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DECLARATION

We hereby declare that this project entitled "**STUDIES ON THE EFFECT OF SALINE WATER INTRUSION IN TAVANUR-PONNANI AREA**" is a bonafide record of project work done by us during the course of project and the report has not previously formed the basis for the award to us for any degree, diploma, associateship, fellowship or other similar title of any other university society.

HASNA AMEENA P O

(2015-02-022)

JESNY M J

(2015-02-023)

ROHIT YADAV

(2015-02-030)

Place: Tavanur

Date:

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CERTIFICATE

Certified that this project report entitled "**STUDIES ON THE EFFECT OF SALINE WATER INTRUSION IN TAVANUR-PONNANI AREA** " is a bonafide record of project work jointly done by Hasna Ameena P O.(*Admn, No. 2015-02-022*), Jesny M J. (*Admn. No. 2014-02-023*) and Rohit Yadav. (*Admn. No. 2014-02-030*) under my guidance and supervision and that is has not previously formed the basis for the award of my degree, diploma, fellowship, associateship, or other similar title of any other University or Society to them.

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Above all we bow our head before **The Almighty**, whose blessings empowered us to complete this work successfully.

HASNA AMEENA

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ROHIT YADAV

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ABSTRACT

Ground water is one of the most valuable natural resources, which supports human health, economic development and ecological diversity. The world is facing a growing demand for high quality water resources while the water availability remains constant. Exploration of ground water as a viable source for domestic, agricultural and industrial use has assumed top priority in recent years. Over exploitation of ground water leads movement of saline water in coastal aquifers thus increased salt content in nearby wells.

Groundwater models are increasingly used in modelling of groundwater flow problems to develop useful information about groundwater resources. In this study combination of two software is used which are Visual MODFLOW 2.8.1 and Visual MODFLOW classic. MODFLOW model is applied to assess the groundwater flow and availability in Ponnani – Tavanur area of Malappuram district, Kerala. SEAWAT, which is included in Visual MODFLOW classic is used for salt water intrusion modelling of the coastal aquifers of the study area. SEAWAT 2000 is computer program for simulation of three-dimensional, variable-density, transient ground water flow in porous media in which MODFLOW-2000 and MT3DMS are combined into a single program.

The objectives of the study were to develop a groundwater flow model, to study the groundwater table fluctuations and to develop a saline water intrusion model for the study area. 18 observation wells were established in the study area. Samples of water were collected from the observation wells established in the study area. Quality analysis of the water sample was done to assess the quality of groundwater and the extent of salt water intrusion in the area.

A conceptual model of the study area was constructed based on the topographical, climatic and hydrogeological data of the area along with the field observation data including the water table level in the observation wells. The recharge in the area was taken as 10% of the average rainfall of the area during the period of study. The study also includes the calibration of the model, the validation of the model and the prediction of the groundwater conditions of the study area in the succeeding year. The model was calibrated for the fifteen months data from May 2017 and the remaining data was used for the validation of the model. The model predicted the flow of groundwater and its velocity in magnitude and direction. Seawat was used to predict

the saline water intrusion from the sea to the coastal aquifers. Simulation of the saline water intrusion into the study area after 1000 days showed an increase in the salt concentration. The groundwater modelling using the visual MODFLOW software is well understood by this study.

APPENDIX I

ELEVATION DATA OF DIFFERENT WELLS

X Coordinates	Y Coordinates	Ground Layer	Lateritic Rock	Lateritic Soil	Sandy Soil
7168.2	9073	20	19.5	11.5	-23.5
6552.1	7025	14	14	8	-27
9000	7600	13	13	7	-43
4824	5690.3	10	10	6	-41
3684.7	5773.3	9	9	4	-41
2352.1	5705.1	10	10	6	-33
1617.5	4729.9	8	8	8	-57
1728.7	3233	8	8	8	-62
1400.6	3203.5	8	8	8	-64
4659.1	6357.7	10	10	5	-40
4734.7	5931.8	11	11	6	-44
7550	5170.5	11	11	5	-30
5300	3258.8	12	12	6	-23
2558.1	1765.6	18	18	14	-41
3000	1256.9	11	11	7	-43
3100	34.7	10	10	5	-36
3176.1	838.4	9	9	4	-51
4805.7	2790.6	9	9	3	-42

CHAPTER 1

INTRODUCTION

1.1 General overview

Water is an essential commodity to all living species and it covers 71% of the earth's surface. The largest available source of fresh water exists in the form of groundwater. Groundwater is the main source of water for industrial, agricultural and domestic uses. The world's total water resources are estimated as 1.37×10^8 million ha-m and only 2.8 % of total water exist as fresh water. Out of the 2.8% about 2.2% is available as surface water and 0.6% as stored water. Only 0.3% can be economically extracted with the present drilling technology, the remaining being unavailable as it is situated below a depth of 800m. Groundwater is replenished by surface water from precipitation, streams and rivers when recharge reaches the water table. The main source of groundwater is precipitated water. The aquifers are geological units that permit the movement of water, this movement being from areas of high pressure to areas of low pressure at a rate that depends on the condition of aquifer material. The movement of groundwater in subsurface is responsible for a variety of environmental and geological process including heat and solute transfer. Saltwater intrusion is the movement of saline water into fresh water aquifers, which can lead to contamination of drinking water sources and other consequences. The groundwater is extracted from aquifer through pumping wells and with an increase in the withdrawal of groundwater; the quality of groundwater has been continuously deteriorating.

Saltwater intrusion occurs naturally in most coastal aquifers, owing to the hydraulic connection between groundwater and sea water. The fresh groundwater flows from inland areas towards the coast where elevation and groundwater levels are lower. Because sea water has a higher content of dissolved salts and minerals, it is denser than fresh water, causing it to have higher hydraulic head than fresh water. The high pressure and density of salt water causes it to move in to the coastal aquifers in a wedge shape under the fresh water. The salt water and fresh water meet in a transition zone where mixing occurs through dispersion and diffusion. Ordinarily the inland extent of the salt water wedge is limited because fresh groundwater levels, or height of the fresh water column, increases as land elevation gets higher.

The increasing demand for water to meet drinking, domestic, agricultural and industrial need is placing greater emphasis on the development of groundwater resources in coastal areas of Kerala. This is because of high population and unpotability of water along the coastal areas. Absence of perennial fresh water bodies in the coastal stretch of the state resulted in an almost complete dependence on groundwater for meeting the drinking and domestic use of the vast majority of population living in the coastal area. Availability of groundwater is therefore an important crucial factor for development and sustained living in the state in general and coastal area in particular.

Kerala state lies as a narrow strip of land along the southwest corner of India bordered by the Western Ghats on the eastern side and Lakshadweep Sea on the western side. The state lie between the North latitudes 8°18′ and 12°48′ and East longitudes 74°52′ and 77° 22′. Though the state is blessed with plenty of rainfall and water resources, the availability of water resources, especially the groundwater, is not uniform throughout. It varies from place to place. The state has varied hydrological and geomorphological characteristics and hence the groundwater potential, too differ from place to place.

Malappuram has a unique place in the geological history in view, the district lies between North latitudes 10°40′ and 11°32′ and East longitude 75°50′ and 76°36′. Geomorphologically the district can be divided into three zones, viz., coastal plain, mid land and highland. Hydrologically, the aquifer system in the district can be broadly divided into crystalline aquifers (fractured basement rock aquifers), laterite aquifers, lateralized sedimentary (tertiary) aquifers and alluvial aquifers. Crystalline and laterite aquifers constitute major part (85%)of the district. The main problem encountered in the coastal belt is the deterioration of the quality of groundwater due to the influence of the adjacent sea. This problem is severe during dry season (April-May) of the year when the rainfall is zero. The groundwater available during this period becomes unsuitable for domestic and irrigation purposes. This problem is less severe during monsoon season (June-November).

So groundwater management has become a critical issue for the current and future generations. Groundwater models can play an important role in the development and management of groundwater resources and in predicting the effects of the management measures. With rapid increase in computational ability and wide availability of computers and modelling softwares, groundwater modelling has become a standard tool for effective groundwater management. Good management requires information on the response of the system to various stresses. A prediction of response of the system can be obtained by constructing and solving mathematical models of the investigated domain. Any planning of mitigation or control measures, once contamination has been detected in the saturated or unsaturated zones, requires the prediction of the path and the fate of contaminants in response of the planned activities. Any monitoring or observation network must be based on the anticipated behaviour of the system.

1.2 Flow models

A model is representation of the actual system. A groundwater model may be a scale model or an electric model used to simulate and predict aquifer conditions. Groundwater models are mainly used to represent the natural groundwater flow in the environment and to make predictions about a groundwater system’s response to a stress. Groundwater models are an attempt to represent the essential features of the actual groundwater system by means of a mathematical counterpart. Some groundwater models include (chemical) quality aspects of the groundwater. Such groundwater models try to predict the fate and movement of the chemicals in natural, urban or hypothetical scenarios.

Groundwater models may be used to predict the effects of hydrological changes (like groundwater abstraction or irrigation developments) on the behaviour of the aquifer and are often named groundwater simulation models. Also nowadays the groundwater models are used in various water management plans for urban areas. As the computations in mathematical groundwater models are based on groundwater flow equations, which are differential equations that can often be solved only by approximate methods using a numerical analysis, these models are also called mathematical, numerical, or computational groundwater models.

The mathematical or the numerical models are usually based on the real physics the groundwater flow. These mathematical equations are solved using numerical codes such as MODFLOW, Parflow, HydroGeoSphere, OpenGeoSys etc. Various types of numerical solutions like the finite difference method and the finite element method are used in these methods.

1.2.1 Inputs

For the calculations one needs inputs like:

- hydrological inputs,
- operational inputs,
- external conditions : initial and boundary conditions,
- hydraulic parameters.

The models may have chemical components like water salinity, soil salinity and other quality indicators of water and soil, for which inputs may also be needed.

1.2.2 Applicability

The applicability of a groundwater model to a real situation depends on the accuracy of the input data and the parameters. Determination of these requires considerable study, like collection of hydrological data (rainfall,evapotranspiration,irrigation,drainage) and determination of the parameters mentioned before including pumping tests. As many parameters are quite variable in space, expert judgment is needed to arrive at representative values. The models can also be used for the if-then analysis: i.e., if the value of a parameter is A, then what is the result, and if the value of the parameter is B instead, what is the influence? This analysis may be sufficient to obtain a rough idea of the groundwater behavior, but it can also serve to do a *sensitivity analysis* to answer the question: which factors have a great influence and which have less influence. With such information one may direct the efforts of investigation more to the influential factors.When sufficient data have been assembled, it is possible to determine some of the missing informations by calibration. This implies that one assumes a range of values for the unknown or doubtful value of a certain parameter and one runs the model repeatedly while comparing results with known corresponding data. For example, if salinity figures of the groundwater are available and the value of hydraulic conductivity is uncertain, one assumes a range of conductivities and selects that value of conductivity as "true" that yields salinity results close to the observed values, meaning that the groundwater flow as governed by the hydraulic conductivity is in agreement with the salinity conditions. This procedure is similar to the measurement of the flow in a river or canal by letting saline water of a known salt concentration drip into the channel and measuring the resulting salt concentration downstream.

1.3 MODFLOW

MODFLOW is the U.S. Geological Survey modular finite-difference flow model, which is a computer code that solves the groundwater flow equation. The program is used by hydrogeologists to simulate the flow of groundwater through aquifers. The source code is free public domain software, written primarily in Fortran, and can compile and run on Microsoft Windows or Unix-like operating systems. Since its original development in the early 1980s, the USGS has made four major releases, and is now considered to be the defacto standard code for aquifer simulation. There are several actively developed commercial and non-commercial graphical user interfaces for MODFLOW.

MODFLOW was constructed in what was in 1980's called a modular design. This means it has many of the attributes of what came to be called object-oriented programming. For example, capabilities (called "packages") that simulate subsidence or lakes or streams, can easily be turned on and off and the execution time and storage requirements of those packages go away entirely. If a programmer wants to change something in MODFLOW, the clean organization makes it easy. Indeed, this kind of innovation is exactly what was anticipated when MODFLOW was designed.

Importantly, the modularity of MODFLOW makes it possible for different Packages to be written that are intended to address the same simulation goal in different ways. This allows differences of opinion about how system processes function to be tested. Such testing is an important part of multi-modeling, or alternative hypothesis testing. Models like MODFLOW and SUMMA, a program from NCAR that simulates surface processes like rainfall-runoff and gully erosion, make this kind of testing more definitive and controlled. This results because other aspects of the program remain the same. Tests become more definitive because they become less prone to being influenced unknowingly by other numerical and programming differences.

Visual MODFLOW(VMOD) is a software program developed by Waterloo Hydrogeologic. Originally released in 1994, Visual MODFLOW was the first commercially available graphical interface for the open source groundwater modeling engine called MODFLOW. As of May 2012, a newer .NET version of the software was rebranded as Visual MODFLOW Flex. The program also combines proprietary extensions, such as MODFLOW-SURFACT, MT3DMS (mass-transport 3D multi-species) and a three-dimensional model explorer. Visual MODFLOW supports MODFLOW-

2000, MODFLOW-2005, MODFLOW-NWT, MODFLOW-LGR, MODFLOW-SURFACT, and SEAWAT.The software is used primarily by hydrogeologists to simulate groundwater flow and contaminant transport.

Visual mudflow can be applied for i.) Evaluating groundwater remediation systems, ii.) Delineating well capture zones, iii.) Simulating natural attenuation of contaminated groundwater, iv.) Design and optimize pumping well locations for dewatering projects v.) Determine containment fate and exposure pathways for risk assessment. The visual MODFLOW interface has been specially designed to increase modeling productivity and decrease the complexities typically associated with building three dimensional groundwater flow and contaminant transport models. The interface is divided into three separates modules, viz., Input Module, Run Module and Output Module.

1.4 Steps in Groundwater Flow Modelling

Every groundwater flow modeling consists of the following stages:

1. Concept development- It is the most important part of modelling and the basis for all further activities.
2. Selection of computer code for simulation - Code is selected such that it can most effectively simulate the concepts and purposes of modeling.
3. Definition of model geometry- It include lateral and vertical extent of area to be modelled defined by boundaries, grid layout, position and number of layers.
4. Definition of cell types - (Active, inactive, constant head cell)
5. Input of hydro-geologic parameters for each cell - Hydraulic conductivity (horizontal and vertical), storage properties and porosity are assigned to each zone.
6. Definition of boundary conditions (boundaries with known head)
7. Definition of initial head.(Distribution of hydraulic head)
8. Definition of stresses acting upon system (areal recharge, well pumpage)
9. Definition of initial concentration (salt water concentration of all wells)
10. Addition of salt water concentration for all wells during the study period
11. Model-run- it includes choosing a mathematical model for solving the system of algebraic equation, iteration criteria and acceptable error criteria for terminating the iteration process.
12. Calibration and sensitivity analysis- This is probably the lengthiest and most demanding part of any modeling process.
13. Verification of model validity- The calibrated model is checked against another set of field data that was not used in model design.
14. Prediction –In most cases it is the purpose of model design
15. Presentation of result- this includes both the prediction result and relevant data documenting stages of model design.

1.5 Study Background and Objectives of the Study

The Tavanur-Ponnani region is selected as the study area which is a coastal belt, for observing the reduction in groundwater levels and salt water intrusion. So the proper management of the available water is main outcome for the current and future periods. Groundwater models play an important role in the development and management of groundwater resources and in predicting effects of the management measures.

So the main objectives of the present study are:

1. To develop a solute transport model for the coastal aquifer using SEAWAT and to study the effects of saline water intrusion in the study area
2. To study the groundwater table fluctuation along the coastal area of Tavanur-Ponnani region of Mallappuram district.
3. To assess the quality of groundwater.
4. To develop a groundwater flow model of study area by using the software Visual MODFLOW

CHAPTER 2

REVIEW OF LITERATURE

The chapter reviews the concepts and literature available on groundwater flow, details of MODFLOW and finally the case studies of salt water intrusion in the coastal belt.

2.1 Groundwater modeling

Hariharan *et al.*(2017) conducted a study on the review of visual MODFLOW applications in groundwater modelling .Visual MODLOW is a graphical user interface for the USGS MODFLOW. It is a commercial software that is popular among the hydrogeologists for its user-friendly features. The software is mainly used for groundwater flow and contaminant transport models under different conditions. The paper reviews the versatility of its applications in groundwater modelling for the past 22 years in the fields of agriculture, airfields, constructed wetlands, climate change and drought studies, Environmental Impact Assessment (EIA), landfills, mining operations, river and flood plain monitoring, salt water intrusion, soil profile surveys, watershed analyses, etc., are the areas where the software has been reportedly used till the current date. The review provided a clarity on the scope of the software in groundwater modelling and research. It is evident from the review that the software has found applications in a variety of groundwater flow simulation settings and shows an optimistic research potential with the software for the future. The Middle East and the Asian countries (especially, China) have used the software comparatively more than other nations in modelling. The study of literature shows that the same research methodologies can be adopted for similar scenarios in other countries as well. Integrating other modelling software such GIS, SWAP, SWAT, etc., with Visual MODFLOW have been attempted in some studies. Such attempts add novelty to the research.

Tiwari *et al*. (2014) developed a modelling for groundwater resources in alluvial region of upper Narmada basin using Visual MODFLOW to suggest a groundwater development and utilization plan for future. The specific objectives were to simulate groundwater system in a selected area of alluvial plain of Narmada basin, to calibrate and validate the model using past data and to predict the groundwater scenario of the selected area in the year 2025. Model calibration for steady-state showed a good agreement between observed and simulated initial water level contour. Results of the calibrated flow model (steady and transient state) indicated that the hydraulic conductivity of upper Narmada basin ranges between 0.000257 and 0.000567 m/s. While predicting for the year 2025 increased abstraction rate by 12% of the current withdrawal rate were considered. It was observed during the prediction run that maximum head range of 456 to 463m and minimum head range 306 to 308 which is 0.2% to 0.3% less than the present head value.

Nassim *et al*. (2013) used MODFLOW Program for evaluation of groundwater resources in alluvial aquifer in Evan sub basin (Iran). The model was calibrated and verified using historical and observed water level data for periods 2005 to 2006 and 2006 to 2007, respectively. The model was run to generate groundwater scenario for a 10 year period from 2005, considering the existing rate of groundwater draft and recharge. The water budget predictions indicated a decrease from 8.34 to 4.43 MCM in groundwater storage system. The predicted water table contour maps for the years 2015 was generated. The study indicated that over exploitation of groundwater will lead to extreme reduction of water resources in period 2014-2015.

Kant *et al*. (2013) studied the groundwater in sonar sub-basin, Madhya Pradesh using Visual MODFLOW. The study of groundwater levels in unconfined aquifer in different regions of the Madhya Pradesh, experienced significant groundwater decline during the last nine decades due to excessive groundwater withdrawal. The results obtained from the model were found to be in agreement with the observed records. Water level data from 15 piezometers were evaluated and analysis of predicted results indicate that the probability of water level drop in the aquifer for the next few years and in the case of a large harvest process, the drop will be very severe.

Koohestani *et al.* (2013) Hernandez *et al.* (2012) worked on modeling groundwater levels on the Calera aquifer region in Central Mexico using MODFLOW. Result of the evaluation yielded average coefficients of determination of 0.81 and 0.67 and root mean square error value lower than 25.1 and 25.9 m. for the calibration and validation process respectively, these results are indicative of a good agreement between predicted and observed groundwater levels. However, further improvements in the conceptual model may be needed to improve prediction in other path of the CAR for evaluating alternatives groundwater management strategies.

Yanxuna *et al*. (2011) studied groundwater flow in Balasu water source in which Visual MODFLOW is applied to set up the mathematical model which is used for groundwater flow numerical simulation. The calibration and validation of results of the numerical model indicated that the model can reflect the actual hydrogeological conditions, and can be applied in predicting the future groundwater flow conditions. They showed that the mathematical model can be used for predicting the groundwater system conditions under thefuture conditions. The main source of runoff is precipitation recharge, but there is no positive means to predict the future precipitation.The Visual MODFLOW software is adopted to simulate the groundwater flow in Balasu water source. By model calibration and verification, the simulation results and the measured results are wellfitted, and showed that it can be applied to predict the water flow under future mining conditions.

Dong (2011) worked on a simple, yet effective method to simulate areal recharge and discharge based on the recharge (RCH) package of MODFLOW, allowing multiple instances of the RCH package to be used in one model. The method has been implemented in MODFLOW2000/ 2005 and has been successfully applied to a regional groundwater flow model to simulate areally distributed precipitation recharge, agricultural discharge and irrigation infiltration recharge in a simple approach.

Post (2011) presented a new package, Periodic Boundary Condition (PBC) package into MODFLOW to overcome the difficulties encountered with tidal boundaries in modeling coastal groundwater system. It highlights the boundary condition for head and concentration during simulations and allows for development of seepage face. This new package was developed for MODFLOW and SEAWAT. Boundary conditions were assigned to the nodes at the sediment water interface depending on a user-defined tidal signal.

Lin *et al*. (2009) developed a simplified numerical model of groundwater and solute transport. In the resultant model, they divided the seepage region into several virtual layers along the z direction and vertical 1-D columns covering x-y 2-D area according to stratum properties. The numerical algorithm replaces the full 3-D water and mass balance analysis as the 2-D Galerkin finite element method in x- and y-directions and 1-D finite differential approach in the z direction. The reasonable method of giving minimum thickness was successfully used to handle transient change of water table, drying cells and problem of rewetting. The solution of the simplified model was preconditioned conjugate gradient and ORTHOMIN method. The validity of the developed 3-D groundwater model was tested with the typical pumping and backwater scenarios. Results of water balance of the computed example revealed the model computation reliability. Based on a representative 3-D pollution case, the solute transport module was tested against computing results using the MT3DMS. The capability and high efficiency to predict non-stationary situations of free groundwater surface and solute plume in regional scale problem was quantitatively investigated and it was shown that the proposed model is computationally effective.

Hai-long *et al.* (2006) developed a three-dimensional groundwater flow and wastewater transport and degradationModel using MODFLOW and MT3DMS modeling for the optimization of design and operation of the wastewatersoil treatment system. The developed model was calibrated using the Soil Infiltration Treatment System (SITS) in the Chongming island of China after considering the river−groundwater interaction and the regional geological and hydrological conditions. Using the calibrated model, the following problems with regard to thedesign and operation of SITS were discussed: (1) Allowable hydraulic load. The hydraulic load increases with the drop inthe water level of the adjoining river, the increase in the actualsoil area under operation, and the increase in the distanceamong the individual operation units of SITS. (2) Optimized layout of the groundwater monitoring wells. The concentration contour of the simulated contaminants is very useful to depict the typical areas that are most severely polluted and very sensitive to the peripheral environment, thus lesser number of monitoring wells can be set up based on the model, and the goal of the accurate assessment of the influence of soil-infiltrated wastewater on groundwater were achieved.

Carrera-herna'ndez *et al*. (2005) developed a module of Open Source Geographic Resources Analysis Support System (GRASS) GIS to integrate it with the finite difference groundwater flow model MODFLOW, to take full advantage of the GIS capabilities. The results obtained with this module, when compared to those obtained with an existing MODFLOW pre and post-processor showed that it can be used to develop groundwater flow models using uniform grid spacing on the horizontal plane. This module provided a tool for groundwater flow modeling to those users who cannot afford the commercially available processors and/or to those who wish to develop their models within a GIS.

2.2 SALT WATER INTRUSION

Anil kumar *et al*.(2015) conducted a study of saline water intrusion into the shallow coastal aquifers of Periyar river basin, Kerala using hydrochemical and electrical resistivity method. Electrical resistivity sounding techniques and hydrochemical studies are widely used to determine the interaction between groundwater and saline water/seawater in coastal aquifers. Vertical electrical soundings were carried out at 15 locations in the midland and coastal plain reaches of Periyar river basin in central Kerala, India (9˚ 55'-10˚ 20'N latitude and 76˚ 05'-76˚ 25' E longitude) using CRM 500 model aqua meter. In-situ water quality parameters of water samples from 63 shallow well were also measured using hand-held multi-parameter instrument. The cat ion and an ion content of selected water samples were also determined. Electrical resistivity profiles were interpreted qualitatively and quantitatively to obtain nature and thickness of different resistivity layers. The depth to fresh-saline water interface was delineated from resistivity model. The study indicated majority of the curves obtained were Q type with 3 layers. The depth to saline-fresh water interface varied from 1 to 5 m at different locations. The salinity clay horizons were identified at various depths. Hydrochemical data was analysed using hill-piper diagram and statistical plots to understand groundwater-seawater mixing/interaction in the coastal aquifers. The dominant groundwater type was NaCl followed by MgCl at few places. Higher pH, EC and TDS were noted in the western part towards seaward side. Turbidity levels were found increasing towards southwest parts. The Na+, Cl^- and $(SO_4)^{2-}$ content was found higher in the northwestern parts.

Gopinath *et al*. (2015) conducted a study on modelling saline water intrusion in Nagapattinam coastal aquifers, Tamil Nadu, India. Groundwater levels were measured at 61 locations in Nagapattinam and Karaikal coastal region, identified flow direction pointing toward the coast with no major change in groundwater table. Groundwater samples were collected and analyzed for major ionic parameters, represented higher concentration of conductivity, total dissolved solids, sodium and chloride along the coastal parts of the study area. A computer package for the simulation of dimensional variable density groundwater flow, SEAWAT, was used to model the seawater intrusion in the coastal aquifers of the study area. The model was stimulated to predict the amount of seawater incursion in the study area for a period of 50 years. Water chemistry data signify higher EC and TDS during both the seasons along the coastal regions suggesting saline water traces. Sodium and Chloride were found to be dominating along the coastal regions. Higher nitrate and sulphate suggests evidences of fertilizer influences. The ionic ratio plots suggest influence of saline water intrusion along the coasts and significance of rock water interaction.

Chan-hee-park (2004) conducted a study on saltwater intrusion in coastal aquifer in Georgia institute of technology in September 2004. He conducted the experiment to optimize the pumping rate as well as the well location in the coastal aquifer for freshwater extraction and controlling the salt water intrusion. And also variable density flow in a saturated porous medium was developed in this study through a 3-dimensional finite element model (Techflow), and tested through various benchmark test problems such as the Elder problem and HYDROCOIN for comparison between the developed model and 3D temporal experimental measurement. The conclusions obtained from the numerical experiment in Elder problem were globally continuous velocity estimation can help to reduce the grid density while obtaining convergent solutions to salt water intrusion problems, it is difficult to solve the Elder problem because of the physical instability, Elder problem is sensitive to local grid regularity. Due to 3D nature of application, the location of well screen does make a difference in lateral saltwater encroachment between upper zone and lower zone. Thus the analysis was focused on the water flow between unsaturated zone and saturated zone. Thus the results obtained from the application can be used for the interpretation of scaled-up applications.

Bobba (2009) conducted a study on numerical modelling of salt water intrusion due to human activities and sea level change in the Godavari Delta, India. The study demonstrated the sensitivity of salt-water intrusion. Physical parameters, initial heads, and boundary conditions of the delta were defined on the basis of available field data, steady-state groundwater model was constructed to calibrate the observed head values corresponding to the initial development phase of the aquifer. Initial and boundary conditions determined from the areal calibration were used to evaluate steady-state, Hydraulic heads. Consequently, the initial position of the hydraulic head distribution was calibrated under steady state conditions. The changes of initial hydraulic distribution, under discharge and recharge conditions, were calculated, and the present-day position of the interface was predicted. The present-day distribution of hydraulic head was estimated via a 20-year simulation. The results indicate that a considerable advance in seawater intrusion can be expected in the coastal aquifer if current rates of groundwater exploitation continue and an important part of the freshwater from the river is channeled from the reservoir for irrigation, industrial and domestic purposes.

Fei Ding *et al.* (2015) developed a numerical model for variable-density groundwater flow and miscible salt transport. The SEAWAT code was used to solve the density-dependent groundwater flow and solute transport governing equations. The simulation was conducted for 55 months from October, 2004 to April, 2009. The numerical model was calibrated by the hydraulic heads measured in April, 2009. Using the calibrated model and the same hydrogeological conditions in 2004, the extent of seawater intrusion prediction was conducted for the next 40 years. The results show that the extent of seawater intrusion area will increase in all geologic layers with nearly 6.2 km in the upper Quaternary aquifer and 4.3 km in lower Quaternary aquifer for 40 years. In the Minhuazhen group aquifer, the maximum speed of seawater intrusion is 62.2 m/yr. Therefore, some protection of the freshwater aquifer from seawater intrusion in the Liao Dong Bay coastal plain is imperative.

Lathashri.U.A et al. (2015) used a grid based variable density numerical model, SEAWAT-2000to conceptually simulate groundwater flow and transport for a coastal stretch in Karnataka state, India. SEAWAT is a coupled version of MODFLOW and MT3DMS designed to simulate three-dimensional, variable density groundwater flow and multi-species transport. The variable density flow process uses the familiar and well established MODFLOW methodology to solve the variable density groundwater flow equation. The aquifer considered for the present study is bounded by Arabian sea on the west, the ridge line along the east and Shambhavi and Pavanje rivers along the northern and southern sides respectively. The study has its focus on managing the available data in the most efficient manner to develop a reliable and sophisticated simulation model. The aquifer parameters are estimated by calibrating the model for two year period with daily time step. The aquifer can be categorized as unconfined having good groundwater potential with aquifer transmissivity and specific yield ranging from 10 to 810 m2 /day and 0.0008 to 0.0122 respectively. The model evaluation in terms of the accuracy is carried out by comparing with the measured data on seasonal basis .From this, the model is found to be scientifically sound for further management applications. The model so developed can be applied in predicting the saltwater intrusion in coastal aquifers for various developmental and climate change scenarios like sea level rise

Chapter 3

MATERIALS AND METHOD

The coastal areas of the Ponnani region have been seriously affected by saline water intrusion problems during the summer months. The quantity and quality of water are both affected. The present study illustrates the application of Visual MODFLOW classic for the development of groundwater flow and saline water intrusion models for the study area of Tavanur–Ponnani region. Establishment of observation wells, measurement of groundwater fluctuations, collections of well water samples and locating the positions of observation wells are detailed under this section. Water samples from 18 observation wells were collected along with the location and water table of individual well for each month. Study period for this project was 15 months. The water samples were analyzed for electrical conductivity and salinity using digital water analyzer. Accession of data and methods used for data processing and methodologies for extracting model input are described in detail. Study was done using Visual MODFLOW and Visual MODFLOW classic, groundwater modeling and saline water intrusion modeling were done on Visual MODFLOW and Visual MODFLOW classic respectively.

A short description of the Visual MODFLOW model, operation and its limitation along the description of input file used for evaluating the model performance are also included in this chapter. Procedure used for all input data and calibration of the model under steady state condition are described in this chapter. Various criteria used for evaluating the model performance for stimulating the groundwater flow are also presented. A saline water intrusion model of the study area was also developed using Visual MODFLOW classic to study the extent of saline water intrusion into the coastal aquifers of the area.

3.1 STUDY AREA

The present study has been accomplished in Tavanur and Ponnani region in Malappuram, Northern part of Kerala, India. The Malappuram district lies between north latitudes 10º 40´ and 11º 32´ and east longitude 75º50´ and 76º36´. The district has geographical area of 3550 sq. km. The main rivers which drain the district are Bharathappuzha, Kadalundi river and chaliyar.

The study area falling in the Malappuram district is located at the estuary of Bharathappuzha (River Ponnani), on its southern bank, and is bounded by the Arabian sea on the west and series of brackish lagoons in the south. Geographical area Ponnani is 25 sq. km. It is more or less flat with a gentle slope towards west and south direction. Main issue facing in this area is the salt water intrusion into the coastal aquifers during the dry summer months. The location map of the study area is given in Fig. 3.1.

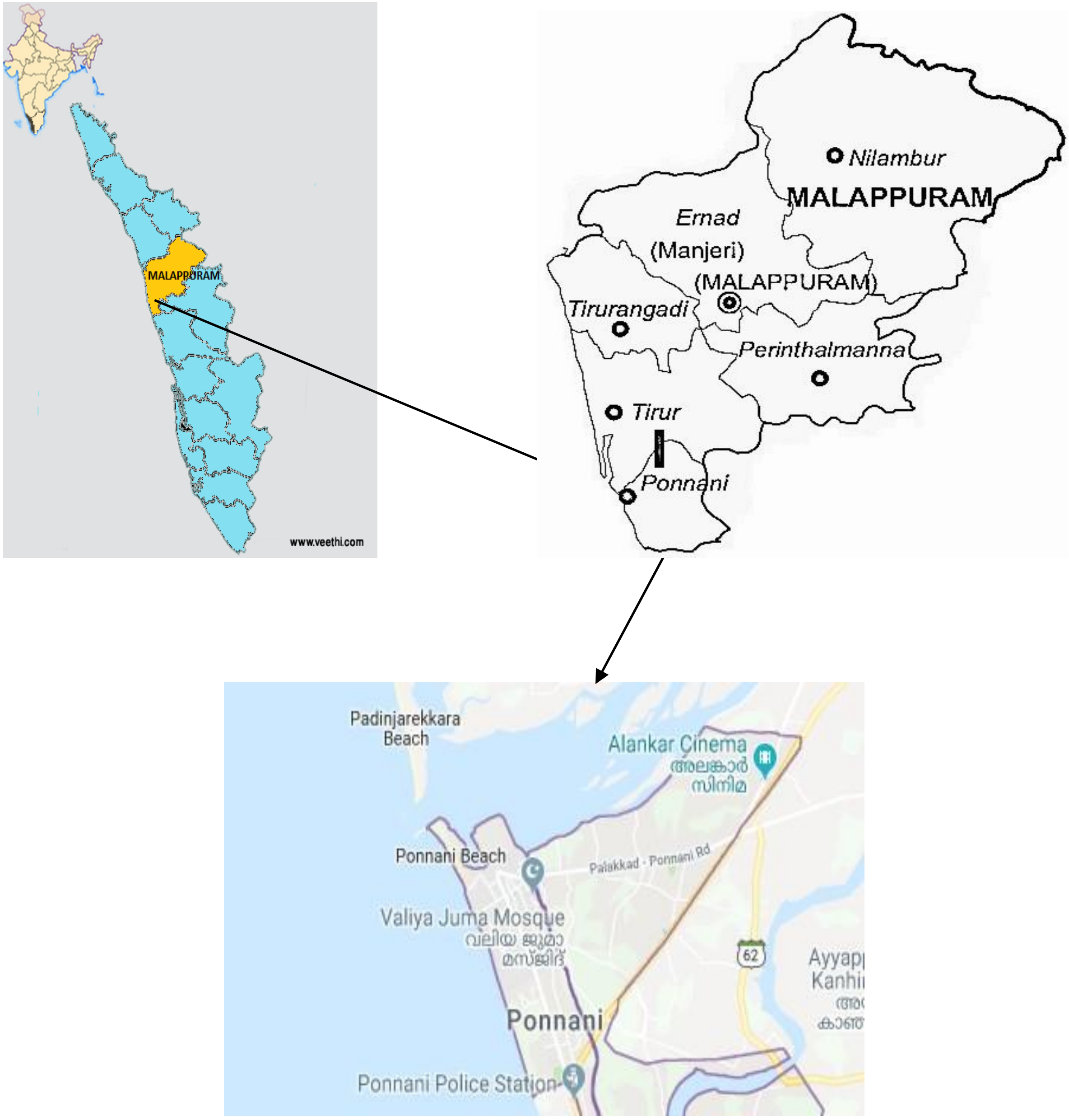

Fig 3.1 Location map of study area

3.1.1 Geographical location

Ponnani lies in north latitude 10.767º and east longitude75.925º. Total geographical area of ponnani is 25sq. km. The population density of the city is 3646 persons per sq. km. It is situated at the estuary of Bharathappuzha (River Ponnani), on its southern bank, and is bounded by the Arabian sea on the west and series of brackish lagoons in the south. It is more or less flat with a gentle slope towards west and north direction.

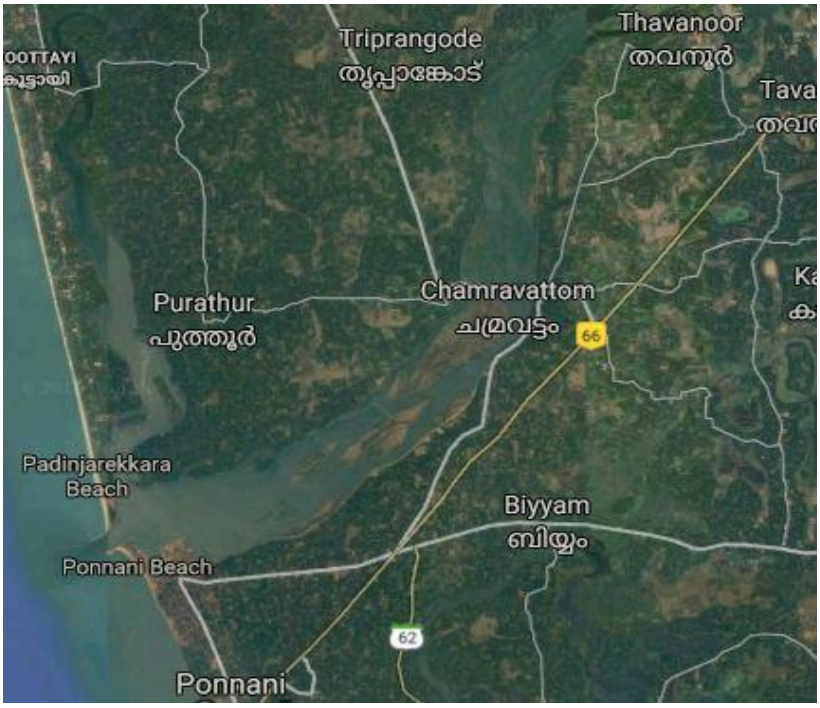

Fig 3.2 BMP Map of study area

3.1.2 Meteorological data

3.1.2.1 Rainfall and Climate

Average annual rainfall of Tavanur - Ponnani is 300 cm. Wet kind of climate is observed in ponnani. South-west monsoon season followed by North-East monsoon season mainly contribute for rainfall in this area. The other seasons are comparatively contributing less rainfall. The South West monsoon is usually very heavy and nearly 73.5% of the rainfall is received during this season. NE monsoon contributes nearly 16.4% and March to May summer rain contributes nearly 9.9% and the balance 0.2% is accounted for during January and February

3.1.2.2 Temperature

The maximum temperatures ranges from 28.9 to 36.2°C and the minimum temperatures range from 17.0 to 23.4°C. The temperature starts rising from January and reaches the peak in the month of March and April and then decreases during the monsoon month and again rising from September onwards. The climate is generally hot and humid. March and April months are the hottest and January and February months are the coldest.

3.1.2.3 Humidity

The humidity observed during june to September which is period of south-west monsoon is comparatively more. During morning hours the relative humidity ranges from 84 to 94%.

3.1.2.4 Wind

During morning and evening hours of the day the wind is prevailing from east as well as west of the region. December to February months experienced higher wind speed compared to other months. It ranges from 2.9 to 7.2 km per hour.

3.1.3 Drainage characteristics

Bharathappuzha river which is also known as Ponnani river flow through town and is the second longest river of Kerala. Anamalai hills which is a part of the Western Ghats is considered as origin of Ponnani river. Bharathappuzha is a non perennial river which drains into the Arabian sea and get dried up in summer, so Ponnani is considered as drought prone area. Kadalundi and Chaliyar are the other two rivers which drain to sea in the district,

3.1.4 Topography

Topography of the district is divided into three natural divisions: lowland, midland and highland. Tavanur-Ponnani region , the study area for this project, has a topography of undulating type, the lowest elevation is at the western boundary of the study area which is around 0-10 m near to the sea. The highest elevation in the study area is towards north-east region which is in range of 35-40 m and is gently sloping towards the Arabian sea.

3.1.5 Study boundaries

The study area includes Bharathappuzha river passing through the middle and bounded by Arabian sea in the South-West and Ponnani-Kuttippuram bypass road in the North-Western side. Along the east and west boundaries the ground is slopping uniformly towards the Arabian sea.

3.1.6 Hydrogeology

The soil in the study area is mainly of metamorphic origin. The subsurface strata of the study area comprises of three different layers, i.e., lateritic rock, lateritic soil and sandy soil. The thicknesses of the various layers vary spatially in different regions in the study area. The lateritic rock which is top layer is present in the high elevation part, i.e., the North-East portion of study area. The layer, below top layer is lateritic soil which is second layer of strata. Third layer which is sandy soil is bottom layer of subsurface strata which is deep towards the south-western portion. The details of hydrogeology and hydraulic conductivities of various layers of the study area is given in Table 3.1.

Layer No.	Soil type	Hydraulic conductivity(m/s)
Layer 1	Lateritic Rock	$10x10^{-5}$–$30x10^{-5}$
Layer 2	Lateritic Soil	4.5×10^{-3}–6×10^{-3}
Layer 3	Sandy Soil	8×10^{-4}-10.5×10^{-4}

Table 3.1 Hydrogeology of the study area

3.1.7 Groundwater

The regional aquifer underlying the area is mainly of lateritic origin. The dominant sources of recharge to the study area are precipitation, river leakage and from the sea.

3.1.8 Recharge

Spatially distributed recharge over the entire first layer of the study area (in mm/y) was taken as one in tenth of the average precipitation for the purpose of the study.

3.2 DATA COLLECTION AND ANALYSIS

3.2.1 Establishment of observation well network

Chamaravattom, Purathur, Nariparambu, Maravancheri, Ponnani, Tavanur and Chamravattom – Ponnani coastal stretch are different parts of the study area. A network of eighteen existing observation wells was selected for water level monitoring in the study area which is distributed over the area. The monitoring of the water levels was done on a monthly basis and water samples were collected for analysis. Each sample represents the quality of water in that particular area and gives a rough idea about the groundwater quality in that area.

3.2.2 Measurement of groundwater table fluctuation

Malappuram district comprises of many rivers which plays role in change of water levels in wells. Daily withdrawal of water from wells, type of geological formation and the relative height from mean sea level are other factors which causes water table variation. The depth to water level in the observation wells were measured from the ground level, with the help of a measuring tape, once in 30 days for the selected wells in the study area. The water levels were recorded from May 2017 to December 2018 at the observation points. The groundwater table fluctuation behavior along the study area was assessed by analyzing the average depth to groundwater level in the observation wells during the consecutive months.

3.2.3 Groundwater quality analysis

Water samples collected from the observations wells of Tavanur-Ponnani region were analysed using the water analyser. A detailed study on quality of well water from the observation wells was done to get an idea about the groundwater quality of the coastal area. Salinity intrusion along the coastal area was assessed by measuring the level of salinity in the water samples collected from the 18 observation wells, selected for this purpose. These samples were tested for electrical conductivity and salinity using the digital water analyzer.

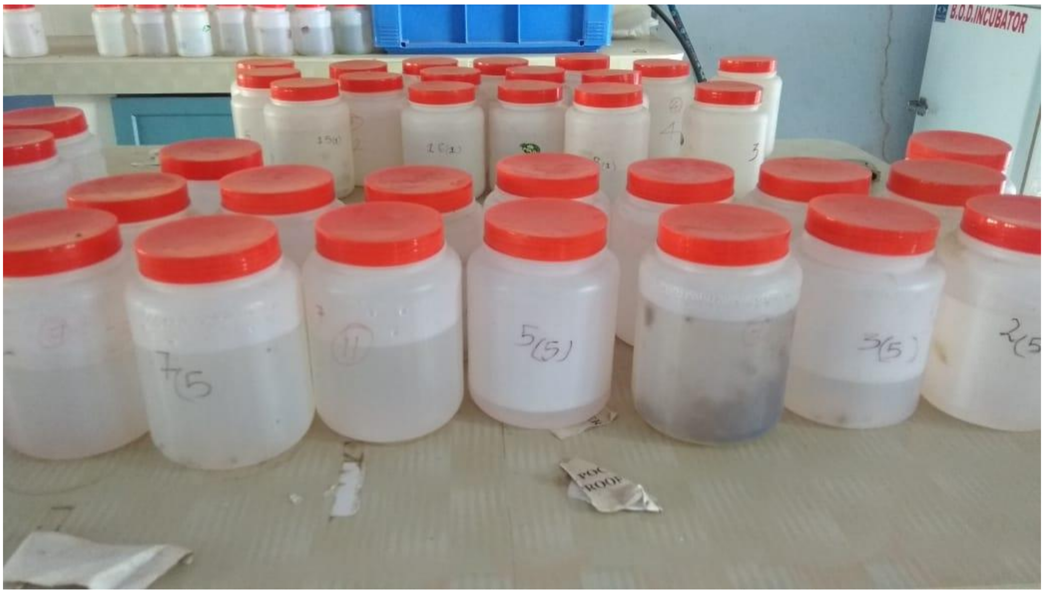

Fig 3.3 Collected water samples

Fig 3.4 Salinity analysis using water analyzer

Fig. 3.5 stock solution preparation

3.2.3.1 Measurement of salinity

Salinity can be defined as a measure of the amount of dissolved salt present in the water sample. Before testing the sample for salinity, the instrument has to be calibrated. So a standard solution of NaCl (10 ppt) was prepared by dissolving 3 g of NaCl in 100 ml of distilled water. This standard solution is used for calibrating the water analyser for salinity. After the calibration of the instrument, the salinity of the samples were tested by dipping electrodes in the collected sample of water with the salinity mode 'ON'. A temperature probe is also inserted into the sample for measuring the temperature. The instrument directly displays the salinity in ppt and temperature in °C.

3.2.3.2 Measurement of electrical conductivity

Electrical conductivity is the property of water, defined as ability to pass electrical current through the water sample due to the presence of dissolved salts. To measure electrical conductivity, instrument was calibrated using 0.1 N KCl standard solution which was prepared by dissolving 0.756 g of KCl in 100 ml of distilled water. Then the instrument is put in the conductivity mode and measurement was done by dipping the electrodes in the water samples. Instrument displays the electrical conductivity in mS and µS. The temperature was adjusted to 25˚C and the same procedure is repeated for other samples.

3.3 GROUNDWATER MODEL

A groundwater model can be defined as a model that simulates groundwater flow and is a simplified portrayal of the subsurface aquifer system. Models can be used for different purposes which are to predict aquifer response to various input/output stresses. The three-dimensional movement of groundwater of constant density through porous medium may be described by partial-differential equation (McDonald and Harbaugh,1988). MODFLOW uses the following equations for groundwater flow simulation:

3.3.1 Flow Equation

Groundwater modelling begins with conceptual understanding of the physical problem. The next step is translating the physical system to mathematical terms. Most models solve the general form of the three- dimensional groundwater flow equation which is a combination of water balance equation and Darcy's law, given by

$$\frac{\partial\ \left(Kx\ \frac{\partial h}{\partial x}\right)}{\partial x} + \frac{\partial\ \left(Ky \frac{\partial h}{\partial y}\right)}{\partial y} + \frac{\partial \left(Kz\ \frac{\partial h}{\partial z}\right)}{\partial z} \pm W = Ss\ \frac{\partial h}{\partial t}$$

where,

K_x, K_y, and K_z are the values of hydraulic conductivity along the x, y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity, h is the potentiometric aquifer head,

W = Volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the groundwater system, and W>0.0 for flow into the groundwater system,

S_s =Specific storage of the porous material, and

t = Time.

This equation describes transient three-dimensional groundwater flow in a heterogeneous and anisotropic medium when combined with boundary and initial conditions, provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions. McDonald and Harbaugh (1988) used a finite difference version of this equation in MODFLOW, where the groundwater flow system is divided into a grid of cells. For each cell there is a single point called node at which the head is calculated. The equation can be solved using the modular three dimensional finite difference groundwater flow model, MODFLOW.

3.3.2 Conceptual Model

The lithological model of the study area was conceptualized with three layers, with lateritic rock forming the top layer, lateritic soil and sandy soils forming second and third layers respectively, thus forming an unconfined aquifer.

3.3.3 Saline Water Intrusion Modelling

Visual MODFLOW includes the SEAWAT Engine to simulate saltwater intrusion. SEAWAT is a computer program for the simulation of three-dimensional, variable-density, transient ground-water flow in porous media. SEAWAT was designed by combining a modified version of MODFLOW-2000 and MT3DMS into a single computer program. SEAWAT contains all of the processes distributed with MODFLOW-2000 and also includes the variable-density flow process (as an alternative to the constant-density ground-water flow process) and the integrated MT3DMS transport process.

3.4 DATA COLLECTED FOR THE MODELLING STUDY

The following data are needed for the present study;

1. Base map of the study area
2. Spatial location of the observation wells obtained using GPS application software.
3. Hydrogeologic and geologic characteristics and parameters of the study area including the hydraulic conductivity and bottom elevations of layers (collected from previous work).
4. Water table data collected from 18 observation wells in the study area.

3.5 DETAILED METHODOLOGY

The model was developed using VISUAL MODFLOW CLASSIC. Microsoft Excel was also used for the input data preparation. The final model design follows several model runs to best match field data with model results. The conceptual model information is translated into mathematical model and model choices are made to suit the data entered and output required. Visual MODFLOW CLASSIC requires model data to be entered in consistent units. Selected units are meters and day, except for recharge where mm/y is used.

The input parameters include:

- Layers
- Recharge
- Surface elevation
- Elevation limits
- Bottom elevation
- River conductance
- Grid
- Concentration

3.5.1 Project information frame

Project name was given as SEAWAT which is displayed in project title field. In case salt water intrusion model, flow simulation is selected as saturated (variable density).Under transport simulation frame, the settings are automatically set for the USGS SEAWAT while in unit section conductivity unit was changed as m/day.

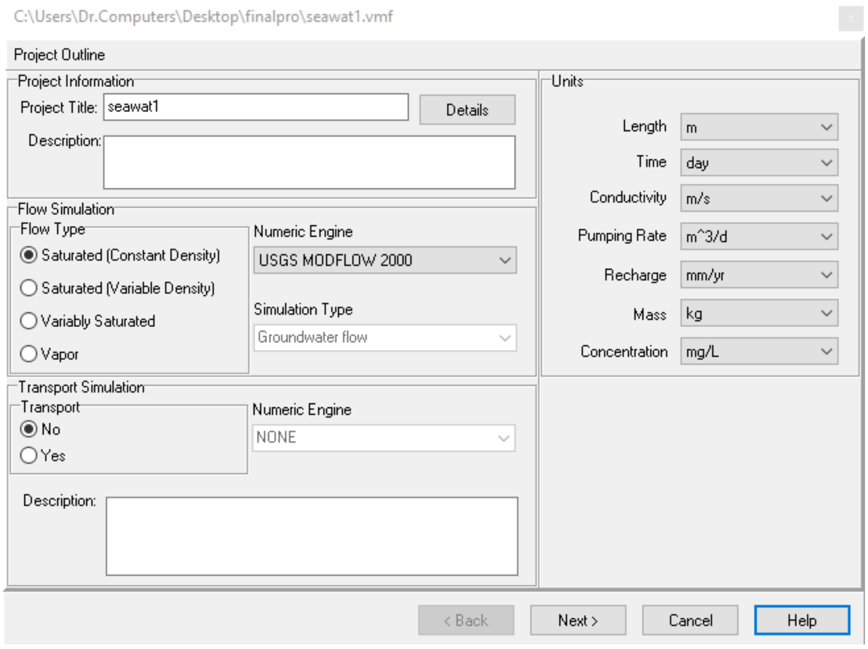

Fig. 3.6 Project Outline

3.5.2 Time option frame

The start date and start time of the model correspond to the beginning of the simulation time period. Currently, this date is relevant only for transient flow simulations where recorded field data may be imported for defining time schedules for selected boundary conditions (Constant Head and River).

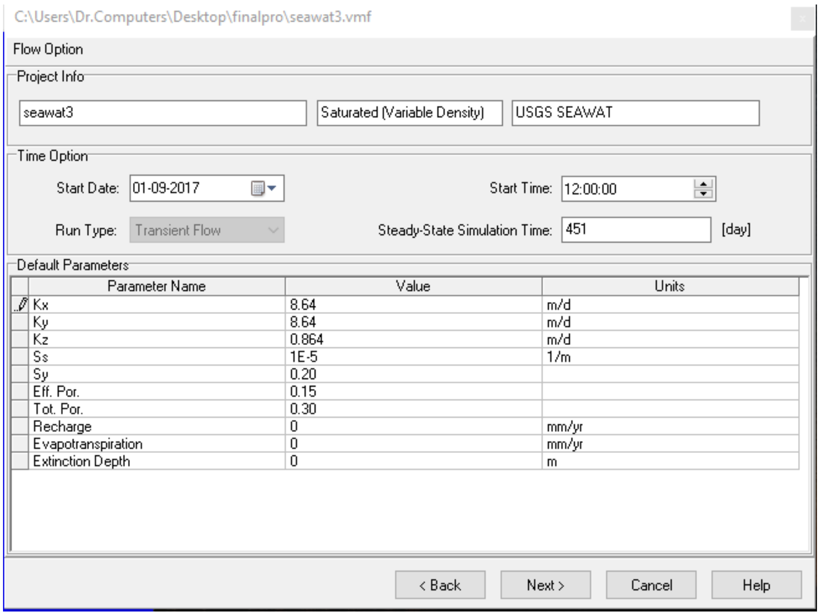

Fig. 3.7 flow option

3.5.3 Default parameters frame

Default parameters were given in flow option field according to following table 3.2;

Table 3.2 default parameters

Model Characteristics	Values
Specific storage, $S_s(m^{-1})$	0.00035
Specific yield, S_y	0.20
Effective Porosity	0.35
Total Porosity	0.40

3.5.4 Default Dispersion Parameters frame

Under this frame dispersion parameters were given:

1. Long dispersivity
2. Diffusion coefficient

Under variant parameters salt concentration was given as 35000 mg/l for study area , rest fields were kept as default values.

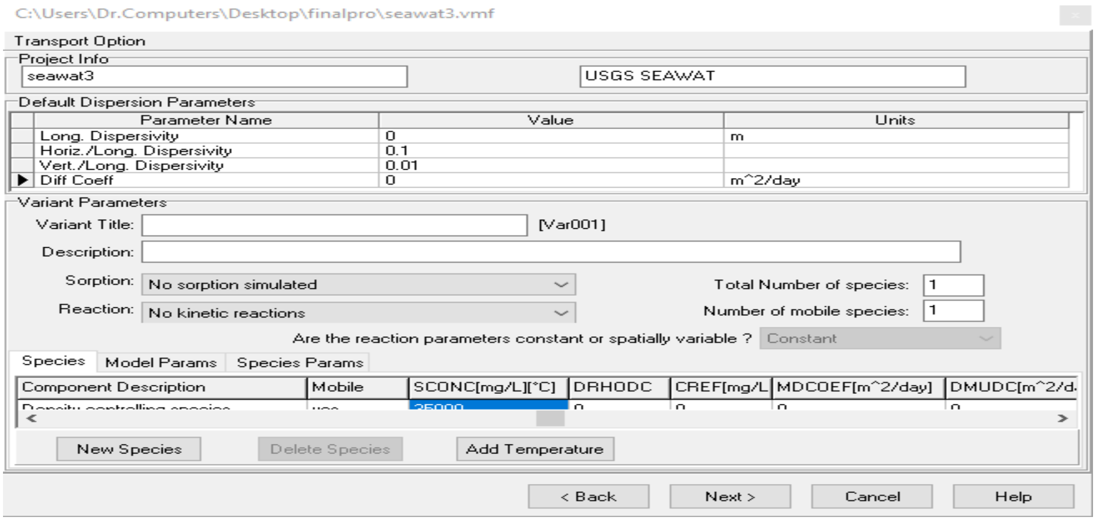

Fig 3.8 Transport Option

3.5.5 Creating the model

Map of the study area coming under Tavanur - Ponnani region obtained from Google Satellite view is taken as base map. And it is converted into bmp format. This converted map is imported into the model. The base map is georeferenced with the co-ordinates. Thus the study area is confined to a base map .The model is based on a rectangular block-centred grid network.

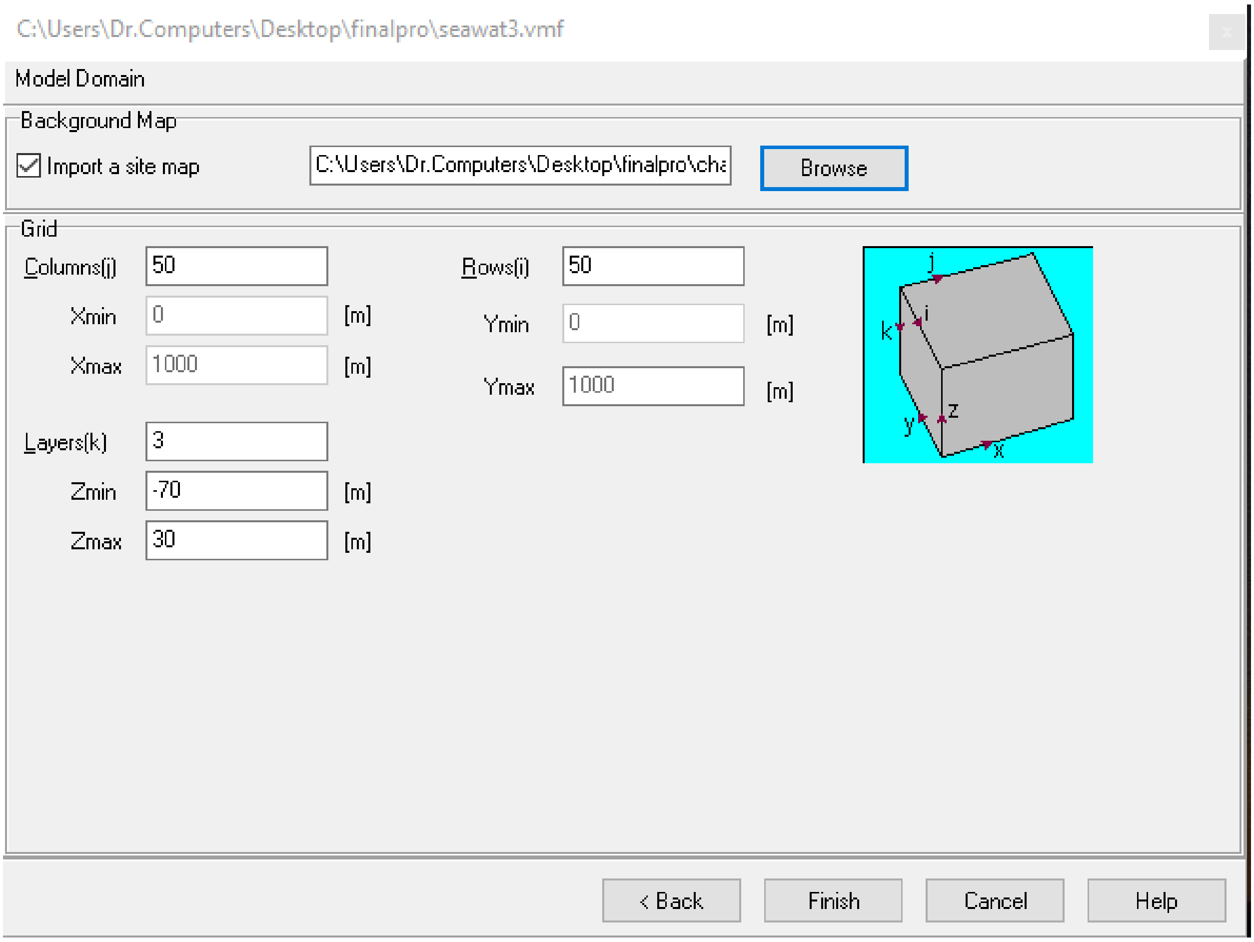

Fig 3.9 Model domain

The above window is used to import the site map by specifying the dimensions of the model domain, and defining the number of rows, columns, and layers for the finite difference grid.

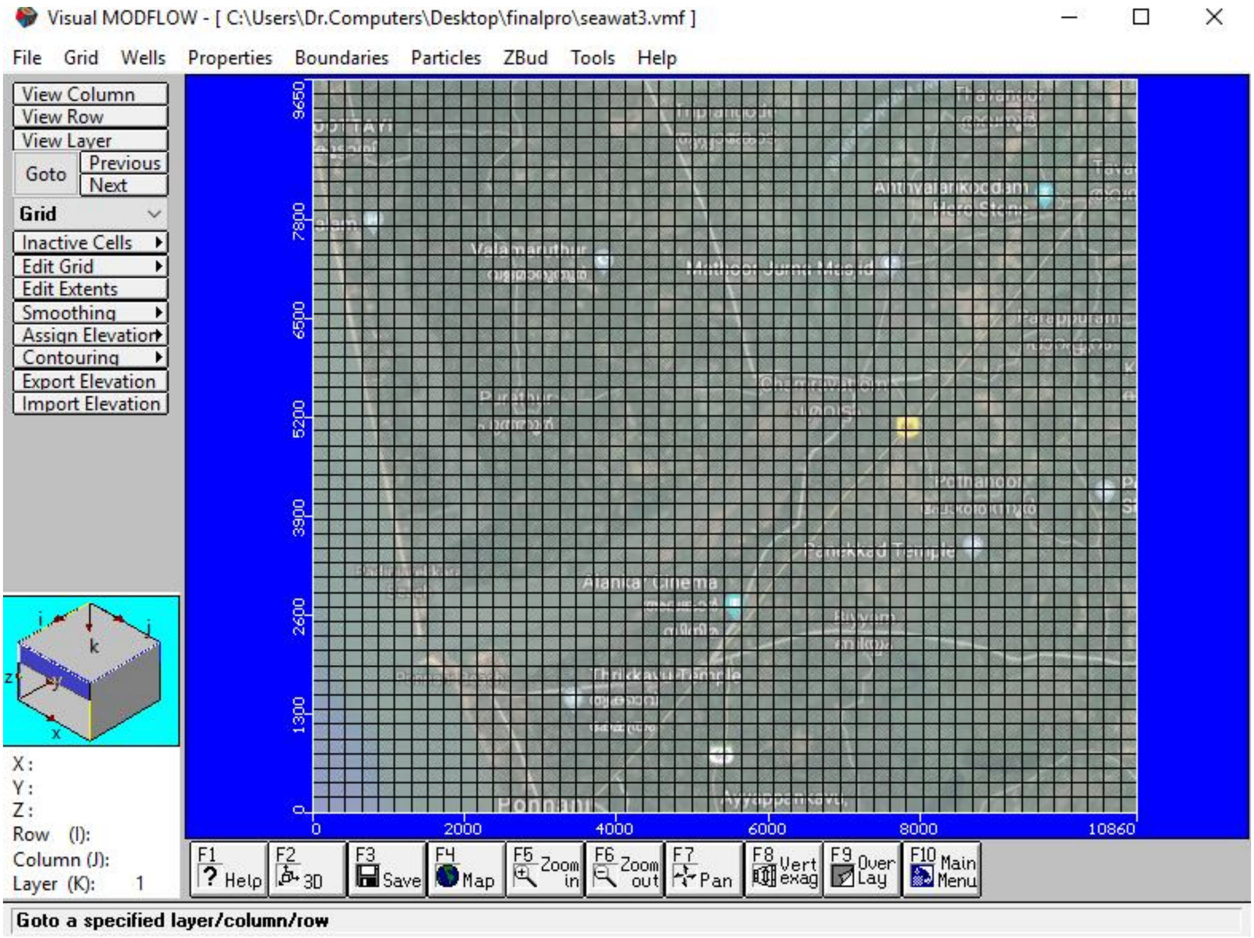

Fig 3.10 Grid formation of study area

3.5.6 Vertical Exaggeration

To properly the display the three layers, add a vertical exaggeration to the cross-section.

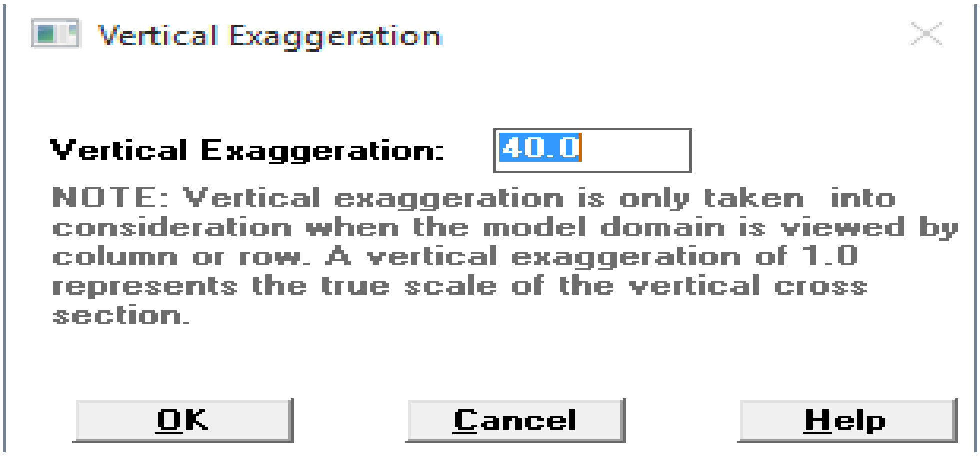

Fig 3.11 Vertical exaggeration

Elevation data of 3 layers were exported from Microsoft Excel and imported to Visual MODFLOW. The model surface elevation values prepared as a Microsoft Excel file and it is given in Appendix 1.

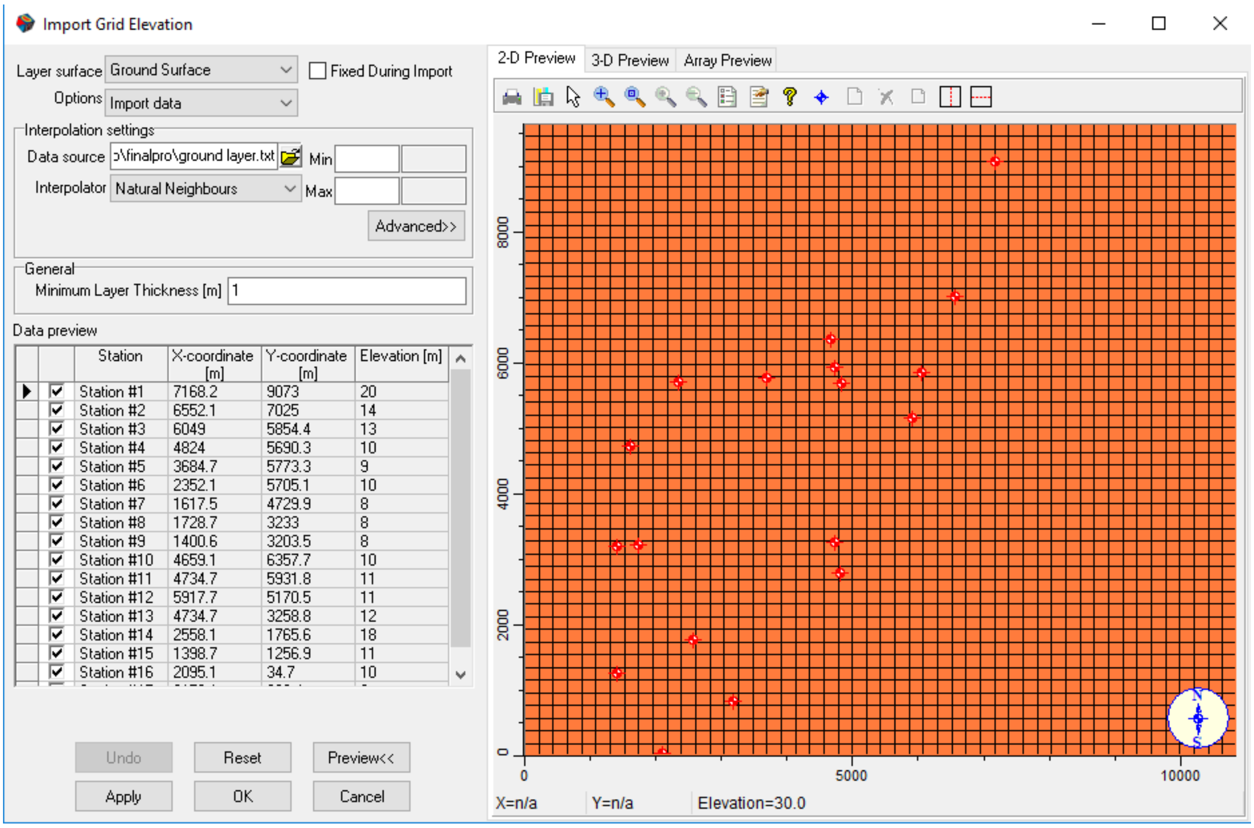

Fig 3.12 Importing elevation

3.5.7 Adding wells

Field observations of elevation and head observations at successive intervals from observation wells are input to the Visual MODFLOW to get model output values. Coordinates for the position of observation wells are also imported. The observation well data are given as a table in Appendix 2.

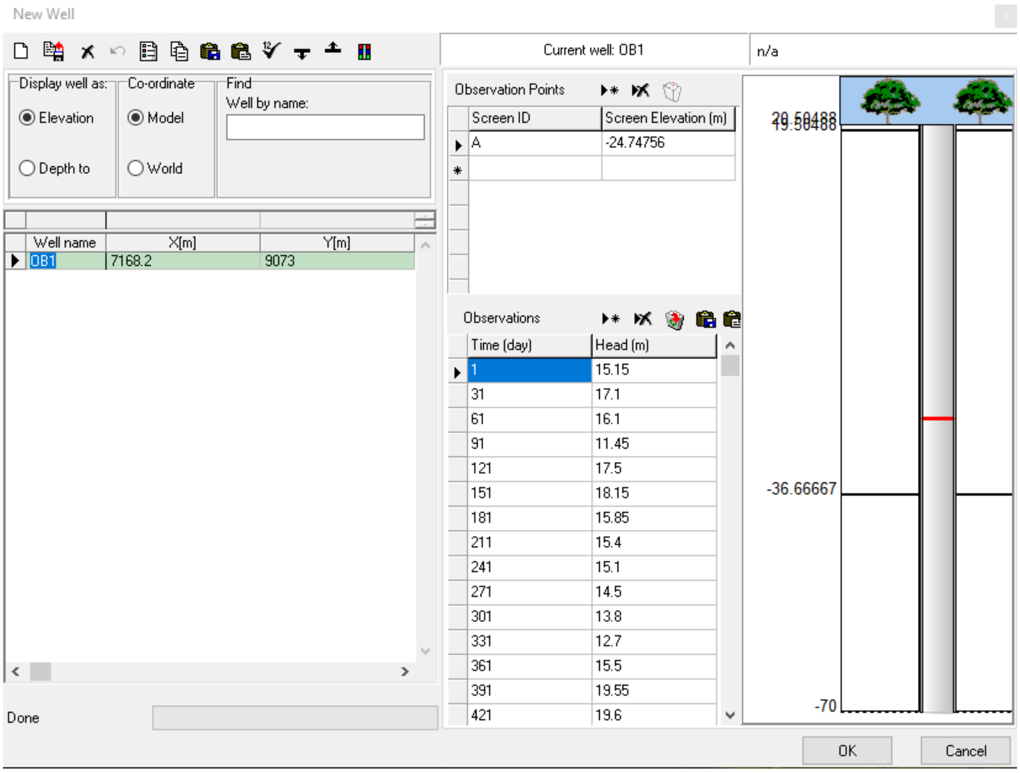

Fig 3.13 Observation wells add mode

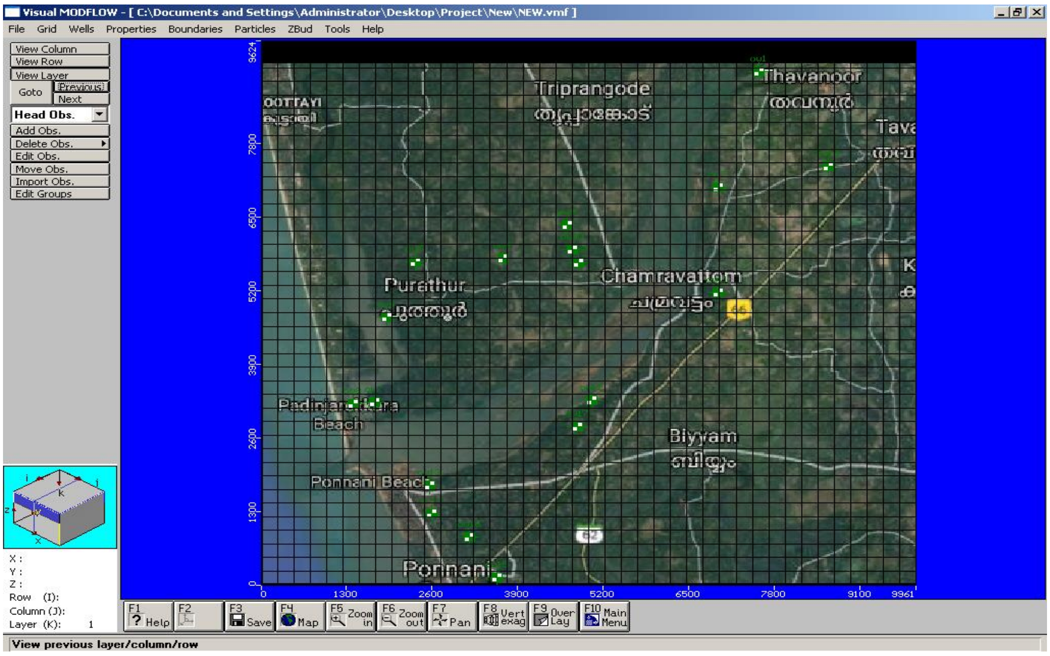

Fig 3.14 Adding wells

3.5.8 Adding salt concentration

Salinity from all observation wells at successive intervals are input to Visual MODFLOW classic to get model output values. Coordinates for the position of observation wells are also imported.

3.5.9 Adding properties

The hydrogeologic layers of the model are bounded by lateritic rock in the top and at bottom bounded by sandy soil and lateritic soil in between these two. The steady state model requires the hydraulic conductivity of each model layer. The hydraulic conductivity zone vary widely in the area and the hydraulic conductivity of various layers given in Table.1.The resulting window is shown in Fig 3.15

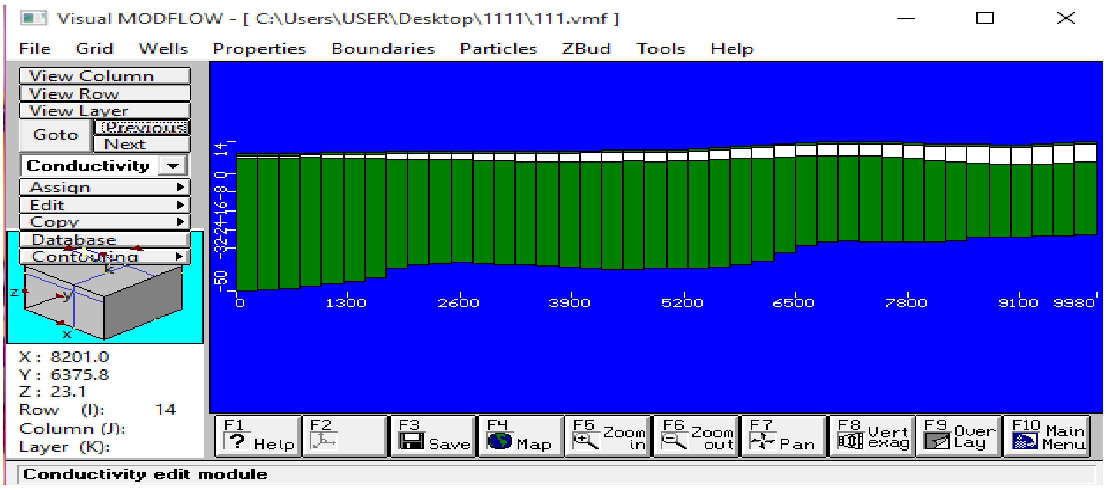

Fig 3.15 Adding hydraulic conductivity-column view

3.5.10 Adding initial head

Initial head of all observation wells along with their position coordinates were imported.

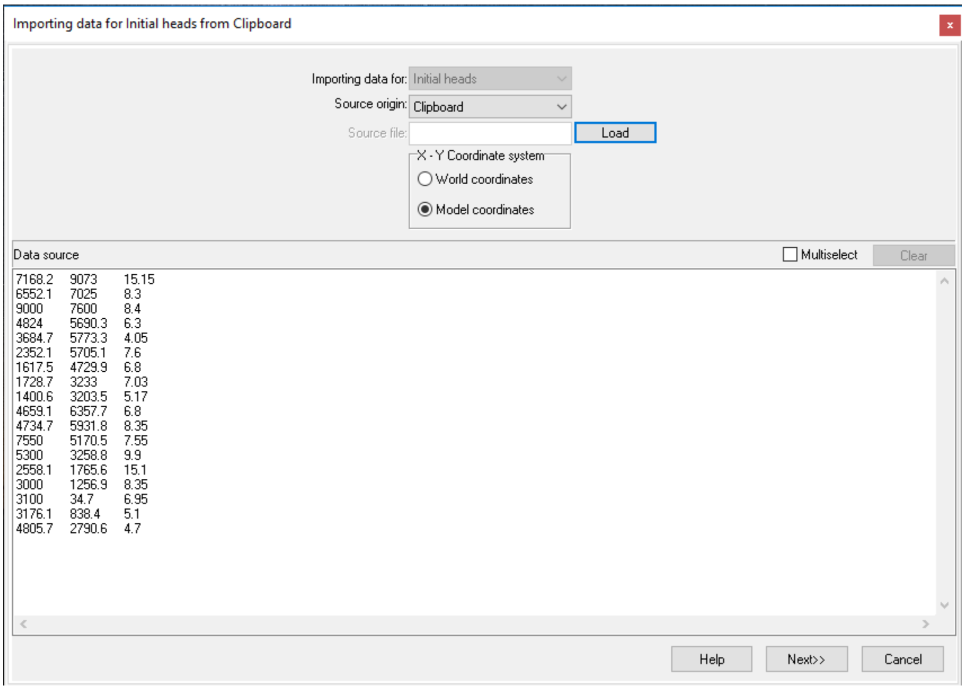

Fig 3.16 Adding initial head

3.5.11 Adding initial concentration

Initial concentration of all observation wells along with their position coordinates were imported.

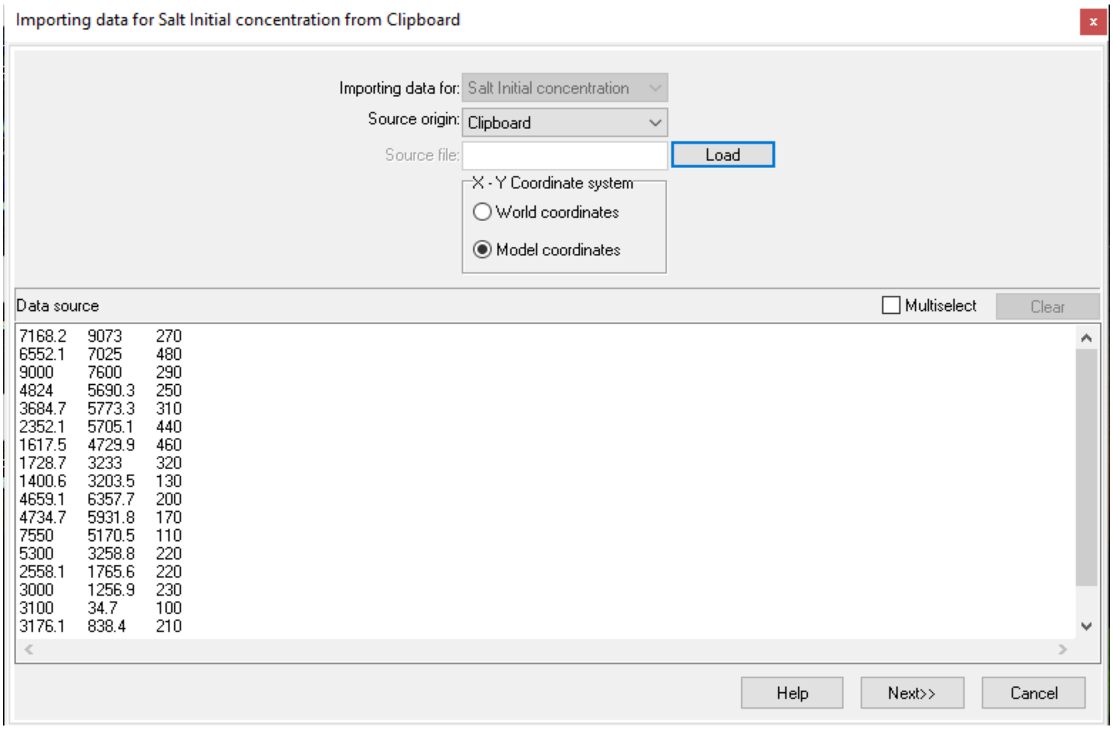

Fig 3.17 Adding initial concentration

3.5.12 Adding boundaries

The boundary conditions of any model must represent the system's relationship with the surrounding areas. Model results depend on the quality of these data. For the study area three types of boundaries supported by MODFLOW were chosen: river, constant head, recharge and constant concentration.

3.5.12.1 River

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

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

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

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

Bharathapuzha river is flowing through the study area and having different river stage elevations. River stage elevation (m), river bottom elevation, start time (day), stop time (day) and conductance of river are entered as shown in fig 3.18.

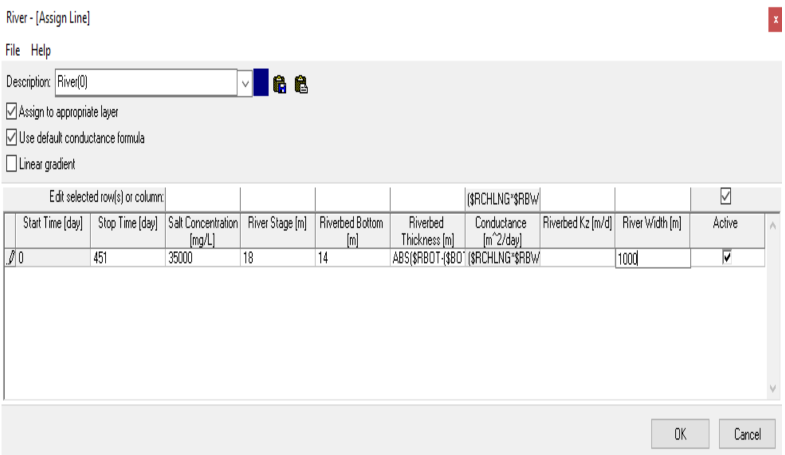

Fig 3.18 Assigning river boundaries

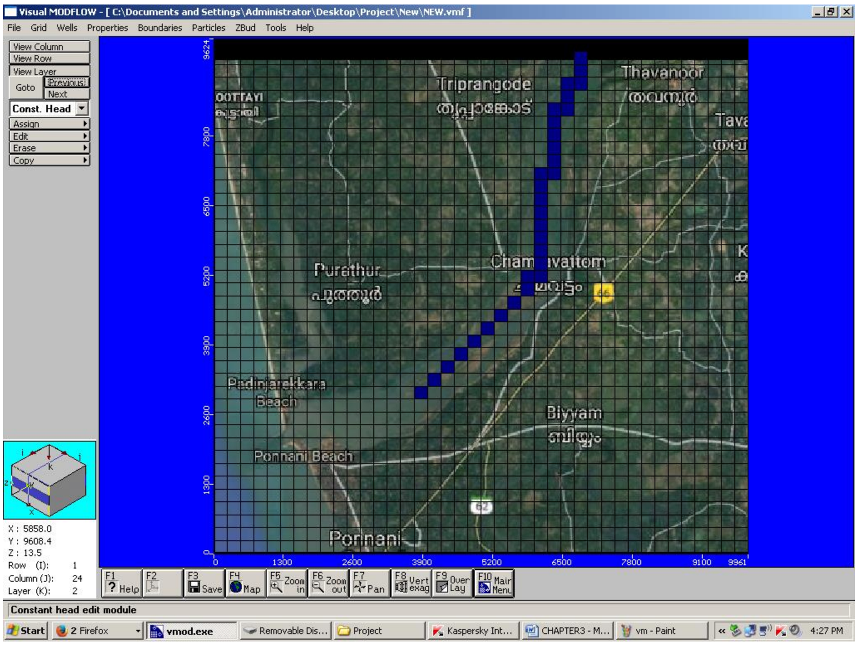

Fig 3.19 River in study area

3.5.12.2 Constant head

The West boundary of Arabian sea is considered as constant head boundary. While entering the data, the start time head and the stop time head are both given as 0.

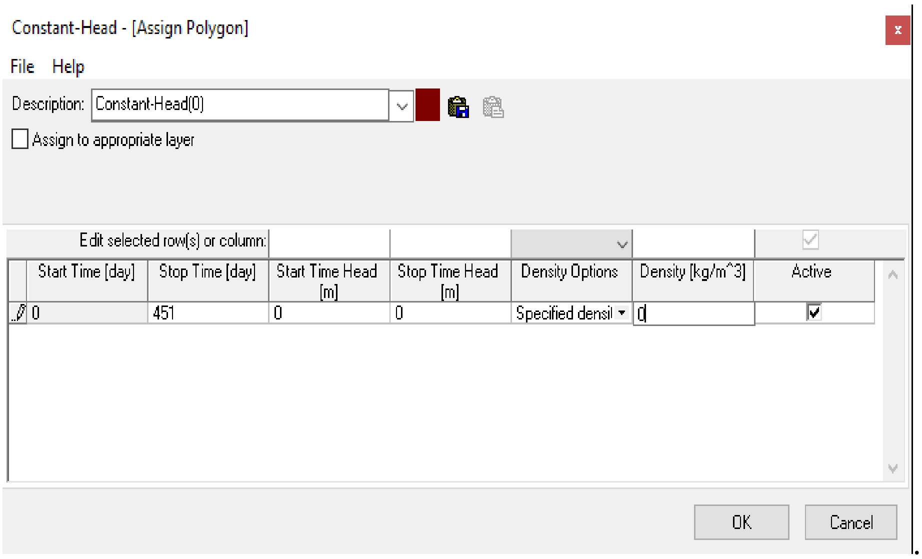

Fig 3.20 Assign constant head

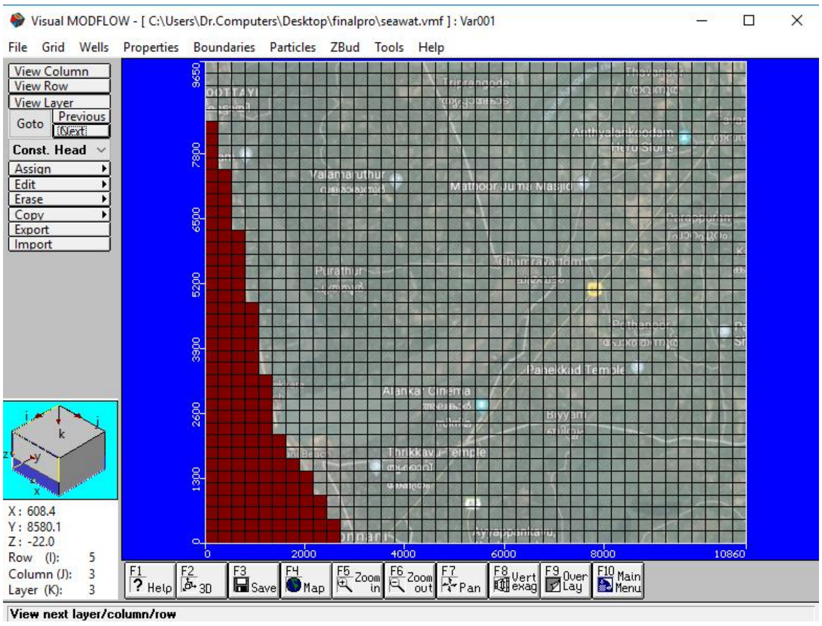

Fig 3.21 Constant boundary

3.5.13.3 Recharge

Most commonly, aerial recharge occurs as a result of precipitation that percolates into the groundwater system. The recharge package is designed to simulate aerial distributed recharge to the groundwater system. The recharge data is entered as given in Fig 3.22 and details given in Appendix 3.

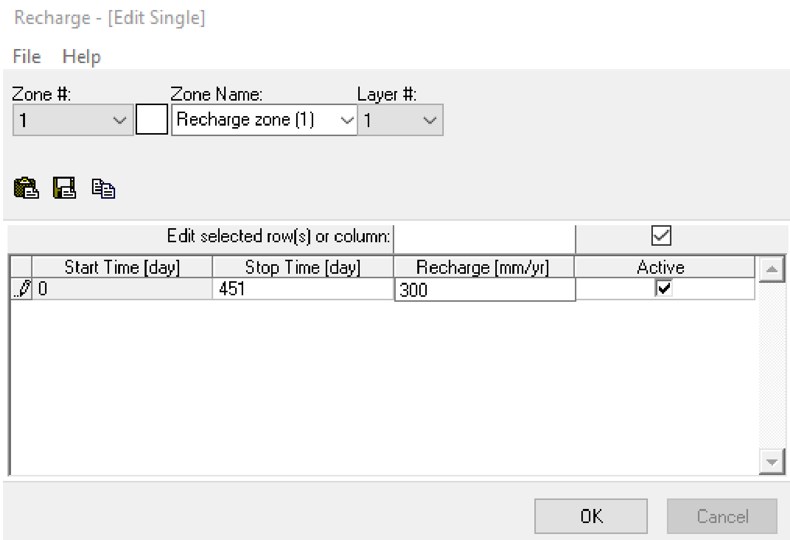

Fig 3.22 Assigning the recharge

3.5.12.4 Constant concentration

Value of constant concentration was given as 35000 mg/l, which is the concentration of salt in sea water.

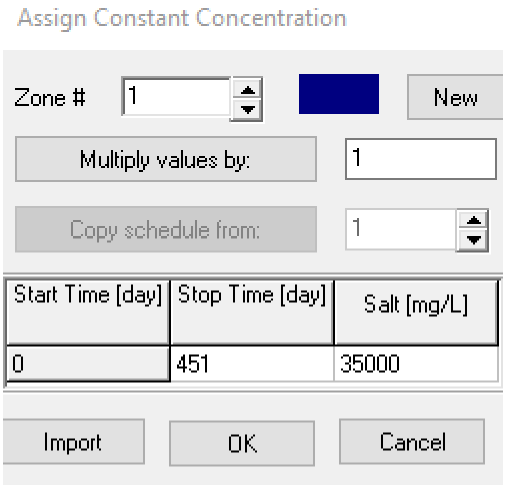

Fig 3.23 Assigning constant concentration

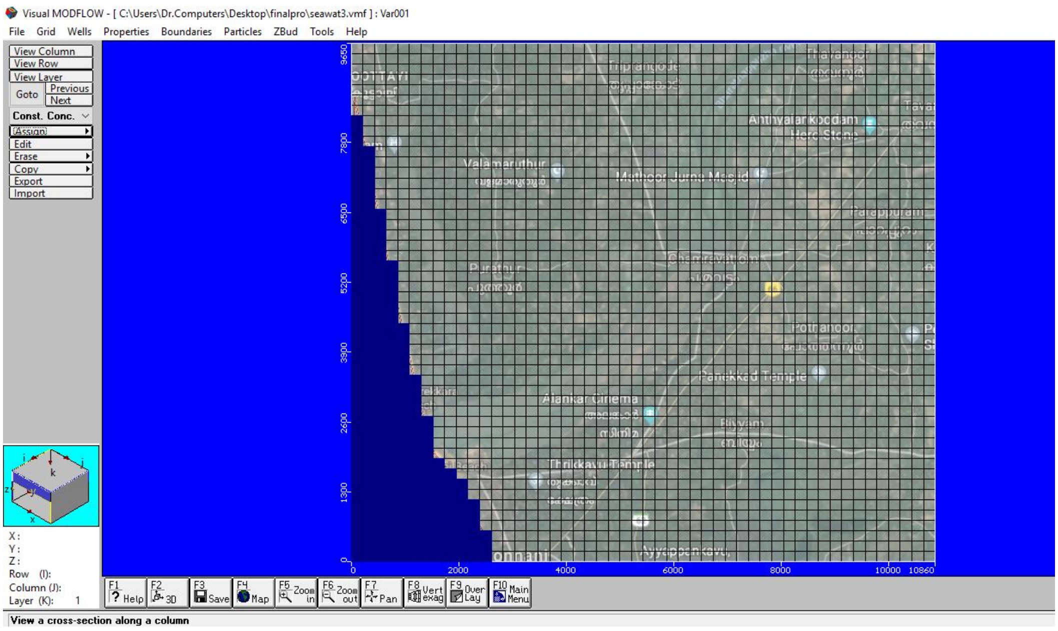

Fig 3.24 Assigned constant concentration

3.5.13 MODFLOW Run

After completing the input parameters, run model is selected. By selecting [Run] in the main menu, select run type dialogue box appears. The model was run for steady state condition as given below.

Fig 3.25 Translate and run

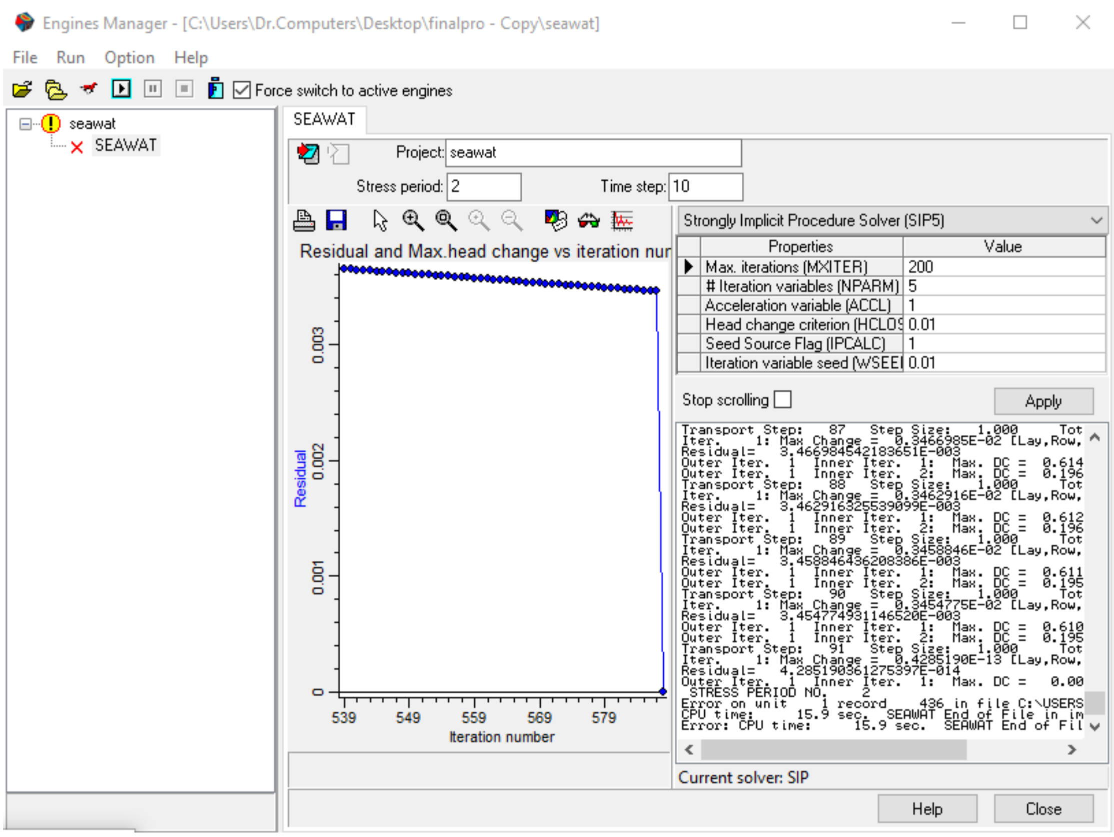

Fig 3.26 After running

3.5.14 Model Calibration

The model was calibrated using observed water level data collected, so that model was capable to produce field measured hydraulic heads and flow. Calibration is a process where in certain parameters of the model such as recharge and hydraulic conductivity are altered in a systemic fashion and the model is repeatedly run until the computed solution matches field observed values within an acceptable level of accuracy. For the calibration, Root Mean Square (RMS) has been chosen as the calibration criteria and calibration process was process was continued till no further reduction in RMS values was possible.

3.5.15 Model Validation

After successful completion of calibration of the steady state, the model was used for validating the results obtained. This is accomplished by testing the system with data, which are not used for calibration. For this study purpose 18 wells were selected in the study area and water samples and water level data were collected for a period of 15 months. During validation the model is verified for its accuracy and predictive capability.

3.5.16 Model Prediction

From the available validated model, we had predicted the water table values of the next few months by adding more days in the output and time steps of [**Run**].

Chapter 4

RESULTS AND DISCUSSIONS

The results of the study related to the saline water intrusion modelling in the coastal belt of Ponnani-Chamravattom region using Visual MODFLOW Classic and its interpretations are presented in detail in this chapter. This chapter also includes the results of calibration and validation under steady state condition and unsteady state condition, which are considered for discussion. The Visual MODFLOW output includes contours of head equipotentials, head difference, water table and elevation and also the velocity vectors with direction of flow. The extent of salt water intrusion into the study area was also studied and presented in this chapter.

4.1 QUALITY ANALYSIS OF THE COLLECTED SAMPLES

The representative samples collected from the eighteen wells in study area, from May 2017 to December 2018, was subjected to various quality analysis such as salinity, electrical conductivity and turbidity etc. by using Water Analyser and Electrical Conductivity Meter. The results are shown below

4.1.1 Salinity

The results of the salinity analysis using Water Analyser is presented in Table4.1 and the variation of salinity with time in some of the wells is plotted in Fig 4.1

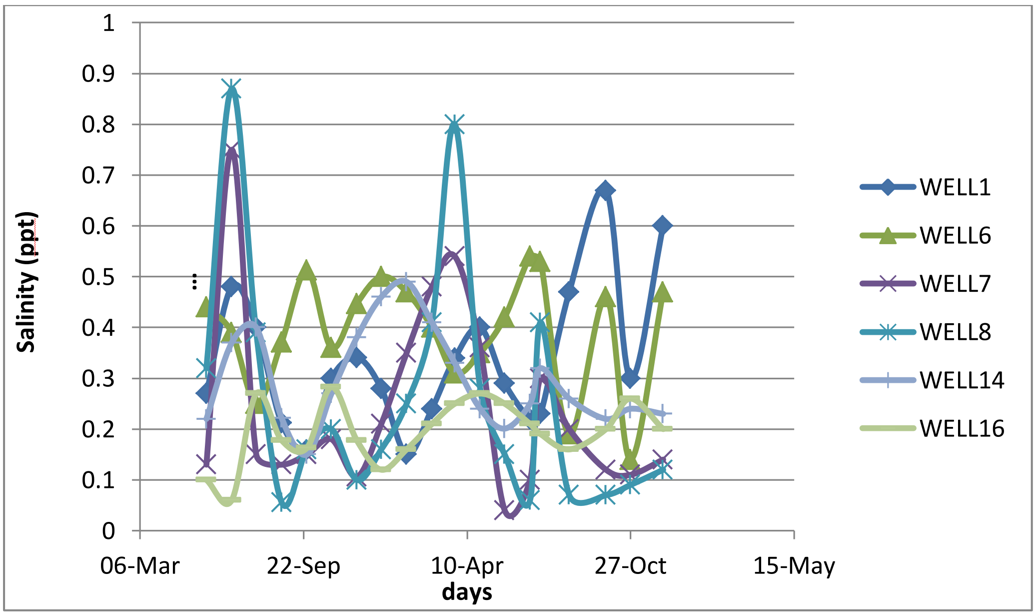

Fig 4.1 Graph showing the effect of salinity with time in various wells

Table 4.1 Salinity (ppt) in 18 observation wells

DAY	1	31	61	91	121	151	181	211	241	271	301	331	361	391	421	451
Ob1	0.212	0.159	0.3	0.341	0.28	0.15	0.24	0.34	0.40	0.29	0.22	0.23	0.47	0.67	0.3	0.6
Ob2	0.261	0.256	0.31	0.351	0.302	0.25	0.294	0.35	0.41	0.38	0.35	0.33	0.35	0.32	0.37	0.39
Ob3	0.188	0.217	0.27	0.188	0.14	0.19	0.25	0.298	0.34	0.31	0.28	0.26	0.24	0.27	0.28	0.26
Ob4	0.178	0.232	0.39	0.31	0.23	0.18	0.22	0.33	0.43	0.38	0.31	0.29	0.3	0.4	0.47	0.47
Ob5	0.017	0.111	0.18	0.13	0.08	0.05	0.1	0.18	0.26	0.37	0.47	0.49	0.42	0.13	0.15	0.14
Ob6	0.371	0.513	0.36	0.447	0.50	0.47	0.40	0.31	0.35	0.42	0.54	0.53	0.19	0.46	0.14	0.47
Ob7	0.202	0.144	0.21	0.154	0.21	0.35	0.48	0.54	0.36	0.04	0.10	0.21	0.07	0.16	0.42	0.17
Ob8	0.056	0.16	0.2	0.1	0.16	0.25	0.41	0.8	0.28	0.15	0.06	0.41	0.07	0.07	0.09	0.12
Ob9	0.202	0.144	0.21	0.154	0.10	0.19	0.31	0.46	0.41	0.32	0.21	0.15	0.07	0.16	0.42	0.17
Ob10	0.14	0.13	0.19	0.163	0.12	0.19	0.27	0.33	0.30	0.24	0.20	0.19	0.27	0.17	0.28	0.28
Ob11	0.149	0.149	0.26	0.217	0.18	0.22	0.28	0.35	0.30	0.25	0.16	0.14	0.16	0.2	0.21	0.2
Ob12	0.227	0.207	0.28	0.17	0.14	0.18	0.28	0.35	0.30	0.25	0.23	0.24	0.27	0.23	0.21	0.2
Ob13	0.202	0.202	0.3	0.235	0.20	0.24	0.31	0.36	0.39	0.34	0.29	0.28	0.24	0.19	0.27	0.26
Ob14	0.222	0.15	0.27	0.38	0.46	0.49	0.41	0.33	0.24	0.20	0.25	0.32	0.26	0.22	0.24	0.23
Ob15	0.193	0.168	0.24	0.197	0.27	0.38	0.44	0.35	0.25	0.19	0.12	0.19	0.2	0.14	0.19	0.21
Ob16	0.178	0.163	0.283	0.178	0.12	0.16	0.21	0.25	0.27	0.25	0.21	0.22	0.16	0.2	0.26	0.2
Ob17	0.232	0.222	0.25	0.437	0.51	0.45	0.37	0.29	0.23	0.39	0.36	0.34	0.27	0.22	0.38	0.61
Ob18	0.149	0.14	0.2	0.193	0.16	0.12	0.19	0.27	0.25	0.23	0.20	0.19	0.16	0.18	0.26	0.25

It can be seen from the graph that for wells nearer to the sea (well 8) the salt content is maximum till the end of June and then decreases as the rain water inflow to the sea increases, indicating salt water intrusion in the coastal areas during summer months.

4.1.2 Electrical Conductivity

The electrical conductivity of the samples were determined using water analyser and is presented in Table 4.2. A graph showing the variation of EC with time for some of the wells is plotted in Fig 4.2. The trend in the variation of EC is also similar to salinity, i. e., having higher variation of EC in wells nearer to sea (both maximum and minimum) and less variation in other wells

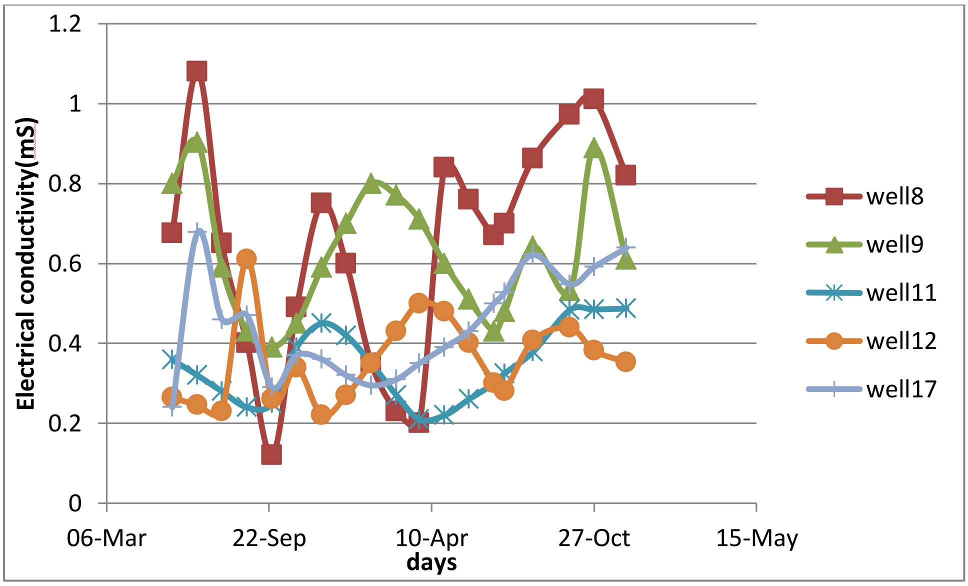

Fig. 4.2 Graph showing the effect of Electrical Conductivity in various wells

4.1.3 Water table fluctuation

Water table in the wells for the study period is presented in Table 4.3 and also as graph in Fig 4.3. The variations of water level in the observation wells is seen to follow the rainfall pattern of the area.

Table 4.2 Electrical Conductivity (mS) in 18 Observation wells

DAY	1	31	61	91	121	151	181	211	241	271	301	331	361	391	421	451
Ob1	0.35	0.33	0.31	0.4	0.51	0.7	0.81	0.76	0.69	0.6	0.52	0.449	0.472	1.42	1.23	1.28
Ob2	0.46	0.32	0.35	0.7	0.78	0.74	0.62	0.55	0.51	0.59	0.64	0.683	0.603	0.52	0.56	0.553
Ob3	0.39	0.31	0.3	0.39	0.46	0.52	0.48	0.42	0.38	0.36	0.41	0.584	0.554	0.651	0.645	0.634
Ob4	0.37	0.3	0.35	0.31	0.25	0.3	0.5	0.73	0.84	0.76	0.67	0.699	0.862	0.972	1.07	1.14
Ob5	0.2	0.23	0.348	0.4	0.43	0.41	0.39	0.35	0.32	0.29	0.4	0.445	0.415	0.346	0.375	0.354
Ob6	0.5	0.19	0.4	0.6	0.73	0.78	0.69	0.58	0.47	0.55	0.67	0.78	0.88	0.86	0.81	0.67
Ob7	0.42	0.3	0.45	0.7	0.77	0.69	0.6	0.51	0.41	0.38	0.43	0.467	0.397	0.366	0.375	0.451
Ob8	0.4	0.12	0.49	0.75	0.6	0.35	0.23	0.2	0.84	0.76	0.67	0.699	0.862	0.972	1.01	0.82
Ob9	0.61	0.26	0.339	0.22	0.27	0.35	0.43	0.5	0.48	0.4	0.3	0.281	0.407	0.439	0.382	0.353
Ob10	0.29	0.27	0.37	0.34	0.28	0.35	0.44	0.52	0.47	0.42	0.4	0.418	0.636	0.404	0.654	0.502
Ob11	0.31	0.25	0.39	0.45	0.42	0.35	0.27	0.21	0.22	0.26	0.3	0.325	0.379	0.483	0.485	0.487
Ob12	0.47	0.29	0.37	0.36	0.32	0.29	0.31	0.35	0.39	0.43	0.5	0.527	0.622	0.548	0.591	0.639
Ob13	0.42	0.42	0.37	0.45	0.48	0.49	0.5	0.47	0.43	0.4	0.5	0.544	0.556	0.459	0.62	0.558
Ob14	0.39	0.33	0.32	0.45	0.54	0.59	0.63	0.55	0.48	0.45	0.6	0.728	1.01	0.761	0.887	0.962
Ob15	0.4	0.35	0.32	0.41	0.46	0.5	0.54	0.56	0.5	0.45	0.44	0.437	0.463	0.339	0.436	0.526
Ob16	0.37	0.34	0.48	0.37	0.3	0.24	0.21	0.24	0.28	0.34	0.4	0.478	0.68	0.484	0.599	0.498
Ob17	0.48	0.39	0.478	0.59	0.7	0.8	0.77	0.71	0.6	0.51	0.45	0.479	0.642	0.531	0.889	0.91
Ob18	0.31	0.29	0.392	0.4	0.37	0.33	0.27	0.21	0.18	0.25	0.38	0.408	0.375	0.434	0.589	0.625

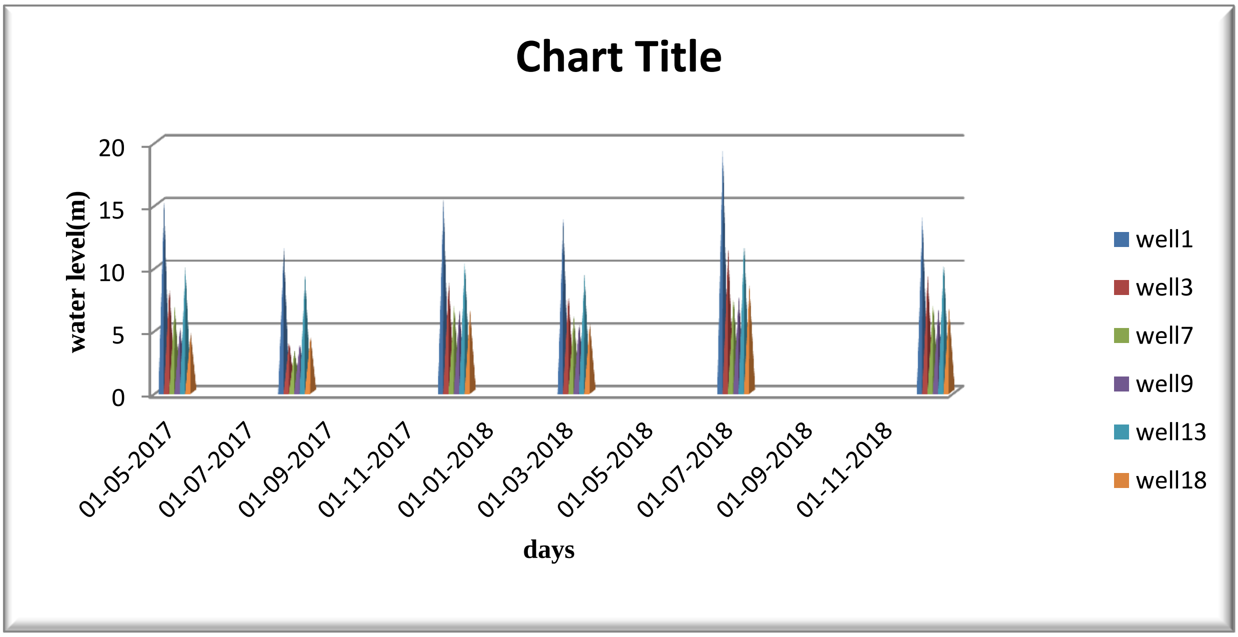

Fig.4.3 Graph showing the Water Table Variations during the Study Period

4.2 MODEL CALIBRATION

For a groundwater model to be used in any type of predictive role, it must be demonstrated that the model can successfully simulate observed aquifer behaviour. The model was calibrated using the observed water level data, so that model is capable to produce field measured hydraulic heads and flow. Calibration is a process where in certain parameters of the model such as recharge and hydraulic conductivity are altered in a systematic fashion and the model is repeatedly run until the computed solution matches field-observed values within an acceptable level of accuracy. Calibration of model in steady state was used in the reduction of unknown terms of governing equations of groundwater system and uses the steady state results in making the unsteady model. The results of the calibration model in steady state for estimating aquifer hydraulic conductivity and recharge were used in the transient state model. The model performance was evaluated using various criteria including graphical and linear regression method, calibration residual, residual mean, absolute residual mean, standard error of estimate, root mean square, normalized root mean square, correlation coefficient and confidence interval. For the calibration in our study, Root Mean Square (RMS) error has been chosen as the calibration criteria and calibration process was continued till no further reduction in RMS values were possible.

Table 4.3 Water Table Variations in Observation Wells

days	1	31	61	91	121	151	181	211	241	271	301	331	361	391	421	451
Ob1	15.15	17.1	16.1	11.45	17.5	18.15	15.85	15.4	15.1	14.5	13.8	12.5	11.9	19.55	19.6	15.35
Ob2	8.3	13.55	12.85	13.3	13.3	12.9	12.1	11.9	11.4	11	10.6	9.9	9.7	13.05	13.55	12.1
Ob3	8.4	11.1	9.6	4	10.26	10.7	9.1	8.8	8.5	8.2	7.8	7.2	6.8	9.95	11.4	9.35
Ob4	6.3	9.53	8.9	6.2	9.2	8.7	7.55	7.1	6.8	6.4	6.1	5.7	5.1	9.3	9.5	7.55
Ob5	4.05	6.15	6.75	1.45	6.9	6.05	5.7	5.4	5	4.7	4.2	3.9	3.15	6.9	7.12	6.01
Ob6	7.6	9.68	8.3	5.65	9.3	9.15	7.85	7.6	7.3	6.8	6.4	6.1	5.8	9.45	9.6	8.8
Ob7	6.8	7.75	6.8	3.3	7.1	7.1	7.1	6.9	6.7	6.4	6	5.7	5.5	7.1	7.6	6.85
Ob8	7.03	7.75	6.88	3.43	7.13	7.38	7.18	6.7	6.5	6.1	5.7	5.2	4.8	7.32	7.66	7.05
Ob9	5.17	7.45	6.75	3.9	6.7	6.7	6.8	6.5	6.2	5.8	5.5	4.8	4.1	6.97	7.57	6.31
Ob10	6.8	9.55	8.7	5.5	9.1	8.5	8.1	7.8	7.5	7.1	6.8	6.3	5.6	9.13	9.45	8.12
Ob11	8.35	10.6	9.85	6.85	10.1	9.7	9.4	9.1	8.7	8.4	7.9	6.6	6.01	10.3	10.51	8.98
Ob12	7.55	10.85	10.05	7.75	10.4	9.8	8.85	8.6	8.3	8.1	7.6	7.2	6.7	10.5	10.82	9.05
Ob13	9.9	12	11.45	9.3	11.6	11.27	10.75	10.5	10.2	9.8	9.4	8.8	7.9	11.7	12.05	10.68
Ob14	15.1	16.8	16.3	10.3	13.5	15.73	15.5	15.3	15	14.6	14.2	13.7	12.7	16.3	16.1	15.53
Ob15	8.35	10.2	9.94	6.3	10.1	9.75	9.3	9	8.8	8.5	8.2	7.8	7.1	10.15	10.4	9.59
Ob16	6.95	9.7	9	6.1	9.2	8.9	8.35	8.2	7.8	7.4	7.1	6.8	5.7	9.25	9.6	8.55
Ob17	5.1	8.41	7.9	4.5	8.05	8.1	7.45	7.25	6.9	6.6	6.3	5.7	4.8	8.39	8.47	7.45
Ob18	4.7	8.35	8.2	4.5	8.5	7.82	6.8	6.5	6.2	5.8	5.5	5.1	4.5	8.35	8.45	6.67

The aquifer condition of May 2017 is assumed as the initial condition for steady state calibration. The hydraulic conductivity values of the aquifer varied such that the RMS error kept a minimum and the scatter plot of the computed Vs. observed head for the selected wells after calibration is shown in Fig. 4.4.

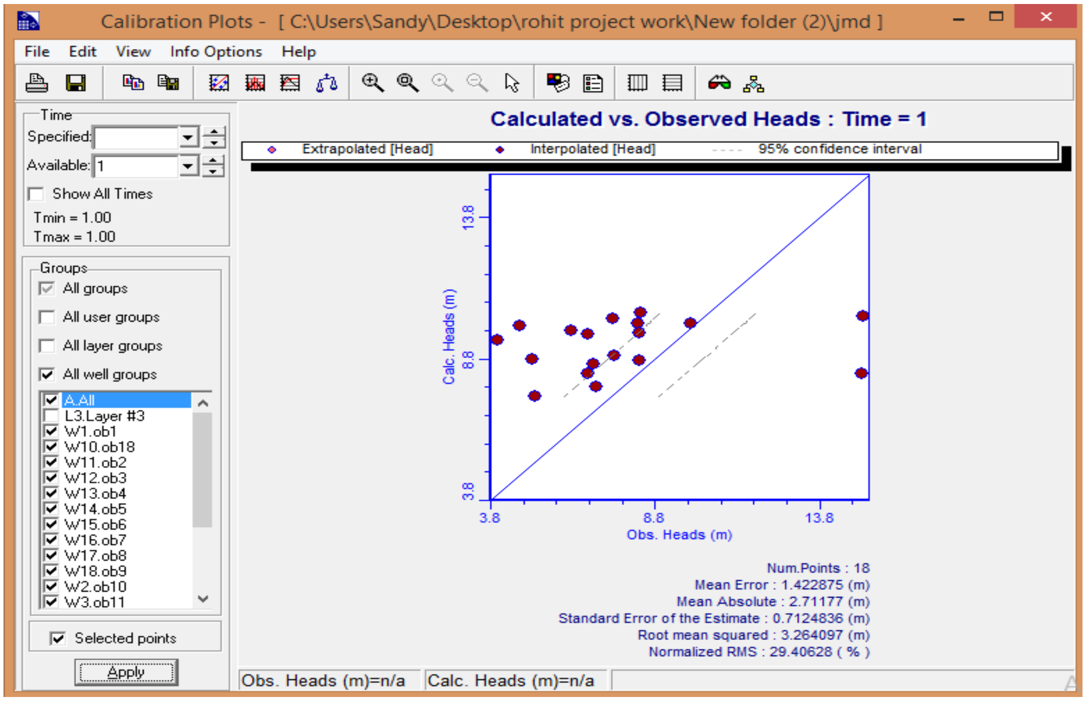

Fig.4.4 Model computed Vs. observed water level after calibration (Steady State)

4.3 MODEL VALIDATION

After successful completion of calibration in steady state, the model was used for validating the results obtained. The validation was carried out to establish greater confidence in the model by using the set of calibrated parameter values and stresses to reproduce a second set of field data.This is accomplished by testing the system with data, which are not used for calibration. In this study, the water level data collected for the first fifteen months of the 18 selected wells in the study area were used for the calibration process. After calibration process, water level data of eighteen months (September 2017 to December 2018) were used for model validation. The scatter plot of computed Vs observed heads for the selected wells after validation shown in Fig. 4.5. Then, the validated model was considered as a useful tool for predicting aquifer response of the study area for various future strategies.

The known observed values of water level for three wells were compared with the validated model computed results of the water levels and is found to be matched. The result is presented below in Table 4.4.

Table 4.4 Model Validated Results

Well No	Observed water level, m (Day- 451)	Calcualted water level , m (Day-451)
OW 5	9.75	9.85
OW 11	7.82	7.97
OW 17	7.75	8.09

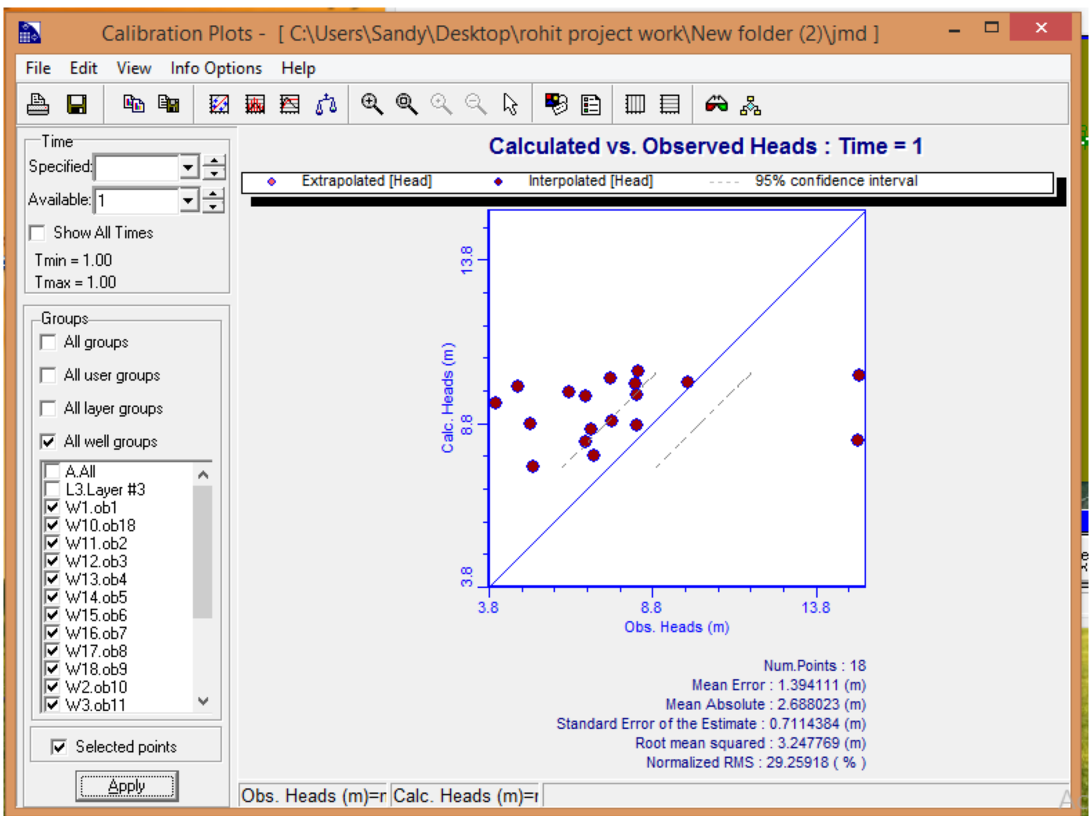

Fig4.5 Model computed Vs. observed water level after validation

4.4 MODEL PREDICTION

The appropriate prediction of water table is possible only if a validated model is available. From the available validated model, we had predicted the water table values of the next few months by adding more days in the output and time steps of [**Run**].

4.5 OUTPUT FROM THE MODEL

4.5.1 Head equipotential

The blue lines with labels in Fig. 4.6 shows water table contours, i.e. lines joining equipotential heads in the study area. South-West boundary of the study area is bounded by Arabian Sea, having constant head and the groundwater level increases when moving to the North-East region of the study area.

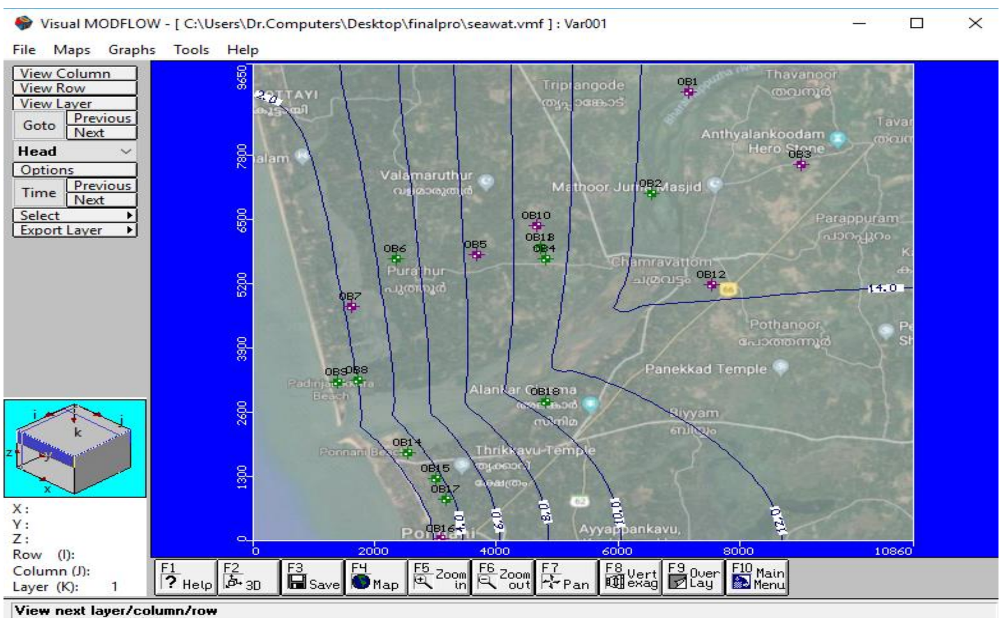

Fig4.6

Head equipotential at the end of the study period (451 days)

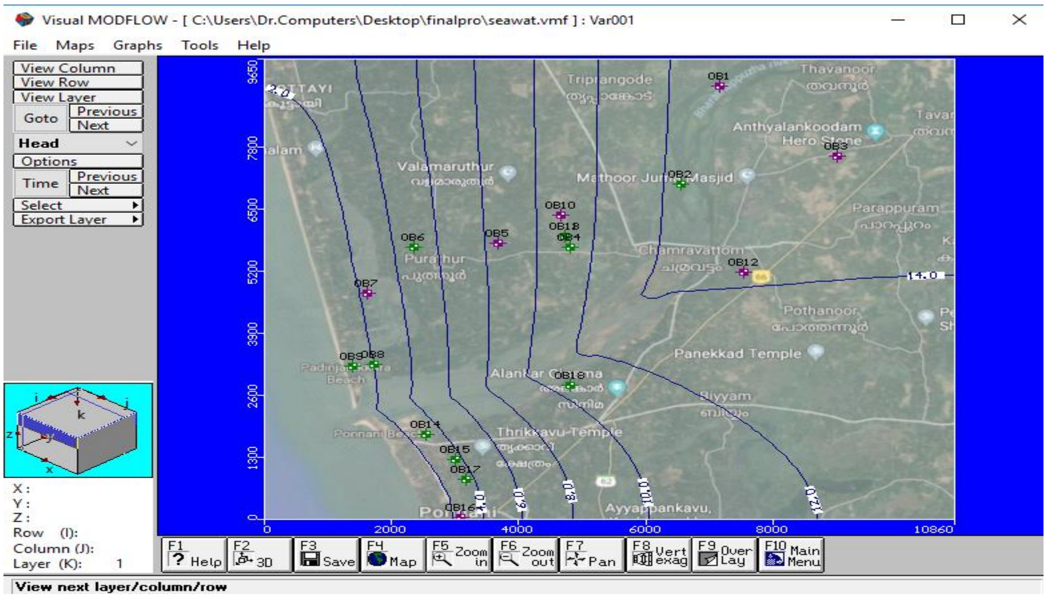

Fig4.7 Predicted head equipotential after 1000 days

The predicted groundwater levels after 1000days obtained from the model is given in Fig. 4.7. From the water table contour map of the study area, it can be seen that there is a gradual lowering of water table and the piezometric level as the ground slopes down to the sea. Simulated groundwater levels after 1000 days showed only a slight decrease in groundwater table.

4.5.2 Salt water intrusion in coastal aquifers

The salt water intrusion model was developed using SEAWAT and the salt concentration at the end of the study period obtained is presented in Fig 4.8. The salt concentration variation in the vertical direction is shown in Fig. 4.9. From the figure it can be seen that the salt water concentration variation in land area and coastal region. The colour chart shows variation of salt water concentration where blue and brown indicates minimum and maximum range of salt concentration respectively.

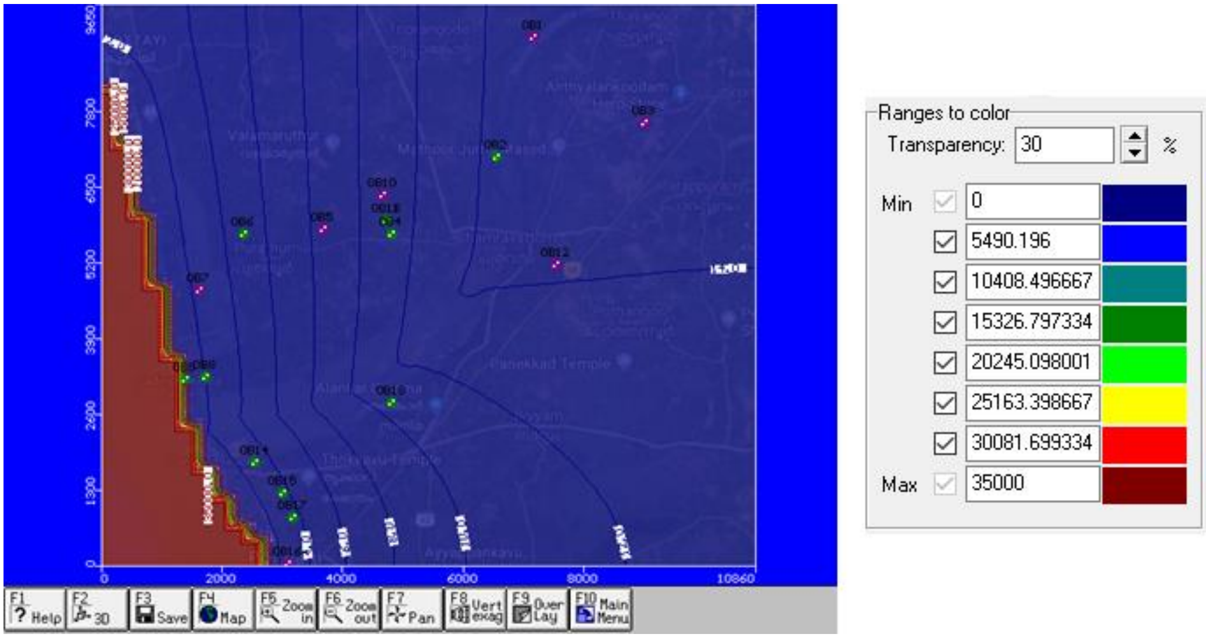

Fig4.8 Salt water intrusion in coastal aquifers

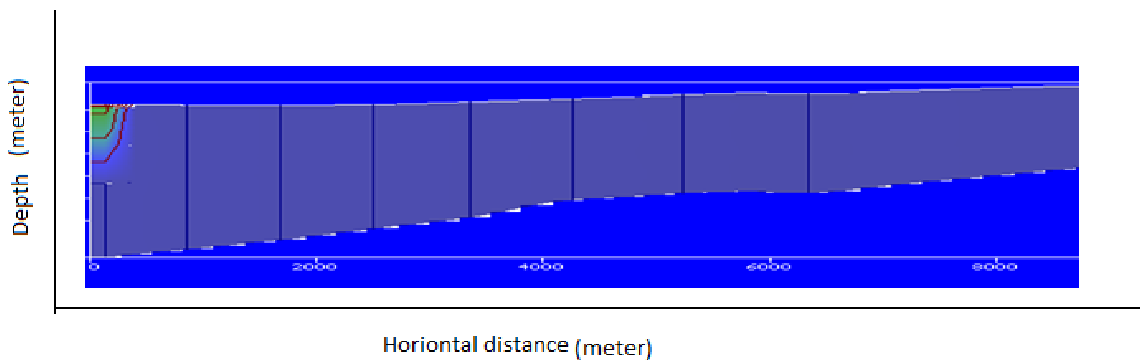

Fig 4.9 cross sectional view of aquifer

The cross sectional view of the study area indicates flow of salt water across the depth and it can be seen that movement of salt water was slow during the study period.

4.5.3 Unsteady state transport

Unsteady state saline water transport was done using the SEAWAT module of visual MODFLOW. From the Fig 4.10, it is observed that calculated head and observed head values are coinciding for majority of wells. It can be observed that RMS value get reduced after calibration.

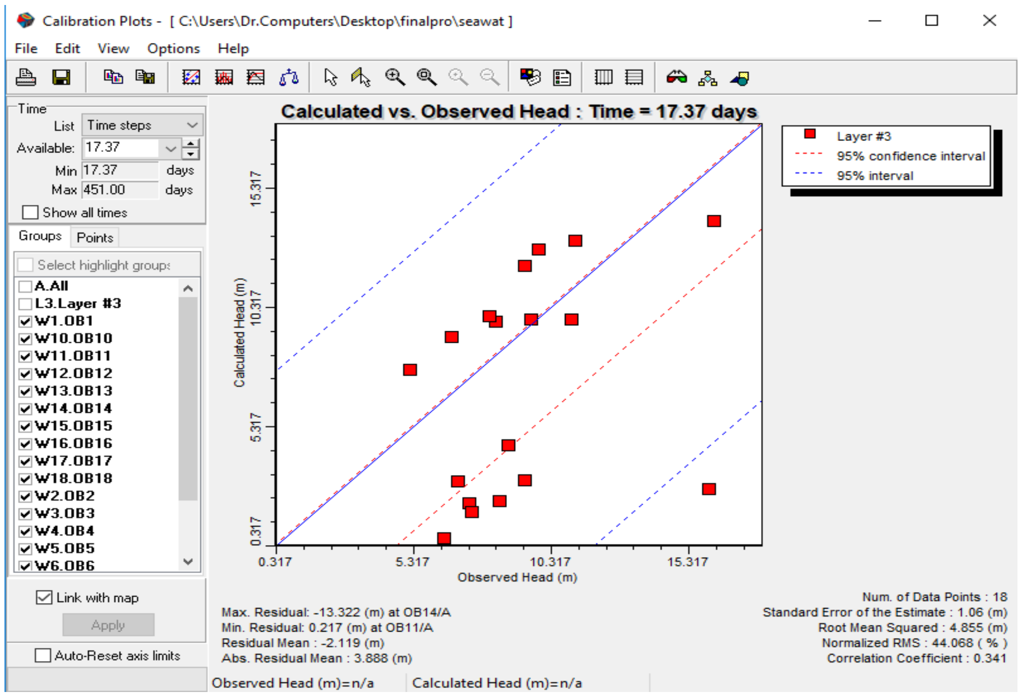

Fig4.10 Unsteady state transport (Head)

In the case of concentration similar trend was obtained. Two different graphs were obtained for first and last day of study period.

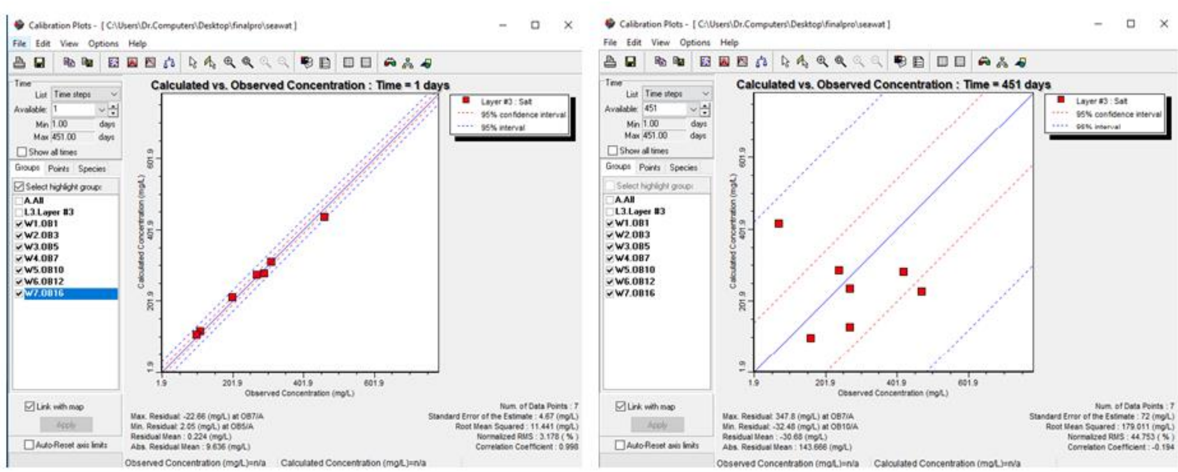

Fig 4.11 Unsteady state transport (concentration)

4.5.4 Prediction

The prediction of salt water intrusion was done for 1000 days using SEAWAT. Simulation of the saline water intrusion into the study area after 1000 days showed an increase in the salt concentration from 5490.196 to 30081.6993 mg/l in the study area as shown in Figs. 4.12 and 4.13.

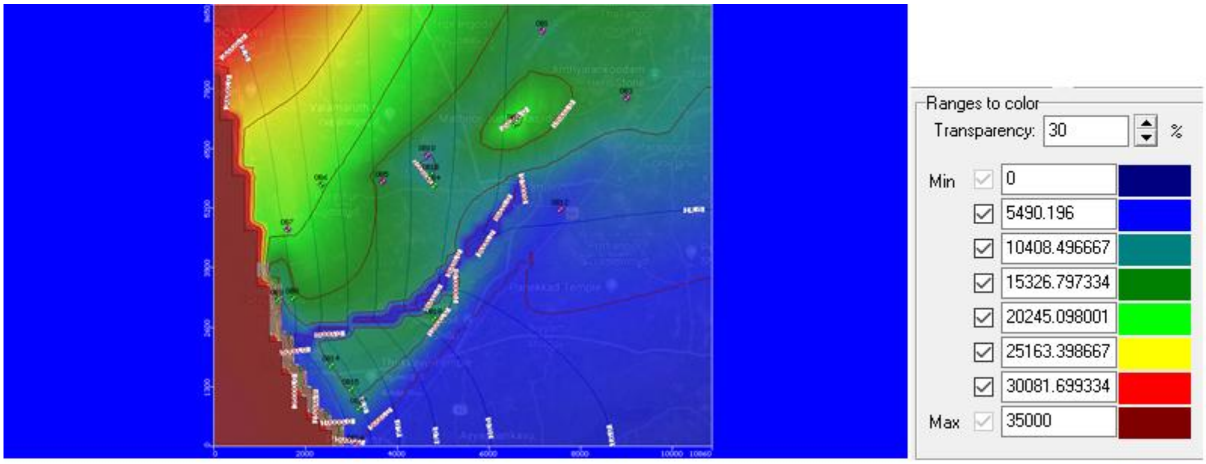

Fig 4.12 1000 days prediction

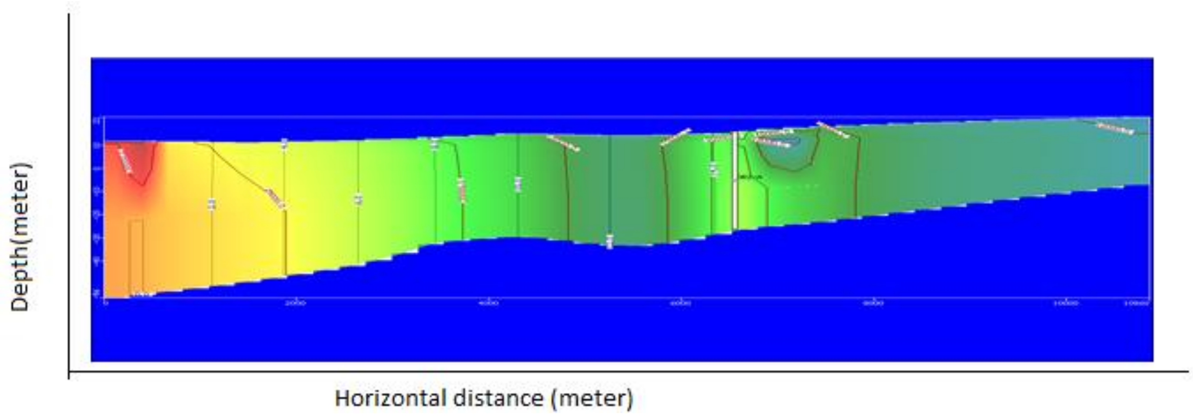

Fig 4.13 cross sectional view of aquifer

4.5.5 Comparison of observed value with interpolated values

Head Vs. Time graph of some of the observation wells showing the observed and calculated heads is shown in Figs. 4.14 to 4.17. The interpolated values are a representation of the observed heads.

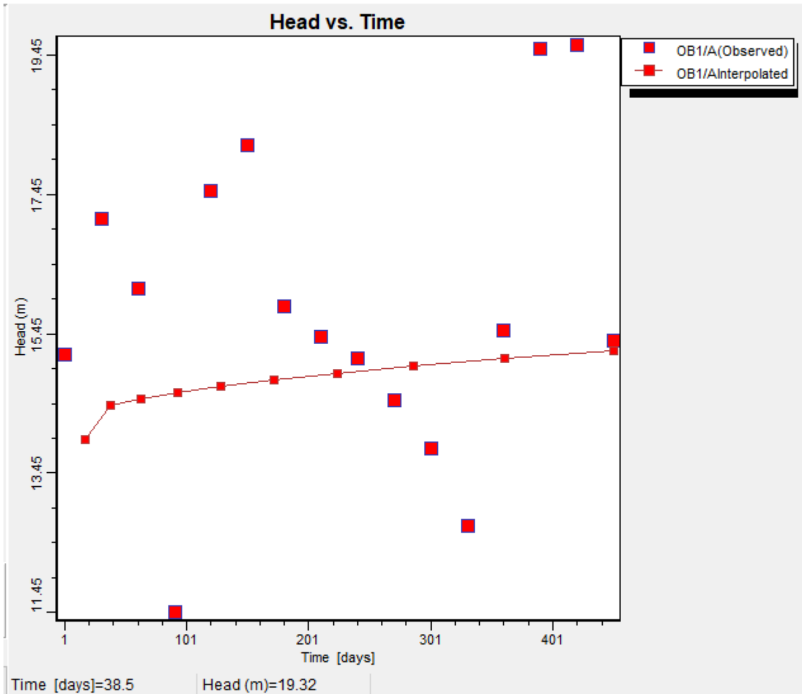

Fig 4.14 Head vs Time (well 1)

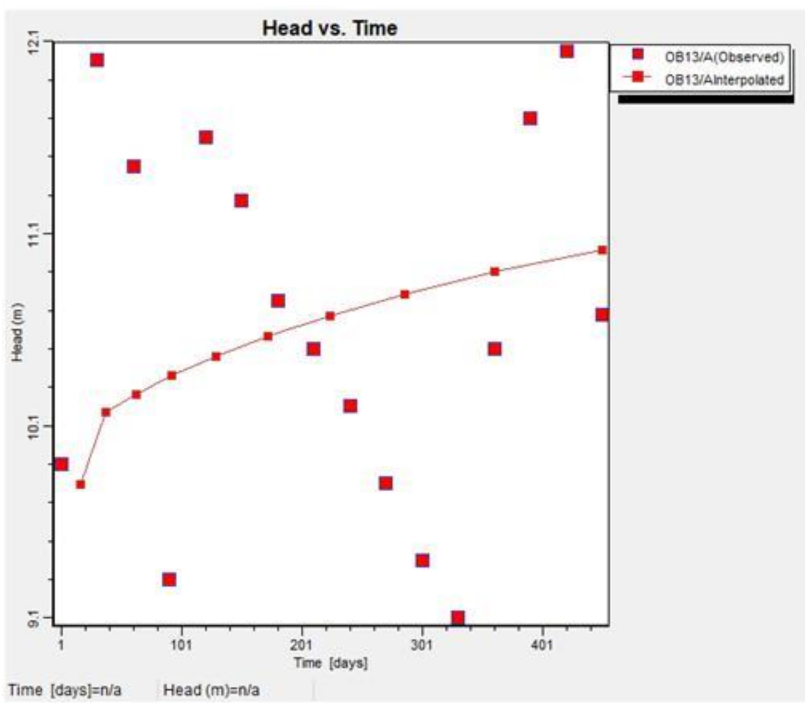

Fig 4.15 Head vs Time (well 13)

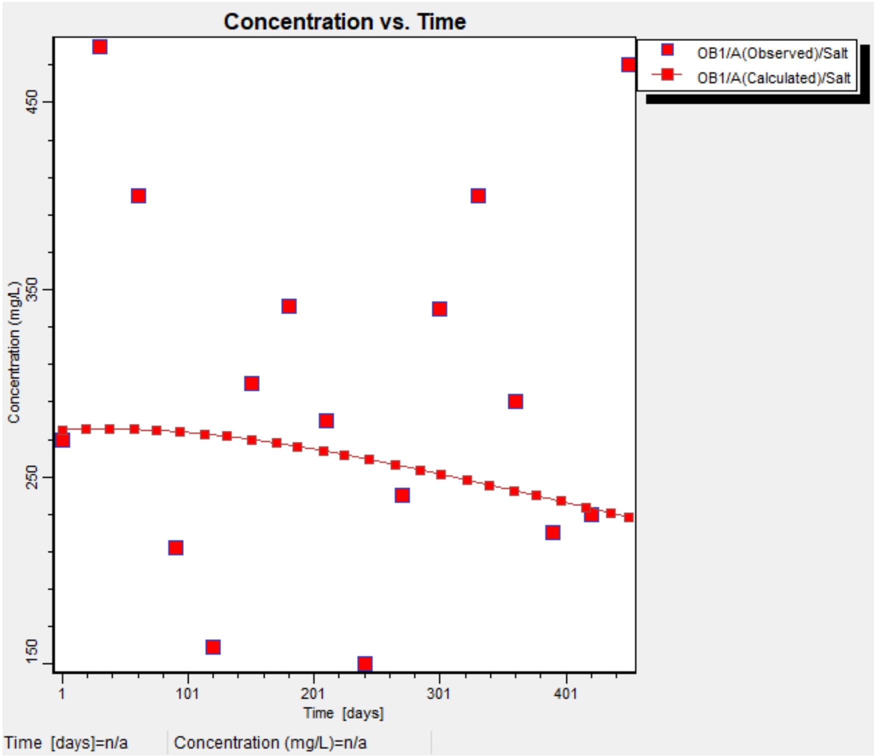

Fig. 4.16 concentration vs time (well 1)

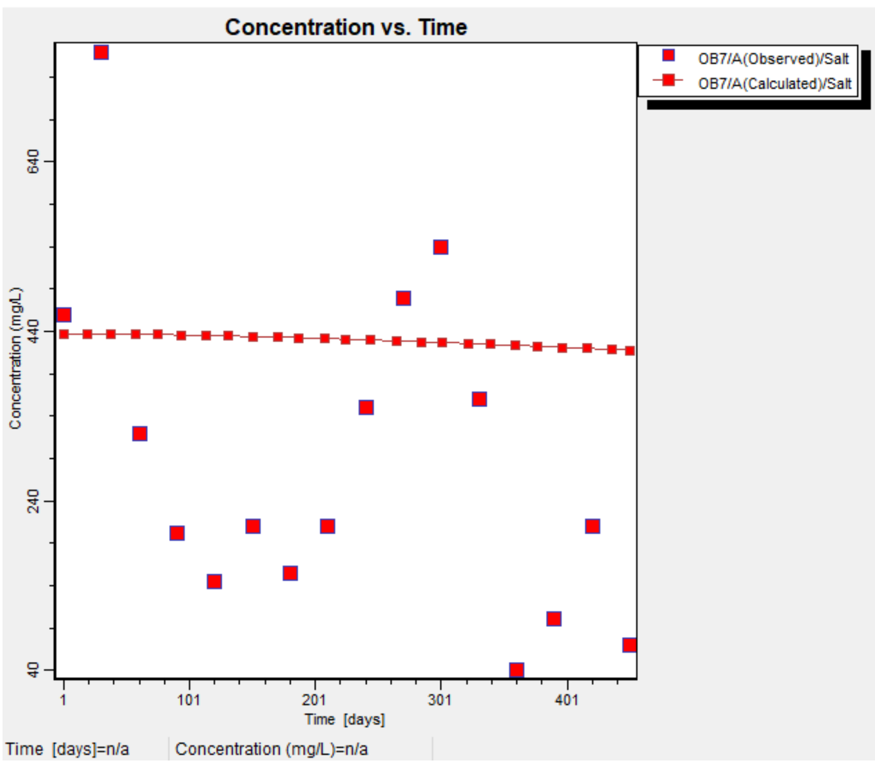

Fig. 4.17 concentration vs time (well 5)

4.5.6 Comparison of concentration of well near most and far most to sea

The observed salt concentration values of wells which are near most and far most to the sea were compared with integrated or calculated concentrations as in the fig 4.18. According tothe given graph the salt concentration is found to be more for the well nearer to the sea.

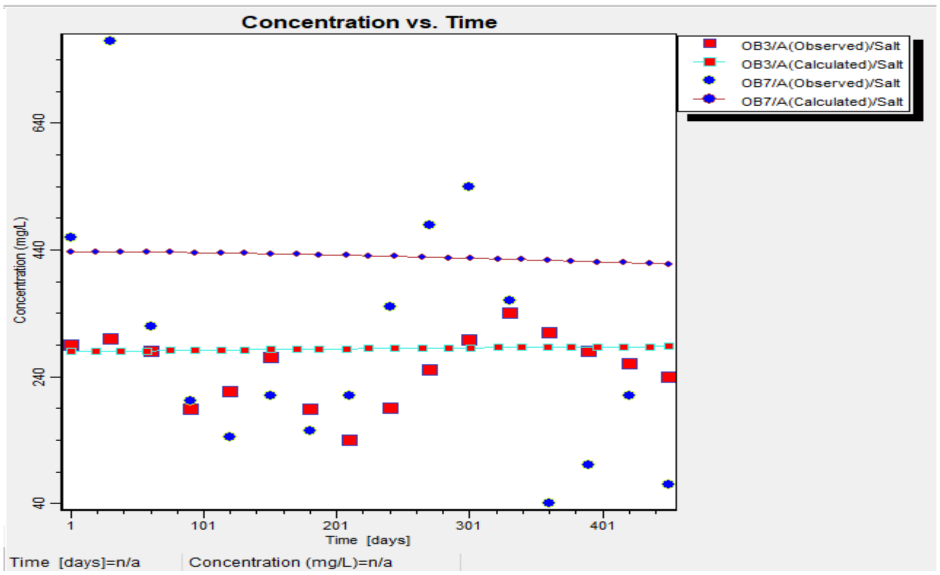

Fig 4.18 concentration comparison(well 1 Vs well 13)

4.5.7 Velocity vectors

The Fig 4.19 shows the direction and rate of movement of ground water. It can be seen from the figure that the flow actually takes place from North-East part of study area and reaches to the Sea through river and the land.

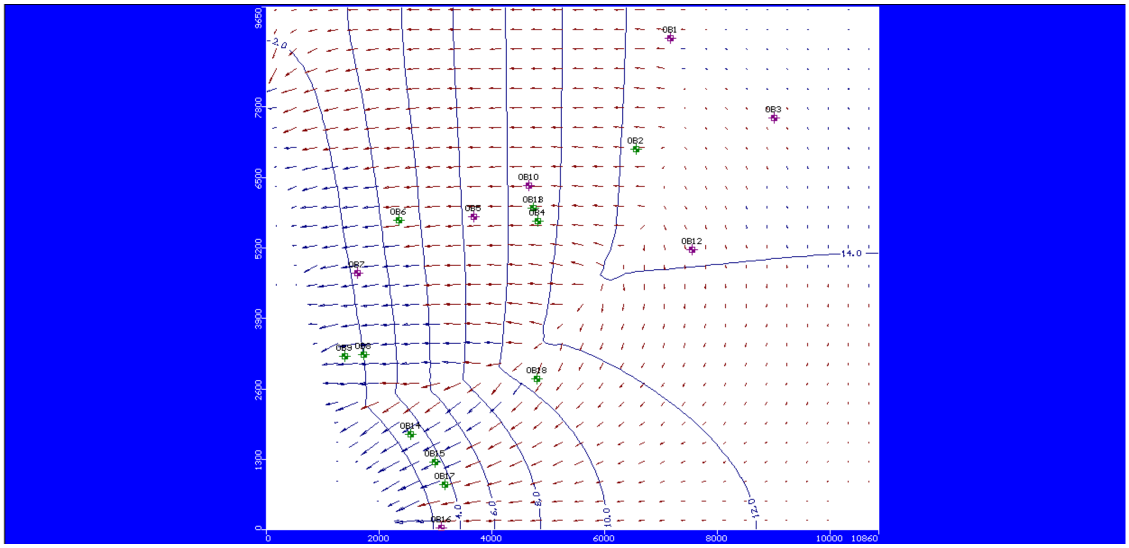

Fig 4.19 Velocity vectors at the end of the study period

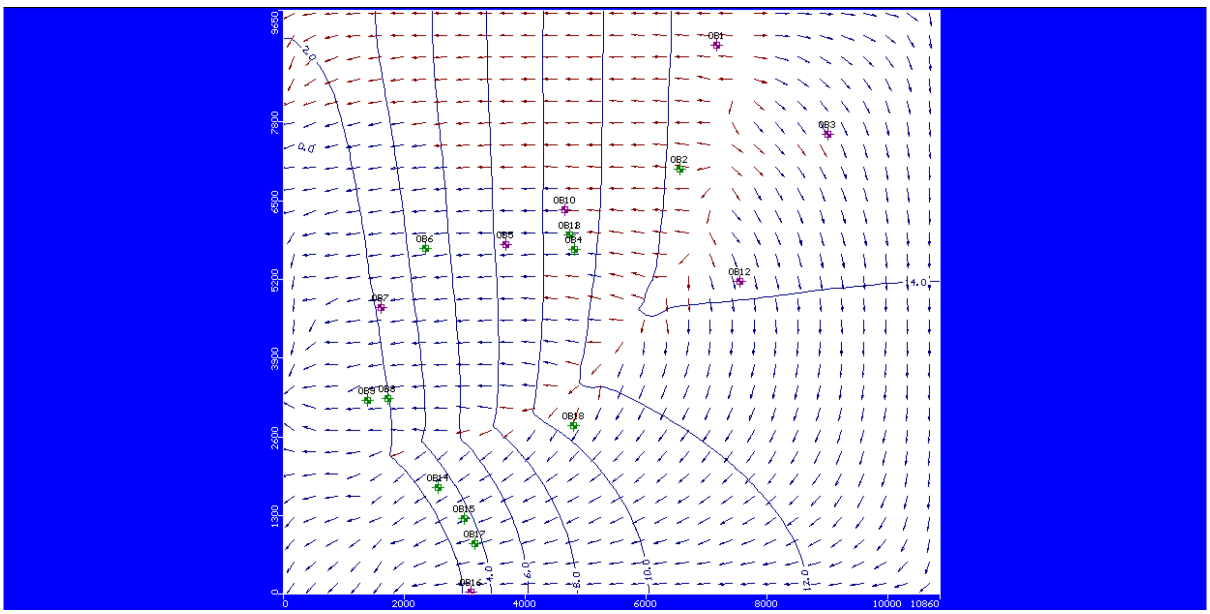

Fig 4.20 Velocity vectors at the end of the predicted period

It can be inferred that the size of velocity vectors obtained after prediction for 1000 days increases, which indicates an increase in velocity of flow.

Chapter 5

SUMMARY AND CONCLUSIONS

Saline water intrusion is a major problem during the summer months in the coastal areas. Modelling studies can be conducted to have a better knowledge of the extent and depth of the saline water intrusion. The coastal belt of the Ponnani region is subjected to saline water problems. In this study, Visual MODFLOW software along with SEAWAT was used to model the saline water intrusion in the Chamravattom – Ponnani coastal area. First a groundwater flow model of the study area was prepared using Visual MODFLOW.

The groundwater level observations and water samples from the study area were taken for a period of fifteen months from 18 observation wells. Minimum groundwater level was observed in May whereas the maximum in August. And these water samples are tested for salinity using water analyser. Electrical conductivity and salinity were tested. The salt concentration was found to be maximum in May in almost all the wells.

For the model analysis base map was prepared using Google earth and imported into the model. The conceptual model for the study area was developed. 18 observation wells are selected from the study area. After the conceptual model development, the study area was divided into square grid of equal sizes. Visual MODFLOW permit to input field observations of observation wells to get model output. Hydrogeological parameters such as hydraulic conductivity, specific storage, specific yield, porosity and initial heads ,initial concentration and boundary conditions of the model domain including constant head, constant concentration, rivers, drains, recharge were used as input of Visual MODFLOW. After completing the uploading of input parameters, the model was run for steady state and unsteady state(variable density) The model was developed and calibrated. After the development of a validated model, it was used to predict the flow head, ground water flow and salt water flow for future.

A steady state groundwater model has been developed by using Visual MODFLOW. The The input parameters were taken from previous studies. In this approach, the distributed wells, vertical and horizontal hydraulic conductivity of the three layers, constant head, constant concentration, river, and recharge boundary conditions were the inputs to the groundwater system. The water table elevations, head equipotential were calculated as outputs of the model.

The general flow direction was towards the river and to the sea. Uncertainty of parameter estimates and boundary conditions may be the most significant limitation. Slight alterations in parameters such as hydraulic conductivity and recharge can lead to dramatic differences in model output. Similarly, boundary conditions strongly control the flow regime, and so a poor representation can result in an inaccurate model.

Salinity and electrical conductivity values reveals that there is an influence of sea water in the study area. The saline concentration is more during summer seasons. That is, we found significance influence of sea water in Chamravattom-Ponnani regions.

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