REGIONAL GROUNDWATER RESOURCE MODELLING USING MODFLOW – A CASESTUDY

By

V. UDAY BHANU PRAKASH

(2016-18-016)

DEPARTMENT OF IRRIGATION AND DRAINAGE ENGINEERING

KELAPPAJI COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY

TAVANUR - 679 573, MALAPPURAM

KERALA, INDIA

2018

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Submitted in partial fulfillment of the requirement for the degree of

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(IRRIGATION AND DRAINAGE ENGINEERING)

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ABSTRACT OF THE THESIS

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2018

Dedicated to

My Parents and Guide

DECLARATION

I hereby declare that this thesis entitled "**Regional groundwater resource modelling using MODFLOW – a case study**" is a bonafide record of research work done by me during the course of research and that 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.

Place: Tavanur **V. UDAY BHANU PRAKASH**

Date: (2016-18-016)

CERTIFICATE

Certified that this thesis entitled "**REGIONAL GROUNDWATER RESOURCE MODELLING USING MODFLOW – A CASE STUDY**" is a record of research work done independently by **V. UDAY BHANU PRAKASH (2016-18-016)** 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 him.

Place: Tavanur

Date:

Dr. Sasikala D

(Chairman, Advisory Committee)

Professor and Head, Dept. of IDE

KCAET, Tavanur.

CERTIFICATE

We, the undersigned members of the advisory committee of Mr. V. UDAY BHANU PRAKASH, a candidate for the degree of Master of Technology in Agricultural Engineering with major in IRRIGATION AND DRAINAGE ENGINEERING, agree that the thesis entitled “REGIONAL GROUNDWATER RESOURCE MODELLING USING MODFLOW – A CASE STUDY” may be submitted by Mr. V. UDAY BHANU PRAKASH in partial fulfillment of the requirement for the degree.

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EXTERNAL EXAMINER

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V.UDAY BHANU PRAKASH

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SYMBOLS AND ABBREVIATIONS

Symbols		**Abbreviations**
°	:	Degree
°C	:	Degree centigrade
cm	:	Centimeter
cm^2	:	Square centimeter
cm^3	:	Cubic centimeter
et al.	:	and others
etc.	:	et cetera
Fig.	:	Figure
g	:	Gram
KAU	:	Kerala Agricultural University
KCAET	:	KelappajiCollege of Agricultural Engineering and Technology
L	:	Length
$l\ min^{-1}$	:	Liter per minute
m	:	Meter
$m\ min^{-1}$	:	Meter per minute
$m\ s^{-1}$	:	meters per second
m^2	:	Square meter
m^3	:	Cubic meter
Mm	:	Millimeter
mm^2	:	Square millimeter
Sl. No.	:	Serial Number
TMC	:	Thousand Million Cubic Feet
BMP		Bitmap

CHAPTER 1

INTRODUCTION

Water is vital for the existence of living organisms in our planet and is essential for sustainable development. Seventy one per cent of earth's surface is occupied by water, out of which 96.5 per cent of water resource is salt water in oceans and the rest 3.5 per cent is fresh water. This fresh water is in the form of polar ice, groundwater, surface water and atmospheric water. Industrialization, urbanization and rise in population resulted decrease of per capita water availability. The world is facing a growing demand for good quality water resources while the water availability remains constant. Now a days climate change and natural variability in distribution and occurrence of water affects the sustainable development of the water resources. The quality and quantity of freshwater from rivers, lakes, groundwater, soil moisture, and ice is under stress around the world. The conservation and management of groundwater resources is a critical challenge for fulfilling the rising water demand for agricultural, industrial, and domestic uses. So a judicious use of the available water is necessary, for which a public awareness about the threat to water resources and surrounding eco system is needed. Also policy decisions regarding the management of the available water resources are to be made. Various simulation and optimization approaches have been used to solve the groundwater management problems.

In India, agriculture is the primary activity and also the backbone of Indian economy. Around 60.4 per cent of the land is under agriculture. In India, rivers are the major source for irrigation. Rivers have undergone drastic change due to urbanization and drought. This situation leads to decrease in productivity which affects Indian economy. This can be overcome by proper management of surface and groundwater. Groundwater is the major source where surface water availability is declining (Mondal *et al.,* 2010). Aquifer is a water bearing strata and is called as reservoir for groundwater. Groundwater level mainly depends on the depth of water bearing strata from the ground surface and soil properties.

Depletion and contamination of water resources have caused more impact on environment. Groundwater is the only alternative for surface water resources in droughts conditions (Calow *et al.,* 1997). From 1990's, utilization of groundwater resources is increasing gradually whereas surface water availability is decreasing (Suhag., 2016). In 2012, CAG (Comptroller and Auditor General) of India reported that groundwater is contaminated with arsenic, nitrites and salinity. Quality and quantity of groundwater is affected due to low rainfall and continuous utilization of groundwater. Declination of groundwater is the sign of water scarcity. It is estimated that around 60 per cent of groundwater is going to a critical stage in the next 20 years. In north-western states, it is observed that groundwater is declining by around 3cm per year from 2002 to 2008 (Wyrwoll., 2012). This represents the critical condition of groundwater availability. In this situation, optimal use and artificial recharge of groundwater are the alternatives to overcome water scarcity (Shankar et al., 2011**)**.

Water audit is a method of quantifying the available water resources. For sustainability of agriculture, cropping pattern should be selected based on the availability of water resources. Existence of groundwater resources can be identified using aerial, surface and sub-surface techniques. Electrical resistivity surveying, VES (Vertical Electrical Sounding) method, Gamma-ray logging method and seismic refraction surveying are the surface techniques. Tracer techniques and geophysical logging techniques comes under sub-surface techniques and photo geologic methods, Landsat/ IRS, infrared imagery and electromagnetic techniques are different aerial techniques.

Quantifying the groundwater can be done by groundwater modeling. Modelling is the best tool that can be used to simulate the historical conditions and also for predicting the future aquifer conditions. The model should be capable of reproducing the field observations before it can be used for prediction purpose. Groundwater models play an important role in the development and management of groundwater resources, and in predicting effects of management measures. In India, water scarcity is the main reason for crop failure. Cropping pattern can be selected according to surface water and groundwater availability. Conceptual model, mathematical model (analytical and numerical modelling), physical models (sand tank models) and digital models (finite difference model and finite elemental model) are different types of models used for groundwater modelling. This study is done using U.S. Geological Survey modular finite difference flow model.

MODFLOW is a FORTRAN based program which is mainly used by hydro-geologists to simulate the groundwater flow. MODFLOW-88, MODFLOW-96, MODFLOW-2000, MODFLOW-2005, MODFLOW-OWHM and MODFLOW 6 are the different versions available. Argus ONE, GMS (Groundwater Modelling System), Groundwater Vistas, Leapfrog Hydro, Processing MODFLOW and Visual MODFLOW are the commercial MODFLOW programs typically used by government agencies and consultants (USGS).

Visual MODFLOW is a user friendly software. This package combines with MODFLOW, MODPATH, MT3D and PEST with a powerful graphic interface. Inputs and outputs can be visualized in 2D and 3D. PCG2, SIP, SOR and WHS are the different solvers available to run the model. Visual MODFLOW can create model for groundwater study, saltwater intrusion and contaminant transport for the site. Groundwater conditions can be studied by creating model on watershed or district wise or area basis.

Along with the strain on surface water, the country is also facing great stress with freshwater. Lack of strict state regulation on ground water development has caused a strain on the amount of freshwater available. By 2030, water demand is projected to be double the supply, implying severe scarcity for hundreds of millions of people.

Several parts of the city are reeling under the serious problem of shortage of drinking water.

Water use in India has been increased over the past 50 years. Out of the total annual freshwater withdrawals, the largest share goes to agriculture, 92 per cent. Industrial use accounts for another 3 per cent and domestic use 5 per cent. The amount of water available per person has declined in recent decades, primarily because of population growth and water scarcity is projected to worsen in the future. India is suffering from the worst water crisis in its history and millions of lives and livelihoods are under threat. Droughts are becoming more frequent, creating problems to rain fed farmers of the country.

Inter linkage of Canals by building storage reservoirs on rivers and connecting them to other parts of the country can impose reduction in regional imbalances and provide lot of benefits by way of additional irrigation, domestic and industrial water supply, hydropower generation, navigational facilities e.t.c.,

The Central Ground Water Board has been setup to develop and disseminate technologies for monitoring and implementing policies for scientific sustainable development and management of ground water resources including exploitation, assessment, conservation, augmentation, protection from pollution and strategy based on economic and ecological efficiency and equality.

According to the CGWB, around 39 per cent of the wells are showing a decline in groundwater level. Out of 6,607 assessment units in the country, 1,071 units (in 15 states and 2 union territories) have been categorized as “over exploited” based on the stage of groundwater withdrawal as well as long term decline in groundwater level.

In India, Andhra Pradesh has the second highest coastline with 974 km. Godavari, Krishna, Tungabhadra, Vamsadhara and Penna are the major rivers flowing through Andhra Pradesh. The rivers are adversely affected by urbanization and climate change. From the last 20 years, rivers have gone through a lot of climatic changes which results in drying of rivers. Generally rivers are the major source of water for agriculture. Andhra Pradesh is also known as ‘Rice bowl of India’. In Andhra Pradesh, major portion of paddy is producing from East Godavari and West Godavari districts. Godavari river is the major water source for Godavari districts. In Godavari river, around 3000 TMC of surplus water drains into sea, whereas, Penna and Krishna rivers are at critical stage. This can be overcome by diverting water from the rivers with surplus water to the rivers in the critical stage. Government of Andhra Pradesh planned interlinkage of Godavari and Krishna rivers by constructing a lift irrigation project named as ‘Pattiseema lift irrigation project’. This lift irrigation project is used to divert the surplus water from Godavari river to Krishna river. Since the groundwater potential of the area is not adequately investigated, lack of knowledge is a problem for the development and management of the aquifer in the area. In order to ensure a judicious management of groundwater, the present status should be evaluated and a prediction of the future water resource scenario should be attempted. This can ensure a proper groundwater management of the area.

Foundation stone for “Pattiseema lift irrigation project” was laid on 29th march 2015 and dedicated to nation on 15th August 2016. Construction of this project was completed in one year. 24 pumps were installed to divert water from Godavari river to canal. Unlined canal was laid from pump house near Godavari river to Krishna river. Length of the canal is around 160 km. Diverted water will meet the Krishna river at ‘Pavitara Sangamam’ in Krishna district. In 2016 around 100 TMC of water from Godavari river is diverted to Krishna river. With this project will irrigate around 1 lakh hectares in Krishna command area.

It is important to know the benefits of river interlinkage program. River interlinkage program will increase availbality of surface water and groundwater. There will be groundwater recharge from the unlined canal. A study of the groundwater system of the area is required to understand the impact of Pattiseema lift irrigation project in West Godavari district. In the present study, a model is developed using visual MODFLOW and groundwater behavior for different scenarios in west Godavari district is studied using this model.

The primary objective of the study is to understand the aquifer system of the area and to develop a realistic and accurate groundwater flow model representing the physical characteristics of the aquifer incorporating the relevant processes.

The main objectives of this research are,

1. To study the spatial and temporal ground water table fluctuation.
2. To identify the potential groundwater zones and to collect the well log details of the study area.
3. To develop a transient groundwater flow model of the study area using MODFLOW and to investigate the effects of future groundwater extractions.

CHAPTER 2

REVIEW OF LITERATURE

The chapter reviews the concepts and literatures available on ground water flow, geophysical methods of ground water investigations, recharge estimation methods and MODFLOW.

2.1. Groundwater

Groundwater is an important component of water resource system and the management of the groundwater system necessitates making decisions related to a number of specific problems in the field. Stress on freshwater resources due to rising demand is already leading to water scarcity in many places. To meet the increasing demand for groundwater and for an effective groundwater management, an understanding of groundwater potential is necessary.

Ground water is the water that seeps through rocks and soil and is stored below the ground. The soil formations in which ground water is stored are called aquifers. Aquifers are typically made up of gravel, sand, sandstone or limestone. Participation at all levels is important in management decisions as well as in the development of a governance framework. As of April 2015, the water resource potential or annual water availability of the country in terms of natural runoff (flow) in rivers is about 1,869 Billion Cubic Meter (BCM)/year. However, the usable water resources of the country have been estimated as 1,123 BCM/year. This is due to constraints of topography and uneven distribution of the resource in various river basins, which makes it difficult to extract the entire available 1,869 BCM/year (Roopal Suhag, 2016)

Gangwar (2013) studied the quality and quantity of groundwater in India. The analysis of available data indicates that contribution made by groundwater to the agricultural economy of India has grown steadily since early 1970’s. In just last two decades, the ground water irrigated lands in India has increased by nearly 105 per cent, this change was most striking in northern India

Bhattacharyya *et al.* (2015) studied the groundwater scenario and proposed different management techniques. They proposed several water conservation techniques like roof water harvesting, flood management techniques, drought management techniques and water budgeting. They suggested some workable solutions for judicious use of water resources. They are a) Banning private well in futile; croud them out by improving public water supply b)regulating final users is impossible, facilitate mediating agencies to emerge, and regulate them. C) Pricing agricultural groundwater use is infeasible; instead, use energy pricing and supply to manage agricultural groundwater draft. d) No alternative to improved supply side management: better rain- water capture and recharge, imported surface water in-lieu-of groundwater pumping. e) Grow the economy, take pressure off land, and formalize the water sector.

2.2 Geophysical methods for groundwater identification

Geophysical methods are used to identify the potential groundwater zones. This method is used to identify the depth of groundwater, depth of different geological formation in the earth and salt content of water.

2.2.1 Electrical Resistivity Method

The electrical resistivity method measures both lateral and vertical variation in ground resistivity from different points on the earth surface. The resistivity of the ground is measured by sending current into the ground at the current electrodes and the corresponding potential difference is measured at the potential electrodes, which is then converted to apparent resistivity value by multiplying with an appropriate geometrical factor. Different factors affect the resistivity in the subsurface (Telford *et al.* 1990).

Electrical resistivity method is used to detect subsurface layers, their thicknesses, and their resistivity's, to investigate the hydrological conditions of the area with the view of delineating the potential area for groundwater development, to map geological structures e.g. faults and fractures, which are conductive bodies, thus may accommodate groundwater, and to locate possible and suitable site for productive boreholes in the study area.

2.2.2 Geophysical Prospecting Methods

The essence of geophysical methods is to analyze the real picture of the subsurface geology of a particular area of interest. Devices used for these methods locate discontinuities caused by contrast in physical properties of the rocks. However, due to the complexity of the geophysical pattern and signature of these discontinuities in geophysical interpretations, an integrated survey or the correlation of two or more geophysical methods are used so as to reveal the subsurface geology of the area of interest, not leaving behind its ability to reduce the problems posed by inhomogeneous nature of the earth. In this project, an integrated geophysical survey was adopted which comprises of seismic refraction and electrical resistivity methods.

2.2.3 Seismic Refraction Method

Seismic refraction method is based on the principle of acoustic impedance which is the product of density and velocity of subsurface layers. Energy is sent through the source which could be a hammer, a weight dropping system, explosives, etc. The method used for this exercise is the hammer method. Energy sent into the subsurface is refracted, travels along the subsurface boundary and back to the surface and is recorded by receiver(s) called geophone(s). This method assumes that velocity increases with depth. So, if the velocity of the layer is less than the velocity in the layer overlying it, there will be velocity reversal. The layer having the low velocity will not be delineated by the refraction method. The factors that affect seismic velocity in rocks are age of the rock, porosity, and depth of burial etc.

Gnanasunder and Elango (1999) carried out groundwater quality assessment of a coastal aquifer lying south of Chennai City, Madras, India, using geo-electrical techniques. This study was able to delineate a fresh water ridge of good groundwater quality in the central portion of the coastal aquifer while the eastern and western margins of the aquifer however contained groundwater of poor quality.

2.2.4 Vertical electrical sounding

Vertical electrical sounding, VES, is used to determine the resistivity variation with depth. Single VES should only be applied in areas, where the ground is assumed to be horizontal layered with very little lateral variation, since the sounding curves only can be interpreted using a horizontally layered earth (1D) model.

The calculated resistivity value is not the true resistivity of the subsurface, but an "apparent" value which is the resistivity of a homogeneous ground which will give the same resistance value for the same electrode arrangement. The relationship between the "apparent" resistivity and the "true" resistivity is a complex relationship. To determine the true subsurface resistivity, an inversion of the measured apparent resistivity values using a computer program must be carried out. The measured apparent resistivity values are normally plotted on a log-log graph paper. To interpret the data from such a survey, it is normally assumed that the subsurface consists

2.3 Groundwater modelling using MODFLOW

Groundwater model is regarded as the best tool to conceptualize the hydro geological situation in the groundwater basin, to simulate the behavior of the flow system and to evaluate the water balance. The groundwater flow model MODFLOW, a physically based groundwater flow model, has been widely used to predict the water table behavior. In the present work, MODFLOW is used to develop a groundwater flow model for a basin where groundwater data is available. The developed model will be used to simulate the response of the hydrogeological system under various stress conditions in future. Groundwater model is a simplified version of the real aquifer system that approximately simulates input-output stresses and responses relation to aquifer system. Groundwater models are the mathematical and digital tools used to study and analyze present aquifer condition and predict future behavior of the aquifer system on local regional scale, under varying geological environment. The models act an important role in the management and predictive measures on groundwater resources. These models resolve the basic partial differential equations that manage the flow through porous medium and solute transport through unsaturated and saturated porous medium.

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.

Visual MODFLOW is a commercial Graphical User Interface for MODFLOW. It was introduced by the 'Waterloo Hydrogeologic' company in August, 1994. The main difference between MODFLOW and Visual MODFLOW is that MODFLOW uses input data in the form of text files which make it complex and time consuming. Whereas, Visual MODFLOW uses Excel files, Surfer grids, GIS and AutoCAD data as input files. This makes modelling user-friendly and consumes comparatively lesser execution time.

GIS has emerged as an effective tool for handling spatial data and decision making in several areas including engineering and environmental fields (Stafford, 1991; Goodchild, 1993)**.** MODFLOW is programmed under the FORTRAN 77 (American National Standards Institute 1978) language environment with the finite–difference method to describe the movement of groundwater flow. It was developed by McDonald and Harbaugh (1984) of US Geology Survey in 1984 and had been updated for three times including MODFLOW-88(McDonald and Harbaugh 1988), MODFLOW-96 (Harbaugh and McDonald, 1996) and MODFLOW-2000 (Harbaugh *et al.,* 2000). The newest version of MODFLOW-2000 could be compiled by FORTRAN language of Visual Studio program and general language of C could be used here.

Gburek (1999) modelled the pollutant transport within a layered and fractured aquifer of an upland agricultural watershed in Pennsylvania, USA. Meriano (2003) developed a groundwater flow model for a drainage basin in Canada. With their forecast they demonstrated the susceptibility of deeper aquifers to urban contaminants and suggested the importance of long term planning for water quality.

Massuel *et al*.(2001) developed a model for groundwater resource to predict the potential renewable storage. They used the interpretation of drill-logs and Digital Elevation Model for surface interpolation. Calibration was performed for the period 1995- 2000 which is the period with the highest variation around the average in terms of water-table fluctuation this calibration consists of inverse modelling of the groundwater levels. In this model, by using MODFLOW Pumping Wells packaging, groundwater abstraction is simulated. A total of 120,000 wells are in use over the modelling domain which means a density of around 12 wells per km^2. Actually, wells density is varying in space and time and ranges from 4 to 18 wells per km^2. At the end they found that mean depth of the water-table varies for pre-monsoon between 11.3 m to 8.0 m below ground level and between 8.6 m to 5.0 m for post-monsoon. They observed that natural recharge from rainfall contributes about 9.4 per cent of the total annual rainfall (652 Mm^3) while 1220 Mm^3 is the sustainable annual groundwater withdrawal yield over the period for the total basin.

A three-dimensional groundwater flow model was developed by Reeve *et al*. (2001) to test the hypothesis that regional ground-water flow is an important component of the water budget in the Glacial Lake Agassiz Peatlands of northern Minnesota. Simulations suggested that ground-water flow within the peatlands consists of local-flow systems with streamlines that are less than 10 km long and that ground water from distant recharge areas does not play a prominent role in the hydrology of these peatlands. Groundwater flow reversals previously observed in the Red Lake Peatlands are either the result of interactions between local and intermediate-scale flow systems or the transient release of water stored in glacial sediments when the watertable is lowered.

Groundwater overexploitation maybe defined as a situation in which, for some years, average abstraction rate from aquifers is greater than or closer to the average recharge rate (Custodio, 2002). The national-level groundwater assessment in India that deals with estimates of groundwater use in proportion to annual replenishment of groundwater, has been made possible through a methodology developed initially by the Groundwater Resources Estimation Committee (Ministry of Water Resources, 1997)

Osman and Bruen (2002) studied the aquifer seepage in an alluvial aquifer and improved loosing-stream package for MODFLOW. They analysed the flow between stream and aquifer, it cannot be determined accurately unless the effects of the suction head beneath the clogging layer. They developed such type of model and successfully incorporated into the widely used groundwater flow model, MODFLOW. This technique was new, simple and gives results much closer to those of complex variably saturated codes, such as simulating water flow and solute transport in two-dimensional variably saturated media (SWMS_2D), than previous methods. They reviewed simple numerical approaches for modelling stream- aquifer interactions through clogging layers and evaluated the differences between them. The most commonly used technique tends to underestimate stream losses because it ignores suction heads below the clogging layer. Finally they compared the steady state seepage flow between SWMS_2D, MODFLOW, and MOBFLOW and seepage flow of MODFLOW very well matched with SWMS_2D.

Chen and Chen (2003) conducted a numerical modeling study using MODFLOW and MODPATH to investigate the effects of stream aquifer fluctuations, aquifer properties, the hydraulic conductivity of streambed sediments, regional hydraulic gradient and recharge and evapotranspiration rates on stream aquifer interaction. They concluded that bank storage solely caused by stage fluctuations differs slightly between losing and gaining streams

Kumar (2004) developed a steady state ground water flow 'North East Musi Basin using Finite Difference Method under MODFLOW package by assuming 8 to 10 per cent of annual recharge. From the water balance computation in steady state, the recharge is estimated as 2.4 MCM out of which 1.1 MCM is Contributed by lakes. Outflow and draft were estimated as 0.4 MCM and 2.1 MCM respectively.

Sylvain et al., (2004) conducted study in the Musi-river sub-basin of 11,000km^2 of Krishna river in Andhra Pradesh. A transient state MODFLOW 2000 model has been used in groundwater management which is calibrated and validated for the area in which the transitivity were analysed by the inverse fitting. The conceptual model composed of 2 layers, the surface interpolation was analysed by the interpretation of drill-logs and digital elevation model. It has been concluded that the model has good water balance than other methods. The result has showed that the model is the best to analyse the general groundwater resource management and concluded that groundwater availability is declining due to pumping effects.

Abdulla and Tamer (2006) carried out processing MODFLOW version (PM5) is used in the study to simulate the groundwater flow for both steady and transient condition to forecast the future changes that occurred under different stages and to investigate different scenarios of artificial groundwater recharge to evaluate their effect on the water table.

A direct approach to designing MODFLOW finite difference model is tedious and less intuitive, specifically for complex boundary and initial conditions. Therefore, a MODFLOW model can be developed either using a grid or conceptual model approach. Kushwaha (2007) conceptual model is created using Geographic Information System (GIS) objects including points, arcs and polygons so that it can more accurately represent real world condition. It is a simplified representation of the site to be modelled including the model domain, boundary conditions, sources, sinks and material zones. Advantage of conceptual model is that most of the input can be in terms of physical objects, such as wells, lakes, recharge zones etc which can then be converted to a grid based mathematical model with the help of preprocessor software. The results obtained from mathematical groundwater model developed for the northern part of Mendha sub-basin in the semi-arid region of northeastern Rajasthan, employing conceptual groundwater modelling approach. For this purpose, Groundwater Modelling Software (GMS) was used which supports the MODFLOW-2000 code. For the purpose of modelling the Source/ Sink Coverage, Recharge Coverage, Extraction Coverage, Return Flow Coverage and Soil Coverage were considered. The model was calibrated against the historical and observed water level data for periods 1998 to 2003 and 2003 to 2005 respectively. The model was run to generate groundwater scenario for a 15 year period from 2006 to 2020 considering the existing rate of groundwater draft and recharge. The water budget predictions indicate a decrease from 349.50 to 222.90 MCM in the groundwater storage system, whereas groundwater abstraction shows an increase from 258.69 to 358.74 MCM per annum. The predicted water table contour maps for the years 2007, 2015 and 2020 have also been generated.

Kim *et al.* (2008) developed and applicated the integrated SWAT–MODFLOW model. They developed an HRU–cell conversion interface, which exchanges flow data between the cells in MODFLOW and the HRUs (hydrologic response units) of SWAT. They used SWAT–MODFLOW to simulate the spatio- temporal distribution of groundwater recharge rates and groundwater evapotranspiration. They divided the SWAT and MODFLOW into two components. They designed this model to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds.

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

Mondal (2009) developed a mass transport model for the migration of tannery effluent contaminants around a tannery industrial belt. It was reported that the migration phenomenon was affected mainly by advection rather than dispersion. The contaminant transport emanated from the tannery belt and moved towards eastern side of a river downstream.

Rajamanickam and Nagan (2010) conducted a study to model a river basin at the downstream of Karur Town using Visual MODFLOW 2.8.1 version. The study area was limited to 320 km^2 which was divided into 4572 cells with grid size of 350m x 200 m with two layers. The groundwater monitoring data, lithology, hydro geological parameters, topography, rainfall data obtained from PWD, CGWB, Survey of India, and India Metrological Department are used in the model. The MODFLOW and MT3D models are calibrated and validated for simulation of the groundwater quality for next 15 years under five difference scenarios. The simulation results show there is no improvement in groundwater quality even the effluent meet the discharge standards for the next ten years. When the units go for zero discharge then there will be an improvement in the quality of groundwater over a period of few years.

SHI developed a groundwater model to assess the sewage plant accident pool leakage and found that the observed NH_3-N concentration of the first layer under the accident pool varied with time. The NH_3-N concentration increased sharply to about 8.0 _ 10–5 mg/L (on the third day) after the first accident, and declined quickly to about 2.5 to 10–5 mg/L (on the thirtieth day) because of dilution of groundwater, adsorption by soil and degradation. When the second accident occurred, the concentration increased sharply once again and reached the maximum (1.1 _ 10–4 mg/L) on the thirty-third day, then it started to decline, and became stable.

Baffour *et al.* (2011) developed a groundwater model for Oda River using MODFLOW. An initial conceptual hydrogeological model of the Oda River basin in Besease with unconfined, semi confined, two layered aquifer was developed with differing hydraulic characteristics. The calibrated MODFLOW model was more acceptable with the average root mean square error (RMSE) of 0.099 m and 0.134 m, (MAE) of 0.067 m and 0.084 m and average (ME) of 0.016 m and -0.006 m for P 1 and P 14 respectively. The Water Table Fluctuation method used as an estimate of groundwater recharge gave a better fit between the simulated hydraulic head and observed sub-surface water level fluctuation.

Ahmed (20012) developed a model to simulate the behaviour of the flow system and evaluate the water balance. The quaternary alluvium hosts the aquifer in the region. The study area forms a part of Yamuna–Krishni interfluve. The sensitivity of the model to input parameters was tested by varying the parameters of interest over a range of values, monitoring the response of the model and determining the root mean square error of the simulated groundwater heads to the measured heads. These analyses showed that the model is most sensitive to hydraulic conductivity and recharge parameters. Three scenarios were considered to predict aquifer responses under varied conditions of groundwater abstraction.

Kumar *et al.* (2012), studied sea water intrusion in the multi-aquifer system in the Krishna River Delta. The results, of hydrochemistry and environmental tritium including the radiocarbon dates, indicate that the origin of salinity in the aquifer systems is due to palaeo-geographical conditions. The salinity front is observed to be at 25, 30 and 50 km distance in shallow, intermediate and deeper aquifers respectively from the coast. The modern irrigation practices using intensive canal network has led to refreshing of the aquifer systems. The extent of refreshing has been mapped using hydrochemistry and environmental tritium. The recharge of groundwater by the canal system can be expedited by developing the canal network in the area having high potential for groundwater recharge. This will result in further reduction of salinity in the Krishna delta region. Further, Cl–/Br– ratio and stable isotopes have been used to study the aquifer– aquifer interconnectivity and to identify perched aquifers within the study area.

Xu *et al.,* (2012) used Soil–Water–Atmosphere–Plant (SWAP) package was integrated into a groundwater flow model (MODFLOW) in such a way that the SWAP package calculates vertical flux for MODFLOW, while MODFLOW provides averaged water table depth to determine the bottom boundary condition for SWAP zones. The SWAP zones in MODFLOW are derived from a combination of topology, soil type, land use, water management practices using geographic information systems (GIS). Then the MODFLOW with SWAP package was tested using a two-dimensional saturated–unsaturated water table recharge experiment. Results showed that the simulated water table elevations matched well with the observed ones except at the early period during which they were slightly higher than the observed ones, probably due to neglecting lateral diffusion in the unsaturated zone. The simulation results validated the applicability of the developed MODFLOW with SWAP package for practical regional groundwater modeling. The simulation results validated the applicability of the developed MODFLOW with SWAP package for practical regional groundwater modeling.

Yeh *et al.* (2012) applied a water balance concept with two models in the Ching-Shui watershed to describe the groundwater recharge. Soil moisture budget model is established to estimate the infiltration, runoff, evapotranspiration, and groundwater recharge in the watershed, where the moisture content of the soil is tracked through time. Secondly, the groundwater recharge was also estimated by the model of the base-flow-record estimation, with the assumption that groundwater evaporation is negligible. In addition, since the analyzed base-flow trends are high, when executing model analysis, the depths of infiltration estimated by stable-base-flow analysis is used to obtain more reasonable groundwater recharge value. The coefficients of groundwater recharge by the precipitation in the Ching-Shui watershed estimated from the established soil moisture budget model and the base-flow model were 12.40 per cent and 9.92 per cent, respectively. Comparison show the result of both models to be close.

Kaviyarasan *et al.* (2013) made an assessment of groundwater flow for unconfined coastal aquifer in Kalpakkam (6.89 sq.km) with the integration of MODFLOW pro 2009.1. The boundary was set in ArcGIS and imported to MODFLOW. Constant head boundary condition was adopted for steady state flow conditions, boundary condition specified by recharge flux was applied in the areas were recharge is limited due to infiltration. Input details were collected from 13 bore wells and 2 open wells. The obtained groundwater head was compared with those, which measured in fields and analysed through regression method. The regression analysis shows good correlation of about 0.91 with RMSE of 0.57. The study also estimated the groundwater flow velocities, which was observed in the range of 0.03 to 0.08 m/day.

Needhidasan and Nallananathel (2013) applied GIS and Visual MODFLOE techniques in groundwater modeling with the intention to conserve groundwater resources in the Thirukkazhukundram Taluk, Tamilnadu. Thematic maps like slope ma[, soil map, Geology map, land use map, geomorphology map as well as rainfall map were prepared in GIS and groundwater potential zone map was derived from these map using weighted overlay analysis. Along with this data like rainfall, infiltration, well log, aquifer characteristics, tank details, water table data etc were compiled in GIS and applied to MODFLOW 2011.1. This model helped to simulated water levels in the observation wells. The model simulated was calibrated and validated using the observed data, which was highly correlated. The study noted that the accuracy of model is confined in availability and accuracy of the number of collateral data chosen for the study.

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

Aniekan et al., (2014) has conducted study to analyse the recharge characteristics and aquifer hydraulic conductivity in Niger Delta in Nigeria using MODFLOW numerical model. Brigham University for the inference of Model developed GMS software with “calculated module”, an optimizer PEST, and pre-processer, post-processor. It was concluded that the MODFLOW showed average recharge which has exhibited dominate recharge potential in this area. This is the dominant model for the future simulation and management of groundwater modeling under unsteady state in the Niger Delta.

Babu *et al.* (2014) developed a groundwater model for the Nellore coastal zone basin 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.

Kumar and Kumar (2014) developed a steady state MODFLOW model to quantify groundwater in Choutuppal Mandal, Nalgonda (Dt) AP., using groundwater data from 19 observation wells. The model was conceptualized as a two layered weathered and fractured aquifer system spread over 19215 m x 10366 m area, and observed and computed groundwater level contours were found in good agreement.

Surinaidu et al., (2014) has developed a numerical model for groundwater in Godavari valley coal fields using 20 layers and thickness of 320m. The saturated groundwater flow fluctuation and conditions in the area were studied using visual MODFLOW. Groundwater model is studied in transient or steady state flow and concluded that the model has helped in knowledge of the groundwater flows at needed depth in the mine pits for pumping infrastructure.

Lakshmi et al., (2015) has studied the adaptability of visual MODFLOW in different hydrogeological situations which is dispersed by manmade or natural situations in the groundwater system. Modeling involves interpretation of data, conceptualization, code setting, field data and input data selection and calibration of model. The study concluded that model is applicable for indicating of the groundwater flow operation and flow rates in and over the boundaries of areas. The model is adaptable in two and three dimensional analysis of groundwater flow system.

Lasya et al., (2015) studied the interaction of the surface water and groundwater in Jakkur catchment in Bangalore area using the MODFLOW software. The methodology steps involved in the study are conceptual model, numerical model in the study area. The hydraulic conductivity, evapotranspiration, draft, storage and recharge are the input parameters given to model. Using MODFLOW groundwater behavior was studied in steady and un-steady state conditions.

Khadri et al., (2016) used three dimensional hydrogeological MODFLOW which is calibrated. This model can be associated with GIS for the groundwater management for akhola and buldhana districts in Maharashtra area. The study concluded that there is correlation between the observed and stimulated hydraulic heads using MODFLOW.

It is studied that the MODFLOW is best method and can be used with minimum modeling errors and the results has estimated that the computed values are good – fitness which showed model reliable. The model used is efficient in rational use and in groundwater management which stimulates the effect on the groundwater resources.

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

Gautam and Swaroop (2015) conducted a study related to groundwater and solute transport modeling to identify the suitability of visual MODFLOW software packages under different ground water conditions. The packages consists of option to calculate ground water quality, quantity and distribution (MODFLOW), to calculate flow velocity (MODPATH) and MT3D software to calculate transportation of groundwater. Input parameters required for this model include climate details, lithology data, slope data, aquifer properties, groundwater level data as well as pumping details. The study concluded that the visual MODFLOW is a best tool for identifying the behavior of ground water system including 2D and 3D assessment of groundwater flow as well as solute transport.

Shashank et al., (2015) carried study to provide groundwater options at north district of Delhi in respective to the aquifer architecture. It was concluded that the groundwater salinity has enhanced with water logging under clay development in semi-arid condition and there is an establishment of enriched recharge from surface runoff and floods in the season of monsoon.

Sajeena (2016) developed a MODFLOW model for groundwater resource flow modelling and mapping of 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 ground water condition after 15 years by increasing the pumping rate by 10, 25 and 50 percent of pumping rate of the validated period.

Sushant *et al.* (2017) developed a groundwater modelling in Bina river basin in Madhya Pradesh. They simulated for better understanding of the groundwater balance by using Visual MODFLOW. The involvement of a steady-state hydrogeological simulation of the two-layered aquifer was used in this model. They assigned those aquifer parameters based on CGWB and WRD, which were then adjusted during the model calibration. Finally they advised that future groundwater resource development plans must be taken to compare balance between the groundwater recharge and the intended abstraction rates to ensure the sustainability of the resource in the catchment of the Bina river basin and the pumping rate should not be kept high so that the groundwater levels in the Bina town becomes lower than the actual level at the outlet.

Sridhar *et al*. (2018) conducted a groundwater modeling study in Ponnaiyar sub-watershed, Tamil Nadu using visual MODFLOW. Water level data, monthly rainfall data, well data along with its location were collected for the study. The base map for the study area was prepared in GIS environment and imported into the MODFLOW. Elevation details were collected through the GPS survey. Aquifer properties were assigned to the study area. The recharge estimated by the groundwater estimation committee was used as boundary condition in this model. The model was run both for steady as well as transient state. The results obtained through both the states were calibrated separately using the observed water level data of the year 2005-2014 and validated using the data of the year 2014-2016. With the help of the model, groundwater condition in the year 2030 was predicted. The study suggested to improve groundwater recharge rate through constructing check dams, contour bunds in different parts of the sub-watershed.

CHAPTER 3
MATERIALS AND METHODS

Water is the basic resource for the planet. Quality and availability of water, both surface water and groundwater, is declining gradually due to urbanization, global warming and climate change. Rivers are the main source of surface water which is in a critical condition. Hence, groundwater is the only substitute available for surface water, but the groundwater alone cannot substitute surface water completely. Groundwater will support agricultural purpose and domestic purpose up to a certain extent only. Proper steps have to be followed for the judicious use of the available groundwater, for which a proper knowledge of the resources available is required. The main objective of the research was to predict the groundwater levels with respect to change in recharge and exploration. To study the groundwater scenario, a model was developed for the ground water resources in West Godavari district using Visual MODFLOW. The developed model was used to study the effect of river inter linkage project on groundwater scenario in the West Godavari district. The materials and methods adopted for the study of the groundwater scenario are discussed in this chapter.

3.1 Features of the study area

3.1.1 Location

West Godavari District is in Andhra Pradesh bounded by river Godavari in the East, Krishna River in the West and Bay of Bengal in the South. Location map of West Godavari district is shown in Fig.3.1. West Godavari district lies between $16^{\circ}51'$ and $17^{\circ}30'$ North latitudes and $80^{\circ}50'$ and $81^{\circ}55'$ East longitudes. West Godavari district falls in the Survey of India toposheet Nos. 65 C, D, G & H. The geographical area of West Godavari district is 7,795 Sq.km. It consists of 46 mandals (910 villages) and 8 municipalities (CWGB 2012-13).

3.1.2 Rainfall

The normal annual rainfall of West Godavari district is varying from 840 to 1283 mm. Average annual rainfall of West Godavari District is 1078 mm. South west monsoon contributes to a major part of rainfall followed by north east monsoon. Generally south west monsoon contributes about 68 per cent from June to September and north east monsoon contributes 23 per cent from October to November.

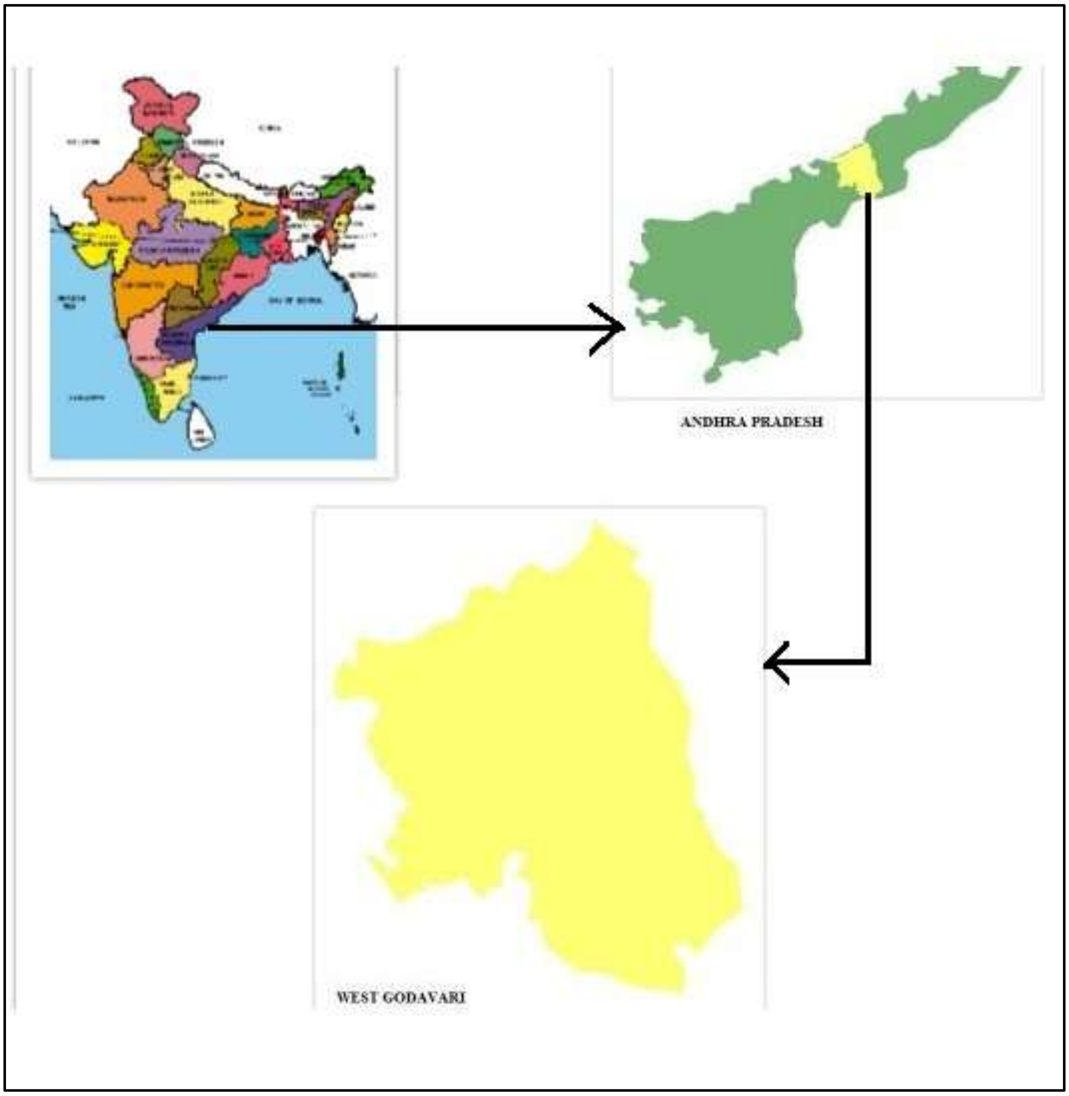


Fig.3.1. Location map of the study area – West Godavari district

3.1.3 Temperature and humidity

The average minimum and maximum temperature of the study area is 23.2^{o} C and 35^{o} C respectively. Generally, maximum temperature can be observed from March to May whereas minimum temperature is in between December and February. In 2017, maximum temperature is recorded as 39^{o} C. In West Godavari, relative humidity generally varies from 62 per cent to 77 per cent. High relative humidity can be observed from July to October. Winds are generally medium and strengthen during July to October.

3.1.4 Drainage

West Godavari district is mainly drained by Godavari, Yerrakalva, Tammileru and Ramileru rivers. Godavari river drains about 20 per cent of the Godavari district. Drainage density is high in northern part and thin in southern part.

Other rivers in the study area join Kolleru lake and it is located at the southern part of the district. Kolleru Lake is India's biggest fresh water lake and its drainage seems to be dendritic. Drainage map in the study area prepared using DEM map and using Arc GIS 10.1.2. In West Godavari District, maximum stream order is 5.

DEM map was processed using tools shown in Fig.3.2. Basin, Fill, Flow Accumulation, Flow Direction, Flow Length, Sink and Stream Order are the different geoprocessing tools used to develop drainage map. Basin is a geoprocessing tool that creates a raster, delineating all drainage basins. Fill is a geoprocessing tool which fills the surface to remove small imperfections in the DEM. After 'Fill', 'Flow Accumulation' is used to create accumulated flow to each cell. Flow accumulation map is shown in Fig.3.3. 'Flow Direction' is used to create flow direction from each cell to its steepest downslope neighbor cell. Flow Direction map is shown in Fig.3.4. 'Flow Length' is used to calculate distance along a flow path. 'Sink' is used to create a raster identifying all sinks or areas of internal drainage. Sink map is shown in Fig.3.5. 'Stream Order' is used to assign a numeric order to segments of a raster representing branches of a linear network. Highest stream order for the study area is 5 and is shown in Fig 3.6.

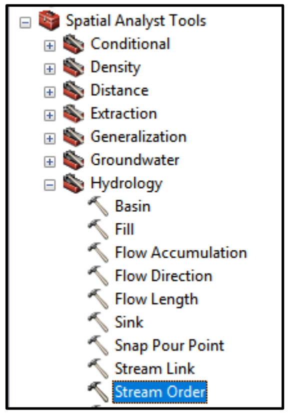


Fig.3.2. Different Geoprocessing tools used to prepare drainage map

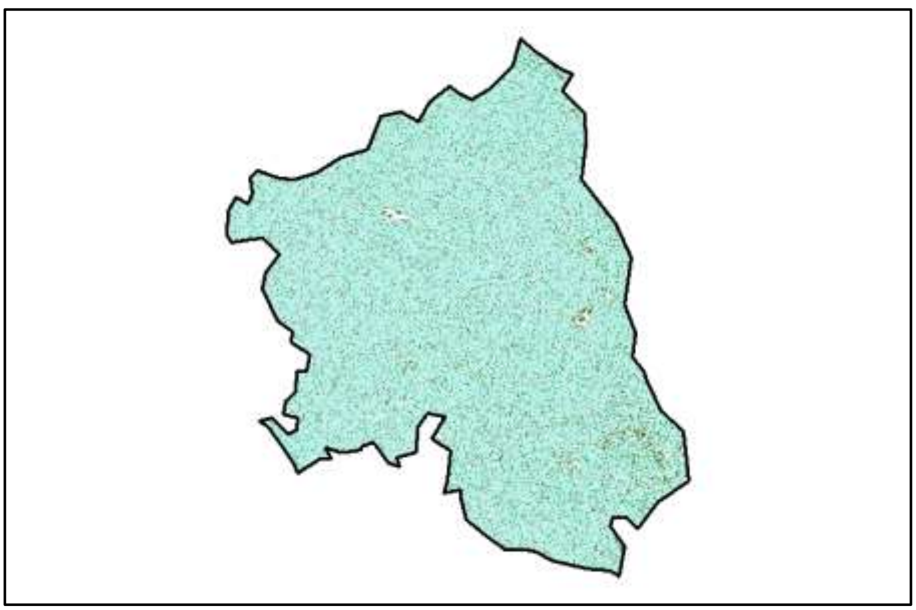


Fig.3.3. Flow Accumulation map for West Godavari District.

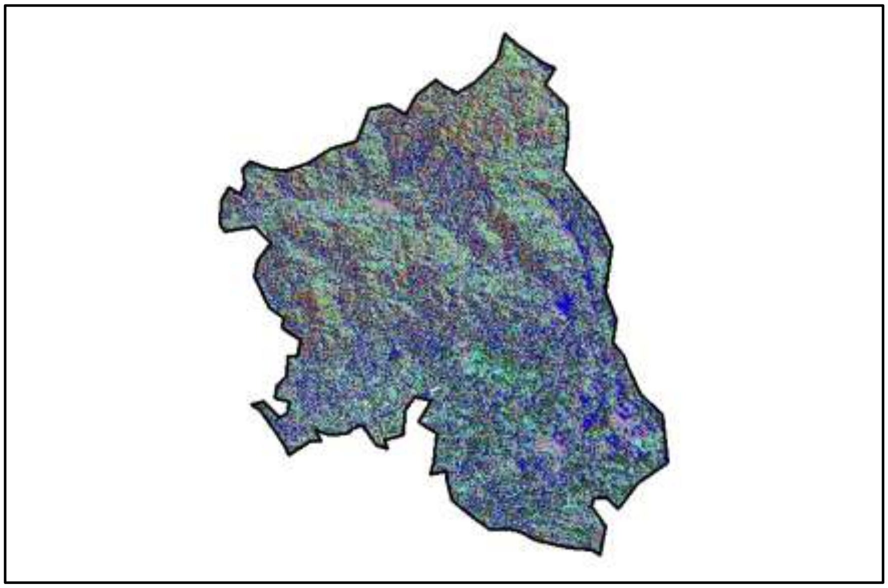


Fig.3.4. Flow Direction map for West Godavari District.

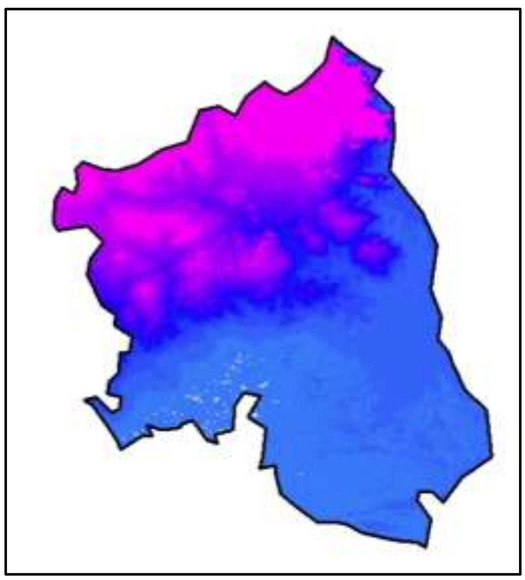


Fig.3.5. Sink map for West Godavari District.

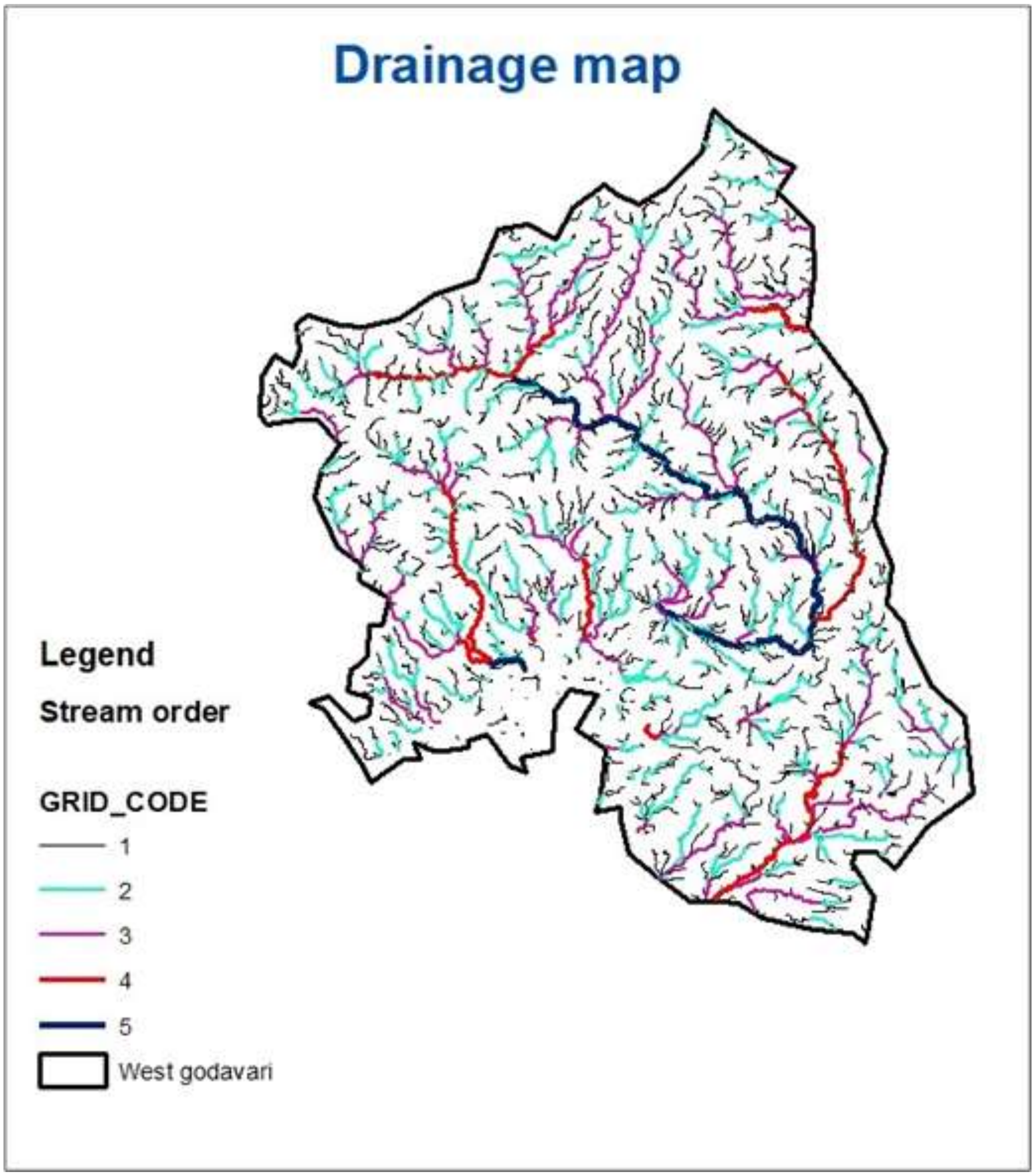


Fig.3.6. Drainage Map for West Godavari district

3.1.5 Land use and cropping pattern

Total geographical area of West Godavari district is 8,50,665 ha. Different land use pattern such as cultivable land, forests, barren and uncultivable land, cultivable waste, permanent pasture land, fallow lands and fish and prawn culture are present in this study area. The land use pattern in the study area indicates that the area is mostly agrarian.

Rice, Jowar, Maize, Horsegram, Greengram, Blackgram, Redgram, Chillies, Turmeric, Curry Leaf, Amla, Papaya, Sapota, Watermelon, Tapioca, Yam, Ridge Guard, Cucumber, Bhendi, Bean, Green Plantain, Brinjal, Green Leafy, Cabbage, Cauliflower, Tomatoes, Drumstick, Groundnut, Sunflower, Palm Oil, Tobacco, Sugarcane, Cashewnut, Mango and Coconut are the different crops grown in West Godavari District.

In this area mainly irrigated by surface water. Major, medium and minor irrigation projects are the major source for irrigation. 214560 ha area is irrigated under Godavari western delta. Groundwater is used for irrigation in upland areas where canal water is not available for for irrigation. Area of 178762 hectares are irrigated through canals and 174648 hectares through groundwater, while 18161 hectares are irrigated through tanks.

3.1.6 Geology of the area

West Godavari district consist of outcrops tertiary formations, quaternary sediments, archaean crystallines, gondwanas and deccan trap. Quaternary sediments formed as thick blankets of alluvium near river valleys and deltas along sea coast. Archaean crystallines and gondwanas formations occupied 45 per cent and 40 per cent of the district respectively.

Table. 3.1. Land Utilisation.

Sl.No.	CATEGORY	Area in Hectares
1	Total geographical area	850665
2	Forests	132902
3	Barren & uncultivable land	40896
4	Land put to non-agricultural uses	120558
5	Cultivable waste	16708
6	Land under miscellaneous tree crops & groves not 'included in net area sown	7897
7	Current fallows	11922
8	Net Area Sown	417156
9	Total Cropped Area	691109
10	Area Sown More than Once	273953
11	Fish & Prawn Culture	51125

Source: Hand Book of Statistics West Godavari District (2015).

Table. 3.2. Irrigation projects in the study area.

Sl.No	Medium Irrigation Project	Area in ha
1	Tammileru Reservoir Project	3712
2	Vijayarai Anicut	4340
3	Jalleru Reservoir Project	1700
4	Yerrakalava Reservoir Project	13709

Source: Hand Book of Statistics West Godavari District. (2015)

3.1.7 Soils

In West Godavari district, most of the area is covered by sandstone as first layer followed by clay, sand, sandstone, clayey-sandstone and granitite gneiss. Hard rock was formed as base for whole study area. Granite gneiss, khondolite and sandstone with more quartz formed as semi permeable layer for the aquifer.

3.1.7.1 Sandstone

Major portion of the District was occupied by sandstone. It is encountered in various forms like clayey sandstone, sandstone with quartz and fractured sandstone. Fractured sandstone have high hydraulic conductivity, whereas, clayey sandstone have low hydraulic conductivity. Sandstone has a minimum depth of 10.5 m at G Kothapali and a maximum thickness of 87.85 m at Vijayarai.

3.1.7.2 Clay

Clay is found as the top layer in western parts of the study area. Most of the areas, clay formed as second layer below the sandstone. Clay has a minimum thickness of 3 m at Nidadavole and maximum of 7.9 m at Kokkirapadu.

3.1.7.3 Sand

Sand formed as third layer at Nidadavole and Eluru region. Sand has a minimum thickness of 4.55m at Nidavadole and maximum thickness of 10.5 m.

3.1.7.4 Granite Gneiss

Granite Gneiss has a minimum thickness of 3 m at Eluru and maximum thickness of 18.5m. Khondolite and sandstone with more quartz formed as semi permeable layer at Munduru and G Kothapalli area of 27.1m and l22m respectively.

3.1.8 Geomorphology and slope

Geomorphology of West Godavari District is moderately undulating topography with the elevation varying from - 48 to 765 m. Uniqueness of West Godavari District is its location between Godavari river, Krishna river on both sides and Bay of Bengal on the other side. Elevation at coastal area is low and increasing away from the coastal area. Elevation map of the study area is shown in Fig. 3.7.

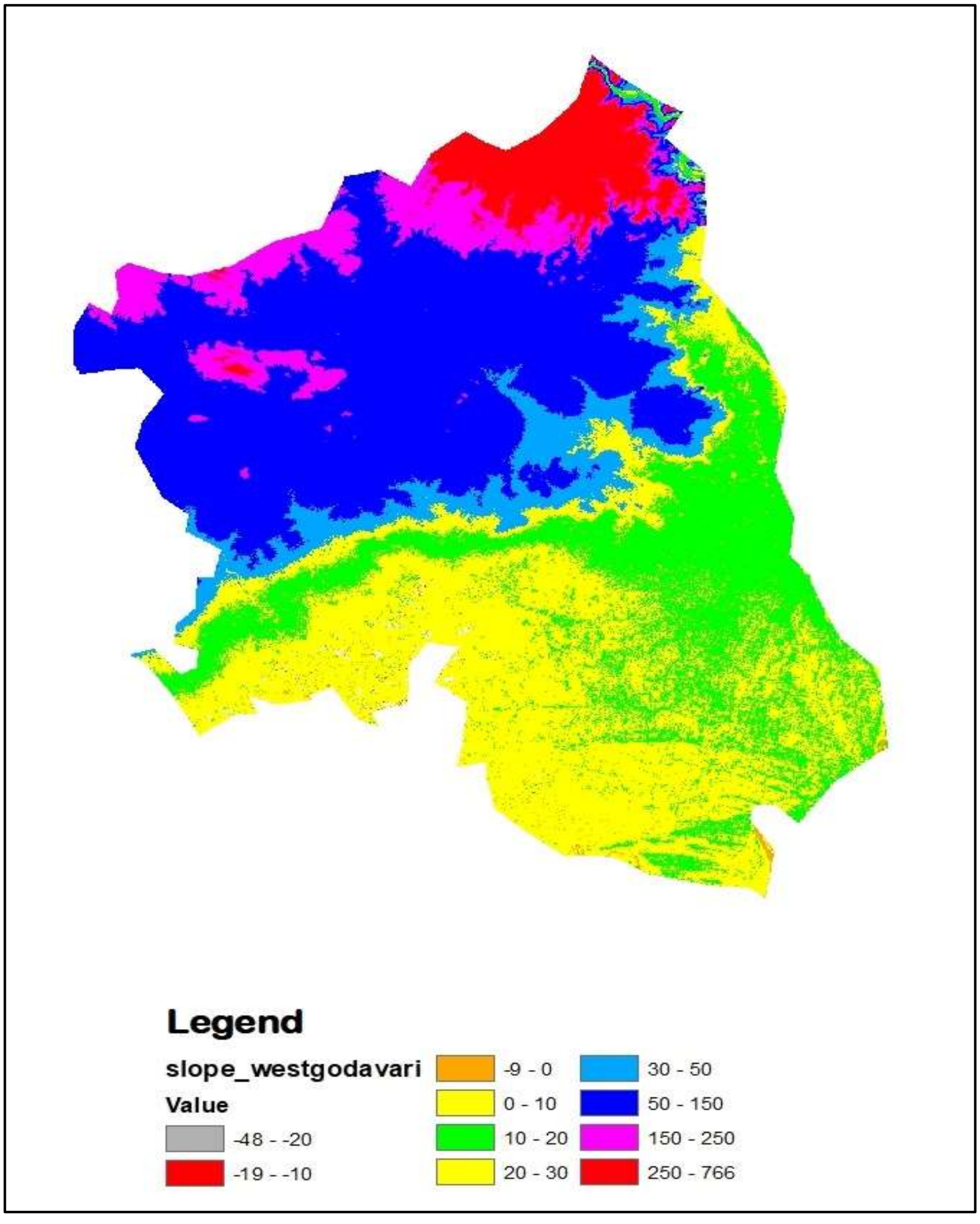


Fig.3.7. Elevation map of West Godavari District

3.1.9 Aquifer systems

Water bearing strata is known as Aquifer. Multiple aquifer system is exposed due to deep exploration of groundwater. Almost all aquifers formed by sandstone. The capability to transmit fluid under a hydraulic gradient is known as permeability. The average permeability in the study area is around 10 m/day. The rate at which water is transmitted through a unit width of gradient is known as Transmissivity (T). The value of Transmissivity (T) varies from 25 to 3540 m^2/day. Volume of water releases or holds into storage per unit surface area with respect to change in head is known as Storage Coefficient(S). The range of Storage Coefficient varies from 8.5×10^{-5} and 1.3×10^{-2}.

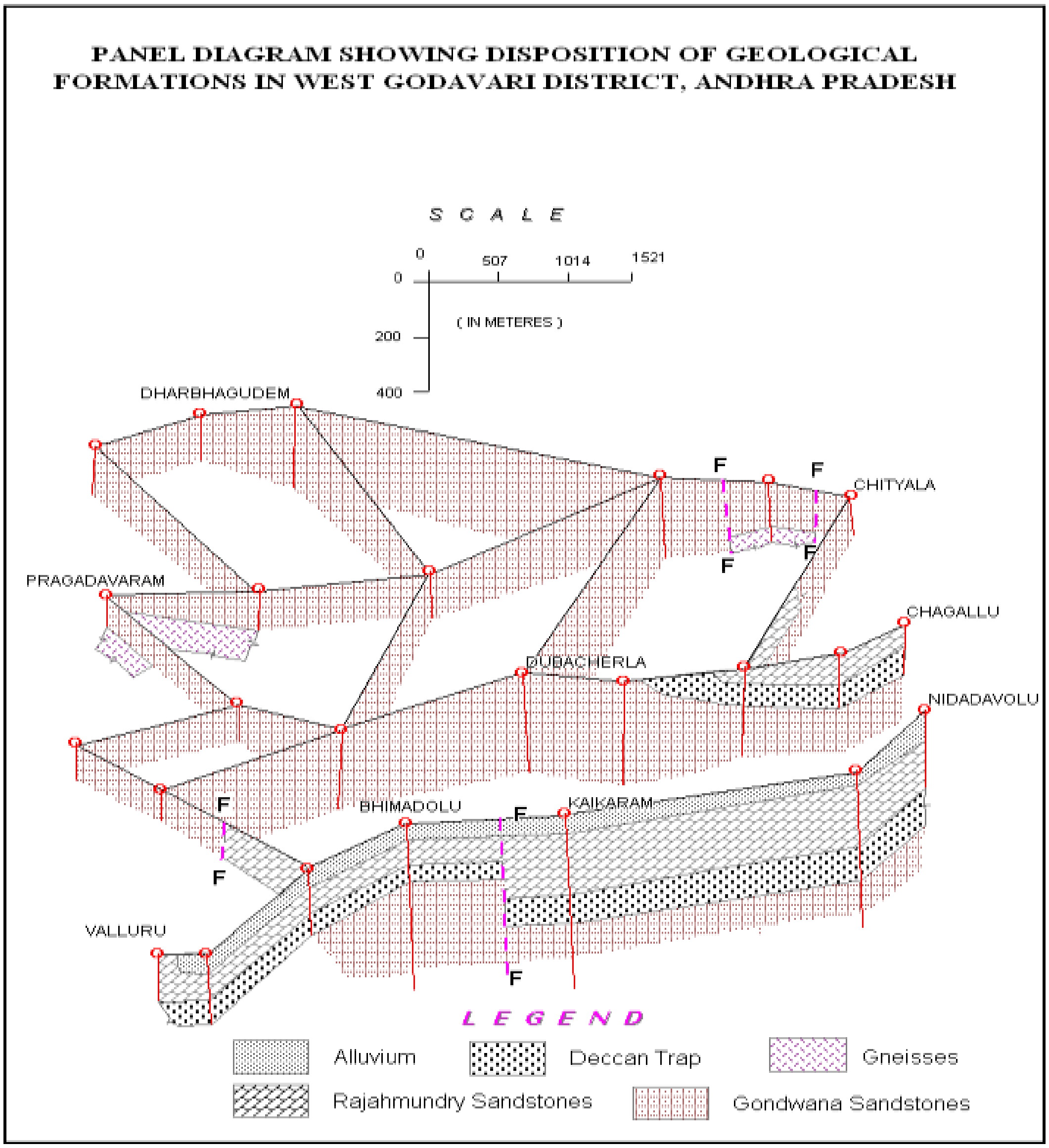
Panel diagram representing aquifer zones in the West Godavari District is shown in Fig.3.8. Sub surface cross-section of aquifer zones is shown in Fig.3.9. In Fig.3.8. Northern part is mainly covered by sandstone in which boreholes are not drilled beyond sandstone. In middle portion of the map, different geological formations are found. In western part, granite gneisses are found at shallow depths.

3.1.9.1 Groundwater Occurrence & Yield outline (Scenario):

Groundwater is available from unconfined and semi confined aquifers. Groundwater occurrence and movement of groundwater is completely driven by environment. Crystalline formation is formed as different layers in West Godavari District. Well yield for these formations varies from 20 – 50 m^3/day. Discharge of bore wells in crystalline formations ranges from 17.280 to 648.000 m^3/day.

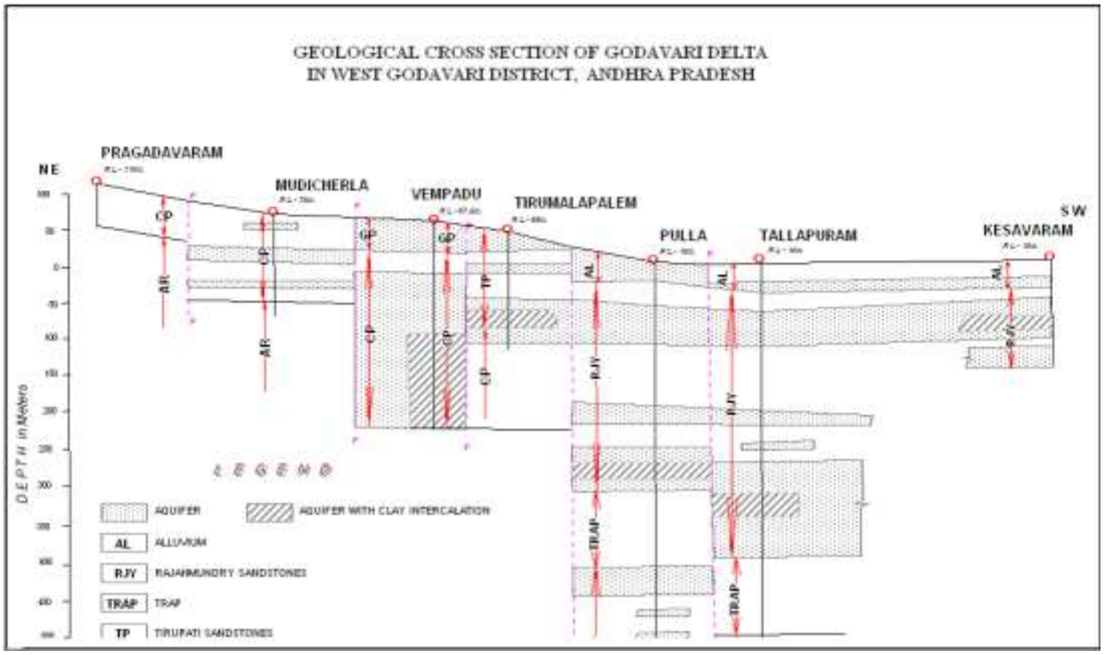
Sandstone (Chintalapudi formations) covered major portion of the West Godavari District. Some portions of the study area are occupied by fractured sandstone for which conductivity is more. Generally sandstone is a hard surface which act as pervious or semi pervious layers. These formations forms good aquifer. Well yield for Chintalapudi formations varies from 604.8 and 2419.2 m^3/day. Granular thickness for Chintalapudi formations varies from 24 to 109m.

Granular thickness for Gollapali sandstone ranges from 12 to 71 m. For these formations well yield ranges from 691 to 1382 m^3/day. Shales and Phyllites found near polavaram region with a maximum thickness of 10 m. These formations are also known as Raghavapuram shales. Generally aquifers these formations have poor yield.



Source: CWGB (2015)

Fig.3.8. Panel diagram representing aquifer zones in the West Godavari District



Source: CWGB(2015)

Fig.3.9. Sub surface cross-section of aquifer zones

3.2 Spatial and temporal variations of ground water level

Ground Water Department, Government of Andhra Pradesh has installed observation wells and piezometers to record the groundwater levels. Ground Water Department installed 59 head observation wells and 70 piezometers to monitor the groundwater levels in 48 mandals. Well log data is available at different locations in West Godavari District.

From 2003 to 2018, Ground water level data for 59 wells were collected from Ground Water and Water Audit Department, Government of Andhra Pradesh. For every 2 months ground water levels were collected by Ground Water Department. Using Arc GIS 10.2, groundwater variations were studied. Using GIS, potential groundwater zones were identified and well log data available from Ground Water Department is collected.

3.3 Identifying potential groundwater zones

District map for West Godavari District is developed in Arc GIS 10.2. Groundwater data collected from Ground Water Department, Government of Andhra Pradesh were added to attribute table of the district map. Using 'characterstics' in 'Symbology', groundwater variations in different years is observed and potential groundwater zones were identified. Well log data of these zones were collected from Ground Water Department, Government of Andhra Pradesh. Groundwater table map of the study area is shown in Fig. 3.10.

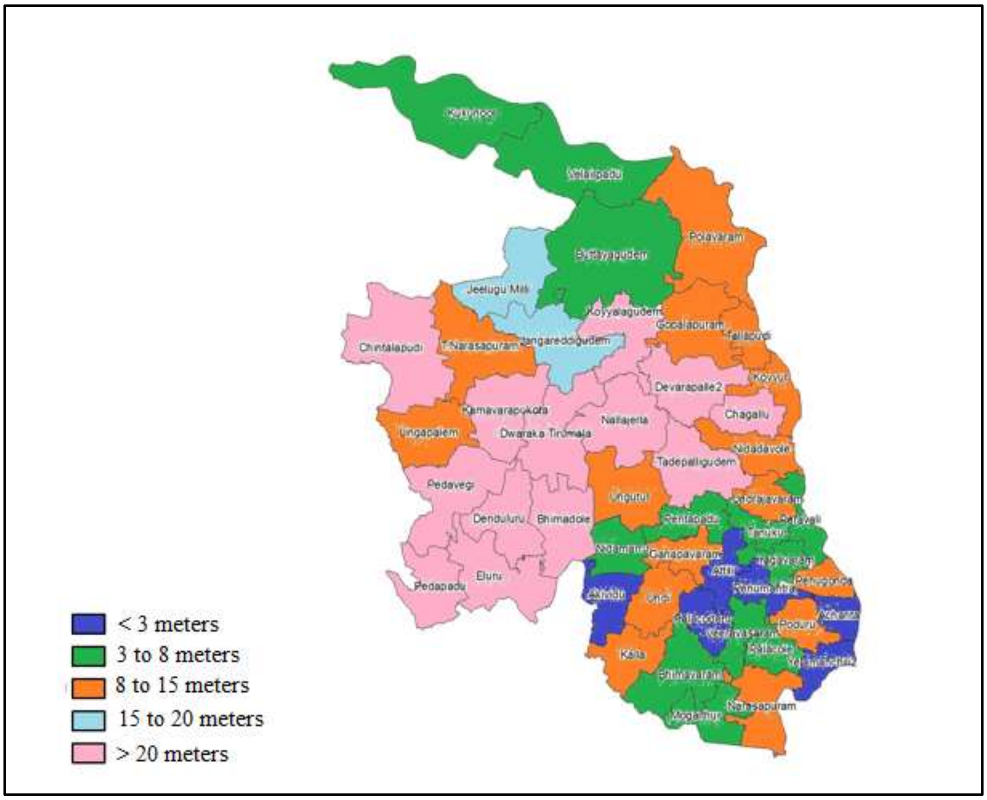


Fig.3.10. Groundwater table map of West Godavari District

3.4 Ground water flow modelling

Modelling is the best tool to optimize the different combinations and to select the best combination. It is the best tool to study the results of different combinations. Using mathematical equations, numerical models were developed. Later, computer models were developed using different computer languages. Using computer models, best solution or scenario can optimize by creating model with real conditions.

MODFLOW is one of the finest software for groundwater modelling. In this research, a model was developed for West Godavari district using Visual MODFLOW. Visual MODFLOW was developed by Waterloo Hydrologic. Using Visual MODFLOW, model was calibrated with existing site conditions and was validated. After validation, groundwater levels were predicted for future.

3.4.1 MODFLOW model development process

In this study, model of West Godavari district was developed. Model is calibrated with groundwater heads from 2003 to 2012 is validated using up to 2017. After validation, model was used to predict ground water scenario due to future extractions. Predictions were made for next 15 years (2018 to 2032). Process involved to develop, calibrate and validate the model is shown as flowchart in Fig.3.11.

3.4.2 MODFLOW input

3.4.2.1 Conceptual model of the West Godavari District

Representing the study area using base map or without map is the first step in Visual MODFLOW. Study area was marked in google maps and is saved using snipping tool which is in JPEG format. Map in JPEG format is converted into BMP format through photo convertor. Map is imported to the model and model domain (number of rows and columns) is selected according to total area of the study area. For this study, model domain was selected as 125 rows and 150 columns. Grid formation of the study area is shown in Fig.3.12. Grids can edit using ‘Edit grid’ option. After selecting number of columns and rows, number of layers in the study area have to be decided. Geological profile of the study area was included in the model based on number of layers obtained from the well logs collected at different locations.

3.4.2.2 Inactive Cells

It is used to demarcate the study area. This option is used to inactivate the cells other than cells representing the study area. Inactivated portion is shown in the above Fig.3.12.

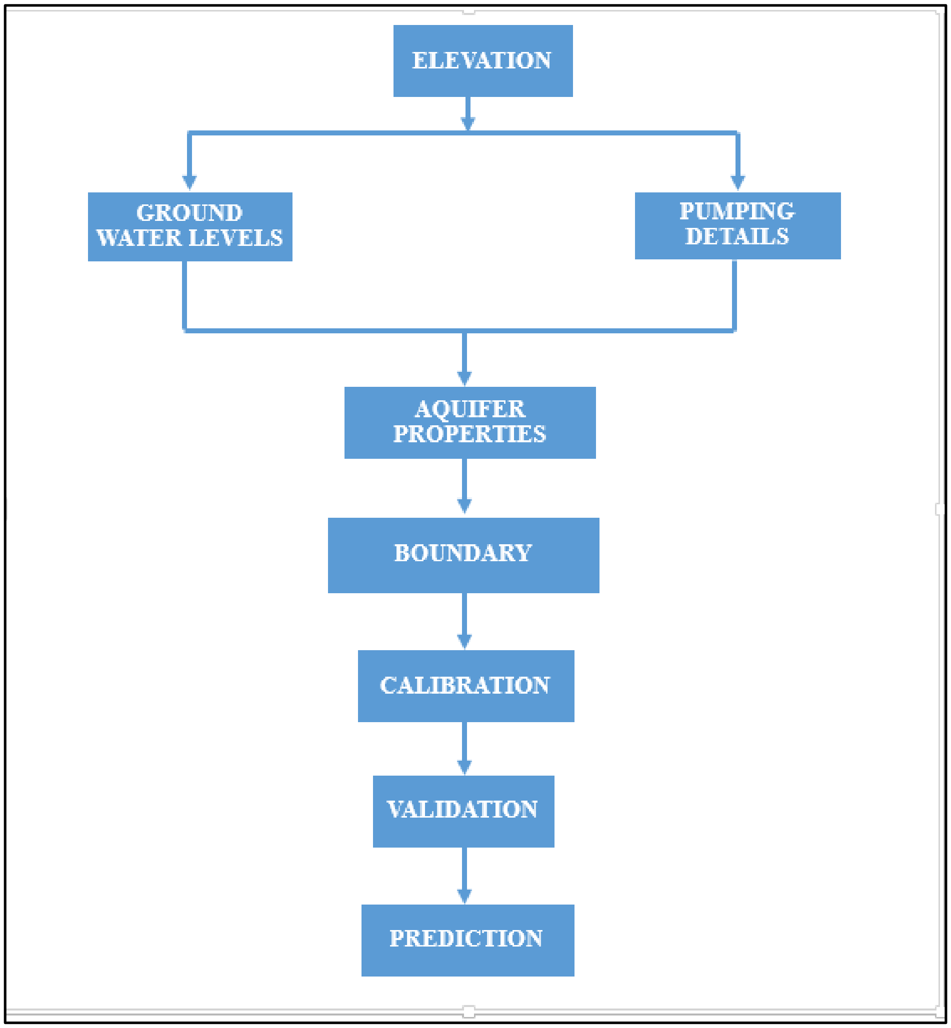


Fig.3.11. Flow chart of MODFLOW model development process

Fig.3.12. Grid spacing for the study area in Visual MODFLOW

3.4.2.3 Import elevations

Elevation of groundsurface was imported using 'Import Surface' option as shown in Fig.3.13. File should be in 'txt' or ASCII(x,y,z) format. X, Y and Z represents latitude, longitude and elevation respectively. After importing ground surface, bottom elevation have been imported into the model. File selected in 'Import bottom elevation of' represents the bottom elevation of the 'layer'. Minimum layer thickness is assigned as 1.

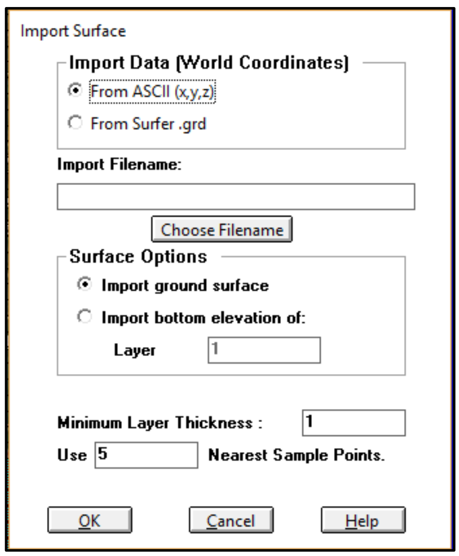


Fig.3.13. Import surface in Visual MODFLOW

3.4.2.4 Wells

Pumping wells, head observation wells and concentrated observation wells are the different inputs available in Visual MODFLOW software.

3.4.2.4.1 Pumping wells

Dug wells used for irrigation and domestic purpose installed in the study area were represented as Pumping wells in the model. Pumping wells are used to know the quantity of groundwater exploration in m^3/day. Pumping wells can be added using add option in the study area. Wells assigned in the model can change the location, copy or delete using options available in the model. Editing the entered details can be done using ‘Edit well’ option in the model. Wells can keep in off using ‘Wells On/Off’ option.

Pumping wells are also used to represent injection wells. Negative sign and positive sign represents pumping wells and injection wells. So, only pumping wells were considered.

3.4.2.4.2 Observation wells

Observation wells and piezometers are used to monitor the groundwater levels. In west Godavari district, head 59 observation wells and 70 piezometers were installed and maintaining by Ground Water Department, Government of Andhra Pradesh. Groundwater levels in observations are recorded once for every two months. Adding observation wells to the model shown in Fig.3.14.

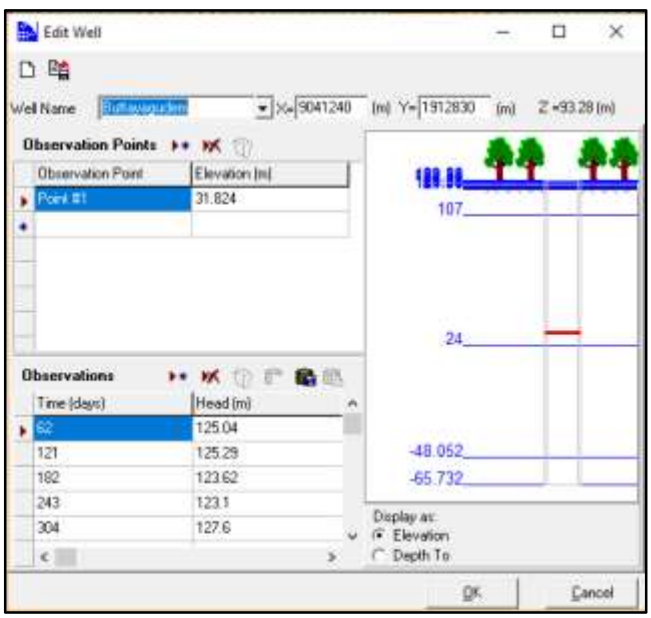


Fig.3.14. Adding observation wells in the model

3.4.2.5 Hydrogeological properties

Conductivity, storage, initial heads, bulk density, species parameters, initial concentration and dispersion are the different properties available to create the real condition of the soil. Hydraulic conductivity, transmissivity and storage properties are added to replicate the geological properties of the study area.

3.4.2.5.1 Hydraulic conductivity

Hydraulic conductivity represents the ability of water to pass through it. It is represented as 'K'. K_x, K_y and K_z represents the hydraulic conductivity in X, Y and Z direction and K_x, K_y and K_z were added for all layers. Generally, K_z is considered as 10 per cent of the K_x and K_y. Hydraulic Conductivity for different soils is shown in table. 3.3.

Table 3.3 Hydraulic conductivity values for different soils in the study area.

S.No	Soil type	K_x
1	Sandstone	5×10^{-13} to 10^{-10}
2	Clay	9×10^{-7} to 6×10^{-3}
3	Sand	1×10^{-11} to 4.7×10^{-9}
4	Clayey Sandstone	2.5×10^{-13} to 5×10^{-11}
5	Granite Gneissis	1×10^{-13} to 2×10^{-9}

3.4.2.5.2 Storage

Specific storage (Ss), specific yield (Sy), effective porosity (Eff. Por.) and total porosity (Tot. Por) are the different properties available to replicate the real situations in the model. These properties represents the water storage capacity of the soil. Horizontal and vertical view of the study area is shown in Fig. 3.15 and 3.16.

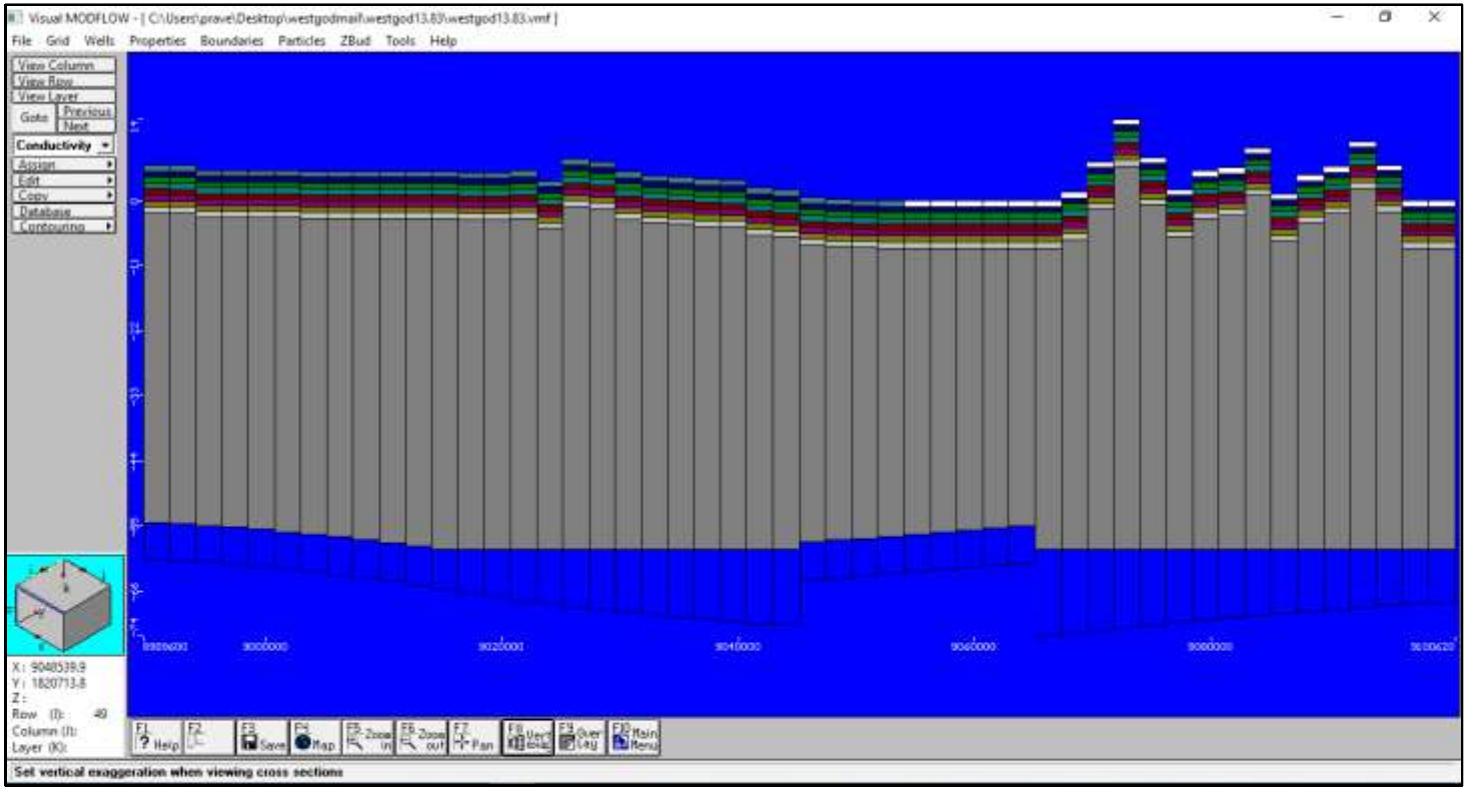


Fig. 3.15. Hydrogeological cross section along row 49 showing the layer

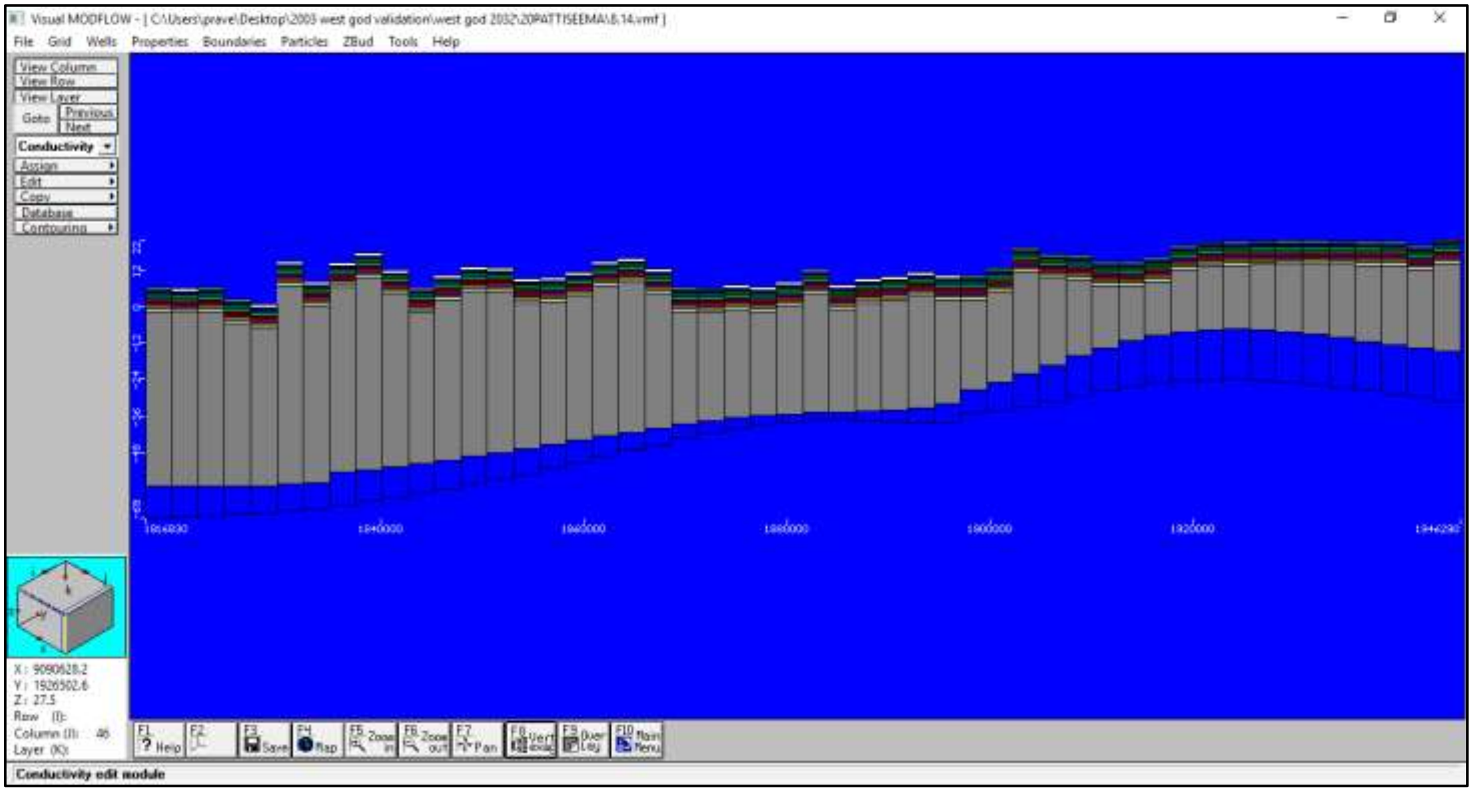


Fig. 3.16. Hydrogeological cross section along column 46 showing the layer

3.5.2.5.3 Initial head

Initial head values are used to assign the head distribution for the simulation. These values were assigned based on water level data collected from Ground Water Department.

3.5.2.6 Boundaries

Constant head, rivers, G.H.B, drain, wall, recharge, evapotranspiration, constant concentration, recharge concentration, evapotranspiration concentration and point source are the different options available in boundary conditions to replicate the real conditions.

To run the model, at least one boundary condition is necessary for simulation. Head level assigned in ‘boundary’ act as reference for calculations. It is necessary to assign reference point to understand the groundwater levels with respect to mean sea level. Boundary conditions can assign using ‘Assign’ option. Assigned cell can edit or erase or copy using different (“edit, erase and copy”) options available in the model. Boundary conditions of West Godavari District is shown in Fig.3.17.

3.5.2.6.1 Constant Head

Bay of Bengal is the southern boundary of the study area. In this study, water level at Bay of Bengal is considered as constant head and is assigned as zero. Grids filled with red color represents sea (constant head).

3.5.2.6.2 River head

The soil properties and river flow in the study area have major role on groundwater flow. Conductance of a river represents the amount of water flows into aquifer. In this study, Godavari river, Upputeru rivers debouches into Bay of Bengal. Grids filled with blue color represents river boundary.

Inputs required to assign river are river stage, riverbed bottom and conductance of the river. Water surface elevation of the river is represented river stage and elevation of bedding material is assigned as riverbed bottom. The resistance to flow from river to groundwater is represented as conductance. For this study, conductance is assigned using equation**.**

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

Where ‘C’ represents conductance in m^2d^{-1}, ‘K’ represents hydraulic conductivity in md^{-1}. Whereas ‘L’ and ‘W’ represents length and width of the river in the cell in m. Thickness of the river is denoted as ‘M’.

3.5.2.6.3 Drains

Drains are used to reduce the water level in water logging conditions. If groundwater level is below the drain, there will be no effect of drain. Drain assigned in the model is shown in Fig.3.17. Drain elevation and conductance are required to assign drain. Water level in the drain is represented as drain elevation and conductance from to the drain was estimated using equation. Grids filled with white color represents drain in the study area.

3.5.2.6.4 Recharge

Major portion of the groundwater is due to recharge. Recharge is from rainfall, excess irrigation and artificial recharge techniques. Recharge was assigned using ‘assign’ option in the model. Recharge (mm/year) can be considered as 10 per cent of the rainfall or using equation (below equation). For this study, recharge is assigned using the equation. Recharge assigned in the study area is shown in Fig.3.18. Blue colored layer in the study area represents more recharge from the canal and river. Recharge assigned in the model shown in Fig. 3.19.

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

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

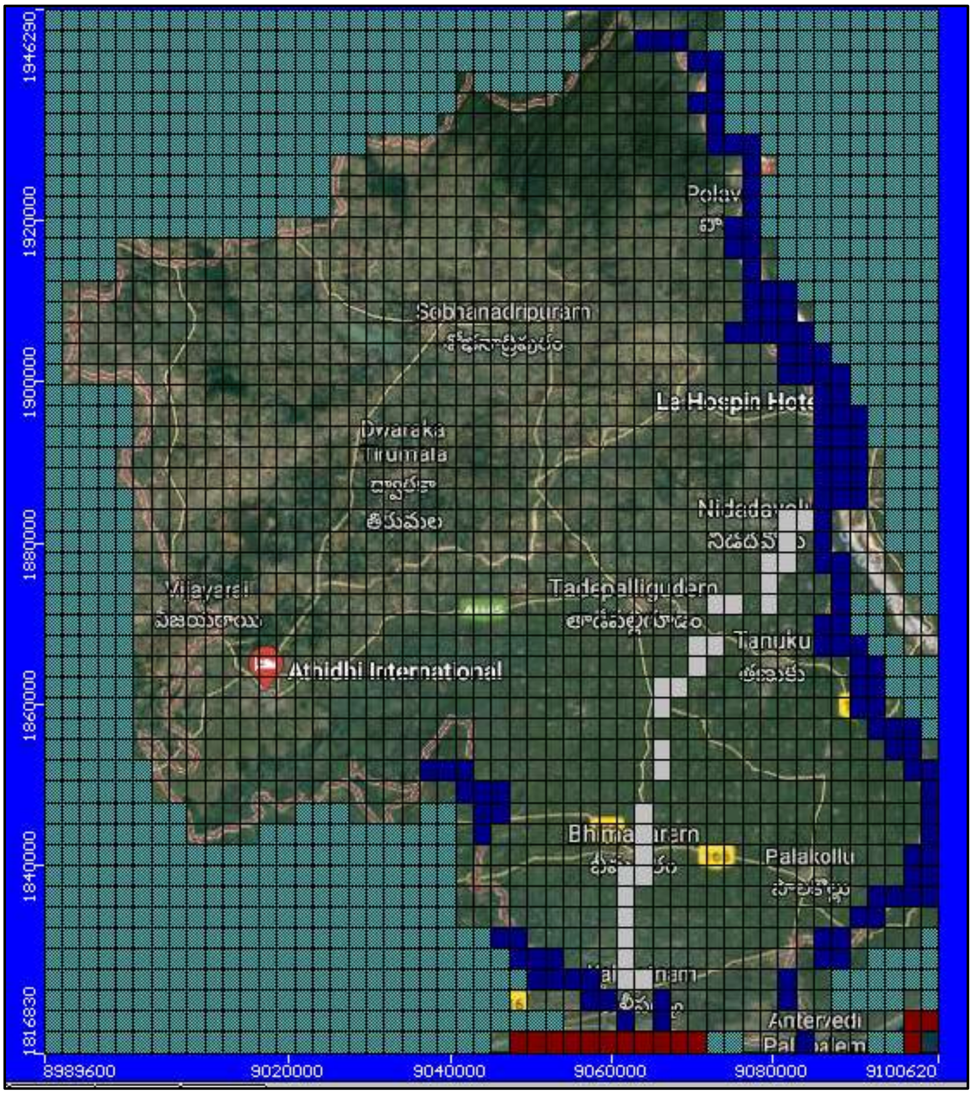


Fig.3.17. Boundary conditions adopted in the model

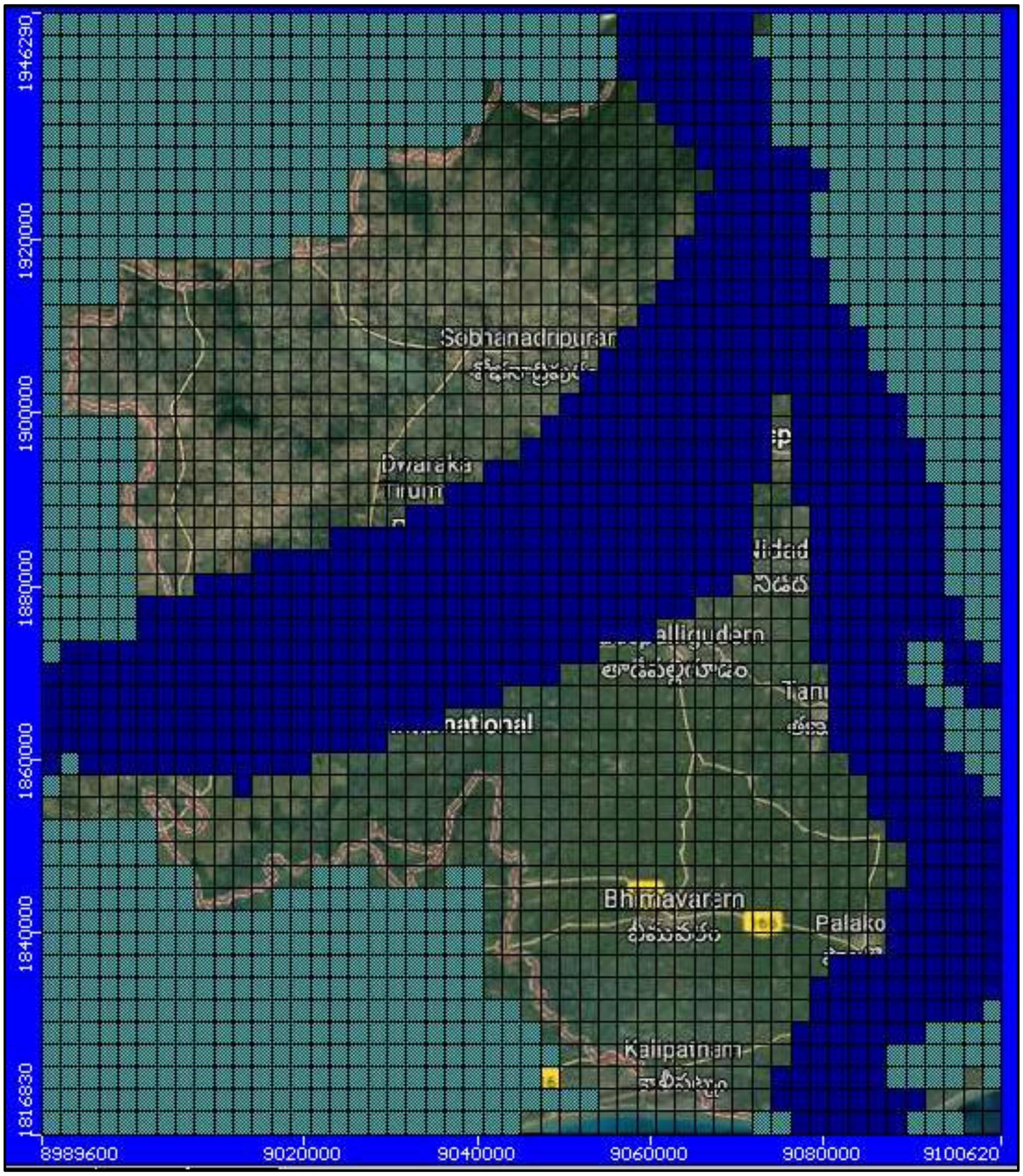


Fig. 3.18. Recharge layer assigned for River, Sea and 'Pattiseema lift irrigation' canal

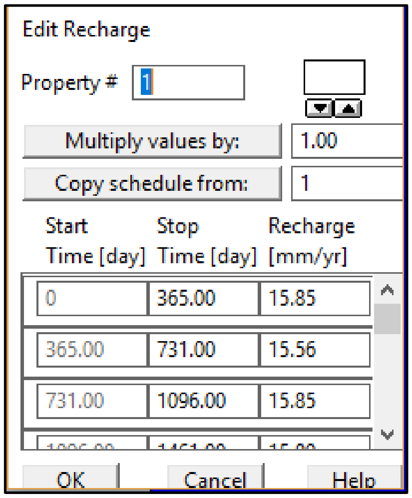


Fig.3.19. Assigning recharge for the study area.

3.5.2.6.5 Evapotranspiration

Evapotranspiration is used to replicate the effect of plant transpiration in the study area. Generally evapotranspiration is considered as 10 per cent of annual rainfall.

3.5.3 Visual MODFLOW run

After replicating the real conditions by assigning all inputs in the model, go to main menu using ‘Main Menu’ option. Select ‘run’ option to run the model in steady state condition or transient condition. WHS, SIR, SOP and WPS are the different solvers available in Visual MODFLOW.

3.5.3.1 Model calibration

Developed model is calibrated using SIP solver in steady state conditions. Model is calibrated using groundwater levels data from 2003 to 2007 collected from Ground Water Department, Government Andhra Pradesh. After processing, RMS error in the equipotential graphs is reduced by changing hydraulic conductivity of different values. RMS value mainly depends on water table elevation for observed and computed values. RMS value will not change after certain point which represents the model is calibrated.

3.5.3.2 Model validation

In modelling, the developed model performance is justified by validation. Calibrated model is validated using 2013 to 2017 existing data from 2013 to 2018. Validated model is used to predict the aquifer response with respect to change in recharge and groundwater pumping data. Influence of 'Pattiseema lift irrigation project' was also studied using developed model.

3.5.3.3 Model prediction

Using the validated model, groundwater level for next 15 years was predicted with different scenarios.

CHAPTER 4
RESULTS AND DISCUSSIONS

In this chapter, the results obtained from the study are discussed in detail. Visual MODFLOW is used to simulate the groundwater flow for steady and transient conditions and to forecast the future groundwater scenario considering the effect of the lift irrigation project commissioned in the study area. Groundwater levels in the study area mainly depends on topography, soil properties, land use and cropping pattern. Calibration and validation of the developed model under steady and transient conditions were discussed in this chapter. The developed model was used to predict the groundwater levels for different scenarios and the results obtained are also discussed in this section.

4.1 Spatial and temporal groundwater table fluctuation

Groundwater table fluctuation in West Godavari district is studied using the historical groundwater level data collected from the groundwater board. Groundwater recharge and subsurface flow are the two factors which affects the groundwater level besides the aquifer properties and soil properties. Subsurface flow mainly depends on hydraulic gradient and conductivity. Based on elevation, the study area may be classified into three categories, low land (elevation up to 7.5 m), mid land (elevation 7.5 to 75m) and high land (elevation more than 75m). Out of the 55 observation wells in the villages, 5 wells are in low land, 22 in mid land and 28 in high land. Elevation at head observation wells are shown in Table 4.1. Spatial variation of groundwater in the study area is studied with respect to elevation.

Spatial and temporal variation of water table in the head observation is studied using Tables 4.2 & 4.3. Average groundwater variation in pre monsoon and post monsoon are shown in Table 4.2 and 4.3 respectively. In table 4.3, the groundwater table fluctuation between pre monsoon and post monsoon seasons is also calculated and is shown in Table. 4.3.

Table 4.1 Elevations of observation well locations

Well. No	Village	Elevation (m)
1	Akiveedu	6.1
2	M.M.Puram	5.4
3	Bhimavaram	7.4
4	Kalla	4.1
5	Veeravasaram	7.0
6	Achanta	8.5
7	Attili	8.9
8	Gundugolanu	9.2
9	Kovvada	8.1
10	Brahmanagudem	15.2
11	Denduluru	9.5
12	Pallantla	38.0
13	S.N.Puram	10.7
14	Eluru	19.6
15	Mogalturu	10.9
16	Narsapuram	10.3
17	Pendyala	13.9
18	Vijjeswaram	15.9
19	Nidamarru	8.1
20	Palakoderu	10.2
21	Palakollu	8.9
22	Pedapadu	8.1
23	Pentapadu	9.8

24	Penugonda	14.8
25	Penumantra	10.2
26	Usurumarru	12.3
27	Poduru	9.02
28	Polavaram	25.1
29	Pedatadepalli	13.7
30	Tallapudi	22.1
31	Tanuku	11.6
32	Undrajavaram	13.8
33	Kaikaram	12.87
34	Kovvurupadu	63.0
35	Sagipadu	60.4
36	Lakshmipuram	71.8
37	Bayyannagudem	72.0
38	Koyyalagudem	62.1
39	Ponguturu	66.2
40	Buttayagudem	129.2
41	Chintalapudi	144.0
42	Mallayagudem	119.0
43	Pragadavaram	118.0
44	Jangareddigudem	83.5
45	Lakkavaram	78.6
46	Jeelakarragudem	84.
47	Kamavarapukota	126.8
48	Kannapuram	131.8

49	Lingapalem	96.5
50	Yelamanchhhili	136.6
51	T.Narasapuram	139.0

Table 4.2 Groundwater variation in pre monsoon

Well No.	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Aver age
1	1.16	1.19	1.16	1.12	0.79	1.41	2.43	0.76	1.08	0.83	0.79	1.21	0.73	0.92	1.03	1.11
2	1.18	2.05	0.83	0.73	1.02	1.36	1.86	0.8	1.16	0.55	0.50	0.79	0.24	1.21	0.75	1.00
3	1.76	1.31	1.36	1.45	1.79	0.76	1.57	1.1	1.52	1.26	1.08	2.34	1.17	2.22	2.27	1.53
4	2.05	1.10	1.35	1.29	1.6	1.72	1.75	1.43	1.97	1.15	1.29	1.65	1.63	1.68	1.52	1.55
5	1.79	1.08	1.58	1.62	1.63	1.78	1.32	0.93	1.74	1.28	1.52	1.67	1.43	1.6	1.57	1.50
6	0.33	0.42	0.13	0.23	0.09	0.38	0.5	0.05	0.57	0.31	0.31	0.48	0.61	1.26	1.24	0.46
7	2.44	1.71	0.24	1.75	1.63	0.90	2.67	0.8	2.26	0.23	1.12	1.60	2.78	1.64	1.93	1.58
8	9.47	6.12	1.50	1.30	1.65	1.83	2.05	1.04	1.99	0.78	1.15	1.68	1.43	1.43	1.18	2.31
9	3.43	1.93	3.12	2.79	3.08	2.60	2.94	2.17	3.23	2.13	1.43	1.79	1.55	1.91	1.59	2.38
10	0.48	1.79	0.60	0.45	0.79	1.01	2.02	1.01	1.98	0.75	0.78	1.21	1.79	1.18	1.29	1.14
11	2.89	3.19	2.15	1.58	2.35	2.75	3.95	1.35	2.37	1.30	1.35	1.27	2.97	1.98	1.54	2.20
12	6.90	4.83	2.05	1.96	3.28	2.49	7.1	1.52	3.35	0.99	1.25	2.27	5.89	5.99	3.52	3.56
13	2.25	1.43	1.97	1.80	3.17	2.75	3.74	1.48	2.88	1.20	1.90	2.88	3.4	3.43	2.83	2.47
14	5.10	2.54	3.29	3.78	4.16	4.32	2.48	2.66	5.36	2.80	3.76	4.48	4.09	4.45	3.73	3.80

15	1.03	1.05	0.75	0.83	1.25	1.33	2.64	0.65	1.87	0.63	0.82	1.72	1.14	1.28	1.23	1.21
16	5.40	3.23	4.05	4.08	3.9	3.53	3.54	3.23	3.53	2.85	3.45	3.56	3.35	3.39	2.79	3.59
17	1.91	4.23	0.93	0.76	0.88	0.96	1.56	0.33	0.86	0.59	0.59	0.77	0.56	0.92	0.75	1.11
18	5.70	4.40	4.60	4.63	4.4	4.31	4.98	4.21	4.39	4.10	4.55	5.05	5.01	4.18	4.29	4.59
19	1.94	2.01	2.25	2.00	2.22	1.89	2.32	2.22	2.16	0.80	0.82	2.08	1.49	1.98	2.36	1.90
20	5.15	3.88	2.72	4.78	4.6	0.00	7.3	3.54	6.93	1.65	3.65	7.69	9.32	7.58	7.92	5.11
21	7.95	9.07	6.20	6.27	6.65	6.76	10.7	5.55	8.08	1.17	2.04	7.22	8.55	7.62	7.92	6.78
22	2.35	1.30	1.70	2.05	2.02	2.46	4.5	1.58	3.89	1.45	2.00	4.44	4.92	2.94	2.95	2.70
23	1.21	1.27	0.80	1.02	1.14	1.38	1.79	0.6	1.25	0.84	0.98	1.02	0.39	1.05	0.8	1.04
24	11.1	7.65	2.65	6.99	8.25	6.15	7.65	3.37	5.98	1.90	3.45	4.13	6.01	5.75	6.19	5.82
25	8.85	7.17	5.32	4.61	5.37	3.41	7.1	3.25	4.79	1.51	1.33	4.32	5.07	4.43	5.15	4.78
26	2.91	3.39	1.40	1.46	1.5	1.40	2.95	0.67	2.63	0.93	1.05	2.09	1.56	1.61	1.44	1.80
27	0.74	0.37	0.67	1.00	1.15	0.65	3	0.82	3.05	0.84	1.12	2.58	2.24	2.44	2.26	1.53
28	3.92	2.01	0.87	0.91	1.25	1.53	1.45	0.85	1.87	0.77	0.80	1.66	1.48	1.57	1.34	1.49
29	1.71	0.92	0.28	1.88	2.16	1.77	3.12	0.99	3.82	0.70	1.01	2.04	3.31	1.59	1.47	1.78
30	3.44	1.30	2.38	1.85	2.4	2.37	3.7	1.23	2.94	0.62	1.44	3.09	3.34	2.15	2.94	2.35
31	5.15	4.27	1.35	2.57	1.5	1.90	7.9	0.84	10.3	1.62	9.20	3.72	1.75	1.65	1.75	3.70
32	1.61	1.25	0.90	0.94	1.45	2.69	3.94	0.78	2.92	0.24	1.56	2.07	2.92	2.22	1.4	1.79

33	10.8	8.60	4.15	3.32	5.16	3.78	11.2	2.01	8.43	1.87	2.42	7.51	11.2	11.3	9.25	6.74
34	1.65	1.87	0.87	0.51	0.97	1.39	1.75	0.01	1.49	0.26	0.57	1.64	0.54	1.47	1.72	1.11
35	0.72	0.52	0.29	0.37	0.18	0.44	0.52	0.11	0.27	0.28	0.01	1.03	0.33	0.41	1.53	0.47
36	1.61	2.64	6.15	5.86	6.5	7.06	6.93	5.6	7.47	6.00	2.71	6.77	6.76	2.99	7.76	5.52
37	2.73	1.38	1.78	1.87	2.47	3.20	3.15	1.28	3.26	1.47	1.37	2.82	2.17	2.53	2.59	2.27
38	2.92	3.00	1.57	2.61	2.55	3.33	2.56	2.16	2.95	2.20	2.46	2.60	2.1	2.77	1.5	2.49
39	3.87	3.35	3.70	3.83	2.8	3.48	3.59	3.11	3.90	3.70	3.83	4.08	3	2.96	3.43	3.51
40	1.07	0.90	0.93	0.70	0.82	0.45	3.54	0.41	0.89	0.46	0.34	0.50	0.17	0.68	0.5	0.82
41	1.41	0.62	0.86	1.28	1.24	0.92	1.76	0.26	1.39	0.59	0.79	1.93	1.26	1.3	1.41	1.13
42	0.90	0.45	0.67	0.70	0.75	2.10	1.36	0.26	1.44	0.46	0.64	1.15	0.51	1.11	1.08	0.91
43	1.78	2.08	2.11	2.25	2.3	2.34	2.4	1.82	2.39	1.90	1.93	2.41	1.99	2.62	2.9	2.21
44	2.19	1.40	1.82	2.11	2.1	2.37	2	1.68	2.43	1.80	1.88	2.39	1.76	2.25	2.28	2.03
45	1.77	1.12	2.15	2.08	2.3	2.62	1.64	1.46	1.93	1.44	1.43	1.95	1.72	2.27	1.66	1.84
46	1.74	1.03	1.05	1.96	1.22	2.76	4.65	1.01	1.29	1.12	0.91	1.35	0.97	1.57	1.43	1.60
47	7.20	7.45	3.44	3.38	3.52	5.27	7.28	3.4	5.95	3.10	4.15	7.21	6.29	4.49	4.18	5.09
48	1.75	0.79	1.20	1.31	1.11	1.01	2.70	1.00	1.18	0.83	0.93	1.02	0.87	1.31	1.4	1.23
49	3.32	3.09	1.88	2.38	1.89	2.36	3.22	0.93	3.03	1.67	1.06	1.21	1.45	1.81	1.5	2.05
50	2.98	3.44	2.70	1.53	1.92	0.55	2.08	0.65	2.31	0.98	2.05	2.03	1.51	2.31	2.18	1.95

51	3.29	3.37	3.25	2.64	3.46	1.04	1.26	2.25	4.00	2.45	2.96	3.68	3.04	3.96	4.5	3.01
52	5.82	2.49	2.60	1.58	2.39	2.59	2.67	0.64	4.00	1.08	0.82	2.93	1.76	1.74	3.11	2.41
53	2.85	3.42	1.74	2.19	0.35	2.56	3.15	2.42	3.60	2.28	2.64	3.22	2.63	3.4	3.2	2.64
54	1.37	1.01	1.17	1.26	1.28	0.76	1.59	0.96	1.02	0.80	0.77	0.98	0.63	1.1	1.05	1.05
55	8.52	8.16	3.84	5.16	6.56	5.39	4.1	5.1	6.50	4.59	6.06	7.85	8.13	8.89	8.73	6.51

Table 4.3 Groundwater variation in post monsoon

Well N0	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average	Fluctuation
1	2.54	1.81	2.12	2.10	2.31	1.94	2.21	2.17	1.98	3.05	2.20	1.36	2.06	1.22	2.31	2.09	0.98
2	2.94	1.89	1.37	1.70	1.99	2.05	2.4	1.55	1.60	2.02	1.69	1.33	1.60	1.07	1.73	1.80	0.79
3	2.96	1.96	1.96	1.97	2.53	2.18	2.7	1.16	2.45	3.35	1.84	1.85	2.80	2.1	3.07	2.33	0.79
4	3.49	2.76	3.30	2.00	2.45	2.34	2.5	2.22	2.23	2.76	2.38	2.42	2.62	2.29	2.51	2.55	1.01
5	2.61	2.13	2.35	1.78	2.08	1.98	2.18	1.71	3.76	2.17	1.99	1.94	2.82	1.86	1.97	2.22	0.72
6	0.81	54.00	1.20	0.50	0.94	0.70	1.57	0.19	0.94	1.12	0.93	0.70	0.72	1.32	2.1	4.52	4.06

7	5.60	4.10	4.80	3.70	4.15	3.93	4.45	4.18	3.65	4.80	4.35	3.79	4.98	5.9	5.53	4.53	2.95
8	10.66	9.85	7.65	4.00	3.75	2.78	3.63	2.94	2.77	3.42	3.03	1.95	6.15	3.69	3.74	4.67	2.36
9	4.07	3.81	3.95	3.65	3.78	3.67	3.9	4.3	3.50	3.80	2.42	1.98	1.78	2.06	2.15	3.25	0.88
10	2.2	2.9	3.83	2.45	3.65	2.75	2.25	3.43	1.45	3.43	3.08	2.10	2.80	3.1	3.63	2.87	1.73
11	5.14	3.94	4.64	3.30	3.61	3.65	3.94	4.5	2.85	3.65	3.04	3.36	3.64	4.29	4.87	3.89	1.70
12	9.13	8.30	7.30	5.90	6.54	6.50	6.66	8.4	5.42	7.03	5.60	5.43	7.43	6.22	9.88	7.05	3.49
13	2.41	2.55	2.65	2.25	2.35	4.30	3.6	4.76	3.15	5.21	3.48	3.37	4.87	5.54	5.31	3.72	1.25
14	8.86	6.61	7.01	5.88	6.02	5.79	6.19	5.37	6.72	6.45	5.94	5.75	5.68	5.81	5.57	6.24	2.44
15	3.37	1.34	2.18	2.10	2.05	2.70	5.35	2.68	2.05	3.40	3.94	1.97	3.03	3.55	2.18	2.79	1.58
16	7.15	4.33	5.94	3.65	4.96	4.12	4.4	3.95	4.65	3.89	3.53	3.52	2.71	3.19	3.35	4.22	0.63
17	7.63	6.03	7.93	2.23	1.54	1.42	2.05	1.74	0.77	2.73	1.45	0.87	2.62	2.76	2.23	2.93	1.83
18	7.19	6.10	6.20	5.00	5.1	5.00	6.1	5.49	4.66	5.81	5.18	5.09	5.72	5.51	5.46	5.57	0.99
19	3.06	2.43	1.84	2.30	2.8	3.51	2.7	2.32	2.68	3.24	2.02	1.30	2.91	1.48	2.93	2.50	0.60
20	8.54	7.93	9.35	7.00	9.0	9.50	11.1	8.95	8.47	9.50	9.40	8.94	9.32	9.35	8.8	9.01	3.90
21	13.60	10.65	9.05	8.95	8.87	10.15	11.4	13.4	9.84	10.80	9.51	8.26	12.61	13.75	13.38	10.95	4.16
22	5.60	5.00	5.38	4.30	2.96	5.71	6.35	6.9	5.80	6.40	7.05	5.85	7.75	7.7	7.75	6.03	3.33

23	2.21	1.38	1.97	1.94	1.71	0.68	1.86	1.29	1.54	1.76	1.47	1.58	1.53	1.17	1.62	1.58	0.54
24	12.13	8.89	11.48	10.30	11.74	11.65	9.05	7.69	7.85	5.93	5.68	5.97	5.87	9.32	6.22	8.65	2.83
25	10.09	8.50	10.45	6.85	7.14	7.58	6.91	8.61	5.47	7.86	5.74	5.42	7.12	7.54	8.11	7.56	2.78
26	5.94	4.70	5.80	3.70	3.6	2.55	3.16	5.1	2.65	4.82	3.28	2.81	3.69	3.44	3.7	3.93	2.13
27	0.94	1.10	1.03	0.80	1.25	1.04	0.95	3.35	2.91	4.32	3.76	3.24	4.10	4.26	3.44	2.43	0.90
28	3.18	3.30	3.23	3.19	2.09	1.94	1.61	1.85	1.93	2.73	2.43	2.51	2.53	2.57	1.57	2.44	0.96
29	8.30	6.03	5.85	4.15	4.15	4.65	4.76	4.62	5.15	7.00	6.22	4.71	6.37	6.7	5.86	5.63	3.85
30	3.60	6.87	6.80	5.50	5.7	4.50	5.69	5.27	4.35	6.25	4.71	4.26	6.25	6.75	5.72	5.48	3.14
31	11.53	10.30	10.27	9.50	5.7	7.70	9.5	9.14	8.62	13.45	14.46	15.05	7.50	5.6	2.77	9.41	5.71
32	8.36	3.90	6.41	5.55	5.45	5.30	6.55	5.06	4.94	5.98	5.65	4.57	5.95	5.25	5.5	5.63	3.84
33	14.41	11.10	9.49	7.30	8.4	8.52	8.48	10.55	5.76	11.24	7.62	8.13	11.32	11.08	10.68	9.61	2.86
34	2.75	2.19	2.59	1.85	2.06	2.08	1.81	1.91	1.27	2.49	2.03	2.10	2.25	1.9	2.5	2.12	1.00
35	1.92	1.08	1.31	0.79	0.86	0.66	0.98	0.63	0.79	1.22	0.50	0.32	0.36	0.6	0.7	0.85	0.38
36	7.31	7.50	7.43	6.45	7.47	8.10	7.72	5.55	8.05	8.45	8.12	5.19	7.77	9.32	7.6	7.47	1.95

37	4.38	3.76	3.34	3.17	3.26	4.29	3.98	3.3	4.00	3.96	3.69	2.99	3.23	3.21	2.99	3.57	1.30
38	3.69	3.54	3.55	2.75	3.32	3.30	1.55	3.25	3.25	3.24	3.09	2.84	2.83	2.73	3.11	3.07	0.58
39	4.83	4.18	4.51	4.04	4.66	4.67	5.05	3.89	3.98	4.49	4.60	4.40	4.18	2.77	3.32	4.24	0.73
40	2.31	1.51	2.56	1.67	1.79	1.85	2.13	1.66	3.93	3.03	1.85	1.25	1.23	0.62	1.29	1.91	1.09
41	2.75	2.21	2.29	1.73	1.99	1.75	2.15	1.79	1.51	2.20	1.82	1.48	1.87	2.45	2.61	2.04	0.91
42	2.48	1.76	1.90	1.15	2.83	3.10	3.05	1.34	1.55	3.24	2.49	1.21	2.89	2.4	2.71	2.27	1.37
43	4.55	2.99	3.20	2.95	3.55	3.55	3.38	3.01	3.42	4.32	2.59	2.90	3.72	3.73	2.82	3.38	1.16
44	3.06	2.44	2.28	2.41	2.65	2.40	3.54	2.11	2.57	2.90	2.94	2.30	2.69	2.38	2.72	2.63	0.60
45	2.22	2.09	1.87	2.40	1.69	2.79	2.68	1.63	2.46	2.42	2.62	2.81	2.13	3.12	2.15	2.34	0.50
46	3.42	3.03	2.73	2.77	2.95	3.07	3.55	2.33	2.43	4.42	2.49	1.74	2.33	1.64	2.84	2.78	1.18
47	10.05	9.66	9.67	7.75	6.91	7.84	8.28	8.68	6.79	8.48	7.33	6.99	8.40	8.84	7.79	8.23	3.14
48	7.46	2.29	2.45	1.28	1.95	3.10	1.86	1.58	1.62	1.55	1.37	1.17	2.10	1.52	2.55	2.26	1.03
49	8.54	6.81	7.21	6.03	6.07	3.63	4.15	3.97	3.33	4.48	4.43	2.22	1.90	2.82	2.99	4.57	2.52
50	4.80	3.90	4.20	2.84	3.04	2.78	3.45	3.5	2.91	4.25	3.17	2.84	3.24	3.45	3.55	3.46	1.51
51	6.54	4.12	4.65	4.45	4.9	4.95	5.15	3.65	4.70	6.50	5.40	4.45	5.12	5.35	5.94	5.06	2.05
52	8.78	7.79	7.50	4.40	7.7	6.96	5.8	7.00	3.65	3.70	3.54	5.03	2.21	4.59	7.11	5.72	3.30

53	4.02	3.60	3.85	3.40	3.59	3.54	3.69	3.6	4.13	4.12	3.89	3.75	4.03	3.81	3.61	3.78	1.13
54	2.46	1.62	2.19	1.68	2.12	2.10	1.95	1.63	1.59	2.15	1.71	1.29	1.47	1.07	2.11	1.81	0.76
55	10.54	9.85	9.90	7.44	9.82	10.05	10.14	10.04	9.9	6.89	7.22	7.96	6.83	8.09	7.39	8.80	2.30

A graph is plotted for the long term variation of groundwater levels with respect to time (days) for a period from January 2003 to January 2018 for the selected observation wells at Akiveedu, Mogalthuru and Narsapuram as shown in the Fig. 4.1. From the graphs it can be seen that the groundwater table is varying with rainfall. The trend is similar in all the three wells selected. Also the water level variation is cyclic and sinusoidal and is seen as a function of time and space. Elevations of the villages collected from DEM (from USGS) of Akiveedu, Mogalthuru and Narsapuram is 6.17, 10.38 and 10.96 m respectively. From Fig. 4.2, it can be seen that groundwater level is rising from August to December and is declining from February to July. Groundwater level in the study area is minimum in the month of May and maximum in the month of November.

During the study period, the maximum groundwater table in head observation well at Akiveedu village was observed as 6.11 m above mean sea level (0.08 m below groundsurface) in September 2008. The minimum was 3.23 m with respect to mean seal level (2.94 m below groundsurface) observed in May 2003 and July 2009. The maximum groundwater table in head observation well at Mogalthuru village was observed as 10.89 m above mean sea level (0.1 m below groundsurface) in November 2010. The minimum was 8.15 m with respect to mean seal level (2.94 m below groundsurface) observed in May 2003. The maximum groundwater table in head observation well at Narsapuram village was observed as 10.37 m above mean sea level (0.01 m below groundsurface) in November 2013. The minimum was 8.46 m with respect to mean seal level (1.92 m below groundsurface) observed in May 2003.

To study the temporal variation of the groundwater table three well each from the three categories (low land, mid land and high land), i.e., the observation wells located at Akkiveedu, Mogalthuru and Buttayagudem villages were selected. Temporal variation of groundwater in pre monsoon and post monsoon seasons for low land, mid land and high land is plotted in the Fig. 4.3, 4.4 and 4.5 respectively for the selected wells. From these figures it can be seen that there is not much reduction in the average groundwater levels in the pre monsoon and post monsoon seasons during the study period of 14 years. From the figures, the groundwater table variation can be observed to depend on the rainfall intensity and aquifer characteristics.

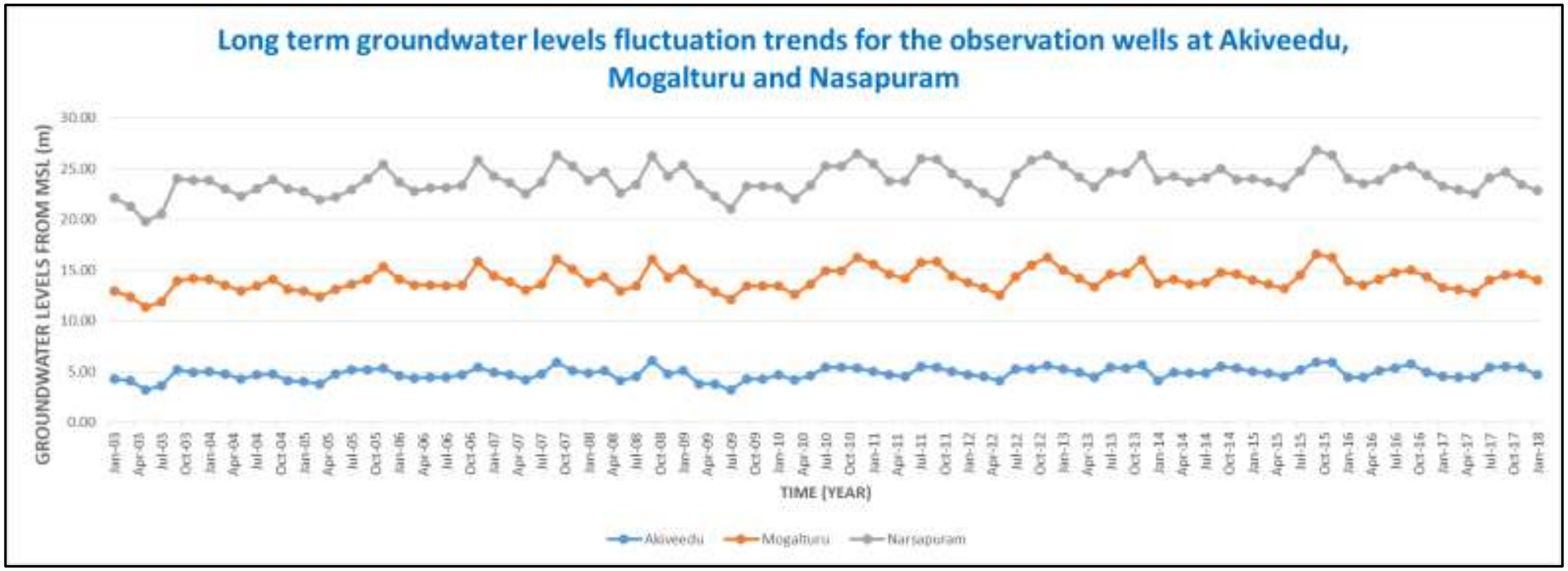


Fig. 4.1. Long term groundwater levels fluctuation trends for the observation wells at Akiveedu, Mogalturu and Nasapuram

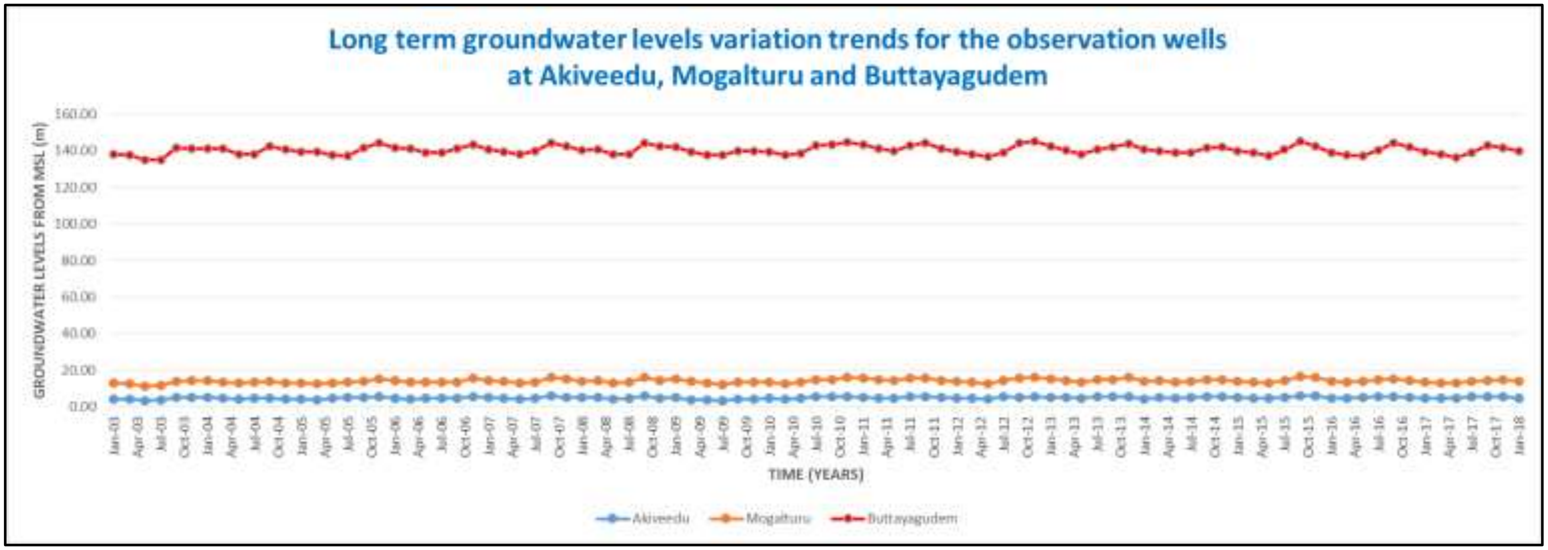
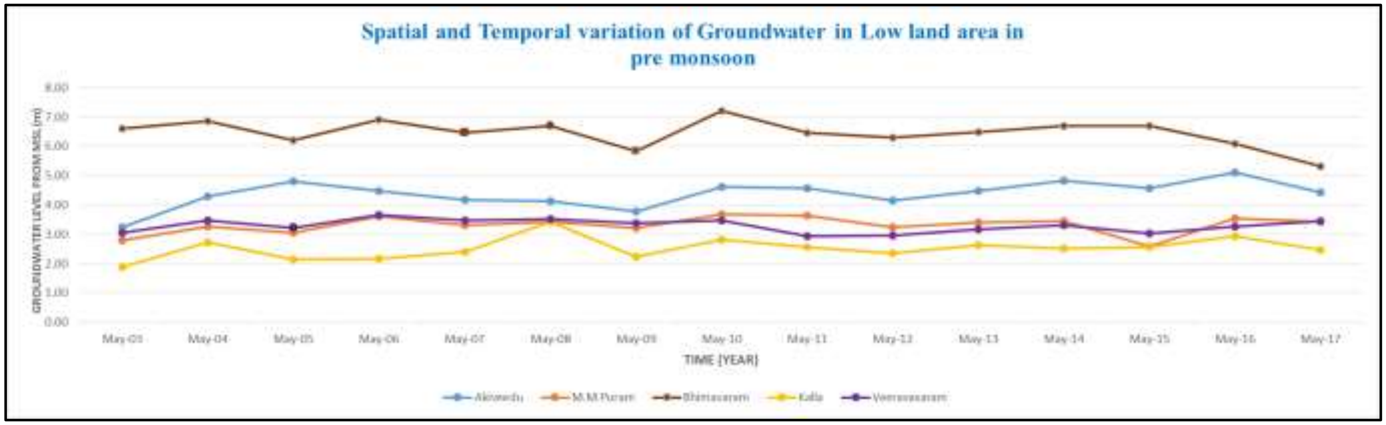


Fig. 4.2. Long term groundwater levels fluctuation trends for the observation wells at low land, mid land and high land



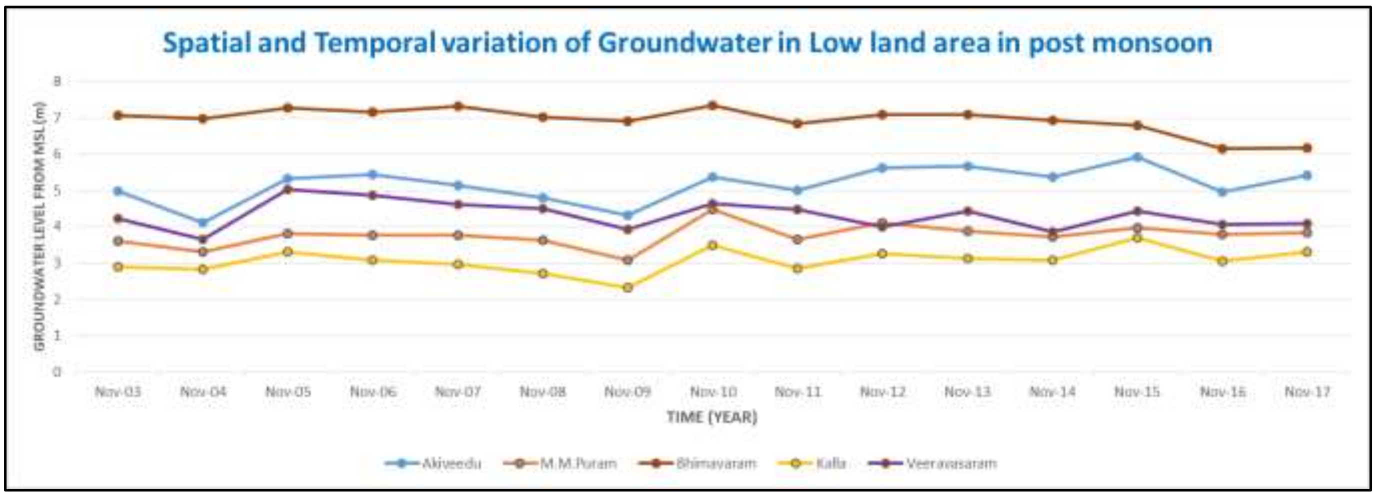
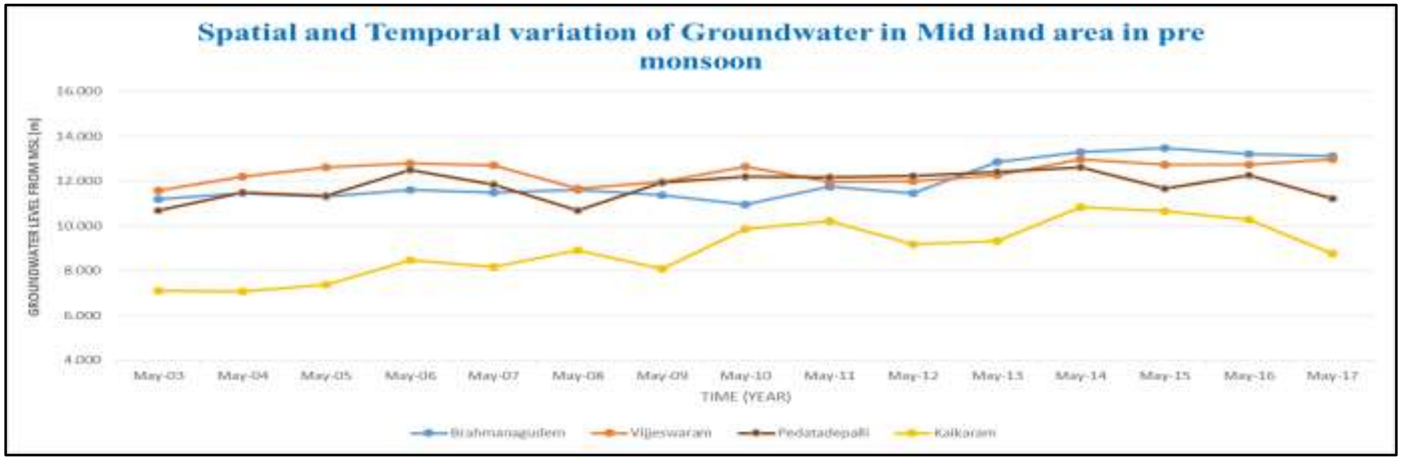


Fig. 4.3. Spatial and temporal variation of groundwater in pre monsoon and post monsoon in low land



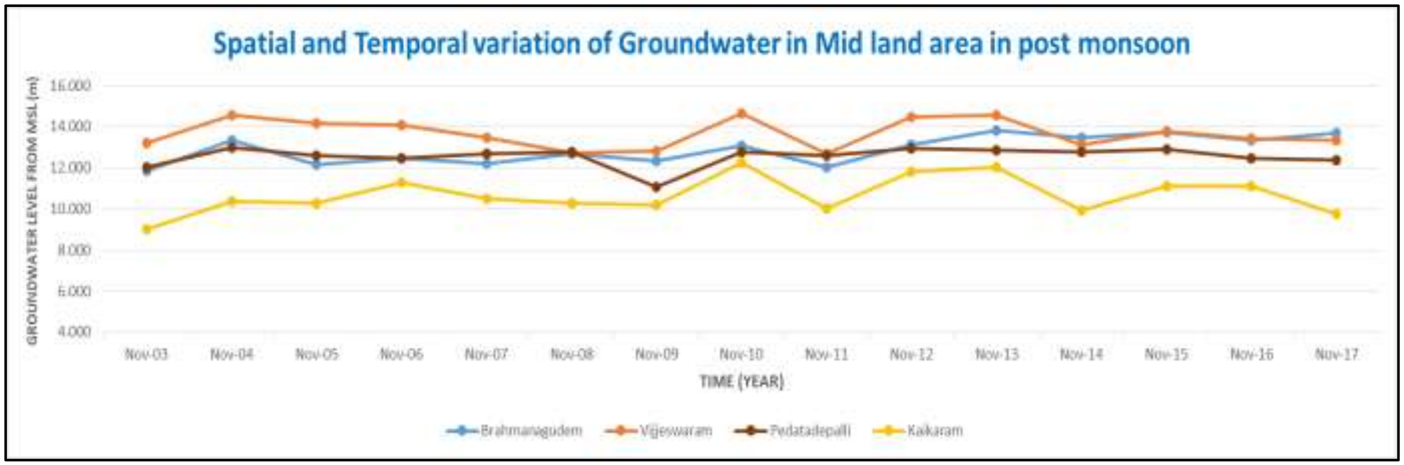
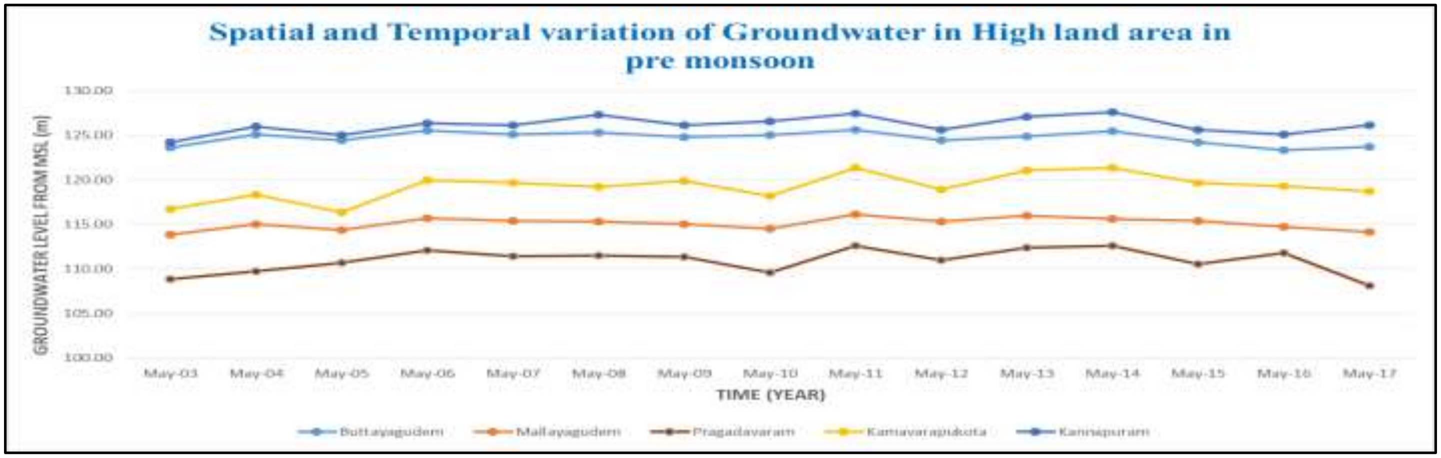


Fig. 4.4. Spatial and temporal variation of groundwater in pre monsoon and post monsoon in mid land



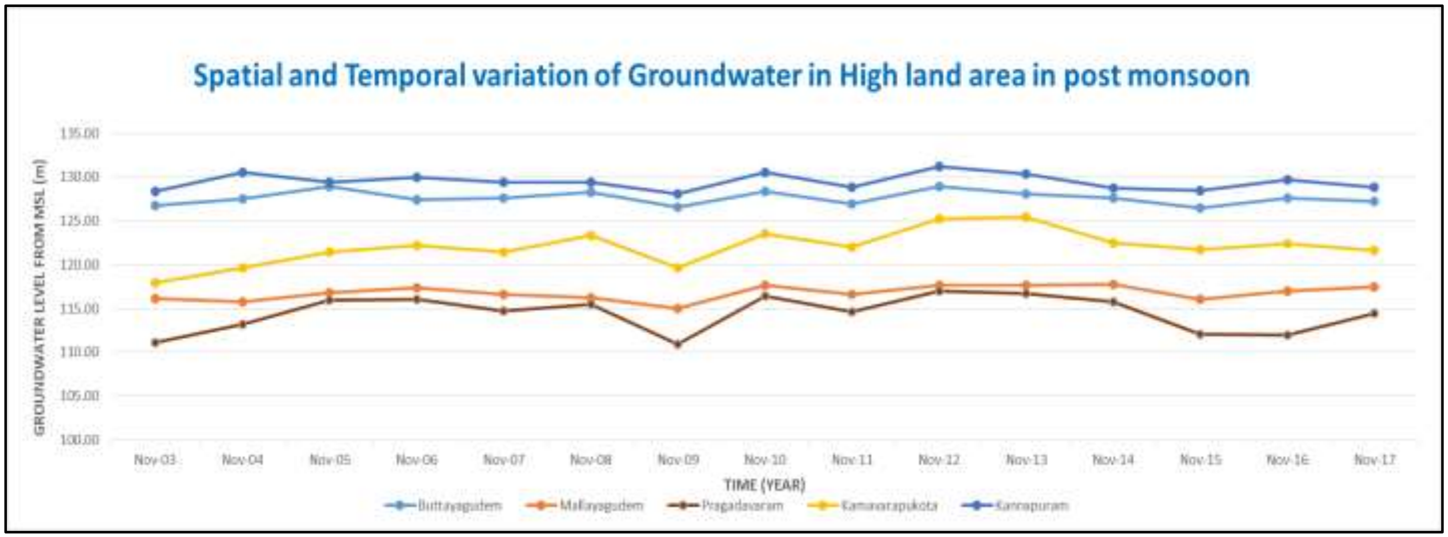


Fig. 4.5. Spatial and temporal variation of groundwater in pre monsoon and post monsoon in high land

4.2. Depth to groundwater level

Spatial variation of groundwater during pre-monsoon and post monsoon seasons of the study area was studied using groundwater level maps prepared using Arc GIS 10.1 and are shown in Fig. 4.6, 4.7 and 4.8. The depth to groundwater level from ground surface is plotted in these figures. From these plots it can be observed that the groundwater table is at a lower level in the pre monsoon season and rising in the post monsoon season. Rise in groundwater table is mainly due to rainfall.

From these groundwater level maps, it can be observed that the groundwater levels in the hilly area of Dwarak Tirumala region is at a lower level from the ground surface compared to other areas in the pre monsoon season. The depth to water level is shallow along the sea coast and also nearer to the river. Groundwater level variation in the study area is studied by dividing it into five groundwater level zones. Range of these zones will vary accordingly as shown in Fig. 4.8.

The post monsoon season depth to groundwater level maps shows significant rise in the groundwater table. This results in a shift in position of the contours. For example, during 2013 the maximum depth to groundwater table was 15 m in pre monsoon whereas water table rise to 10 m below groundsurface in post monsoon as seen in Fig. 4.7.

Comparing the groundwater level maps, maximum decline in the groundwater level was observed during May 2003 for the pre monsoon seasons. In post monsoon seasons, November 2005 recorded the highest water level followed by November 2007.

The effect of 'Pattiseema lift irrigation project' on groundwater level for both pre monsoon and post monsoon seasons can be seen in Fig.4.8. Depth to groundwater level during 2017 varies from 1 - 2 m, whereas, it was 2 - 4 m during 2015 which shows a rise in groundwater level of 1 - 2 m.

Groundwater head is varying mainly due to rainfall. Fluctuation in water level for head observation wells near to rivers, drains and canals was observed as less. Groundwater fluctuation was more for high land area and hills because time available for recharge is less. Groundwater table is varying spatially due to soil properties and characteristics of the aquifer. Groundwater recharge is more for high hydraulic conductivity soils, thus rising the water table.

4.2.1. Groundwater table fluctuation map

The difference between successive rise and fall in the water level in observation wells during a year is called fluctuation, where rise is due to the recharge and fall because of the discharge. Groundwater table fluctuation map was developed using Arc GIS 10.1. To study the groundwater variation between the pre monsoon and post monsoon seasons in the study area. The average groundwater fluctuation in the study area for the period 2003 to 2017 was calculated and given in Table 4.5 is plotted and is shown in Fig. 4.9. From the figure it can be seen that the area has been divided into twelve fluctuation zones with 0.5 m variation. Low fluctuation is represented in green color whereas medium fluctuation and high fluctuation in yellow and red color respectively.

From the groundwater fluctuation map, maximum fluctuation in the groundwater level (5.5 to 6 m) was observed in the hilly regions of the study area and minimum (0 – 0.5 m) in the low altitudes and nearer to the sea.

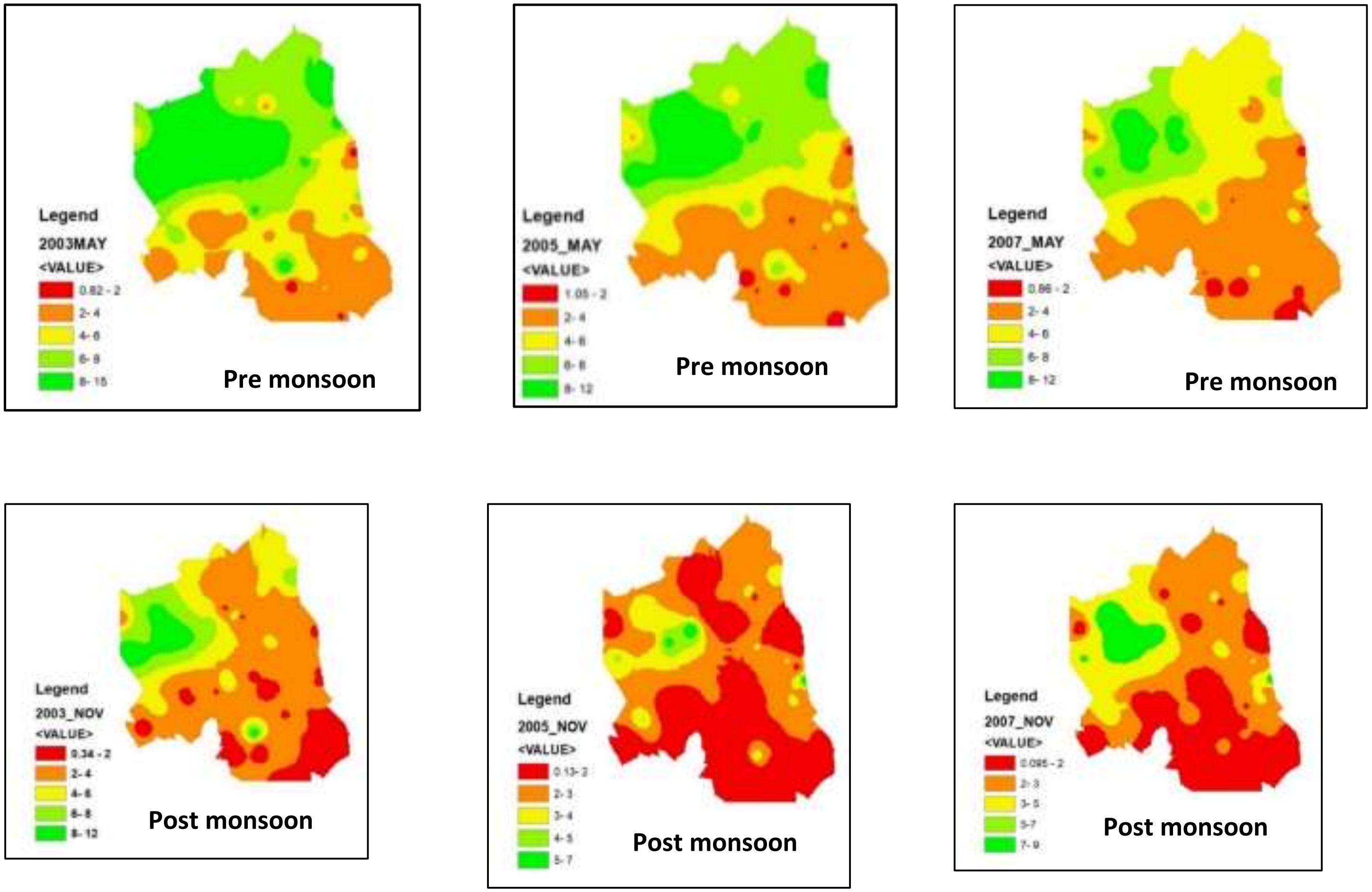


Fig. 4.6. Groundwater level maps for the pre monsoon and post monsoon seasons in 2003, 2005 and 2007

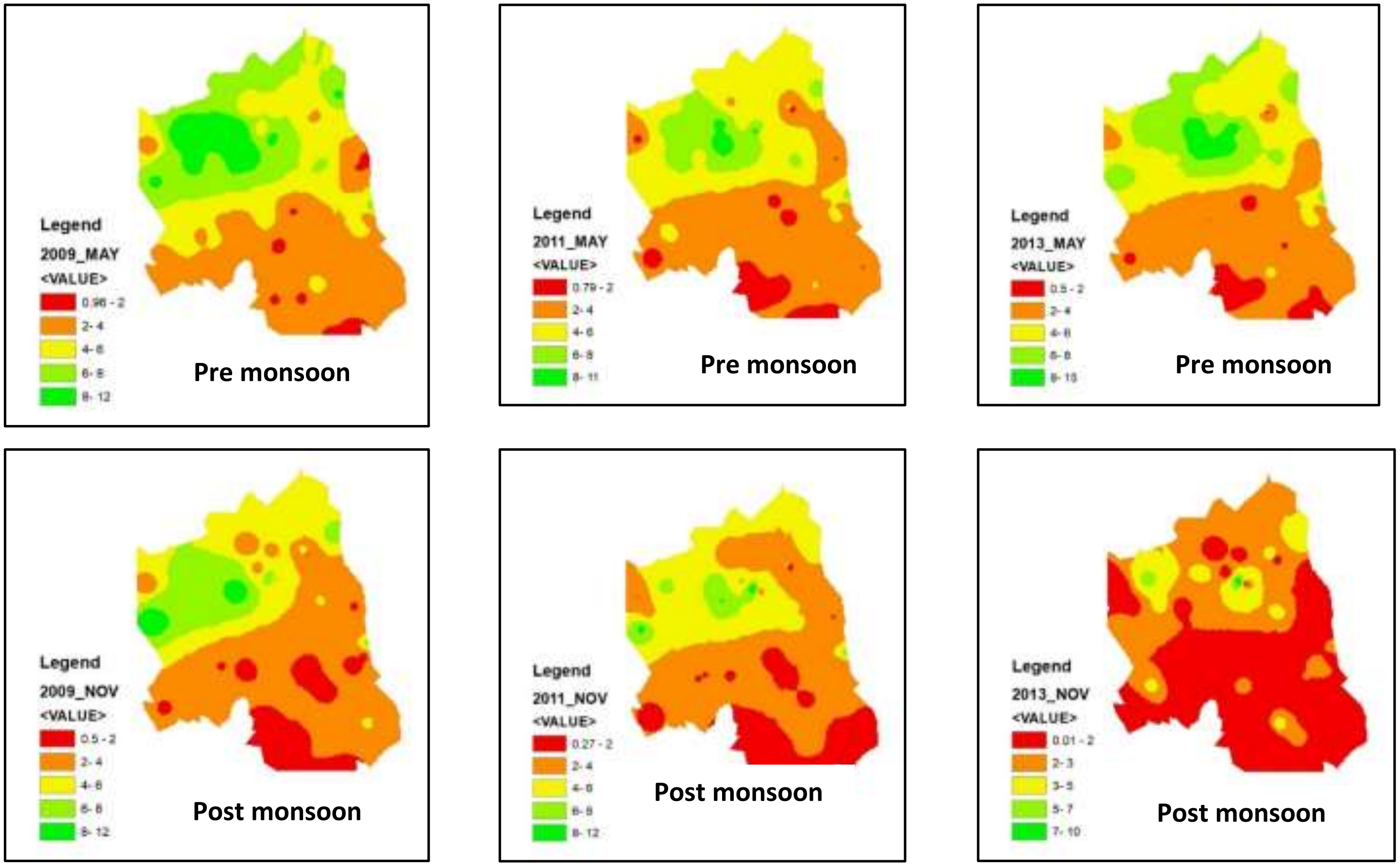


Fig. 4.7. Groundwater level maps for the pre monsoon and post monsoon seasons in 2009, 2011 and 2013

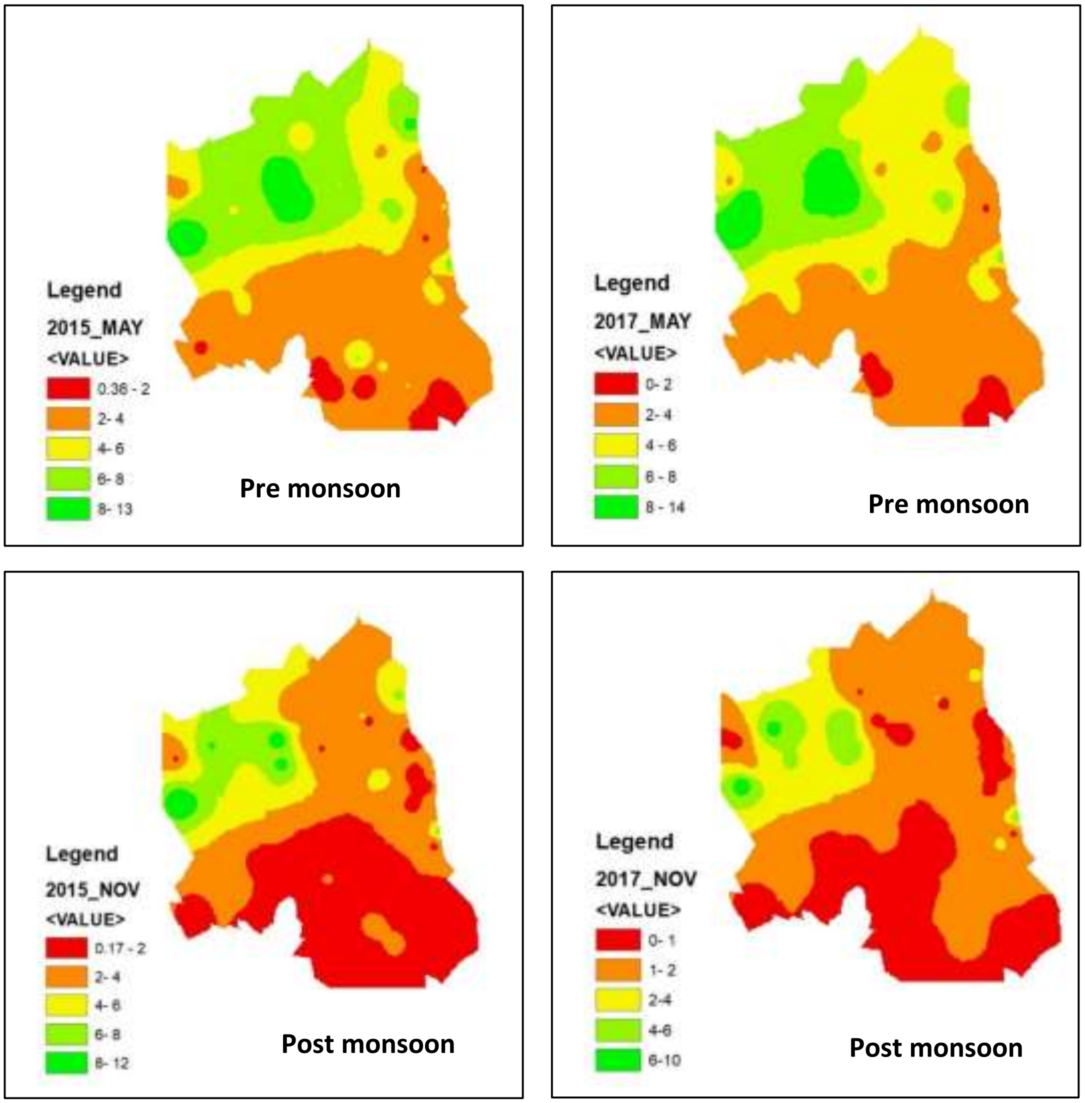


Fig. 4.8. Groundwater level maps for the pre monsoon and post monsoon seasons in 2015 and 2017

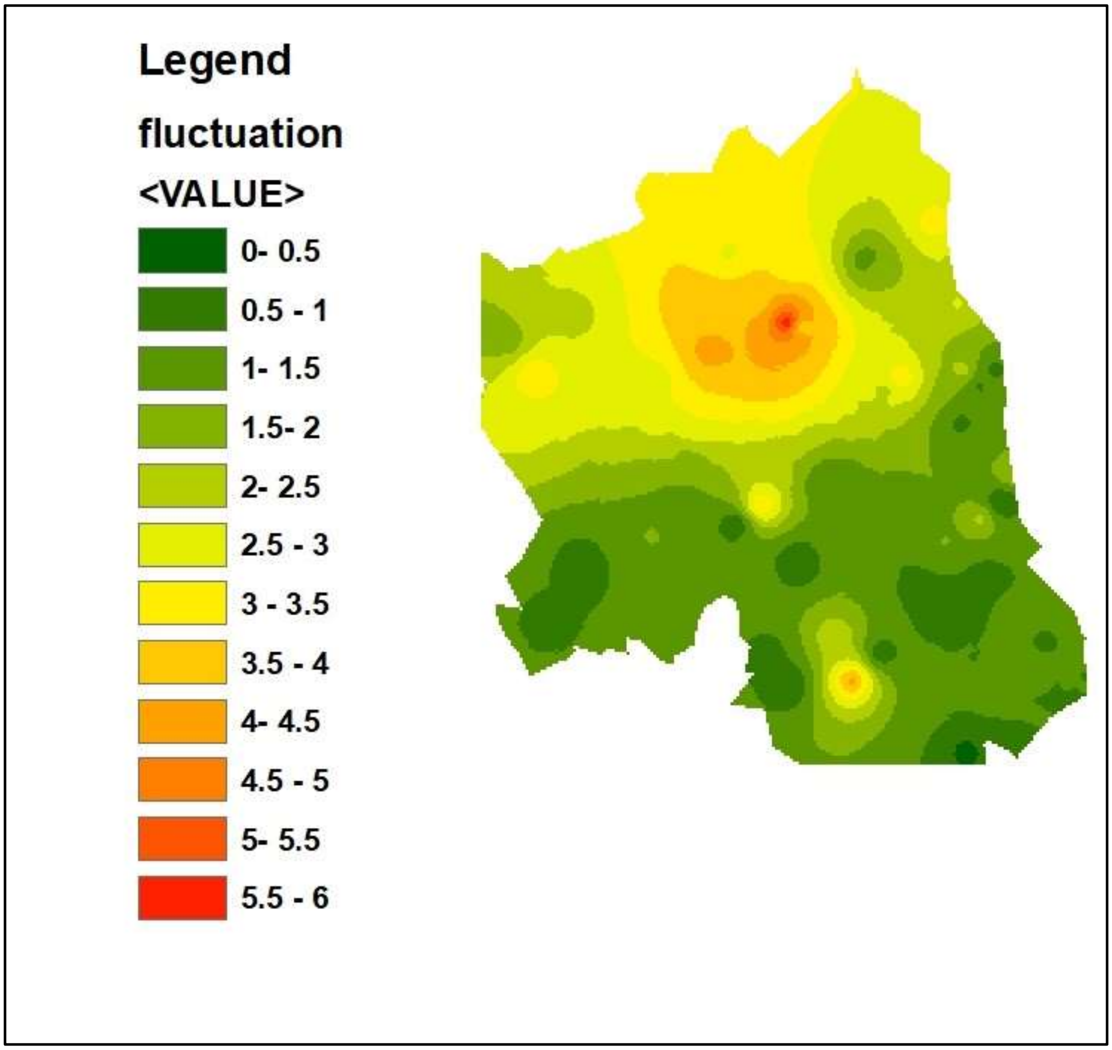


Fig. 4.9. Groundwater fluctuation map for the pre monsoon and post monsoon seasons

4.2 Potential groundwater zones:

By using the groundwater level maps of pre monsoon and post monsoon seasons, the potential groundwater zones were identified to collect lithology. Ten locations widely distributed in the study area were selected. Kokkirapadu, Munduru, Vijayarai, Polavaram, Nidadavole, Eluru, G Kothapalli, Gopalapuram, Dubacherla and

Dharmavaram were the different locations selected and lithology at these zones were collected from the Department of Groundwater and Water Audit, Government of Andhra Pradesh. By studying the lithology of the study area, it can be observed that sandstone and clay formed the top layer in most parts of the study area. Sandstone occupied major portion of the West Godavari district. Clay, sand, clayey-sandstone and granite-gneissis could be seen at different locations in the study area. Clayey-sandstone and Granite Gneissis were found as bottom layer for the study area. Lithology of different locations was collected and assigned in the model to replicate the real conditions in the model

4.3 Groundwater flow modelling

Visual MODFLOW was used to simulate the groundwater flow for steady state and transient calibration and to forecast future behavior of the system under various scenarios. This process requires a broad knowledge about the hydrogeology of the area, the groundwater flow process and its governing equations and methods for checking the reliability of the model.

Calibration, validation and prediction are the different steps involved in groundwater modelling. Model was calibrated using groundwater levels data from 2003 to 2005 in steady state and 2006 to 2012 in transient state. Then the model was validated using 2013 to 2017 data in transient state condition. After validation, model was used for prediction. The sensitivity of the model to input parameters was tested by varying only the parameters of interest over a range of values, and monitoring the response of the model by determining the root mean square error of the simulated heads compared to the measured heads.

The output from Visual MODFLOW includes contours of water table, elevation, head equipotential, net recharge and drawdown. Other outputs include velocity vectors showing direction of flow and graphs of calculated vs. observed heads.

4.3.1 Model calibration

Calibration of developed model under transient conditions mainly depends on the hydraulic conductivity of different layers and boundary conditions of the steady state calibrated model. Storage properties have great influence in transient conditions. The hydraulic conductivity values, water levels and boundary conditions arrived at the steady state calibration is used as the initial condition for the transient state calibration.

4.3.1.1 Steady state calibration

Developed model was calibrated using groundwater level data obtained from 53 wells located in the West Godavari District. The time period of January 2003 is taken as initial state for steady state model calibration. Groundwater level data from 2003 to 2005 was used for calibration. Aquifer properties were adjusted to reduce the RMS error in steady state condition. RMS error is mainly depends on observed and calculated water levels in the model. Thus model was calibrated in steady state condition by assigning hydraulic conductivity values, boundary conditions and the water levels. Output obtained from the calibration in steady state is shown in Fig. 4.11. The results of the model calibration for steady state condition shows good agreement between observed and simulated initial water level contours. Results obtained from the calibrated model are Standard error, RMSE and NRMSE and have values 2.17, 16.41 and 12.06 respectively.

4.3.1.2 Transient state calibration

The transient calibration was carried out for the period up to 2012. Time step in the transient simulation was divided into 11 time steps. In transient calibration the storage properties and aquifer properties were adjusted to reduce the RMS error. After a number of trail runs in which the input and output were varied, the computed water levels were matched fairly reasonable to the observed values. Output obtained from the calibration in transient state condition is shown in Fig. 4.12.

From the scatter plot for computed vs. observed head for the observation wells (Fig. 4.11 and 4.12), it can be seen that there is good agreement between the calculated and observed heads in most of the wells in steady state and transient state calibration. Figures 4.12 and 4.13 showed that the comparison between computed and observed hydraulic heads in transient model calibration at a time step of 14 and 3653 days. Transient state calibration results and statistics are summarized in Table 4.4.

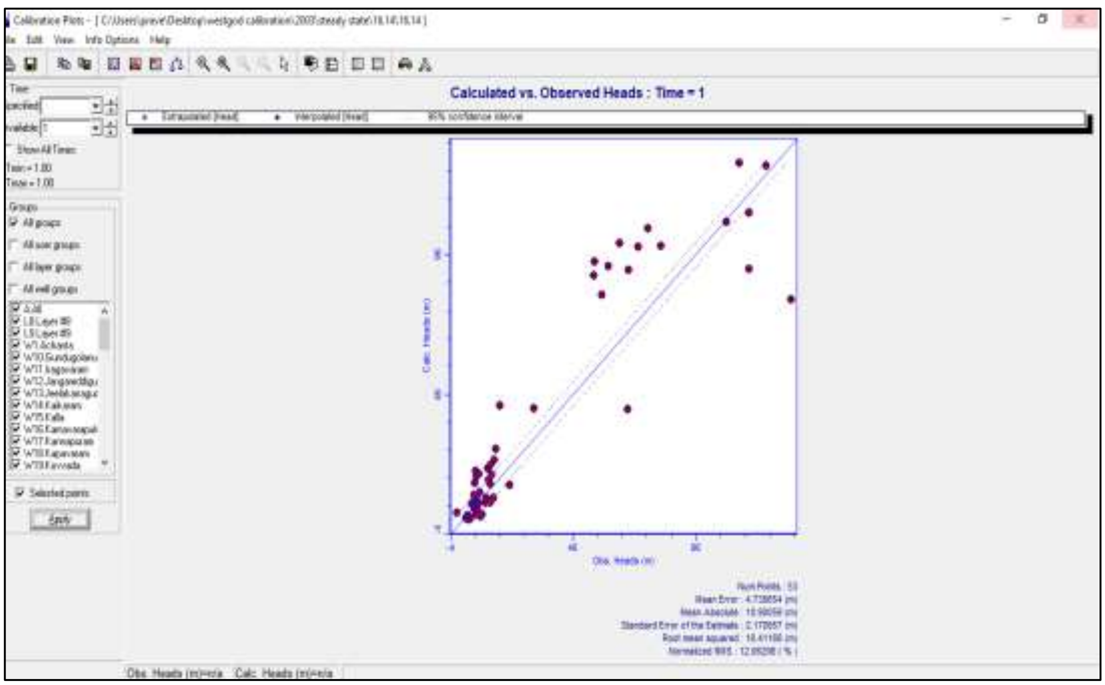


Fig. 4.11. Calculated water levels vs. observed water levels for calibration (steady state condition)

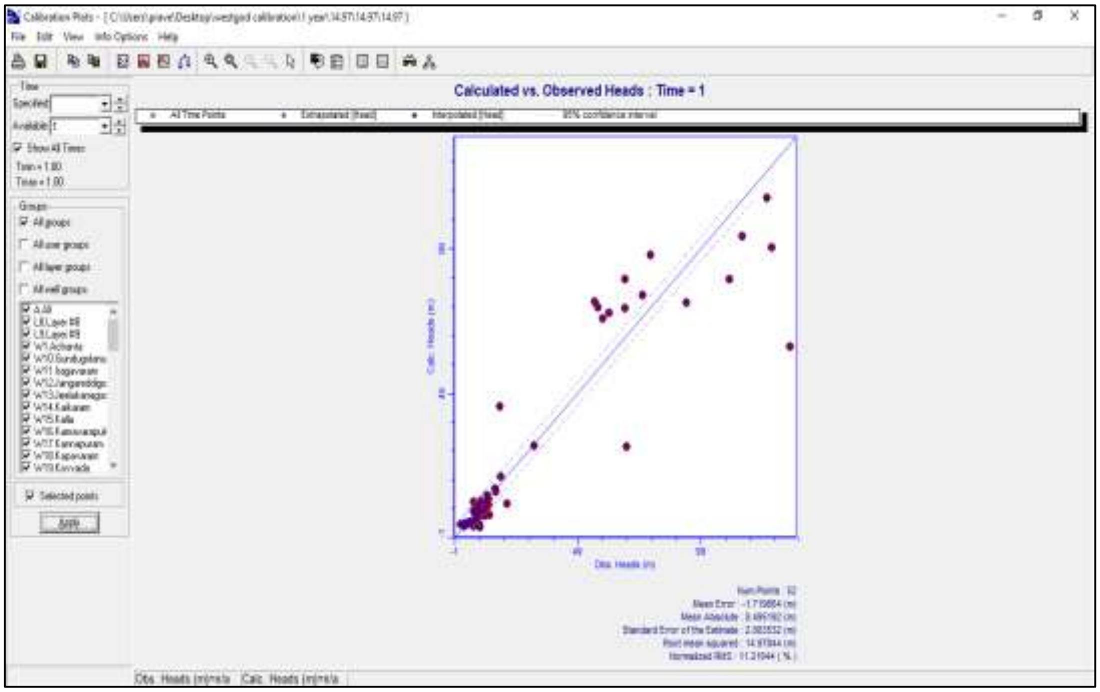


Fig. 4.12. Calculated water levels vs. observed water levels for calibration on 14 day in Transient condition

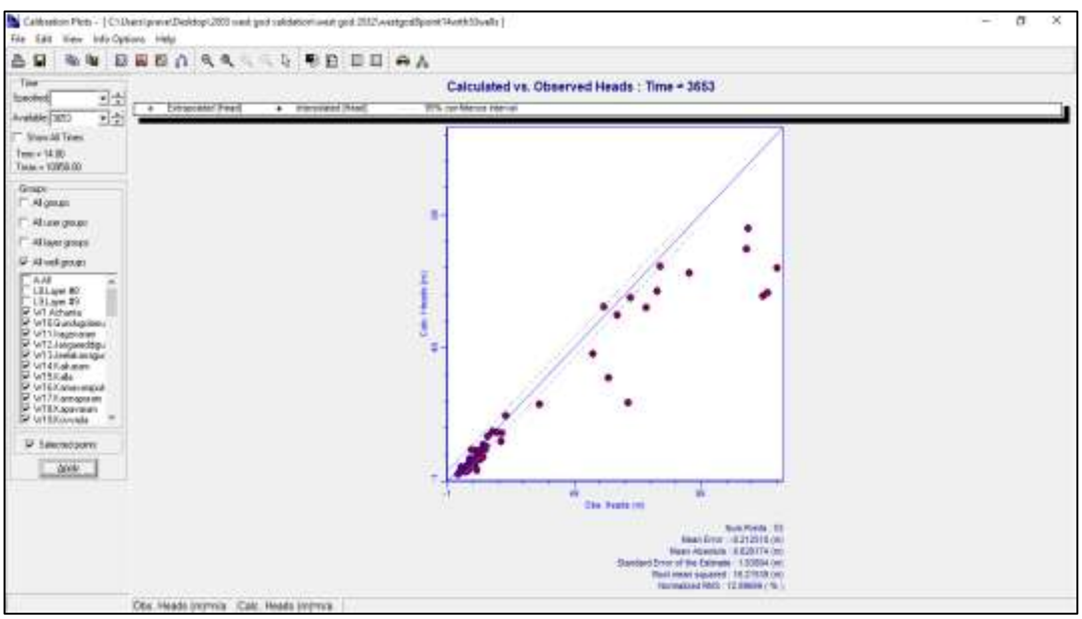


Fig. 4.13. Calculated water levels vs. observed water levels for calibration on 3653 day in Transient condition

Table 4.4 Summary of transient state calibration statistics at 14 days

Parameter	Values
Number of observation wells	53
Mean Error (m)	-8.21
Mean Absolute (m)	8.62
Standard Error of the Estimate	1.93
Root mean squared (m)	16.21
Normalized RMS (%)	12.89

Hydraulic conductivity (K_x, K_y, K_z) in md^{-1}, specific storage (Ss) in m^{-1}, specific yield (S_y), effective porosity and total porosity are the different properties used to replicate the real conditions in the model. RMS error for the developed model was mainly depends on hydraulic conductivity and storage properties. In steady state condition, RMS error can reduce by changing Hydraulic conductivity of different layers. For transient state condition, RMS error mainly depends on Hydraulic conductivity and storage properties. Hydraulic properties assigned for this study is shown in Fig. 4.14. Storage properties assigned for this study are shown in Fig. 4.15.

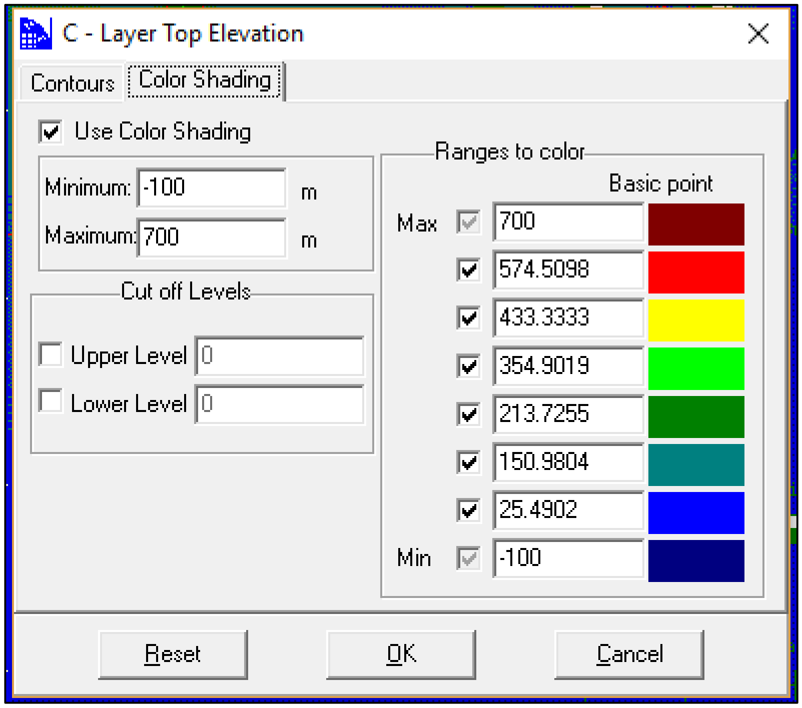


Fig. 4.14. Properties assigned in model model.

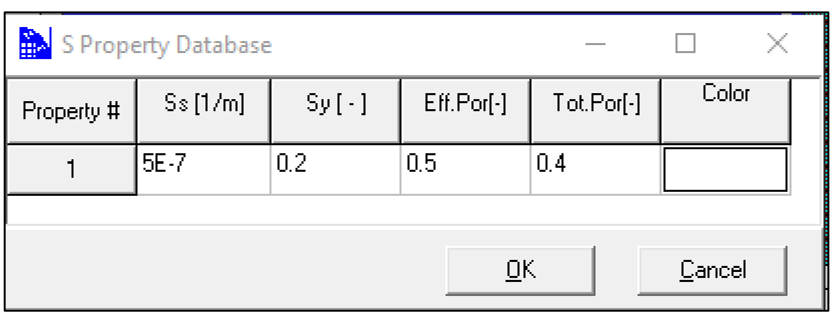


Fig. 4.15. Storage Properties assigned in model.

4.3.2 Model validation

Validation of the calibrated model is necessary to ascertain the predictive capability of the calibrated model and to have a greater confidence in the calibrated model. In this study, groundwater levels from 2013 to 2017 was used for the validation process. After validation, the observed and calculated heads are compared and a good match exists between the computed and observed head values at a time step of 14 days is shown Fig. 4.16.

Table 4.4 Summary of transient state Validation statistics at 14 days

Parameter	Values
Number of observation wells	53
Mean Error (m)	-1.740304
Mean Absolute (m)	4.135732
Standard Error of the Estimate	1.103628
Root mean squared (m)	8.146433
Normalized RMS (%)	6.4721

For validation, ‘Pattiseema Lift Irrigation Project’ is assigned in the model. Lift Irrigation project is used divert Godavari river to Krishna river through canal. This canal is contributing more amount of water for groundwater recharge. New recharge layer is assigned considering the recharge from canal. Output obtained from the validated model is shown in table 4.16.

Calculated head vs observed head for the head observation wells at Eluru, Usurumaru, Undrajavaram and Pedatadepalli is shown in Fig.4.17. Calculated and observed heads for the selected wells is almost same.

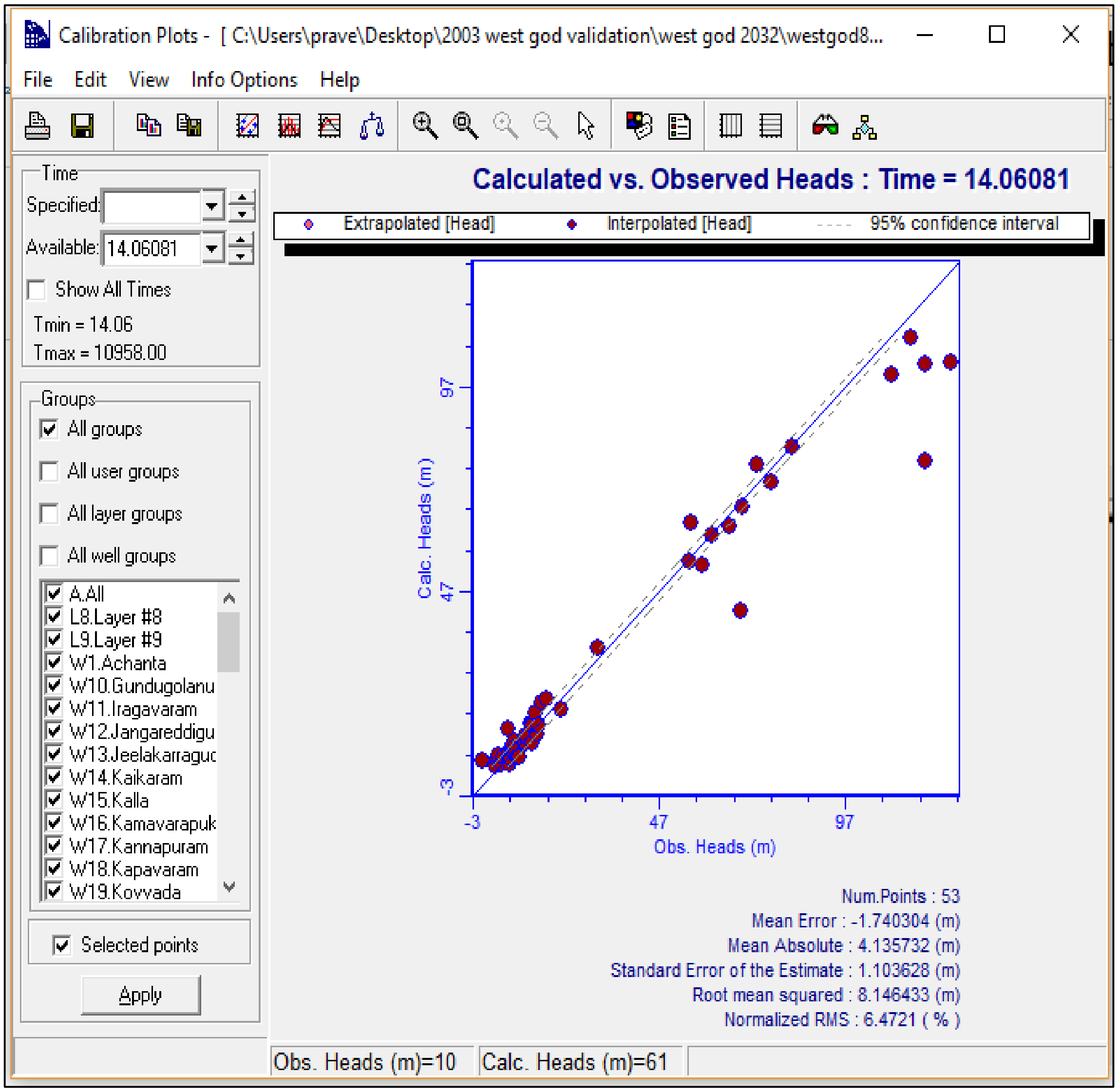


Fig. 4.16 Calculated water levels vs. observed water levels for validated model.

Table 4.5 Summary of transient state Validation statistics at 14 days

Observation Point			
Calculated vs. Observed Heads : Time = 14.06081			
Well number	**Obs. Heads (m)**	**Calc. Heads (m)**	**RMS error**
1	-0.83	5.221192837	6.051192837
2	2.67	3.846563339	1.176563339
3	3.23	5.615700245	2.385700245
4	3.51	6.00660181	2.49660181
5	3.69	6.479279518	2.789279518
6	4.32	4.373247147	0.053247147
7	5.01	6.043900967	1.033900967
8	6.03	6.118915081	0.088915081
9	6.15	13.08039665	6.930396652
10	6.44	5.605717659	-0.834282341
11	6.6	7.527404308	0.927404308
12	6.69	4.505517483	-2.184482517
13	6.78	6.52975893	-0.25024107
14	7.08	5.737092018	-1.342907982
15	7.23	8.159771919	0.929771919
16	7.37	9.075595856	1.705595856
17	7.65	9.800222397	2.150222397
18	7.67	7.175890446	-0.494109554
19	7.74	8.274868011	0.534868011
20	7.81	8.110585213	0.300585213
21	8.1	7.248784542	-0.851215458
22	8.21	7.465451717	-0.744548283
23	8.64	5.999253273	-2.640746727

24	9.18	6.043357849	-3.136642151
25	10.69	9.737325668	-0.952674332
26	10.86	11.33491325	0.474913254
27	11.48	10.77820015	-0.70179985
28	12.019	14.25938511	2.240385109
29	12.45	14.49737263	2.047372627
30	12.64	13.95294952	1.312949524
31	12.7	9.790312767	-2.909687233
32	13.28	16.74855995	3.468559952
33	13.94	11.90345955	-2.036540451
34	14.1	13.99738979	-0.102610207
35	14.96	19.47487831	4.514878311
36	16.44	20.34744072	3.90744072
37	20.45	17.66364098	-2.786359024
38	30.26	33.00541687	2.74541687
39	54.9	53.88169098	-1.018309021
40	55.22	63.62098312	8.400983124
41	58.17	53.21670914	-4.953290863
42	60.67	60.38685608	-0.283143921
43	65.5	62.68959808	-2.810401917
44	68.77	42.02177048	-26.74822952
45	68.97	67.18687439	-1.78312561
46	72.85	77.66170502	4.811705017
47	76.83	73.42990112	-3.400098877
48	82.18	82.12078857	-0.059211426
49	108.9	99.56082916	-9.339170837
50	114.15	108.6491165	-5.500883484

51	118	78.59024048	-39.40975952
52	118.05	101.9989624	-16.0510376
53	125.04	102.6505432	-22.38945679

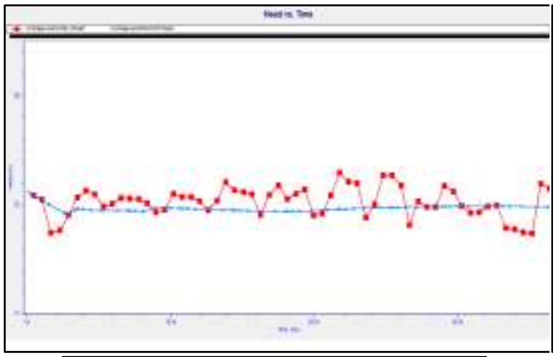
4.3.2.1 Equipotential map

Water table contours with 1m interval was obtained from the model and is shown in Fig. 4.18. From the figure it can be seen that the groundwater levels at coastal area was less than 7 m whereas it is around 140 m in hilly area. Groundwater levels for 17 wells which are located near river and sea have groundwater contours less than 10m. Ground water contours near Godavari river was between 2 m to 29 m. In highland area, groundwater contours were found at a range of 100 m.

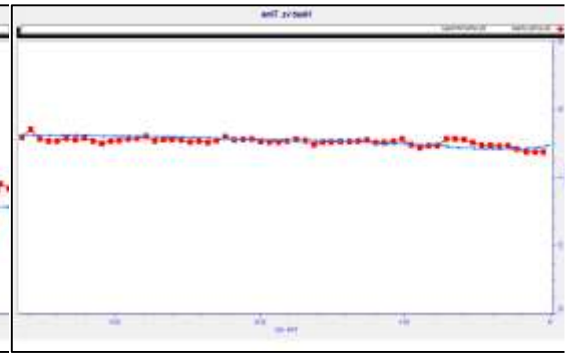
4.3.2.2 Velocity vector map

Velocity vector obtained from the developed model is shown in Fig. 4.19. This map represents that the groundwater movement in the study area was towards the drains, river and sea. Maroon color vectors represents movement inwards whereas navy and green vectors represents outwards and in plane flow.

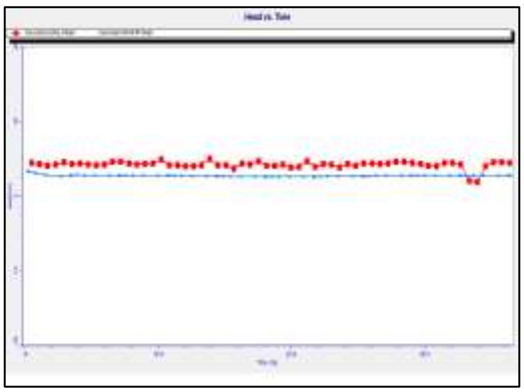
In coastal area, velocity vectors are towards Bay of Bengal. In central portion of the study area, groundwater is moving towards the drain and Upputeru river. In upper parts of the study area, groundwater movement is towards the Godavari river.



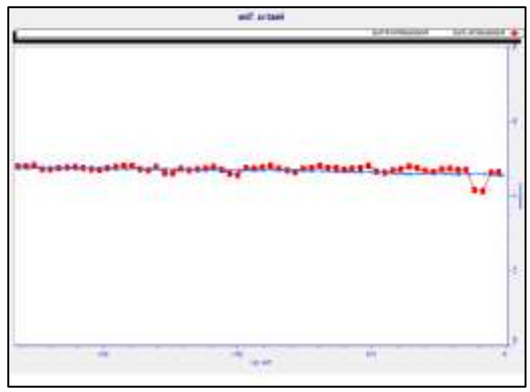
Head observation well at Eluru



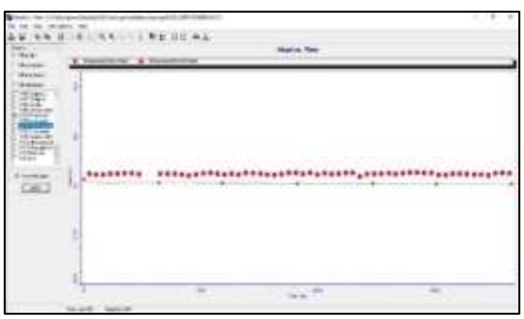
Head observation well at Undrajavaram



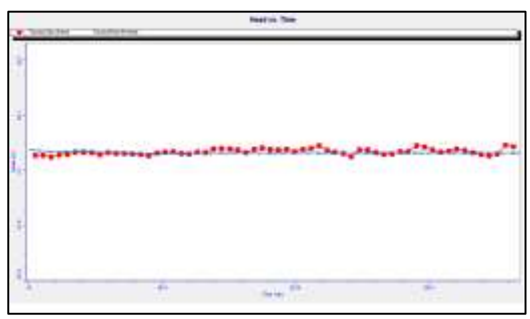
Head observation well at Pedatadepalli



Head observation well at Usurumarru



Head observation well at Bhimavaram



Head observation well at Tanuku

Fig.4.17. Calculated head vs Observed head for the selected wells

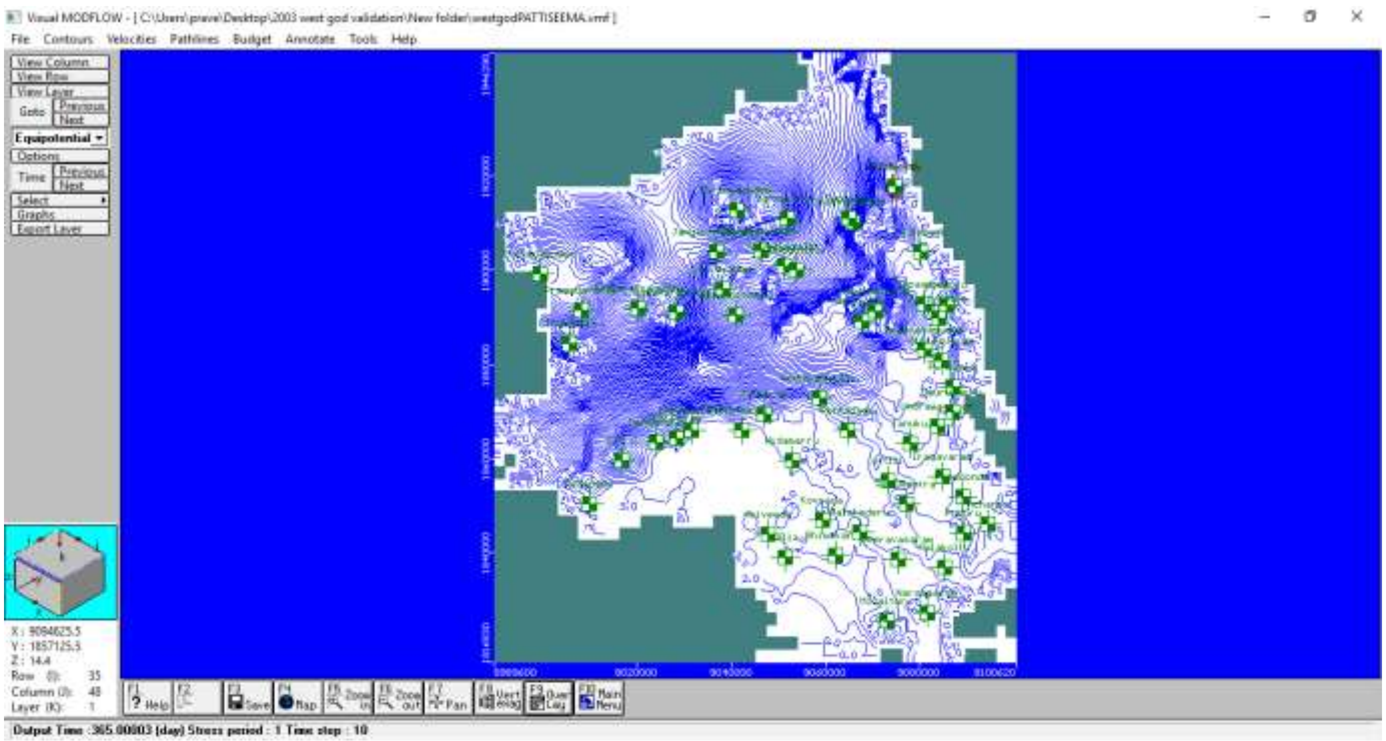


Fig. 4.18. Water table contours in the study area.

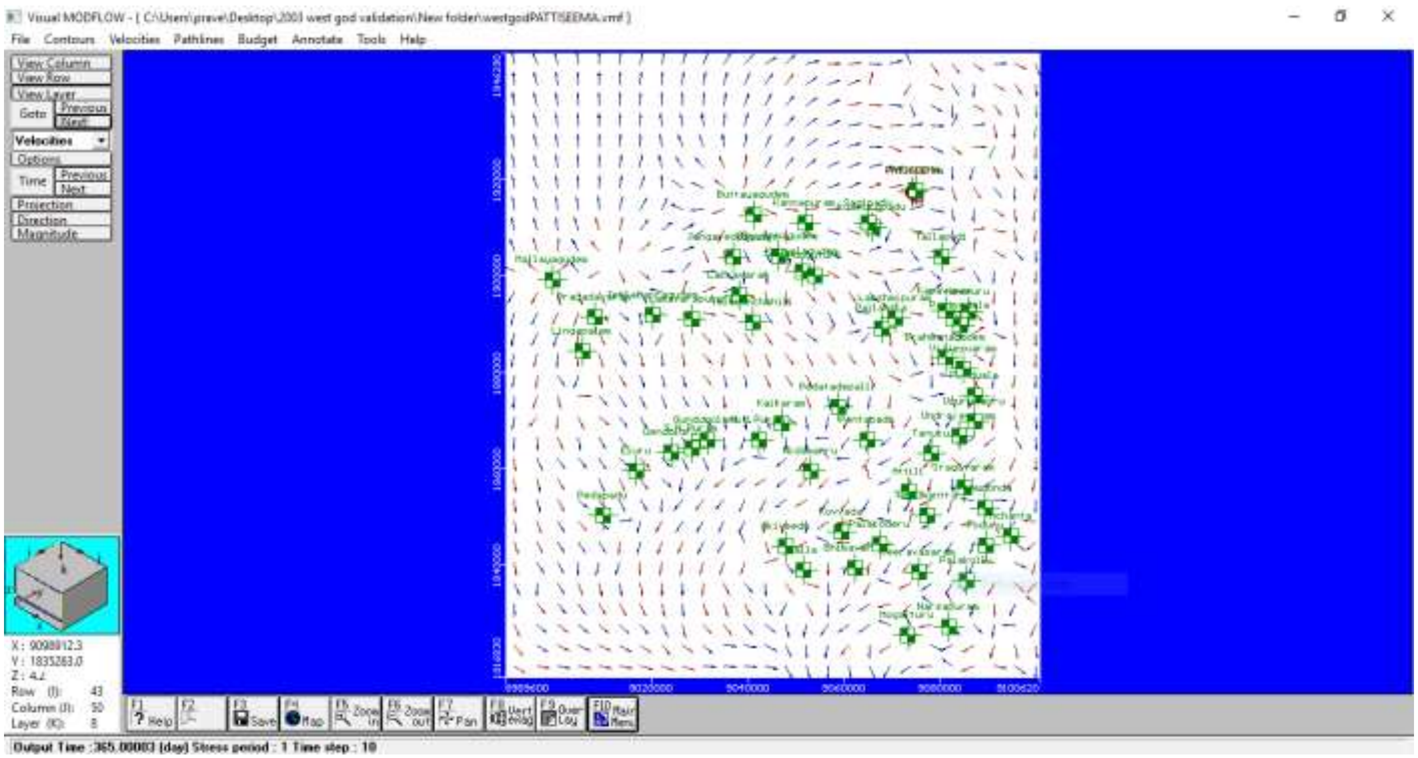


Fig. 4.19. Velocity vector of ground water flow.

4.3.3 Model prediction

Validated model was used to predict the groundwater levels for 15 years (2018 to 2032) in 3 steps with decrease in recharge and increase in pumping rate by 5per cent for every five years. Developed model was also used to study the effect of 'Pattiseema lift irrigation project' in West Godavari district.

4.3.3.1 Scenario 1

Validated model was used to predict the groundwater levels for next 5 years (7305 days), 10 years (8766 days) and 15 years (10958 days) from 2018 to 2022, 2023 to 2027 and 2028 to 2032. Output obtained for 14 days and 10958 days are shown in Fig. 4.20 and 4.21. respectively. The predictive simulation was done for 30 stress periods.

Pattiseema, the lift irrigation project, interlinking Godavari and Krishna rivers through the Polvaram right canal, is a project of the Andhra Pradesh government to divert surplus Godavari water to the Krishna river to meet the irrigation needs of Krishna delta. The project was designed to lift around 100 TMC of Godavari water. In this study the impact of this project on the groundwater resources of the area was also studied.

4.3.3.2 Scenario 2

The validated model was also run without 'Pattiseema lift irrigation project' to study the effect of lift irrigation project in the study area. Comparing scenarios 1 and 2, it can be seen that the rise in the groundwater table in the vicinity of the lift irrigation project is about 3 m (Fig. 4.31). With this 3 m rise in the groundwater, there is a significant increase in the groundwater storage also. So the inter linking of the rivers can solve the water shortage problem of the rivers. Using unlined canals for inter linking of the rivers will increase the groundwater recharge also.

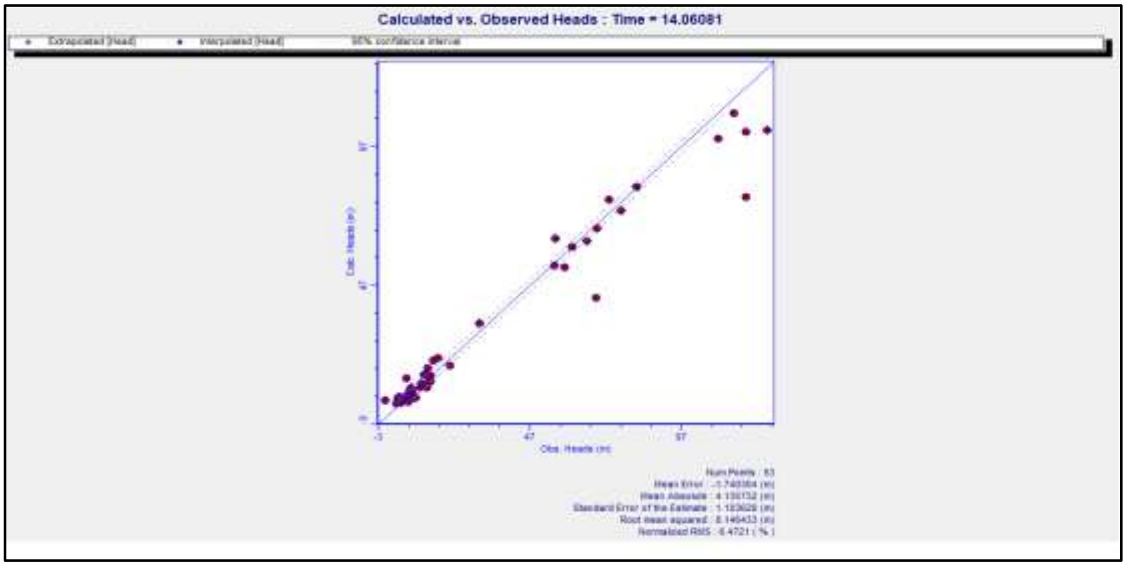


Fig. 4.20. Calculated water levels vs. observed water levels for 14 days

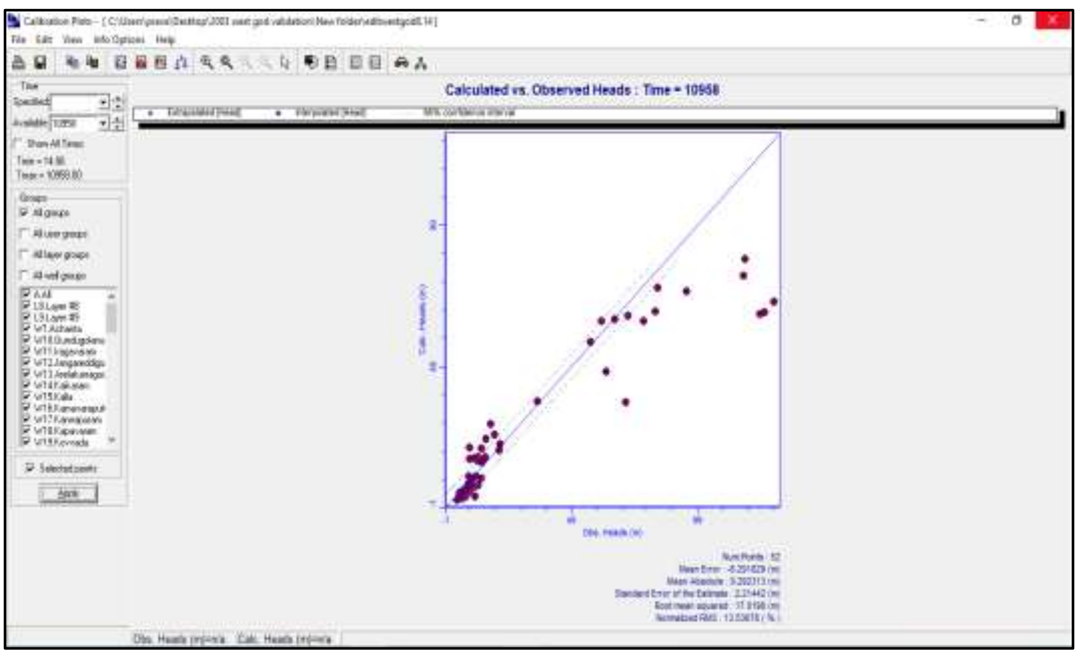


Fig. 4.21. Calculated water levels vs. observed water levels for 10958

Observed heads vs calculated heads for different wells in coastal area, midland and highland were studied. Predicted heads for the observation well in Tanuku, Bhimavaram, Mogalturu, Poduru and pedatadepalli wells were shown below. Predictive head for the observation well in Tanuku which is located near the Godavari river is shown in Fig. 4.22. Predictive head for the observation well in Bhimavaram is shown in Fig. 4.23**.** For Bhimavaram, predicted groundwater head value during 2032 was observed as 2.957 m. Predictive head for the observation well in Mogalturu is shown in Fig. 4.24**.** Predicted groundwater head for Mogalthuru in 2032 is was observed as 3.78 m. Predicted head for the observation well in Poduru is shown in Fig. 4.25**.** Predicted groundwater head for Poduru in 2032 is around 6.2 m. Predicted head for the observation well in Pedatadepalli is shown in Fig. 4.26**.** During 2015, groundwater level is raising because of lift irrigation project. Pattiseema canal is passing through Pedatadepalli. Predicted groundwater head for Poduru in 2032 is around 14.8m. Due to the lift irrigation project, groundwater level in the canal area raised by around 3 meters.

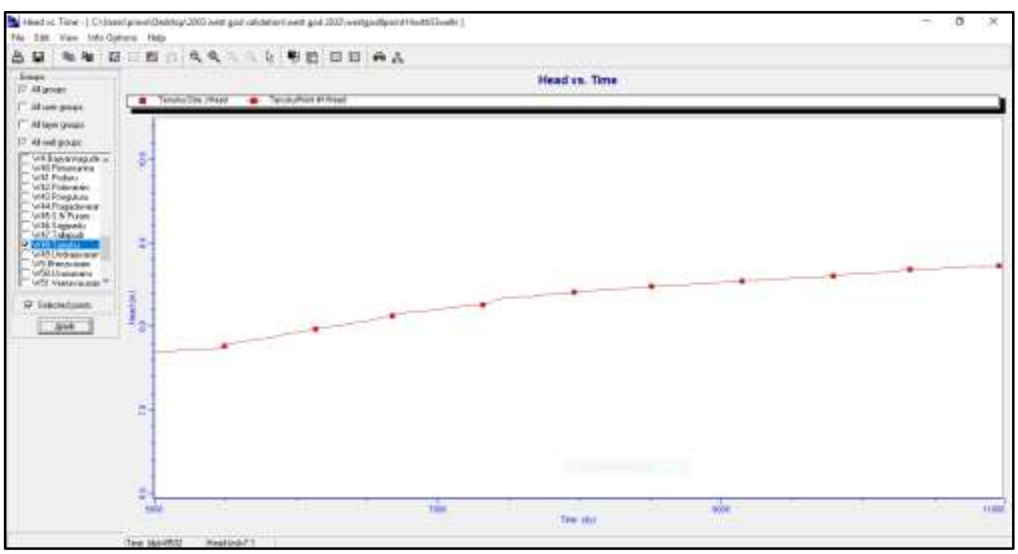


Fig. 4.22. Predicted head for the head observation well at Tanuku.

Fig. 4.23. Predicted heads for Bhimavaram.

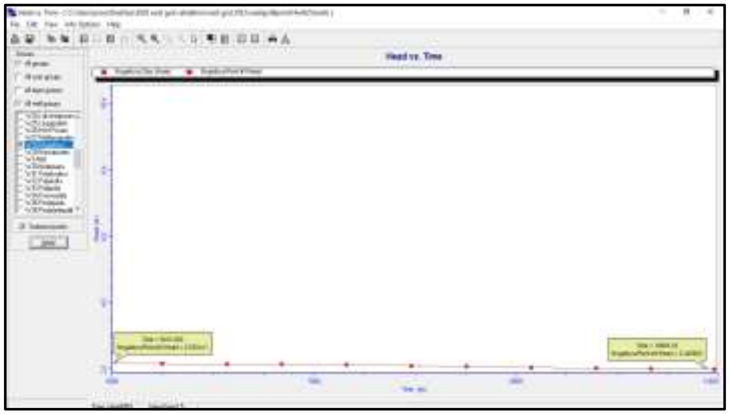


Fig. 4.24. Predicted heads for Mogalthuru.

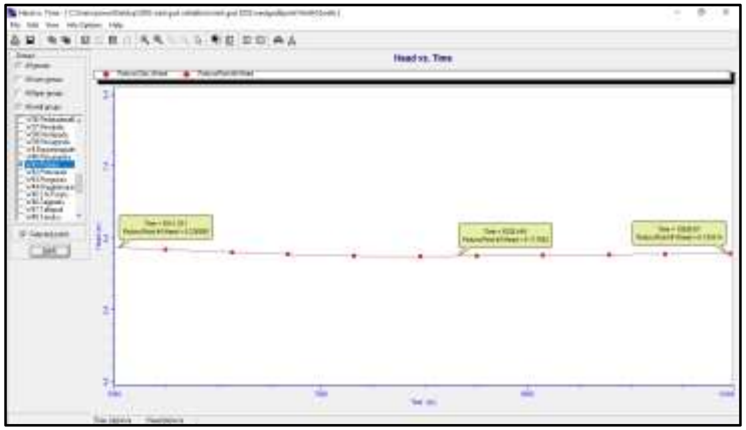


Fig. 4.25. Predicted heads for Poduru.

Fig. 4.26. Predicted heads for Pedatadepalli.

4.3.4 Net Recharge Map

Net recharge map of the study area is shown in Fig. 4.29. Range of net recharge used for the model without 'Pattiseema lift irrigation project' is shown in Fig. 4.27 and with 'Pattiseema lift irrigation project' is shown in Fig. 4.28. Red color shade in the net recharge map represents more recharge. More percentage of recharge is due to the presence of Godavari river, Pattisema lift irrigation project and Bay of Bengal.

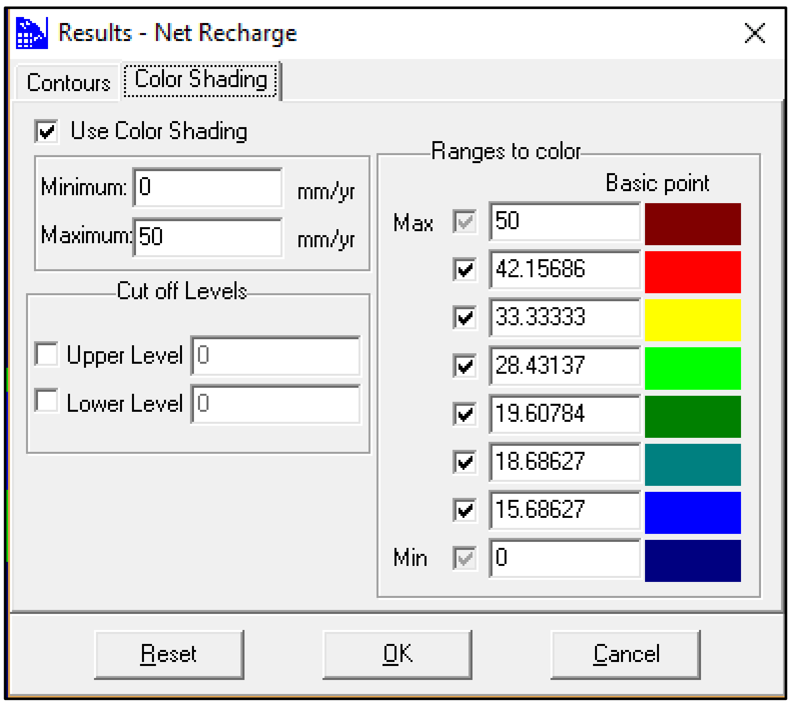


Fig. 4.27. Range of net recharge used for the model without lift irrigation project.

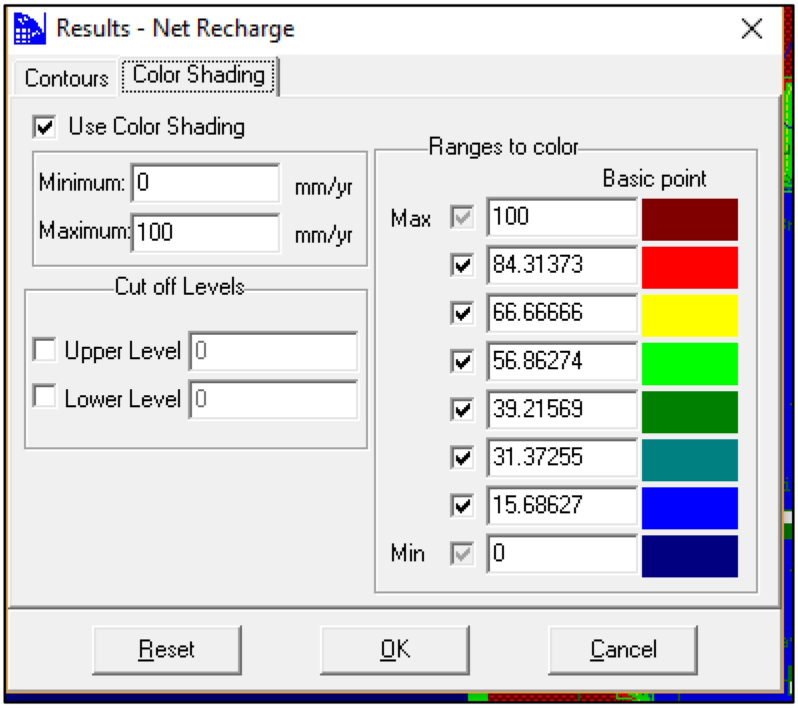


Fig. 4.28. Range of net recharge used for the model with lift irrigation project

Fig. 4.29 represents the 'Net Recharge' map before the construction of 'Pattiseema lift irrigation project"**.** Fig. 4.30. represents the 'Net Recharge' map with 'Pattiseema lift irrigation project". From Fig. 4.29 & 4.30, it was observed that 'Pattiseema' lift irrigation project contributing more amount of water for recharge, about 50 mm/year to 100 mm/year. Due to the presence of canal, groundwater level in the canal area is raised around 3 m. In net recharge figures, color shaded area represents the amount of groundwater recharge in mm/year. Comparing both figures, groundwater recharge is more in Godavari river area and Pattiseema canal area.

Model without 'Pattiseema lift irrigation project' is used to study the groundwater scenario without canal. Predicted groundwater heads for the observation well in Pedatadepalli is shown in Fig. 4.31. From Fig. 4.31, it is found that groundwater head difference between two cases was around 3 m which represents the effect of 'Pattiseema lift irrigation project'.

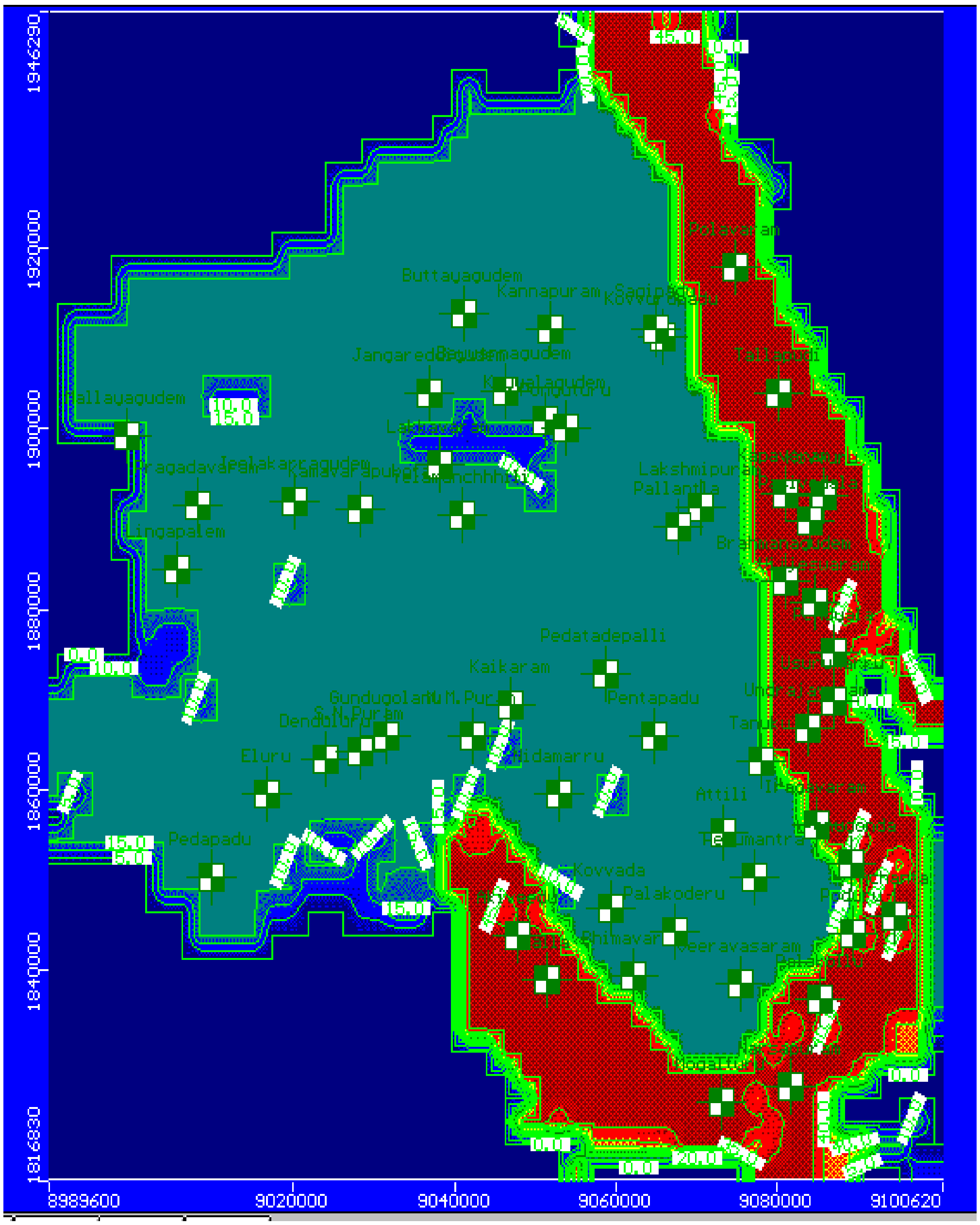


Fig. 4.29. Net recharge map without Pattiseema lift irrigation project.

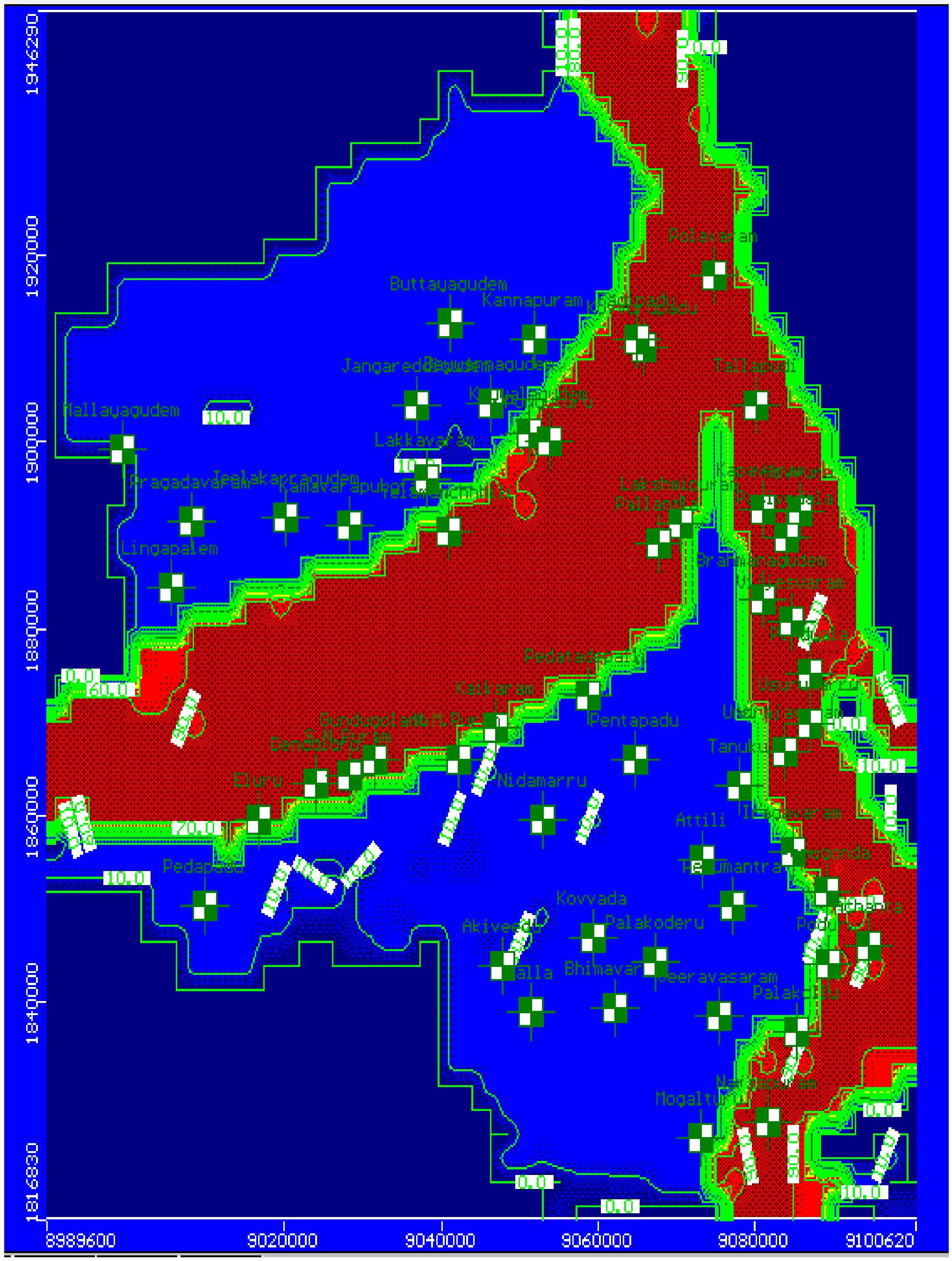


Fig. 4. 30. Net recharge map with Pattiseema lift irrigation project.

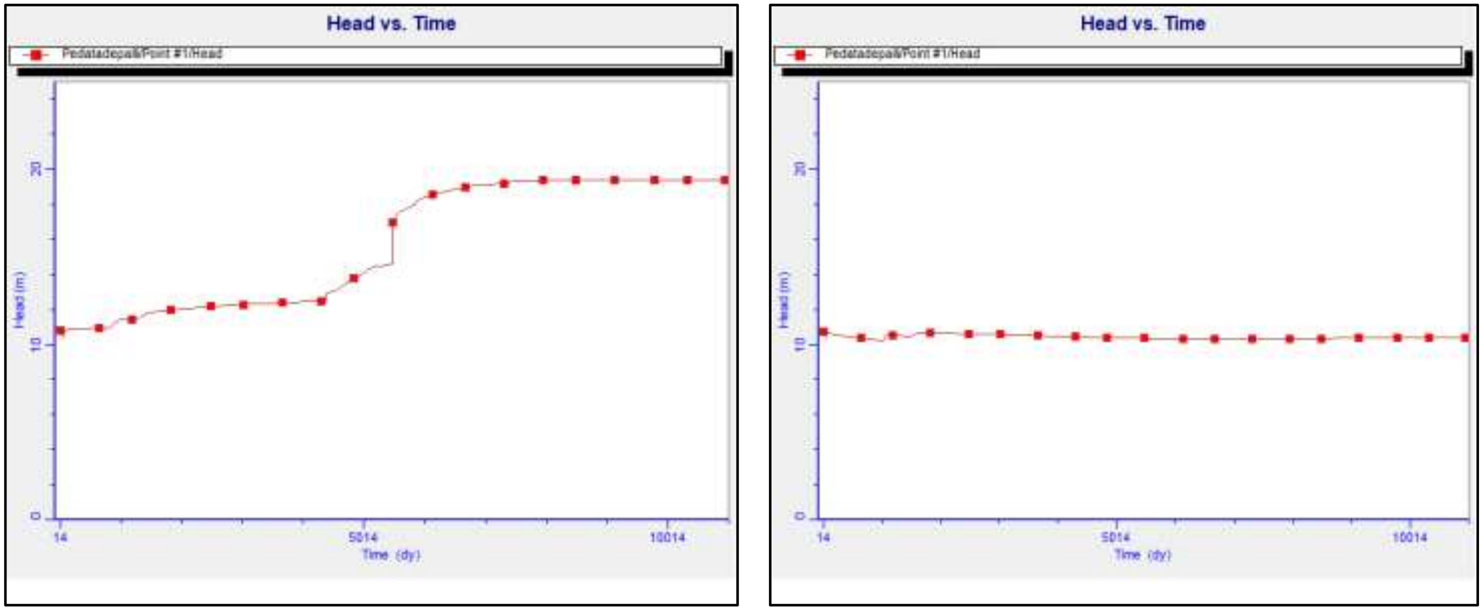


Fig. 4.31. Predicted heads for Pedatadepalli with and without Pattiseema lift irrigation project

Spatial and temporal variation of groundwater was studied in this study. Groundwater scenario in the West Godavari District was studied and identified and different potential groundwater zones were identified. Major portion of the West Godavari District was covered by Sandstone. Using Visual MODFLOW, a digital model was developed similar to West Godavari District to predict the groundwater levels and to study the effect of 'Pattiseema lift irrigation project'. The replica of West Godavari District was achieved using well log at different locations, aquifer properties and groundwater levels at different locations. Using the developed model, groundwater heads were predicted up to 2032 with 5 per cent increase in pumping rate. Impact of river interlinkage project was studied using Visual MODFLOW and observed that the rise in groundwater levels. From this study, West Godavari district remains safe due to river interlinkage project and it was also found that Visual MODFLOW can be used efficiently for evaluation and prediction of groundwater resources.

CHAPTER 5
SUMMARY AND CONCLUSIONS

The farmers in the Indian state of Andhra Pradesh are affected by recurrent drought and are fighting back by drilling wells deeper and deeper in search of water to support cultivation of high-value crops, which promises greater returns. Agriculture, which drives the region's economy, has become increasingly water intensive and expensive in increasing manner. So the Government of Andhra Pradesh is taking necessary steps to enable the rural communities to understand the groundwater system and to make appropriate decisions. To make decisions related to management and efficient use of the available water resources we need to have a better knowledge of the quantity of the water resources available. In this context, modeling of the groundwater resource can give the sufficient data required for the management of the available water in future. In the present work, the West Godavari district of Andhra Pradesh is selected as the study area, which includes the Pattiseema lift irrigation project also.

Initially the spatial and temporal variation of groundwater levels of the study area was analysed using the monthly water table data of four number of wells in the area for the period from January 2003 to January 2018. The groundwater table for the pre monsoon and post monsoon seasons, and also the water table fluctuation between the seasons were calculated and plotted spatially using Arc GIS. The pre monsoon and post monsoon groundwater table maps for the study period at an interval of two years were prepared with depth to groundwater table. Using groundwater data, spatial and temporal fluctuation of groundwater was studied and it was found that groundwater availability depends mainly on topography, rainfall, hydraulic gradient and aquifer properties. Observing monthly groundwater levels, it was found that groundwater rise was maximum in September and November months whereas minimum groundwater level was recorded in the month of May.

Groundwater scenario in the West Godavari district was studied and identified different potential groundwater zones were identified. Sandstone, clay, sandy soils, Granite Gneissis and clayey sandstone are the different soils formed as different layers in the study area. Major portion of the West Godavari district was covered by sandstone followed by clay. Granite gneissis and clayey sandstone are found in the lower layers.

Visual MODFLOW software version 2.8.1 developed by Waterloo Hydrogeologic. It was used for the flow modelling of the study area. To study the groundwater behavior in West Godavari district, a model was developed using Visual MODFLOW. Ground Water and Water Audit Department, Andhra Pradesh is monitoring groundwater behavior using head observation wells and piezometers. Government of Andhra Pradesh installed 59 head observation wells in the study area. Data collected from Groundwater Department was used to model the real groundwater conditions. Lithology, groundwater levels at different locations, aquifer properties and soil properties were used to replicate the real conditions in the model. First a conceptual model was developed using DEM and well logs of the study area. Hydrogeological parameters such as hydraulic conductivity, porosity, specific storage and specific yield and boundary conditions of the domain such as constant head, rivers, drains and recharge were used as input. West Godavari district is bounded by Bay of Bengal in one East and Godavari River in the North. Upputeru River is passing towards the Bay of Bengal. A drain is draining towards Bay of Bengal. All these boundary conditions were assigned in the model to create real boundary conditions in the model.

After giving the input parameters, the developed model was calibrated in steady state condition first assuming the aquifer condition of year 2003 as initial condition for steady state model calibration. 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 using data from 2003 to 2012. The storage coefficient was varied iteratively till a reasonably good match was obtained between the observed and computed groundwater levels. The model output showed that the computed water levels compared well with the observed values. The calibrated model was validated using data from 2013 to 2017. After validation, model was used to predict groundwater levels for the next fifteen years, i.e. up to 2032.

Developed model was also used to study the effect of Pattiseema lift irrigation project which was constructed in 2015 to divert the water from Godavari river to Krishna river. Around 100 TMC of water is being diverted using 24 motors through a canal passing through the West Godavari district**.** The developed model was used to study the groundwater recharge due to the project and also to predict the groundwater heads for the next fifteen years with increase of 5 per cent pumping rate for every five years and decrease in recharge 5 per cent.

Considering the lift irrigation project, recharge in the study area was assigned by considering both rainfall and recharge from the lift irrigation canal. So more recharge was assigned in the lift irrigation canal area from 2015 onwards. For this area separate recharge layer was assigned in the model. From this study, we observed that considering the lift irrigation project, there was an additional increase in the net recharge from 50 mm/yr to 100 mm/yr. There is also a 3 m rise in groundwater level nearer to the canal route as observed in Fig. 4.22 and 4.26.

From these results, West Godavari district remains safe due to river interlinkage project. From the study, it was found that Visual MODFLOW can be used for evaluation and prediction of groundwater resources. A better understanding of the behavior of the groundwater resources of the area can help in making efficient managerial decisions in future. This detailed study carried out can be set as an example for the similar studies also. The study has revealed the groundwater situation in the area with details of the system conditions with a greater certainty and is useful for further development and judicious planning to avoid the groundwater crisis.

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APPENDIX

Table. 1. Ground water heads at selected locations

Year	Akiveedu	Mogalturu	Narsapuram
Jan-03	4.32	8.64	9.18
Mar-03	4.10	8.29	8.89
May-03	3.23	8.15	8.46
Jul-03	3.63	8.23	8.74
Sep-03	5.19	8.79	10.03
Nov-03	4.99	9.25	9.66
Jan-04	5.02	9.13	9.75
Mar-04	4.80	8.78	9.46
May-04	4.28	8.71	9.30
Jul-04	4.68	8.79	9.58
Sep-04	4.82	9.27	9.90
Nov-04	4.12	9.03	9.86
Jan-05	4.03	8.94	9.83
Mar-05	3.81	8.59	9.54
May-05	4.80	8.31	9.07
Jul-05	5.20	8.39	9.35
Sep-05	5.20	8.91	9.89
Nov-05	5.34	10.03	10.09
Jan-06	4.58	9.55	9.55
Mar-06	4.36	9.20	9.26
May-06	4.47	9.05	9.59
Jul-06	4.46	8.99	9.70
Sep-06	4.72	8.86	9.83
Nov-06	5.44	10.39	10.01

Jan-07	4.92	9.55	9.85
Mar-07	4.74	9.17	9.71
May-07	4.18	8.84	9.52
Jul-07	4.82	8.83	10.02
Sep-07	5.93	10.20	10.19
Nov-07	5.15	9.93	10.20
Jan-08	4.90	8.90	10.06
Mar-08	5.12	9.25	10.35
May-08	4.12	8.82	9.72
Jul-08	4.52	8.90	10.00
Sep-08	6.11	9.96	10.16
Nov-08	4.81	9.51	9.94
Jan-09	5.12	10.03	10.20
Mar-09	3.83	9.86	9.73
May-09	3.77	9.09	9.40
Jul-09	3.23	8.92	8.95
Sep-09	4.31	9.15	9.86
Nov-09	4.31	9.15	9.86
Jan-10	4.73	8.76	9.69
Mar-10	4.17	8.47	9.41
May-10	4.62	8.99	9.75
Jul-10	5.42	9.55	10.30
Sep-10	5.42	9.55	10.30
Nov-10	5.37	10.89	10.27
Jan-11	5.02	10.55	9.98
Mar-11	4.72	9.91	9.17
May-11	4.57	9.63	9.59

Jul-11	5.50	10.25	10.28
Sep-11	5.45	10.38	10.13
Nov-11	5.01	9.41	10.11
Jan-12	4.67	9.12	9.75
Mar-12	4.51	8.78	9.38
May-12	4.15	8.41	9.16
Jul-12	5.31	9.03	10.13
Sep-12	5.28	10.24	10.31
Nov-12	5.62	10.64	10.10
Jan-13	5.27	9.76	10.33
Mar-13	4.97	9.22	10.05
May-13	4.48	8.87	9.88
Jul-13	5.44	9.19	10.03
Sep-13	5.39	9.32	9.88
Nov-13	5.67	10.33	10.37
Jan-14	4.15	9.57	10.18
Mar-14	4.94	9.22	10.10
May-14	4.84	8.8	10.06
Jul-14	4.87	8.93	10.35
Sep-14	5.5	9.26	10.30
Nov-14	5.38	9.26	9.35
Jan-15	5.07	8.94	10.00
Mar-15	4.84	8.82	10.04
May-15	4.57	8.65	10.02
Jul-15	5.19	9.37	10.21
Sep-15	5.92	10.67	10.25
Nov-15	5.93	10.36	10.05

Jan-16	4.46	9.49	10.09
Mar-16	4.47	9.05	10.00
May-16	5.1	9	9.78
Jul-16	5.35	9.46	10.22
Sep-16	5.74	9.31	10.19
Nov-16	4.96	9.43	9.97
Jan-17	4.5	8.82	10.00
Mar-17	4.44	8.69	9.84
May-17	4.44	8.4	9.68
Jul-17	5.48	8.55	10.11
Sep-17	5.56	8.96	10.18
Nov-17	5.42	9.18	8.85
Jan-18	4.72	9.34	8.78

ABSTRACT

Water is the basic need for all living organisms and is essential for sustainable development. World is facing a growing demand for high quality water resources while the water availability remains constant. Quantifying the water resources is necessary for efficient use of water resources.

Groundwater modelling is a tool used to study the groundwater behavior and quantify the groundwater resource. In this study, Visual MODFLOW was used to study the groundwater behavior and predict groundwater heads at different scenarios in West Godavari district. Andhra Pradesh is known as 'Rice bowl of India'. East Godavari and West Godavari districts contribute to the maximum production of paddy in Andhra Pradesh. Around 3000TMC of Godavari river is draining into bay of Bengal, whereas flow in Krishna River is in a critical condition. So, Government of Andhra Pradesh planned to divert surplus water in Godavari river to Krishna river using 'Pattiseema lift irrigation project'. Pattiseema lift irrigation project will pumping around 100 -125 TMC using 24 motors to Godavari river.

The main objective of the study is to analyse the spatial and temporal variation of groundwater, identifying the potential groundwater zones to collect the lithology and developing the groundwater flow model for the study area were the different objectives of the study. Spatial and temporal variation of the groundwater heads was studied using a plot between groundwater heads at different locations with respect to time and observed that groundwater vary with respect to topography, climate and soil properties. Potential groundwater zones were identified by developing map using groundwater heads. Different locations were selected and well log was collected from Groundwater and Water audit Department, Government of Andhra Pradesh. From lithology data, it is observed that major portion of the West Godavari district was occupied by sandstone followed by clay, sand, clayey sandstone, granite gneissis and shales. Model is developed using data from 53 head observation wells from 2003 to 2017.

A model was developed by assigning all boundaries, aquifer properties and head observation levels. Calibration and validation of the model was done. The model has been used for prediction with different scenarios and also used to study the groundwater behavior at different scenarios. Model was also used to study the effect of 'Pattiseema lift irrigation project' on groundwater recharge.

After assigning all inputs, the model was calibrated with 2003 to 2005 year data in steady state condition with and 2006 to 2011 data was added for transient state condition. Calibrated model was validated using groundwater heads up to 2017. In validation a new recharge layer is added considering the effect of lift irrigation canal. Validated model was used for prediction. In prediction the effect of decreasing recharge by 5 per cent in every five year for the next fifteen years was studied. The effect of increasing the pumping rate by 5 per cent in every five year for the next fifteen years was also studied. The effect of 'Pattiseema lift irrigation project was also studied and we observed that considering 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

From this study, it was observed that West Godavari district is safe with increase in pumping rate and decrease in recharge up to 2032. This is due to the recharge from rivers and lift irrigation canal. Considering the predicted heads and surface water availability, proper cropping pattern can be adopted to increase productivity. Conjunctive use of surface and groundwater can also be adopted in the study area to solve the water shortage problem. A better understanding of the behavior of the groundwater resources of the area can help in making efficient managerial decisions in future.