EFFECT OF BAKKIKAYAM REGULATOR ON GROUNDWATER USING GEOPHYSICAL TECHNIQUES AND VISUAL MODFLOW

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By

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THESIS

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DECLARATION

I, hereby declare that this thesis entitled “**EFFECT OF BAKKIKAYAM REGULATOR ON GROUNDWATER USING GEOPHYSICAL TECHNIQUES AND VISUAL MODFLOW”** is a bonafide record of research work done by myself 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 **Smegha N. C.**

Date: **2018-18-005**

CERTIFICATE

Certified that this thesis entitled “**EFFECT OF BAKKIKAYAM REGULATOR ON GROUNDWATER USING GEOPHYSICAL TECHNIQUES AND VISUAL MODFLOW”** is a bonafide record of research work done independently by **Ms. Smegha N. C. (2018-18-005)** 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.

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Dedicated to My
Loving Family

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ABBREVIATIONS USED

AMSL	-	Above Mean Sea Level
CGWB	-	Central Ground Water Board
CWRDM	-	Centre for Water Resource Development and Management
et al.	-	and others
Fig.	-	Figure
GIS	-	Geographical Information System
GPS	-	Global Positioning System
J.	-	Journal
Int.	-	International
M	-	Metre
MCM	-	Million Cubic Meter
md^{-1}	-	metre per day
ms^{-1}	-	metre per second
RMSE	-	Root Mean Square Error
Viz.	-	Namely
Vs	-	Versus
%	-	Percentage

Introduction

Chapter 1

INTRODUCTION

Groundwater is one of the most precious natural resources required for sustainable human life. Nowadays people are facing many problems regarding the availability of groundwater for various uses viz., domestic, agricultural, or industrial, mainly for the rural population (Ahmed *et al.*, 2008). At present, development within different fields in the Asian countries, mainly in India, has led to an increase in the demand of water supply which is mostly met from the exploitation of groundwater resources (Venkateswaran *et al.*, 2016).

Surface water is typically abundant during the monsoon, while during the summer season water needs to be abstracted from groundwater sources (Babel and Wahid, 2009; Ha et al., 2015). Growing population and food demand is leading to increase groundwater abstraction, and will further intensify groundwater stress in future years (Erban and Gorelick, 2016; ICEM, 2013).

Nowadays, the use and sustainability of water is getting more complex due to population growth, urbanization and industrialization. All developmental activities are related either directly or indirectly with water utilization. For any developmental activity, both surface and groundwater sources are the main components depending on their quality and availability. In an area where surface water is not feasible for the desired activity, groundwater is the next alternative, if it is available in the anticipated amount and quality. Hence, a site investigation/exploration, which is also known as pre-construction evaluation, has to be performed primarily for an effective and sustainable utilization of groundwater resources (Shishaye et al., 2016).

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 investigations in most geological formations due to simplicity. Among various geophysical studies, Vertical Electrical Sounding (VES), a depth sounding galvanic method has proved very useful in ground water studies due to simplicity and reliability of the method.

"MODFLOW, a U.S. Geological Survey modular finite-difference flow model, is a set of computer programs that solves the ground water flow equation" (Harbaugh, 2005). The program is used by hydro-geologist to simulate the ground water flow through aquifers. The code of this software is written primarily in FORTRAN and run on Microsoft Windows or Unix-like operating systems. The Visual MODFLOW is a complete and user friendly modeling environment for three dimensional ground water flow and contaminant transport simulation. "A model can be defined as a simplified version of a real world system (here, a ground-water system) that approximately simulates the relevant excitation-response relations of the real-world system" (Lakshmi et al., 2015).

Modular finite-difference flow model (MODFLOW) is a popular groundwater modeling software. "Visual MODLOW is a Graphical User Interface for the USGS MODFLOW". It is commercial software that is popular among the hydro-geologists for its user friendly features. The software is mainly used for Groundwater flow and contaminant transport models under different conditions.

Bakkikayam regulator is located across Kadalundipuzha at Bakkikayam near Pandikasala in Vengara Panchayath of Malappuram district. The project was implemented during 2018 with the financial assistance of Jalanidi and World Bank. The intended purpose of the regulator was to increase both quantity and quality of the ground water available in the Ayacut region and thereby to increase the water use efficiency of that region. Even though regulator is beneficial for many Grama Panchayaths in the upstream side including Vengara, Kannamangalam, Oorakam, A.R.Nagar, Parappur and Edarikode, it is reported to have negative impact in the downstream side panchayaths of the regulator viz. Nannambra, Munniyoor, Thirurangadi and Thehjipalam. The inhabitants of this locality are mostly farmers who are facing severe water shortage during the summer season. The complete closing of regulator during summer months creates acute water shortage for the paddy cultivation of around 950 acres during its critical stages in Nannambra Panchayath, known as KUTTANAD OF MALAPPURAM.

A massive dispute has happened for last two years between upstream and downstream famers and authorities on the closing of regulator during summer months. During the critical stages of paddy crop in downstream side, it requires sufficient water for crop development, otherwise complete failure of crop will happen. Water scarcity is a major problem in several parts of the downstream side of Bakkikayam regulator due to insufficient water to meet the drinking and irrigation demands, it is necessary to conduct a study on the effect of Bakkikayam regulator on the ground water flow seems to be essential.

It is also necessary to find an alternative source of water in downstream side to meet their water demands during summer. Hence, for fulfilling the above requirements the present study is carried out for a groundwater flow modeling using Visual MODFLOW.

The specific objectives of the research are:

1. To study the aquifer characteristics of the area using earth resistivity studies

2. To assess the groundwater flow variation due to the presence of Bakkikayam Regulator.

3. To develop ground water resource map of the study area using Visual MODFLOW.

4. To identify the potential ground water zones of the study area.

Review of Literature

Chapter 2

REVIEW OF LITERATURE

This chapter deals the concepts and literature available on groundwater, geophysical techniques of ground water investigations, ground water modeling, Visual MODFLOW software and flow regulation structures.

2.1 GEOPHYSICAL METHODS FOR GROUNDWATER AND AQUIFER CHARACTERISTICS

2.1.1 Groundwater

Water is the most important resource on earth as it forms the basis of sustenance of environment and life on the planet. It is distributed widely, but in a highly unbalanced manner all over the planet. It is the most important renewable but finite natural resource, since it is required for all facets of human life including agriculture, industry and domestic purposes. Its abundant availability in our day to day perception disguises the fact that its availability is limited.

The ground water flow depends on parameters such as size of the pores in the rock or within the soil particles and how well the spaces are interconnected. Ground water theory begins with discussion of the basic empirical formula called Darcy’s law by a French hydraulic engineer Henry Darcy (Freeze and Cherry, 1979).

2.1.2 Aquifer

Aquifers in simple words can be described as water bearing formations. It can be a single geologic formation or a group of geologic formations that can transmit and yield water in usable quantities. Aquifers are the target for all groundwater exploration and development programs.

There are two major types of aquifers, namely unconfined and confined aquifers. The aquifer in which there is no overlying impervious layer is known as “unconfined aquifer”. This indicates the upper layer of this unconfined aquifer will be permeable.

Vertical recharge of an unconfined aquifer by rain or irrigation that moves downward through the soil is not restricted. Confined aquifers are bounded both above and below by the impermeable layer, which makes the aquifer under pressure. Hence confined aquifers are also known as "pressure aquifers" or "artesian aquifers".

A geologic formation having little or no intrinsic permeability is known as confining layer. Confining layers can be classified as "leaky confining layers" and "non-leaky confining layers" (Fetter, 2000) depending on whether they can contribute significant leakage through them or not. Confining layers are further classified as aquitards, aquicludes and aquifuges.

2.1.3 Groundwater exploration methods

Groundwater is usually being explored using various methods. The major classification of groundwater exploration methods are the esoteric methods, areal method, surface method and subsurface method, where esoteric method is not based on science, mostly based on traditional indicators. These groundwater exploration methods are again divided into different sub-methods. Geophysical survey is a surface method of groundwater exploration (Al-grani, 2009).

2.1.3.1 *Geophysical Methods*

The geophysical method plays a vital role in ground water exploration because of its accuracy and adequacy of the results. The information about subsurface conditions such as type and depth of consolidated or unconsolidated materials, depth of weathered or fractured zone, depth to the ground water table and bed rock and also the salt content of ground water can be found using geophysical methods (Bouwer, 1978).

A study was conducted by Sajeena and Kurien (2015) on application of geophysical techniques for geophysical investigations in Kadalundi river basin. Vertical Electrical Sounding method using signal stacking resistivity meter was adopted for the study. Total of 22 locations were surveyed out which nine were schlumberger and rest were wenner configuration. The apparent resistivity values obtained were interpreted with the help of

IPI2WIN software. From the study it was concluded that there is no significance difference in the water level during pre monsoon and post monsoon seasons. In addition, the VES method of survey is proved to be a very reliable method for the ground water studies.

The study carried out by Inverarity (2016) investigated on four mound spring groups such as “Beresford Spring, Warburton Spring, the Bubbler Spring group and Freeling Springs”, having discrete geological settings, using a range of geophysical techniques: self-potential (SP), magnetotellurics (MT) and time-domain electromagnetics (TEM). From the results obtained, it can be concluded that although they exhibits similar mound morphologies at the surface, spring vents in various groups possess different mechanisms for sourcing water from the GAB aquifer. SP measurements effectively showed the locations of vertical flow at all groups, where as the MT and TEM models identified the fault locations, other geological structures and the thickness of the Bulldog Shale aquitard.

The study by Rajsanjeev (2017) conducted electrical resistivity surveys through Vertical Electrical Sounding (VES) at six sites in various location of Gwalior city. Available information on geological and hydro-geological parameters of the study area also collected. Study was aimed to understand the nature and extent of aquifer and to identify the location and thickness of unsaturated zones as well as evaluate the possibility of artificial recharge structures at suitable locations. The interpretation of VES data when correlated with the available litholog data indicates existence of a prominent water bearing zone between 30 and 45 mbgl. Moreover possibility of occurrence of ground water in the underlying hard and compact shale has very less. The top unsaturated and unconfined granular zone up to a depth of 30 m could therefore be easily recharged artificially through rainwater harvesting measures, thereby augmenting the groundwater resources of the existing aquifers.

Investigations by Sara *et al.* (2017) aimed to locate new wells that can deal with water insufficiency. The integration of advanced methods like remote sensing, geographic information systems (GIS) and geophysical techniques led to breakthrough for groundwater prospecting. Based on these techniques, several factors contributing to groundwater potential in El-Qaà Plain were determined. Geophysical data were supported by information derived from a DEM and from geologic, geomorphologic and hydrologic data, to reveal the promising sites. An appropriate weightage was specified to each factor based on its relative contribution towards groundwater potential, and the resulting map delineates the study area into five classes, from very poor to very good potential. The great potential zones are located in the Quaternary deposits, with topography varying from flat to gentle, dense lineaments and structurally controlled drainage channels. The groundwater potential map was tested against the distribution of groundwater wells and cultivated land. The integrated methodology provides a powerful tool to design a suitable groundwater management plan in arid regions.

A study was conducted by Gaghik *et al.* (2019) to evaluate the spatial distribution of soil properties at different depths; the electrical resistivity method was selected because of its non-destructive nature and high spatial resolution. For this study pole-pole configuration of electrodes was selected. The arrangement consists of two mobile electrodes (one current electrode and one potential electrode) with the second pair (current and potential) of electrodes, remote and fixed far enough from the prospecting area, to be considered as an infinite distance. The use of the pole-pole electrode array is worth while it reduces the number of mobile electrodes from 4 to 2 for each measurement, and thus gives high productivity. The results of electrical resistivity mapping of the investigated trial showed strong lateral variations associated to the soil thickness, soil texture and other soil properties.

Geophysical survey is the safest or non-invasive method for detecting subsurface geological structures (hidden faults). The combination of microtremor and geoelectrical methods improved the accuracy of the results. Moreover, electrical resistivity with schlumberger configuration and continuous resistivity profiling (CRP) were used for surveying and the results were compared with data collected through microtremor (Khalili *et al.*, 2019).

Rajkumar et al. (2019) reported that the study conducted for assessing the ground water quality and aquifer characteristics utilized the 71 groundwater samples collected from the study area and also conducted 23 Vertical Electrical Sounding for better understanding the subsurface characteristics. The interpretation of the VES data were done manually using IPI2WIN software, it indicated the presence of three or four electrical layer in the various parts of study area with different curve types.

2.1.3.2 *Magnetic (or geo-magnetic) Method*

Magnetic techniques intended to measure the remaining magnetic field associated with a material or the change in the earth's magnetic field associated with a geologic structure or man-made object.

Electromagnetic techniques have been extensively developed and adapted over the last 15 years to map lateral and vertical changes in conductivity. This method has been extensively used in groundwater geophysical investigations because of the correlation that often exist between electrical properties, geologic formations and their fluid content. Most electromagnetic techniques induce an electrical current in the ground by directly coupling with the ground. The resulting electrical potential is then used to measure the variation in ground conductivity, or its inverse, resistivity. Different materials, and the fluids within them, will exhibit different pattern in conducting an electric current thus respond differently to magnetic field.

2.1.3.3 *Vertical electrical survey*

Geophysical survey incorporates the Vertical Electrical Sounding (VES) and Horizontal Profiling (HP) activities. While Vertical Electrical Sounding (VES) is the current popular method of groundwater investigation due to its simplicity of operation (Oyedele *et al.,* 2012: Ojoina, 2014). VES data with schlumberger configuration is useful for imaging electrical resistivity variation with depth at a single azimuth. It is also effective in detecting fractures, their orientation and the coefficient of anisotropy (Jide *et al.*, 2018).

Electrode configuration

In electrical resistivity method of geophysical survey, current is sent to the ground using a pair of electrodes (source) and resulting potential is measured with another pair of electrodes (receiver) known as potential electrodes. The most widely used electrode configurations are Wenner and Schlumberger configurations.

Wenner array is a four-electrode array and three combinations of electrodes position are possible (Carpenter and Habberjam 1956). The potential electrodes and current electrodes are arranged as shown in Fig.1 the with an equal electrode spacing ‘a’. The survey proceeds by expanding the electrodes spacing equally about a centre point. The depth of penetration of the current is equal to the electrode spacing ‘a’. This configuration is less sensitive to horizontal changes in the subsurface resistivity. The signal strength is inversely proportional to the geometric factor used to calculate the apparent resistivity value for the array. The geometric factor for the Wenner array is 2πa which is smaller than the geometric factor of other arrays.

In general, the Wenner array is useful for resolving vertical changes (i.e. horizontal structures), while relatively poor in detecting horizontal changes (i.e. narrow vertical structures).

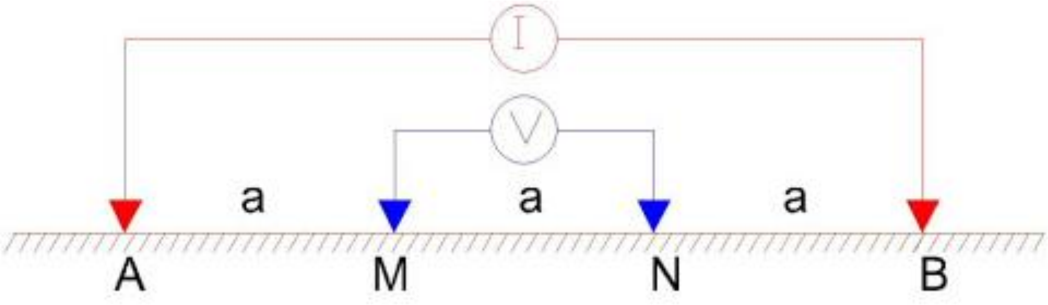


Fig. 1. Electrode configuration of wenner array

The schlumberger array requires of four collinear electrodes same as that of wenner array as shown in Fig. 2. The outer two electrodes are current electrodes and the inner two electrodes are the potential electrodes. The potential electrodes are installed at the center of the electrode array with a small separation, typically less than one fifth of the spacing between the current electrodes .The current electrode spacing is increased during the survey while the potential electrodes are kept in the same position until the observed voltage becomes too small to measure.

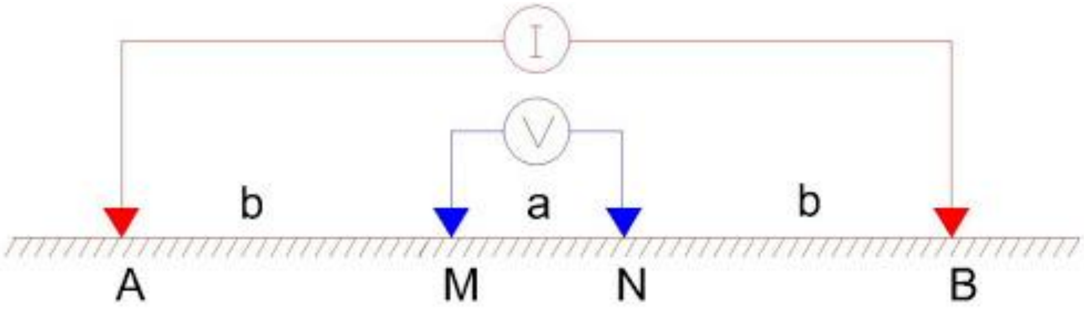


Fig. 2. Electrode configuration of schlumberger array

The advantages of the Schlumberger array over wenner array are movements of electrodes required are less in each sounding and the cable length needed for the potential electrodes is shorter. Also the resulted soundings have better resolution, greater probing depth and less time-consuming field deployment compared to the Wenner array.

2.1.3.4 *Electrical resistivity tomography*

ERT is one among the geophysical technique that used to measure the electrical properties of a section of ground by measuring the potential drop occurring when an electrical current introduced in the electrodes (Reynolds, 1997). The ERT technique has been used to investigate internal mechanisms inside the body of dams (Sjödahl *et al*., 2008; Song et al., 2005; Sjödahl *et al*., 2009) and employed in both laboratory and field conditions to assess the condition of embankments (Jones *et al*., 2014).

Sebastian *et al*. (2017) studied the spatial variability of the thickness of a clay layer, controlling surface – groundwater interactions that affect aquifer vulnerability with the help of electrical resistivity tomography (ERT). Geoelectrical imaging is completed with 12 ERT profiles and the data acquired is then linked with the properties of samples collected from borehole like particle density and composition. This relationship helps to translate the field electrical resistivities into lithologies.

2.1.3.5 *Combinations of geophysical methods*

1D inversion of vertical electrical sounding and 2D electrical resistivity tomography combination used for acquiring the integrated electrical conductivity indices (IEC) in the study of assessing aquifer vulnerability and extent of aquifer protection (Akapan *et al.*, 2015). Electromagnetic (EM) sensing was used as complementary method to verify the results obtained from ERT techniques in the study of dam structure (Michalis *et al.*, 2016). Integration of 1D and 2D vertical electrical sounding has been conducted for determining the thickness and resistivity of different layers of soil strata (Helaly, 2017). Integrated geophysical survey combining electrical resistivity tomography (ERT) and ground penetrating radar (GPR) applied for studying the subsurface geologic structures (Hemeda *et al.*, 2016), and studying the subsurface routing of stream flow (Li Guo *et al.*, 2020).

2.2 GROUNDWATER FLOW VARIATION DUE TO THE PRESENCE OF FLOW REGULATION STRUCTURES

Flow regulation methods and water diversion structures for irrigation have considerable effect in the exchange of surface water between river and its floodplains. While, the way in which both have effected groundwater–surface water interactions is not completely revealed (Jorge *et al.*, 2013).

A study was conducted by Mahesh *et al.* (2013) for evaluating the effect of bridge-pier-strengthening work over Tama River at Nagata district, Japan. The investigation on hydrological condition of the flood plain was done by analyzing data collected from the monitoring wells and results of ANN models. A conceptualization of surface and subsurface of flow condition based on field observations was made and linked with the behavior of monitored data at various monitoring wells. The spatio-temporal variation of hydrological variables in the study area was found to have influenced by the morphological change of the river and its flood plain in the last 120 years.

Rajaveni *et al.* (2014) conducted a study on spatial and temporal variations of ground water level and its relation to drainage and intrusive rocks in a part of Nalgonda District, Andhra Pradesh. The region predominantly comprise of granites and gneisses. Observed ground water levels were compared with drainage and dyke density. The study indicated that the drainage density plays a major role in ground water level fluctuations.

Sajeena and Kurien (2017) conducted a study on Hydrogeological Characteristics and Groundwater Scenario of Kadalundi River Basin and reported 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.

2.2.1 Regulator Cum Bridge

A study conducted by Balachandran and Padmakumar (2008) on improvement of paddy cultivation in the command area of Kattampally RCB. The RCB was constructed in the year 1996 by the Government of Kerala, at the confluence point of Kattampally tributary with thirteen operable shutter lock gates and Road Bridge. Excessive floods during monsoon because of faulty construction and intrusion of saline water through the shutters caused destruction to paddy cultivation which also increased salinity of impounded water. In addition hardening of soil and extensive occurrence of leeches and massive weed growth also reduced the results.

Regulator Cum Bridge (RCB) accounts multipurpose and likely create sufficient storage for irrigating the ayacut areas and also for meeting the demand of drinking water supply. It can be effectively used for controlling the saline water intrusion to the upstream side of regulator. In fact the bridge will improve the communication facilities and the increase employment opportunities of the area (Hakkim *et al*, 2013).

2.2.2 Drainage canals

A study on groundwater response to controlled water release in limitrophe region of the Corolado River by Jorge *et al.* (2013) reported a strong relation between the flow discharge volume and the ground water elevation after conducting the hydrologic analysis of the study area. The findings of the study are helpful in understanding the spatial variability in hydraulic connections with the river channel and channel abstraction. Moreover, the vertical recharge is essential in the designing of the flood plain remediation programmes.

Qiang *et al*. (2016) carried out a study to assess influence of different drainage canals designs on ground water using Visual MODFLOW interface. They also focused on regulation of ground water through drainage canals. For the study they have installed 15 ground water observation wells in the study area. Also they have established 68 temporary ground water level measuring spots for generating model initial hydraulic head. To generate the calculated ground water level data, five calculated hydraulic head observation wells were established in the agricultural area. The study concluded that the ground water level decreased in the adjacent areas of the drains, where there is no significant change in ground water level in the areas without drainage canals.

2.2.3 Lift irrigation

Sharda *et al.* (2015) studied the environmental effect of lift irrigation scheme at Saswad – Purandar. The extent of pollution of the river Mula-Mutha at the source, Koregaon - Mul as well as at three different upstream locations in Pune has been assessed through the study. The soil and groundwater pollution levels are determined and compared with the permissible limits for the respective parameters. Considering the pollution levels of the river a low cost treatment such as aerated facultative lagoons has been suggested. This is found to be economical as well as effective in improving the quality of the water.

Uday (2018) carried out a study focusing on the effect of 'Pattiseema lift irrigation in the West Godavari district. From the study it is observed that after the implementation of the lift irrigation project there was an increase in the net recharge from 50 mm/year to 100 mm/year. There was also a 3 m rise in groundwater level nearer to the canal. The study came to a conclusion that West Godavari district is safe with increase in pumping rate and decrease in recharge up to 2032.

2.3 GROUNDWATER RESOURCE MODELING

2.3.1 MODFLOW

It is a modular finite difference groundwater model which is developed by U.S Geological Survey (USGS) and consists of computer program that simulate common features in groundwater systems (McDonald and Harbaugh, 1998).

MODFLOW designed to stimulate the aquifer system considering the following conditions:

- Existence of saturated flow conditions
- Application of Darcy's law
- Constant groundwater density
- The principal directions of horizontal hydraulic conductivity or constant transmissivity.

The world widely-used groundwater flow model, MODFLOW can simulate external flow stressed such as wells, areal recharge, evapotranspiration, drains and rivers with a set of stress packages (Harbaugh, 2005). MODFLOW is able to simulate variety of hydrologic processes in steady as well as transient states for different kinds of aquifers. Interactions between the land surface and groundwater and between surface water and groundwater are simulated using a variety of boundary condition packages, including the Recharge, Well, Drain, Lake, Reservoir and Stream flow Routing packages.

2.3.2 Application of MODFLOW

Groundwater flow in aquifer systems can be simulated in MODFLOW using finite difference method. In this method, an aquifer system is divided into rectangular blocks by a grid (Fig.4). The grid blocks are organized by rows, columns and layers and each block is commonly called a “cell” (Leake, 1997).

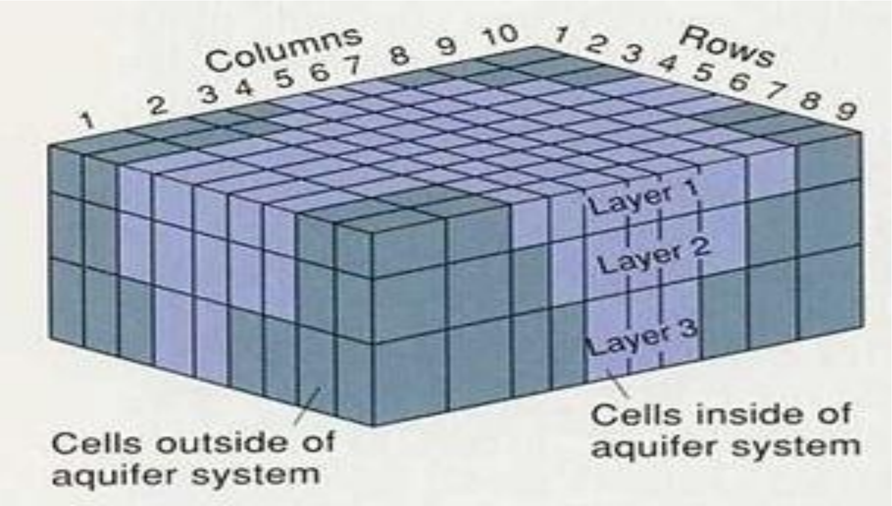


Fig. 3. Model grid for simulating three- dimensional ground water flow (Leake, 1997)

2.4.2 Visual MODFLOW

Babu *et al.* (2014) developed a groundwater model for the Nellore coastal zone to predict the potential environment and socioeconomic impacts of the groundwater abstractions. They estimated the aquifer parameters by developing a transient groundwater flow model in Visual MODFLOW and predicted the groundwater head for future years in the Nellore district situated at sea coast.

Zare *et al.* (2014) conducted a study for analyzing the effects of an irrigation/drainage network on groundwater table fluctuations using 3D groundwater flow modeling in the Miandarband plain of the Kermanshah province, Iran. With the establishment of irrigation/drainage networks and the decreased use of groundwater resources, the groundwater table has risen and which in turn led to water logging, followed by salinization of the arable soils in the plain. The study concluded that by using a transient groundwater flow model it is possible to control the ground water levels and thus to prevent the occurrence of detrimental water logging events in irrigated agricultural areas.

From a study conducted by Lakshmipriya *et al*. (2015) it is concluded that Visual MODFLOW software is suitable for simulating and predicting the aquifer conditions and to represent the natural groundwater flow in the environment. It can also be utilized to forecast the outcome of future groundwater behavior and simulate hydraulic heads and ground water flow rates within and across the boundaries of the system as well as to simulate the concentrations of substance dissolved in groundwater.

In order to have better understanding on groundwater regime of the study area, Lasya *et al*. (2015) conceptualized, designed and calibrated a model in Visual MODFLOW. It is a generic model with an objective to quantify the input and output stresses on the aquifer system for a period of 720 days. A numerical model, like Visual MODFLOW, is a mathematical representation of the groundwater environment. It is based on professional interpretation of the available data. It is built in a structured way to provide some assurance that the site-specific model will provide meaningful results. For the study, Visual MODFLOW Pro is chosen for modeling the groundwater which aimed to understand the ground water system and also to quantify the input and output stresses.

Knowling and Werner (2016) carried out a study on the estimability of recharge through groundwater model calibration to inform recharge within a regional setting using a series of highly parameterized steady-state inverse modeling experiments containing varying degrees of hydraulic parameter constraints. The study offered guidelines to groundwater modeling practitioners on the potential effects of non-uniqueness in terms of recharge estimability in a real-world modeling scenario and the results of this study created a benchmark for evaluating the extent to which field scale groundwater models can be used to inform recharge under practical data availability limitations.

Visual MODFLOW is a commercial Graphical User Interface for MODFLOW, developed by the “Waterloo Hydrogeologic” company in August, 1994. The major difference between MODFLOW and Visual MODFLOW is that MODFLOW requires input data in the form of text files which make it complex and time consuming. While, Visual MODFLOW uses Excel files, Surfer grids, GIS and AutoCAD data as input files.

This makes modeling user-friendly and requires lessr execution time (Hariharan et al., 2017). The study reviewed the versatility of MODFLOW application in the aspects of groundwater modeling for the past 22 years. It included all the areas where the model is used like agriculture, airfields, constructed wetlands, climate change, drought studies, Environmental Impact Assessment (EIA), landfills, mining operations, river and flood plain monitoring, salt water intrusion, soil profile surveys, watershed analyses, etc. The review defined the scope of the software in the field of research and groundwater modeling.

The groundwater model which usually predicts the effects of hydrological changes like groundwater extraction or irrigation developments on the behavior of the aquifer and is referred as groundwater simulation model. Sridhar *et al.* (2018) used Visual MODFLOW for modeling the groundwater Lower Ponnaiyar Sub-Watershed, Tamilnadu. For this study, spatial distribution of hydraulic conductivity and storage properties are optimized by trial and error method. Also from the simulation results it can be concluded that the fluctuations of hydraulic heads are dependent on seasonal variation in recharge from natural infiltration of precipitation as well as irrigation. The study suggested that groundwater recharging can be improved by constructing check dams, contour bund in different parts of the sub watersheds.

A study was conducted by Uday (2018) on regional groundwater resource modeling using MODFLOW. In this study, Visual MODFLOW was used to study the ground water behavior and predict groundwater heads at different scenarios in West Godavari district. The effect of lift irrigation on the groundwater was also monitored in the study.

A coupled SWAT-MODFLOW model was developed by Aliyari (2019) to study large scale mixed agro-urban river basins. Updated version of SWAT-MODFLOW software code is adapted for the study. All the major water transfer pathways for managed river basins are included in the model as well as MODFLOW pumping is linked to SWAT HRU’s for groundwater irrigation.

Namitha *et al.* (2019) studied a river basin namely Nileshwar of Kasargod district, which is said to be a drought prone district. A steady state groundwater model for the proposed study area was developed using Visual MODFLOW 2.8.1. Water balance was calculated using the model. Well data, vertical and horizontal hydraulic conductivity of the six layers, boundary conditions viz. constant head, recharge and river stage elevations were the inputs to the groundwater model. The groundwater level and the flow budget were calculated as outputs of the model. Major limitations reported after the completion of the study were the uncertainty of parameter estimates and boundary conditions. Small differences in parameters such as hydraulic conductivity and recharge can cause significant errors in model output. Similarly, boundary conditions strongly control the flow regime, and so a poor representation of the data could result an inaccurate model.

Sajeena and Kurien (2019) developed a Visual MODFLOW model for modeling the groundwater resource flow mapping of the Kadalundi river basin of Malappuram district of Kerala. The model was developed to study the aquifer characteristics and spatial and temporal groundwater fluctuations in the area. The model was calibrated for steady state and transient conditions and also predicted the flow head and groundwater conditions for various pumping rate and recharge. Predictions were made for the next 5, 10 and 15 years with five per cent decrease in recharge for every year and also predict the groundwater condition after 15 years by increasing the pumping rate by 10, 25 and 50 percent of pumping rate of the validated period. 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.

An advanced three-dimensional visualization and animation module such as Visual MODFLOW 3D-Explorer can be used for displaying and presenting water flow, path lines, as well as solute transportation by representing in a set of variety three-dimensional graphical formats (Sun *et al.*, 2019).

Measurement and evaluation of groundwater resources can be successfully done by applying modelling approaches such as Visual MODFLOW Flex software (Modular Finite Difference Groundwater Flow Model). The model calibration was achieved by Parameter Estimation (PEST), and the model performance was verified using coefficients like R2, RMSE and NRMSE (Nagraj *et al.*, 2020).

Sajeena *et al.*, (2020) conducted a study in the Kadalundi river basin to assess the simulation of salt water intrusion into the coastal aquifers using Visual MODFLOW. For simulating the real condition, water level data of six observation wells were collected and boundary condition, hydrological and storage properties and initial head values were also given as inputs. The model was run in the transient state for analyzing the match between observed and calculated values. This study reported that there is a chance of saline water intrusion in the coastal stretch of study area. There are chances of saline water intrusion to a lateral distance of 0.5 km to 1.9 km from the coast which extents 3.2 to 4.5km along the coast from northern boundary of Kadalundi river basin.

2.4 IDENTIFICATION OF POTENTIAL GROUND WATER ZONES

A hydro-geophysical investigation on ground water resources was conducted by Kurien *et al.* (2013) in the KCAET campus. During the study all the possible locations were explored to find the presence of ground water. The potential areas of sustainable water supply were identified as the result of the study. Among the six locations under consideration, three sites found to be potential ground water reserves which could be ideal for ground water exploration. A possible location for filter point well was identified near the Barathapuzha River.

Kurien *et al.* (2016) carried out a hydro-geophysical investigation of ground water resources in coconut garden of College of Horticulture, Vellanikkara. The primary objective of the study was to identify the potential ground water zone to meet the various requirements of the campus. ‘Resistivity Scanning’ method is adapted for delineating the fractured geometry of formation and found to be a successful technique.

Materials and Methods

CHAPTER 3

MATERIALS AND METHODS

Groundwater is an essential natural resource for the existence of the life. The increasing demand of water with increasing population leads to find availability and to monitor the distribution of groundwater. The objective of the study was to model the groundwater scenario near the Bakkikayam regulator using Visual MODFLOW and study the impact of the regulator on the groundwater level. Bakkikayam regulator across Kadalundi River and its ayacut area is taken as the study area for this research work. Materials and methods chosen for carrying out the study are discussed in this chapter.

3.1 GENERAL FEATURES OF THE STUDY AREA

3.1.1 Study Area

The area selected for this study is the ayacut area of Bakkikayam Regulator constructed across the Kadalundi River at Pandikasala in Vengara Panchayth of Malappuram District. The study area of about 290 km^2 lies between 11º 03’ 33” to 11º 04’ 1.01” N Latitude and 75º 53’ 3.80” to 76º 02’ 1.92” E Longitude. Location map of the study area is shown in Fig.4. The ayacut area of Bakkikayam regulator is spread through fifteen panchayaths viz. Vengara, Kannamangalam, Edarikode, Oorakam, Othukkungal, Parappur, Kottakkal, Perumannaklari and A.R. Nagar panchayths in upstream side and Nannambra, Thennala, Munniyur, Thenhipalam, Peruvallur and Thirurangadi panchayaths in downstream side of the regulator. Plate 1 shows the upstream side and downstream side of the Bakkikyam regulator.

The regulator is beneficial for upstream side of the regulator while it create acute water shortage in downstream side for the paddy cultivation of around 950 acres during its critical stages in Nannambra Panchayath as shown in Plate 2 and 3. This had been lead to a massive dispute between upstream and downstream famers and authorities on the closing of regulator during summer months (Plate 4). During the critical stages of paddy crop in downstream side, it requires sufficient water for crop development, otherwise complete failure of crop will happen.

3.1.2 Topography

Kadalundi river basin has an undulating topography along with steep slope. The basin has small intermittent hillocks whose elevation ranges between 50 to 100 meters above MSL. The ground elevation of Kadalundi river basin lies between MSL to 1200 meters above MSL.

3.1.3 Physiography

Based on topography, study area can be classified into three well defined natural divisions or physiographic zones such as lowland (MSL to 7.5 m above MSL), midland (7.5 to 75 m above MSL) and highland (more than 75 m above MSL) which are running parallel to the north- south orientation. Lowland lies in the costal belt, which has nearly flat and monotonous topography covered by quaternary sediments. Midland region lies in the central portion of the study area which exhibits undulating and dissecting topography. The high land region lies in the north eastern side of the study area covered some parts of Peruvallur and Kannamangalam Panchayaths (CWRDM, 2012).

3.1.4 Rainfall

The average annual rainfall of study area is 2700 mm. The major portion is contributed by South-West monsoon (June to September) and remanining portion is from North-East monsoon (October to December) and summer showers.

3.1.5 Temperature and humidity

The average daily maximum temperature of the study area is 32°C and the average daily minimum temperature is 21°C. The air condition is highly humid and the basin relative humidity generally varies from 60 to 88 per cent. The wind is predominant from east as well as west during morning and evening hours. The wind speed is more during December to February months which ranges from 2.9 to 7.2 kmph.

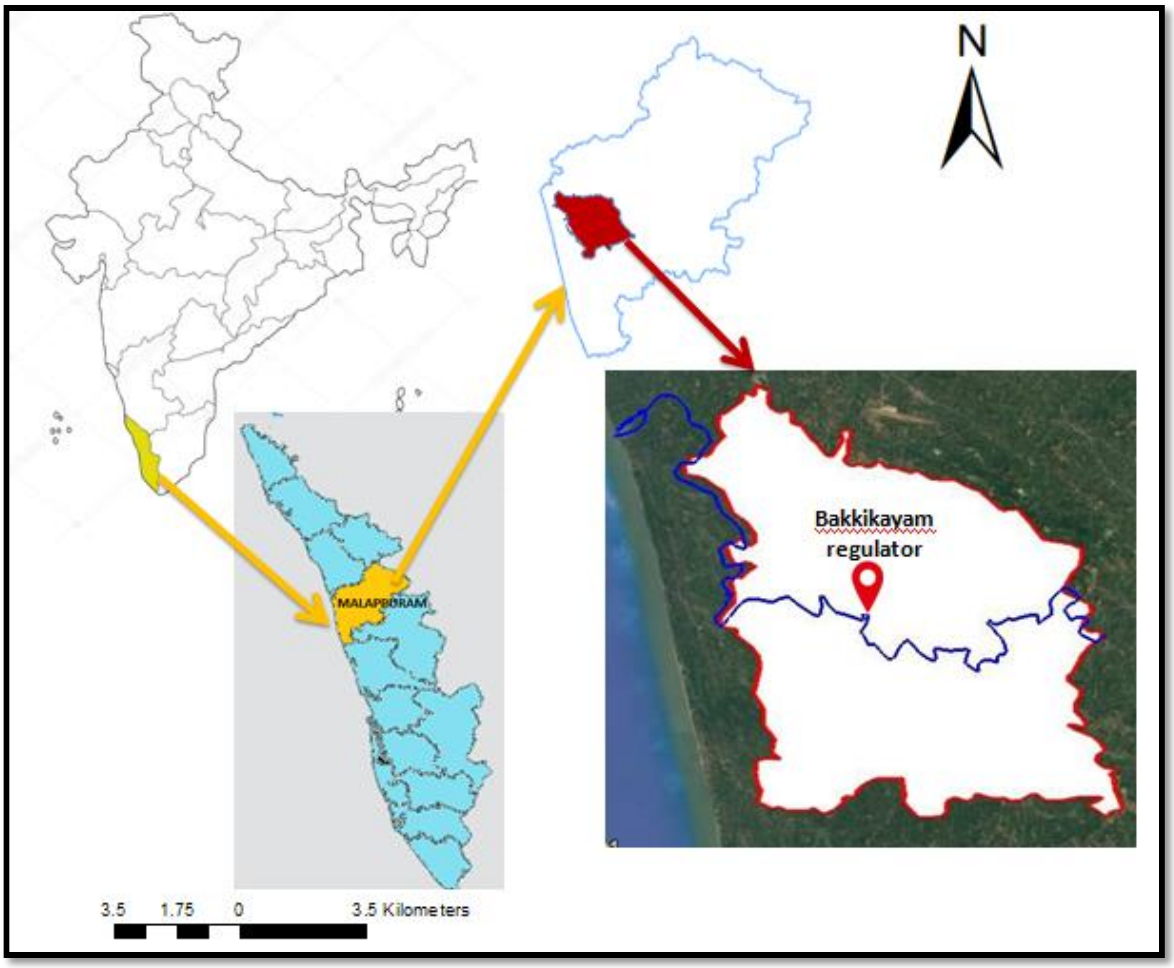


Fig. 4. Location map of the study area

Plate 1. Upstream and Downstream side of Bakkikayam Regulator

Plate 2. Paddy field at Nannambra during its critical stage.

സുപ്രഭാതം

❑ കൊടിഞ്ഞി തിരുത്തി വയലിൽ വെള്ളമില്ല

ഏക്കർകണക്കിന് നെൽകൃഷി നശിക്കുന്നു

നന്നമ്പ്രയിലെ വയലുകൾ ഉദ്യോഗസ്ഥർ സന്ദർശിച്ചു

കൃഷിയും ജലവിതരണവും മുടങ്ങാത്തവിധം ബാക്കിക്കയം ഷട്ടർ തുറക്കാൻ തീരുമാനം

Plate 3. Dispute among the farmers and authorities which received media attention

3.1.6 Drainage

The Bakkikayam regulator is constructed across the Kadalundi River at Bakkikayam, Vengara Panchyath and the river has 130 km length with a drainage area of 1274 sq. km. The basin is identified as having a dendritic pattern with varying density of drainage channels. Kadalundi river basin has stream of fifth order. According to various geological and geomorphological characteristics the drainage density ranges between 0.65 to 3.15 Km/Km^2.

3.1.7 Land use and cropping pattern

Various land use classification such as river, stream, water bodies, plantations, arable land, forest land and waste lands are seen in the study area. Since the basin has different physiographic zones with varying climatic conditions, numerous varieties of crops are cultivated in the region while paddy as the major crop.

3.1.8 Geology

The study area is distinguished by laterites of pliestocene age and alluvial formations of recent to sub recent ages. Occurrence of laterite was due to the tropical weathering of crystalline rocks and found in the form of both primary (insitu) as well as secondaray(transported) material. The recent alluvial deposition includes coastal sand, riverine alluvium and valley fill.

The available data from existing observation wells in the study area have been used to verify the subsurface lithology. Fine to medium grained deposits of 5 to 15 m thickness is seen in the coastal region followed by laterites, lithomarge clay and weathered and/ or hard rocks. Lateritic soil is seen with 0.5 to 15 m thickness at midland region overlying lithomarge clay of thickness followed by weathered rock of 0.5 to 2 m.

3.1.9 Soils

The soil present in the study area is generally acidic and gravely in nature along with low water holding capacity. The factors influencing soil formation are climate, topography, vegetation and hydrological conditions. Considering physiographic zones of the region, the lowland soil is generally sandy to sandy loam also alluvium along the banks where as midland is having lateritic soil.

3.1.9.1 Laterite soil

Laterite soil is the major soil type, especially in the midland region. The high temperature and heavy rainfall in the region carried out the formation process of the laterite soil. The color of surface soil varies from reddish brown to yellowish red with a variation of texture from gravely loam to gravely clay loam. The depth of soil ranges from shallow (less than 50 cm) to deep (more than 150 m). This type of soil is having poor water holding capacity hence well drained and suitable for agricultural management practices. The pH ranges from 4.5 to 6.2.

3.1.9.2 Coastal alluvium

This type of soil is having highly porous nature and low water retention rate and is seen along the coastal belt with a width of 5 to 10 Km which are resulted by the recent marine deposit. Texture of soil having high percentage of sand includes loamy sand and sandy loam. The soil is acidic in nature with pH value less than 6.5.

3.1.9.3 Riverine alluvium

This kind of soil is mostly seen along the river banks or valleys like a narrow belt. The soil is highly porous with low water holding capacity. They are very deep soil with range of sandy loam to clay texture. The organic content is moderate and acidic in nature.

3.1.9.4 Brown Hypodermic soil

This type of soil is the second dominant soil type in the upstream side of the study area. These soils are mostly seen as patches and confines to the valley bottom of undulating topography. The soil is formed by the transportation of materials from the nearby hill side and deposition of the materials by the rivers. It is composed of high organic matter causing dark reddish brown to black color.

3.1.10 Groundwater scenario

Considering the Hydrogeology of the study area, the aquifer system in the area falls into four categories such as crystalline, laterite, lateralized sedimentary (tertiary) and alluvial aquifers.

The crystalline formation composed of charnockite, biotite gneiss and migmatite rock covers majority of the area. Fractured aquifers in the crystalline areas form potential aquifers and ground water occurs under semi-confined to confined conditions. The occurrence and movement of ground water is controlled by the presence of lineaments, fractures and joint pattern (CGWB, 2013).

Laterites formation is the most widely distributed aquifer system covering the midland region. The laterite constitutes the potential aquifer because of its porous and highly permeable nature. The laterite is derived from both the tertiary formation and also from the crystallines. This mainly occurs at the hill top areas as laterite capping, it also occupy the low land areas where thickness is very less.

Lateralized sedimentary formation is one of the major aquifer occurring along the coastal tract of the study area confined between the coastal sandy plain and the laterites basement rock aquifers. They comprise of gravel, coarse sand and clay. This aquifer is widely used for tapping groundwater for domestic requirements through shallow tube wells or deep dug wells.

Alluvial formation is the most potential aquifer in the entire study area and it is basically composed of sand, silt and clay. In this formation, groundwater occurs under water table conditions and suitable for dug wells and filter point wells. Filter point wells are feasible along the coast wherever the saturated sand thickness exceeds 5 m. Open dug wells and shallow tube wells are feasible in this stretch.

3.2 AQUIFER CHARACTERISTICS OF THE AREA USING EARTH RESISTIVITY STUDIES

In the study area, Vertical Electrical Sounding (VES) was carried out using Signal Stacking Resistivity Meter (MODEL-SSR-MP-ATS) (plate 5). VES survey was carried out in 18 locations using Wenner electrode configuration and the locations are given in Fig 5. The Wenner electrode configurations were carried out with current electrode spacing (AB) ranging from 6 to 66 m (AB/2 = 3 to 33 m) and potential electrode spacing (MN) ranging from 2 to 22 m (MN/2 = 1 to 11 m). In order to conduct VES survey, electrodes were placed in a straight line and inter electrodes spacing was increased gradually about a fixed centre, where the instrument is placed. Current (I) was applied to the ground through the current electrode and the potential difference (V) created by applying the current were measured and recorded against the electrode spacing. As the spacing of current electrode increases depth of penetration of current also increases. The apparent resistivity (ρ_a) can be got from the instrument using the applied value of current (I) and corresponding potential (V) of the electrode configuration. The apparent resistivity value varies with different substrata as it decreases with fractures, joints, water content etc of the formation.

3.2.1 Interpretation of VES Data

The VES data collected in the field was initially interpreted using IPI2 window based resistivity software to get the resistivity and thickness of layer formations. The layer parameters so obtained have been used as initial model parameters in an iterative least squares inversion program. The software automatically displays the layer resistivity, thickness and depth of the layers from the ground surface as the output (Shishaye et al., 2016).

3.2.2 IPI2WIN

IPI2WIN is a computer software for analyzing geoelectrical data from one or more VES (Vertical Electrical Sounding) studies from different kinds of electrode configuration such as Schlumberger, Wenner α, Wenner β etc. IPI2WIN has some basic steps including data input, data error correction, adding data point and pseudo cross section creation.

3.2.2.1 *Inputs for IPI2WIN*:

1. Field data (sounding data such as AB/2,V,I and K)
2. Electrode configuration used (Schlumberger, Wenner α, Wenner β or Dipole)
3. Number of layers, layer resistivities (ρ) and thickness of each layer (h)

The following procedure was adopted for interpreting the VES data (inversion techniques) using IPI2WIN software to get the good result.

3.2.2.2 *Inversion Techniques*

1. Open IP2 Win program
2. Click File>New VES point (Fig. 6)
3. Before data input choose electrode configuration
4. Input data in column by clicking the each column. Then points will be plotted in a graph and click OK button (Fig. 7)
5. Data can be saved in*.txt format using Save TXT button
6. Input data will be saved as VES data file using SAVE AS window
7. Curves and table will be displayed from saved VES file.
8. Close IPI2 Win software by clicking File>Exit. Run IPI2 Win software again to input another VES point data.

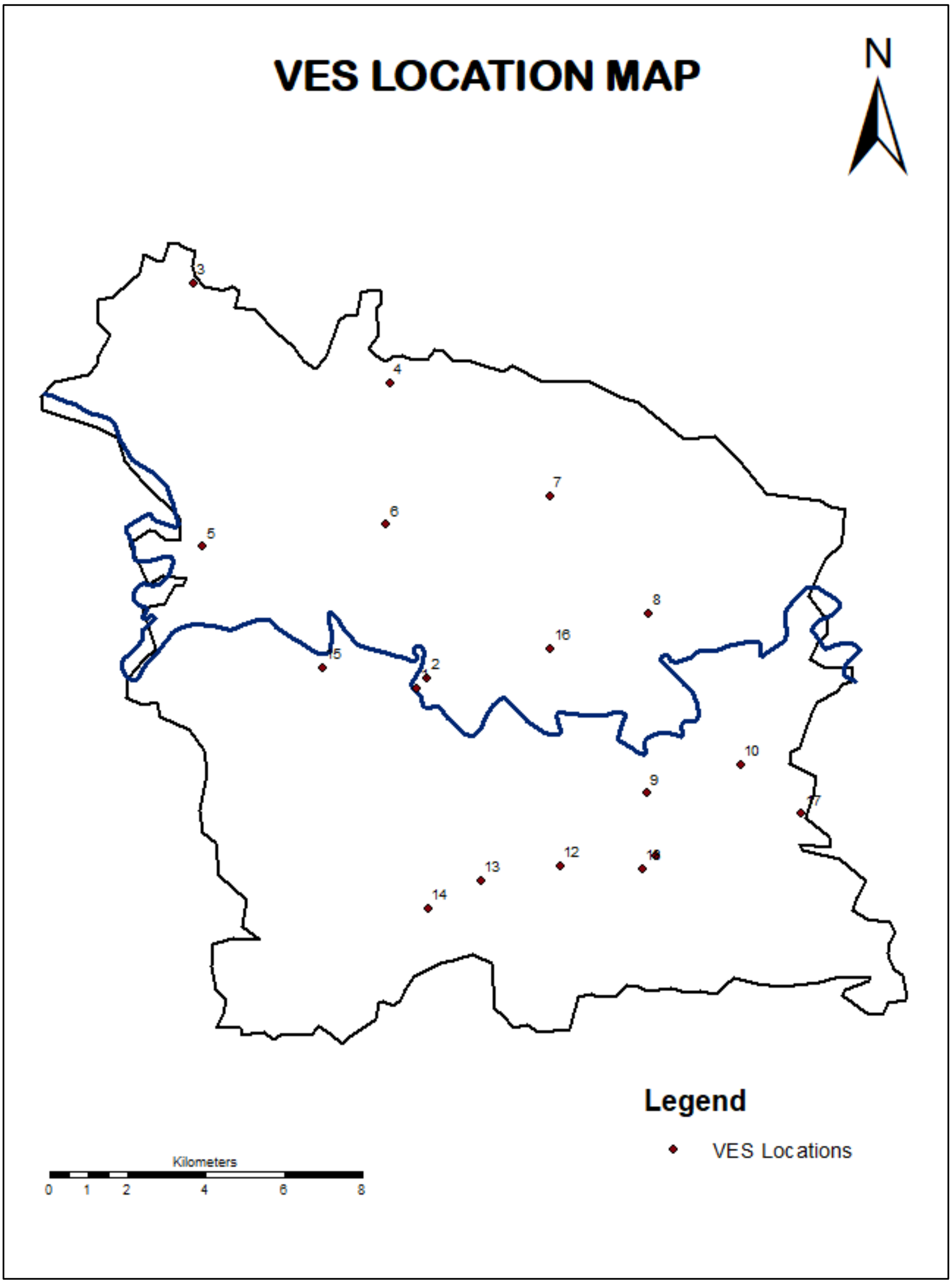


Fig. 5. VES location

Plate 4. VES survey using SSR meter

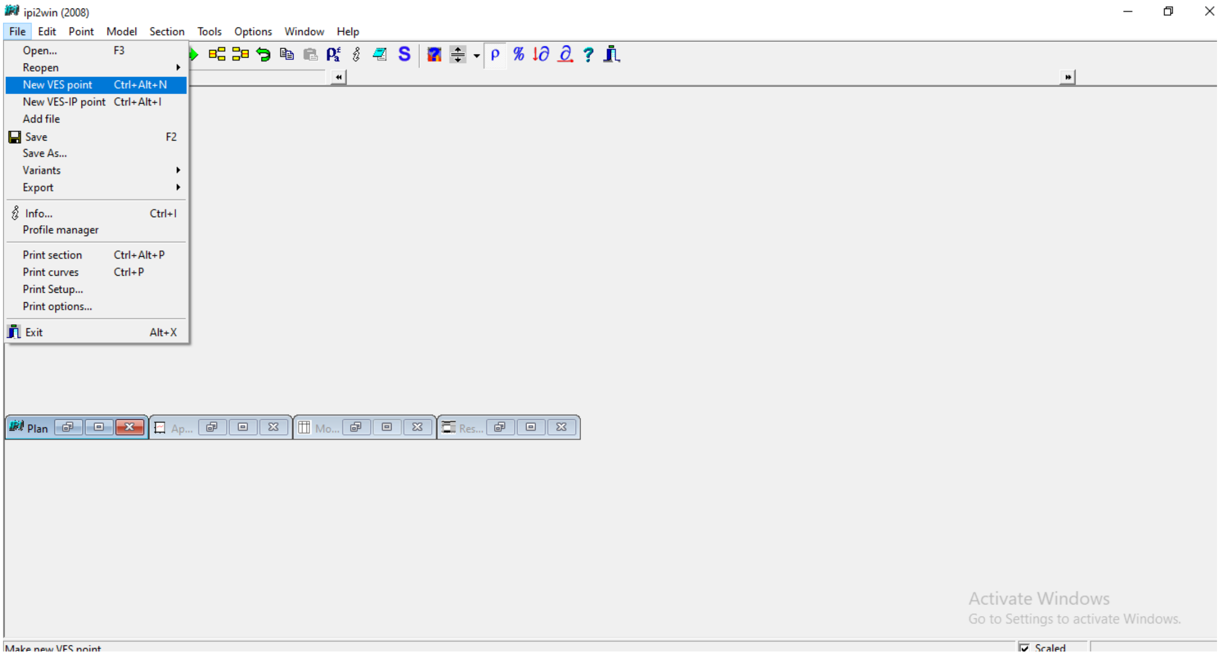
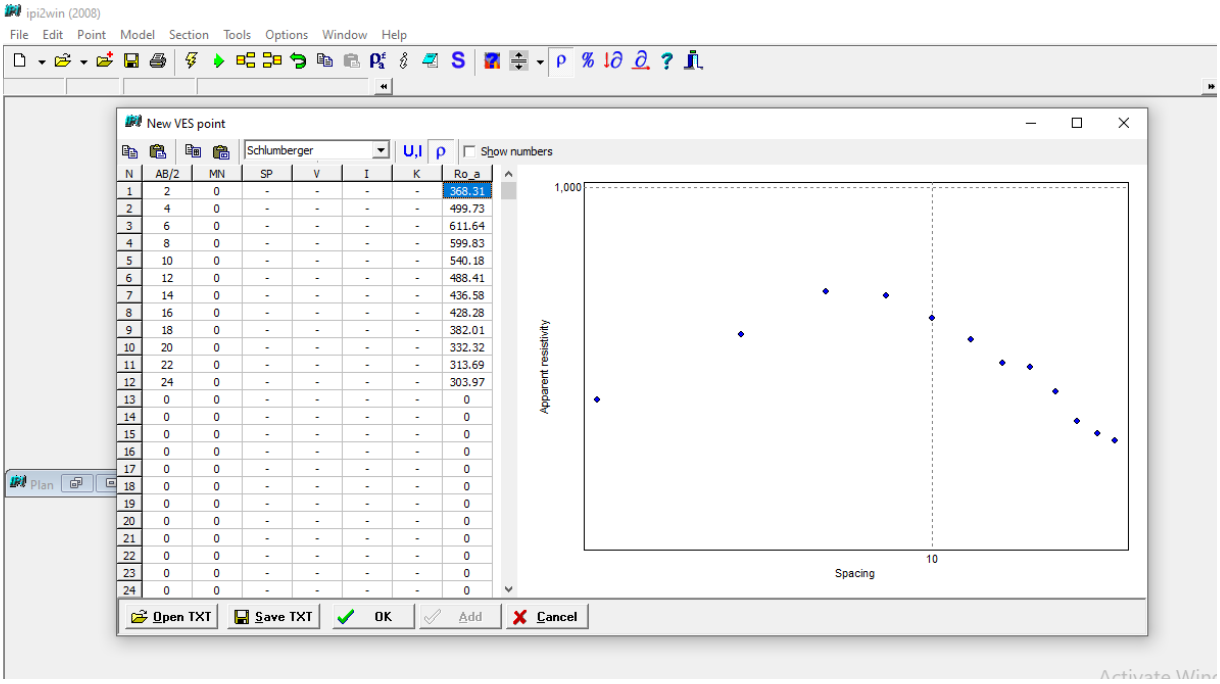


Fig. 6. Creating VES File



Schlumberger

N	AB/2	MN	SP	V	I	K	Ro_a
1	2	0	-	-	-	-	368.31
2	4	0	-	-	-	-	499.73
3	6	0	-	-	-	-	611.64
4	8	0	-	-	-	-	599.83
5	10	0	-	-	-	-	540.18
6	12	0	-	-	-	-	488.41
7	14	0	-	-	-	-	436.58
8	16	0	-	-	-	-	428.28
9	18	0	-	-	-	-	382.01
10	20	0	-	-	-	-	332.32
11	22	0	-	-	-	-	313.69
12	24	0	-	-	-	-	303.97
13	0	0	-	-	-	-	0
14	0	0	-	-	-	-	0
15	0	0	-	-	-	-	0
16	0	0	-	-	-	-	0
17	0	0	-	-	-	-	0
18	0	0	-	-	-	-	0
19	0	0	-	-	-	-	0
20	0	0	-	-	-	-	0
21	0	0	-	-	-	-	0
22	0	0	-	-	-	-	0
23	0	0	-	-	-	-	0
24	0	0	-	-	-	-	0

Fig. 7. Adding inputs in VES file

3.2.2.2 *Sounding curves*

Various combination of sounding curves were produced based upon the geological and hydrogeological formations and the maximum electode spacing adopted. The simplest sounding curves are asending and desending type of curves with two layer cases, where the ground has two layered structure, with loose top soil or a weathered and a compact basement and curve will be asending type. If the top layer is highly resistive and the bottom layer is conductive due to saline water or some other saturated conditions, the a desending cureve is produced (Brijesh and Balasubrahmanian, 2014).

Four types odf sounding curevs are possible in three layered geology of ground substrata. If ρ1,ρ2 andρ3 are the resistivities of three successive layers, a sounding curve with a low resistivity at centre (ρ1>ρ2<ρ3) is known as H type curve. This type of curves are obtained 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 steadly increasing (ρ1<ρ2<ρ3) the curve is known as A type curve. This type of curves occurs in the hard rock terrain with conductive soil. Sounding curve showing a maximum hump flanked by low resistivity values (ρ1<ρ2>ρ3) are called K type curves. In case of coastal areas, these curves are encountered due to the presence of fresh water aquifer underlying a clayey layer overlying a saline water layer (Brijesh and Balasubrahmanian, 2014). A sounding data which has a steadly decreasing resistivity (ρ1>ρ2>ρ3) will give a Q type curve, found in the coastal areas where saline water is present.

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).

3.2.3 Pseudo and resistivity cross section

The psuedo cross-section reveals the observed values vertically along the selected profiles in logarithmic scale and resistivity cross section shows the vertical true resistivity variation by using the interpreted parameters of the sounding along the profile in a linear scale.

The psuedo cross-section of a particular point can be displayed in the pseudo cross-section window. The horizontal ruler on the top represents name of the sounding points where the bottom ruler represents coordinates of the corresponding sounding points. A color column is displayed beside the cross sections.

3.3 ASSESSMENT OF GROUNDWATER FLOW VARIATION DUE TO THE PRESENCE OF BAKKIKAYAM REGULATOR

Ground water level data of observation wells in the study area are collected for the period from 2005 to 2019 from Ground Water Department, Government of Kerala. The pre and post monsoon water levels of these wells for the years 2017 and 2019 were mapped using Arc GIS 10.4. Spatial and temporal variations of ground water level of the wells in the study area are monitored to analyze the impact of Bakkikayam regulator. Ground water table of the months April and October were taken as the pre and post monsoon water table respectively.

3.4 GROUND WATER RESOURCE MAPPING USING VISUAL MODFLOW

Modeling is the process of simplifying or representing the complex real life condition in simple forms such as mathematical equations or computer generated models. Without modeling it is practically impossible to study the entire system with the human abilities. A model is developed for a particular system with all the existing site condition similar to the real system. The process is called calibration, once the calibration is done model is validated with data of certain years. After the calibration and validation the model is ready for predicting the sensitive parameters.

3.4.1 MODFLOW model development

A general flow chart of the modeling methodologies of an aquifer is shown in the schematic block diagram (Fig.8). For this study a ground water model was developed using Visual MODFLOW software (2.8.1). The model was developed and calibrated using 8 years data (2005 to 2012) and validated with 5 year data (2013 to 2017) and run upto 2019. With this validated model it is able to predict the ground water scenario after introducing artificial recharge at specific areas in the downstream side.

3.4.2 Model input

3.4.2.1 *Conceptual model of the study area*

Importing the study area into the Visual MODFLOW using base map (Fig.9) is the first step in the model creation. The boundary of the study area was marked in the Google Earth pro and converted into BMP format with help of paint tool. The number of rows and columns are chosen based on total study area. The number of layer is selected as a result of the field data collected using VES. The edit screen of the model development is shown in Fig. 10. The imported base MAP was georeferenced using georeferencing option in the MODFLOW software. For that set model corner as the model origin. Using input option data such as grid properties, wells, boundaries can be added to the model.

3.4.2.2 *Discretization of the study area*

The study area was discretized by dividing it into 50 rows and 50 columns with a grid spacing of 530 m x 520 m. The entire study area was discretized into 2500 cells. The grid formation of the area is shown in Fig. 11. Based on the available ground water level data, a time step of month was chosen within which all hydrological stresses are assumed to be constant.

3.4.2.2.1 Inactive cells

This is done for demarcating the study area from the other surrounding unnecessary areas. For inactivating the cells other than the study area there are many ways like mark polygon inactive, mark polygon active, mark single, copy single, copy polygon. Selecting the appropriate options from this, the active cells are differentiated from inactive cells.

3.4.2.3 Import elevations

Elevation of the top and bottom of each layer is imported to the model as shown in Fig.12. The data files should be in ASCII format or text file. The assigned minimum thickness is 1 m.

3.4.2.4 Wells

Field observations such as pumping rate and water table variations of different wells located in the study area can be added into the model. It is possible to add, delete, move or edit pumping wells and observation wells using the options given in the well drop down menu.

3.4.2.4.1 Pumping wells

A total of four pumping wells are selected for the study in which two wells are located in the upstream side and two wells are in the downstream side. The pumping wells are mainly dug wells and used for irrigation and household purpose. The pumping data are imported in the text files. The negative sign is used to indicate the pumping rate and positive sign indicates injection. No injection pump was found in the study area. Edit screen for the pumping well is shown in Fig.13.

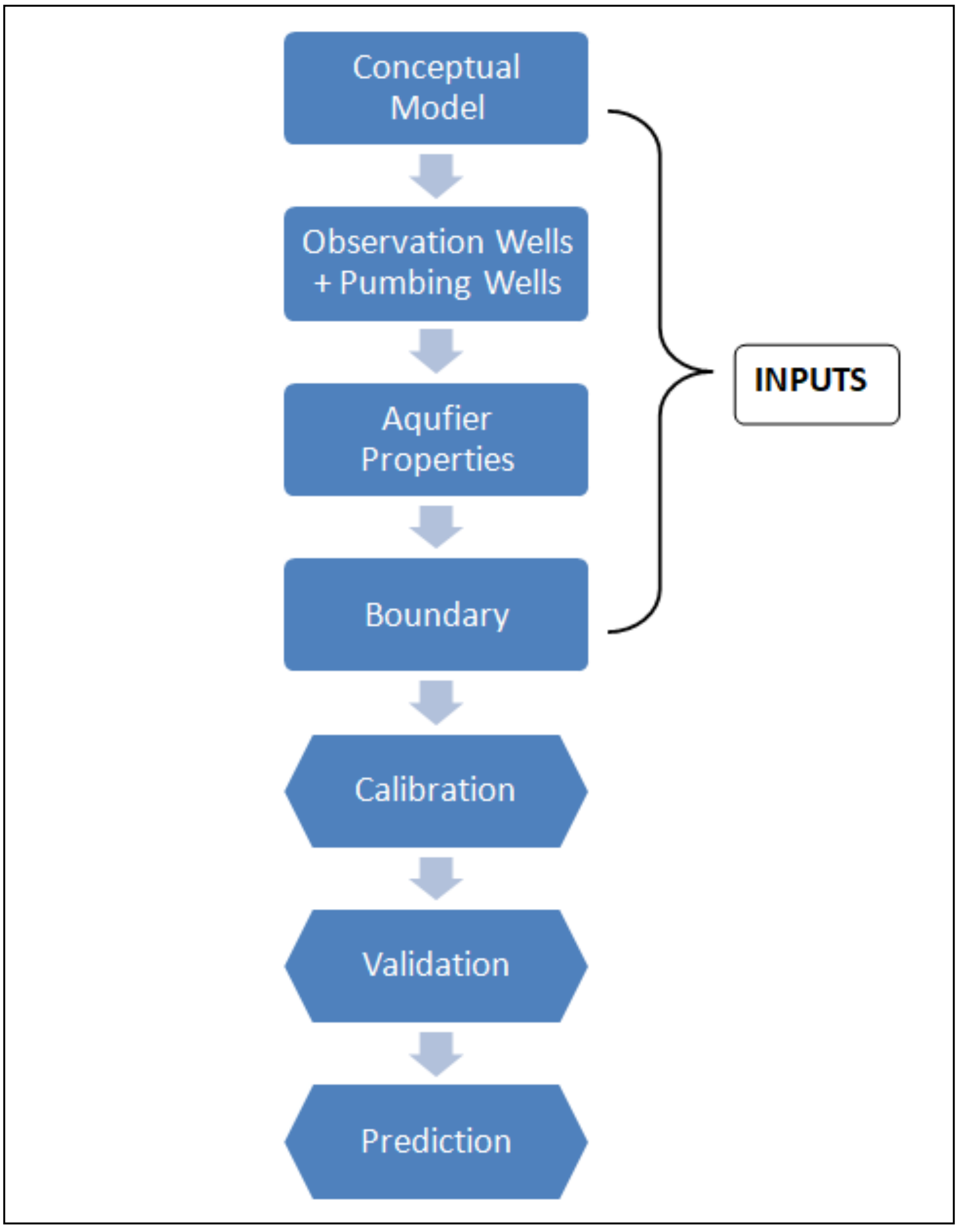


Fig. 8. Flow chart of Visual MODFLOW model development process

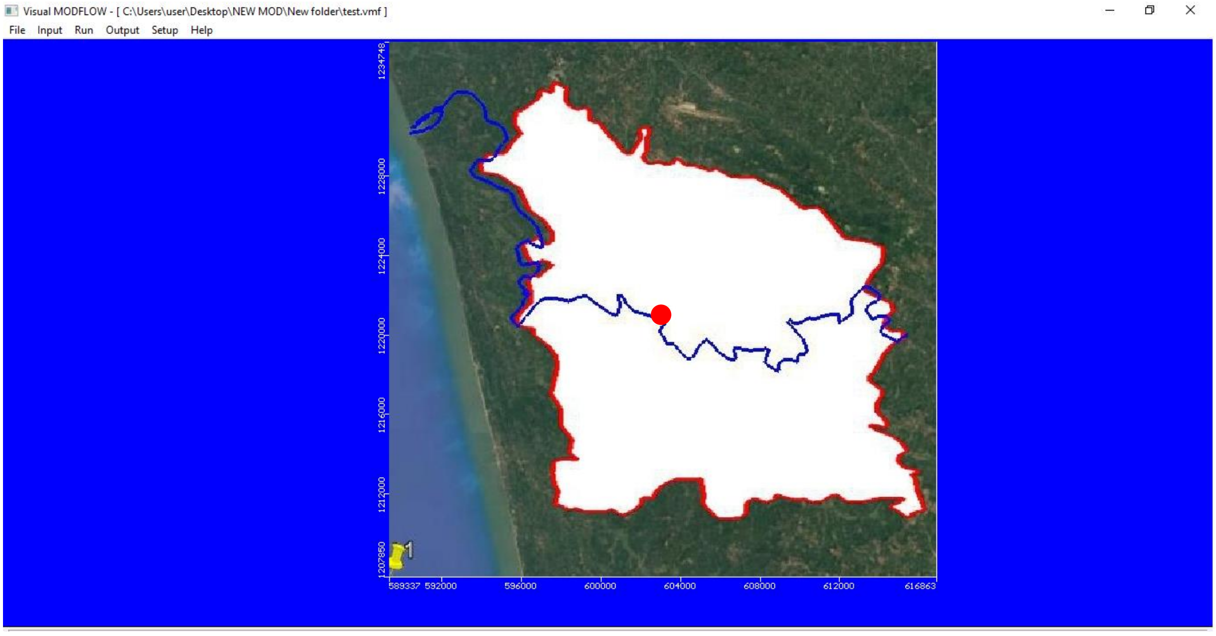
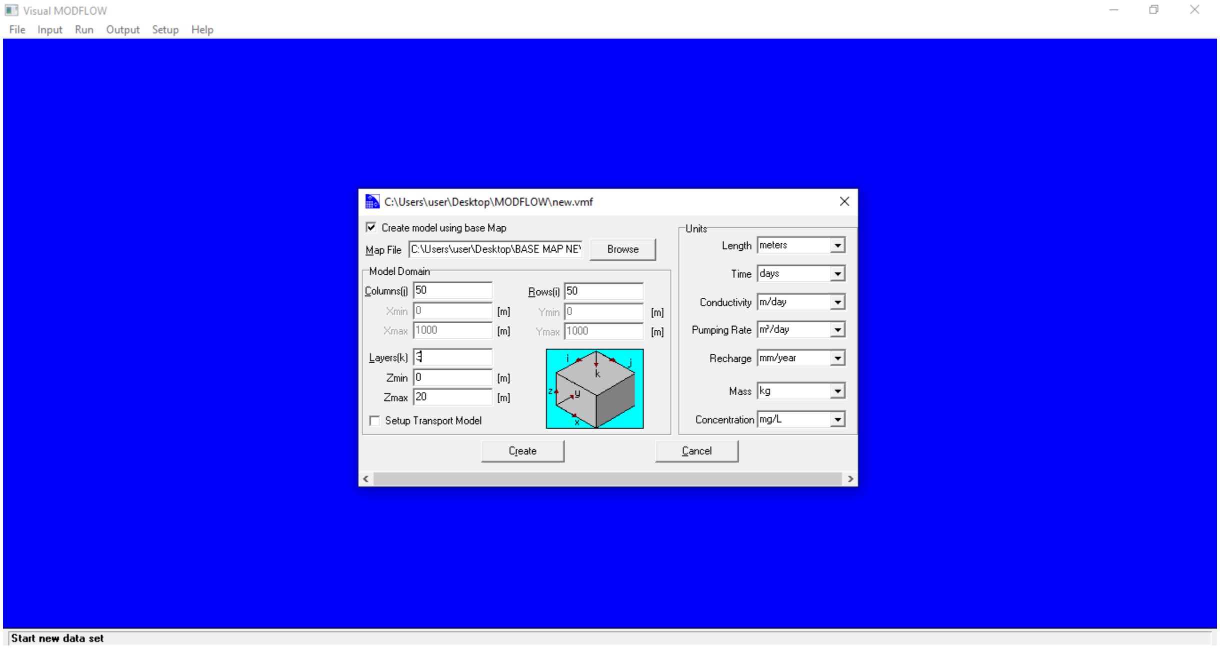


Fig 9. Base map of the model



☑ Create model using base Map

Map File C:\Users\user\Desktop\BASE MAP NE'

Columns(j) 50

Rows(i) 50

Xmin 0 [m]

Ymin 0 [m]

Xmax 1000 [m]

Ymax 1000 [m]

Layers(k) 3

Zmin 0 [m]

Zmax 20 [m]

☐ Setup Transport Model

Length meters

Time days

Conductivity m/day

Pumping Rate m³/day

Recharge mm/year

Mass kg

Concentration mg/L

Start new data set

Fig. 10. Creating model

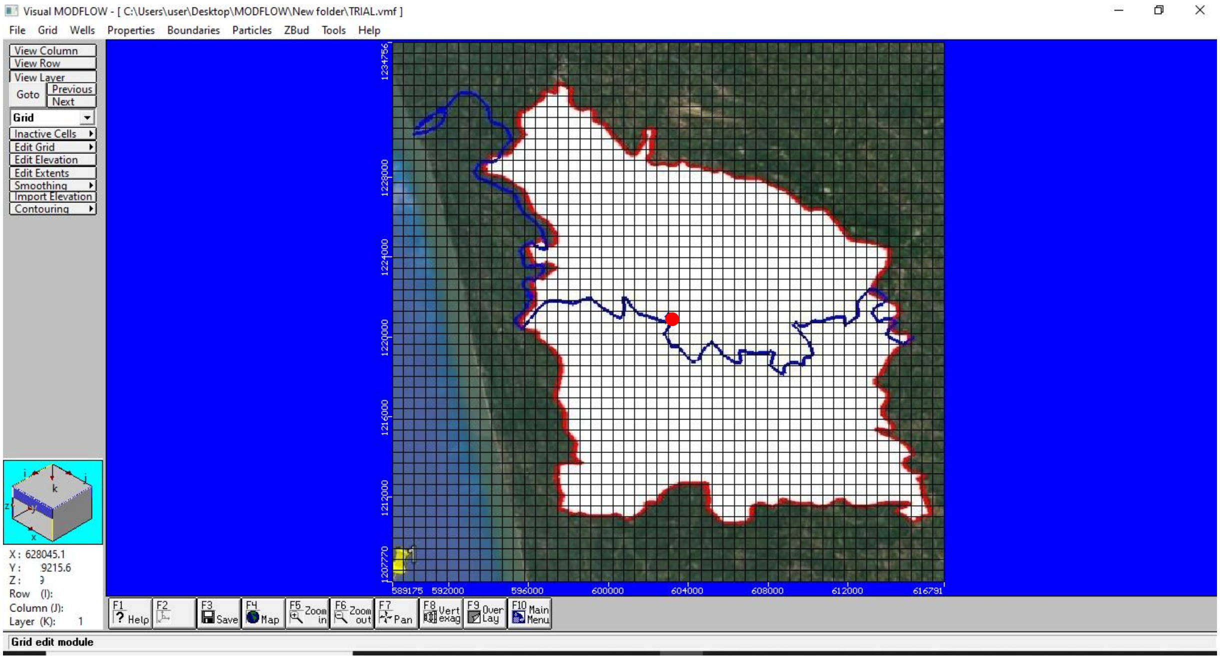
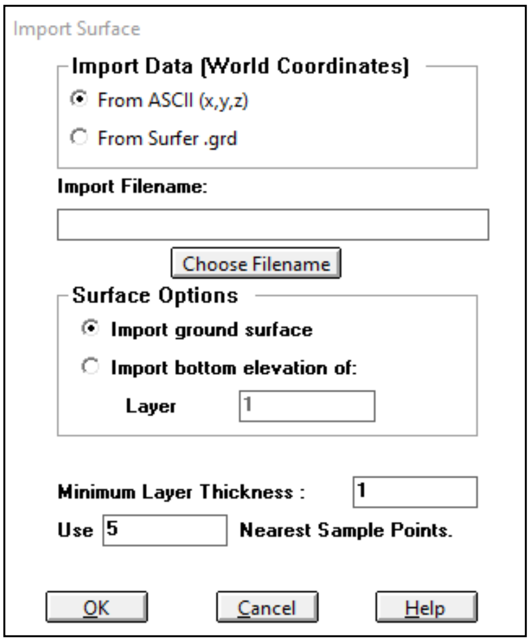


Fig. 11. Grid formation of the study area



Import Surface

Import Data (World Coordinates)

● From ASCII (x,y,z)

○ From Surfer .grd

Import Filename:

Choose Filename

Surface Options

● Import ground surface

○ Import bottom elevation of:

Layer 1

Minimum Layer Thickness : 1

Use 5 Nearest Sample Points.

OK Cancel Help

Fig. 12. Impoting elevation in Visual MODFLOW

3.4.2.4.2 Observation wells

Ground Water Department, Kerala is having 6 ground water monitoring wells within the study area. Among the six ground water monitoring wells (GWMW) four wells are dug wells/ open wells and two wells are bore wells. Ground water levels of each well are recorded for every month. The GWD monitoring wells were marked in the grids using head observation well menu and water levels from year 2005 to 2012 were entered through edit screen of observation wells as shown in Fig.14.

3.4.2.5 Hydrological Properties

The soil hydrogeological properties like conductivity, storage, initial heads, bulk density, species properties and initial concentration and dispersion values are inputs which are used to simulate real soil condition.

3.4.2.5.1 Hydraulic Conductivity

This is the property describes ease of a medium with which a fluid can pass through the pore space or fractures. The conductivity values changes with soil type. Longitudinal hydraulic conductivity (K_x), lateral hydraulic conductivity (K_y) and vertical hydraulic conductivity (K_z) represents hydraulic conductivity in the X, Y and Z direction respectively. From the earlier studies, the hydraulic conductivity of the lateritic soil is 20-30 md^{-1}. Generally K_z is taken as 10 percentage of K_x and K_y.

3.4.2.5.2 Storage

Storage parameters like Specific storage (S_S), Specific yield (S_y), Effective porosity (Eff. Por.) and Total porosity (Tot. Por) are also required by Visual MODFLOW for creating the exact replication of the study area. Hydraulic properties of the aquifers in the study area are given in Table 1.

Table 1. Hydraulic properties of the layers

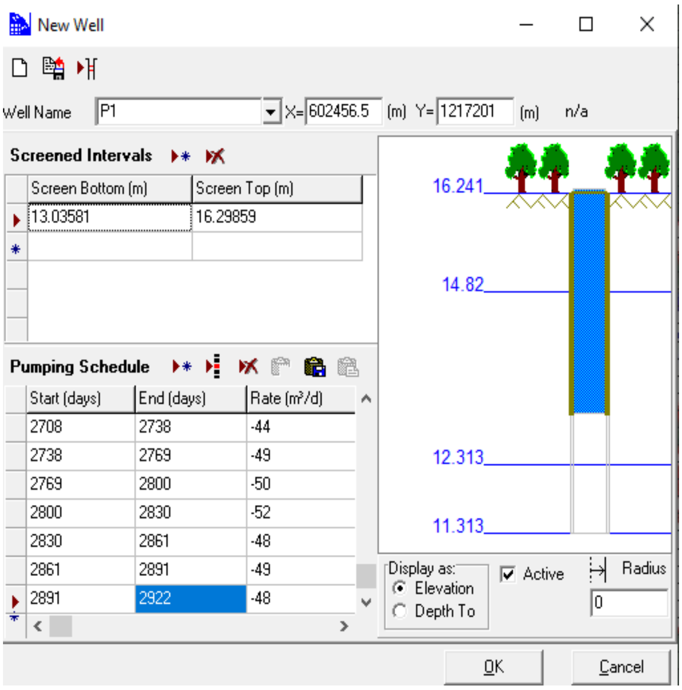
Sl.No.	Model Properties	Layer I Laterite	Layer II Clay	Layer III Weathered rock
1	Hydraulic conductivity in longitudinal direction K_x,md^{-1}	30	0.0002	15
2	Hydraulic conductivity in lateral direction K_y,md^{-1}	30	0.0002	15
3	Hydraulic conductivity in vertical direction K_z,md^{-1}	3	0.00002	1.5
4	Specific storage , Ss (m^{-1})	0.00035	0.00078	0.0005
5	Specific Yield, Sy	0.20	0.06	0.068
6	Effective Porosity	0.35	0.5	0.3
7	Total Porosity	0.40	0.5	0.35

3.4.2.5.3 Initial head

Initial head values are required in Visual MODFLOW to assign the head distribution for the steady state simulation, while a starting head for transient simulation. Also drawdown values were calculated from initial head values and assigned based on water level data recorded by Ground Water Department.

3.4.2.6 Boundaries

Constant head, rivers, general head, drains, walls, recharge and evapotranspiration are the different boundary options provided in the MODFLOW for recreating the boundary condition of the study area and thus evaluating the effects of interaction between the study area and the surroundings.



Well Name P1 X= 602456.5 (m) Y= 1217201 (m) n/a

Screened Intervals

Screen Bottom (m)	Screen Top (m)
13.03581	16.29859

Pumping Schedule

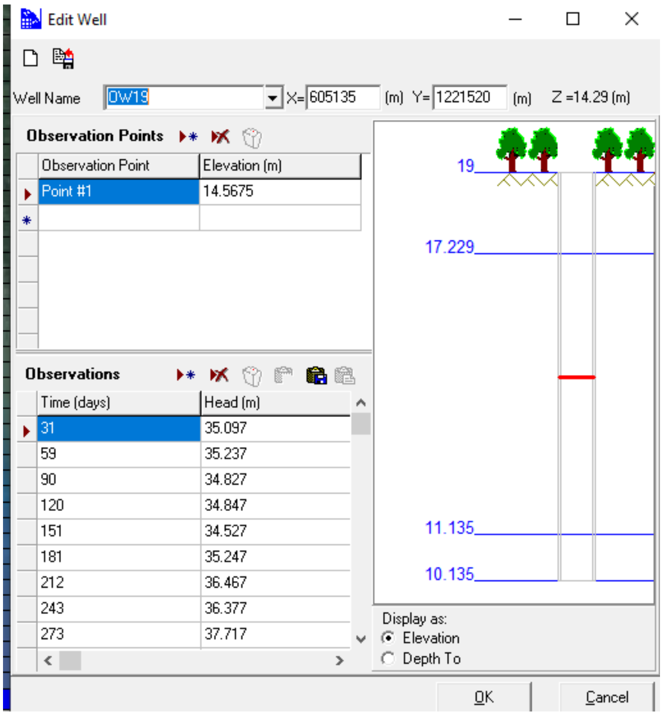
Start (days)	End (days)	Rate (m³/d)
2708	2738	-44
2738	2769	-49
2769	2800	-50
2800	2830	-52
2830	2861	-48
2861	2891	-49
2891	2922	-48

Display as:
● Elevation
○ Depth To

☑ Active

Radius 0

Fig. 13. Adding pumping well



Well Name OW19 X= 605135 (m) Y= 1221520 (m) Z =14.29 (m)

Observation Points

Observation Point	Elevation (m)
Point #1	14.5675

Observations

Time (days)	Head (m)
31	35.097
59	35.237
90	34.827
120	34.847
151	34.527
181	35.247
212	36.467
243	36.377
273	37.717

Display as:
● Elevation
○ Depth To

Fig. 14. Adding observation well

For running the model, a minimum of one head boundary should be specified. During the simulation, head boundary is considered as the reference level for the entire calculation. Boundary conditions are assigned using ‘Assign’ option where these assigned conditions can be edited or erased or copied with the edit, erase and copy functions in the model.

3.4.2.6.1 Constant head

Arabian Sea is the western boundary of the study area. Hence for this study, the water level in the Arabian Sea is considered as constant and value is assigned as zero. The screen showing assigning the constant head is given as Fig. 15.

3.4.2.6.2 River head

In this study, Kadalundi River debouches into Arabian Sea and the river is represented by blue color grids as shown in Fig.16.

$$C = \frac{K*L*W}{M}$$

Where C is the conductance in m^2d^{-1}, K is Hydraulic conductivity in md^{-1}, L is Length of a reach through a cell in m. Whereas W and M represents the width and thickness of the river in m.

3.4.2.6.3 Drains

The Visual MODFLOW software is assigned to simulate the effects created by the agricultural drains whose function is to remove the water from aquifers at the rate proportional to head difference between aquifer and a specified datum or elevation of the drain. An assumption is made that the drain has no effect on the head of flow is considered if the head in the aquifer falls below the datum head.

3.4.2.6.4 Recharge

Recharge is occurring through several modes like rainfall, excess irrigation, seepage from nearby areas, deep percolation and artificial recharge techniques. Recharge is considered only for the top layer. In the model recharge was assigned using 'assign' option while recharge (mm/year) is considered as 10 per cent of the rainfall or calculated using equation (given equation). For this study, annual rainfall data from 2005 to 2019 is collected and recharge is calculated using the equation. Recharge assigned in the model shown in Fig. 17.

$$\mathbf{R = 3.984\ (R_{av} - 40.64)^{0.5}}$$

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

(Chandra and Saxena, 1975)

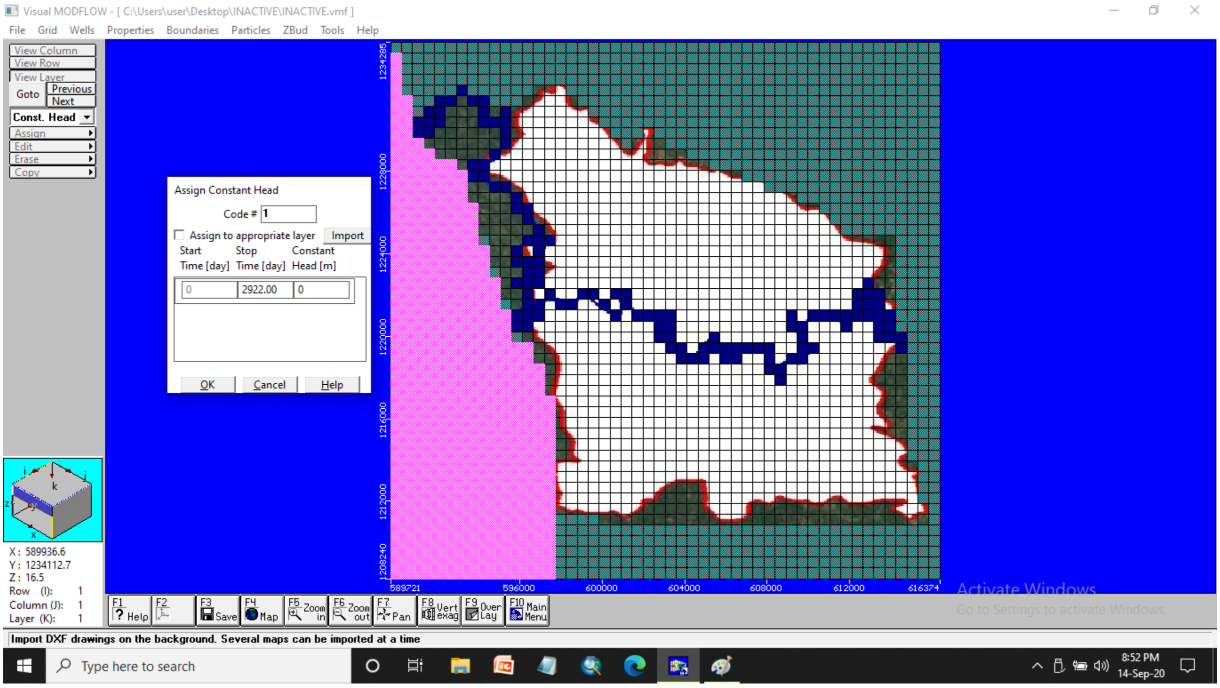
3.4.2.6.5 Evapotranspiration

Addition of Evapotranspiration (ET) is required for simulating the effect of plant transpiration through capillaries in the saturated zones. For the study, the Evapotranspiration is assumed to be uniform for the entire area and as 10 percentage of the total rainfall. The edit screen of evaporation is shown in Fig. 18.

3.4.3 Visual MODFLOW run

Replication of the real system conditions were done by assigning all input parameters in the model. Then from the 'Main Menu' select 'run' option to run the model. Choose the 'Run type' as steady state condition or transient condition from the dialogue box as shown in Fig. 19. Firstly the model was run for the steady state conditions followed by transient state condition. WHS, SIR, SOP and WPS are the different solvers available in Visual MODFLOW. For this study WHS solver was selected.

Other run parameters such as initial head options recharge options, WHS solver parameters, rewetting options, anisotropy factor and output control options are shown in Fig. 20.



Visual MODFLOW - [C:\Users\user\Desktop\INACTIVE\INACTIVE.vmf]

Assign Constant Head

Code # 1

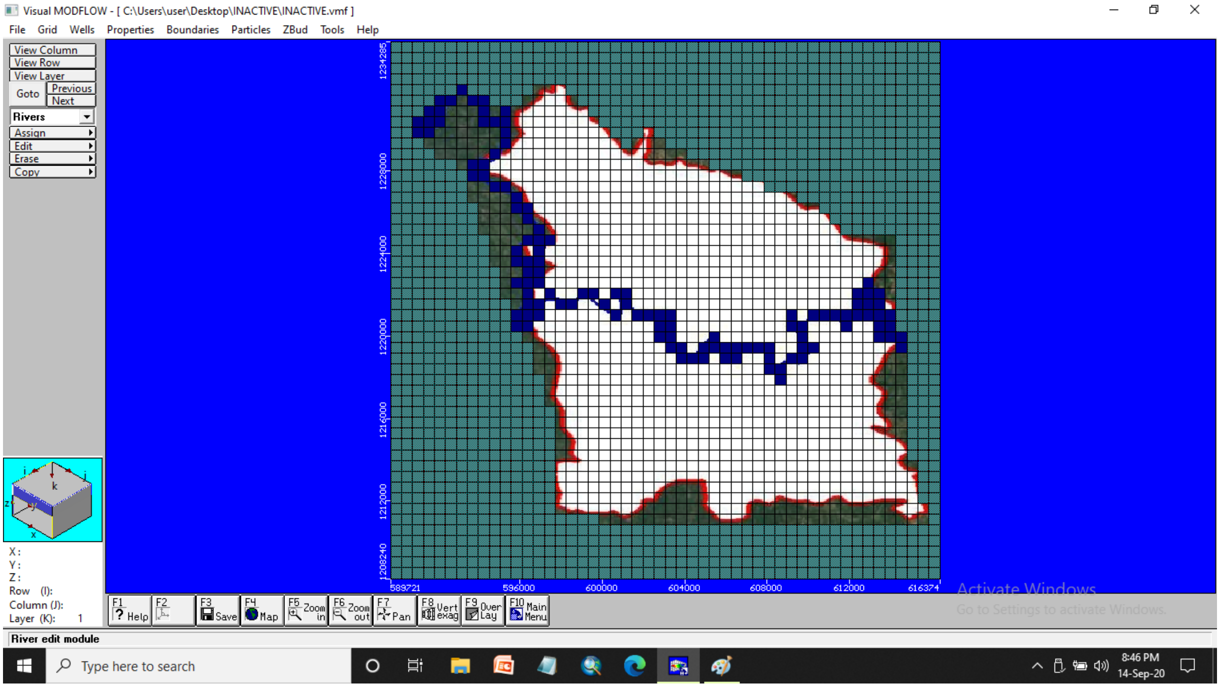
☐ Assign to appropriate layer

Start Time [day]	Stop Time [day]	Constant Head [m]
0	2922.00	0

X : 589936.6
Y : 1234112.7
Z : 16.5
Row (I): 1
Column (J): 1
Layer (K): 1

Import DXF drawings on the background. Several maps can be imported at a time

Fig.15. Assigning constant head



Visual MODFLOW - [C:\Users\user\Desktop\INACTIVE\INACTIVE.vmf]

X :
Y :
Z :
Row (I):
Column (J):
Layer (K): 1

River edit module

Fig.16. Assigning river

3.4.3.1 Model calibration

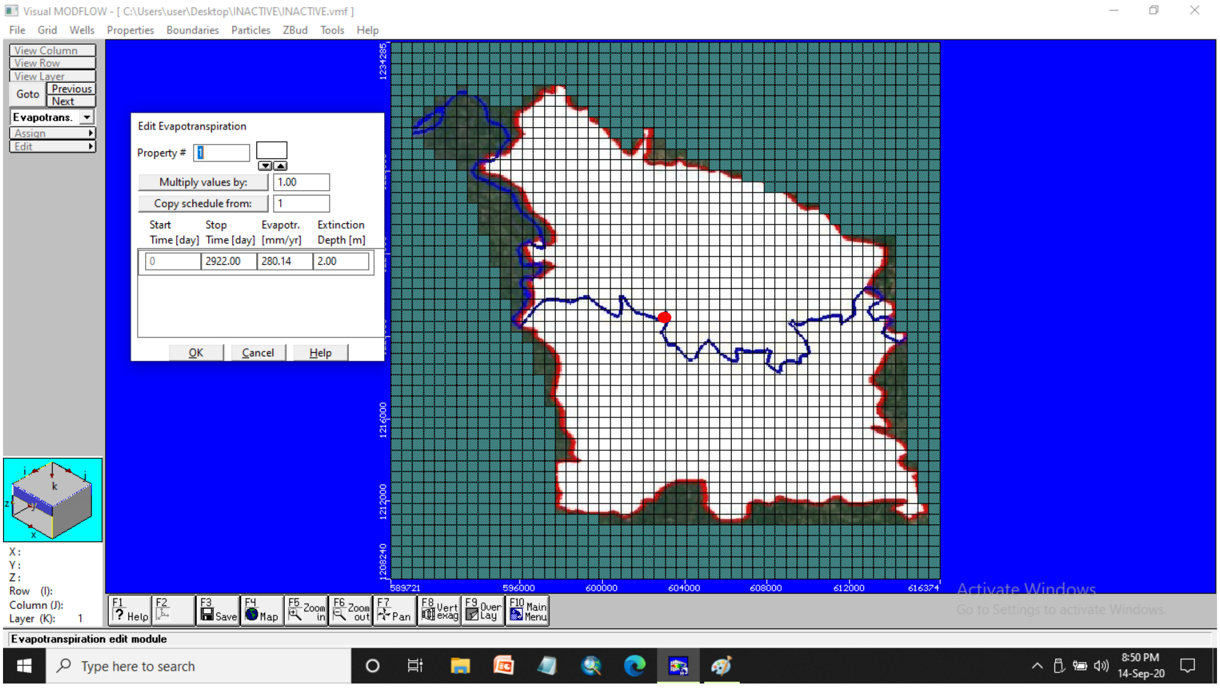
The model was developed and first calibration was done using 8 years data (2005 to 2012). After processing, RMS error in the equipotential graphs was minimized by varying the values of hydraulic conductivity. RMS value mainly depends on water table elevation for observed and computed values. No change in RMS value after certain point indicates that the model is calibrated.

3.4.3.2 Model Validation

The calibrated model was then validated with the groundwater level data of five years (2013 to 2017) and continued upto 2019 to study the effect of Bakkikayam regulator on ground water flow in the study area. This model is capable of predicting the aquifer responses according to the change in the scenarios. The influence of Bakkikayam regulator cum bridge on groundwater level can also be studied using the model.

3.4.3.3 Model prediction

In order to find the solution of water scarcity during summer months, the validated model was used to predict the ground water scenario of the study area for the next five years. The prediction was carried out by assuming that the ground water recharge will be increased by 10 %, 20%, 30% recharge of the validated year 2019.



Edit Evapotranspiration

Property # 1

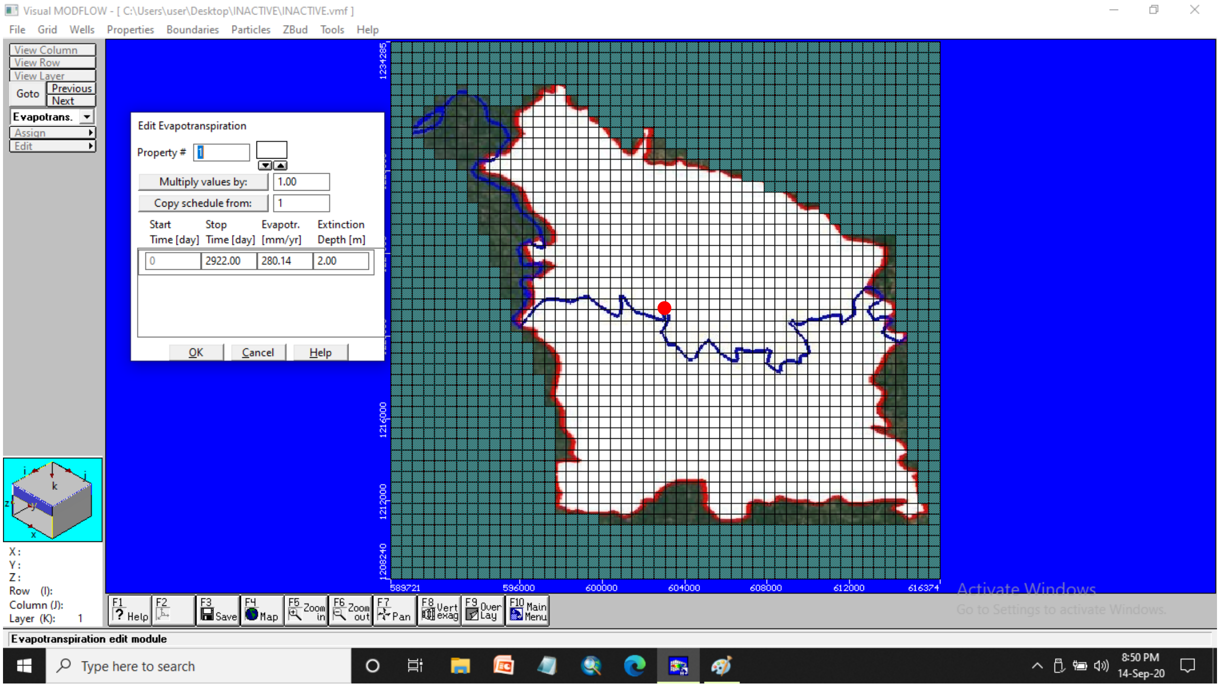
Multiply values by: 1.00

Copy schedule from: 1

Start Time [day]	Stop Time [day]	Evapotr. [mm/yr]	Extinction Depth [m]
0	2922.00	280.14	2.00

Evapotranspiration edit module

Fig. 17. Assigning recharge



Edit Evapotranspiration

Property # 1

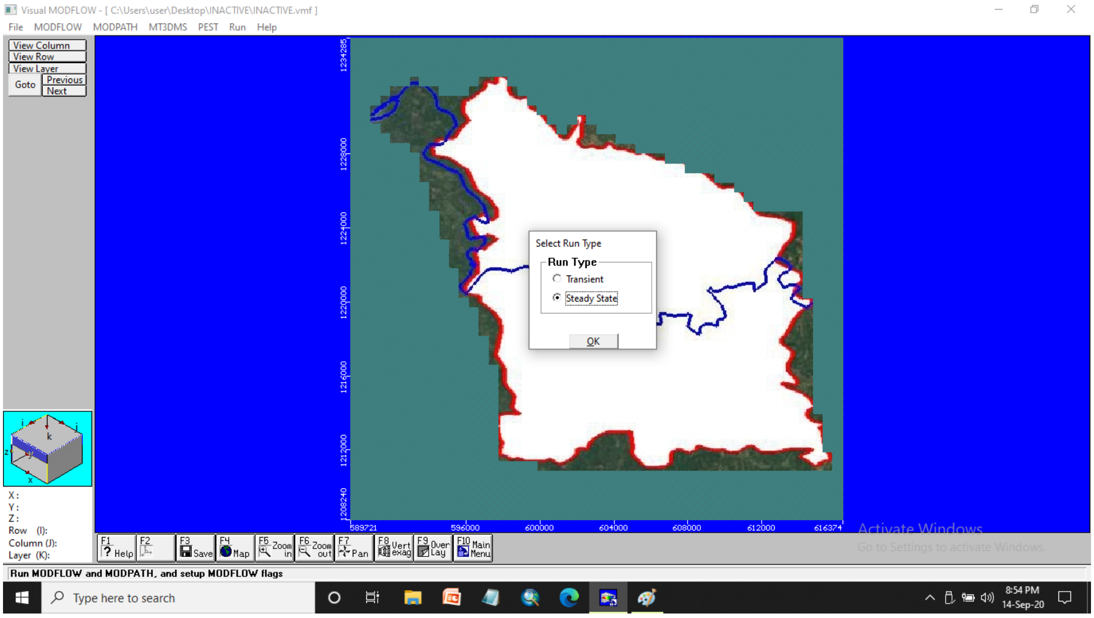
Multiply values by: 1.00

Copy schedule from: 1

Start Time [day]	Stop Time [day]	Evapotr. [mm/yr]	Extinction Depth [m]
0	2922.00	280.14	2.00

Evapotranspiration edit module

Fig. 18. Assigning evapotranspiration


Visual MODFLOW - [C:\Users\user\Desktop\INACTIVE\INACTIVE.vmf]

Select Run Type

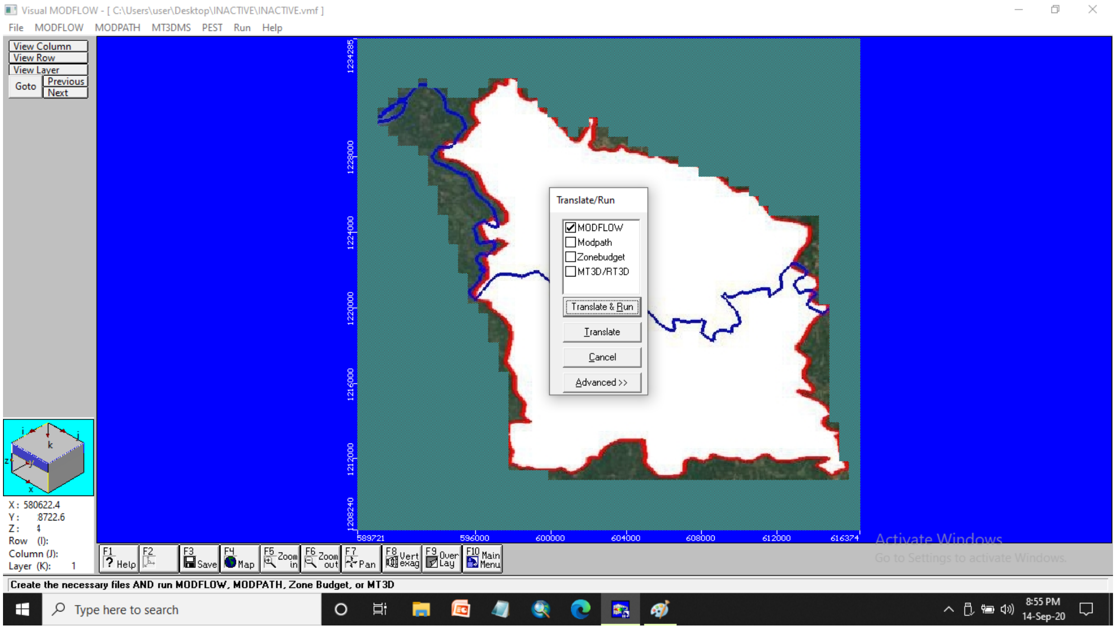
Run Type

○ Transient

● Steady State

OK

Run MODFLOW and MODPATH, and setup MODFLOW flags


Visual MODFLOW - [C:\Users\user\Desktop\INACTIVE\INACTIVE.vmf]

Translate/Run

☑ MODFLOW

☐ Modpath

☐ Zonebudget

☐ MT3D/RT3D

Translate & Run

Translate

Cancel

Advanced >>

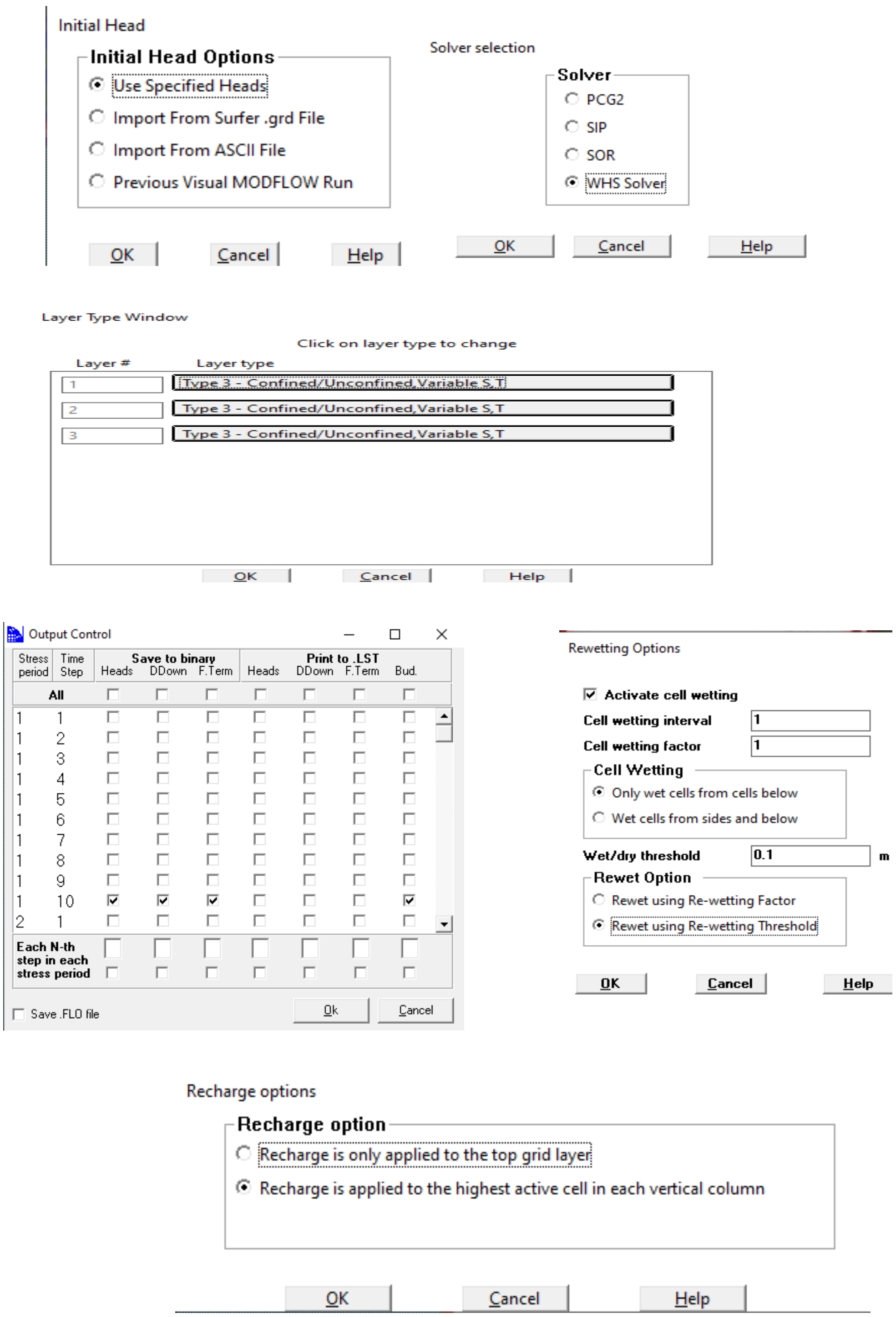
X : 580622.4

Y : 8722.6

Layer (K): 1

Create the necessary files AND run MODFLOW, MODPATH, Zone Budget, or MT3D

Fig. 19. Model Run



Initial Head

Initial Head Options

● Use Specified Heads

○ Import From Surfer .grd File

○ Import From ASCII File

○ Previous Visual MODFLOW Run

Solver selection

Solver

○ PCG2

○ SIP

○ SOR

● WHS Solver

Layer Type Window

Click on layer type to change

Layer #	Layer type
1	Type 3 - Confined/Unconfined,Variable S,T
2	Type 3 - Confined/Unconfined,Variable S,T
3	Type 3 - Confined/Unconfined,Variable S,T

Output Control

Stress period	Time Step	Save to binary Heads	Save to binary DDown	Save to binary F.Term	Print to .LST Heads	Print to .LST DDown	Print to .LST F.Term	Print to .LST Bud.
All		☐	☐	☐	☐	☐	☐	☐
1	1	☐	☐	☐	☐	☐	☐	☐
1	2	☐	☐	☐	☐	☐	☐	☐
1	3	☐	☐	☐	☐	☐	☐	☐
1	4	☐	☐	☐	☐	☐	☐	☐
1	5	☐	☐	☐	☐	☐	☐	☐
1	6	☐	☐	☐	☐	☐	☐	☐
1	7	☐	☐	☐	☐	☐	☐	☐
1	8	☐	☐	☐	☐	☐	☐	☐
1	9	☐	☐	☐	☐	☐	☐	☐
1	10	☑	☑	☑	☐	☐	☐	☑
2	1	☐	☐	☐	☐	☐	☐	☐
Each N-th step in each stress period		☐	☐	☐	☐	☐	☐	☐

☐ Save .FLO file

Rewetting Options

☑ **Activate cell wetting**

Cell wetting interval 1

Cell wetting factor 1

Cell Wetting

● Only wet cells from cells below

○ Wet cells from sides and below

Wet/dry threshold 0.1 **m**

Rewet Option

○ Rewet using Re-wetting Factor

● Rewet using Re-wetting Threshold

Recharge options

Recharge option

○ Recharge is only applied to the top grid layer

● Recharge is applied to the highest active cell in each vertical column

Fig. 20. Run parameters in MODFLOW

Results and Discussions

CHAPTER 4

RESULTS AND DISCUSSIONS

Results obtained from the interpretation of Vertical Electrical Sounding (VES) data, analysis of ground water level data and ground water flow modeling of the study area using Visual MODFLOW are discussed in this chapter. Effect of Bakkikayam Regulator on ground water level is analyzed based on the results obtained from the geophysical survey and the ground water flow modeling.

4.1 AQUIFER CHARACTERISTICS OF THE AREA USING EARTH RESISTIVITY STUDIES

4.1.1 Interpretation of VES Data

Collected field data from VES survey were interpreted using IPI2WIN software to obtain the resistivity values of different subsurface layers and thickness of each layer are given in Table 2. From sounding curve interpretation, 2 to 4 subsurface layers where identified within the study area and resulting sounding curves were H, K, A, HK, QH, KH and AK. The presence of three layer substrata were represented by H, K, A and Q sounding curves, while the combination curves such as HK, QH, KH and AK curves represents four layer sub strata. Among the 18 VES survey, two locations showed two layer substrata, seven locations showed three layer substrata and nine locations showed having four layer sub strata.

Surface resistivity map of the study area was prepared using the first layer resistivity data collected from the interpretation of VES data. The map was prepared in the Arc GIS (10.4) software and shown in Fig. 21. From the figure, it could be seen that the major portion of the study area is having the resistivity ranging from 100 to 1000 ohm-m. This indicates that the major portion of the study area is covered with lateritic formation and hypodermic soil which is in agreement with the conclusion of Sajeena and Kurien (2015). Some pockets like Peruvallur and Kannamangalam indicated high resistivity ranging from 2000 to 4000 ohm-m.

The map of depth to bed rock was prepared using Arc GIS (10.4) and shown in the Fig. 22. From the map it could be revealed that major portion of study area have same depth range of 12 to 22m to the bed rock. Some locations viz. Vengara, Nammabra, Tirurangadi and Thennala found to have shallow bed rock of 2-12 m. A small portion of Peruvallur has deep bed rock with 43- 63 m.

4.1.1.1 *H type curve*

Soundings from Kannamangalam (VES 7) and Thirurangadi (VES 15) showed ‘H’ type curve with three layer model ($\rho_1 > \rho_2 < \rho_3$) as shown in Fig. 23. This type of curve represents a high resistivity first layer such as dry top soil and second layer of low resistivity i.e. saturated weathered layer followed by last layer of very high resistivity hard rock. Results of the field study showed that the resistivity of top layer ranged from 140 to 3762 ohm-m with thickness ranging from 1.7 m to 5.8 m. This in turn indicates the presence of lateritic formation. The second layer has resistivity ranging from 56.5 to 60.8 ohm-m, indicated the presence of clay or clayey laterite zone of thickness 8.34 m to 9.75 m. The third layer has resistivity ranged from 1834 to 10073 ohm-m indicated the presence of hard laterite and hard rock and this result is in agreement with the lithology data obtained from the Department of Groundwater, Govt. of Kerala.

4.1.1.2 *K type curve*

Soundings from Thenhipalam (VES 3) and Kottakkal (VES 11, VES 18) revealed three layered model ($\rho 1 < \rho 2 > \rho 3$) with ‘K’ type curve as shown in Fig. 24. The resistivity of first layer ranged from 303 to 897 ohm-m with a thickness of 2 to 2.4 m. This pinpoints presence of lateritic/hydomorphic topsoil. The second layer has resistivity range 1693 to 1744 ohm-m which indicate the presence of hard laterite/ gnesis with thickness range of 3.53 m to 3.95 m. Third layer is a low resistivity substrata (45.8-239 ohm-m) such as weathered rock. These results were in agreement with the result reported by Sajeena and Kurien (2015).

4.1.1.3 *A type curve*

Soundings of Vengara (VES 1) and Kuruvapadam (VES 16) were morphologically defined by three layer model with the resistivity sequence of $\rho 1<\rho 2<\rho 3$ as shown in Fig. 25. This type of curve implies the soil having a low resistivity top layer and a high resistivity third layer showing a steady increase in the resistivity with increase in the depth. The first layer has a resistivity range of 123 – 230 ohm-m of thickness 1 to 2.5 m. this result indicated that this area is suitable for open wells and is correlated with the lithology of Department of Groundwater, Govt. of Kerala.

4.1.1.4 *Q type curve*

Soundings from Vengara (VES 2) and A. R. Nagar (VES 6) could be explained by the three layer model with steady decrease in the soil resistivity ($\rho 1>\rho 2>\rho 3$) which indicates the top soil is a high resistivity soil and the substrata followed a low resistivity pattern as shown in the Fig. 26. In the present study, at Vengara (VES 2) Q type of curve is obtained as it is near to the river. The first layer is having the resistivity 109 ohm-m followed by a layer of resistivity 46.7 ohm-m. This indicated that the top soil is riverine alluvium underlying by clay layer. Whereas at A.R. Nagar (VES 6), the top layer having resistivity 1154 ohm-m, and decreasing towards the bedrock. This indicated the presence of hard laterite layer at the top and its hardness decreases towards the bottom.

4.1.1.5 *KH type curve*

Soundings from Munniyur (VES 5), Oorakam (VES 8), Perumannaklari (VES 13) revealed four layer model with a resistivity sequence of $\rho 1<\rho 2>\rho 3<\rho 4$ (KH type curve) as shown in Fig. 27. The third layer with low resistivity of 43 to 252 ohm-m and thickness of 2.06 to 7.26 m, indicated the presence of weathered zone. This area is more suitable for open wells.

Table 2. 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	Vengara	204	750		-	2.05		-	2.05
2	Vengara	109	46.7		-	2.4		-	2.4
3	Thenjipalam	714	1503	220	-	1	4.49	-	5.49
4	Peruvallur	2314	1243	4.43	229	1.35	5.85	54.7	61.9
5	Moonniyur	270	1396	43.6	4556	1.79	4.38	7.28	13.5
6	A R Nagar	1154	700	115	-	7.05	4.72		11.8
7	Kannamangalam	3762	60.8	1834	-	5.8	8.34	-	14.1
8	Oorakam	1017	3463	261	153484	2.62	2.33	2.68	7.64
9	Parappur	1857	175	3161	76.3	1	0.543	2.11	3.65
10	Othukkungal	511	3049	3.4	-	1.33	3.61		4.93
11	Kottakkal	303	1693	45.8	-	2	3.53	-	5.53
12	Edarikode	530	113	1767	4.94	1.16	1.39	5.43	6.71
13	Perumannaklari	648	7273	383	6274	1	1.15	2.06	6.76
14	Ozhur	195	382	3188	17.5	1.02	2.68	3.17	6.87
15	Tirurangadi	140	56.5	10073	-	1.7	9.75	-	11.4
16	Kuruvapadam Vengara	123	382	73148	-	1	13.5	-	14.5
17	Kuruvikundu Othukkungal	1943	1161	4062	726	0.75	4.79	3.89	9.43
18	Kottakkal	897	1744	239	-	2.47	3.95	-	6.42

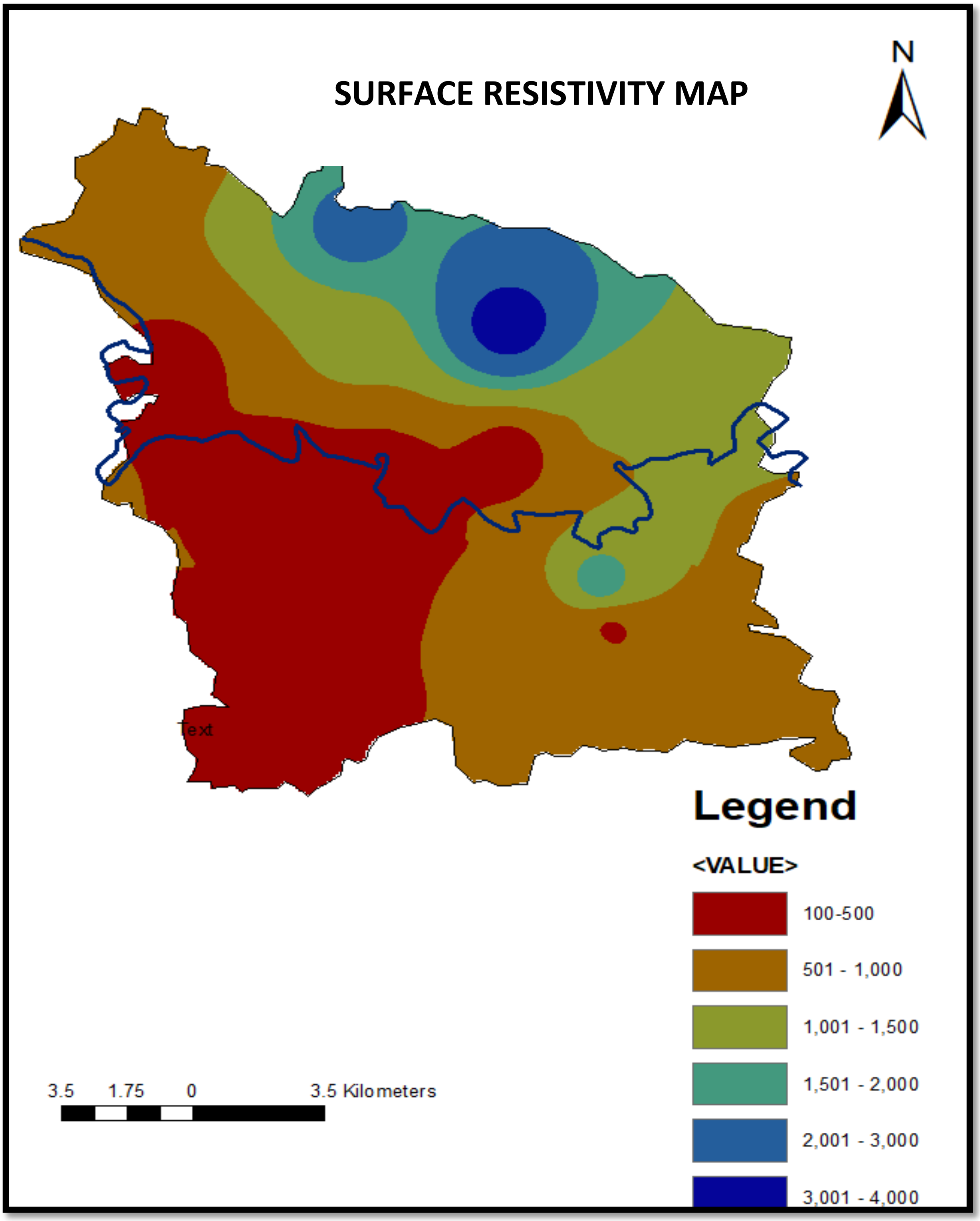


Fig.21. Surface resistivity map of the study area

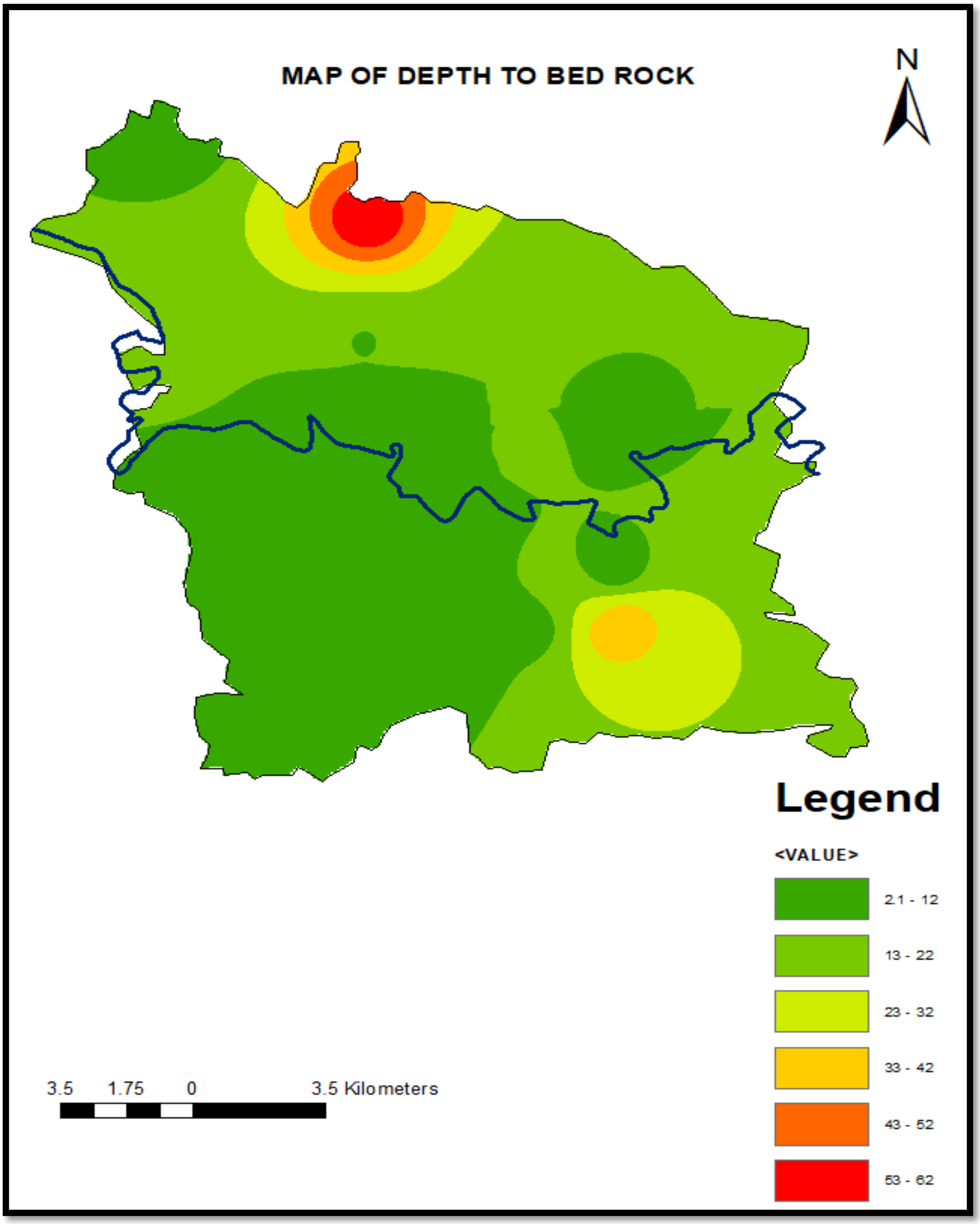


Fig.22. Map of depth to the bed rock

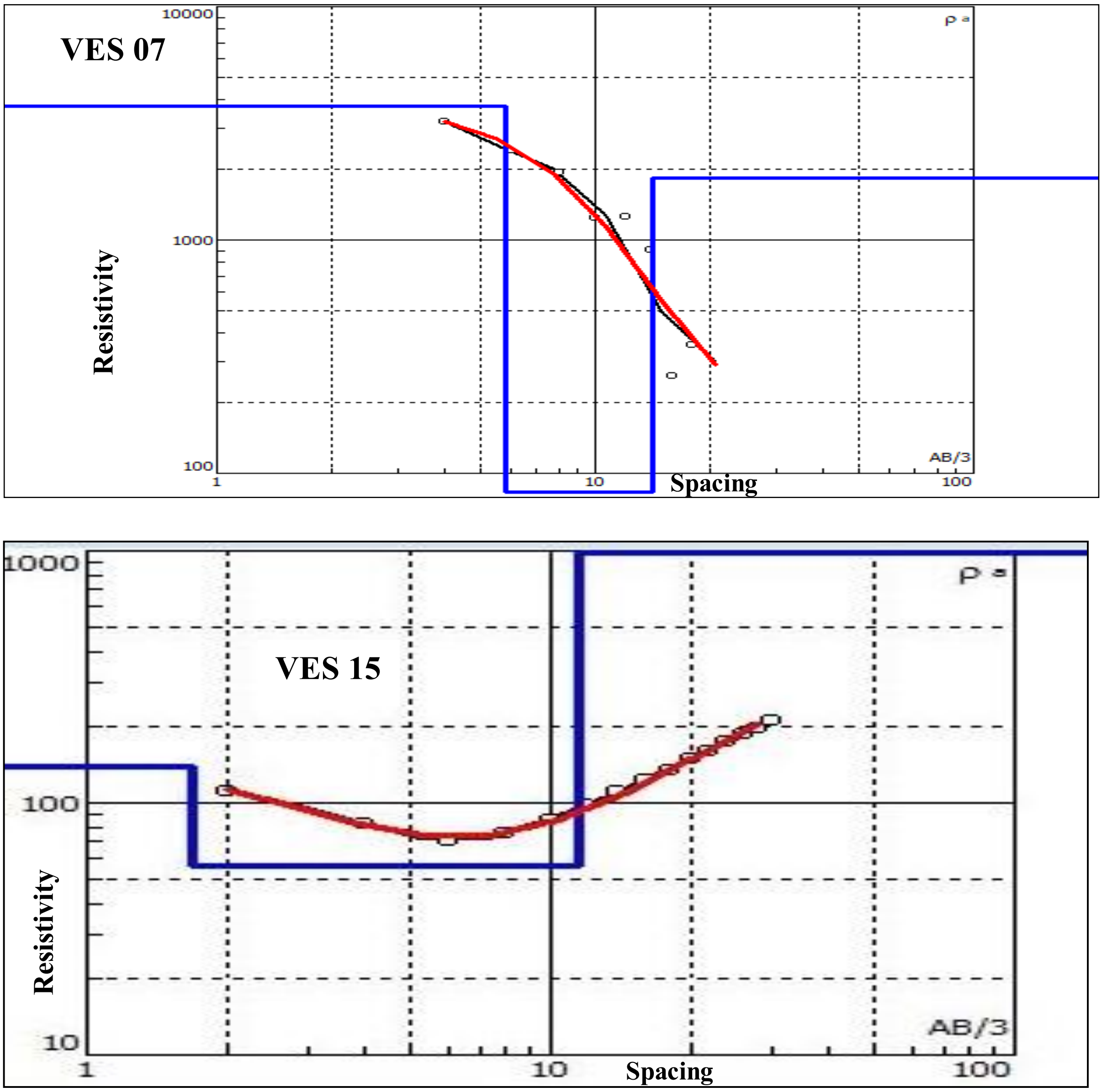


Fig.23. Resistivity sounding curves (H type)

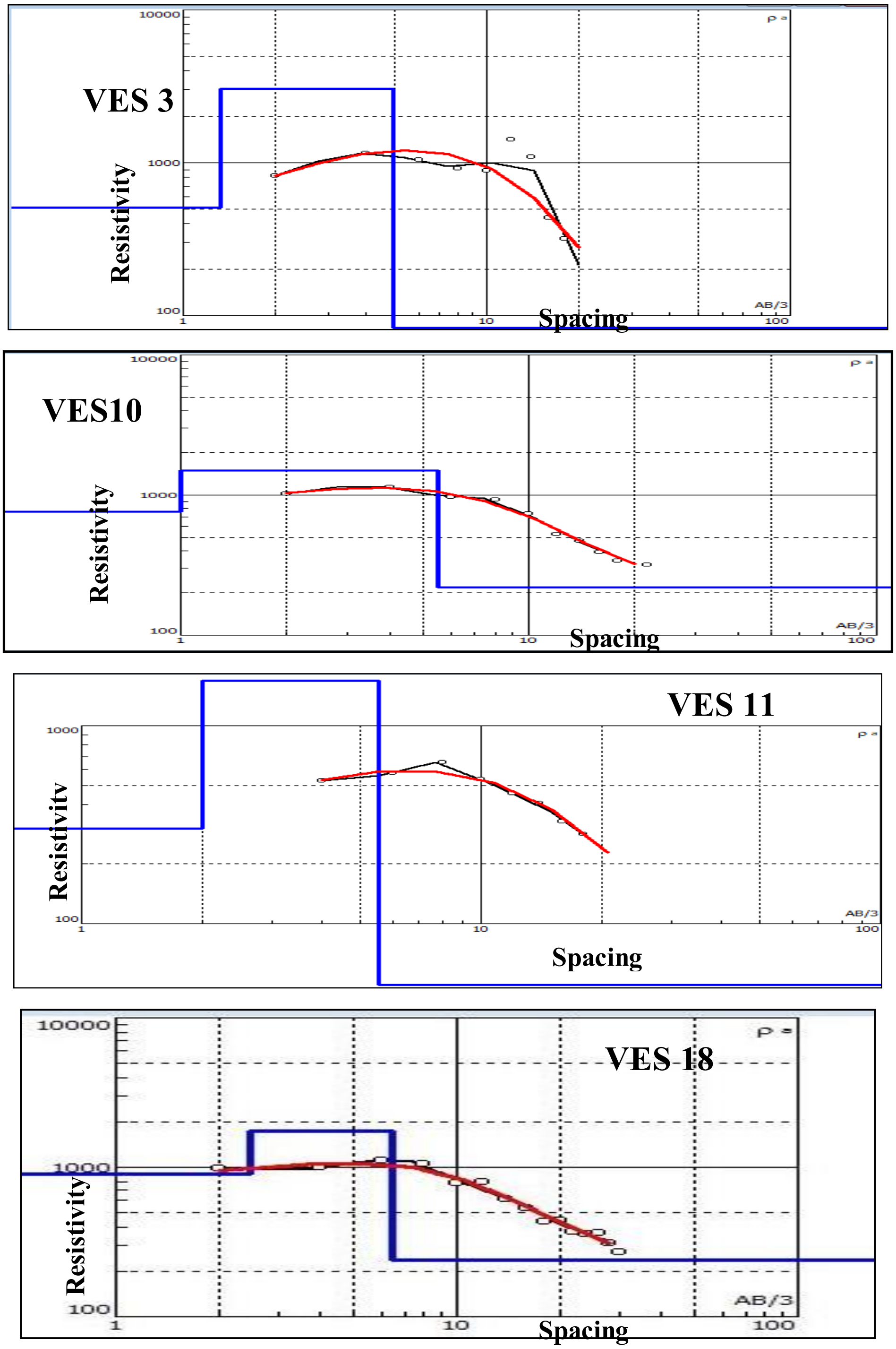


Fig. 24. Resistivity sounding curves (K type)

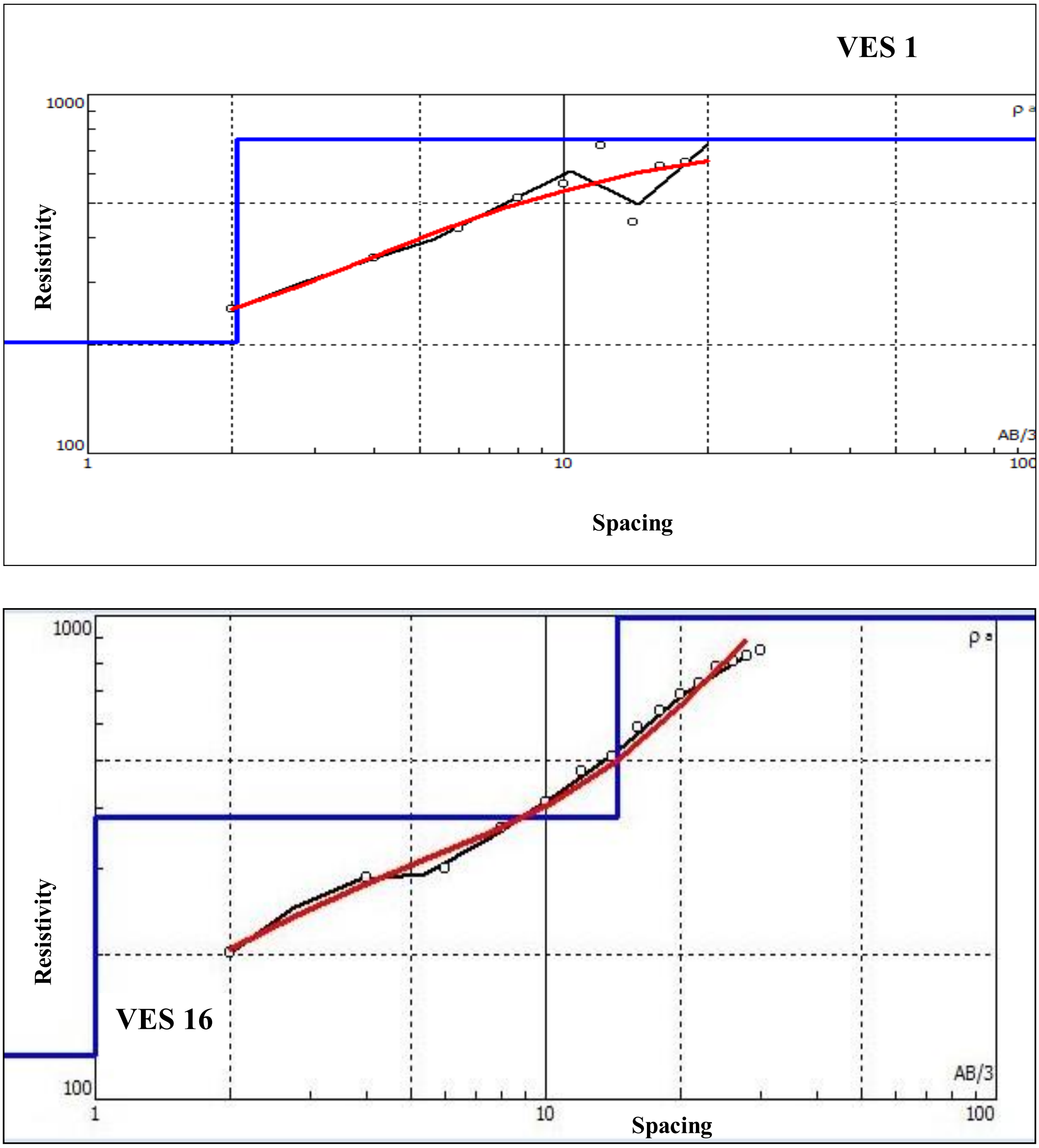


Fig. 25. Resistivity sounding curves (A type)

4.1.1.6 *HK type curve*

Soundings obtained from Vengara (VES 1, VES 2), Kuruvikundu Othukkungal (VES 17) could be explained with a four layer model with a resistivity sequence of $\rho 1>\rho 2<\rho 3>\rho 4$, ‘HK’ type curve as shown in Fig. 28. This showed the probability of existence of a weathered rock as second layer which can act as better path for groundwater movement down to deep aquifers. The third layer shows a sudden raise in resistivity value with the indication of the absence or lack of fractured rock layers. Fourth layer is indicating slight reduction in the resistivity value due to the presence of interconnected fractures which can be used for moderate groundwater supply.

4.1.1.7 *QH type curve*

Soundings of Peruvallur (VES 4) showed QH type curve representing four layered model which can be morphologically explained by resistivity sequence $\rho 1>\rho 2>\rho 3<\rho 4$ as shown in Fig. 29. This type curve indicated the lateritic soil/ moderate laterite followed by weathered rock/clay with a thickness of 5.85 m. The fourth layer has high resistivity 229 ohm-m indicated the presence of confining layer.

4.1.1.8 *AK type curve*

Soundings of Ozhur (VES 14) showed a four layer model having a resistivity sequence of $\rho 1<\rho 2<\rho 3>\rho 4$ with ‘AK’ type curve as shown in Fig. 30. The first and second layers have a resistivity of 195 and 382 ohm-m respectively. The third layer exhibits a high resistivity of 3188 ohm-m with a thickness of 2.68 m. The fourth layer is a low resistivity layer (17.5 ohm-m).

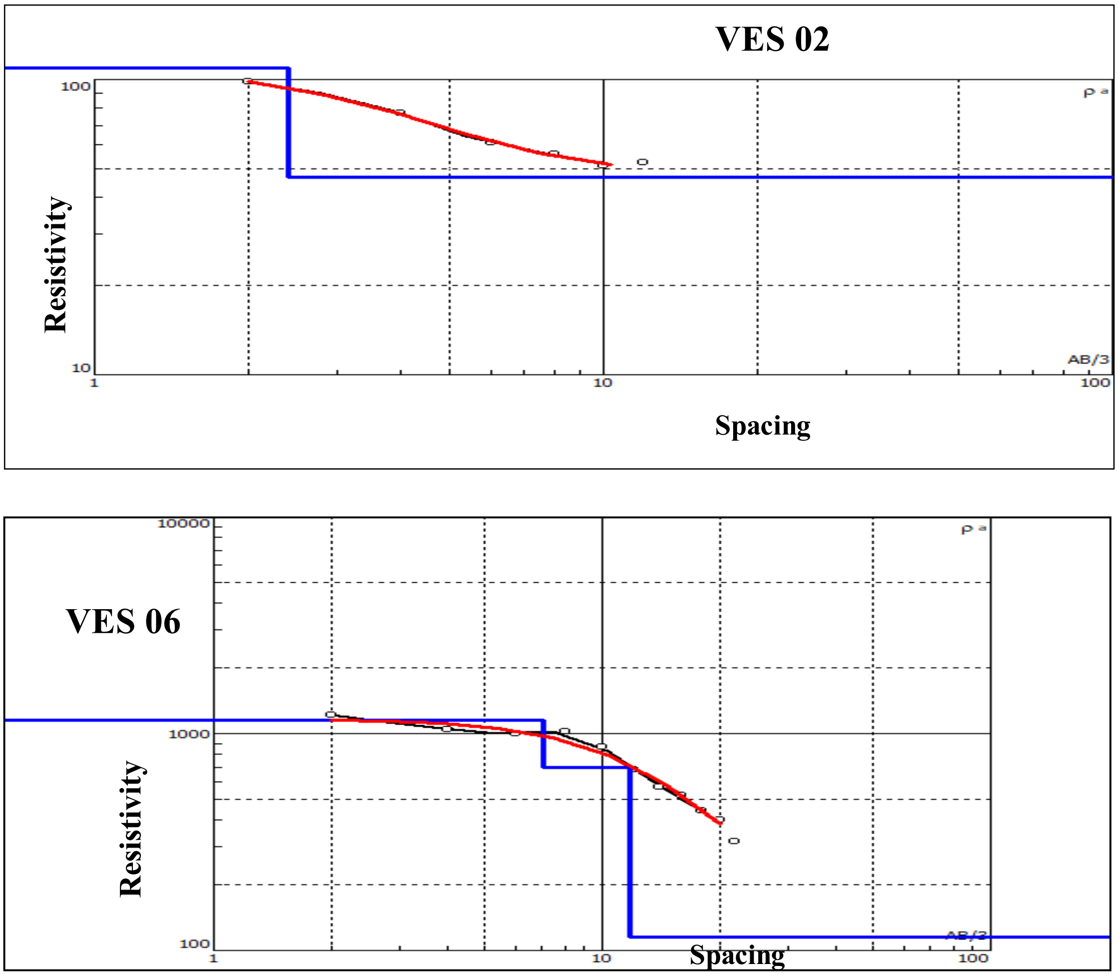


Fig. 26. Resistivity sounding curves (Q type)

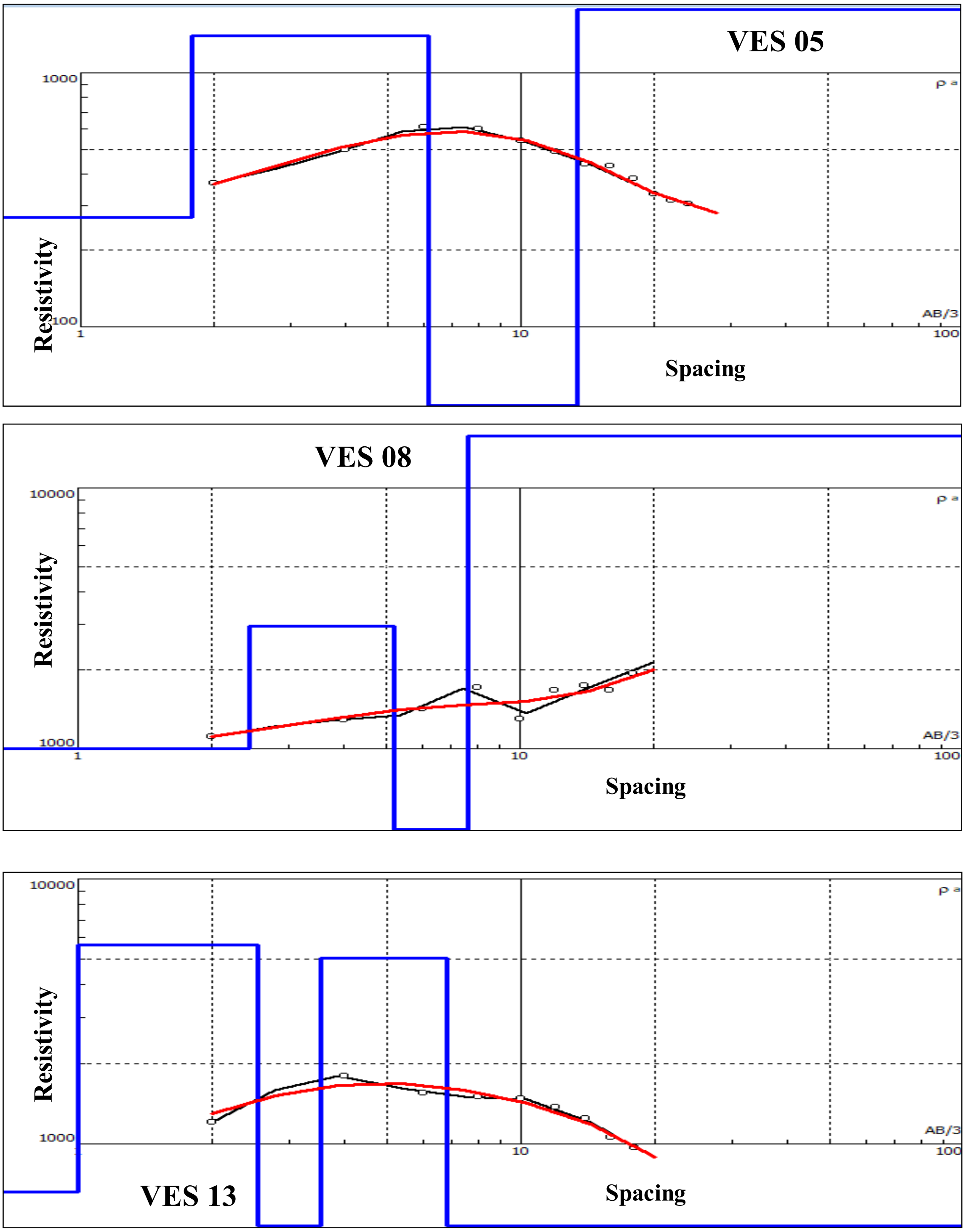


Fig.27. Resistivity sounding curves (KH type)

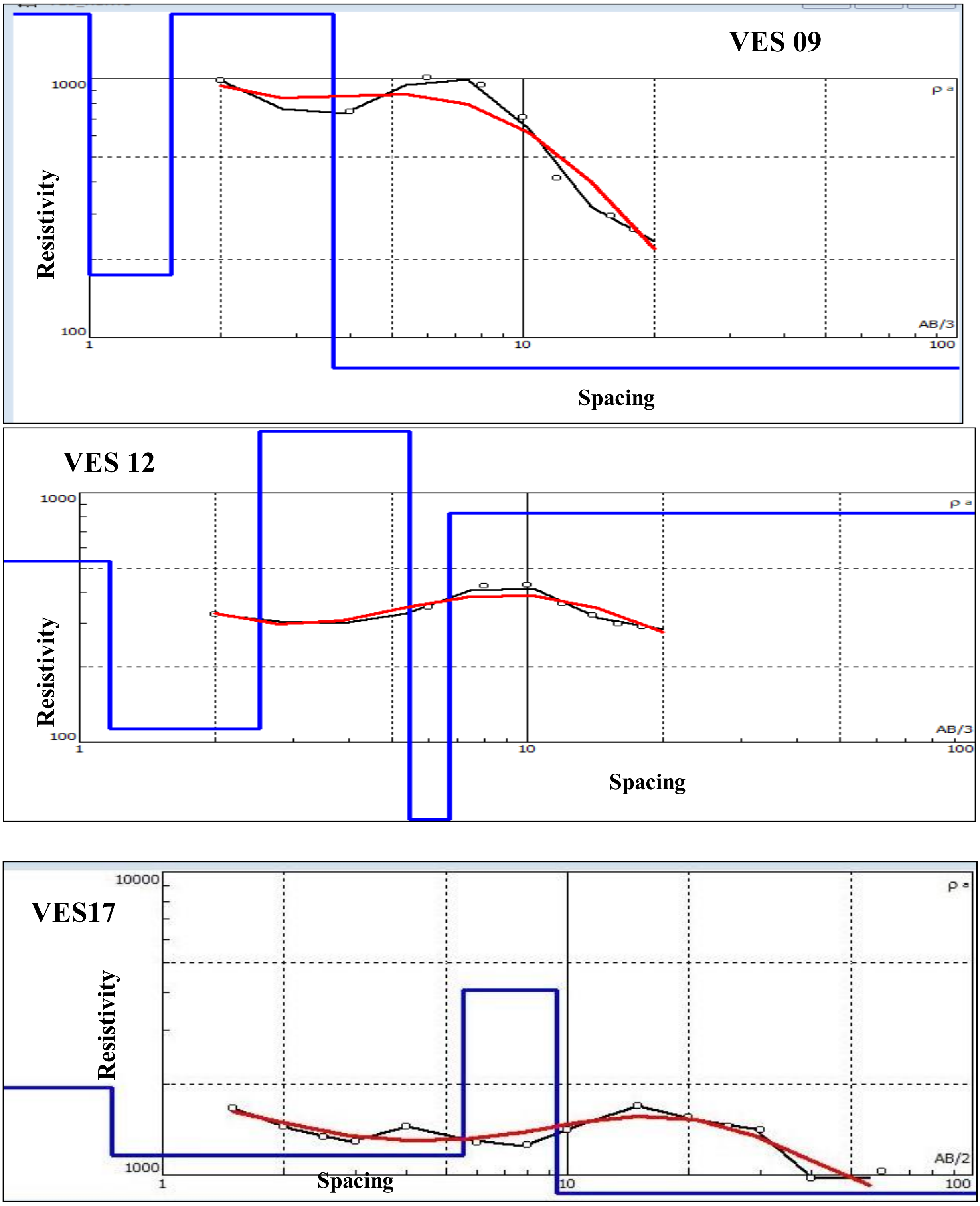


Fig. 28. Resistivity sounding curves (HK type)

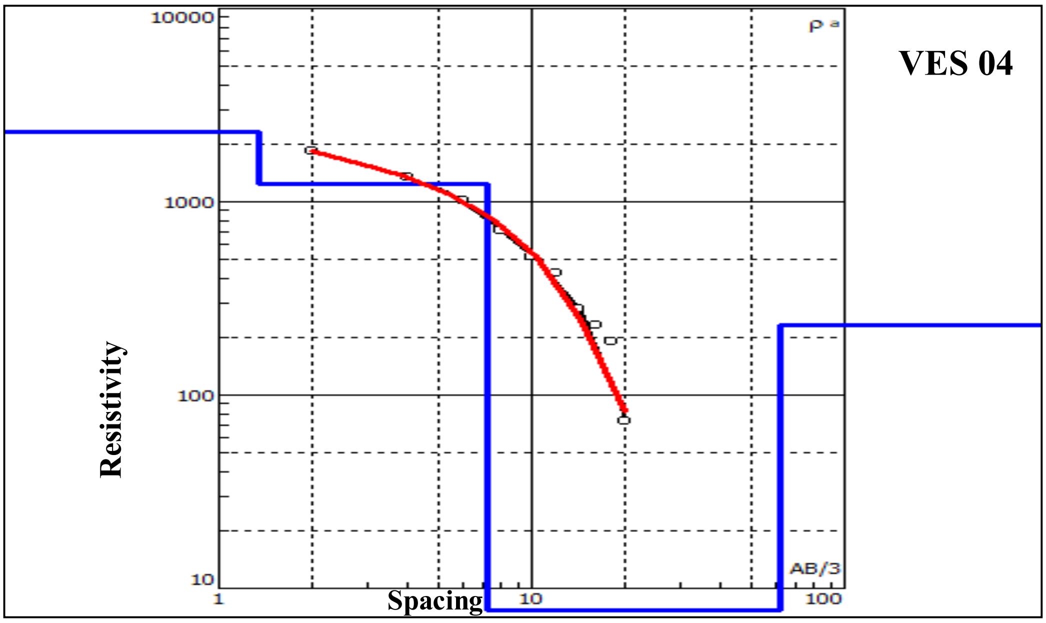


Fig. 29. Resistivity sounding curves (QH type)

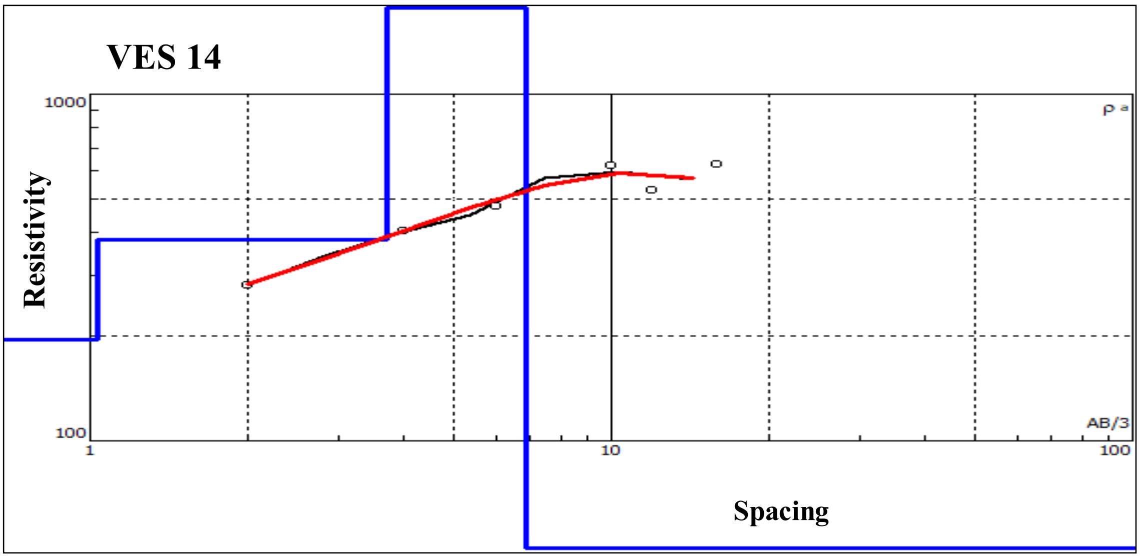


Fig. 30. Resistivity sounding curves (AK type)

4.1.2 Resistivity and Psuedo sections

The resistivity and pseudo cross section along AA' and BB' were prepared using true and apparent resistivity values. AA' represents the cross section along the VES locations viz A. R. Nagar and Ozhur while BB' represents cross section along the VES locations viz. Oorakam, Parappur and Kottakkal.

4.1.2.1 *Section AA'*

This section was plotted with the soundings VES 6 and VES 14 in North South direction as shown in Fig. 31. A high resistivity layer was observed in A.R. Nagar (VES 6) and the resistivity is decreasing towards Ozhur (VES 14). Similarly the resistivity decreases towards the bottom from 1679 - 178 ohm-m at A. R. Nagar and 1188 – 420 ohm-m at Ozhur. This indicated that hard laterite at top layers, and gradually decreasing the hardness of laterite.

4.1.2.2 *Section BB'*

This section was plotted with the soundings VES 8, VES 9 and VES 11 in North South direction as shown in Fig. 32. A medium resistivity layers ranging from 1103 – 529 ohm-m was observed throughout the cross section indicated the presence of laterite or hypodermic soil at a depth of 4.68 – 8.58 m. A patch of very low resistivity zone was observed at a depth of 11 m from Parappur (VES 9) to Kottakkal (VES 11) indicated the presence of either lithomargic clay or weathered rock.

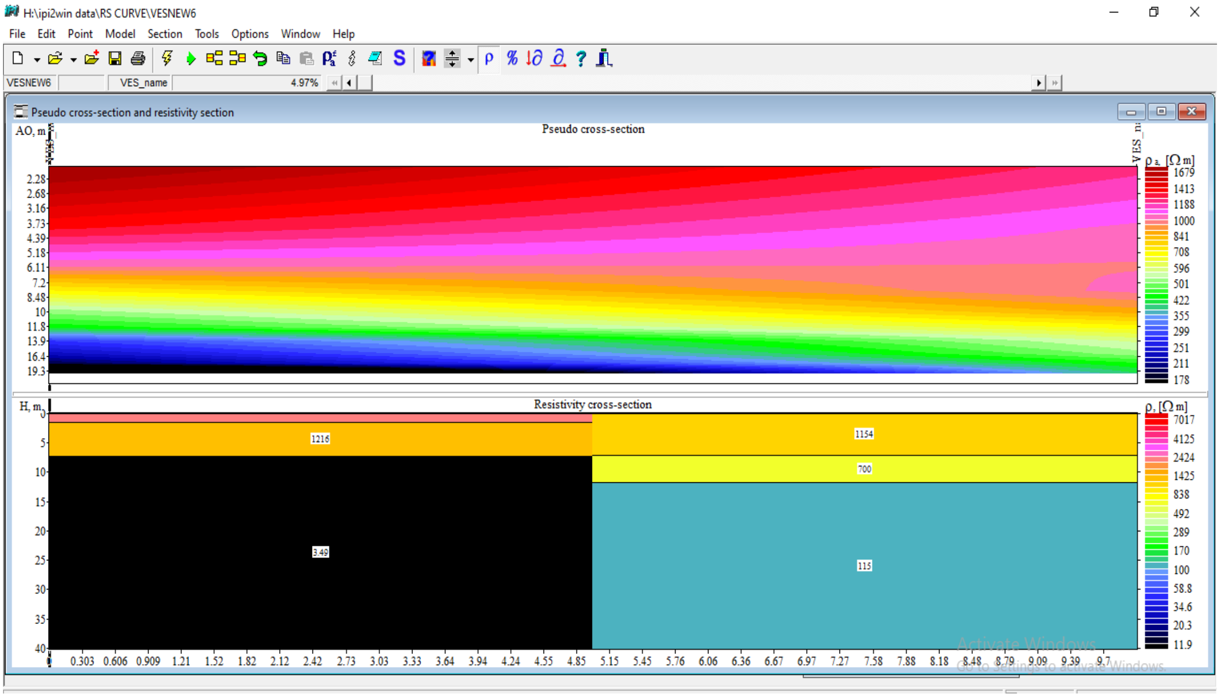


Fig. 31. Pseudo and Resistivity cross sections along section AA’

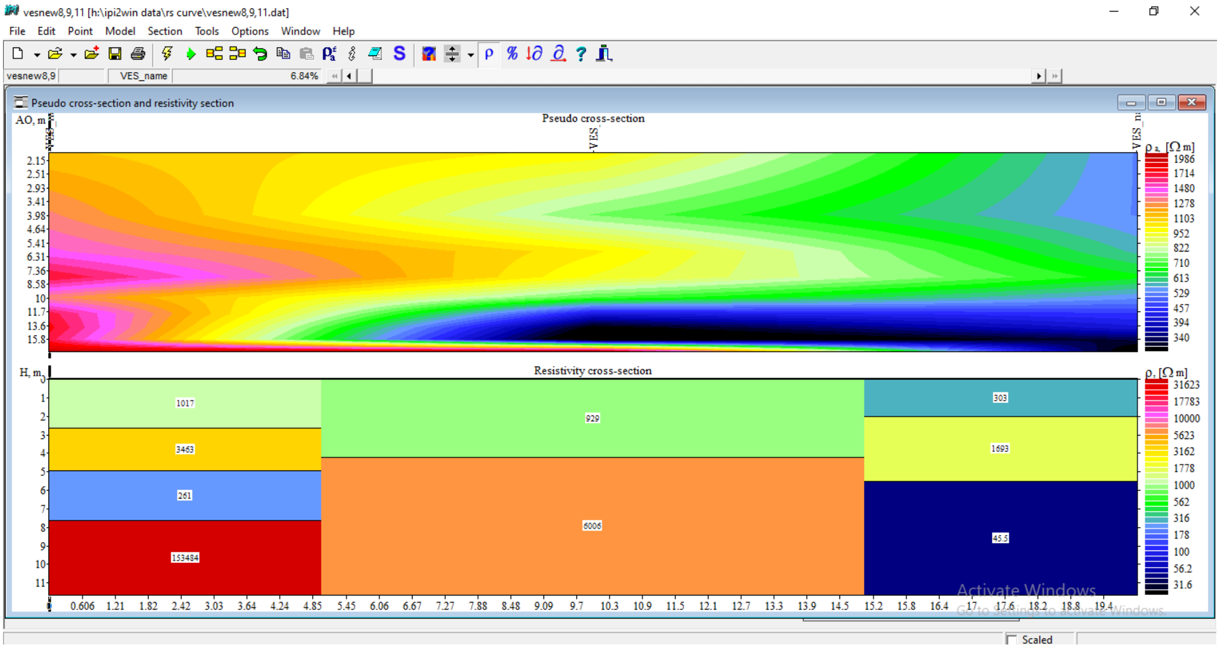


Fig. 32. Pseudo and Resistivity cross sections along section BB’

4.2 ASSESSMENT OF GROUND WATER FLOW VARIATIONS OF THE STUDY AREA

Ground water table fluctuations of study area were analyzed with the help of ground water level data collected from dug wells. In order to analyze the effect of Bakkikayam regulator on ground water table fluctuations, monthly water level data from 4 dug wells during the years 2017 and 2019 were used since the implementation and functioning of the regulator was on the year 2018. The location of the observation wells are shown in Fig. 33.

4.2.1 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 4 dug wells located upstream and downstream side of the Bakkikayam regulator were observed and the difference between pre and post monsoon water table (water table fluctuations) are given in Table 3. It was observed that the water table fluctuation in the well OW 6, located at downstream was ranged from 5.41 to 5.62 m.

Ground water table maps were prepared for both pre monsoon and post monsoon periods for 2016 and 2019 using Arc GIS (10.4) and are shown in Fig. 34 & 35 respectively.

Table 3. Pre and post monsoon variations of water level in dug wells

Well Name	**Pre monsoon water table**					**Post monsoon water table**					**Fluctuations,m**
	2016	**2017**	**2018**	**2019**	**average**	**2016**	**2017**	**2018**	**2019**	**average**	
OW 6	9.06	11.58	16.99	17.2	13.71	9.28	7.69	8.9	9	8.72	4.99
OW 7	10.09	10.34	10.4	10.34	10.29	8.58	6.39	8.82	8.31	8.03	2.26
OW 19	13.10	13.3	13.51	15.32	13.81	10.47	8.93	10.42	10.09	9.98	3.83
OW 23	12.69	12.61	15.68	15.32	14.08	12.21	9.73	11.67	12.45	11.52	2.56

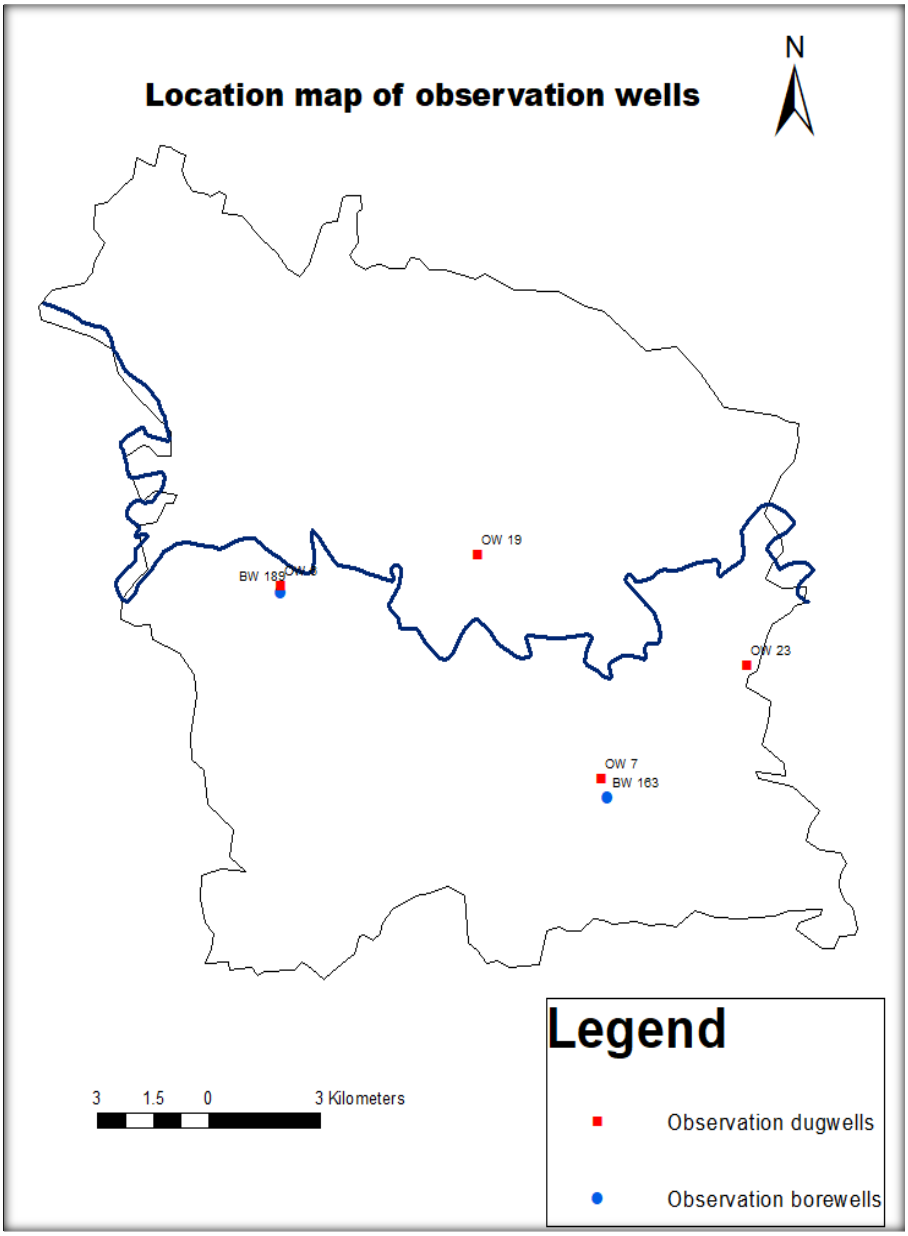


Fig. 33. Location map of observation wells

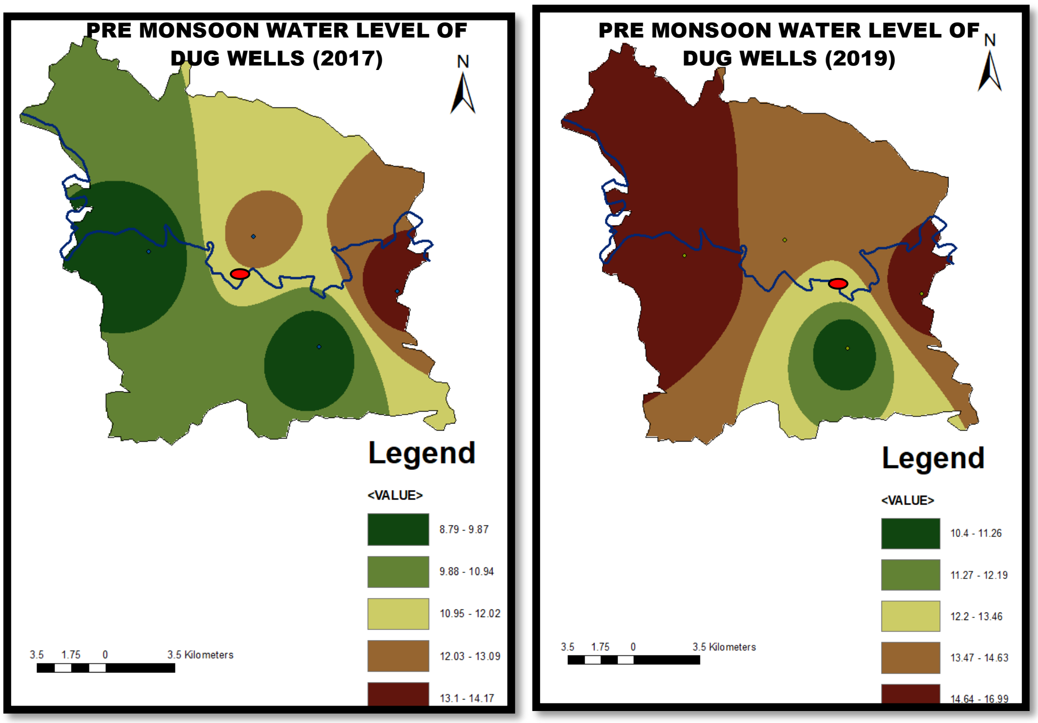


Fig. 34. Pre monsoon water level map of dug wells during 2017 and 2019

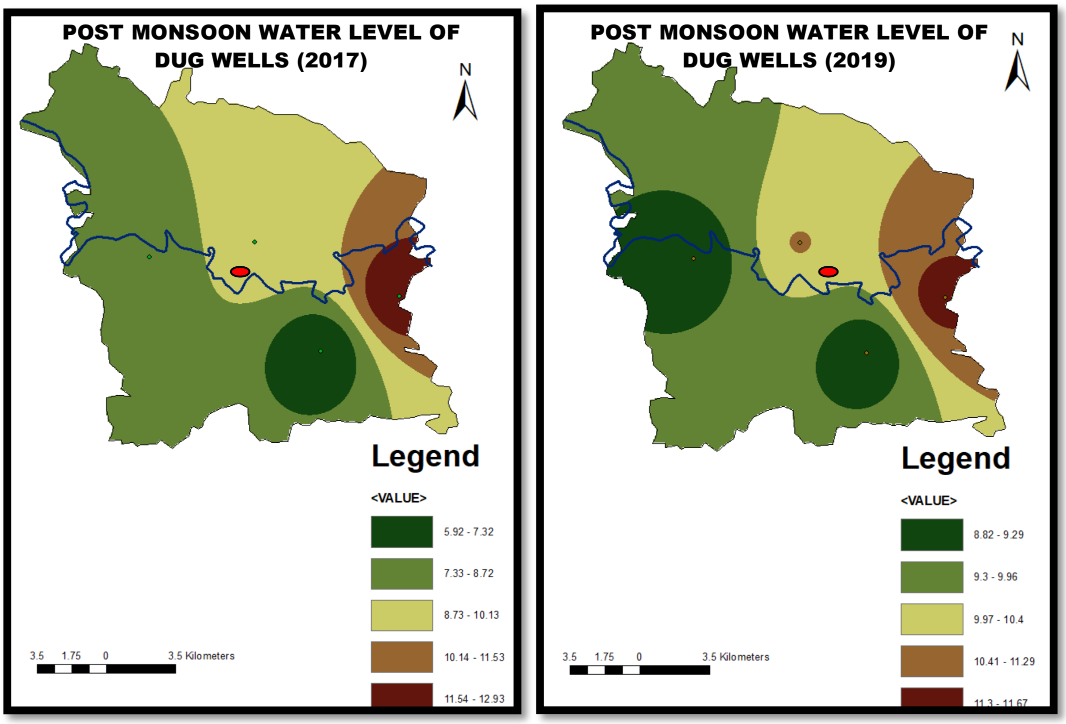


Fig. 35. Post monsoon water level map of dug wells during 2017 and 2019

4.3 GROUND WATER RESOURCE MAPPING USING VISUAL MODFLOW

Visual MODFLOW is the most popular ground water model used all over the world for the study of ground water. In this study, Visual MODFLOW model is used for the groundwater modeling of the study area.

4.3.1 Visual MODFLOW output

Outputs of Visual MODFLOW are contours of head equipotential, drawdown, elevation and water table. The model also provides graphs of calculated Vs observed heads, head Vs time, drawdown Vs time and normalized RMS Vs time. The model provides velocity vectors with magnitude and direction of flow.

4.3.1.1 *Steady state calibration*

For the present study model was calibrated for steady state condition with the aquifer condition of 2005 as the initial condition of the study area. The steady state model calibration was done by minimizing the difference between the computed and the observed water level for each observation well. The hydraulic conductivity values of the aquifers varied iteratively so that root mean square (RMS) error could be kept less than 10 m. The scatter plot of computed Vs observed head for 6 selected observation wells are shown in Fig. 36. From the figure it could be seen that there was a very good match between the calculated and observed water levels in most of the wells.

4.3.1.2 *Transient state calibration*

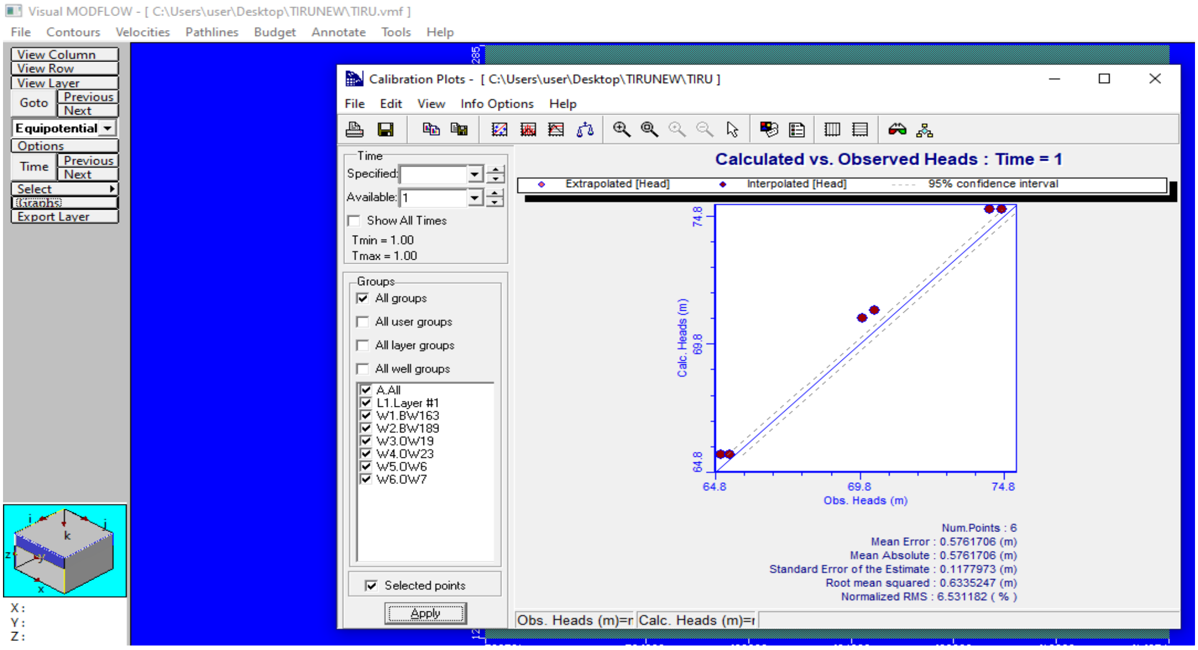
The hydraulic conductivity, specific storage and specific yield values of three layers as well as the water levels, boundary conditions, initial head values, recharge and evaporation data were used for transient state calibration. The transient state calibration was done for the period from year 2005 to 2012 (2992 days). The hydraulic conductivity and storage values were varied iteratively to obtain a reasonably good match between observed and calculated values. The values of conductivity and storage after the calibration are given in the Table 4.

The graph of calculated head Vs observed head for the 31 day is shown in Fig. 37. From the scatter plot for computed Vs observed head for the observation wells, it can be seen that there is good match between the calculated and observed heads in most of the wells in steady state as well as transient state calibration at 95% confidence level.

Table 4. Hydraulic properties of the layer after calibration

Sl.No.	Model Properties	Layer I Laterite	Layer II Clay	Layer III Weathered rock
1	Hydraulic conductivity in longitudinal direction K_x,md^{-1}	55	0.0002	30
2	Hydraulic conductivity in lateral direction K_y,md^{-1}	55	0.0002	30
3	Hydraulic conductivity in vertical direction K_z,md^{-1}	3.5	0.00002	1.5
4	Specific storage , Ss (m^{-1})	0.00035	0.00078	0.0005
5	Specific Yield, Sy	0.20	0.06	0.068
6	Effective Porosity	0.4	0.5	0.3
7	Total Porosity	0.40	0.5	0.35

The ground water contour map after the calibration is shown in the Fig. 38. From the figure it could be concluded that the water table elevation at coastal region was very low ranging from 10 to 16 m. while major portion of the study area is having the same elevation ranging from 10 m (Dark blue) to 22 m (bluish green). Some pockets of Oorakam and Kottakkal found to have high water table ranging from 43 to 50 m and this may due to the high elevation of that area. Water table elevation of some part of Parappur, Kannamanagalam and Edarikkode were ranged from 25 to 32 m. This result correlates with the results obtained from the VES studies conducted in the study area.



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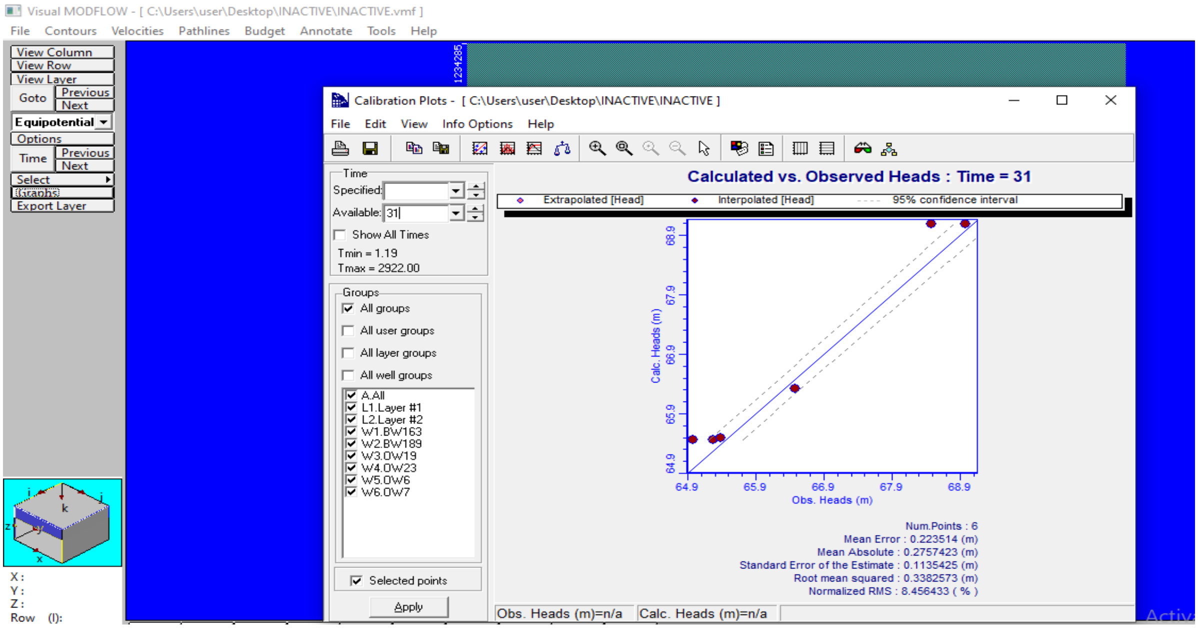
☑ W1.BW163
☑ W2.BW189
☑ W3.OW19
☑ W4.OW23
☑ W5.OW6
☑ W6.OW7
☑ Selected points

```
                               Num.Points : 6
                       Mean Error : 0.5761706 (m)
                    Mean Absolute : 0.5761706 (m)
    Standard Error of the Estimate : 0.1177973 (m)
              Root mean squared : 0.6335247 (m)
               Normalized RMS : 6.531182 ( % )
```

Obs. Heads (m)=r Calc. Heads (m)=r

Fig. 36. Model computed Vs observed water level of the year 2005 (steady state)



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☑ W6.OW7
☑ Selected points

```
                               Num.Points : 6
                        Mean Error : 0.223514 (m)
                    Mean Absolute : 0.2757423 (m)
    Standard Error of the Estimate : 0.1135425 (m)
              Root mean squared : 0.3382573 (m)
               Normalized RMS : 8.456433 ( % )
```

Obs. Heads (m)=n/a Calc. Heads (m)=n/a

Fig. 37. Model computed Vs observed water level at 31 days (Transient state)

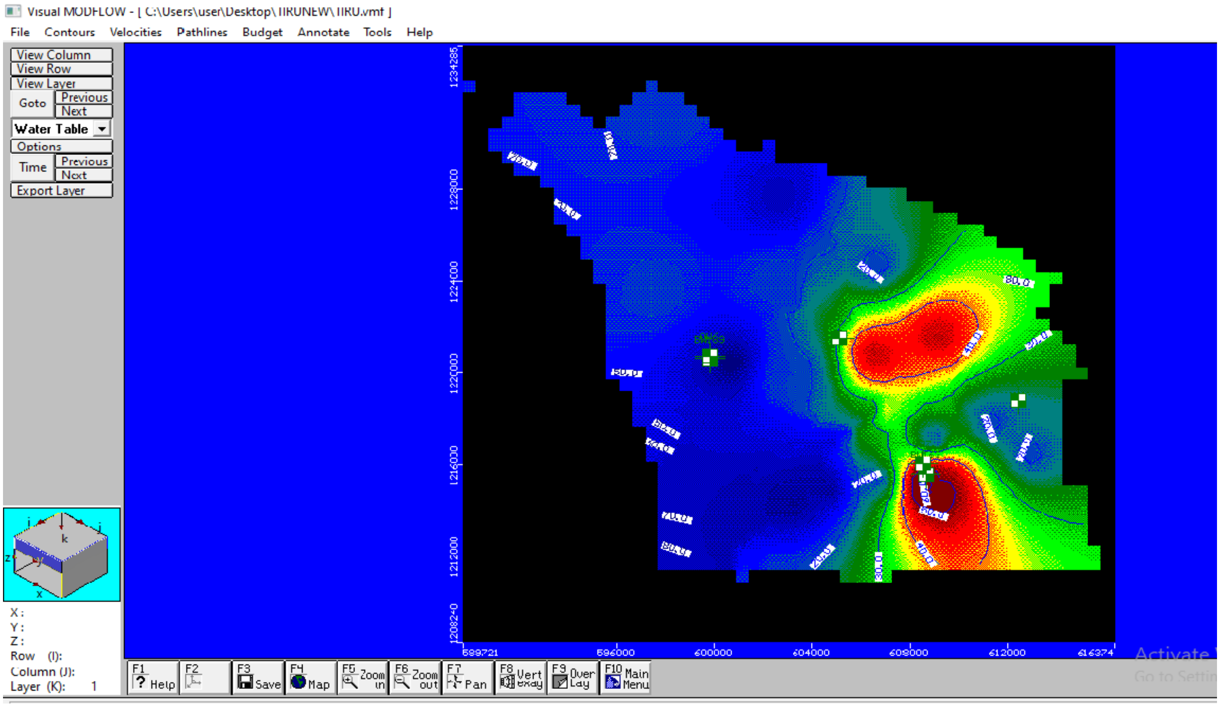
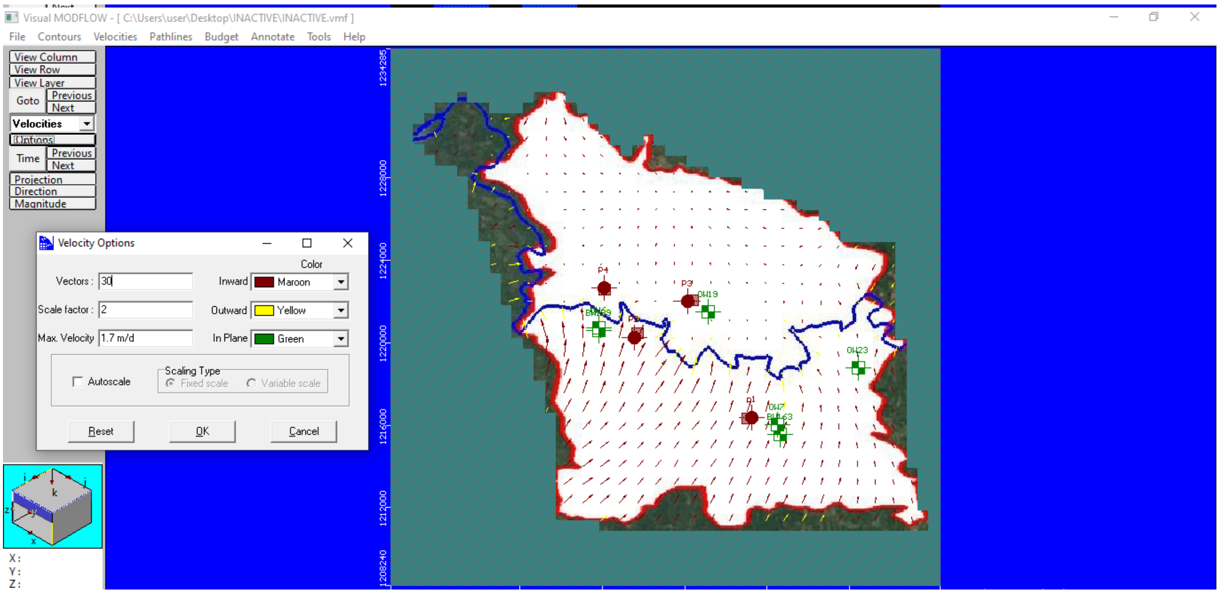


Fig. 38. Computed water table contour map after calibration

The Fig. 39 and 40 show the velocity vector of ground water flow in the study area. From the map, it could be seen that ground water flow is towards the river which is north east to south west direction. This proves that the input parameters of the model are correct and can be used for validation and prediction.



Vectors : 30

Scale factor : 2

Max. Velocity 1.7 m/d

Inward: Maroon

Outward: Yellow

In Plane: Green

☐ Autoscale

Scaling Type: ● Fixed scale ○ Variable scale

Fig. 39. Velocity vector magnitude of the study area

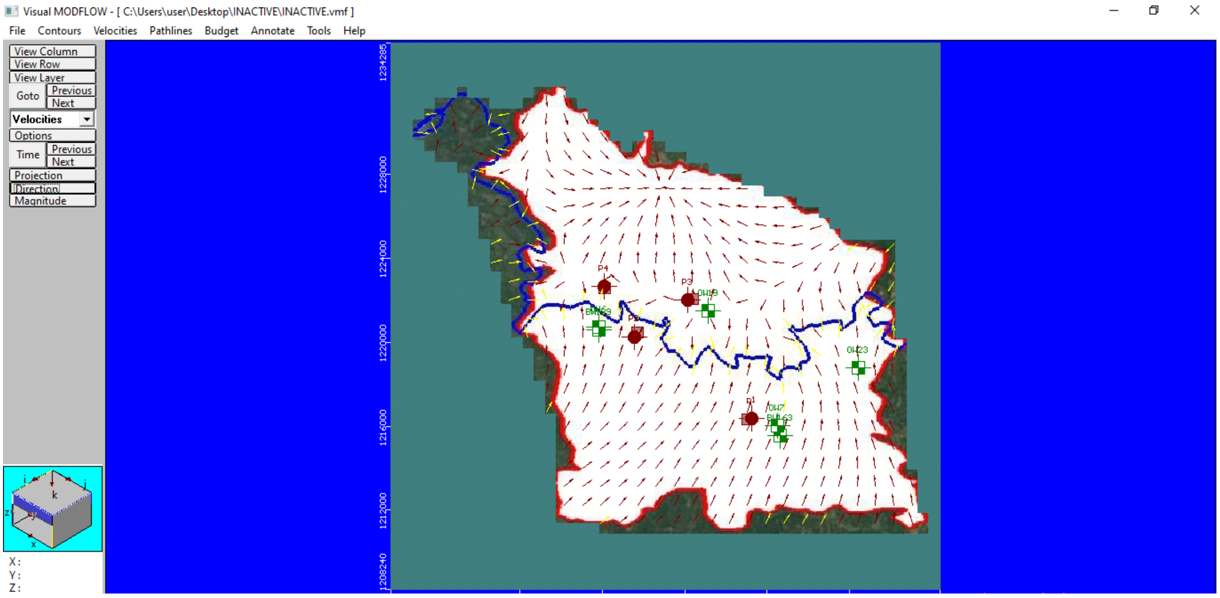


Fig. 40. Velocity vector direction of the study area

4.3.1.3 *Validation*

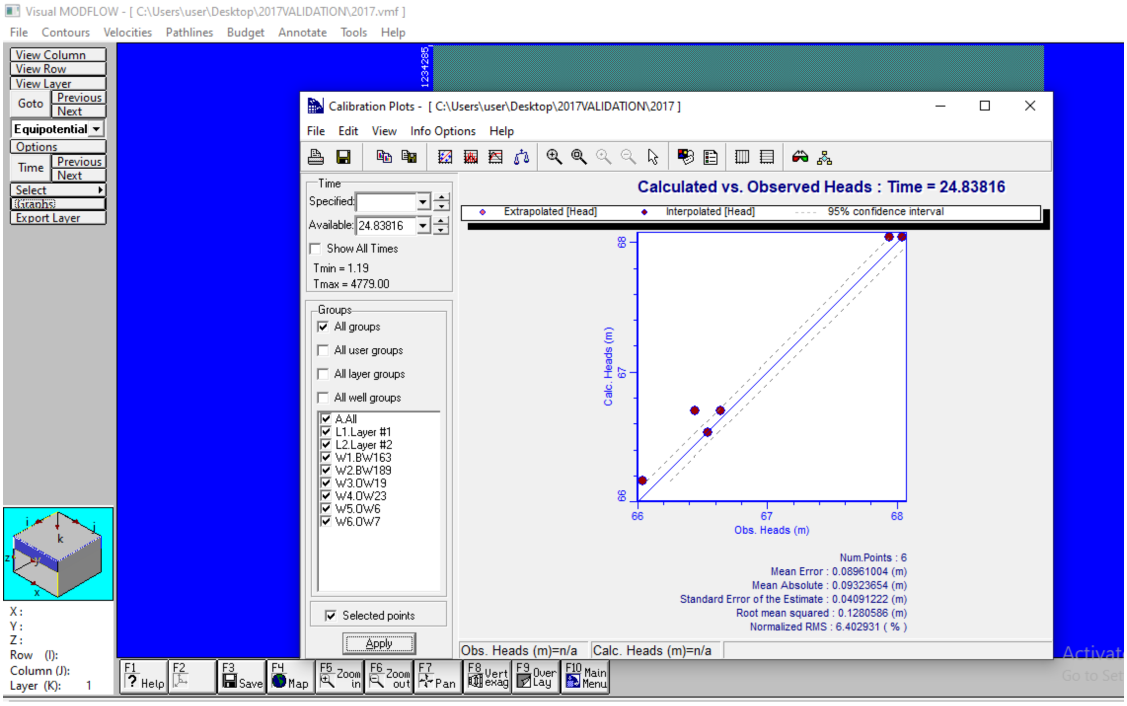
The calibrated model was then validated with the groundwater level data collected from 2013 to 2017 (4748 days) and upto 2019 (5478 days) for analyzing the impact of Bakkikayam Regulator, since the implementation of the regulator was done in the year 2018. The influence of Bakkikayam regulator on groundwater level can also be studied using the model.

The scatter plot of calculated Vs observed heads after running the model up to the year 2017 is shown in the Fig.41 and corresponding ground water contour map of the study is shown in Fig. 42. The validated values of observed and calculated heads of observation wells are given in Table 5.

The scatter plot of calculated Vs observed heads after running the model up to the year 2019 is shown in the Fig.43.From the graph, it could be seen that the calculated heads are in good match with the observed heads in most of the wells and the RMS error value was within the acceptable limit.

Fig. 44 illustrates the ground water contour map of the study area after running the model upto the year 2019 (5478 days) to analyze the change in the ground water table after the implementation of the Bakkikkayam regulator. This ground water contour map was compared with the water table contour map obtained after validation (4748 days) and it could be seen that the light blue color is changed to green color, which indicates that there was a decline in water table about 3 to 4 m in the downstream side of the regulator.

Fig. 45 shows the hydrographs of computed and observed water levels for selected observations wells after validation. The computed well hydrographs for dug wells at Tirurangadi (OW6), Vengara (OW 19), Othukkunmgal (OW 23) and bore well at Kottakkal (BW 163) showed good correlation with observed values of head.



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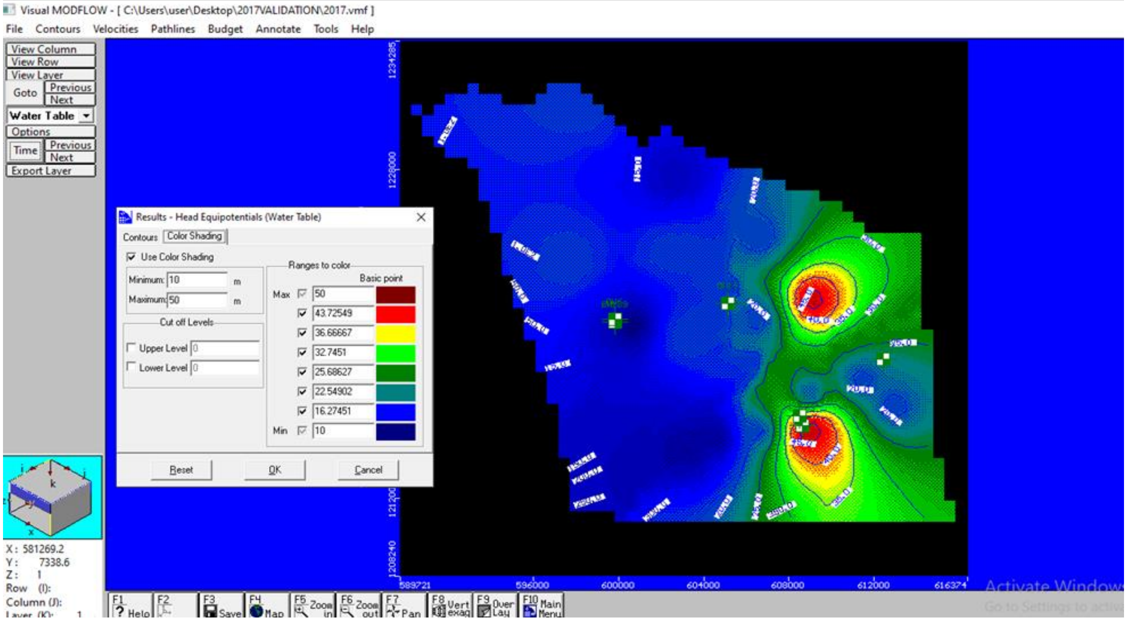
☑ W2.BW189
☑ W3.OW19
☑ W4.OW23
☑ W5.OW6
☑ W6.OW7
☑ Selected points

Num.Points : 6
Mean Error : 0.08961004 (m)
Mean Absolute : 0.09323654 (m)
Standard Error of the Estimate : 0.04091222 (m)
Root mean squared : 0.1280586 (m)
Normalized RMS : 6.402931 (%)

Obs. Heads (m)=n/a
Calc. Heads (m)=n/a

X :
Y :
Z :
Row (I):
Column (J):
Layer (K): 1

Fig. 41. Model computed Vs observed water level after validation upto 2017 (24 Days)



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Maximum: 50 m

Cut off Levels
☐ Upper Level 0
☐ Lower Level 0

Ranges to color

		Basic point
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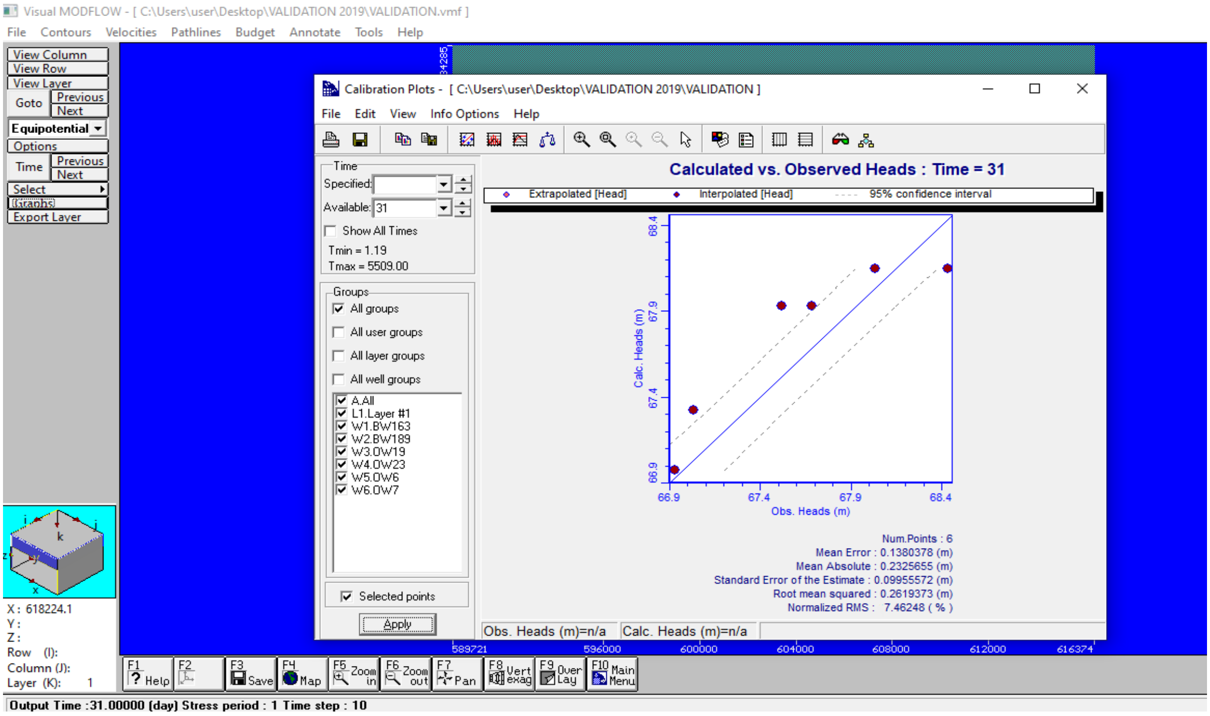
	☑ 43.72549	🟥
	☑ 36.66667	🟨
	☑ 32.7451	🟩
	☑ 25.68627	🟩
	☑ 22.54902	🟦
	☑ 16.27451	🟦
Min	☑ 10	🟦

X : 581269.2
Y : 7338.6
Z : 1
Row (I):
Column (J):
Layer (K): 1

Fig. 42. Groundwater table contour map of the study area after validation

Table 5. Validated values of observed and calculated heads (from MSL) of observation wells

Sl. No	Well Name	Observed Head (m)	Calculated Head (m)	RMSE value
1	BW 163	67.49	67.90	0.4092
2	BW 189	68.40	68.12	0.2835
3	OW6	68.00	68.12	0.1164
4	OW 7	67.65	67.90	0.2492
5	OW 19	66.90	66.94	0.0433
6	OW 23	67.00	67.27	0.2937



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☐ All well groups

☑ A.All
☑ L1.Layer #1
☑ W1.BW163
☑ W2.BW189
☑ W3.OW19
☑ W4.OW23
☑ W5.OW6
☑ W6.OW7

☑ Selected points

Num.Points : 6
Mean Error : 0.1380378 (m)
Mean Absolute : 0.2325655 (m)
Standard Error of the Estimate : 0.09955572 (m)
Root mean squared : 0.2619373 (m)
Normalized RMS : 7.46248 (%)

Obs. Heads (m)=n/a
Calc. Heads (m)=n/a

X : 618224.1
Y :
Z :
Row (I):
Column (J):
Layer (K): 1

Output Time :31.00000 (day) Stress period : 1 Time step : 10

Fig. 43. Model computed Vs observed water level after run upto 2019 (31 days)

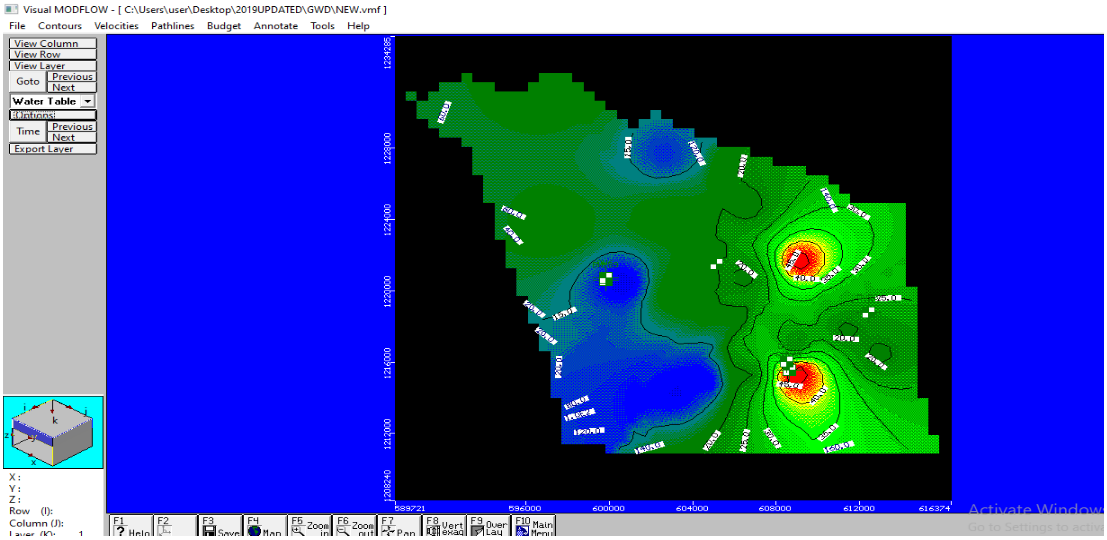
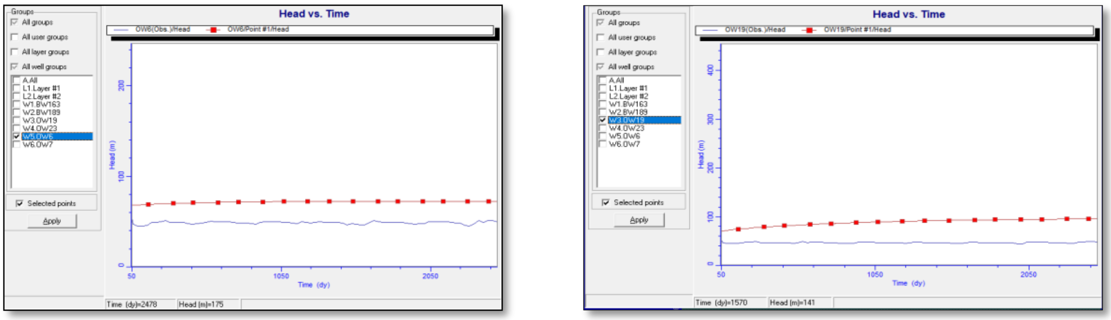
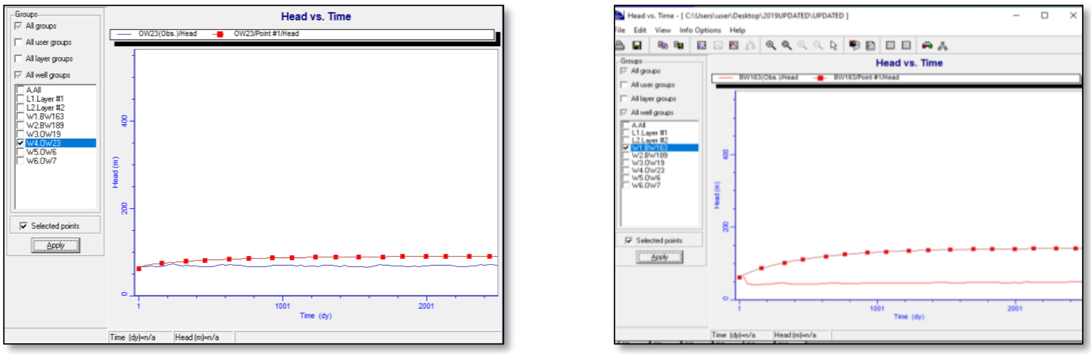


Fig. 44. Water table contour map after running upto 2019



OW 6 at Tirurangadi

OW 19 at Vengara



OW 23 at Othukkungal

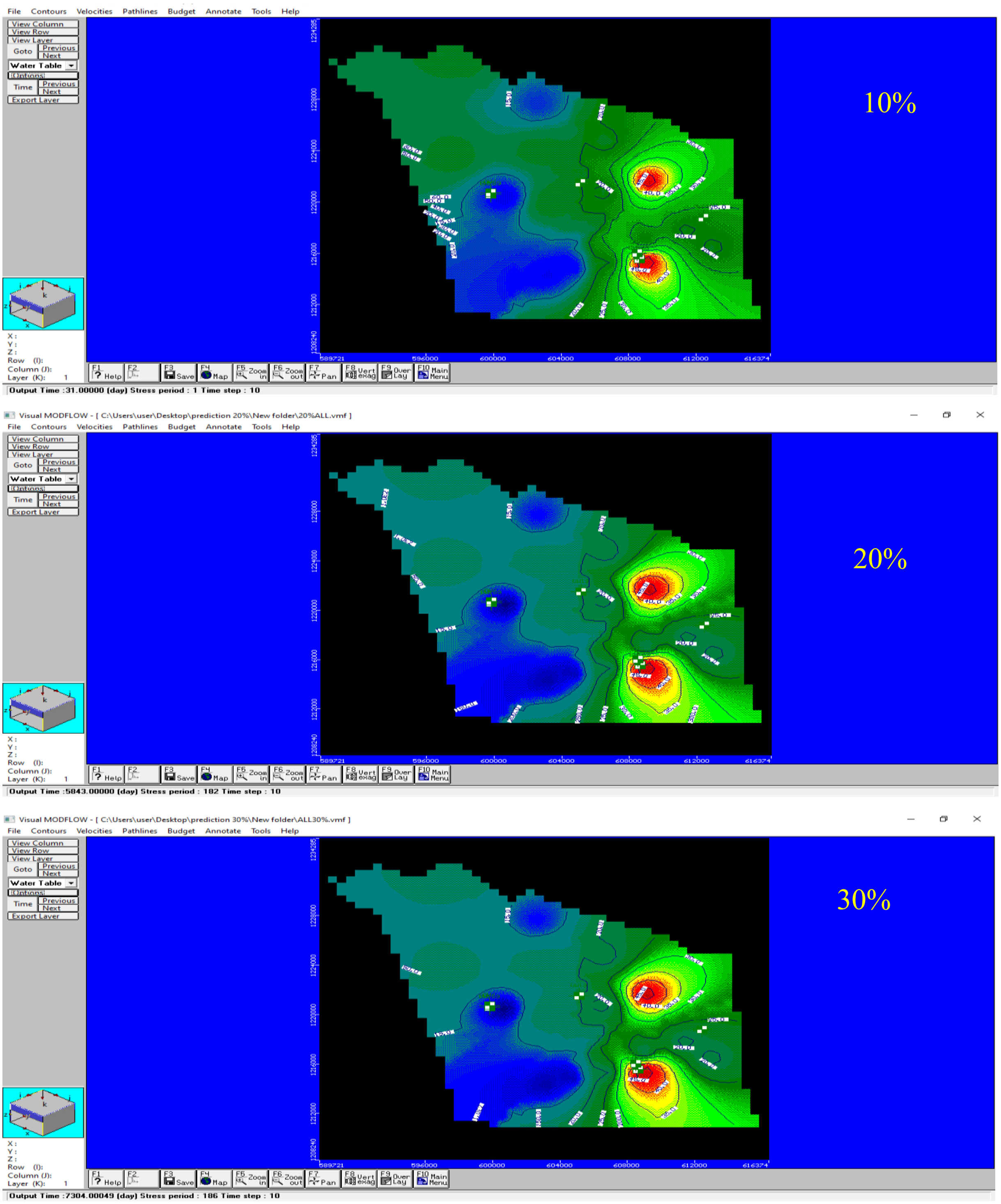
BW 163 at Kottakkal

Fig. 45. Computed and observed ground water level hydrographs for the selected observation wells after validation

4.3.1.4 *Prediction*

In order to analyze the solution of water scarcity during summer months in downstream area, the validated model was used to predict the ground water scenario for the coming years by assuming that recharge of the study area will be increased by 10, 20 and 30 percent of the recharge rate of the validated period (2019) in entire study area.

Predicted water table contour maps of the study area by increasing the recharge rate 10, 20 and 30 percent are shown in Fig. 46. From the figure, it could be observed that there is an increase of 2 m water table up to the 20% increase of ground water recharge. After that there is no significant change in water table and remained more or less constant. This is because of the topography of the downstream area of the Bakkikayam regulator especially Nannambra and Tirurangadi Panchayaths. Most part of these Panchayaths is under low land area and the ground water flow is towards the river from where water drains into Arabian sea, unless there is any obstructions to check the flow or any other water conservation measures at the estuary.



Output Time :31.00000 (day) Stress period : 1 Time step : 10

Visual MODFLOW - [C:\Users\user\Desktop\prediction 20%\New folder\20%ALL.vmf]

Output Time :5843.00000 (day) Stress period : 182 Time step : 10

Visual MODFLOW - [C:\Users\user\Desktop\prediction 30%\New folder\ALL30%.vmf]

Output Time :7304.00049 (day) Stress period : 186 Time step : 10

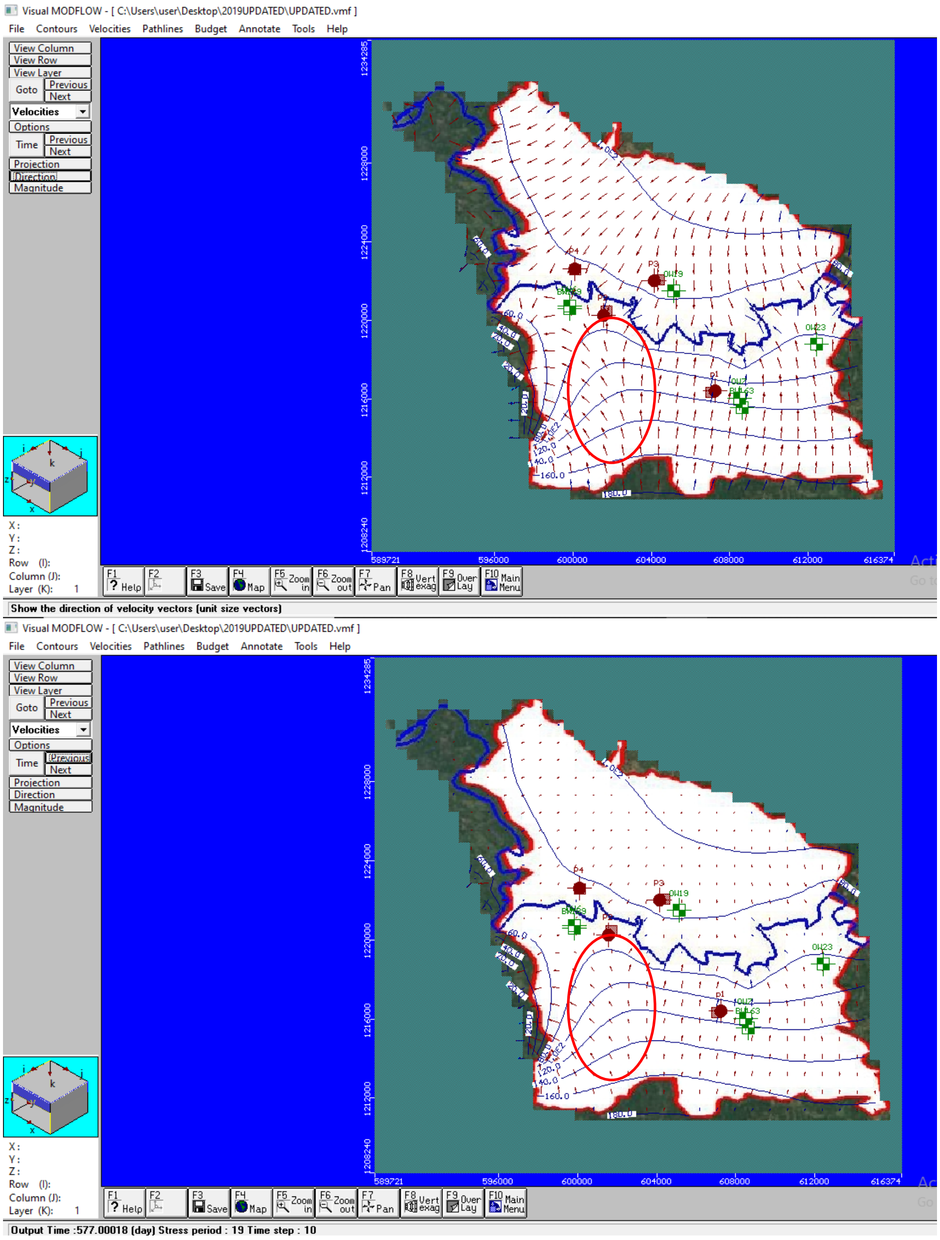
Fig.46. Predicted water table contour map of the study area by increasing recharge rate 10, 20, 30 percent

4.4 IDENTIFICATION OF POTENTIAL GROUNDWATER ZONES

In order to identify the potential groundwater zones in the downstream side of the Bakkikayam regulator during summer season, the velocity vector direction and magnitude obtained from Visual MODFLOW after validation were analyzed and the velocity vector maps are shown in Fig. 47. From the maps it could be seen that the flow direction and magnitude is maximum in the marked area, which can be identified as high ground water potential area. From the field investigation, it could be seen that two water bodies locally known as ‘Morya Kappu’ and ‘Venchali Kappu’ is located in this area.

A water body, locally known as ‘Morya Kappu’, which is located in Morya Kappu padasekharam has an area of 1.92 ha as shown in Fig.48. The water source for the Morya Kappu is originating mainly from Vattachira thodu. Another thodu which is a distributory of Poorapuzha is flowing to the field. Venchali Kappu is the water body located in Venchali Padasekharam having an area 0.833 ha. The map of the Venchali Kappu is shown in Fig. 49.

At present these water bodies and their drainage channels of around 10,000 m are filled with sediment deposits. The area gets flooded with large volume of rain water during the monsoon season and then subsequently draining to the Sea. At the same time, during the summer season the area is lacking sufficient water for irrigation purpose. Hence these two Kapps require deepening of 3 m and drainage channels require deepening of 1.6 m, in order to solve the problems encountered for the paddy cultivation in Nannambra Panchayath to a large extent.



Visual MODFLOW - [C:\Users\user\Desktop\2019UPDATED\UPDATED.vmf]

Show the direction of velocity vectors (unit size vectors)

Visual MODFLOW - [C:\Users\user\Desktop\2019UPDATED\UPDATED.vmf]

Output Time :577.00018 (day) Stress period : 19 Time step : 10

Fig. 47. Velocity vector of the study area after run upto 2019

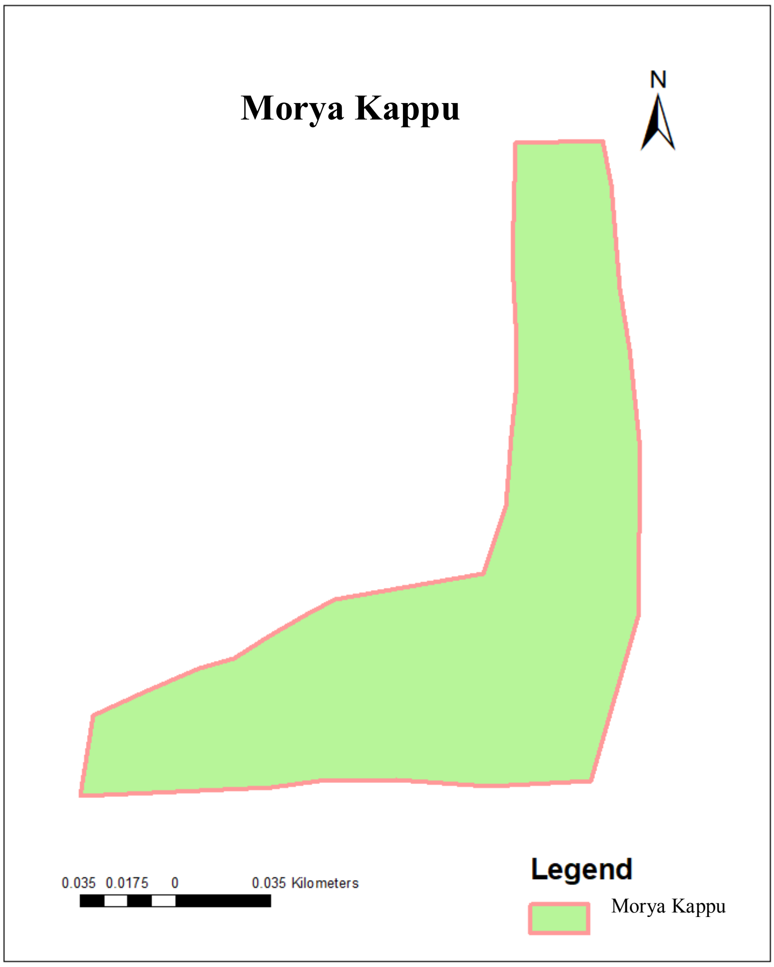


Fig. 48. Map of the Morya Kappu

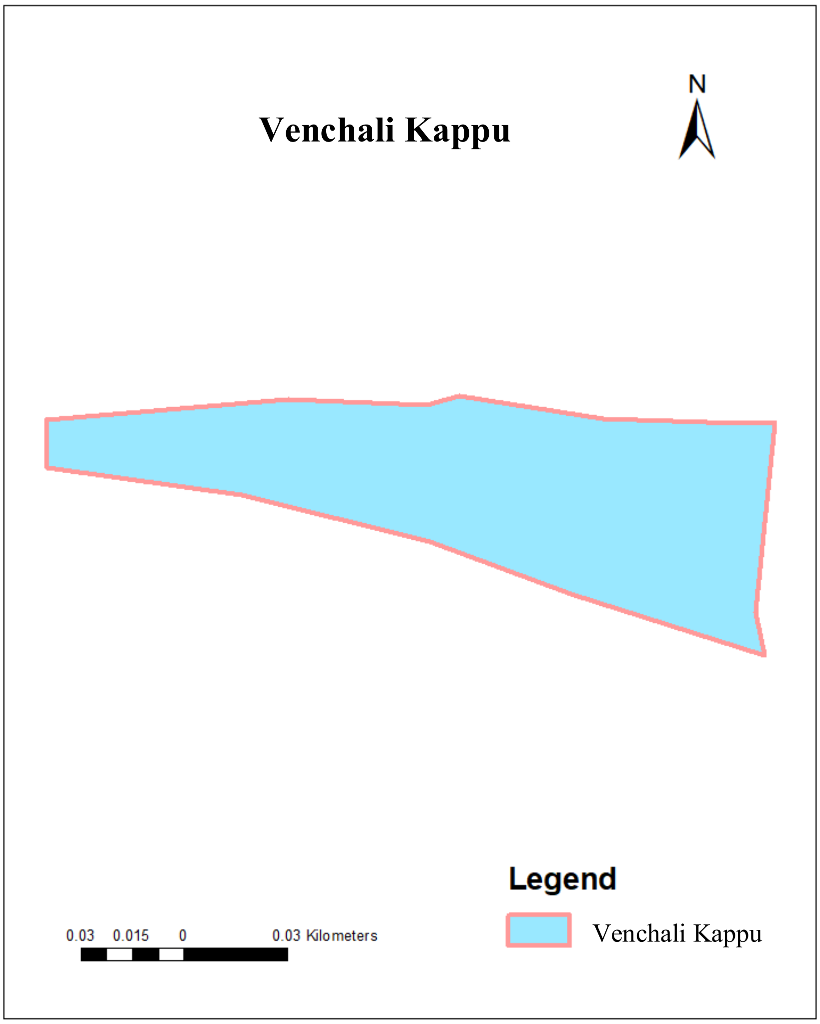


Fig. 49. Map of the Venchali Kappu

Plate 6. Morya Kappu padasekharam a) premonsoon b) post monsoon

Summary and Conclusion

CHAPTER 5

SUMMARY AND CONCLUSIONS

Bakkikayam Regulator is constructed across the Kadalundi River at Pandikasala in Vengara Panchayth of Malappuram District. The main intension of the regulator is to store and conserve water for drinking and agriculture purposes of nearby areas. The regulator is beneficial for upstream side of the regulator, at the same time it creates acute water shortage in downstream side for the paddy cultivation of around 950 acres during its critical stages in Nannambra Panchayath, known as KUTTANAD OF MALAPPURAM. This had led to a massive dispute between upstream and downstream famers and authorities regarding the closing of regulator during summer months. During the critical stages of paddy crop in downstream side, it requires sufficient water for crop development, otherwise complete failure of crop can happen. Hence it was necessary to conduct a study on the effect of Bakkikayam regulator on the ground water flow.

Vertical Electrical Sounding (VES) was conducted at 18 locations using signal stacking resistivity meter (MODEL-SSR-MP-ATS) to study the aquifer characteristics of the study area which is highly essential for ground water studies. Data collected through VES Survey were interpreted qualitatively and quantitatively using IPI2WIN software. The results obtained from the VES data interpretation were used to prepare a surface resistivity map and depth to bed rock of the study area using Arc GIS (10.4).

In order to assess the groundwater flow variation due to the presence of Bakkikayam Regulator in the study area, ground water table during pre and post monsoon periods in dug wells located at different locations were analyzed and water table fluctuations were noted. Ground water table for the month of April and October were taken as pre and post monsoon water table level respectively. The pre and post monsoon ground water table contour map of 2017 and 2019 were prepared using Arc GIS (10.4) since the implementation of the regulator was in the year 2018.

Visual MODFLOW software version 2.8.1 developed by Waterloo Hydrogeologic Inc. was used for the ground water flow modeling of the study area. This study intended to monitor the groundwater behavior in the ayacut regions of Bakkikayam Regulator. A base map was prepared using Google earth and Arc GIS (Arc Map 10.4) and imported in to the model as bmp format. The conceptual model for the study area was developed using base map, well logs at 6 sites and the data collected by conducting geophysical survey of the study area. After the development of conceptual model, the study area was discretized by dividing into 50 rows and 50 columns with a grid spacing of 530 m x 520 m throughout the area. Thus the study area was discretized into 2500 cells and the cells outside the boundary of the study area were marked inactive.

Field data such as pumping well and observation well data were used as input of Visual MODFLOW to simulate real field conditions. Four major pumping wells of Kerala Water Authority were selected for the study. Data collected from six observation wells of Ground Water Department including four dug wells and two bore wells were used for modeling the real groundwater conditions. Lithology of the area, aquifer properties and soil properties were used to replicate the real conditions of the study area in the model.

Hydrogeological parameters viz. hydraulic conductivity, specific storage, porosity and specific yield and boundary conditions of the domain such as constant head, rivers, recharge and evapotranspiration were used as input. After adding all the input parameters, the developed model was calibrated and run in steady state condition.

Aquifer condition of the year 2005 was assumed as the initial condition for steady state. The hydraulic conductivity values, groundwater levels and boundary conditions from the steady state calibration were used as initial condition for the transient calibration. The transient state calibration of the model was done with eight years data from 2005 to 2012. The storage coefficient was varied iteratively until a reasonably good match was obtained between the observed and computed groundwater heads. The calibrated model was validated with seven years data from 2013 to 2019. After validation process, the model was used for predicting the ground water table for the next five years by increasing the recharge rate 10, 20 and 30 percent of the recharge rate of the validation period (2019).

From the VES survey conducted at eighteen locations, two locations are having two layer substrata, eight locations are having three layer substata and rest eight locations are having four layer substrata. From the values of the fourth layer substrata, it can be considered as clay or hard rock. Hence for the further study the fourth layer is neglected and the study area is considered to have three layer substrata. These three layers are laterite, clay and weathered rock. From the surface resistivity contour map the major portion of the study area is having the resistivity ranging from 100 to 1000 ohm-m. This indicates that the major portion of the study area is covered with lateritic formation and hypodermic soil which is in agreement with the conclusion of Sajeena and Kurien (2015). Some pockets like Peruvallur and Kannamangalam have high resistivity ranging from 2000 to 4000 ohm-m.

From the map of depth to bed rock it could be inferred that major portion of study area has 12 to 22 m depth to the bed rock. In some places like Vengara, Nammabra, Tirurangadi and Thennala found to have shallow bed rock of 2-12 m. A small portion of Peruvallur has deep bed rock with 43-63 m.

From VES data interpretation using IPI2WIN software, it could be inferred that most part of the study area showed H and HK type curve indicating the presence of good to moderate quality ground water. From the studies it could be concluded that, top soil of the study area is either laterite soil or hydromorphic soil of thickness 0.75 to 4 m, followed by laterites with varying hardness to a depth of 4 m to 17 m. Lithomargic clay of thickness less than 2 m is seen below the laterites in some places. These layers are overlying weathered rock of 2 to 14 m thickness followed by hard rock with or without fractures. Major aquifer formations in the study area are identified as laterite, clay and weathered rock.

Effect of Bakkikayam regulator on ground water variation was analyzed based on pre and post monsoon water table data. The ground water level during pre and post monsoon from 4 dug wells located in upstream and downstream side of the Bakkikayam regulator were observed and the difference between pre and post monsoon water table (water table fluctuations) were noted .It was observed that the water table fluctuation in the wells located in downstream side ranged from 5.41 to 5.62 m.

By comparing the water table contour map obtained from the validated model before and after the implementation of Bakkikayam Regulator, it could be seen that the light blue color is changed to green color, which indicated that there was a decline of 3 to 4 m water table in the downstream side of the regulator.

The validated model is used to predict the water table contour maps of the study area for next five year by increasing the recharge rate 10, 20 and 30 percent of the recharge rate of the validated period (2019). From this study it could be observed that there is significant change in water table up to an increase of 20% in ground water recharge, that is around 2 m increase of water table in major part of the downstream area. Beyond 20% increase in recharge, there was no significant change in water table and remained more or less constant. This is because of the topography of the downstream area of the Bakkikayam regulator especially Nannambra and Tirurangadi Panchayaths, part of these Panchayaths are under low land area. The ground water flow from this area is towards the river from where water drains into Arabian Sea. This necessitates some obstructions to check the flow of river or any other water conservation measures at downstream side.

From the velocity vector map obtained from the Visual MODFLOW model, it could be observed that the flow direction and magnitude are maximum in two water bodies locally named ‘Morya Kappu’ and ‘Venchali Kappu’, which can be identified as high ground water potential area. At present these water bodies and their drainage channels of around 10,000 m are filled with sediment deposits. The area gets flooded with large volume of rain water during monsoon season and then subsequently drains to the sea. At the same time, during the summer season the area is facing acute water shortage for drinking and irrigation purposes. Hence it is recommended that the deepening of two water bodies upto 3 m and their drainage channels upto 1.6 m, in order to solve the problems encountered for paddy cultivation in Nannambra Panchayath to a large extent.

References

REFERENCES

Akpan, A. E., Ebong, D. E., and Chimezie, N. E. 2015. Exploratory assessment of groundwater vulnerability to pollution in Abi, southeastern Nigeria, using geophysical and geological techniques. Environ Monit Assess (2015) 187: 156.

Al-garni M. A. (2009) Geophysical Investigations for Groundwater in a Complex Subsurface Terrain, Wadi Fatima, KSA: A Case History. *Jordan J. of Civil Eng*. 3: 118-136.

Aliyaria, F., Ryan, B., Ali, T., Doziera, A., Mazdak, A., Zeilerb, K. 2019. Coupled SWAT-MODFLOW Model for Large-Scale Mixed Agro-Urban River Basins. *Environ. Modelling and Software*. doi: 10.1016/j.envsoft.2019.02.014.

Babel, M. S., Wahid, S. M., 2009. Freshwater under threat: South East Asia – vulnerability assessment of freshwater resources to environmental change. United Nations Environment Programme, Nairobi.

Balachandran and Padmakumar. 2008. improvement of paddy cultivation in the command area of Kattampally RCB.

Bouwer, H. 1978. *Groundwater Hydrol*. McGraw-Hill, New York.

Brijesh, V. K. and Balasubramanian, A. 2014. Hydrogeological studies and groundwater modelling, Bharathapuzha basin, Kerala, India. Scholar’s Press, Germany. ISBN: 978-3-639-71113-4. pp: 129 -154.

Carpenter, E. W. and Habberjam, G. M. 1956. A tri-potential method of resistivity prospecting. *Geophys*. 21: 455-469.

CGWB [Cental Ground Water Board]. 2013. Ground water information booklet of Malappuram District, Kerala. In. ground water information booklet of Malappuram District: 1-27.

Chandra, S., Saxena, R. S. 1975. Water balance study for estimation of ground water resources. *Irrig. Power J.* 32(4): 443-449.

Erban, L. E., Gorelick, S. M., 2016. Closing the irrigation deficit in Cambodia: implications for transboundary impacts on groundwater and Mekong River flow. *J. Hydrol.* 535, 85–92.

Fetter, C. W. 2000. *Applied Hydrogeol.* 4th Edition. Prentice Hall, N.J.

Freeze, R. A. and Cherry, J. A. 1979. *Ground water*. Englewood Cliffs. New Jersey: Prentice-Hall Inc. 604p.

Gaghik, H., Pascal, P., Yann L. T., Sandile M., Rianto, V. A. 2019. Mapping spatial distribution of soil properties using electrical resistivity on a long term sugarcane trial in South Africa. *Geoderma.* 349: 56-67.

Guo, L., Mount, G. J., Hudson, S., Lin, H., Levia, D. Pairing geophysical techniques improves understanding of the near-surface Critical Zone: Visualization of preferential routing of stem flow along coarse roots. *Geoderma.* 357: 113953. Available: https://doi.org/10.1016/j.geoderma.2019.113953

Ha, K., Ngoc, N. T. M., Lee, E., Jayakumar, R., 2015. Current status and issues of Ground water in the Mekong River Basin (No. TH/SC/15-02). Korea Institute of Geoscience and Mineral Resources (KIGAM), CCOP Technical Secretariat, UNESCOBangkok Office.

Hakkim, A. V. M., Praveena, N., Rakhi, J. F. and Ajay, G. A. J. 2013. Impact study of koottayi regulator cum bridge. *Int. J. of Engg Res. and Dev.* 9(3): 1-4.

Harbaugh, A. W. 2005. MODFLOW-2005, the U.S Geological Survey modular groundwater model. The ground water flow process, U. S. Geological Survey. Reston, Virgina. Available: http:// pubs.usgs.gov/ tm/ 2006/ tm6a12/pdf/TM6-A12.pdf.

Hariharan, V., Uma Shankar, M. 2017. A review of visual MODFLOW applications in groundwater modeling. IOP Conf. Series: Materials Sci. and Eng. 263 (2017) 032025.

Helaly, A. S. 2017. Assessment of groundwater potentiality using geophysical techniques in Wadi Allaqi basin, Eastern Desert, Egypt – Case study. *NRIAG J. of Astronamy and Geophys*. 6: 408-421. Available: https://doi.org/10.1016/j.nrjag.2017.09.003.

Hemeda, S., Pitilakis, K. 2016. Geophysical Investigations at Cairo's Oldest, the Church of Abu Serga (St. Sergius), Cairo, Egypt. *Research in Nondestructive Evaluation*. DOI: 10.1080/09349847.2016.1143991.

ICEM. 2013. USAID Mekong ARCC Climate Change Impact and Adaptation Study for the Lower Mekong Basin: Main Report. USAID Mekong ARCC Project, Bangkok.

Inverarity, K., Heinson, G. and Hatch, M. 2016. Groundwater flow underneath mound spring tufas from geophysical surveys in the southwestern Great Artesian Basin, Australia, *Australian J. of Earth Sci.* 63(7): 857-872. DOI: 10.1080/08120099.2016.1261942.

Jide, N. O., Emmanuel, A M., Wahab S. A., Harrison, A., Olamide, A. and Chukwuebuka, R. U. 2018. Panoramic azimuthal Schlumberger Vertical Electrical Sounding for fracture orientation and anisotropy quantification. *Heliyon.* 4:e00998. doi: 10.1016/j.heliyon.2018. e00998.

Jones, G., Sentenac, P., Zielinski, M. 2014. Desiccation cracking detection using 2-D and 3-D Electrical Resistivity Tomography: Validation on a flood embankment. *J. of Applied Geophys*. doi: 10.1016/j.jappgeo.2014.04.01.

Jorge, R. H., Osvel, H. H., Mauricio P. L., Alejandra C. F., Edgar C. V. 2013. Groundwater responses to controlled water releases in the limitrophe region of the Colorado River: Implications for management and restoration. *Ecol. Eng*. 59: 93-103.

Khalili, M., Mizakurdeh, A. M. 2019. Fault detection and using microtremor data(HVSR-based approach) and electrical resistivity survey. *J. of Rock Mech. and Geotechnical Eng*. 11: 400-408. Available: https://doi.org/10.1016/j.jrmge.2018.12.003.

Knowling, M. J. and Werner, A. D. 2016. Estimability of recharge through groundwater model calibration: Insights from a field-scale steady-state example. *J. of Hydrol.* 540: 973-987. Available: https://doi.org/10.1016/j.jhydrol.2016.07.003.

Kurien, E. K., Sheeja, P. S., Ritu P. and Shahanaz, K. 2013. A hydo-geophysical investigation of groundwater potential. *Int. J. Eng. Res. And Dev*. 9(4):30-35.

Kurien, E. K., Fasaludeen, N. and Afthab, S. P. P. 2016. A hydro-geophysical investigation of groundwater by electrical profiling. *Int. J. Eng. Sci. and Technol*. 5(1):258-265.

Lakshmipriya, C., Narayanan, R. M. 2015. Study on Groundwater Modeling of Aquifers Using Visual Modflow. *Int. Res. J. of Eng and Technol.* 2(2). *https://www.researchgate.net/publication/311707286*.

Lasya, C. R., Inayathulla, M. 2015. Groundwater Flow Analysis Using Visual Modflow. *IOSR J. of Mech. and Civil Eng.* 12(2): 05-09.

Leake, S. A. 1997. U. S. Geological Survey (USGS) [on-line]. Modeling groundwater flow with MODFLOW and related programs. Avaliable: http//water.usgs.gov/public/wrd011.html/.

Liu, Q., Mou, X., Cui, B., Ping, F. 2017. Regulation of drainage canals on the groundwater level in a typical coastal wetlands. *J. of Hydrol*. 555: 463–478. Available: https://doi.org/10.1016/j.jhydrol.2017.10.035.

McDonald, M. G. and Harbaugh, A. W. 1998. A modular three dimensional finite groundwater flow model. US Geological Survey, *Tech. Manual of Water Resour. Investigation*, Book 6. US Geological Survey, Reston.

Mahesh, R. G., Watanabea, K., Hiroyuki, O. 2004. Effect of bridge construction on floodplain hydrology—assessment by using monitored data and artificial neural network models. J. of Hydrol. 292: 182–197.

Michalis, P., Sentena, P., MacBrayne, D. 2016. Geophysical Assessment of Dam Infrastructure: the Mugdock Reservoir Dam Case Study. *3rd Joint International Symposium on Deformation Monitoring Vienna.*

Nagraj, S. P., Chetan, N. L., Nataraja, M. and Surindra, S. 2020. Climate change scenarios and its effect on groundwater level in the Hiranyakeshi watershed. *Groundw. for Sustain. Dev.* 10: 100323. https://doi.org/10.1016/j.gsd.2019.100323.

Namitha, M. R., Devi Krishna J. S., Sreelekshmi, H. and Muhammed Ashik, P. 2019. Groundwater flow modelling using Visual MODFLOW. *J. of Pharmacognosy and Phytochemistry*. 8(1): 2710-2714.

Ojoina, O. A. 2014. Hydrogeophysical Investigation for Groundwater in Lokoja Metropolis, Kogi State, Central Nigeria. *J. of Geogr. and Geol*. 6: 1-10.

Oyedele, E. A. A., Olayinka, A. I. 2012. Statistical Evaluation of Groundwater Potential of Ado-Ekiti, Southwest, Nigeria. *Transnational J. of Sci.and Technol.* 2: 110-127.

Prasad, N. N. B., Shivaraj, P. V. and Jagatheesan, M. S. 2007. Evaluation of groundwater development prospects in Kadalundi river basin. *J. Geol. Soc. India*. 69: 1103- 1110.

Rajsanjeev. 2017. Geophysical resistivity survey (VES) for selection of appropriate artificial recharge (Ar) structures for augmentation of groundwater resources in Gwalior, M.P, India. Environ. and Earth Sci. Res. J. 4(1): 7-11.

Rajaveni, S. P., Brindha, K., Rajesh, R. and Elango, L. 2014. Spatial and temporal variations of groundwater level and its relation to drainage and inverse rocks in a part of Nalgonda District, Andhra Pradesh, India. *J. Indian Soc. Remote Sens.*42(4): 765-776.

Rajkumar, S., Srinivas, Y., Nithya, C. N. Arunbose, S. 2019. Groundwater quality and vertical electrical sounding data of the Valliyar River Basin, South West Coast of Tamil Nadu, India. *Data in brief.* 24: 103919.

Raut, S. 2012. Geoelectrical investigations for shallow ground water in a canal command of Orissa. *J. Geophys*. 33(2): 3-14.

Reynolds, J. M. 1997. An introduction to applied and environmental Geophysics. UK.

Sajeena, S. and Kurien, E. K. 2015. Application of geophysical techniques for groundwater investigation - A case study of Kadalundi River basin, Malappuram, Kerala. *J. Trends in Biosciences*. 8 (16): 4238-4248.

Sajeena, S., Kurien, E. K. and Brijesh, V. K. 2017**.** Identification of groundwater potential zones using geophysical technique in Kadalundi river basin, Malappuram, Kerala. Available: https://www.researchgate.net/publication/316215516.

Sajeena, S. and Kurien, E. K. 2019. Studies on groundwater resources using visual MODFLOW – A case study of Kadalundi river basin, Malappuram, Kerala. *Indian J. of Soil Conservation.* 47(1): 21-29.

Sajeena, S., Swathy, P. S. and Hakkim, A. V. M. 2020. Studies on saline water intrusion in the coastal stretch of Kadalundi river basin, Malappuram district, Kerala using visual MODFLOW – A case study. *Research Square.* Available: https://doi.org/10.21203/rs.3.rs-34501/v1.

Sara, M. A. and Hamed, A. A. 2017. Mapping of groundwater prospective zones integrating remote sensing, geographic information systems and geophysical techniques in El-Qaà Plain area, Egypt. *Hydrogeol J.* 25:2067–2088. DOI 10.1007/s10040-017-1603-3.

Sharda.A.N., Kruttika, A. and Amar, D. 2015. Environmental effect of lift irrigation scheme - a case study. *Int. J. of Innovations in Engg Res. and Technol*. 2(9): 2394-3696.

Sebastian, U., Oliver, K., Laura A. R., Emma, N., David, A. P. 2017. Electrical resistivity tomography determines the spatial distribution of clay layer thickness and aquifer vulnerability, Kandal Province, Cambodia. *J. of Asian Earth Sci.* 147: 402-412. Available: http://dx.doi.org/10.1016/j.jseaes.2017.07.043.

Shishaye, H. A. and Abdi, S. 2016. Groundwater exploration for water well site locations using Geophysical survey methods. *Hydrol Current Res*. 7(1). doi: 10.4172/2157-7587.1000226.

Sjödahl, P., Dahlin, T., Johansson, S. 2009. Embankment dam seepage evaluation from resistivity monitoring data. Near Surf. Geophys. 7:463–474. http://dx.doi.org/10.3997/ 1873-0604.2009023.

Sjödahl, P., Dahlin, T., Johansson, S., Loke, M. 2008. Resistivity monitoring for leakage and internal erosion detection at Hall by embankment dam. *J.Appl.Geophys*. 65:155–164. http://dx.doi.org/10.1016/j.jappgeo.2008.07.003

Sridhar, N., Ezhisaivallabi, K., Poongothai, S., Palanisamy, M. 2018. Groundwater Flow Modelling Using Visual MODFLOW - A Case Study of Lower Ponnaiyar Sub-Watershed, Tamilnadu, India. *Int. J. of Eng. Research in Mech. and Civil Eng*. 3(2).

Sun, Y., Wang, Y., Cao, X., Song, X. 2019. Hydraulic performance evaluation of a quasi-two dimensional constructed wetland microcosm using tracer tests and Visual MODFLOW simulation. *J. of Contaminant Hydrol*. 226: 103537. Available: https://doi.org/10.1016/j.jconhyd.2019.103537.

Sun, Y., Xu, S. G., Ping P. K., Fu, Y. Z. and Wang, T. X. 2019. Impacts of artificial underground reservoir on groundwater environment in the reservoir and downstream area. *Int. J. Environ. Res. Public Health* 2019 (16): 1921.

Uday, B. P. V. 2018. Regional ground water resource modeling using MODFLOW – A case study. M Tech. (Agrl. Engg.), Thesis, Kerala Agricultural University, Thrissur, 3p.

Zare, M., Koch, M. 2014. Studying the effects of an irrigation/drainage network on groundwater table fluctuations using 3D groundwater flow modeling. ICHE 2014, Hamburg - Lehfeldt & Kopmann .ISBN 978-3-939230-32-8.

Appendices

APPENDIX I

Location of Ground Water Monitoring wells of Study Area

Well Name	X- Coordinates (m)	Y- Coordinates (m)	Location
BW163	608644.01	1215544.93	Kottakkal
BW189	599827.12	1220585.47	Thirurangadi
OW6	599826.65	1220739.07	Thirurangadi
OW7	608490.83	1216005.24	Kottakkal
OW19	605134.54	1221523.63	Vengara
OW23	612426.84	1218783.20	Othukkungal

APPENDIX II

Top and bottom elevation of the layers used in Visual MODFLOW

X	Y	Top elevation of 1st layer	Bottom elevation of 1st layer	Bottom elevation of 2nd layer	Bottom elevation of 3rd layer
602887.43	1220142.88	19	18	17.443	17.443
603156.38	1220423.51	19	16.6	16.6	16.6
597410.01	1231782.83	19	18	13.51	13.51
602194.36	1227952.49	13	11.65	5.8	-48.9
597419.83	1223773.2	19	17.21	12.83	5.55
602109.62	1224328.32	19	18	16.42	9.69
606276.61	1225060.47	19	13.2	4.86	4.86
608804.39	1222057.51	47	44.56	41.78	39.39
608759.53	1217480.15	19	14.93	13.63	13.63
611154.19	1218194.84	19	17.25	15.31	-3.59
609007.38	1215884.09	47	45	41.47	41.47
606549.83	1215630.51	19	17.84	16.45	11.02
604517.68	1215254.62	11	10	8.39	7.25
603179.27	1214544.85	11	9.97	7.31	4.13
600474.76	1220675.03	19	17.3	7.55	7.55
606295.82	1221175.61	19	18	4.5	4.5
612700.05	1216950.47	19	18.25	13.46	9.57
608643.57	1215544.48	47	44.53	40.58	40.58

APPENDIX III

Recharge of the study area based on rainfall

Year	Annual rainfall (cm)	Recharge (cm)
2005	274.60	60.94
2006	372.70	72.60
2007	345.70	69.58
2008	224.70	54.05
2009	283.80	62.12
2010	298.00	63.91
2011	202.60	50.70
2012	191.02	48.32
2013	274.96	60.31
2014	252.40	57.33
2015	231.19	54.39
2016	132.82	37.83
2017	204.48	50.43
2018	297.97	63.20
2019	304.06	63.95

APPENDIX IV

Water table data of observation wells

Period days	BW 163 (m)	BW 189 (m)	OW 6 (m)	OW 7 (m)	OW 19 (m)	OW 23 (m)
31	28.02	26.80	10.7	9.85	11.08	12.8
59	29.76	24.77	10.91	9.79	10.94	12.81
90	32.20	27.62	12.6	10.47	11.35	12.55
120	33.03	30.00	12.6	9.22	11.33	13.4
151	33.37	30.18	12.4	9.1	11.65	13.01
181	29.72	29.62	8.64	8.67	10.93	11.83
212	31.63	14.50	8.6	8.02	9.71	9.47
243	30.57	12.43	8.24	7.02	9.8	6.53
273	29.46	15.48	7.03	8.14	8.46	11.11
304	27.72	15.03	8.58	8.77	10.03	11.35
334	28.77	19.11	8.58	7.56	9.87	10.66
365	30.51	24.48	8.8	9.13	10.16	11.37
396	31.96	30.17	9.05	9.13	10.33	11.95
424	32.33	30.91	10.24	9.06	10.44	12.8
455	32.53	31.33	10.68	9.4	10.72	13.07
485	32.52	30.58	10.07	10.36	11.04	13.09
516	32.62	29.22	9.26	10.2	11.32	13.8
546	32.15	23.46	8.54	8.34	9.87	10.37
577	30.79	13.72	7.54	6.29	8.46	8.6
608	30.13	12.62	8.47	7.85	9.81	10.37
638	29.1	12.36	8.21	6.61	9.21	9.48
669	29.07	16.93	8.14	7.29	9.37	10.68
699	27.57	18.99	8.47	7.37	9.68	9.97
730	29.05	27.69	8.82	8.25	10.25	11.77
761	29.85	28.73	9.24	8.88	10.34	12.74
789	30.42	29.36	9.52	9.15	10.93	12.82
820	30.07	29.50	9.8	9.77	11.19	13.08
850	29.75	29.22	10.45	9.97	11.48	13.1
881	29.60	29.08	10.9	8.86	11.69	12.95
911	29.44	28.93	8.58	9.57	11.23	11.98
942	28.70	19.04	8.43	8.74	8.62	11
973	28.05	19.20	8.35	7.27	9.67	9.84
1003	28.72	19.01	8.2	7.31	9.65	10.54
1034	28.53	20.25	8.49	6.66	9.71	9.6
1064	28.67	17.75	8.57	7.14	9.85	9.85
1095	28.97	25.33	8.82	8.61	10.17	11.81

1126	29.17	28.43	9.72	9.21	10.51	10.67
1155	29.18	29.79	10.02	9.7	10.68	13.14
1186	29.09	28.17	8.32	6.46	10.29	11.38
1216	29.05	23.7	8.76	8.78	10.42	11.63
1247	29.07	22.76	9.64	9.6	11.14	13.53
1277	28.9	18.8	8.55	7.9	9.87	10.66
1308	28.5	17.08	8.36	7.45	9.72	9.67
1339	28.19	24.9	8.66	7.41	9.56	10.35
1369	28.08	25.7	8.85	7.82	10	11.78
1400	28.05	26.34	8.70	9.21	10.15	12.77
1430	27.83	26.04	8.81	8.71	10.55	10.91
1461	27.98	26.38	9.32	8.76	10.45	12.86
1492	27.98	26.15	11.55	9.27	10.73	13.14
1520	28.02	26.08	10.44	9.77	10.96	13.85
1551	28.19	23.72	10.68	9.81	11.18	14.06
1581	28.19	19.46	11.82	9.75	11.74	14.31
1612	28.19	20.55	11.49	9.19	11.95	12.95
1642	27.99	18.94	8.65	9.02	10.83	11.88
1673	27.32	14.69	7.08	6.45	8.58	8.32
1704	26.59	14.94	8.33	7.11	9.51	9.99
1734	27.25	14.14	8.65	7.55	9.82	10.22
1765	27.5	14.89	8.68	8.62	9.85	11.36
1795	27.52	18.79	9.17	8.20	10.19	12.25
1826	27.51	19.95	9.00	7.83	10.31	11.99
1857	27.52	24.42	9.15	8.66	10.48	12.75
1885	28.02	27.47	9.56	8.89	10.65	13.11
1916	28.98	28.9	10.38	9.56	10.78	12.64
1946	29.52	30.56	11.01	9.71	10.89	12.85
1977	27.6	30.60	9.94	9.69	12.34	11.98
2007	27.53	30.22	9.97	9.62	12.37	11.81
2038	28.22	27.34	8.42	7.78	9.72	9.70
2069	26.22	25.52	8.33	7.64	9.54	9.76
2099	26.38	24.87	8.36	7.52	9.46	9.76
2130	26.69	23.39	8.43	7.47	9.32	9.75
2160	26.54	20.30	8.48	7.35	9.80	10.7
2191	27.03	16.65	9.13	8.37	10.03	11.35
2222	26.7	19.68	9.21	9.62	10.56	13.13
2250	26.83	24.07	9.63	9.57	10.72	13.45
2281	26.82	25.00	11.93	9.99	11.00	12.95
2311	26.77	26.75	12.61	10.28	11.36	12.48
2342	27.1	27.38	10.13	10.06	11.92	12.48
2372	26.13	20.80	6.45	7.44	8.68	9.00
2403	25.59	19.42	8.70	7.81	9.70	10.02

2434	25.01	13.84	6.50	5.79	7.67	8.14
2464	25.22	13.15	6.61	5.94	8.19	8.39
2495	25.52	25.21	8.47	7.82	9.80	12.1
2525	25.42	25.08	8.79	8.58	10.09	11.85
2556	25.49	26.8	9.94	9.02	10.66	13.81
2587	25.22	27.45	12.58	9.31	10.87	13.97
2616	25.39	27.61	10.79	9.68	11.48	14.74
2647	25.34	27.56	11.29	10.05	12.02	14.74
2677	25.39	27.54	10.71	9.42	12.48	14.86
2708	25.56	28.34	10.51	8.40	12.65	13.30
2738	25.09	28.24	9.09	7.35	12.61	12.98
2769	24.42	26.52	7.39	5.55	8.68	9.99
2800	23.71	25.37	8.57	6.41	9.89	12.22
2830	23.99	23.36	7.89	6.40	9.17	9.82
2861	24.19	24.91	8.68	7.57	10.07	13.90
2891	24.15	27.13	8.97	7.39	10.43	13.52
2922	24.72	26.94	9.06	8.08	10.55	13.97
2953	25.36	20.1	9.74	8.62	11.07	12.85
2981	25.86	18.15	10.04	9.63	11.84	13.15
3012	25.98	18.64	9.95	9.72	12.12	12.81
3042	26.19	18.65	10.07	10.37	12.61	12.71
3073	27.18	18.66	10.44	10.34	13.01	13.85
3103	26.43	19.28	9.13	8.55	12.90	11.12
3134	25	14.35	7.23	5.41	8.08	8.28
3165	24.358	12.06	7.11	4.98	8.04	8.38
3195	24.394	13.96	8.28	6.25	9.81	11.16
3226	25.12	13.81	8.61	7.63	10.12	11.88
3256	25.38	13.32	8.64	8.23	10.08	12.48
3287	25.54	13.85	8.80	8.86	10.57	12.68
3318	25.8	14.13	8.94	9.13	10.89	13.34
3346	25.95	14.89	9.12	9.47	11.17	13.76
3377	25.9	14.66	9.19	9.64	11.80	13.88
3407	25.88	15.31	9.28	10.00	12.22	13.48
3438	25.43	14.4	8.88	8.71	11.48	12.92
3468	24.8	13.9	8.45	6.63	9.90	11.06
3499	24.07	11.15	7.23	6.30	8.91	9.15
3530	23.65	13.72	7.13	0.46	8.94	11.95
3560	23.62	13.65	8.60	8.34	9.99	13.10
3591	23.57	14.32	8.35	6.64	9.84	11.85
3621	23.5	24.64	8.32	7.39	9.95	12.31
3652	23.84	20.43	8.79	8.73	10.40	13.39
3683	24.32	15.68	8.69	9.36	10.94	13.65
3711	24.61	24.67	8.83	10.55	11.56	13.75

3742	24.66	28.56	8.82	9.65	11.76	14.17
3772	24.66	29.9	8.97	8.79	12.49	14.52
3803	25.02	30.01	8.59	8.50	12.05	13.35
3833	25.07	29.67	8.63	7.80	11.48	13.47
3864	24.18	19.02	7.39	5.78	8.62	10.67
3895	24.31	25.83	7.82	6.22	9.38	12.10
3925	24.24	26.9	8.43	7.48	10.00	13.01
3956	24.25	24.06	7.59	5.92	9.77	12.93
3986	26.18	22.36	8.62	7.74	10.18	12.82
4017	24.66	26.16	9.20	8.65	10.44	12.05
4048	24.94	19.92	9.07	8.92	11.19	12.02
4077	29	26.4	8.75	9.31	11.84	12.01
4108	24.93	26.64	9.03	9.77	11.31	12.43
4138	24.99	27.44	9.06	10.09	13.1	12.69
4169	25.08	27.6	8.83	9.61	12.64	12.23
4199	21.12	16.3	8.31	7.13	11.28	10.10
4230	24.52	20.08	8.52	7.80	9.94	11.06
4261	24.71	25.21	8.63	8.69	10.06	11.28
4291	24.77	25.92	9.03	8.10	10.19	11.96
4322	24.87	26.43	9.20	8.58	10.47	12.21
4352	25.17	26.25	9.61	9.26	10.97	11.70
4383	25.34	26.18	9.98	9.06	10.49	11.74
4414	25.75	26.05	10.35	9.48	11.59	11.98
4442	25.54	25.99	10.40	9.52	12.08	11.80
4473	25.8	26.3	10.89	10.40	12.88	12.49
4503	25.26	25.96	11.48	9.35	13.68	12.61
4534	25.33	25.76	11.58	9.54	12.59	12.38
4564	24.99	25.24	8.45	7.18	11.70	10.67
4595	25.26	24.07	7.17	5.68	9.54	9.88
4626	25.33	21.42	8.40	7.14	9.76	11.07
4656	25.42	21.87	8.44	7.14	9.82	10.43
4687	25.27	22.06	7.69	6.39	8.93	9.73
4717	25.5	18.77	8.75	8.03	9.87	12.33
4748	25.74	21.38	8.98	8.75	10.16	12.15
4779	26	20.33	9.89	8.72	10.81	13.41
4807	26.24	17.19	10.27	9.70	12.02	13.79
4838	26.3	16.49	10.26	9.52	12.23	14.30
4868	26.42	17.64	16.99	10.39	13.51	15.68
4899	26.53	12.81	11.63	9.15	11.47	13.74
4929	20.68	22.95	8.99	8.66	9.97	12.38
4960	25.37	21.58	8.16	10.84	9.74	10.64
4991	25.31	12.3	8.93	7.91	10.85	10.28
5021	23.55	16.9	9.18	9.40	10.49	12.81

5052	24.58	24.96	8.91	8.82	10.42	11.67
5082	26.3	25.45	9.00	8.66	10.58	13.20
5113	25.94	25.6	9.21	8.74	10.64	13.33
5144	25.46	25.82	10.70	9.85	11.08	12.8
5172	26.62	26.28	10.91	9.79	10.94	12.81
5203	26.14	25.87	12.60	10.47	11.35	12.55
5233	26.27	25.84	12.60	9.22	11.33	13.4
5264	26.68	25.83	12.40	9.10	11.65	13.01
5294	26.78	26.18	8.64	8.67	10.93	11.83
5325	26.69	23.86	8.60	8.02	9.71	9.47
5356	26.15	24.85	8.24	7.02	9.80	6.53
5386	25.4	16.93	7.03	8.14	8.46	11.11
5417	25.7	24.96	8.58	8.77	10.03	11.35
5447	26.51	25.45	8.58	7.56	9.87	10.66
5478	26.01	25.36	8.80	9.13	10.16	11.37

EFFECT OF BAKKIKAYAM REGULATOR ON GROUNDWATER USING GEOPHYSICAL TECHNIQUES AND VISUAL MODFLOW

By

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ABSTRACT OF THESIS

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ABSTRACT

A study on ‘Effect of Bakkikayam Regulator on groundwater using Geophysical Techniques and Visual MODFLOW’ was conducted at the ayacut areas of Bakkikayam regulaor, situated across the Kadalundi River at Pandikasala, Vengara, Malappuram district. The objectives of the research work were to study the aquifer characteristics of the area using earth resistivity studies, to assess the groundwater flow variation due to the presence of Bakkikayam Regulator, to develop ground water resource map of the study area using Visual MODFLOW and to identify the potential ground water zones of the study area.

In order to analyze the aquifer characteristics of the study area, Vertical Electrical Sounding (VES) survey was carried out using Signal Stacking Resistivity Meter (MODEL-SSR-MP-ATS at 18 locations and were interpreted using IPI2WIN software. The sounding curve obtained from the interpretation of resistivity studies revealed that most part of the study area showed H and HK type curve indicating the presence of good to moderate quality ground water. From the VES studies it could be concluded that, top soil of the study area is either laterite soil or hydromorphic soil of thickness 0.75 to 4 m, followed by laterites with varying hardness to a depth of 4 m to 17 m. Lithomargic clay of thickness less than 2 m is seen below the laterites in some places. These layers are overlying weathered rock of 2 to 14 m thickness followed by hard rock with or without fractures. Major aquifer formations in the study area are identified as laterite, clay and weathered rock.

Effect of bakkikayam regulator on ground water variation was analyzed based on pre and post monsoon water table data. The ground water level during pre and post monsoon from dug wells located in upstream and downstream side of the Bakkikayam regulator were observed and the difference between pre and post monsoon water table (water table fluctuations) were noted .It was observed that the water table fluctuation in the wells located in downstream side ranged from 5.41 to 5.62 m.

Visual MODFLOW software version 2.8.1 was used for the groundwater modeling of the study area. A base map was prepared and imported in to the model as bmp format. The conceptual model for the study area was developed using base map, well logs and the data collected by conducting geophysical survey of the study area and the study area was discretized by dividing into 50 rows and 50 columns with a grid spacing of 530 m x 520 m. By comparing the water table contour map obtained from the validated model before and after the implementation of Bakkikayam Regulator, it could be seen that the light blue color is changed to green color, indicating that there was a decline of 3 to 4 m water table in the downstream side of the regulator.

The validated model was used to predict the water table contour map of the study area for the next five years by increasing the recharge rate 10, 20 and 30 percent of the recharge rate of the validated period (2019). An increase in water table of 2m was observed during the predicted period due to 20% increase of ground water recharge rate. Beyond that there was no significant change in water table and remained more or less constant. This is due to the reason that topography of the downstream area of the Bakkikayam regulator especially parts of Nannambra and Tirurangadi Panchayaths comes under low land. The ground water flow from this area is towards the river and from where water drains into Arabian Sea. This necessitates some obstructions to check the flow of river or any other water conservation measures at downstream side.

From the velocity vector map obtained using the Visual MODFLOW model, it was observed that the flow direction and magnitude were maximum in two water bodies locally named ‘Morya Kappu’ and ‘Venchali Kappu’, which can be identified as high ground water potential area. At present these water bodies and their drainage channels of around 10,000 m are filled with sediment deposits. Hence it is recommended that the deepening of two water bodies upto 3 m and their drainage channels upto 1.6 m, is essential to solve the problems encountered for paddy cultivation in Nannambra Panchayath to a large extent.