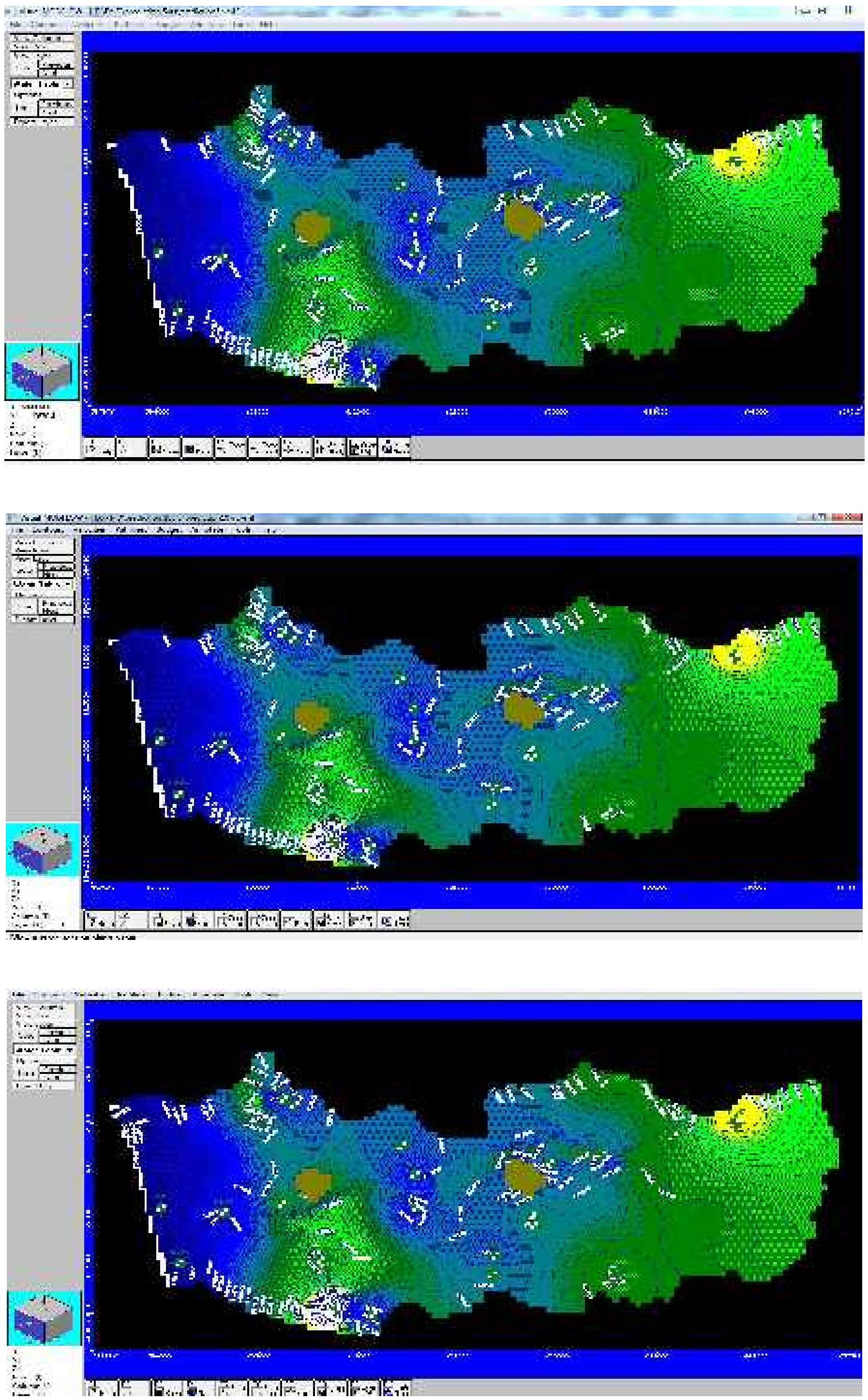


Fig.74. Predicted water table contour map of the study area after 5, 10 and 15 years.

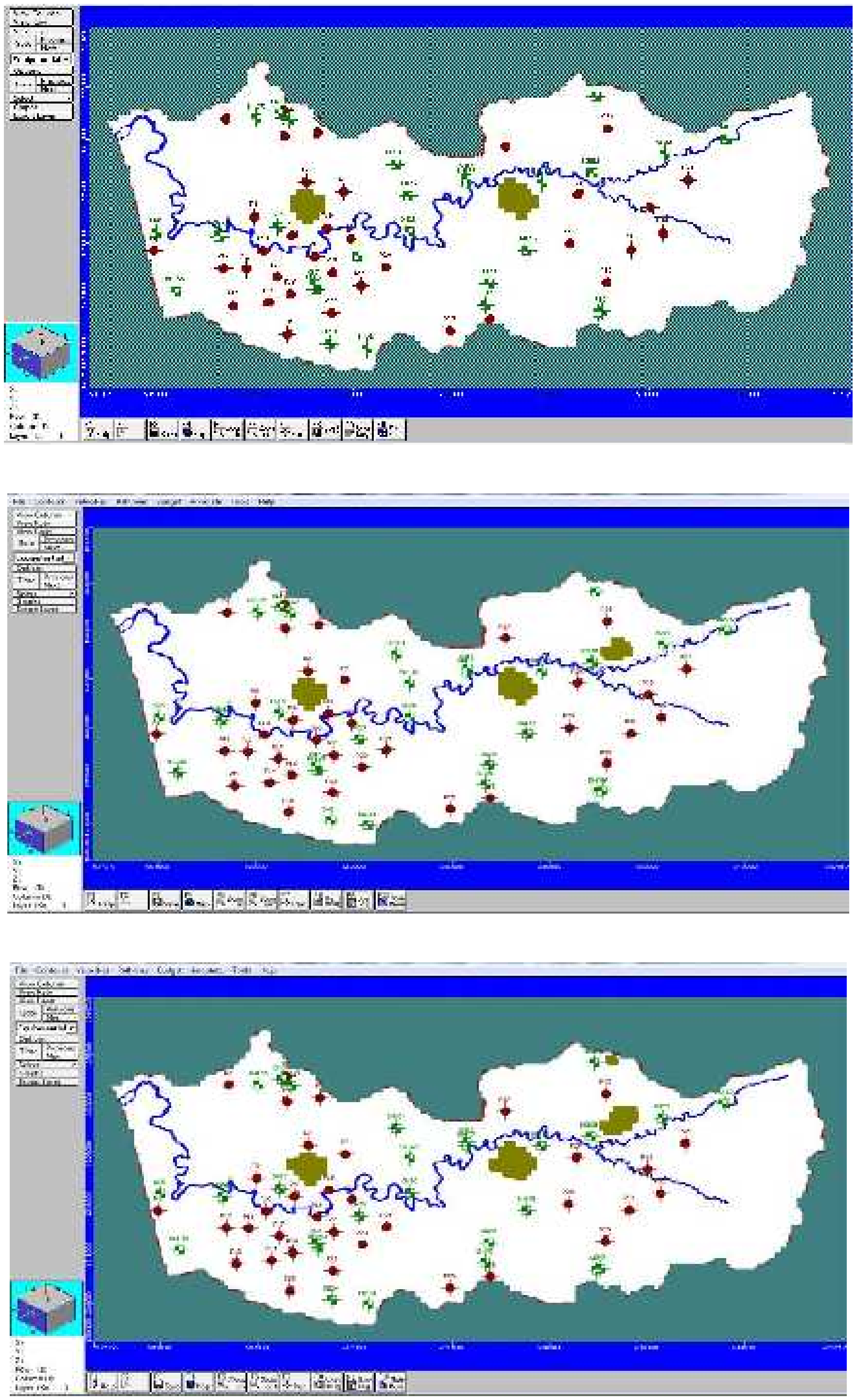


Fig. 75. Predicted ground water deficit zone by increasing pumping rate 10, 25 and 50 percent

From the results of the study, it could be seen that the water table and piezometric level fluctuations in low land, mid land and high land areas are well correlated with rainfall, except some locations like Kottakkal, Marakkara and Tanur. This indicated that the aquifer formations in major part of the basin are more or less homogeneous with thickness of 10 m to 20 m. Coastal region occupies alluvial formations and major portion of the study area comprises of mid land region which occupies laterite formations, that are porous and highly permeable in nature. Hence this formation constitutes the potential aquifer of the basin and dug wells are the most suitable abstraction structures in these aquifers. This is also in agreement with the results of Vertical Electrical Sounding (VES) studies conducted at 22 locations. It was also observed that Visual MODFLOW can be effectively used for evaluation of the ground water resources and for the future prediction with specific strategies. From the modelling studies, it could be noted that the Kadalundi river basin will remain safe for a short span of five years for future ground water development and subsequently the water table will coincide with the bed rock. This necessitates artificial ground water recharge techniques in the study area to supplement the ground water recharge through rainfall.

The characteristics of the river basin can bring an insight to the general water table fluctuations and water availability status of the Malappuram district because Kadalundi river is the unique river which passes through all the different geographical regions, soil types and water bearing formations of the district.

CHAPTER 5

SUMMARY AND CONCLUSION

Malappuram is the most populous district of Kerala and the demand for ground water is increasing year by year in the district due to recurring drought, growing population, urbanisation and increased agricultural and industrial activities. To meet this increasing demand, a realistic estimation of ground water and related information are needed to mitigate water scarcity, water pollution and ecological problems. Kadalundi river basin covers major geographical area of Malappuram district comprising of 34 per cent of the total area of the district and this river basin can be considered as a general representation of the district. Hence Kadalundi river basin is selected as study area of this research work.

Spatial and temporal variations of ground water levels of dug wells and bore wells were analyzed separately for evaluating the aquifer characteristics. Monthly water table data from 16 bore wells and 14 dug wells during the period from 2008 to 2013 were used for the analysis.

For the analysis of water table in the study area, ground water table during pre and post monsoon in 14 dug wells located at different physiographic locations were observed and pre and post monsoon water table fluctuations were noted. Ground water table for April and October were monitored to study the pre and post monsoon fluctuations respectively. The pre and post monsoon ground water table maps for six consecutive years and the average ground water recharge map were prepared using Arc GIS (10.1).

The depth to ground water table recorded from the dug wells located at different physiographic regions such as low land, mid land and high land areas were used to prepare the water table hydrographs corresponding to the variation of rainfall in the study area. Statistical analysis were carried out to check the correlation between water table and rainfall and F test were carried out to check the temporal variation of water table fluctuations.

In order to study the characteristics of confined aquifers in the study area, piezometric water level during pre and post monsoon periods in 16 bore wells located at different physiographic locations were observed and the difference between them were noted to study the influence of rainfall. The pre and post monsoon piezometric level maps for six consecutive years and the average ground water recharge map between pre and post monsoon were prepared using Arc GIS (10.1). The depth of piezometric water level recorded from the bore wells located at different physiographic regions such as low land, mid land and high land areas were used to prepare the water table hydrographs corresponding to the variation of rainfall in the study area and statistical analysis were carried out to check the correlation between piezometric level and rainfall and also the temporal variations.

In order to check the hydraulic continuity of different layers of a particular area, variations of ground water table in dug wells and bore wells in that particular area needed to be analyzed with the rainfall variations. Hydraulic continuity analysis was carried out at eight locations of Kadalundi river basin viz. Kondotty, Thirurangadi, Karuvarakundu, Anakayam, Pandikkad, Kottakkal, Perinthalmanna and Kuttippuram comprising of all physiographical regions.

For the identification of ground water potential zones, Electrical Resistivity Meter (ERM) method with Vertical Electrical Sounding (VES) was carried out in 22 locations using Signal Stacking Resistivity Meter (MODEL-SSR-MP-ATS). Field data obtained from VES survey were processed and interpreted qualitatively and quantitatively using IPI2WIN software to obtain the resistivity values of different subsurface layers and their corresponding thickness. The results obtained from VES data interpretation were used to prepare the map of resistivity and depth to bed rock of the study area using Arc GIS(10.1). Resistivity and pseudo cross sections along different sections were prepared using true and apparent resistivity values.

In this study, Visual MODFLOW software version 2.8.1 developed by Waterloo Hydrogeologic Inc. was used for the flow modelling of the study area.

Base map was prepared using Arc GIS (Arc Map10.1) and imported into the model. The conceptual model for the study area was developed using the topo sheet of the area, well logs at 30 sites and the data obtained from the geophysical studies conducted in the study area. After the conceptual model developement, the study area was discretized by dividing it into 62 rows and 136 columns with a grid spacing of 500 m x 500 m throughout the area. Thus the study area was discretized into 8432 cells and the cells outside the boundary of the study area was made as inactive.

Visual MODFLOW permitt to input field observations of pumping and observation wells to get model output. Total 35 numbers of major pumping wells of Kerala Water Authority and Jalanidi Malappuram were selected for this study. the ground water abstraction for irrigation and domestic purposes in the study area was calculated by carrying field observations and the available data from Ground Water Department and CWRDM. Thirty ground water monitoring wells (consisting of 14 dug wells and 16 bore wells) of Ground Water Department (GWD), Government of Kerala located in the Kadalundi river basin were selected as observation wells.

Hydrogeological parameters such as hydraulic conductivity, specific storage, specific yield, porosity and initial heads and boundary conditions of the model domain including constant head, rivers, drains, recharge and evapotranspiration were used as input of Visual MODFLOW. After completing the uploading of input parameters, the model was run for steady state and transient state subsequently.

The model was developed and calibrated with four years data (2008 to 2011) and validated with two years data (2012 & 2013). After the development of a validated model, it was used to predict the flow head for the next 15 years assuming five per cent decrease in recharge for every year and also to predict the ground water condition by increasing the pumping rate 10, 25 and 50 percent of pumping rate of the validation period (2013).

From the pre and post monsoon ground water table fluctuations studies of dug wells, it was observed that the water table fluctuations in all the wells are similar, which ranged from 1.31 m to 4.31 m, except the maximum water table fluctuation of 7.98 m noted in well OW24 located at Marakkara at an elevation 98.54 m.

The pre-monsoon variation was similar for all the six years from 2008 to 2013. At Malappuram, Kondotty, Mankada, Manjeri, Wandoor, part of Perinthalmanna and Palakkad, comprising of more than 60 per cent of the study area and the average depth to water table during pre- monsoon periods from 2008 to 2013 ranged from 5.1 m to 8.1 m. In some parts of Thirurangadi, Vengara and Kuttippuram blocks, the average depth to water table varied from 7.0 m to 10.2 m whereas, at elevated parts of Thirurangadi and vengara, it varied from 8.9 m to 12.5 m.

Similar trend was observed in post monsoon water table for the study period from 2008 to 2013. During post monsoon, average depth to water table varied from 2.5 m to 5.8 m and 4.3 m to 8.0 m in major parts of the study area. It was also observed that the ground water fluctuation is almost similar along the central and eastern part of the study area from the average ground water recharge contour map between pre- monsoon and post monsoon period during 2008 to 2013 and ranged from 1.31 m to 2.65 m.

In coastal region and some parts of Kondotty, Thirurangadi, Tanur and Wandoor, ground water fluctuation was 2.65 m to 3.98 m, due to the remarkable recharge from rainfall, which indicated that the aquifer formation in this area has high porosity and permeability. The coastal region comprises of coastal alluvium with high porosity and permeability. Laterite act as a potential aquifer because of its high porosity and permeability and the mid land region is mostly occupied with laterite aquifer.

The pre and post monsoon ground water level above mean sea level(AMSL) against average annual ground water level AMSL at different physiographical regions during the study period from 2008 to 2013 indicated that the depth of water table and its temporal variation in the area are closely related to topography and aquifer properties of the area.

General observation of water level data from the dug wells indicated that water table tends to rise during June to September, reaching the peak in September and declines from October to the end of May in every year. It was also observed that the water table fluctuation in low land, mid land and high land area are correlated with rainfall except for few locations like Kottakkal, Marakkara and Tanur. This indicated that the major part of the basin occupies laterite formations which are porous and highly permeable in nature. Hence this formation constitutes the potential aquifer of the basin and dug wells are the suitable abstraction structure in the aquifer.

The variation of piezometric water level fluctuation between pre and post monsoon indicates groundwater resources development in the study area. The maximum fluctuation was noted as 8.64 m in BW 166 located at Perinthalmanna, a highly elevated area of 53.98 m and minimum was 0.30 m in BW190 located at Tanur, coastal region with an elevation of 3.80 m. Most of the bore wells are located in mid land region, where the piezometric water level fluctuation between pre and post monsoon ranged from 0.78 m to 3.48 m. In major part, comprising of more than 75 per cent of the total study area, depth to piezometric water level in pre- monsoon period ranged from 2.6 m to 9.5 m and 7.6 m to 15.4 m during the study period.

The post monsoon piezometric water level contour maps follows similar trend during all the six years of the study (2008 to 2013). The increase in piezometric water level is directly proportional to the rainfall in major part of the study area. This may be due to the fact that the bore wells in that area mainly abstract water from fractured aquifers in the crystalline formations and ground water occurs under semiconfined to shallow confined conditions.

The piezometric water level fluctuation in some locations of Malappuram, Wondoor, Thirurangadi and Mankada blocks were well correlated with rainfall variations, which indicates that the bore wells in these areas abstract water from semiconfined or shallow confined aquifer with lithomargic clay as upper confining layer.

The well at Tanur (BW190) is very near to sea shore and abstract water from shallow sandy aquifer, hence the influence of sea water may be a reason for low correlation of water table with rainfall.

In mid land region, water table variations of all the wells are similar and correlated with variations of rainfall, which indicate that the mid land region comprising of ground water potential aquifer of laterites and the dug wells are the more suitable as ground water abstraction structure.

In the well at Kottakkal (BW163), the piezometric water level fluctuations with rainfall is poorly correlated with a value of 0.13 which indicate that the bore well at Kottakal (BW163) originate from deep confined aquifer and this area is suitable for bore wells..

At Kondotty, Karuvarakundu, Anakayam, Pandikkad and Kuttippuram variations of ground water table and piezometric water level were correlated with rainfall variations. This indicated that hydraulic continuity of ground water and surface water exists between aquifers of dug well and bore well in these areas. At Thirurangadi and Kottakkal, variations of piezometric water level were poorly correlated with rainfall variations than the correlation between water table and rainfall, which indicate that there was no hydraulic continuity between upper unconfining and lower confining layers. In the case of wells at Perinthalmanna, negative correlation was observed indicating that a delayed recharge is occurring in that aquifer due to the absence of fractures and joints in the confining layers of the confined aquifer.

Among the total twenty two VES locations, seventeen locations are having three layer cases and these three layers are laterite, weathered zone and hard rock. From the contour map of resistivity of the study area, it could be seen that major part of river basin having same range of resistivity, 101-500 ohm-m. This indicate that the formation of the first layer in these areas are lateritic soil or brown soil. In some pockets like Wandoor and Vengara blocks, hard rock with greater resistivity is exposed.

From the contour map of depth to bed rock, it could be seen that almost all parts of the study area have same range of depth to bed rock, ie, 10 -20 m. In some part of Wandoor, Vengara and Malappuram blocks shallow bed rock was seen, ie, within 0-10 m. A small part of Mankada block has deep bed rock ranging from 20 – 60 m.

Most parts of the study area are dominated by H type curve which indicate the presence of good quality groundwater. In the coastal region, fine to medium grained alluvial deposit of 1.5 to 6 m is available, followed by clay formation of thickness varying from1.5 m to 22 m containing freshwater, which is overlying sand formation containing saline water. In the midland region, top soil (lateritic soil/ hydromorphic soil) of thickness 0.75 to 3 m is seen, followed by laterites with varying hardness to a depth of 3 m to 18 m. Lithomargic clay of thickness less than 2 m is seen below the laterites in some areas of midland. These clay/laterites are overlying weathered rock of 1 to 14 m thickness followed by hard rock with or without fractures. The highland region is covered by brown soil of 1 to 2 m thickness followed by laterites, weathered rock and rock with or without fractures.

Resistivity cross section shows the vertical true resitivity variation from the interpreted parameters of the soundings along the profile in a linear scale. The sections show shape, vertical variation of resistivity and layer sequence along selected profile which help in understanding the subsurface geology.

A low resistivity zone of less than 250 ohm-m was observed throughout Nooradi (VES15) and Anakayam(VES1) area, indicating the presence of river in that area, which continues towards Cherukode (VES03) area. These areas have high potential for dug wells.

In Kottakal (VES07) area, hard laterites with gradually decreasing resistivity were seen on upper layers indicating that this area is suitable for bore wells. A low resistivity zone was observed in Pandikkad (VES17) region upto a depth of 10 m below ground level and which continues towards Cherukode (VES03) area with a decreasing depth and hence these are high potential areas for dug well.

A patch of high resistivity zone of more than 1000 ohm-m was observed in Kolarkunnu (VES06) location from the depth of 10 m to 30 m, which indicate the presence of massive charnokite. A weathered zone was obsevrved below this hard rock up to a depth of 70 m and hence this area can be suggested for bore wells.

A low resistivity zone of less than 100 ohm-m was observed in the central part of Thirurangadi (VES 21) and it continued upto Tanur (VES 20). This zone continues to a depth of more than 20 m which indicated the presence of clayey soil.

Based on the above observations of substrata, the model was calibrated for steady state conditions by assuming the aquifer condition of year 2008 as the initial condition for the steady state model calibration. The hydraulic conductivity values, boundary conditions and the water levels obtained from the steady state model calibration were used as the initial condition in the transient model calibration. The above values were used along with the specific storage and specific yield distribution, time variable recharge and dumping distribution. The transient (dynamic) calibration was carried out for the time period from 2008 to 2011 (1461 days). The storage coefficient values varied iteratively so that a reasonably good match was obtained between computed and observed water levels. The calculated heads are well matching with observed heads at 95 per cent confidence level.

The computed and observed ground water level hydrographs for the selected observation wells (bore wells at Porur, Morkanad and Karuvarakundu and dug wells at Karuvarakundu Perinthalmanna and Puzhakattiri) showed that the computed water table hydrographs were comparable with the observed values. In the coastal region the water table elevation was very low ranging from 0 to 15 m and at extreme west side, it is '0' because of the presence of Arabian sea as boundary.

In the central part of the study area comprising of Malappuram, Mankada and Manjery blocks, the water table elevation ranged from15 m to 32 m and 32 m to 40 m, indicating that major part of study area are under same range of water table elevation. At some pockets of Wandoor and Kuttippuram blocks, the water table elevations were found to be high, ranging from 66 m to 85 m and this may be due to high elevation of that area.

The perusal of model run revealed that some dried cells are seen in the Vengara and Perinthalmanna block comprising an area of 6.75 and 8.5 km^2 respectively. This indicated that this area is comprising of hard rock and it is supported by the results of earth resistivity studies.

The model was validated with the water table data of 24 selected observation wells for the period from 2012 to 2013. The root mean square error (RMSE) for almost all the wells during validation are reasonably low and are within acceptable limit except for dug well OW28 located at Malappuram and bore wells BW163, BW165 and BW 189 located at Kottakal, Mankada and Thirurangadi respectively. Wells OW28 and BW189 are very close to the river and are most likely to be influenced by the interflow to the river.

The computed well hydrographs for bore wells at Porur (BW170), Moorkanad (BW181) and Mankada (BW165) and dug wells at Karuvarakundu (OW10), Perinthalmanna (OW9) and Puzhakattiri (OW20) showed fairly good agreement with observed values of head.

The ground water flow direction during pre and post monsoon indicted that flow was more active and towards the river and Arabian sea during post monsoon than pre monsoon period. It was also noted that there was no reverse flow from Arabian sea even during pre monsoon period.

The drawdown Vs. time curve of dug wells as well as bore wells for particular areas like Kondotty, Pandikkad and Kuttippuram showed similar trend, indicating that there is no significant demarcation between unconfined and confined aquifers. This results are in agreement with the results of hydraulic continuity analysis of the study area

Predicted water table for dug wells at Karuvarakundu, Marakara and Malappuram indicate that there can be a fast decline of water table during the first five years with the decrease of recharge. In the case of wells at Karuvarakundu, the reduction of water table predicted was found to be from 66.49 m to 63.6 m and in the subsequent years it will be very meagre from 63.6 m to 63.21 m. This is because of the reason that the ground water table reaches the level of bed rock in that area. Similar trend was observed in case of dug wells OW24 and OW28. In the case of OW24, the water table decline was about 68.1 m to 53.8 m during the first five years and then attains a more or less constant level. High decline of water table predicted in this well may be due to the reason that this well is located at high elevated area.

The predicted piezometric level hydrograph for the selected bore wells located at Mankada, Pandalur and Karuvarakundu showed that the decline of piezometric level is very low (1.5 m for the next 15 years) in BW165 when compared to BW 183 and BW187. It was also noted that, BW187 showed similar trend of decline in piezometric level as that of water table in that area and this is in agreement with the results of hydraulic continuity studies in that area.

Ground water deficit or vulnerable zones were predicted using visual MODFLOW assuming increased pumping rate by 10, 25 and 50 percent with the existing recharge and other aquifer properties and it could be seen that there will not be any further increase of existing deficit zone in the study area due to increase in the pumping of ground water draft by 10 per cent. The vulnerable zone, would increase from 15.25 km^2 to 18.5 km^2 when pumping rate is increased by 25 per cent and the area would further increase to 23 km^2 with 50 per cent increase of pumping rate.

It could be concluded that the water table and piezometric level fluctuation in low land, mid land and high land areas are correlated with rainfall, except for locations of Kottakkal, Marakkara and Tanur. This indicated that the aquifer formations in major part of the basin are more or less homogeneous and it occupies laterite formations, which are porous and highly permeable in nature. Hence this formation constitutes the potential aquifer of the basin and dug wells are the most suitable abstraction structure in the aquifer. This is also in agreement with the results of Vertical Electrical Sounding (VES) studies conducted at 22 locations. Most parts of the study area are dominated by H type curve which indicate the presence of good amount of groundwater. Lithomargic clay of thickness less than 2 m is seen below the laterites in some areas of midland. It is also observed that Visual MODFLOW can be effectively used for evaluation of the ground water resources and for the future prediction with specific strategies. From the modelling studies, it could be noted that the Kadalundi river basin may remain safe for a short span of five years from the point of future ground water development and subsequently the water table will reach the bed rock. This necessitates artificial ground water recharge techniques in the study area to supplement the ground water recharge through rainfall.

A well planned programme for ground water development to meet both drinking and irrigation water requirement need to be initiated for the optimum utilisation of ground water potential zones located in the Kadalundi river basin. Visual MODFLOW is also a suitable model for salt water intrusion studies and contaminant transport. Hence it is recommended that sea water intrusion studies may also be carried out along the coastal region of the basin.

APPENDIX I

Top and bottom elevation of the layer used in Visual MODFLOW

X – Coordinates (m)	Y- Coordinate (m)	Top elevation	Bottom elevation
606162.97	1231817.75	27.42	6.42
603128.97	1231961.55	57.52	39.52
608644.01	1215544.93	54.75	30.75
617110.31	1224482.75	21.55	-8.45
622415.71	1225731.05	31.78	13.78
629242.74	1225757.45	27.55	-27.45
615885.67	1227550.35	33.18	0.18
634452.26	1213336.47	54.61	1.61
599827.12	1220585.47	12.50	5.50
646216.50	1229976.86	72.20	2.20
634215.07	1234072.35	47.19	17.19
633790.43	1226697.43	39.51	9.51
627902.00	1219301.00	37.50	25.00
624144.00	1214070.00	35.96	10.96
624425.00	1216062.00	32.80	20.40
595790.00	1215316.00	4.00	-26.00
609876.00	1210327.00	99.90	44.90
613255.00	1209830.00	18.73	0.73
593496.00	1225014.50	4.00	-20.00
592163.80	1229810.50	1.00	-20.00
643480.30	1218939.70	40.00	27.00
598078.80	1225387.60	6.30	-5.00
627334.00	1223948.80	80.00	62.00
607883.80	1222989.60	70.00	52.00
590266.69	1229539.40	1.00	-14.00
594180.83	1216538.77	1.00	-15.00
592661.80	1224826.01	1.00	-14.00
634722.13	1225368.81	22.00	15.00
595587.16	1214607.03	2.00	-15.00
621758.52	1225246.29	29.00	14.50
608595.62	1215506.73	61.72	37.72
594969.50	1214017.10	1.20	-12.00
589907.20	1230984.20	1.00	-9.50
592966.90	1222528.50	1.50	-11.50
600475.00	1220675.00	10.00	-20.00
621755.00	1225246.00	29.00	11.70
631293.00	1212904.00	58.00	28.00
634412.00	1234282.00	54.00	24.00
636829.00	1225950.00	42.00	12.00
623706.00	1221435.00	38.00	8.00
620770.00	1227599.00	30.00	1.00
608644.00	1215544.00	68.00	38.00
620501.00	1219138.00	24.00	-6.00
616853.00	1220274.00	16.00	-14.00
606296.00	1221176.00	47.00	17.00
591578.50	1227001.80	1.00	-15.00
593294.00	1218710.30	1.50	-13.00

APPENDIX II

Location of Ground Water Monitoring Wells of Kadalundi river basin

Well Name	X – Coordinates (m)	Y- Coordinate (m)	Location
BW161	613255.00	1209830.00	Kuttippuram
BW162	617110.31	1224482.75	Melmuri
BW163	608644.01	1215544.93	Kottakkal
BW165	627902.00	1219301.00	Mankada
BW166	634452.26	1213336.47	Perinthalmanna
BW167	606162.97	1231817.75	Nediyiruppu
BW170	634215.07	1234072.35	Porur
BW171	633790.43	1226697.43	Pandikkad
BW175	603128.97	1231961.55	Pallikkal
BW177	622415.71	1225731.05	Anakkayam
BW181	624144.00	1214070.00	Moorkanad
BW183	629242.74	1225757.45	Pandalur
BW184	615885.67	1227550.35	Pookkoottur
BW187	646216.50	1229976.86	Karuvarakundu
BW189	599827.12	1220585.47	Thirurangadi
BW190	595790.00	1215316.00	Tanur
OW5	594060.26	1221029.05	Parappanangadi
OW6	599826.65	1220739.07	Tirurangadi
OW7	608490.83	1216005.24	Kottakkal
OW9	634785.47	1213491.45	Perinthalmanna
OW10	646064.78	1229976.17	Karuvarakundu
OW15	622413.97	1226191.88	Anakkayam
OW18	605250.96	1232429.09	Kondotty
OW19	605134.54	1221523.63	Vengara
OW20	624425.00	1216062.00	Puzhakattiri
OW21	633942.15	1226698.06	Pandikkad
OW22	640457.82	1228568.91	Thuvvur
OW23	612426.84	1218783.20	Othukkungal
OW24	609876.00	1210327.00	Marakkara
OW28	617122.45	1221103.60	Malappuram

APPENDIX III

Initial head of observation wells in Kadalundi river basin

Well Name	X - Coordinates	Y- Coordinate	Initial Head
BW161	613255.00	1209830.00	13.29
BW162	617110.31	1224482.75	17.913
BW163	608644.01	1215544.93	35.577
BW165	627902.00	1219301.00	34.16
BW166	634452.26	1213336.47	40.26
BW167	606162.97	1231817.75	20.648
BW170	634215.07	1234072.35	42.235
BW171	633790.43	1226697.43	30.872
BW175	603128.97	1231961.55	59.93
BW177	622415.71	1225731.05	29.77
BW181	624144.00	1214070.00	30.18
BW183	629242.74	1225757.45	21.307
BW184	615885.67	1227550.35	27.362
BW187	646216.50	1229976.86	68.706
BW189	599827.12	1220585.47	1.866
BW190	595790.00	1215316.00	0.9
OW5	594060.26	1221029.05	0.24
OW6	599826.65	1220739.07	7.687
OW7	608490.83	1216005.24	56.046
OW9	634785.47	1213491.45	44.423
OW10	646064.78	1229976.17	68.721
OW15	622413.97	1226191.88	26.161
OW18	605250.96	1232429.09	18.246
OW19	605134.54	1221523.63	35.667
OW20	624425.00	1216062.00	23.54
OW21	633942.15	1226698.06	27.324
OW22	640457.82	1228568.91	40.741
OW23	612426.84	1218783.20	69.897
OW24	609876.00	1210327.00	96.13
OW28	617122.45	1221103.60	12.521

APPENDIX IV

Recharge of the Kadalundi river basin based on rainfall

Period days	Rainfall (mm)	Recharge (mm)	Period days	Rainfall (mm)	Recharge (mm)
31	0	0	1127	0	0
60	2	0.46	1155	20	4.6
91	245	56.35	1186	21	4.83
121	26	5.98	1216	172.2	39.606
152	123	28.29	1247	108.4	24.932
182	582	133.86	1277	759	174.57
213	363	83.49	1308	456.9	105.087
244	262	60.26	1339	452.1	103.983
274	270	62.1	1369	388.6	89.378
305	374	86.02	1400	229.7	52.831
335	0	0	1430	147	33.81
366	0	0	1461	0	0
397	0	0	1492	0	0
425	0	0	1521	0	0
456	61	14.03	1552	0	0
486	58	13.34	1582	114.5	26.335
517	188	43.24	1613	130.5	30.015
547	326	74.98	1643	681.2	156.676
578	1126	258.98	1674	572.5	131.675
609	267	61.41	1705	273.4	62.882
639	266	61.18	1735	174.1	40.043
670	178	40.94	1766	430.9	99.107
700	345	79.35	1796	245.1	56.373
731	23	5.29	1827	10.5	2.415
762	0	0	1858	0	0
790	0	0	1886	79.5	18.285
821	0	0	1917	55.2	12.696
851	149	34.27	1947	0	0
882	196	45.08	1978	89.7	20.631
912	692	159.16	2008	873.3	200.859
943	519	119.37	2039	1061.6	244.168
974	355	81.65	2070	88.1	20.263
1004	234	53.82	2100	242.2	55.706
1035	547	125.81	2131	186.2	42.826
1065	286	65.78	2161	73.8	16.974
1096	2	0.46	2192	0	0

APPENDIX V

Water table data of observation wells

Period days	BW161 (m)	BW162 (m)	BW163 (m)	BW165 (m)	BW166 (m)	BW167 (m)	BW170 (m)	BW171 (m)
31	13.29	17.91	35.58	29.49	40.26	20.648	42.235	30.87
60	12.98	17.44	35.57	29.4	37.73	20.378	42.175	30.74
91	13.62	17.30	35.66	29.18	33.47	19.878	42.195	30.56
121	12.66	17.47	35.70	29.26	32.6	20.428	42.205	31.12
152	12.64	16.98	35.68	28.97	30.96	19.628	42.105	30.92
182	13.92	18.30	35.85	29.08	30.55	21.208	42.275	31.86
213	15.25	19.34	36.25	29.63	30.42	22.478	42.295	34.39
244	14.77	18.94	36.56	31.03	33.72	21.958	42.375	31.71
274	14.25	18.90	36.67	30.93	34.69	21.958	43.075	32.61
305	13.82	18.47	36.70	30.43	36.46	20.868	43.775	33.11
335	14.82	18.39	36.92	29.68	37.04	20.688	42.305	31.10
366	13.35	18.32	36.77	29.36	36.11	20.268	42.255	30.88
397	12.55	17.65	36.77	29.34	33.82	20.278	42.205	30.70
425	12.37	17.58	36.73	29.25	32.5	20.218	42.145	30.39
456	11.93	16.93	36.56	29.02	29.01	19.688	42.115	30.31
486	11.18	16.85	36.56	29.01	26.36	19.318	42.065	30.65
517	12.59	17.28	36.56	28.32	23.64	19.328	42.235	30.65
547	13.81	18.25	36.76	29.07	21.25	20.658	42.365	31.87
578	16.17	19.34	37.43	31.66	20.7	23.618	44.185	33.50
609	15.76	19.08	38.16	29.75	24.32	22.938	42.415	32.50
639	14.78	19.14	37.50	30.6	30.72	20.598	43.555	32.65
670	15.59	19.32	37.25	31.18	34.23	21.238	42.395	31.65
700	13.79	18.28	37.23	29.06	36.52	20.538	42.335	31.17
731	13.77	18.21	37.24	27.82	35.84	18.608	42.295	30.87
762	13.41	16.25	37.23	27.69	35.92	18.688	42.225	28.87
790	12.66	17.40	36.73	27.52	33.8	20.758	42.205	30.52
821	11.94	16.45	35.77	27.04	32.78	19.578	42.085	30.36
851	11.7	16.47	35.23	26.91	32.61	19.458	42.055	30.24
882	13.22	14.90	37.15	26.88	27.41	19.028	42.015	30.75
912	13.44	14.99	37.22	28.61	27.79	19.118	42.025	30.60
943	15.41	19.09	36.53	26.15	25.31	23.068	44.925	30.71
974	15.68	18.97	38.53	31.67	28.84	23.148	42.405	32.12
1004	14.51	18.68	38.37	29.14	37.58	21.518	42.435	31.70
1035	15.85	18.94	38.06	29.68	34.05	22.398	42.455	32.29
1065	14.6	18.61	38.21	30.38	34.88	22.198	42.505	32.21
1096	13.68	18.24	37.72	29.59	37.07	21.338	42.355	31.03
1127	13.38	17.64	38.05	29.46	36.54	20.738	42.275	30.74

1155	13.13	17.33	37.92	29.31	35.96	20.488	42.235	30.64
1186	12.93	14.90	37.93	29.18	34.36	20.268	42.205	30.46
1216	12.33	14.89	37.98	28.95	30.95	19.548	42.155	29.30
1247	12.14	16.89	37.65	29.11	28.52	19.878	42.135	29.14
1277	15.89	19.25	38.62	30.28	26.43	24.098	42.545	33.20
1308	14.96	18.67	39.16	29.29	27.08	22.398	42.385	32.33
1339	16.61	19.08	39.74	31.26	32.36	23.238	44.175	33.32
1369	16.44	18.94	39.53	32.56	34.66	23.088	42.545	32.76
1400	14.56	18.32	39.23	29.69	39.41	21.488	42.305	32.25
1430	14.04	18.44	39.33	30.86	40.82	21.728	42.325	31.29
1461	13.41	17.90	39.26	29.23	39.57	21.098	42.275	30.82
1492	13.18	17.623	39.53	29.36	37.45	20.868	42.235	30.60
1521	12.75	17.053	39.36	29.22	33.19	20.508	42.195	30.76
1552	12.2	16.613	39.41	28.14	30.43	20.138	42.155	28.61
1582	11.98	16.763	39.36	28.94	29.61	19.448	42.095	30.60
1613	12.32	17.183	39.19	28.80	24.11	19.868	42.135	29.20
1643	13.43	16.723	39.66	28.62	21.91	20.448	42.215	31.19
1674	15.30	18.733	40.33	29.68	20.57	21.928	42.365	32.35
1705	15.03	18.813	41.04	29.73	21.73	21.888	42.475	32.19
1735	16.29	18.923	40.76	29.24	23.71	23.858	42.525	32.26
1766	14.15	18.163	40.56	29.92	26.49	21.018	42.325	31.11
1796	14.12	18.043	40.60	29.55	27.57	20.488	42.285	30.95
1827	13.50	17.803	40.03	29.48	27.9	20.428	42.245	30.72
1858	13.09	17.783	39.39	29.39	26.92	20.408	42.085	30.50
1886	12.47	16.963	38.89	29.23	24.6	19.948	42.105	30.27
1917	12.20	16.613	38.77	29.07	22.59	19.678	42.005	30.16
1947	11.79	16.523	38.56	28.42	20.51	19.388	41.895	30.38
1978	11.66	15.503	37.57	28.27	17.13	18.568	41.755	30.15
2008	12.90	17.683	38.32	28.83	16.93	20.678	42.315	31.95
2039	16.32	19.673	39.75	31.68	15.69	25.258	45.835	34.53
2070	16.42	19.463	40.39	29.73	21.49	23.768	42.535	32.11
2100	14.45	18.543	40.35	29.94	23.38	21.478	42.485	30.38
2131	14.16	18.383	39.63	29.64	25.62	21.708	39.375	31.36
2161	13.96	18.373	39.37	29.58	26.76	21.398	42.335	31.07
2192	13.43	17.923	39.21	29.53	26.56	21.148	42.245	30.81

APPENDIX V (Continue…)

Water table data of observation wells

Period days	BW175 (m)	BW177 (m)	BW181 (m)	BW183 (m)	BW184 (m)	BW187 (m)	BW189 (m)	BW190 (m)
31	49.93	29.77	25.18	21.31	27.36	68.71	1.87	0.9
60	49.20	29.28	25.12	20.14	26.92	68.37	0.51	0.77
91	49.01	29.20	24.98	19.72	26.53	68.28	2.13	0.85
121	49.82	29.46	25.30	21.01	27.16	68.38	6.60	0.8
152	49.51	29.01	25.15	20.80	26.53	68.14	7.54	0.72
182	52.87	30.52	25.30	22.38	28.36	69.23	11.50	0.89
213	54.08	31.14	25.95	21.98	31.00	69.74	13.22	0.89
244	54.08	30.87	25.80	23.20	30.48	69.98	5.40	0.92
274	52.51	30.46	25.35	23.10	29.47	70.06	4.60	0.96
305	51.29	30.09	25.41	24.92	28.32	70.51	3.96	1
335	53.58	30.06	25.48	21.66	28.55	69.98	4.26	0.97
366	51.24	29.55	25.26	21.40	28.21	68.92	3.92	0.9
397	49.22	29.39	25.15	20.75	27.93	69.22	4.15	0.81
425	49.39	29.25	25.16	20.23	27.34	68.90	4.22	0.75
456	49.56	28.86	25.08	19.54	26.29	68.73	6.58	0.71
486	48.36	28.72	25.02	19.41	26.14	69.05	10.84	0.56
517	48.82	29.23	25.01	19.23	25.77	68.85	9.75	0.56
547	49.51	30.03	25.52	22.27	27.25	69.67	11.36	0.61
578	52.60	31.62	29.22	25.26	31.57	71.55	15.61	0.83
609	53.06	31.15	27.79	24.88	30.90	70.93	15.36	0.84
639	53.84	30.85	26.85	24.05	30.61	71.33	16.16	0.86
670	53.58	31.12	25.82	22.66	30.74	70.43	15.41	0.91
700	50.95	29.78	25.28	20.04	30.66	70.17	11.51	0.84
731	49.97	29.8	25.32	19.80	27.80	67.96	10.35	0.86
762	48.42	29.43	25.27	21.55	27.61	69.47	5.88	0.79
790	49.77	29.65	25.11	20.56	24.60	69.15	2.83	0.76
821	48.90	29.13	24.91	19.73	24.29	68.75	0.29	0.49
851	48.58	28.89	24.92	19.35	25.87	68.52	-0.26	0.54
882	47.12	29.18	25.14	19.11	26.21	68.53	-0.30	0.53
912	47.75	29.00	25.08	18.95	26.03	68.65	0.08	0.53
943	54.51	30.92	28.73	24.39	30.34	70.27	2.96	0.74
974	54.71	30.92	27.70	23.36	31.19	70.57	4.78	0.76
1004	52.73	30.57	25.80	22.93	29.87	70.59	5.43	-0.17
1035	52.66	30.77	26.10	23.38	30.62	70.44	6.91	-0.05
1065	52.57	30.81	27.23	23.11	30.06	71.20	10.00	0.66
1096	52.32	30.17	25.36	21.73	28.84	69.98	13.65	0.91
1127	50.28	29.54	25.21	21.34	27.96	69.43	10.62	0.84
1155	50.17	29.22	25.18	21.31	27.62	69.23	6.23	0.79
1186	50.20	27.13	25.16	20.59	27.13	68.84	5.30	0.75
1216	48.81	28.68	25.07	19.56	24.29	68.82	3.55	0.65

1247	48.05	29.19	25.06	20.75	27.63	69.26	2.92	0.66
1277	53.72	31.08	28.55	24.53	30.40	70.67	9.50	0.89
1308	53.57	30.78	25.97	24.38	28.80	70.28	10.88	0.84
1339	54.31	30.99	27.41	25.00	31.56	71.39	16.46	0.93
1369	54.23	31.16	29.62	24.29	30.25	70.82	17.15	0.96
1400	50.53	30.36	25.46	22.76	29.30	70.31	5.09	0.94
1430	50.86	30.39	25.84	22.09	29.07	69.86	5.22	0.92
1461	50.45	29.37	24.79	21.44	27.73	69.34	3.50	0.8
1492	47.72	29.41	25.18	20.61	27.77	68.95	2.85	0.73
1521	48.69	29.14	25.08	21.69	27.31	68.60	2.69	0.62
1552	45.65	28.72	25.03	19.70	26.27	68.53	2.74	0.54
1582	47.03	28.86	24.99	19.38	26.25	68.87	2.76	0.47
1613	47.34	29.13	25.04	19.20	26.38	68.50	1.96	0.47
1643	50.30	29.41	25.11	19.28	25.86	68.74	2.06	0.59
1674	51.68	30.7	26.00	23.43	28.47	69.66	3.78	0.78
1705	52.24	30.69	26.85	23.61	29.84	70.47	4.93	0.77
1735	55.23	31.11	26.82	23.99	31.35	70.55	6.94	0.86
1766	51.46	29.76	25.56	21.69	29.45	69.49	5.39	0.77
1796	50.40	29.68	25.34	20.95	28.32	69.52	3.17	0.71
1827	50.47	29.54	25.30	20.92	26.00	69.10	3.36	-0.34
1858	49.97	29.18	25.22	20.13	27.65	68.78	10.20	0.56
1886	49.29	28.75	25.01	19.44	26.28	68.49	12.15	0.46
1917	46.16	28.81	24.96	19.06	26.61	67.37	11.66	-0.02
1947	47.66	28.48	24.69	18.60	25.30	68.43	11.65	0.32
1978	43.39	28.08	24.74	18.25	24.90	67.04	11.64	0.18
2008	49.27	29.83	25.25	20.54	26.33	69.23	11.02	0.23
2039	56.54	31.45	27.48	25.45	32.15	71.53	15.95	0.52
2070	55.49	31.51	25.48	23.30	32.36	70.77	18.24	0.62
2100	50.82	30.8	26.27	23.68	29.87	70.42	16.34	0.6
2131	51.69	30.36	25.37	22.27	29.92	70.21	16.49	0.65
2161	51.51	30.96	25.45	21.76	30.06	69.42	16.98	0.59
2192	51.07	29.96	25.20	21.56	28.89	69.30	16.45	0.54

APPENDIX V (Continuing…)

Water table data of observation wells

Period days	OW5 (m)	OW6 (m)	OW7 (m)	OW9 (m)	OW10 (m)	OW15 (m)	OW18 (m)
31	0.24	7.69	46.05	44.42	68.72	26.16	18.25
60	-0.4	7.39	45.56	42.24	68.51	25.86	16.95
91	-0.26	9.09	48.80	41.97	67.94	25.78	16.61
121	-0.28	8.65	46.48	44.36	67.79	25.95	18.73
152	-0.9	7.77	45.66	44.22	67.32	25.66	17.71
182	0	8.86	47.36	44.23	69.12	29.48	19.68
213	1.01	9.05	47.81	45.50	69.47	29.86	20.15
244	1.67	8.75	47.85	46.63	69.44	27.05	19.95
274	1.64	8.73	47.44	46.86	69.61	26.84	20.04
305	1.02	8.71	46.05	45.93	70.06	26.41	20.10
335	1.16	8.60	46.55	45.19	69.18	26.52	19.75
366	0.4	8.09	46.50	44.61	68.87	26.34	19.91
397	-0.27	5.86	45.99	44.41	68.60	26.08	17.68
425	-1.51	6.97	45.49	44.15	67.54	25.90	17.06
456	-1.76	6.73	45.45	43.93	67.00	25.54	14.52
486	-2.39	5.59	45.51	43.58	68.46	25.34	15.11
517	-2.55	5.92	46.07	43.48	67.30	25.49	16.42
547	-2.08	8.76	46.24	44.44	69.04	26.39	17.49
578	0.04	10.33	48.81	48.01	70.37	29.76	20.57
609	1.24	9.08	48.15	45.95	69.56	28.45	20.54
639	1.02	8.76	47.71	47.09	70.15	27.06	20.11
670	0.97	8.73	46.64	45.79	69.55	29.87	20.35
700	0.02	8.24	47.06	44.90	69.33	26.47	20.09
731	-0.08	8.41	47.43	44.88	68.93	26.36	19.57
762	-0.66	8.26	46.60	44.79	68.77	26.11	19.10
790	-0.9	7.85	46.37	44.47	68.02	25.97	18.03
821	-1.94	6.52	45.70	44.21	67.91	25.38	16.23
851	-2.04	6.40	45.55	44.54	68.39	25.41	15.04
882	-2.39	7.47	45.57	44.62	67.75	25.52	15.01
912	-2.54	7.44	45.64	44.56	66.71	25.44	15.97
943	0.6	8.99	47.48	46.44	69.43	28.77	20.22
974	1.25	9.08	47.62	46.44	69.63	28.57	20.38
1004	1.19	9.06	47.74	46.21	69.77	27.75	20.31
1035	1.08	8.98	47.79	45.38	69.89	26.88	20.23
1065	1.01	8.93	47.91	46.62	70.10	27.73	19.91
1096	0.22	8.28	46.89	44.48	69.08	26.58	19.63
1127	-0.26	8.20	45.64	44.58	68.65	26.06	18.47
1155	-0.71	7.78	45.69	44.54	68.71	25.92	18.43
1186	-1.1	5.48	45.27	44.58	68.52	25.48	16.63
1216	-1.52	4.80	44.98	44.54	68.13	25.75	16.15

1247	-1.49	7.28	45.20	44.39	68.96	25.84	17.66
1277	0.87	10.96	47.82	46.23	69.98	28.64	20.80
1308	1.3	8.71	47.45	45.32	69.63	26.78	20.12
1339	1.39	10.91	49.47	45.99	70.20	28.48	20.39
1369	1.41	10.80	49.32	48.98	69.83	28.81	20.34
1400	0.24	8.94	47.44	46.29	69.05	26.30	20.18
1430	0.07	8.62	46.68	45.87	69.32	26.56	19.82
1461	-0.74	7.47	46.24	44.74	68.87	25.99	18.99
1492	-1.07	4.83	45.95	44.71	68.67	25.64	15.83
1521	-1.51	6.62	45.58	44.45	67.76	25.70	15.56
1552	-1.93	6.12	45.21	44.24	67.77	25.62	16.28
1582	-2.24	6.70	45.84	44.25	67.82	25.31	16.16
1613	-2.56	6.90	46.86	44.43	67.40	25.57	17.33
1643	-2.51	8.32	47.91	44.09	67.78	25.38	19.31
1674	-1.07	10.02	49.71	45.28	69.28	26.53	20.29
1705	0	8.84	48.85	45.65	69.60	26.97	20.31
1735	1.29	9.52	48.86	45.49	69.72	27.87	20.53
1766	0.27	8.73	47.69	45.13	69.14	26.18	19.62
1796	-0.47	8.44	47.87	44.71	69.07	26.20	19.20
1827	-0.73	8.35	47.18	44.62	68.71	25.93	18.46
1858	-1.27	7.67	46.64	44.38	68.22	25.71	17.38
1886	-1.92	7.37	45.63	44.06	67.31	25.33	17.54
1917	-2.08	7.46	45.54	43.83	66.64	25.20	16.49
1947	-2.54	7.34	44.89	43.61	66.98	25.30	14.45
1978	-2.88	6.97	44.92	43.35	68.05	24.76	14.44
2008	-2.97	8.28	46.71	43.73	68.85	25.70	19.07
2039	1.29	10.18	49.85	45.97	70.53	30.02	20.39
2070	1.95	10.30	50.28	45.30	69.53	29.54	20.55
2100	1.4	9.13	49.01	45.37	69.51	26.49	19.99
2131	1.12	8.80	47.63	45.06	69.46	26.39	19.97
2161	1.42	8.77	47.03	45.17	68.88	26.78	19.95
2192	0.56	8.61	46.40	44.73	68.70	26.32	19.80

APPENDIX V (Continuing…)

Water table data of observation wells

Period days	OW19 (m)	OW20 (m)	OW21 (m)	OW22 (m)	OW23 (m)	OW24 (m)	OW28 (m)
31	35.67	19.54	27.33	40.74	44.90	96.13	12.52
60	35.50	17.57	27.07	40.03	42.43	95.71	12.12
91	35.89	17.28	26.94	40.00	44.19	95.76	13.30
121	35.76	17.00	27.59	38.98	43.94	95.87	13.18
152	35.04	15.25	27.53	39.79	42.04	95.28	12.58
182	36.31	15.39	28.47	39.98	44.91	96.81	14.12
213	36.46	24.40	28.22	42.20	45.90	97.37	14.18
244	36.62	25.04	28.72	42.80	45.22	97.40	14.07
274	36.33	24.99	31.03	43.39	44.59	97.25	13.80
305	36.03	24.68	31.98	43.92	42.80	96.83	13.65
335	35.63	23.93	30.91	41.12	44.66	96.88	13.66
366	35.73	22.02	30.22	40.95	42.71	96.46	13.02
397	35.45	18.86	29.98	39.00	42.43	95.90	12.43
425	35.22	17.65	29.65	38.31	41.72	95.88	12.01
456	35.00	15.32	29.40	39.44	41.51	95.46	11.94
486	34.44	14.79	29.57	39.68	41.26	94.89	12.09
517	34.23	15.46	28.72	39.98	42.62	94.49	12.63
547	35.35	16.42	30.82	39.70	43.69	94.75	13.40
578	37.60	25.78	32.06	44.29	47.25	96.76	14.56
609	36.67	25.12	31.23	43.34	45.58	97.50	14.09
639	36.36	25.14	31.46	43.07	45.35	97.22	14.00
670	36.33	24.49	30.84	41.92	44.21	96.96	14.41
700	35.99	23.31	30.51	41.47	43.32	96.51	13.55
731	35.87	23.70	30.27	39.40	43.58	96.56	13.65
762	35.70	22.56	30.52	40.60	42.82	96.20	12.90
790	35.53	20.26	29.83	39.80	42.46	95.80	12.67
821	35.44	18.11	29.19	39.90	41.36	94.70	12.17
851	35.29	17.75	28.97	39.99	42.72	95.30	12.07
882	33.84	16.37	29.25	39.94	43.59	94.77	12.97
912	33.81	15.70	28.60	39.37	43.76	94.47	13.03
943	36.46	25.30	30.29	42.53	45.87	97.37	14.19
974	36.64	25.60	31.31	42.85	45.81	97.30	14.48
1004	36.75	25.52	31.29	42.69	45.75	97.35	14.27
1035	36.86	24.71	31.36	42.51	45.82	97.30	14.15
1065	36.38	25.28	31.17	42.29	44.87	97.21	14.25
1096	36.15	23.81	30.42	41.50	44.22	97.07	13.92
1127	35.62	22.95	30.70	40.45	42.44	96.18	12.96
1155	35.46	22.75	30.26	40.35	42.12	96.33	12.52
1186	35.18	22.42	29.73	38.72	42.62	95.72	12.43

1216	34.82	21.27	29.91	40.02	43.09	95.47	12.56
1247	34.26	20.57	29.90	40.34	43.09	95.00	12.74
1277	37.50	23.48	31.93	43.37	46.57	97.56	14.56
1308	36.48	24.91	31.17	43.02	45.55	97.38	14.40
1339	38.51	25.63	31.92	43.84	47.43	98.19	14.97
1369	37.99	26.24	31.45	43.29	47.18	98.09	15.07
1400	36.38	24.01	31.18	42.63	43.47	96.71	13.99
1430	36.09	24.80	30.77	41.51	43.72	96.89	13.90
1461	35.52	22.83	30.45	40.94	41.76	96.27	13.20
1492	35.31	22.03	29.89	39.45	41.60	96.07	12.97
1521	34.70	20.77	30.69	38.93	40.83	95.68	12.56
1552	34.16	20.04	29.24	40.49	40.83	95.42	12.26
1582	33.70	19.22	29.07	39.77	40.71	95.15	13.18
1613	33.53	16.99	29.62	40.95	42.27	94.92	12.97
1643	33.57	16.52	29.30	39.03	42.59	94.59	12.79
1674	37.50	24.11	31.36	41.46	45.58	97.30	14.20
1705	36.29	25.08	31.14	42.79	43.35	97.32	14.30
1735	37.01	25.24	31.21	42.65	45.75	97.63	14.59
1766	36.11	24.42	30.42	41.10	41.67	96.91	13.86
1796	35.75	23.67	30.35	40.09	42.05	96.77	13.54
1827	35.63	23.00	30.51	39.49	41.60	96.49	13.28
1858	35.11	21.86	30.01	39.24	42.72	96.10	12.81
1886	34.34	20.49	29.23	38.49	42.42	95.63	12.90
1917	34.06	19.13	28.88	38.45	42.76	95.50	12.97
1947	33.57	18.19	29.74	39.51	42.86	95.02	12.35
1978	33.17	16.64	27.99	39.26	41.72	94.59	11.86
2008	33.28	16.45	30.53	39.37	44.45	94.48	13.66
2039	38.10	25.92	32.32	45.07	47.29	97.58	14.92
2070	38.14	24.91	30.92	42.52	47.19	97.83	15.17
2100	36.37	24.58	31.42	41.43	44.41	96.86	14.29
2131	36.06	24.22	30.69	41.51	43.69	96.76	14.02
2161	36.10	24.02	30.80	40.75	43.09	96.51	13.67
2192	35.61	23.53	30.22	39.90	42.89	96.12	13.18

Appendix VI
Results of F-test for dug wells

1. Anova: Single Factor Well Name: OW5

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	20.38	1.698333	0.716124
2009	12	33.03	2.7525	1.910639
2010	12	30.8	2.566667	2.247588
2011	12	26.22	2.185	1.205918
2012	12	38.21	3.184167	1.415772
2013	12	31.6	2.633333	3.753006

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	15.55068	5	3.110137	1.65888	0.15693	2.353809
Within Groups	123.7395	66	1.874841			
Total	139.2902	71				

2. Anova: Single Factor Well Name: OW6

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	107.54	8.961667	0.320852
2009	12	115.54	9.628333	2.30227
2010	12	111.66	9.305	0.952409
2011	12	108.97	9.080833	3.910881
2012	12	115.53	9.6275	2.35162
2013	12	108.04	9.003333	1.210188

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.512428	5	1.102486	0.598731	0.700993	2.353809
Within Groups	121.5304	66	1.84137			
Total	127.0428	71				

3. Anova: Single Factor Well Name: OW18

SUMMARY

Groups	Count	Sum	Average	Variance
2008	12	23.21	1.934167	1.689208
2009	12	31.53	2.6275	4.822039
2010	12	30.98	2.581667	4.727233
2011	12	23.06	1.921667	2.402524
2012	12	32.16	2.68	3.612491
2013	12	31.02	2.585	5.004409

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7.70845	5	1.54169	0.415589	0.836291	2.353809
Within Groups	244.837	66	3.709651			
Total	252.5454	71				

4. Anova: Single Factor Well Name: OW15

SUMMARY

Groups	Count	Sum	Average	Variance
2008	12	58.85	4.904167	1.945445
2009	12	58.05	4.8375	2.555293
2010	12	60.65	5.054167	1.568408
2011	12	60.15	5.0125	1.474457
2012	12	67.86	5.655	0.557991
2013	12	63.22	5.268333	2.77527

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.405828	5	1.081166	0.596403	0.702749	2.353809
Within Groups	119.6455	66	1.812811			
Total	125.0513	71				

5. Anova: Single Factor Well Name:OW28

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	33.6	2.8	0.4658
2009	12	35.04	2.92	0.932145
2010	12	32.73	2.7275	0.771202
2011	12	30.5	2.541667	0.978797
2012	12	33.3	2.775	0.536336
2013	12	32	2.666667	0.998406

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.984974	5	0.196995	0.252412	0.937152	2.353809
Within Groups	51.50956	66	0.780448			
Total	52.49453	71				

6. Anova: Single Factor Well Name: W24

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	149.05	12.42083	0.515372
2009	12	153.92	12.82667	1.012497
2010	12	151.96	12.66333	1.375461
2011	12	147.01	12.25083	1.028627
2012	12	152.55	12.7125	1.05902
2013	12	153.82	12.81833	1.182979

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.219679	5	0.643936	0.625793	0.680619	2.353809
Within Groups	67.91351	66	1.028993			
Total	71.13319	71				

7. Anova: Single Factor Well Name: OW22

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	110.3	9.191667	2.47527
2009	12	114.6	9.55	3.806764
2010	12	110.23	9.185833	1.827354
2011	12	105.72	8.81	2.704345
2012	12	118	9.833333	1.708806
2013	12	118.7	9.891667	3.71607

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	10.6648	5	2.132959	0.788107	0.56198	2.353809
Within Groups	178.6247	66	2.706435			
Total	189.2895	71				

8. Anova: Single Factor Well Name: OW23

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	138.55	11.54583	1.542136
2009	12	144.32	12.02667	3.312115
2010	12	137.79	11.4825	2.405366
2011	12	137.8	11.48333	4.154552
2012	12	158.01	13.1675	2.910148
2013	12	141.35	11.77917	3.197499

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	25.31218	5	5.062437	1.733532	0.139187	2.353809
Within Groups	192.74	66	2.920303			
Total	218.0522	71				

Appendix VII
Results of F-test for bore wells

1. Anova: Single Factor Well Name: BW190

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	37.43	3.119167	0.006954
2009	12	38.86	3.238333	0.015252
2010	12	41.51	3.459167	0.10959
2011	12	38.03	3.169167	0.011008
2012	12	41.03	3.419167	0.100354
2013	12	42.75	3.5625	0.044857

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.888629	5	0.377726	7.868895	7.37E-06	2.353809
Within Groups	3.168158	66	0.048002			
Total	5.056788	71				

2. Anova: Single Factor Well Name: BW189

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	298.09	24.84083	14.32814
2009	12	232.3	19.35833	18.28383
2010	12	311.35	25.94583	19.13561
2011	12	267.18	22.265	24.10605
2012	12	320.97	26.7475	2.206675
2013	12	194.83	16.23583	8.327263

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1014.406	5	202.8812	14.091	2.27E-09	2.353809
Within Groups	950.2632	66	14.39793			
Total	1964.669	71				

3. Anova: Single Factor Well Name: BW 161

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	59.99	4.999167	0.737208
2009	12	61.07	5.089167	2.628536
2010	12	59.26	4.938333	1.932179
2011	12	55.54	4.628333	2.380124
2012	12	61.11	5.0925	1.801148
2013	12	62.51	5.209167	2.505627

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.422611	5	0.484522	0.242568	0.942078	2.353809
Within Groups	131.833	66	1.99747			
Total	134.2556	71				

4. Anova: Single Factor Well Name: BW171

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Year1	12	94.25	7.854167	1.358354
Year2	12	97.21	8.100833	1.056536
Year3	12	102.72	8.56	0.991327
Year4	12	97.87	8.155833	2.00919
Year5	12	103.58	8.631667	1.282488
Year6	12	100.45	8.370833	1.592136

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.269978	5	1.053996	0.762841	0.579851	2.353809
Within Groups	91.19033	66	1.381672			
Total	96.46031	71				

5. Anova: Single Factor Well Name: BW165

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	37.52	3.126667	0.495533
2009	12	39.88	3.323333	1.264715
2010	12	52.7	4.391667	2.814815
2011	12	34.78	2.898333	1.220997
2012	12	43.28	3.606667	0.267206
2013	12	40.65	3.3875	0.762202

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	16.07901	5	3.215801	2.826884	0.022539	2.353809
Within Groups	75.08016	66	1.137578			
Total	91.15917	71				

6. Anova: Single Factor Well Name: BW177

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	21.95	1.829167	0.473336
2009	12	21.56	1.796667	0.952297
2010	12	21.92	1.826667	0.670752
2011	12	23.47	1.955833	1.442136
2012	12	25.21	2.100833	0.587754
2013	12	23.19	1.9325	1.406639

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.783494	5	0.156699	0.169927	0.972827	2.353809
Within Groups	60.86203	66	0.922152			
Total	61.64553	71				

7. Anova: Single Factor Well Name: BW175

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	73.12	6.093333	3.756442
2009	12	74.38	6.198333	8.203961
2010	12	74.2	6.183333	10.55568
2011	12	66.06	5.505	11.0435
2012	12	92.03	7.669167	7.205627
2013	12	87.38	7.281667	13.10316

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	39.88607	5	7.977215	0.888523	0.493942	2.353809
Within Groups	592.5521	66	8.978061			
Total	632.4381	71				

8. Anova: Single Factor Well Name: BW163

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	343.09	28.59083	0.285645
2009	12	332.25	27.6875	0.242802
2010	12	330.25	27.52083	1.068827
2011	12	312.6	26.05	0.565873
2012	12	297.17	24.76417	0.41819
2013	12	306.792	25.566	0.675321

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	128.1601	5	25.63202	47.22393	1.67E-20	2.353809
Within Groups	35.82323	66	0.542776			
Total	163.9833	71				

9. Anova: Single Factor Well Name: BW187

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2008	12	36.1	3.008333	0.692179
2009	12	29.61	2.4675	1.301657
2010	12	30.28	2.523333	0.896824
2011	12	28.15	2.345833	0.693754
2012	12	35.42	2.951667	0.499761
2013	12	35.41	2.950833	1.792772

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.179779	5	1.035956	1.057647	0.391854	2.353809
Within Groups	64.64641	66	0.979491			
Total	69.82619	71				

GROUND WATER RESOURCES MODELLING OF A WATERSHED USING MODFLOW

By

SAJEENA S

(2012-28-101)

ABSTRACT

Submitted in partial fulfillment of the requirement for the degree of

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(*Soil and Water Engineering*)

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Kerala Agricultural University

DEPARTMENT OF LAND AND WATER RESOURCES AND CONSERVATION ENGINEERING

KELAPPAJI COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY

TAVANUR P.O., MALAPPURAM-679573

KERALA, INDIA

2015

ABSTRACT

A study on 'Ground water resources flow modelling and mapping of a watershed using MODFLOW', was carried out for Kadalundi river basin of Malappuram District in Kerala. The objectives of the research were 1. to study the aquifer characteristics of the study area, 2. to study the spatial and temporal ground water variations in the study area, 3. to identify the potential ground water zones within the study area using earth resistivity studies and 4. to develop a ground water flow model for the river basin using Visual MODFLOW.

Kadalundi river basin has a drainage area of 1122 km^2 with a main stream length of 130 km, originating from the Western Ghats at the western boundary of Silent Valley. River flows through the district of Malappuram and downstream reach of the river falls into Arabian Sea. In order to evaluate the aquifer characteristics of the study area, spatial and temporal variations of ground water level of dug wells and bores wells were analyzed separately. Monthly water table data from 16 bore wells and 14 dug wells during the period from 2008 to 2013 were used for the study. From the pre and post monsoon water table and piezometric water level variations and from the water table and piezometric water level hydrograph studies, it was observed that the water table and piezometric level fluctuation in low land, mid land and high land area were correlated with rainfall except at some locations like Kottakkal, Marakkara and Tanur.

Hydraulic continuity studies were carried out with the help of statistical analysis and it indicated that the hydraulic continuity of ground water and surface water exists between aquifers of dug wells and bore wells in major part of study area. Areas like Thirurangadi, Kottakkal and Some part of Perinthalmanna, variation of piezometric water level was poorly correlated with rainfall, which indicated that hydraulic continuity does not exist in that areas and these areas are suitable for deep bore wells.

Vertical Electrical Sounding (VES) method was carried out using Signal Stacking Resistivity Meter (MODEL-SSR-MP-ATS) at 22 locations. The apparent resistivity values obtained from the resistivity meter were interpreted with the help of 'IPI2WIN' software to obtain the layer parameters. The sounding curves are of A,H,K,Q,HK and KH types reulting in 3 to 4 layer sequence. The curves are prominently of H, Q, K and A type indicating the presence of three layer and combination of curves like HK and KH indicating the four sub surface layers. Most parts of the study area are dominated by H type curve which indicates the presence of good quantity groundwater.

Visual MODFLOW software version 2.8.1 developed by Waterloo Hydrogeologic Inc. was used for the flow modelling of the study area. The conceptual model for the study area was developed based on the base map of Kadalundi river basin, topo sheet of the area, well logs at 30 sites and the data obtained from the geophysical studies conducted in the study area. Discretization was done by dividing it into 62 rows and 136 columns with a grid spacing of 500 m x 500 m throughout the area and the cells outside the boundary of the study area were made as inactive.

Monthly pumping rate from 35 pumping wells and monthly water level data from thirty head observation wells of Ground Water Department (GWD), Government of Kerala were used as well inputs of Visual MODFLOW. Hydrogeological parameters such as hydraulic conductivity, specific storage, specific yield, porosity and initial heads and boundary conditions of the model domain including constant head, rivers, drains, recharge and evapotranspiration were used as input of Visual MODFLOW. After uploading input parameters, the model was run for steady state and transient state subsequently. Model was developed and calibrated using four years data from 2008 to 2011 and a reasonably good agreement was obtained between computed and observed water levels. After calibration, the model was validated for two years data of 2012 and 2013. The root mean square error (RMSE) for almost all the wells during validation were reasonably low and within acceptable limits except a few wells very close to the river which are most likely to be influenced by the interflow of river.

After the model development and validation, it was used to predict the flow head for the next 15 years assuming five per cent yearly decrease in recharge and also to predict the ground water condition by increasing the pumping rate by 10, 25 and 50 per cent of pumping rate of the validation period (2013). From the modelling studies, it can be concluded that the Kadalundi river basin will remain safe for next five years from the point of future ground water development and subsequently the water table may reach the bed rock. This necessitates artificial ground water recharge techniques to supplement the recharge of rainfall to the ground water.

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