A FRAMEWORK FOR GROUND WATER QUALITY MODELLING IN THE COASTAL AQUIFER OF NETRAVATHI AND GURPUR RIVER CONFLUENCE

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

Konstantin Sylus J

DEPARTMENT OF WATER RESOURCES AND OCEAN ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,
SURATHKAL, MANGALORE – 575 025
SEPTEMBER 2020

A FRAMEWORK FOR GROUND WATER QUALITY MODELLING IN THE COASTAL AQUIFER OF NETRAVATHI AND GURPUR RIVER CONFLUENCE

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

Konstantin Sylus J

Under the guidance of

Dr. H. Ramesh

Associate Professor
Dept. of Water Resources & Ocean Engineering
NITK, Surathkal

DEPARTMENT OF WATER RESOURCES AND OCEAN ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE – 575 025

SEPTEMBER 2020

DECLARATION

By the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled ‘***A Framework For Ground Water Quality Modelling In The Coastal Aquifer Of Netravathi and Gurpur River Confluence’,*** Which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Water Resources and Ocean Engineering Department** is a *bonafide report of the research work* carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

121155AM12F04, KONSTANTIN SYLUS J

(Register Number, Name & Signature of the Research Scholar)

Department of Water Resources and Ocean Engineering

Place: NITK-Surathkal

Date:

CERTIFICATE

This is to *certify* that the Research Thesis entitled '**A Framework For Ground Water Quality Modelling In The Coastal Aquifer of Netravathi and Gurpur River Confluence',** submitted by KONSTANTIN SYLUS J (Register Number: 121155AM12F04) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

Dr. H RAMESH
Associate Professor
Research Guide
(Name and Signature with Date and Seal)

Chairman - DRPC
(Signature with Date and Seal)

ACKNOWLEDGEMENTS

With deep sense of gratitude, I express my heartfelt thanks to the eminent Professor from the Department of Water Resources and Ocean Engineering, NITK, Surathkal, Dr. H Ramesh for doing a marvelous job at supervising my research work. His logical and tactical suggestions have been very valuable and encouraging during the development of this research.

I am grateful to Research Progress Committee members, Prof. Nagaraj M K and Dr. Udhaya kumar D, for their critical evaluation and useful suggestions during the progress of the work.

I am greatly indebted to Prof. Subba Rao, Prof. Amai Mahesha and Prof. Dwarakish G S, the former Head of the Department of Water Resources and Ocean Engineering, NITK, Surathkal, and Prof. Amba Shetty., the present Head of the Department, for financial assistance and granting me the permission to use the departmental computing facilities available for necessary research work to the maximum extent, which was very vital for the completion of the computational aspects relevant to this research.

I thank the Director of the NITK, Surathkal, Prof. Karanam Uma Maheshwar Rao, for granting me the permission to use the institutional infrastructure facilities, without which this research work would have been impossible.

I sincerely acknowledge the help and support rendered by all the Faculties, staffs and Research scholars of Department of Water Resources and Ocean Engineering and other departments. I express heartfelt gratitude to authors of all those research publications which have been referred in this thesis.

Finally, I wish to express gratitude, love and affection to my beloved family members for their encouragement and moral support on the road to the completion of my research.

Konstantin Sylus J

ABSTRACT

Coastal river confluence is vulnerable to the degradation of groundwater quality around the World. Since the primary source of groundwater is precipitation, the chance of contamination of groundwater is very less compared to surface water bodies like rivers, streams and lakes. Even though the soil has filtering capacity, it overloaded by the excess amount of pollutants, which automatically leads to groundwater pollution. The present study investigates the status of groundwater quantity and quality in the coastal river confluence of Netravathi and Gurpur, which lies near Dakshina Kannada district of Karnataka state on the West coast of India. The study area is bounded by Arabian sea in the West and river Gurpur in the North and river Nethravathi in South with an areal extent of 140 km^2. The proximity to the sea, growing population and high demand for groundwater and climate changes make the area vulnerable to the decreasing and degradation of groundwater quantity and groundwater quality. In this regard, the groundwater samples are collected, tested and statistically analysed for groundwater quality. The groundwater head and groundwater quality in the study area is modelled using numerical groundwater flow and transport model and the contamination distance from the coast is assessed.

In this study, the field investigation was carried out to identify the aquifer characteristics of the study area. The formation is a shallow unconfined aquifer which consists of lateritic soil. The well samples are collected from different locations of the confluence of Netravathi and Gurpur river with well depth varying from 3 m to 20 m below the ground level. The aquifer parameters in the study area are identified from the pumping test. The pumping test results are analysed for aquifer parameters such as transmissivity, specific storage and hydraulic conductivity. The pumping test results show that transmissivity values are ranging from 241.56 m^2/day to 950.4 m^2/day and specific storage ranging from 0.000107 to 0.000197 respectively. The transmissivity and the hydraulic conductivity calculated from pumping test are used for the groundwater flow and transport modelling.

The field investigation is carried out to collect the groundwater samples and groundwater level data from January 2013 to December 2014 and April 2016 to May 2017 on a monthly basis. The groundwater samples are tested in the laboratory to find the status of the groundwater quality over the study region. With the help of ArcMap 10.2, groundwater quality maps are generated to represent the spatial and temporal variation of quality parameters. The

groundwater level data is used as an input data for groundwater flow model and groundwater quality data used as an input data for groundwater transport model. Statistical analysis of Sodium absorption ratio (SAR), piper plot, Two-tail significant test, factor of sea correlation, groundwater quality status, prediction of significant chemical parameters and geostatistical methods of groundwater quality mapping for the month of April and May 2016 are carried out to know the status of the groundwater quality. The SAR result shows that the groundwater quality has no contamination of SAR parameters and the quality status is well within the permissible limit for the month of April and May 2016.

The piper plot also shows good groundwater quality in the month of April and May 2016 even though a slight increase in the concentration of groundwater quality parameters is observed which infers a chance of contamination in the future. In the 2-tailed significant test, the groundwater quality parameters EC, TDS, Cl and Ca are strongly correlated for the month of April and May 2016. For the month of April and May 2016, the groundwater quality maps for the Thumbe and Maripal wells shows excellent groundwater quality. From the maps, it can be observed that Panganimuguru and Kunjatbail wells are of poor groundwater quality.

In the statistical analysis, the present scenario of groundwater quality status is within the permissible limit of the drinking water standards. Even though the quality is under the permissible limit, the trend of groundwater quality shows an increase in the concentration of the groundwater quality parameters beyond the permissible limits, imposing a threat of future contamination. Thus, the groundwater flow and transport model are developed and run for groundwater quantity and quality using FEMWATER, which in the three-dimensional Finite elements (FEM) coupled in Groundwater Modelling System (GMS 10.0). The groundwater flow model and groundwater transport model are run for both steady state condition and transient state condition for a time period of September 2013 to May 2017.

In steady state condition, the R^2 value of the groundwater head is found to be 0.98 for calibration and 0.9 for validation respectively. In the transient state condition, the model is simulated for calibration with a time period of 486 days (September 2013 to December 2014) with a constant time interval of 30 days. In the validation, the model is simulated with a time period of 425 days (April 2016 to May 2017) with a constant time interval of 30 days. In transient state condition, the R^2 value of the simulated groundwater head and observed found to be 0.86 for calibration and 0.86 for validation. The groundwater flow model has better performance since the R^2 value is found to be above 0.85.

In the groundwater transport model, the model is run for both steady state condition and transient state condition for different groundwater quality parameters such as Cl, TDS and Bicarbonate. In the steady state condition, the R^2 value obtained for the groundwater quality parameters namely Cl, TDS and Bicarbonate are 0.94, 0.9 and 0.88 respectively. In the transient state condition, the model is calibrated for a time period of 486 days with a constant time interval of 30 days. The R^2 value of the transient state calibration of the groundwater quality parameters Cl, TDS and Bicarbonate are 0.92, 0.85 and 0.87 respectively. The model validation for transient state condition is validated for a time period of 425 days with a constant time interval of 30 days. The R^2 value of the transient state validation of the groundwater quality parameters Cl, TDS and Bicarbonate are 0.88, 0.95 and 0.93 respectively. The results infer that the model performs better for groundwater transport model.

The transient validated groundwater transport model is then considered for prediction. The prediction scenarios are classified based on the recharge and injection wells inflow rate. The recharge is further classified into three scenarios. (i.e.,) Minimum recharge, average recharge and maximum recharge calculated based on the historical rainfall data. The recharge scenarios give reduced groundwater quality and high concentration distance from the coast compared to the injection wells. The injection wells inflow rate considered for the scenario is 20 m^3/hr and 40 m^3/hr. The injection wells inflow rate of 40 m^3/hr gives an improved groundwater quality in the coastal wells and also reduction of the concentration distance of the groundwater quality in the coastal river confluence from the coast.

In this study, it is found that the current status of groundwater quality is portable. Even though the quality is good, the groundwater quality parameters concentrations are seeming to be increasing, which indicates the vulnerability of quality degradation in the future. In this situation, the groundwater modelling helps us to understand the status of groundwater head and groundwater quality of the study area. Based on the groundwater modelling study, it is found that the injection wells with an inflow rate of 40 m^3/hr can improve the groundwater quality of the coastal wells and it also reduces the concentration distance of the groundwater quality in the coastal river confluence.

Key words: *Aquifer characterization, Pumping test, Coastal aquifer, Groundwater quality assessment, FEMWATER, Groundwater flow modelling, Groundwater transport modelling, Predictive scenarios.*

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Groundwater contamination is one of the major problems in the Twenty-first century due to increased population, irrigation and industrial activities, Further impact by the increased lifestyle of the people across the shore. The quality of drinking water has deteriorated and hence, it is necessary to explore the current status of the quality of groundwater in the aquifers.

According to the UNESCO (2009) report, nearly 60% of the world population lives in coastal regions due to many benefits such as health, transportation, navigation, trade and recreation etc. However, these regions face many hydrological problems like flood due to cyclones, wave surge and drinking water scarcity due to seawater intrusion. Therefore, the coastal aquifers are under pressure both in terms of quantity and quality of water. The development and management of coastal groundwater aquifers is a very delicate issue. Groundwater quality deterioration has become one of the significant constraints affecting groundwater management. As groundwater quality deteriorates, existing pumping wells particularly close to the coast become saline and have to be abandoned, which reduces the importance of the aquifer as a source of freshwater.

Change in groundwater levels with respect to mean sea level along the coast largely influences the extent of seawater intrusion in the freshwater aquifers. The smaller the change in the groundwater levels, the lesser is the groundwater quality contamination in the aquifers (Polemio et al. 2009). In other words, the magnitude of change in sea level would have an identical effect on seawater intrusion if the groundwater levels were held constant. In the past, sea levels have changed many times with the changes in natural climatic conditions. However, at present, the climate is primarily influenced by human interference in the form of air and water pollution. Hence, the groundwater level tends to deplete below mean sea level along the coast causing seawater intrusion and contaminates the freshwater aquifers.

The groundwater extraction changes the dynamic balance between the flow of freshwater and the seawater interface. The seawater interface will move and attain an equilibrium position governed by the quantity extracted and the outflow of freshwater to the sea in the coastal aquifer. When the groundwater withdrawals are more than the recharge close to the seawater interface, then the seawater intrusion will occur around the wells and turn the water saline on the other hand if the extraction of groundwater is more than the recharge, seawater intrusion occurs by upconing seawater at the pumping wells. The schematic diagram of seawater intrusion is shown in fig.1.1.

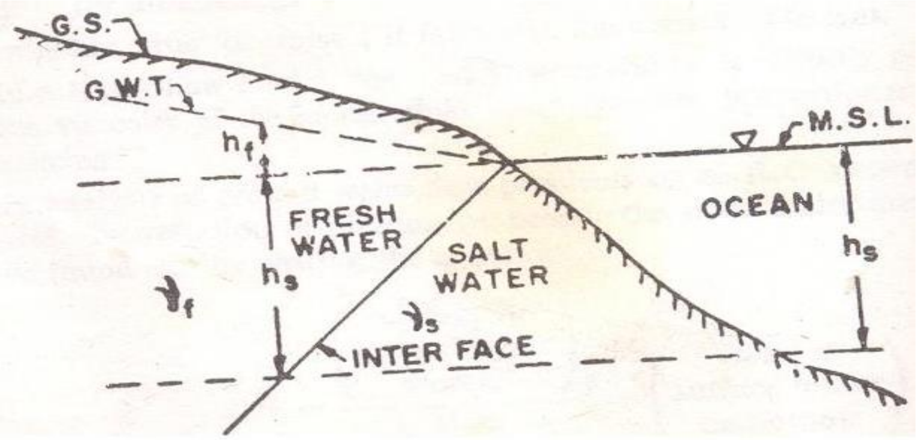


Fig.1.1 Freshwater and seawater interface (Raghunath 2007)

Figure 1.1 shows the Ghyben-Herzberg relation for seawater intrusion (Raghunath 2007). The Ghyben-Herzberg relation for seawater intrusion is given in Eqn 1.1.

$$H = \frac{\rho_f}{(\rho_s - \rho_f)} h \tag{1.1}$$

Where the thickness of freshwater zone above sea level is represented as h and that below sea level is represented as H. The two thicknesses h and H, are related with the density of freshwater (ρ_f) and the density of saltwater (ρ_s). Freshwater has a density of about 1.000 grams per cubic centimetre (g/cm^3) at 20°C, whereas that of seawater is about 1.025 g/cm^3. Therefore Eqn (1.1) can be simplified as,

$$H = 40h \tag{1.2}$$

The flow of seawater inland is limited to coastal areas. Further inland, the freshwater column is higher due to the increasing altitude of the land and also equalise the pressure from the seawater, preventing seawater intrusion. The higher water levels in inland also cause the freshwater to flow seaward. Therefore, at the sea-land boundary, freshwater flows out from the highest point of the aquifer, and at the lowest point, seawater flows in. The seawater intrusion then forms a wedge in the freshwater-seawater interface. Pumping of freshwater from an aquifer reduces the water pressure and intensifies the effect of drawing seawater into new areas. However, when the freshwater level drop causes seawater intrusion inland, towards the pump wells. As a result, seawater makes the freshwater unfit for drinking or irrigation, produced by the well. To prevent this, more and more countries adopt extensive monitoring schemes and numerical models to assess the extent of water can be pumped without causing such effects spatially and temporally.

Water quality modelling is essential to know the temporal and spatial changes and also to take the necessary preventive measures to reduce the seawater intrusion. A review paper by Werner et al. (2012), reported that numerical modelling could be carried out using FEMWATER (Finite Element Model for Groundwater). The FEMWATER developed by the U.S. Environmental Protection Agency and the U.S. Army Engineer Waterways Experiment Station in the 1990's. The FEMWATER consists of a flow and transport model in which the saturated flow and unsaturated flow modelled in the aquifer. The flow data used as the input data for the transport model. Based on the result of the transport model, the contamination will be found out, which helps to decide the type of recharge structures and amount of recharge to keep groundwater quality within the permissible limit.

1.2 GROUNDWATER ISSUES

Groundwater plays a vital role in the economic status of most of the countries in the world. More than 60% of the world population lives in a coastal region and 20% of the world drinking water supply depends upon the groundwater (Tomaszkiewicz et al. 2014). The source of the groundwater is surface water which infiltrates mainly through the soil, subsurface rocks and cracks. It has very less chance of contamination compared to rivers, streams, and lakes, where the pollutant has to pass through the ground. The groundwater which is far down is less prone to the vulnerability. Even though the soil has filtering capacity, it overloaded by the excess amount of pollutants, which automatically leads to groundwater pollution. Septic tanks near groundwater wells, industrial and sewage, petroleum tank, excess pesticide and fertilizers from agricultural fields also contaminate groundwater (Michigan Water Stewardship Program).

Groundwater is being used in agriculture, industries and domestic water supplies (Kumar et al. 2008). The major health problem in groundwater is contamination, which leads to waterborne disease and skin diseases after consumption. The urbanization also plays a significant role in which the mixing of untreated sewage contaminates groundwater and make it unsafe for consumption. The excess pumping of groundwater for agriculture and industrial purpose reduces the groundwater level and leads to a shortage of freshwater. When the excess pumping

is carried out in the coastal region, this automatically leads to seawater intrusion contaminating freshwater and making it unfit to the drinking and domestic use.
Some of the land use activities affecting groundwater quality are residential, industrial, mining, rural and coastal areas. The residential land use activities contaminate groundwater through untreated sewer sanitation, stream discharge of sewage in groundwater, sewage oxidation ponds, sewer leakage, solid waste disposal, road and urban runoff (Wastewater management, UN-Water Analytical Brief).

The source of industrial pollution to the groundwater, system include process water from the textile industry, tank, pipeline leakage and accidental spills, well disposal of effluent, landfill disposal, solid wastes, hazardous wastes, poor housekeeping, spillage and leaking during handling of materials.

The mining activities also lead to groundwater pollution through mine drainage discharge, process water, sludge lagoons, solid mine tailing and open cast mining etc. The rural activities such as cultivation with agrochemicals, irrigation with wastewater and livestock rearing acts as the source of the contamination.

The coastal areas have an excellent source of fresh groundwater. However, due to the increase in population, excess groundwater is pumped in this area, which automatically causes seawater intrusion, making it vulnerable for drinking and domestic use.

The groundwater quality is tested according to Indian and World Health Organization (WHO) standards for drinking water parameters. Table 1.1 shows the permissible values of some of the drinking water quality parameters along with standard instruments recommended by Indian and WHO standards. If the parameter exceeds the permissible limit, it shows the vulnerability of contamination.

Table 1.1 The standards of BIS 10500 (2012), APHA (1999) and WHO (2008)

Parameter	Notation	Instrument	Permissible limit	Health hazard
Potential Hydrogen	pH	pH meter	6.5-8.5	Nil
Electrical Conductivity	EC	Conductivity meter	700 - 2000	Nil

Total Dissolved Solids	TDS	Conductivity meter	500-2000	Nil
Bicarbonate	HCO_3	Burette	200-600	Gastrointestinal problems
Chloride	Cl	Burette	250-1000	Gastrointestinal problems
Calcium	Ca	Burette	75-200	Gastrointestinal problems
Magnesium	Mg	Burette	30-100	Gastrointestinal problems
Sodium	Na	Flame photometer	10-100	Gastrointestinal problems
Potassium	K	Flame photometer	10-100	Gastrointestinal problems
Sulphate	SO_4	Spectrophotometer	200-400	Gastrointestinal problems

The laboratory testing of groundwater quality carried out as per the above standards are shown in Table 1.1. The results of the laboratory test give information on where the quality is within the permissible limit or excess. If the quality of water is excess the permissible limits, the different management strategies to improve through artificial recharge structures such as rainwater harvesting, injection wells and subsurface barriers can be thought of. The remedial measures are considered only after the laboratory testing of groundwater. In India, groundwater quality is being monitored by the Central Groundwater Board (CGWB) and Central Pollution Control Board (CPCB). Based on their monitoring and recommendations, the artificial recharge structures are considered in the coastal aquifers (CGWB, 2012).

1.3 PROBLEM IDENTIFICATION

Dakshina Kannada district is one of the coastal regions of Karnataka state which spreads widely along the west coast of India. The chief occupation of the people is agriculture and fishing. However, due to the developmental activities and urbanization in recent years, mainly in the fields of industry, commerce and trade, the demand for freshwater has enormously increased.

At present, the domestic and industrial water requirements are met primarily by the Netravathi river water, which is being supplied by the Mangalore City Corporation and from groundwater resources (Vyshali et al. 2008). However, soon an alternate source of water supply needs to be identified to meet the increasing demand for freshwater. During summer (March–May) as the baseflow in Netravathi river recedes making water resources scarce. Apart from this, many major industries like MRPL and other small-scale industries close their operation due to the scarcity of water in summer months. In many houses in Mangalore which depends upon water supply from municipality gets weekly supply due to the drop of water level in Netravathi river during summer. This automatically leads the people to depend on tank water which are more expensive. At the same time, the groundwater levels are also depleting due to excessive groundwater pumping in the study area, which leads to seawater intrusion. Thus, the water scarcity problem is rising year after year.

1.4 PROBLEM FORMULATION

Based on problem identification, the problem is formulated to assess the current status of groundwater quality by field and laboratory methods. The results of the laboratory test act as the input data for numerical modelling. The modelling of the groundwater system is carried out to understand the aquifer conditions for flow and transport. After development and calibration of the model, various prediction scenarios were carried out to assess the seawater interface and to bring the water quality within the permissible limits. The historical precipitation and recharge scenarios are considered for the modelling of the groundwater system. The effects of the injection wells for reducing contamination is simulated.

1.5 OBJECTIVES

The present study assesses groundwater quality through sample collection and laboratory testing. The three-dimensional Finite Element Model for Groundwater (FEMWATER) code of Groundwater Modeling System (GMS) model is used to study the spatial and temporal flow and transport of groundwater in the study area. Based on the above knowledge, the following objectives are framed:

1. To assess the status of groundwater quality parameters and mapping spatial and temporal distribution of groundwater quality over Netravathi and Gurpur river confluence.
2. To assess the vulnerable area for groundwater quality parameters and to investigate

seawater intrusion through geochemical analysis of groundwater.

3. To simulate the groundwater flow and contaminants in the urban coastal aquifer of Nethravathi and Gurpur river confluence through a numerical model.
4. Development of contaminant remedial scenarios based on historical rainfall recharge and injection wells.

1.6 SCOPE OF PRESENT WORK

In the study area, most of domestic water supply is supplied through Nethravathi and Gurpur river basin. The average rainfall in the study area is found to be 3000 mm to 4000 mm. Even though a high rainfall is received in monsoon seasons, water scarcity is found to be a major problem during the period of the summer season (March to May). This is mainly due to the excess pumping and increased use of groundwater for different purposes. Many industries such as Mangalore Chemical and Fertilizers (MCF) and Mangalore Refinery and Petrochemicals Limited (MRPL), NMPT etc. also depend upon the Nethravathi and Gurpur river.

In this context, the scope of this research study is to understand the current situation of water quality in the study area. The remedial measures with the help of modelling can be carried out in quality degraded areas. Most of the coastal aquifers are in contact with seawater, which drawn into the freshwater aquifer system can diminish the water portability as well as its usefulness for other purposes. Both vertical intrusion and lateral intrusions occur due to over-pumping in the sensitive portion of the aquifer. For this reason, the understanding of quantity and quality patterns of movement and mixing between the fresh and seawater is necessary. Due to inadequate storage facilities, a vast quantity of rainfall flows towards the sea as runoff. At the same time, increasing population, agricultural, industrial and domestic requirements exploit the groundwater more than the recharge rates. Because of the high porous medium and exploitation of groundwater, coastal regions might be affected by the seawater intrusion. In this study, the relationship between the rainfall quantity available for recharge and length of the interface studied using sampling and modelling technique. The effect of injection wells in improving the groundwater quality or length of seawater interface is well numerically simulated.

1.7 ORGANIZATION OF THE THESIS

The entire study is organised in nine chapters. Each chapter deals with a specific study or investigations that are undertaken. A brief scope of each chapter is highlighted below.

Chapter 1 presents the introduction of the study, groundwater issues, problem identification, problem formulation, objectives and scope of the present work. In this chapter, the main focus is to identify different problems based on groundwater issues in the study area. In a further study, it gives the details of the objectives and scope of the present work.

Chapter 2 provides the literature review on hydrogeochemical analysis, numerical modelling, remedial measures, summary and research gap of literature. The hydrogeochemical analysis mainly deals with the analysis and review of different groundwater quality parameters such as the potential of hydrogen (pH), Electrical conductivity (EC), Total dissolved solids (TDS) and Chloride (Cl) etc. and their permissible limits. This chapter also reviews various numerical model used for groundwater modelling. Based on this review, the summary and the research gap of the literature are formed.

Chapter 3 presents the physiographic description of the study area and the climate, geology, soil, geomorphology, population index and Land use land cover (LU/LC).

Chapter 4 provides the aquifer characterization based on the hydrogeology, pumping test and aquifer parameters.

Chapter 5 presents the water quality assessment and statistical analysis of water quality based on sampling data and laboratory experiments. In this chapter, the results of the statistical methods are analysed through Piper plot and groundwater quality status is assessed.

Chapter 6 presents the development of a groundwater flow model based on the governing equation of groundwater flow, steady state condition and transient state condition. This chapter also presents the groundwater flow results.

Chapter 7 presents the development of groundwater transport model based on the governing equation of groundwater transport for steady state condition and transient state condition and the results are reported.

Chapter 8 provides the prediction scenarios based on recharge, injection wells and the results are presented.

Chapter 9 presents the overall conclusion of the study and provides a summary of the research work.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Groundwater contamination is the most serious threats to groundwater resources in the coastal aquifer, which constitute an essential supply for human needs. There are many studies of groundwater flow models to understand and predict the behaviour of groundwater contamination. The groundwater flow model is a mathematical model concerned with the movement of flow, whereas the solute transport model is necessary for solving most of the groundwater quality problems. This chapter presents the state of the art of literature review on studies conducted across the world to address groundwater issues and problems. The entire literature survey, which is necessary for this study, is categorized into three groups viz., hydrogeochemical analysis, numerical modelling and remedial measures. Each of these groups is presented in the subsequent sub-heading.

2.2 HYDROGEOCHEMICAL ANALYSIS

The hydrogeochemical analysis is a laboratory-based testing method for chemical parameters in the water samples. According to Revelle (1941), electrical conductivity less than 250 µS/cm is considered as excellent, 250 to 750 µS/cm as good, 750 to 2250 µS/cm as poor quality. Many researchers have done the hydrogeochemical analysis for the identification of groundwater quality in the coastal aquifer of different regions of the world. (Bhat and Subrahmanya (2000), Victor et al. (2000), Canales et al. (2001), leboeuf (2004), American Public Health Association (APHA 2005), Mohan et al. (2005), Zhou (2006), Avvannavar (2007), Jeevanandam et al. (2007), Raju (2007), Rajagopal et al. (2008), Sotirios et al. (2008), Mondal et al. (2010), Sharma (2010), Andrade et al. (2011), Ahmed (2011), Mishra et al. (2011), Rao et al. (2012), Suribabu et al. (2012), Sindhu et al. (2012), Lin et al. (2012) Werner et al. (2012), Khashogi and Magdy (2013), Sun and Gui (2014), Balakrishnan et al. (2015), Nosrati (2015), Boateng et al. (2016), Tay et al. (2017) and Kanagaraj et al. (2018)). The chemical parameters such as potential of hydrogen (pH), Electrical conductivity (EC), Total Dissolved Solids (TDS), Sodium (Na), Potassium (K), Calcium (Ca), Magnesium (Mg), Lithium (Li), Boron (B), Lead (Pb) and Chloride (Cl) will help to find out the quality of water. The permissible limit of various parameters considered for the drinking water quality are pH at 6.5-8.5, EC at 1,000 (micromhos/cm), TDS at 500 mg/l, Total alkalinity at 200 mg/l and Cl at 250 mg/l. TDS ranging from 0 to 1000 mg/l is considered as freshwater, 1000 to 10000 mg/l as Brackish water and 10000 to 100000 mg/l as seawater. The groundwater samples from the study area are collected and tested in the laboratory based on the BIS 10500 (2012), APHA (1999) and WHO (2008). The various ratios, such as Cl/(HCO_3+CO_3) and Mg/Ca are considered to identify the groundwater quality. The ratio of Cl/Total alkalinity shows that less than 0.5, considered as normally fresh groundwater, 0.5 to 1.3 considered as slightly contaminated groundwater, 1.3 to 2.8 considered as moderately contaminated groundwater, 2.8 to 6.6 considered as injuriously contaminated groundwater, 6.6 to 15.5 considered as highly contaminated groundwater and greater than 200 considered as seawater (Werner et al. 2012). The above chemical parameters demarcated using mapping software such as ArcGIS and MapInfo. The mapping of water quality also helps to identify the vulnerable areas which are affected by contamination.

Tomaszkiewicz et al. (2014), Kumarasamy et al. (2014), Narany et al. (2014) and Teikeu et al. (2016) had given the permissible limit value for Cl, EC and TDS parameters in order to judge the quality of water. The Cl parameter concentration less than 2.8 meq/l is considered as freshwater, 2.8 meq/l to 7.1 meq/l as slightly saline groundwater, 7.1 meq/l to 14.1 meq/l as moderately saline groundwater. 14.1 meq/l to 28.2 meq/l as highly contaminated groundwater, 28.2 meq/l to 282.2 meq/l as very highly polluted groundwater and values greater than 282.2 meq/l is considered as seawater. The permissible limit for Electrical conductivity (EC) less than 700 µS/cm is considered as freshwater, 700 µS/cm to 2000 µS/cm as slightly saline groundwater and 2000 µS/cm to 10000 µS/cm as moderately saline groundwater, 10000 µS/cm to 25000 µS/cm as highly saline groundwater, 25000 µS/cm to 45000 µS/cm very highly saline groundwater and greater than 45000 µS/cm is seawater. The permissible limit for TDS less than 500 mg/l considered as freshwater, 500 mg/l to 1500 mg/l as low saline, 1500 mg/l to 7000 mg/l as moderately saline groundwater, 7000 mg/l to 15000 mg/l as highly saline groundwater, 15000 mg/l to 35000 mg/l as very highly saline groundwater and above 35000 mg/l is seawater.

Panaskar et al. (2016). Tomaszkiewicz et al. (2014), Forcada (2014) and Askri (2015) considered the traditional increase of Cl concentration mainly due to the mixing of the seawater and freshwater which was easily traceable due to the conservative nature of the anion. The fraction of seawater (Fsea) in a water sample can be determined using the concentration of Cl, as shown in Eq. (2.1). The Fsea value ranges from 0 to 100, where the freshwater value starts from 0 and the seawater value ends in 100.

$$\text{Fsea} = \frac{\text{M cl}(\text{sample}) - \text{M cl}(\text{freshwater})}{\text{M cl}(\text{seawater}) - \text{M cl}(\text{freshwater})} \tag{2.1}$$

where,

M = concentration

The simple tool for identifying the seawater intrusion is the fraction of seawater, which leads to the groundwater quality index of chloride (GQI Cl). The groundwater quality index value ranges from 0 to 100, where low quality or seawater starts from 0 and high quality or freshwater ends in 100. The groundwater quality index of Cl is expressed in Eq. (2.2).

$$\text{GQI Cl} = (1 - \text{Fsea Cl}) \times 100 \tag{2.2}$$

Groundwater quality parameter can be plotted on the piper plot diagram (Yang et al. 2016), which provides good inferences to understand groundwater contamination. The unit considered for the chemical parameters of the piper plot is milliequivalents per litre (meq/l). Sodium Absorption Ratio (SAR) is considered for groundwater contamination of sodium and given in Eq. (2.3). (Edet 2016). The permissible limit of SAR value is less than 10 for freshwater. If the SAR value goes above the permissible limit, then the groundwater is contaminated by sodium and it gives health hazards.

$$\text{SAR} = \frac{Na^{+}}{\sqrt{\frac{1}{2}\left[\left(Ca^{2+}\right)+\left(Mg^{2+}\right)\right]}} \tag{2.3}$$

The groundwater quality was classified into four categories viz. excellent, good, permissible and poor. In this analysis, the number of samples taken under consideration and represented in percentage wise to know the status of groundwater. Table 2.1 describes the groundwater quality status.

Table 2.1 Groundwater quality status (Yang et al. 2016)

Index	**I**	**II**	**III**	**IV**
TDS	≤300	≤500	≤1000	>1000
Cl	≤50	≤150	≤250	>250
TH	≤150	≤300	≤450	>450
EC	≤450	≤750	≤1500	>1500
Ca	≤100	≤250	≤400	>400

I = Excellent, II = Good, III = Permissible, IV = Poor

The time series prediction of groundwater quality using statistical method will help to find the correlation of observed and predicted data of significant groundwater quality parameters. The error of prediction can be assessed using the Mean Absolute Percentage Error method (MAPE), which represented in Eq. (2.4). (Parmar and Bharadwaj 2014 and Sebri, 2016). For a perfect fit, MAPE value will be zero, but in real conditions, the allowable value can be less than 10%.

$$M = \frac{100\%}{n} \sum_{i=1}^{n} \left| \frac{A_i - F_i}{A_i} \right| \qquad (2.4)$$

where M = Mean absolute percentage error, n = number of samples, A_i = actual value, F_i = Forecast value

Zaldis et al. (2002) evaluated the impacts of agricultural practices on soil and water quality in the Mediterranean region, which causes land degradation, soil salinization and loss in organic matter. Due to this, the freshwater gets affected and the agriculture yield gets reduced in the Mediterranean region. Tuong et al. (2003) evaluated the loss in agricultural production and livelihood changes due to the seawater intrusion in the Mekong river delta, Asia. A groundwater model was carried out using DEM (digital elevation model) to find the recharge and discharge to establish the amount of the fresh groundwater available (Dhakate et al. 2016).

White (2006) has evaluated the details of freshwater contamination, which occurs mainly due to the human settlements, wastes and excess pumping. The pollution causes mostly health hazards. Due to this, the financial condition becomes very low in the contaminated area. Lopez and Vurro (2008) reported that water resources management for agricultural wastewater reuse could effectively contribute to filing the increasing gap between water demand and water availability, particularly in semi-arid areas of the Apulia region. Few initiatives were taken for the availability of the local water resources by the reuse of treated wastewater mainly in the agricultural sector.

Zekri (2008) evaluated the economic impacts of Oman due to water quality degradation. It was described that the farmer's loss and the domestic user loss due to the salinity in freshwater. It also suggests that the excessive pumping of groundwater for the agricultural purpose should reduce by removing the electric subsidy for farmers to reduce the rate of groundwater contamination.

After the review of the various literature, it shows that analysing chemical parameters such as pH, EC, TDS, HCO_3, CO_3, Ca, Mg and Cl will help to find out the quality of groundwater.

The total alkalinity and total hardness is found out based on the sum of CO_3 and HCO_3 for total alkalinity and the sum of Ca and Mg for total hardness. The ratio, such as $Cl/(HCO_3+CO_3)$ and Mg/Ca gives the exact state of contamination when groundwater pollution occurs. Based on the literature it is concluded that Cl/Total alkalinity ratio less than 0.5 considered as fresh groundwater, 0.5 to 1.3 considered as slightly contaminated groundwater, 1.3 to 2.8 considered as moderately contaminated groundwater, 2.8 to 6.6 considered as injuriously contaminated groundwater, 6.6 to 15.5 considered as highly contaminated groundwater and more significant than 200 considered as seawater.

2.3 NUMERICAL MODELLING

Modelling is carried out to know the past status and current status of the groundwater quality in the coastal aquifer. The data such as water level, water quality and geophysical information considered for modelling. The reactive transport modelling strengthens the interpretation of environmental tracer data. The laboratory experimentation for water quality will help to carry the numerical simulation.

The recharge for the model is calculated based on two methods groundwater balance equation and Krishna Rao empirical formula method. In the groundwater balance equation, evapotranspiration data extracted from the MODIS data. The recharge was calculated based on precipitation and evapotranspiration. In the second method, Krishna Rao (1970) gave the empirical relationship to determine the groundwater recharge in limited climatological homogenous areas as given Eq. (2.5).

$$R = K\,(P - X) \tag{2.5}$$

The following relation is applicable for different parts of Karnataka;
$R = 0.20\,(P - 400)$ for areas with annual normal rainfall P between 400 and 600mm
$R = 0.25\,(P - 400)$ for areas with P between 600 and 1000mm
$R = 0.35\,(P - 600)$ for areas with P above 1000mm
where,
R = recharge in mm
P = precipitation in mm

Mahesha and Nagaraja (1996), reported a study on the effect of natural recharge in coastal aquifers by establishing a relationship between seawater reduction and uniform recharge using the interface model. This relationship is directly useful in estimating the effect of rainfall in repelling seawater intrusion, applicable for a wide range of practical aquifers. The effects of non-uniform intensities of rainfall such as daily, weekly and monthly average values did not show any significant deviation from the seasonal average values regarding the overall reduction of the intrusion achieved. Under favourable conditions, the annual reduction achieved by the rainfall may reach 5-6% of the initial length of intrusion.

Bhat and Subrahmanya (2000), reported the study on shoreline changes and evolution of the coastal zone in southern Karnataka, which comprises of Netravathi and Gurpur river basin. In this study, they have used the topographic maps, Naval Hydrographic charts and Indian remote sensing satellite imagery of different years. Reghunath et al. (2005), has carried out a study in Netravathi river basin in which a time series analysis has been carried out using depth and height to the water table above mean sea level for ten locations.

Mohan and Pramada (2005), reported a study using SEAWAT modelling software in south Chennai for predicting seawater intrusion in 2010. In this study, the construction of a semi-permeable barrier reduces contamination. Based on the model study, it was found that the seawater-freshwater interface movement was 20-30 m per year towards the landside. A two-dimensional control volume finite element transport model was used to simulate the seawater intrusion into the Queensland aquifer system (Liu et al. 2006). Yang (2008), reported a study on the effects of reservoirs on the groundwater system by using a predictive simulation of 2D and 3D finite element model in Ping Tung plain of Southwestern Taiwan.

Datta et al. (2009), reported the groundwater modelling using FEMWATER in the coastal aquifer of Andhra Pradesh, India. In this study, the flow model was developed using hydraulic head data and the transport model was developed using chloride concentration. The result shows the different management strategies in the coastal aquifers. Milnes (2011), reported salinization risk assessment in southern Cyprus, through the FEM-based numerical model.

Web and Howard (2011), has published a study which provides initial qualitative estimates for the expected rate of intrusion and predicted the degree of disequilibrium generated by sea level rise for a range of hydrogeological parameter value. Werner et al. (2012) and Sindhu et al. (2012) has carried out a study on SEAWAT modelling, which help to identify the groundwater contamination in the coastal aquifer.

A review paper by Werner et al. (2012), reported that numerical modelling could be carried out using SUTRA, SEAWAT, MODFLOW, FEFLOW and FEMWATER. SUTRA, SEAWAT and MODFLOW developed by the U.S Department of the Interior and U.S Geological Survey. The SEAWAT program was designed to simulate three-dimensional, variable-density, transient groundwater flow in porous media. The source code for SEAWAT is developed by combining MODFLOW and MT3DMS into a single program that solves the coupled flow and solute-transport equations. The FEMWATER is developed by the U.S. Environmental Protection Agency and the U.S. Army Engineer Waterways Experiment Station in the year 1990s. The FEMWATER is a transport model in which the saturated flow and unsaturated flow modelled in the aquifer.

Kim et al. (2012), used the FEMWATER model to find the seawater intrusion in the coastal aquifer in Korea. In this study, FEMWATER a three-dimensional groundwater simulation program, which allows the flow and mass transport of groundwater to be simulated simultaneously, was used to simulate seawater intrusion. By using observation data, the stratum and groundwater levels set, and initial concentrations were also set to match actual situations. Based on this, seawater intrusion is simulated for 300 days and the results compared to the observation data, which resulted in the following conclusions. In the case of low depths, the range of seawater intrusion was limited to the vicinity of the coastline and did not affect areas inland. When the depths became more, the seawater intrusion became more extensive from the point of the coast and its moves towards the freshwater zone. At the depths of 90 m, at the 1km point from the coastal, seawater intrusion was shown to have progressed seriously, and there was a significant increase in the salinity levels inland as well.

Lu and Werner (2013), has used the conceptual and numerical model for the seawater intrusion. The study showed that the boundary water level controls seawater intrusion timescale while distance dominates for the coastal aquifer.

Ojha et al. (2013) have given a case study on groundwater droughts, the effect of groundwater droughts on the ecosystem, characterization of groundwater droughts and management. Ramadas et al. (2013) have carried out a case study on groundwater quality modelling based on different layer strata.

Chen et al. (2014), has followed the Internal-Deviation approach for water quality model evaluation. The Internal-Deviation Method (IDM) calculated by the distance between paired uncertainty intervals or probability distributions of each simulated value and measured data. The model setup will run for both known partial differential function and the unknown partial differential function. The model founds out the uncertainty in flow, sediment and total phosphorous.

Khadri and Pande (2016) used MODFLOW for simulating groundwater flow in a case study of Mahesh river basin, India. Khorasani et al. (2016) used ARIMA model for forecasting groundwater table in Hamadan province, Iran. Paldor et al. (2019) used groundwater flow and transport of numerical modelling in the confined coastal aquifers of Northern Israel.

From the above literature it is observed that groundwater models can identify the exact groundwater quality situation in the coastal aquifer. In most of the models, the water level, water quality and recharge are mainly taken as the input data. The expected output shows the artificial recharge structures and other techniques to control the seawater intrusion. In the numerical modelling, the models such as SUTRA, SEAWAT, MODFLOW, FEFLOW and FEMWATER are used for modelling the flow in the aquifer.

2.4 REMEDIAL MEASURES

Johnson (2007), has given the effect of the injection wells in reducing the seawater intrusion in the central and west coast basin of Los Angeles. Further, the length of the interface can be reduced by different methods such as injection well, vented dams and mangroves, etc. (Obe et al. 2016)

Senthilkumar and Elango (2011) carried out a study on the subsurface barrier. In this study, the author has used numerical model MODFLOW for groundwater flow assessment. The model predicts that the impacts of the subsurface barrier would decrease groundwater head by 0.4m to 0.6m reducing pollution.

Based on the literature review, to avoid groundwater contamination and to reduce the length of the interface, the structures such as injection wells, vented dams and subsurface barrier, etc. can be used.

2.5 SUMMARY AND RESEARCH GAPS

The following summary and research gap are found in the literature review. The water quality parameters such as pH, EC, TDS and Cl, etc., can be used for finding the pollution and seawater intrusion. From the literature review, it shows that Cl/Total alkalinity less than 0.5 considered as fresh groundwater, 0.5 to 1.30 considered as slightly contaminated groundwater, 1.3 to 2.8 considered as moderately contaminated groundwater, 2.8 to 6.6 considered as injuriously contaminated groundwater, 6.6 to 15.5 recognized as highly contaminated groundwater and higher than 200 regarded as seawater. The desired permissible limit of TDS taken as 500 mg/l for freshwater, 500 mg/l to 1500 mg/l as low saline, 1500 mg/l to 7000 mg/l as moderately saline groundwater, 7000 mg/l to 15000 mg/l as highly saline groundwater, 15000 mg/l to 35000 mg/l as very highly saline groundwater and above 35000 mg/l considered as seawater. The desired permissible limit of EC was taken up to 250 µS/cm as excellent, 250 to 750 µS/cm as good, 750 to 2250 µS/cm as poor quality. The fraction of seawater (Fsea) in a water sample can be found out using the concentration of chloride ion as given in Eq. (2.1).

The groundwater quality index of seawater intrusion represented by Eq. (2.2) should be above 90 for good quality of groundwater. Sodium Absorption Ratio (SAR) for groundwater contamination, can also be considered which expressed in Eq. (2.3). The permissible limit of SAR is 10 for freshwater. The groundwater quality status was represented in Table 2.1, which gives the current conditions of the groundwater wells. The mean absolute percentage error represented by Eq. (2.4) should be less than 10. The piper plot is considered as one of the essential sources to identify the groundwater vulnerability in the sampled study area.

In the literature, the simulation is done by developing a numerical model. FEMWATER model from GMS used for modelling the coastal aquifer. The recharge can be calculated based on the groundwater balance equation and Krishna Rao empirical formula. From the literature, it is observed that the length of the interface could be reduced using injection wells, vented dams, subsurface barrier and mangroves, etc. The numerical models such as FEMWATER, FEFLOW and MODFLOW, etc. are widely used to model groundwater quality and flow globally.

The research gap found from the literature review are as follows

- A study on groundwater quality processes in various hydrogeological setting particularly in coastal environment should be carried out.
- The resilience of coastal aquifers in combination with a suitable artificial recharge in controlling groundwater quality, is not much studied in Indian context.
- The groundwater flow and transport modelling and groundwater quality monitoring in urban area of river confluence in coastal river basin is not much reported in the literature.

- The impact development policies and anthropogenic activities on groundwater extraction and contamination should be adequately studied based on site specific area. i.e., at local scale level.

CHAPTER 3

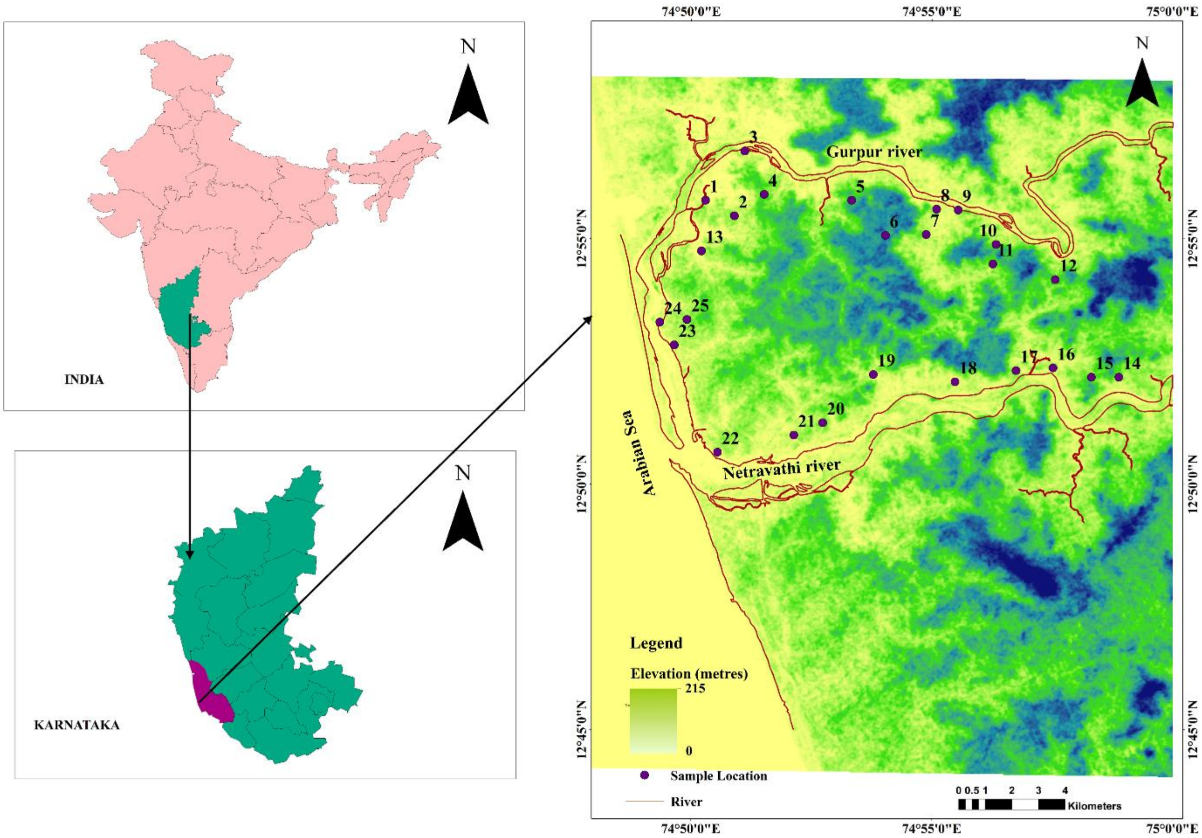
PHYSIOGRAPHIC DESCRIPTION OF STUDY AREA

The physiographic descriptions of study area considered are climate, geology, soil, geomorphology, population index and Land use land cover (LU/LC). The population index is considered based on the census report. The LU/LC classification prepared from satellite image is agriculture, Barren land, Road, Urban, Water and Forest.

3.1 STUDY AREA

The study area considered is the confluence of Gurpur and Nethravathi river basin of Mangaluru city, which is located on the west coast of India (Fig 3.1). Mangaluru city is a port city of Karnataka state and developing at a faster rate as the city has all modes of transportation networks both nationally and internationally. This facilitates considerable improvements in imports and exports. The study area lies between the latitude 12°50’38” N to 12°55’46” N and longitude 74°50’13” E to 74°58’52” E which is bounded by Arabian Sea in the west and the Western Ghats in the East. The total study area is 140 km^2, which consists of urban and peri-urban units having small-scale industries and large-scale industries. Many small companies situated close to the banks of Gurpur and Netravathi river and large fertilizers and petrochemical companies are founded near to the bank of Gurpur river. Groundwater depletion is one of the major problems during summer, which automatically lead to contamination of groundwater mainly due to excessive pumping of groundwater for agriculture and domestic supply. The agriculture crop found in the study area is paddy, areca nut and coconut. The irrigation for agriculture purpose considerably depends upon the surface water of Nethravathi and Gurpur river and also groundwater.

Twenty-five observation wells are considered for sampling and groundwater level monitoring, as shown in Fig. 3.1. The details of the groundwater sampling wells presented in Table 3.1. The sampling locations considered near the river basin of Netravathi and Gurpur river consist of an unsaturated aquifer at a distance of 0.1 km to 1 km from the river basin and the total depth of sampling wells vary from 3m to 20m below the ground level. The sampling strategy followed in the study area is the random sampling, as the terrain has the undulating surface, which was contributed mainly by valleys and peaks. The elevation data of the study area for the wells vary from 6m to 87m above mean sea level. The groundwater head measured from the study area on a monthly basis during the field visit by measuring tape for level and GPS for finding elevation with respect to mean sea level. The groundwater head is the input data for the conceptual modelling and groundwater simulation. In the modelling after providing the input data, the aquifer properties are given to the model.



(*The blue colour indicates the hills and terrain of study area)

Fig. 3.1 Study area location map

Table 3.1 Sampling wells information

Well No	Wells location (Village)	Latitude	Longitude	Total depth of well below ground level (m)
1	Panganimuguru	12° 55' 47"	74° 50' 18"	4.25
2	Kavur	12° 55' 28"	74° 50' 54"	10.77
3	Kunjatbail	12° 56' 47"	74° 51' 07"	7.21
4	Marakkada	12° 55' 54"	74° 51' 31"	5.03
5	Moodusheddu	12° 55' 47"	74° 53' 20"	12.73
6	Omangur	12° 55' 04"	74° 54' 02"	14.47
7	Tiruvail	12° 55' 05"	74° 54' 53"	4.91
8	Parari	12° 55' 36"	74° 55' 06"	8.07
9	Ularbettu	12° 55' 35"	74° 55' 33"	11.37

10	Permanki	12° 54' 53"	74° 56' 20"	13.76
11	Paduvu	12° 54' 29"	74° 56' 16"	12.17
12	Malluru	12° 54' 10"	74° 57' 34"	6.76
13	BankeraKulur	12° 54' 45"	74° 50' 13"	4.55
14	Thumbe	12° 52' 11"	74° 58' 53"	7.78
15	Maripal	12° 52' 11"	74° 58' 19"	10.1
16	Farangipet	12° 52' 22"	74° 57' 31"	7.75
17	Arkula	12° 52' 19"	74° 56' 45"	8.19
18	Adyar	12° 52' 05"	74° 55' 29"	8.29
19	Kannuru	12° 52' 14"	74° 53' 47"	3.87
20	Bajala	12° 51' 15"	74° 52' 44"	13.02
21	Jeppinamogaru	12° 51' 00"	74° 52' 08"	6.58
22	Bolar	12° 50' 39"	74° 50' 33"	4.88
23	Pokka patnam	12° 52' 50"	74° 49' 39"	5.2
24	Bolloor	12° 53' 18"	74° 49' 21"	4.8
25	Urwa	12° 53' 21"	74° 49' 55"	15.04

3.2 CLIMATE

The climate of the study area is humid tropical weather which prevails in a region for an extended period. The climate varies based upon different seasons. The variation of atmosphere mainly depends upon the temperature, humidity, atmospheric pressure, wind and precipitation. The precipitation is the primary source for groundwater. In this study, the average monthly temperature, precipitation and relative humidity are considered for the analysis of climate in the study area.

The study area of Netravathi and Gurpur river confluence consist of five rain gauge stations. (i.e.,) Bantwal, Bajpe, Mangalore RS, Mangalore DC office and Gurupur. The precipitation data of those rain gauge stations have been collected from the Statistical Department and plotted with temperature. Fig. 3.2-3.6 represents the average monthly precipitation and temperature for the five rain gauge stations. South West monsoon brings more than 80% to 90% of the total annual rainfall from June to October. The characteristic of rainfall is high-intensity thunderstorm, which is something like a downpour. The rainfall reduces drastically after October month. The average number of rainy days during South-West monsoon is about 80 to 100 days and North East monsoon is about 10 to 20 days. The period of June to October found to be higher precipitations in all the rain gauge stations. The total average rainfall and temperature in the study area is found to be 3000 mm to 4000 mm and 26.5 ºC to 29 °C. The relative humidity in the study area is observed between 65% to 90% and shown in Fig. 3.7.

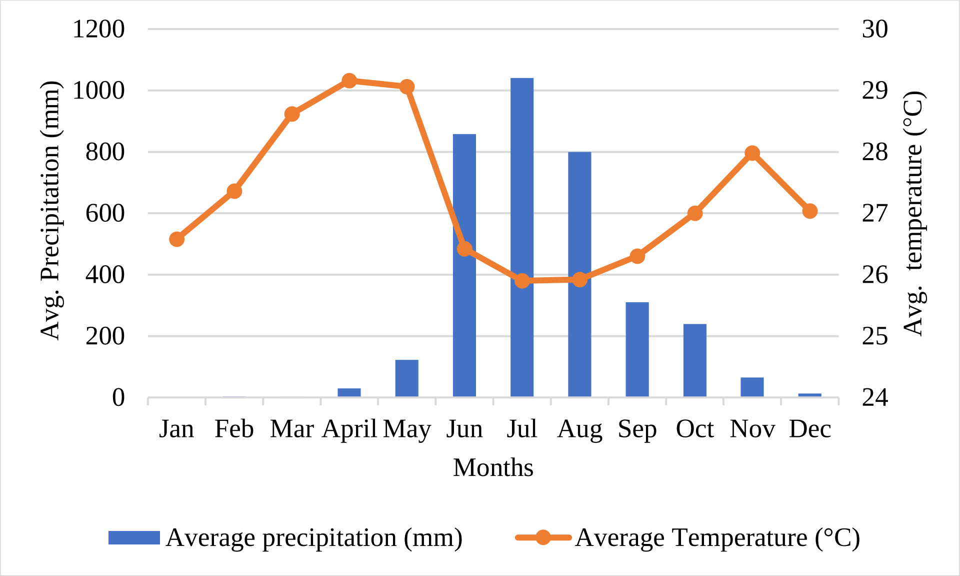


Fig. 3.2 Average precipitation and temperature of Bantwal

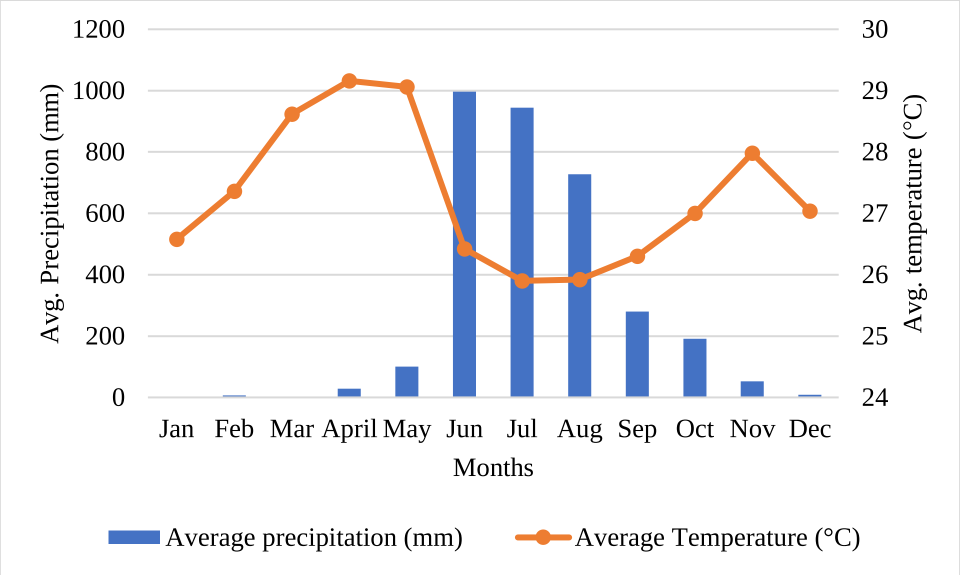


Fig. 3.3 Average precipitation and temperature of Bajpe

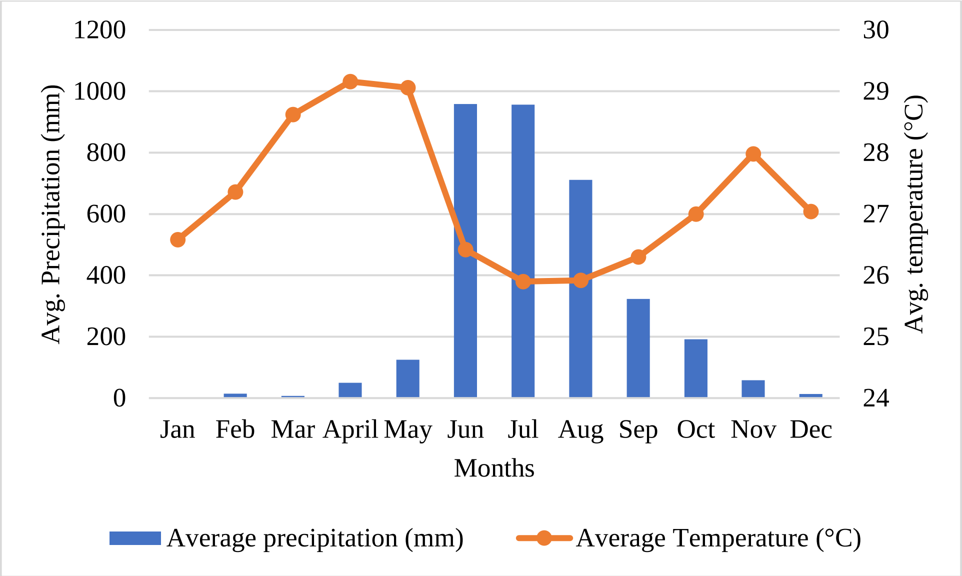


Fig. 3.4 Average precipitation and temperature of Mangalore RS

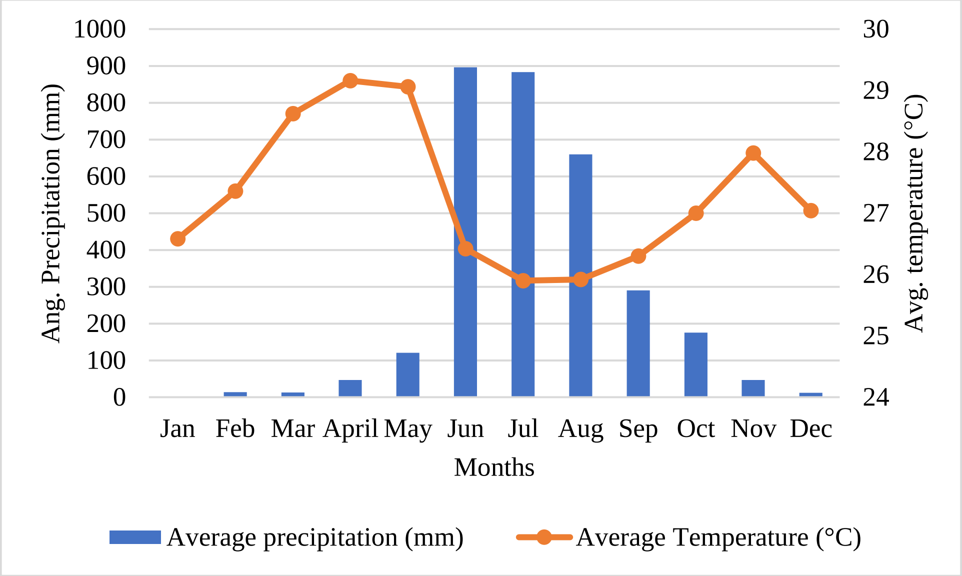


Fig. 3.5 Average precipitation and temperature of Mangalore DC office

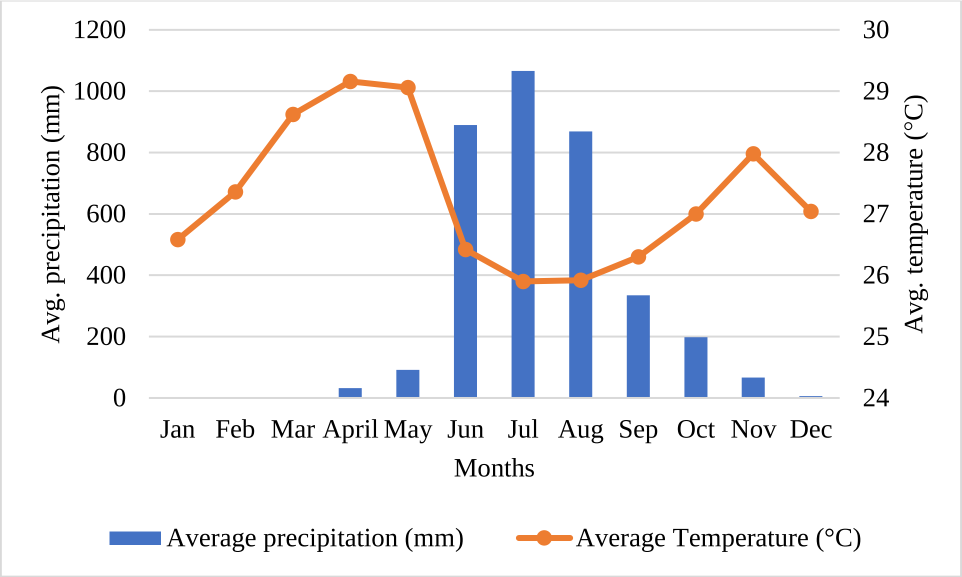


Fig. 3.6 Average precipitation and temperature of Gurpur

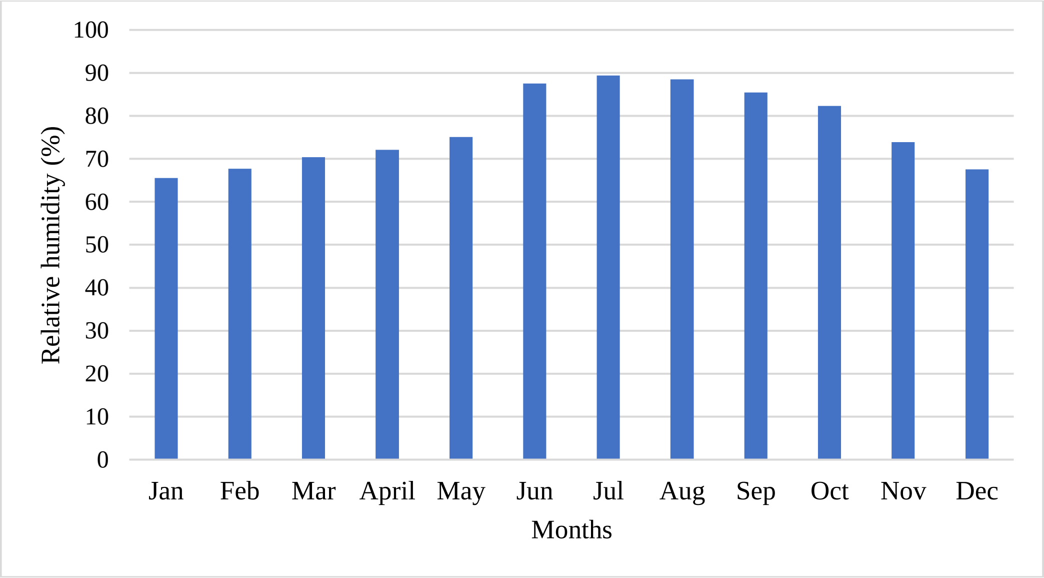


Fig. 3.7 Relative humidity of the study area

3.3 SOIL

The soil in the district has been a lateritic type, found distributed in Netravathi and Gurpur river confluence. Lateritic soil primarily red in colour and yellow loamy, pale to bright red colours is seen in most of the places in the study area. Lateritic soil is significantly suitable for paddy, sugarcane, areca nut and plantation crops, viz. crops like cardamom & plantains (CGWB, 2012). Red lateritic soil is the most dominant soil type in the area. The texture of the soil varies from fine to coarse. Silty and loamy soils are of transported origin and are found mostly along river banks and in valley plains and are well-suited for agriculture due to rich in nutrients. Fig 3.8 represents the soil map prepared from the National Bureau of Soil Survey and Land Use

Planning (NBSS and LUP, 1998) is extracted for the present study area using ArcMap 10.2. The spatial distribution of soil classification in the study area is described in Table 3.2

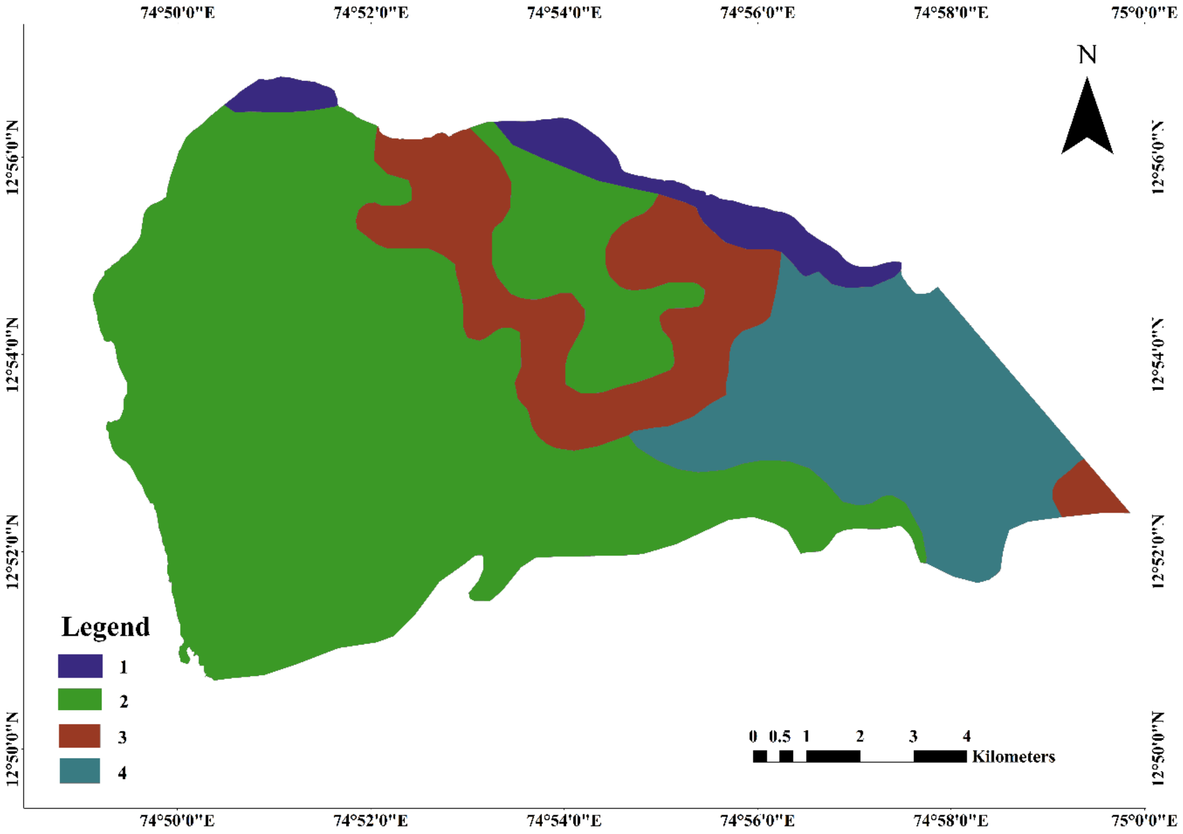


Fig. 3.8 Soil map of the study area

Table 3.2 Soil classification

Sl. No	Soil classification
1	Deep, imperfectly drained, sandy over loamy soils of valleys, with the shallow water table
2	Very deep, well drained, gravelly clay soils with surface crusting and compaction on undulating uplands, with moderate erosion.
3	Moderately shallow, somewhat excessively drained, gravelly clay soils with hard ironstone on coastal plateau summits, with moderate erosion.
4	Moderately deep, well-drained, gravelly clay soils with low AWC and surface crusting on undulating uplands, with moderate erosion.

3.4 GEOLOGY

Weathered and fractured gneiss, granite and schist are the significant water-bearing formations. Alluvial formation of limited thickness and great extent found along with the courses of major rivers. Groundwater occurs under phreatic (water table) condition in weathered zones of gneiss, schist and granite in semi-confined to confined conditions in joints and fractures of these rocks at deeper levels (CGWB, 2012). Weathered and fractured gneiss is the predominant aquifer found in the study area followed by schistose and granitic aquifers, which occur as isolated patches in some taluks. In the study area, the aquifer is multi-layered and unconfined.

3.5 GEOMORPHOLOGY

Geomorphologically the study area consists of a coastal plain. The coastal plain is a narrow, thickly populated and intensely cultivated area adjoining the coast. There is a patch of barren land found along the coast due to sandy, rocky, and marshy formation. The area near the seashore is covered with coconut gardens.

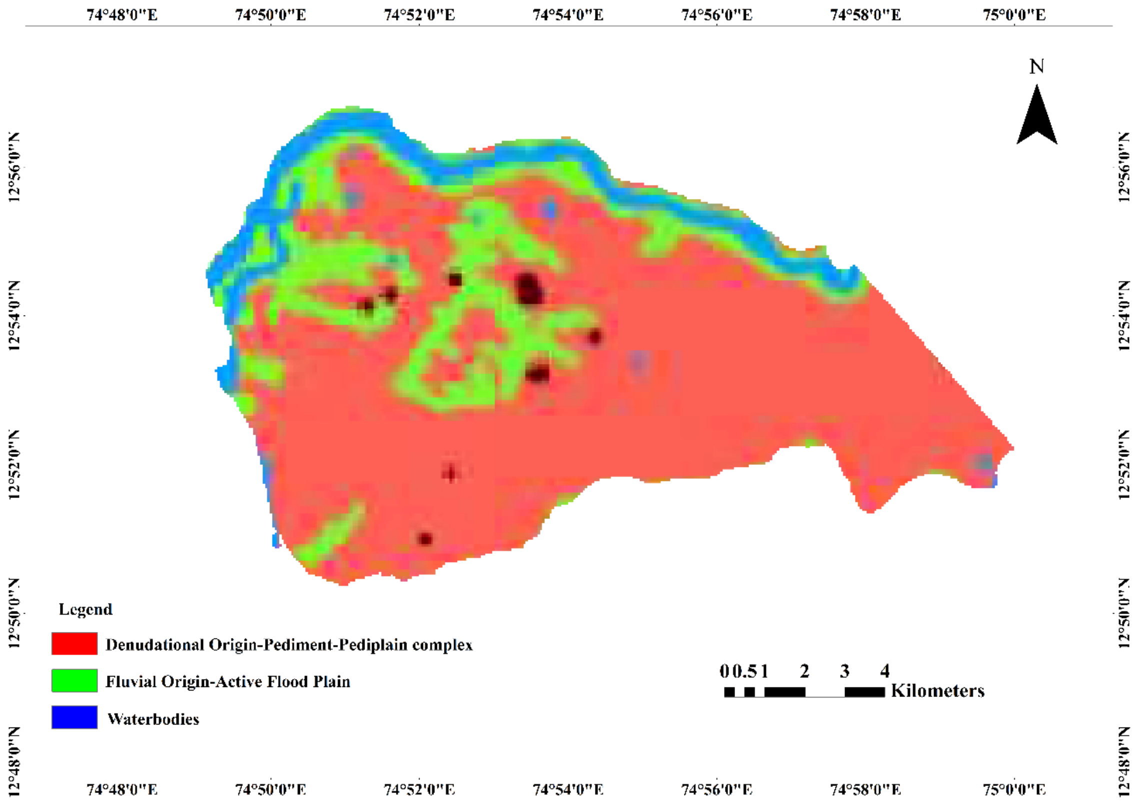


Fig 3.9 Geomorphology map of the study area

As per the Central Groundwater Board (CGWB) report "the upland area interspersed with low hills between the Western Ghats and the coast, which moderately cultivated with a considerable extent of fallow land, which can put to agricultural use. The Eastern hilly area in the eastern part of the study area is hilly with thick forest cover, which forms part of the Western Ghats. The elevation hills of the western ghat range from 1200m to 1500m above mean sea level (m.s.l.) and capped with laterite, which forms plateau usually of an oval or elongated configuration (Dahanukar et. al. 2004). The hill ranges consist of numerous streams and origin of both Netravathi and Gurpur river which significantly contributing the water to the confluence. Fig 3.9 represents the Geomorphology map of the study area extracted from LISS III data from Bhuvan.

3.6 POPULATION INDEX

The population index denotes the total amount of the population in a particular place or district or state or a country. This index is mainly calculated based on the census report. The study area comes under the Mangalore district. Further, as per the provisional reports of the Census of India, the population of Mangalore in 2011 was found to be 488,968 in which male and female are 242,512 and 246,456 respectively. Although Mangalore city has a population of 4,88,968 it was found that urban and metropolitan population are 623,841 of which 309,380 males and 314,461 females. The total average literacy rate found to be 93.40%. Fig. 3.10 represent the population decade growth of Dakshina Kannada district from the year 1911 to 2011.

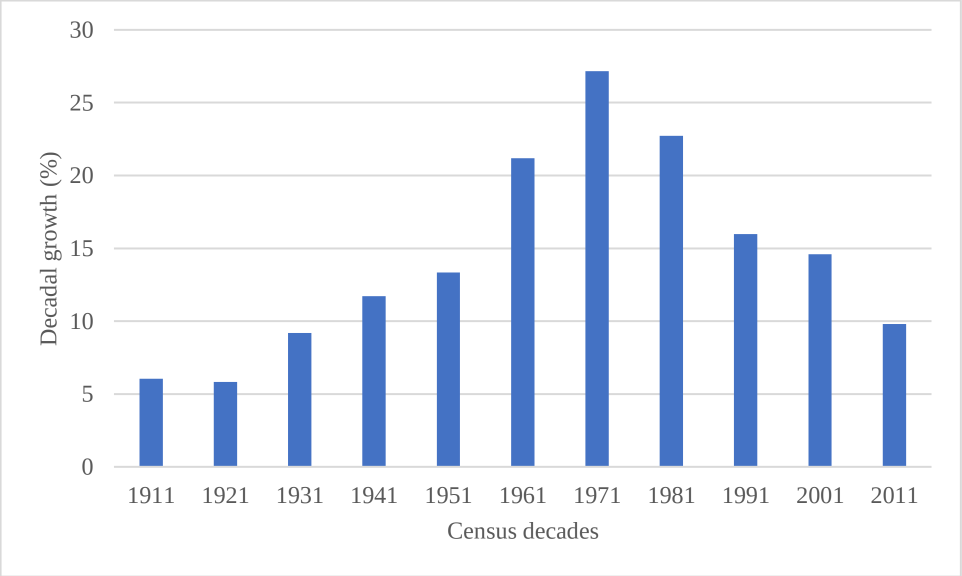


Fig. 3.10 Population decadal growth percentage of Dakshina Kannada district

3.7 LAND USE /LAND COVER (LU/LC)

Identifying, delineating and mapping land cover is vital for any monitoring studies, resource management, and planning activities. Land cover refers to the surface cover on the ground, whether vegetation, urban infrastructure, water, bare soil or other. Identification of land cover establishes the baseline from which monitoring activities (change detection) can be performed, and provides the ground cover information for baseline thematic maps.

LU/LC for the study area is carried out using the raw image of IRS LISS III, which has the resolution of 23.5m and procured from NRSC. The raw image was from 6th February 2016. In the study area, the LU/LC is classified into agriculture, barren land, road, urban, water and forest and shown in Fig. 3.11. The overall LU/LC accuracy is found to be 88.57% with an overall kappa statistic of 0.8667. The spatial extent of the study area is 140 km^2 and the classification of each class given in Table 3.3 and Fig. 3.12. The forest and agriculture found to be 64% of the total spatial extent, which shows the study area consists of high vegetation. The urban and road area combinedly found to be 24% of the study area, which shows the urban is less compared to the agriculture and the forest cover. The 21% of productive land found to be areca nut, paddy and coconut etc.

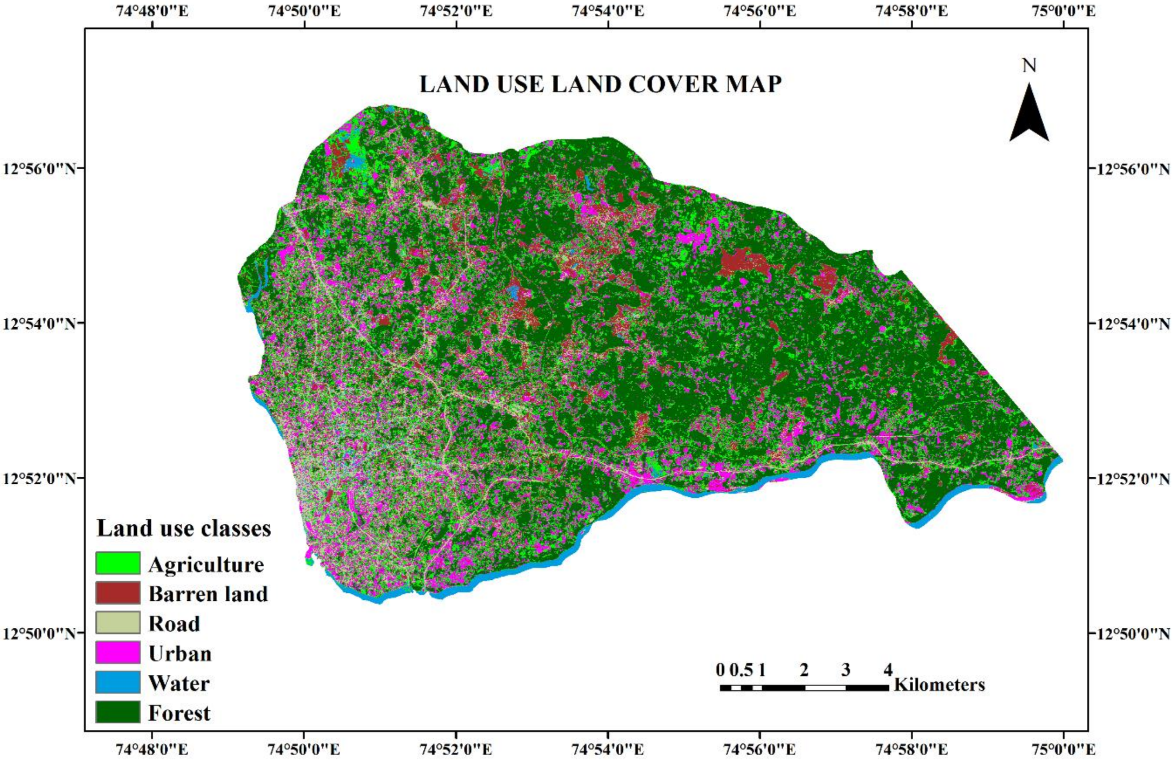


Fig 3.11 LU/LC of Netravathi and Gurpur river confluence

Table 3.3 Spatial extent of each class

LULC classes	Area in Sq.Km	Percentage area
Agriculture	28.978	21%
Barren	14.134	10%
Road	10.406	7%
Urban	23.649	17%
Water	3.595	3%
Forest	60.234	43%

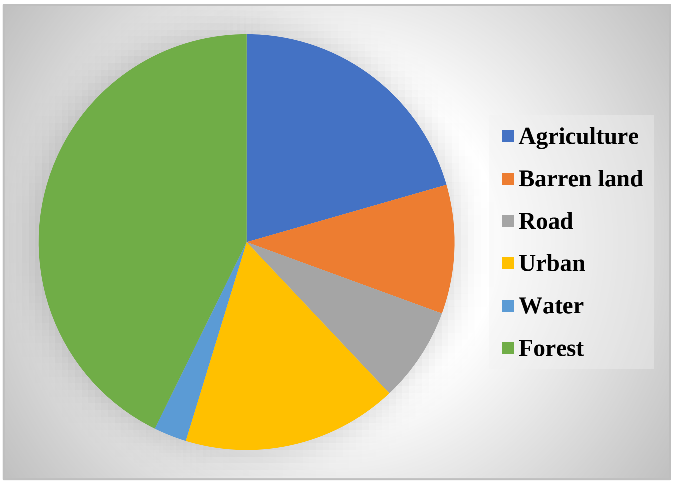


Fig 3.12 Spatial extent of each class

CHAPTER 4

AQUIFER CHARACTERISATION

4.1 GENERAL

Aquifer characterisation is the process of defining the hydraulic properties and hydraulic parameters in the aquifer. The aquifer characterisation is based on pumping test conducted in the study area. The purpose of the pumping test is to determine the time taken for recovery, pumping rate and also to find out the different aquifer parameters, such as transmissivity, storativity and hydraulic conductivity, which are important data for modelling groundwater.

4.2 HYDROGEOLOGY

Hydrogeology is the movement or flow of groundwater through aquifers and other porous media (Fitts 2010). The hydrogeology study helps us to understand the lithology of the study area. The Central Groundwater Board (CGWB 2012) for Dakshina Kannada district of Karnataka, India shows the major water-bearing formations as weathered and fractured gneiss, schist and granite and alluvium. The transmissivity in the Dakshina Kannada ranges from 3 m^2/day to 476 m^2/day and it is generalised for 3 m^2/day to 20 m^2/day as per CGWB (2012). In the study area, the lithology layer found is soil, sand, silt, laterite and Gneiss based on previous studies and field visit investigations.

4.3 PUMPING TEST

An aquifer test (or a pumping test) is conducted to evaluate hydraulic properties of an aquifer through constant pumping, and observing the aquifer's "response" (drawdown) in observation wells (Lathasri 2016 and Karanth, 1987). Aquifer testing is a standard tool that hydrogeologists use to characterize a system of aquifers, aquitards and flow system boundaries. The pumping is carried out for the various time period based on certain intervals in which the water level is collected. After pumping, the recovery of water level is also monitored for the various time period.

4.3.1 Methodology

In the study area, three groundwater wells are considered for conducting pumping tests. The basic information such as the diameter of well, the total depth of the well, depth of water level before the test is recorded. The details of the groundwater pumping wells are presented in Table

4.1. The groundwater wells selected for pumping test are found to be shallow depth (less than 10m) since the wells are near the river confluence.

Before starting the pumping test, the initial water level is noted and the water level in well almost reached a steady state. The well dried up for a maximum pumping for 1 hour 15 minutes with a discharge of 0.00603 m^3/s at 2 minutes interval after 10 minutes, at 5 minutes interval between 20 to 45 minutes and for every 10 minutes after 45 minutes. At the end of pumping the recovery of the water level measured.

Table 4.1 Details of the pumping wells

Well no	Well location (Latitude, Longitude)	Place	Dia. of the well (m)	Total depth of the well (m)	Depth to water level before the test (m)	Discharge (m^3/s)
PW1	12º55’37” N 74º50’22” E	Panganimuguru	5.70	7.24	0.76	0.00603
PW2	12º55’09” N 74º56’05” E	Permanki	2.53	7.05	1.68	0.00335
PW3	12º52’04” N 74º58’22” E	Thumbe	1.63	5.38	4.42	0.0029

4.4 AQUIFER PARAMETERS

An aquifer test is conducted by pumping water from one well at a steady rate for at least one day, while carefully measuring the water levels in the monitoring wells. When water is pumped from the pumping well the pressure in the aquifer increases and makes the well declines. This decline in pressure will show up as drawdown (change in the hydraulic head) in an observation well. Drawdown decreases with radial distance from the pumping well and drawdown increases with the passing time that the pumping continues. Based on the field visit it is found out that the aquifer in the study area is unconfined aquifer with one layer. The depth of the aquifer found between 20m to 30m. The lithology of the study area is given in Fig 4.1.

The aquifer characteristics which are evaluated by aquifer tests in the study area are

- Discharge
- Hydraulic conductivity

- Specific Yield
- Transmissivity

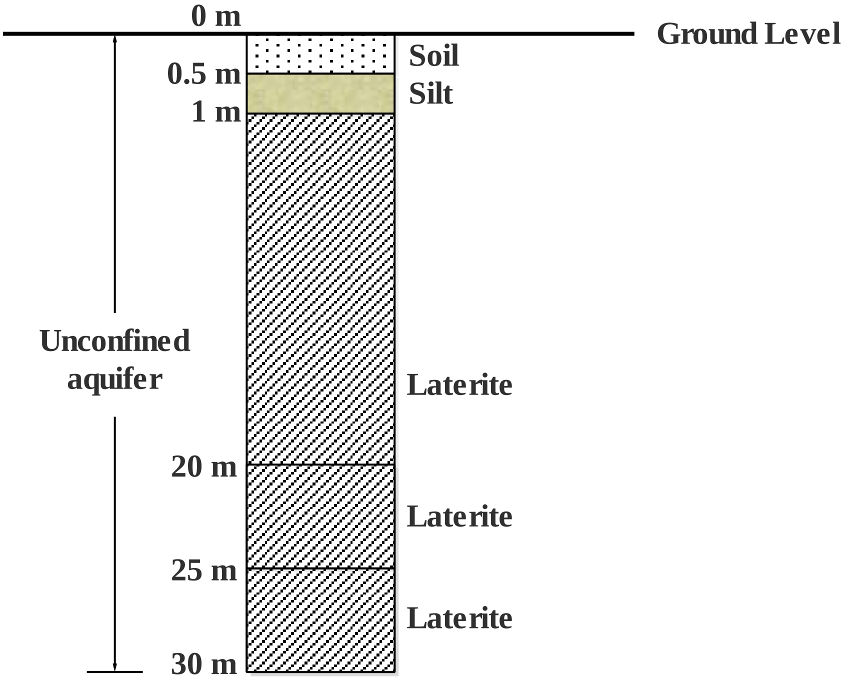


Fig 4.1 Lithology of the study area (CGWB, 2012)

4.4.1 Discharge

Discharge is the rate of water flow that is transported through a given cross-sectional area. The volumetric flow rate, (also known as volume flow rate), is the volume of fluid which passes per unit time. In the present study, the pumping rate (Q) is measured by the time required to fill a collecting tank of known volume and discharge rate is calculated as follows (Lathasri 2016)

$$Q = \frac{\text{Volume of collecting tank } (m^3)}{\text{Time required to fill the collecting tank (seconds)}} \quad (m^3/sec) \qquad (4.1)$$

4.4.2 Hydraulic conductivity

The rate of flow of water through a unit cross-sectional area of an aquifer at a unit hydraulic gradient. A medium has unit hydraulic conductivity if it transmits in unit time a unit volume of groundwater at the prevailing kinematic viscosity through the unit cross-section of area, measured at right angles to the direction of flow, under a unit hydraulic gradient (Todd and Mays 2005). The pumping test gives the transmissivity (T) result and the thickness of aquifer (b) to calculate the hydraulic conductivity.

$$K = T/b \qquad (m/d) \qquad (4.2)$$

4.4.3 Specific storage or storativity:

The specific yield of a soil or rock is the ratio of the volume of water that after saturation against the force of gravity to its volume (Todd and Mays 2005). In the case of an unconfined aquifer, the concept of storage is analogous to that of specific yield. In a confined aquifer, the storage coefficient depends on the compressibility of the aquifer and the expansion of water. Since the unconfined aquifer is not bounded by confining layers, the specific yield does not depend upon the compressibility of the aquifer (Lathasri 2016).

4.4.4 Transmissivity

The rate at which water is transmitted through the whole thickness and unit width of an aquifer under a unit hydraulic gradient. It is therefore, the product of the average hydraulic conductivity (K) and the thickness (b) of the aquifer (T = Kb, m^2/day). As per Central groundwater board (CGWB) for Dakshina Kannada district, the transmissivity ranges from 3 to 476 m^2/day and in most of the places it generally ranges from 3 to 20 m^2/day.

4.5 ANALYSIS OF PUMPING TEST DATA

The pumping test mainly carried out to estimate the hydraulic properties of groundwater flow in the study area. The graphical method used to analyse the time-drawdown measurements of hydraulic head in the observation wells. The hydraulic conductivity and specific yield of the unconfined aquifers are estimated by the Cooper-Jacob's time-drawdown method.

4.5.1 Cooper-Jacob's time-drawdown method

Cooper and Jacob (1946) simplified Theis (1935) equation, who noted that for large values of time t, and a small value of r, (u<= 0.01), the series expansion of the Theis (1935) equation after the first two terms become negligible, so that:
Theis (1935) drawdown equation:

$$s = \frac{\mathrm{Q}}{4\pi T}\left[-0.5772 - ln\, u + u - \frac{u}{2.2!} + \frac{u}{3.3!} - \cdots\right] \tag{4.2}$$

where:

$$u = \frac{\mathrm{r}^2 s}{4Tt} \tag{4.3}$$

According to Jacob's (1946) assumptions, the drawdown equation simplified to:

$$s = \frac{\mathrm{Q}}{4\pi T}\left[-0.5772 - ln\, u\right] \tag{4.4}$$

Then rearranging the equation and changing -0.5772 to $ln1.78$:

$$s = \frac{\mathrm{Q}}{4\pi T}\left[-ln1.78 - ln\frac{\mathrm{r}^2 s}{4Tt}\right] \tag{4.5}$$

$$s = \frac{\mathrm{Q}}{4\pi T}\left[-(ln1.78 + ln\frac{\mathrm{r}^2 s}{4Tt})\right] \tag{4.6}$$

$$s = \frac{\mathrm{Q}}{4\pi T}\left[-(ln\frac{1.78\,\mathrm{r}^2 s}{4Tt})\right] \tag{4.7}$$

inverse the term using Ln rules to get:

$$s = \frac{\mathrm{Q}}{4\pi T}\, ln\left[\frac{4Tt}{1.78\,\mathrm{r}^2 s}\right] \tag{4.8}$$

For a small value of r, the eq. (4.8) is the equation of a straight line plotted between drawdown(s) and the log of time(t) on semi-log paper, and rewriting the equation in the logarithmic form, it becomes:

$$s = \frac{2.3\mathrm{Q}}{4\pi T}\,\mathrm{Log}\left[\frac{2.25Tt}{\mathrm{r}^2 s}\right] \tag{4.9}$$

thus, the straight-line equation is:

$$s = \frac{2.3\mathrm{Q}}{4\pi T}\,\mathrm{Log}\left[\frac{2.25Tt}{\mathrm{r}^2 s}\right] + \frac{2.3\mathrm{Q}}{4\pi T}\,\mathrm{Log\ t} \tag{4.10}$$

Y = B (intercept) + A(slope) x

The plot of s against Log t should be a straight line and the extend of the straight line at zero drawdown, $t = t_o$ as Fig 4.2, so that:

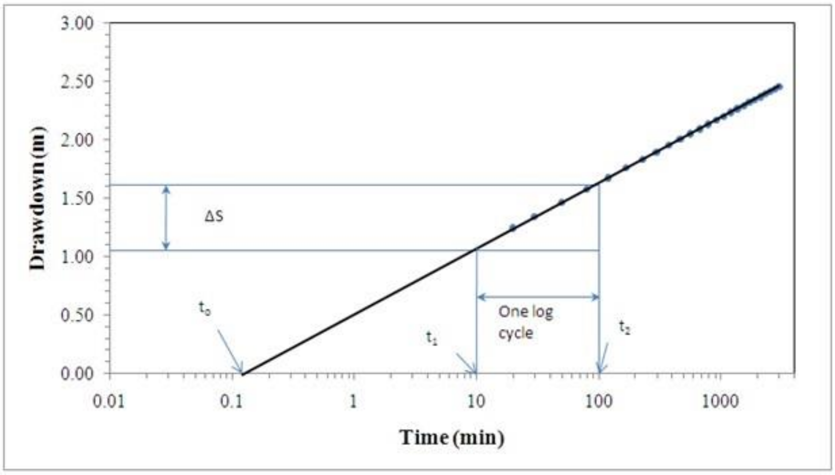


Fig 4.2 Time drawdown representation of Cooper-Jacob's method

$$\frac{2.25T\,t_o}{\mathrm{r}^2 s} = 1 \tag{4.11}$$

or:

$$S = \frac{2.25T\,t_o}{\mathrm{r}^2} \tag{4.12}$$

and:

$$\Delta s = \frac{2.3\mathrm{Q}}{4\pi T} \tag{4.13}$$

then Transmissivity is:

$$T = \frac{2.3\mathrm{Q}}{4\pi \Delta s} \tag{4.14}$$

The Fig 4.3 shows the section of the well (Mawlood and Mustafa 2016) which clearly represents the well radius (rw) and the effective radius of the well (re) for Cooper-Jacob's method.

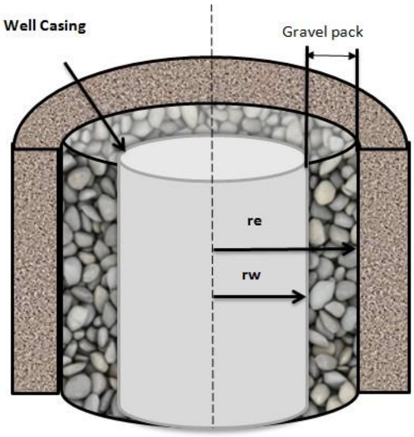


Fig 4.3 Section of the well (Mawlood and Mustafa 2016)

where:

s - drawdown [m]

Q - constant rate pumping test [m^3/sec]

T - Transmissivity [m^2/day]

S - Storativity [unit less]

r - radial distance [m]

r_w - well radius [m], Figure 4.3

u - well constant (Mawlood and Mustafa (2016))

W(u) - well function

t - time of pumping [min]

Δs - slope of the line per one log cycle [m]

t_o- the initial time of pumping test at zero drawdown [min]

ɣ - Euler number = -0.5772

h - aquifer thickness in water-table aquifer [m] (This aquifer thickness is suitable for the study area since the aquifer is an unconfined aquifer)

b - the aquifer thickness in case confined [m]

rw - radius of the well [m].

re - the effective radius of the well [m]

sw - the drawdown at the well [m]

Sc - the specific capacity of the well [m^2/min drawdown]

Y - linear equation

B - intercept of the line.

C - the slope of the line.

x - x-axis.

swl - static water level [m]

dwl - dynamic water level [m]

4.6 RESULTS AND DISCUSSION

The pumping test carried in three different locations of the study area. The analysis of the data is carried out based on the graphical type-curve method. Cooper-Jacob's time-drawdown method used to find out hydraulic conductivity, transmissivity and specific yield. The time-drawdown and recovery data for the test conducted in pumping well number PW1, PW2 and PW3 are listed in Table 4.2, 4.3 and 4.4 respectively.

Table 4.2 Time-drawdown and recovery data for Well No. PW1 Panganimuguru

Time (mins)	During pumping		Recovery period		Residual Drawdown (m)
	Depth to water level (m)	Drawdown (m)	Depth to water level (m)	Drawdown (m)	
0	0.760	0	1.500	0	0.740
1	0.770	0.010	1.500	0	0.740
2	0.780	0.020	1.495	0.005	0.735
3	0.790	0.030	1.490	0.010	0.730
4	0.800	0.040	1.490	0.010	0.730
5	0.810	0.050	1.490	0.010	0.730
6	0.820	0.060	1.485	0.015	0.725
7	0.830	0.070	1.485	0.015	0.725
8	0.840	0.080	1.480	0.020	0.720
9	0.850	0.090	1.480	0.020	0.720

10	0.860	0.100	1.480	0.020	0.720
12	0.870	0.110	1.480	0.020	0.720
14	0.885	0.115	1.470	0.030	0.710
16	0.900	0.130	1.470	0.030	0.710
18	0.920	0.150	1.470	0.030	0.710
20	0.940	0.170	1.465	0.035	0.705
25	0.990	0.220	1.460	0.040	0.700
30	1.040	0.270	1.455	0.045	0.695
35	1.090	0.320	1.455	0.045	0.695
40	1.140	0.370	1.450	0.050	0.690
45	1.200	0.430	1.445	0.055	0.685
55	1.310	0.540	1.440	0.060	0.680
65	1.410	0.640	1.430	0.070	0.670
75	1.510	0.740	1.420	0.080	0.660
105	-	-	1.400	0.100	0.640
135	-	-	1.380	0.120	0.620
165	-	-	1.370	0.130	0.610
195	-	-	1.365	0.135	0.605
225	-	-	1.350	0.150	0.590
285	-	-	1.320	0.180	0.560
345	-	-	1.300	0.200	0.540
405	-	-	1.290	0.210	0.530
465	-	-	1.285	0.215	0.525

Table 4.3 Time-drawdown and recovery data for Well No. PW2 Permanki

Time (mins)	During pumping		Recovery period		Residual Drawdown (m)
	Depth to water level (m)	Drawdown (m)	Depth to water level (m)	Drawdown (m)	
0	1.200	0	1.650	0	0.450
1	1.220	0.020	1.640	0.010	0.440
2	1.230	0.030	1.645	0.015	0.435
3	1.240	0.040	1.630	0.030	0.420
4	1.250	0.050	1.625	0.035	0.415
5	1.250	0.050	1.625	0.035	0.415
6	1.253	0.053	1.625	0.035	0.415
7	1.254	0.054	1.620	0.040	0.410
8	1.260	0.060	1.620	0.040	0.410
9	1.262	0.062	1.620	0.040	0.410
10	1.270	0.070	1.620	0.040	0.410
12	1.280	0.080	1.615	0.045	0.405
14	1.290	0.090	1.615	0.045	0.405
16	1.300	0.100	1.615	0.045	0.405
18	1.320	0.120	1.610	0.050	0.400
20	1.330	0.130	1.610	0.050	0.400
25	1.380	0.180	1.605	0.055	0.395
30	1.400	0.200	1.600	0.060	0.390
35	1.420	0.220	1.595	0.065	0.385

40	1.450	0.250	1.590	0.070	0.380
45	1.480	0.280	1.585	0.075	0.375
55	1.520	0.330	1.580	0.080	0.370
65	1.580	0.380	1.570	0.090	0.360
75	1.650	0.450	1.560	0.100	0.350
105	-	-	1.530	0.130	0.320
135	-	-	1.510	0.150	0.300
165	-	-	1.495	0.165	0.285
225	-	-	1.450	0.210	0.240
285	-	-	1.425	0.235	0.215
345	-	-	1.400	0.260	0.190

Table 4.4 Time-drawdown and recovery data for Well No. PW3 Thumbe

Time (mins)	During pumping		After pumping is stopped		Residual Drawdown (m)
	Depth to water level (m)	Drawdown (m)	Depth to water level (m)	Drawdown (m)	
0	1.680	0	2.530	0	0.850
1	1.710	0.030	2.510	0.020	0.830
2	1.760	0.080	2.490	0.040	0.810
3	1.800	0.120	2.480	0.050	0.800
4	1.840	0.160	2.470	0.060	0.790
5	1.880	0.200	2.465	0.065	0.785
6	1.900	0.220	2.460	0.070	0.780
7	1.900	0.220	2.455	0.075	0.775
8	1.910	0.230	2.450	0.080	0.770
9	1.920	0.240	2.450	0.080	0.770
10	1.930	0.250	2.445	0.085	0.765
12	1.940	0.260	2.430	0.100	0.750
14	1.960	0.280	2.420	0.110	0.740
16	1.970	0.290	2.410	0.120	0.730
18	1.990	0.310	2.400	0.130	0.720
20	2	0.320	2.390	0.140	0.710
25	2.150	0.470	2.330	0.200	0.650
30	2.250	0.570	2.280	0.250	0.600
35	2.320	0.640	2.250	0.280	0.570
40	2.390	0.710	2.230	0.300	0.550
45	2.440	0.760	2.220	0.310	0.540
50	2.470	0.790	2.215	0.315	0.535
55	2.510	0.830	2.210	0.320	0.530
60	2.530	0.850	2.210	0.320	0.530
70	-	-	2.190	0.340	0.510
80	-	-	2.180	0.350	0.500
90	-	-	2.170	0.360	0.490
120	-	-	2.150	0.380	0.470
150	-	-	2.140	0.390	0.460
180	-	-	2.130	0.400	0.450
240	-	-	2.120	0.410	0.440

300	-	-	2.110	0.420	0.430
360	-	-	2.100	0.430	0.420

Based on the pumping test data of drawdown and recovery, the graph is plotted for drawdown and recovery versus time shown in Fig 4.4 to 4.6 for PW1, PW2 and PW3. Table 4.5 gives the transmissivity and storage parameters obtained from the pumping test analysis. Based on earlier studies near the study area, it is found that Transmissivity ranges between 10 to 1440 m^2/day. The initial aquifer parameters of the previous studies are given in Table 4.6

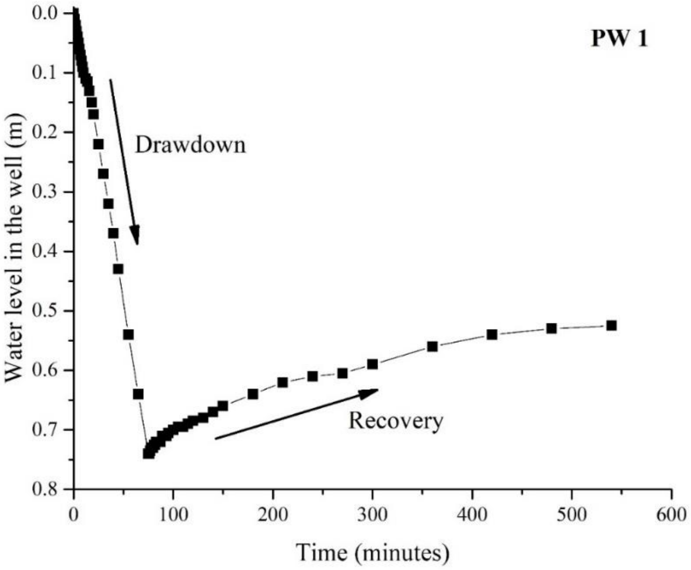


Fig 4.4 Drawdown and recovery curve for pumping Well No. 1 at Panganimuguru

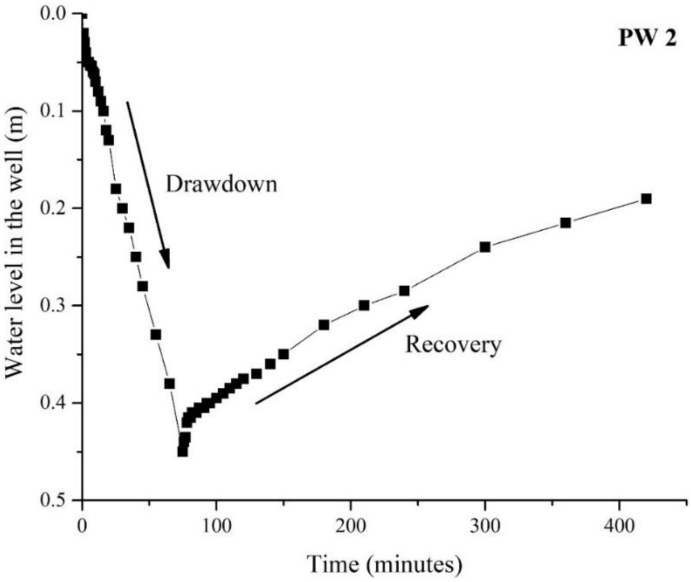


Fig 4.5 Drawdown and recovery curve for pumping Well No. 2 at Permanki

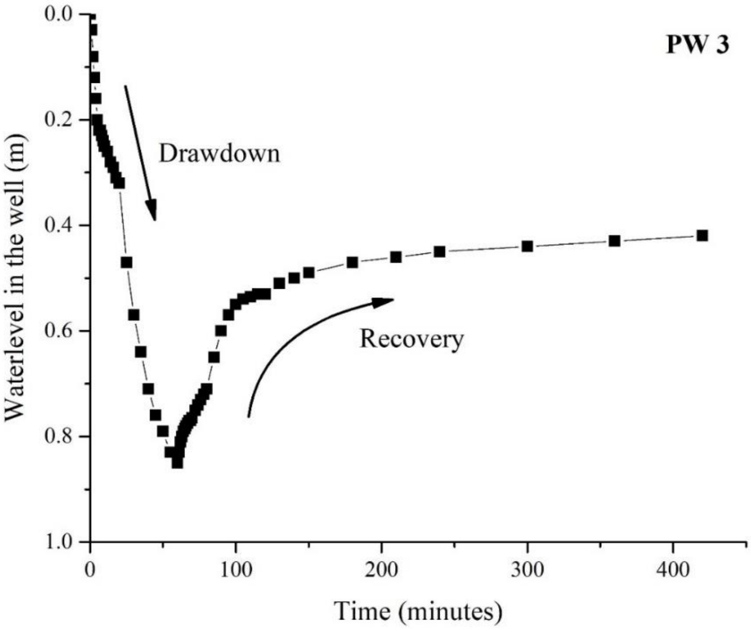


Fig 4.6 Drawdown and recovery curve for pumping Well No. 3 at Thumbe

Table 4.5 Transmissivity and storage parameters obtained from pumping test analysis

Well No	Cooper-Jacob's time-drawdown method	
	T (m^2/day)	Specific storage
PW1	950.4	0.000107
PW2	241.56	0.000197
PW3	764.64	0.00013

Table 4.6 Aquifer parameters of the surrounding area from previous studies

T (m^2/day)	Specific storage	Source	No of wells
10-810	0.0008-0.0122	Harshendra, 1991	8
69-461	0.0008-0.2805	Vyshali, 2008 and Udayakumar, 2008	18
16-1440	0.00058-0.2432	Shetkar, 2008	5
100-256	0.0008-0.1131	Ranganna et al. 1986 and Shivanagouda, 2015	6
15.44- 275.8	0.001-0.50	Lathasri, 2016	3

The aquifer in the study area was found to be unconfined aquifer. In this regard the aquifer characterisation based on pumping test gives the Transmissivity value ranges from 241.56 m^2/day to 950.4 m^2/day and the specific storage ranges from 0.000107 to 0.000197. When the results of the transmissivity are compared with the Central Groundwater Board (CGWB 2012) for Dakshina Kannada district of Karnataka, India, the transmissivity in the Dakshina Kannada district ranges from 3 m^2/day to 476 m^2/day and it is generalised for 3 m^2/day to 20 m^2/day as per CGWB (2012). Based on CGWB (2012), the transmissivity results are found to be higher.

In this regard, the previous studies of the surrounding area are considered, where the transmissivity value range from 16 m^2/day to 1440 m^2/day (Shetkar, 2008). Based on the previous studies in the surrounding area, the transmissivity of the study area is found to be within the limits of previous studies.

The specific storage in the study area ranges from 0.000107 to 0.000197. This indicates the considerably reduced value of specific storage (Ss) of aquifer comparing to the previous studies of the surrounding area. This reduction might be mainly due to climate change and the reduction of precipitation at the non-monsoon season in the study area. Fig 4.4 to 4.6 shows the water level recovery of pumping Wells Panganimuguru, Permanki and Thumbe. The well Permanki found to be faster recovery comparing to the other wells of Panganimuguru and Thumbe. Further, aquifer characterisation results are used as the input data for the development of flow and transport model in the study area.

CHAPTER 5

GROUNDWATER QUALITY ASSESSMENT

5.1 INTRODUCTION

Groundwater quality is an important component in the present days as it is directly used for drinking without treatment. The chances of groundwater getting contaminated are less compared to surface water since the pollutants have to pass through the topsoil strata of the ground. However, in coastal and industrial locations, the pollutants mix with freshwater through excess pumping in the coastal region and mixing of industrial waste in groundwater. In this regard, the groundwater quality assessment is carried out in the study area since it is near to the West Coast. This assessment helps to understand the status of the groundwater quality. The sampling locations are identified in the study area near the Netravathi and Gurpur river confluence. A total of 25 sampling locations are selected in the study area, based on elevation and proximity to the river bank. The laboratory test conducted for different chemical parameters such as the potential of hydrogen (pH), Electrical conductivity (EC), Total Dissolved solids (TDS), Bicarbonate (HCO_3), Carbonate (CO_3), Calcium (Ca), Sodium (Na), Potassium (K), Magnesium (Mg) and Chloride (Cl). Based on the laboratory results of these parameters, the groundwater quality status and maps were generated. Also, statistical analysis carried out to predict these water quality parameters. The results of the laboratory experiments are further used for statistical methods such as piper plot, mapping and groundwater quality status and as the input data for transport modelling. Further, the water level data, precipitation and well depth are given as the input data for the flow modelling. Based on the statistical and modelling results, the status of the groundwater quality is demarcated. Modelling helps us to identify the distance affected by the contamination in the coastal aquifer. Based on the effect of pollution, management strategies are considered for the reduction of contamination. The present chapter deals with the

(1) Assessment of groundwater quality through chemical analysis in the laboratory and
(2) Statistical analysis of groundwater quality to find the relationship between the parameter element and to predict the groundwater quality parameters.

5.2 CHEMICAL ANALYSIS OF GROUNDWATER

Water quality assessment provides the exact status of the groundwater quality. The parameters of groundwater such as pH, EC, TDS, Cl, Ca, Mg, TH, HCO_3, Na, K and SO_4 are tested in the laboratory. According to Indian standard code IS 10500:2012, the result of chemical analysis is used as an input for statistical analysis like SAR, Piper plot, correlation of chemical parameters and groundwater quality mapping. Based on this assessment, the status of the groundwater quality is understood and the management scenarios to improve groundwater quality is modelled.

5.2.1 Groundwater sampling strategies

The groundwater sampling strategy followed in the study area is random sampling. The water samples in the wells located near the banks of Netravathi Gurpur river basin are collected at a proximity of 0.1 km to 1 km from the river. Groundwater samples collected and analysed for different chemical parameters in the lab on a monthly basis from January 2013 to May 2017. The water level data are also monitored on a monthly basis from January 2013 to May 2017. The Fig. 5.1 shows the sampling locations of the study area.

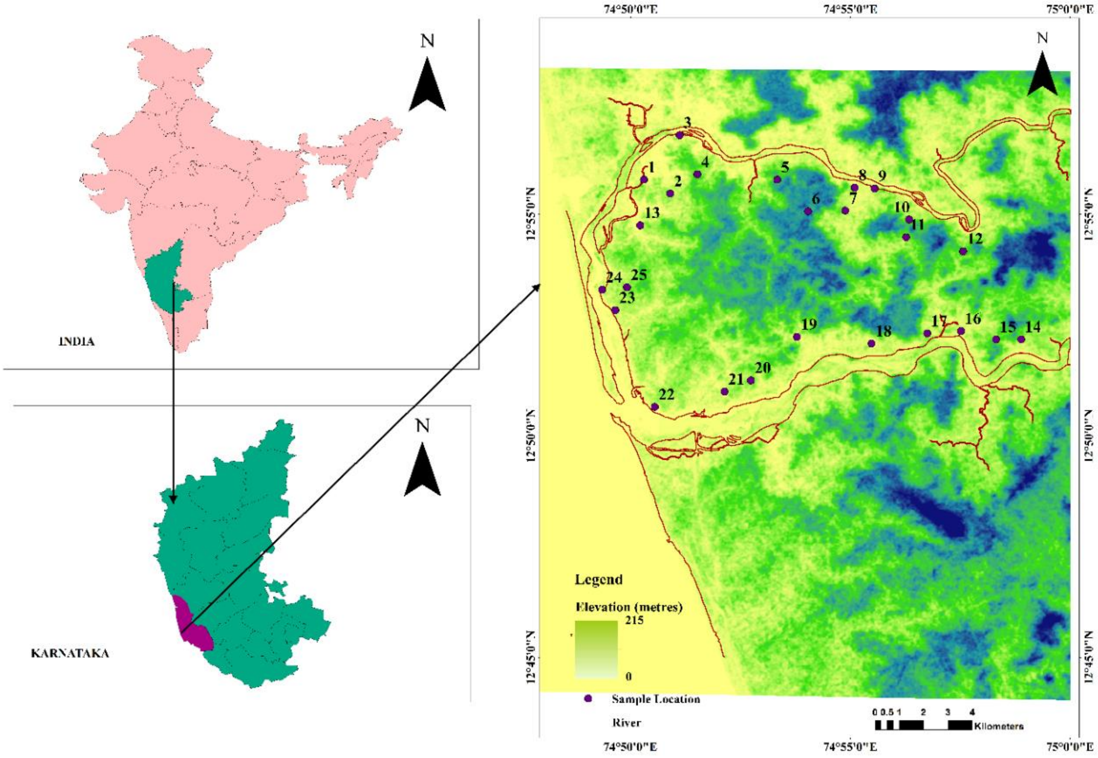


Fig. 5.1 Sampling locations of the study area map

5.2.2 Water quality sampling

The sampling for water quality is carried out once in a month in the study area. The significant result of the water quality sampling shows that the groundwater quality is excellent around the Thumbe and Maripal region of the study area. The groundwater samples at Panganimuguru (well no. 1) and Kunjatbail (well no. 3) have indicated low groundwater quality for most of the chemical parameters during the period of pre-monsoon season. The main reasons for analysing the water quality is

1. To know the quality of the groundwater.
2. To compare it with the standards
3. To locate the area of contamination.
4. To identify the reason for contamination.

The groundwater samples are chemically analysed for the following parameters according to BIS 10500 (2012), APHA (1999) and WHO (2008) along with permissible limits with Table 5.1. The parameters include

Table 5.1 The standards of BIS 10500 (2012), APHA (1999) and WHO (2008)

Parameter	Notation	Instrument	Permissible limit	Health hazard
Potential Hydrogen	pH	pH meter	6.5-8.5	Nil
Electrical Conductivity	EC	Conductivity meter	700 - 2000	Nil
Total Dissolved Solids	TDS	Conductivity meter	500-2000	Nil
Bicarbonate	HCO_3	Burette	200-600	Gastrointestinal problems
Chloride	Cl	Burette	250-1000	Gastrointestinal problems
Calcium	Ca	Burette	75-200	Gastrointestinal problems
Magnesium	Mg	Burette	30-100	Gastrointestinal problems
Sodium	Na	Flame photometer	10-100	Gastrointestinal problems
Potassium	K	Flame photometer	10-100	Gastrointestinal problems
Sulphate	SO_4	Spectrophotometer	200-400	Gastrointestinal problems

5.2.2.1 Determination of pH

pH is more important for a healthy human body. It is significant in deciding the corrosivity of water. It is necessary since the water with a pH of 7 can reduce the acidity of the foods (Eska). The test for pH decides the acidic or alkaline nature of water. The pH values are determined by using a pH meter. According to drinking water standards, water for domestic consumption should have a pH between 6.5 to 8.5. pH value below four will produce sour taste and value above 8.5 produce a bitter taste.

The pre-monsoon season data of pH parameter are considered from January 2013 to May 2013 and January 2017 to May 2017. In pre-monsoon season of 2013, the wells numbered 2-4, 8-11, 14-17 and 20-22 are found to have low pH value than the permissible limit and shows the acidic nature. In the pre-monsoon season of 2017, the well numbered 10 shows less value of pH than the permissible limits. The monsoon season data for pH parameter are considered from June 2013 to October 2013 and June 2014 to October 2014. In the monsoon season of 2013, the pH value found to be less than the permissible limit value for well numbers 2-6, 8-17, 20 and 21. In the monsoon season of 2014, the well number 2, 6 and 11 are found to be less than the permissible limit value. The post-monsoon season data of pH parameter considered from November 2013 to December 2013 and November 2014 to December 2014. In post-monsoon season 2013, well number 25 has low pH value than the permissible limit. In post-monsoon season 2014, the well number 6 has low pH value than the permissible limit. In well number 2 it may be the effect of brackish water since it is near to the coast. In other wells, it may be due to the effect of fertilizers used in agriculture.

5.2.2.2 Determination of conductivity

Conductivity is important since it is a better indicator of groundwater quality, especially in irrigation field and health. It is a good indicator of total salinity. It is necessary to understand low quality water which may have effects of sodium, fluoride and high concentrations of chloride. Conductivity is the capability of a solution such as water in a stream to pass an electric current to indicate the conductivity. In conductivity meter, the conductivity meter diode is dipped in the water sample which indicates the conductivity. Higher conductivity suggests the presence of various ions including nitrate, phosphate, and sodium. The basic unit of measurement for conductivity is micromhos per centimetre (µmhos/cm) or micro siemens per centimetre (µS/cm).

All the groundwater wells in the study area tested for conductivity parameter, found to be good and within the permissible limits for pre-monsoon season, monsoon season and post-monsoon season.

5.2.2.3 Determination of total dissolved solids

Total dissolved solids (TDS) in excess mostly shows that the water is sewage or industrial wastewater. It is necessary since it helps us to understand the standard of groundwater. Lesser the TDS is good for drinking water. TDS in water consists of inorganic solids and dissolved materials. In natural groundwater, salts are chemical compounds comprised of anions such as carbonates, chlorides, sulphates and nitrates and cations such as potassium, magnesium, calcium, and sodium. In ambient conditions, these compounds are present in proportions that create a balanced solution. If there are additional quantity of dissolved solids in the system, the balance is altered. The instrument used for identifying TDS is conductivity meter.

All the groundwater wells for TDS parameter in the study area are found to be good and within the permissible limits for pre-monsoon season, monsoon season and post-monsoon season.

5.2.2.4 Determination of carbonate and bicarbonate

The Carbonate and Bicarbonate have a huge role in freshwater content. It found to be necessary since it formed from the dissolution of Carbonate minerals, decomposition of organic matter and exchange of carbon cycling (Zhan et al. 2016). Carbonate and Bicarbonate in water can be determined by titrating a known volume of the sample against diluted H_2SO_4 solution using phenolphthalein and Methyl orange as indicators.

All the groundwater wells for the Carbonate parameter in the study area are found to be good and within the permissible limits for pre-monsoon season, monsoon season and post-monsoon season.

In the Bicarbonate parameter for pre-monsoon season, it is found that well number 1, 2 and 3 have high concentration values than the permissible limits. The high concentration of the Bicarbonate parameter indicates mineral dissolution (Prasanth et al. 2012). In monsoon and post-monsoon season the Bicarbonate parameter in the study area is found to be good and within the permissible limit for all the wells.

5.2.2.5 Determination of chloride

As per WHO, in humans, 88% of chloride is extracellular and contributes to the osmotic activity of body fluids. The electrolyte balance in the body is maintained by adjusting the total dietary intake and by excretion via the kidneys and gastrointestinal tract. Chloride is almost completely absorbed in normal individuals, mostly from the proximal half of the small intestine. In a neutral or slightly alkaline solution, potassium chromate can indicate the end point of the silver nitrate titration of chloride. Silver chloride is precipitated quantitatively before red silver chromate is formed in the laboratory test for chlorides.

All the groundwater wells in the study area for chloride parameter are found to be good and within the permissible limits for pre-monsoon season, monsoon season and post-monsoon season.

Environmental significance of chlorides associated with sodium exerts salty taste when its concentration is more than 250 mg/l. There is no evidence that chlorides constitute any human health hazards. For this reason, chlorides are generally limited to 250 mg/l in water supplies intended for public use.

5.2.2.6 Determination of Total Hardness

According to WHO, the total hardness does not have any adverse effect on a human being. The very hard water may contribute more to calcium and Magnesium parameter. The high intake of total hardness may cause intestinal problems. Total hardness is determined when the dye Erichrome Black T (EBT) indicator when added to a solution containing calcium and magnesium, a wine-red colour is formed and when it is titrated with Ethylene Diamine Tetra-Acetic acid (EDTA), replacing calcium and magnesium ions, giving blue colour.

All the groundwater wells in the study area are found to be good and within the permissible limits for pre-monsoon season, monsoon season and the post-monsoon season for the total hardness parameter tested.

5.2.2.7 Determination of Sulphate

Sulphate can be found almost in all source of water. The origin of sulphate is mostly of industrial waste. High concentrations of sulphate in water can have a laxative effect. Drinking water with high levels of sulphate can cause dehydration and diarrhoea.

The sulphate concentration present in the water sample is analysed using a spectrophotometer. The sulphate ions are precipitated in an acetic acid medium with barium chloride ($BaCl_2$) to form barium sulphate ($BaSO_4$) crystals of uniform size. Light absorbance of ($BaSO_4$) suspension is measured by a spectrophotometer and the sulphate ion concentration is determined by comparing the reading with the standard curve.

All the groundwater wells in the study area for sulphate parameter are found to be good and within the permissible limits for pre-monsoon season, monsoon season and post-monsoon season.

5.2.2.8 Determination of Sodium and Potassium

In drinking water, sodium can occur naturally or be the result of road salt application, water treatment chemicals or ion-exchange water-softening units. The human body needs sodium in order to maintain blood pressure, control fluid levels and for normal nerve and muscle function. Sodium in drinking water is not a health concern for most people but maybe for someone with specific health issues that require them to be on a sodium-restricted diet. As per WHO standards, the potassium is an essential element in humans. The increased exposure to potassium for human beings may result in kidney disease or other conditions such as heart disease, hypertension, diabetes, adrenal insufficiency and pre-existing hyperkalaemia. The amount of sodium and potassium content present in the water sample is analysed by using sodium flame emission photometer.

All the groundwater wells in the study area for parameters sodium and potassium are found to be good and within the permissible limits for pre-monsoon season, monsoon season and post-monsoon season.

5.2.2.9 Determination of Calcium

Calcium is naturally present in water. When one takes up large amounts of calcium this may negatively influence human health. A 20 mL sample was taken in a beaker and 2 mL 1N NaOH and mureoxide are added. The titration carried out against EDTA continued until the colour changes from red to blue-violet. It is further calculated from Eq. (5.1).

$$Ca^{2+} \rightarrow (A*B*1000)/100mL \tag{5.1}$$

Where A is the mL titrant of the sample and B is the normality of EDTA

All the groundwater wells in the study area for calcium parameter are found to be good and within the permissible limits for pre-monsoon season, monsoon season and post-monsoon season.

5.2.2.10 Determination of magnesium

Magnesium originates from rocks. In drinking water guideline, there is no magnesium toxicity. A large overdose of magnesium may cause vomiting and diarrhoea. Magnesium is calculated by the following equation,

$$Mg^{2+} = TH - Ca^{2+} \tag{5.2}$$

All the groundwater wells in the study area for magnesium parameter are found to be good and within the permissible limits for pre-monsoon season, monsoon season and post-monsoon season.

5.3 Statistical analysis of groundwater quality

The statistical analysis of groundwater quality plays an important role in the determination of the characteristics of groundwater quality. In this study, different statistical methods such as Sodium absorption ratio, Piper Plot, Significant Chemical parameter, Factor of sea parameter correlation and Groundwater Quality Status. Panaskar et al. (2016). Tomaszkiewicz et al. (2014), Forcada (2014) and Askri (2015) considered the traditional increase of Cl concentration mainly due to the mixing of the seawater and freshwater which was easily traceable due to the conservative nature of the anion. The fraction of seawater (Fsea) in a water sample can be determined using the concentration of Cl, as shown in Eq. (2.1). The Fsea value ranges from 0 to 100, where the freshwater value starts from 0 and seawater value ends in 100. Groundwater quality parameter can be plotted on the piper plot diagram (Yang et al. 2016), which provides good inferences to understand groundwater contamination. The unit considered for the chemical parameters of the piper plot is milliequivalents per litre (meq/l). Sodium Absorption Ratio (SAR) is considered for groundwater contamination of sodium and given in Eq. (2.3). (Edet 2016). The permissible limit of SAR value is less than 10 for freshwater.

5.4 RESULTS AND DISCUSSION

5.4.1 Laboratory results

The laboratory results from the month of January to December for different years are given in Table 5.2–5.13. In these tables represent the groundwater quality results of different parameters such as pH, EC, TDS, HCO_3, CO_3, Ca, Na, K, Mg and Cl. The laboratory results of these parameters are compared with the permissible limits value. Based on the comparative results of groundwater wells and permissible limits, the quality of groundwater wells in month wise for different parameters can be observed. These results help to understand the status of the groundwater quality in different seasons.

In the pH groundwater quality parameter data for the month of January 2013, from Table 5.2 it is seen that the well number 2,5,8-11,14,16,17,20 and 21 have acidic characteristic since it shows the less values than the permissible limit. In the month of January 2014, it is found that all the groundwater wells for pH parameters are found to be within permissible limits. In January 2017, the pH value for the well number 10 and 22 are found to be less than the permissible limit. The bicarbonate parameter shows the high value than the permissible limit for the well number 1-14 and 17-22 in the month of January 2013. In the month of January 2014 and 2017, all the wells are within the permissible limit for the Bicarbonate parameter. All the other groundwater quality parameters such as EC, TDS and Cl are found to be within the permissible limit for the month of January 2013, 2014 and 2017. Ca, Mg, Total Hardness, Na, K and SO_4 are found to be within the permissible limit for the month of January 2017.

Table 5.3 shows the different groundwater quality parameters for the month of February 2013, 2014 and 2017. The pH parameter for February 2013 shows the well number 2-5, 7-12, 14-17 and 19-22 have values less than permissible limits. In February 2014, the pH value of well number 2 have less value than the permissible limit. In February 2017, the pH value of well number 5 and 10 have values less than the permissible limits. This indicates the acidic nature of the well samples. In Bicarbonate parameters, for the month of February 2013 it is found that well number 1,2, 16 and 18 found to be slightly higher than the permissible limits. The well number 7 found to be very much higher than the permissible limits. In the month of February 2014 and 2017, all the wells are within the permissible limit for the Bicarbonate parameter. All the other groundwater quality parameters such as EC, TDS and Cl are found to be within the permissible limit for the month of February 2013, 2014 and 2017. Ca, Mg, Total Hardness, Na, K and SO_4 are found to be within the permissible limit for the month of February 2017.

The pH value for the month March 2013 infers the well number 2, 8-11, 14-16,20 and 21 have values lesser than the permissible from Table 5.4. The well number 2 of pH parameter also has less values than permissible limits in the month of March 2014.In March 2017, the pH parameter for all the groundwater wells are found to be within permissible limit and good quality. All the other groundwater quality parameters such as EC, TDS, HCO_3 and Cl are found to be within the permissible limit for the month of March 2013, 2014 and 2017. Ca, Mg, Total Hardness, Na, K and SO_4 are found to be within the permissible limit for the month of March 2017.

Table 5.5 represents the laboratory results of the groundwater quality data for the month of April. The pH for the month of April 2013 indicates that the well number 2-4, 7-11, 14-17 and 20-22 shows the value less than the permissible limits. In the month of April 2014, the well number 2 shows the least value of 4.6 pH considering the permissible limits. In April 2016, the well number 2 and 25 are found to have low pH value than the permissible limits. The pH value found to be less than the permissible limits in the wells 5, 7-15, 17-18, 22 and 25 for the month of April 2017. The bicarbonate parameter for the month of April 2013 is found to be less than the permissible limits in well number 1 and 2. In the month of April 2014, 2016 and 2017 all the wells are within the permissible limit for the Bicarbonate parameter. All the other groundwater quality parameters such as EC, TDS and Cl are found to be within the permissible limit for the month of April 2013, 2014, 2016 and 2017. Ca, Mg, Total Hardness, Na, K and SO_4 are found to be within the permissible limit for the month of April 2016 and 2017.

The pH value for the month of May 2013 from Table 5.6 shows that the well number 2-4, 7-9, 11, 14-16, 18 and 20-22 have low values than the permissible limits. In May 2014, the pH value is found to be less than the permissible limits for the well number 2,8 and 10. In the month of May 2016, the well number 2-4, 7, 9, 14-18 and 20-23 has pH value less than the permissible limits. In the month of May 2017, the pH value is found to be less than the permissible limits for the well number 1, 3 and 4. In the EC parameter for the month of May 2013, the well number 3 is found to be higher than the permissible limits. In the month of May 2014, 2016 and 2017 of EC parameter values are found to be within the permissible limits and good groundwater quality. In the HCO_3 parameter for the month of May 2013, it is found that well number 1, 3, 10, 11 and 20-22 are found to be higher than the permissible limits. In the month of May 2014, 2016 and 2017 all the wells are within the permissible limit for the HCO_3 parameter. All the other groundwater quality parameters such as EC, TDS and Cl are found to be within the permissible limit for the month of May 2013, 2014, 2016 and 2017. Ca, Mg, Total Hardness, Na, K and SO_4 are found to be within the permissible limit for the month of May 2016 and 2017.

Table 5.7 shows the laboratory groundwater quality parameters result data for the month of June. In June 2013, the pH parameter for the groundwater wells 2-5, 8, 9, 13-17, 19-22 are found to be less than the permissible limits. In June 2014, the pH parameter value for the groundwater wells 2, 11, 12, 20 and 25 are found to be less than the permissible limits. All the other groundwater quality parameters such as EC, TDS, HCO_3 and Cl, are found to be within the permissible limit for the month of June 2013 and 2014.

The pH parameter for the month of July 2013 from Table 5.8 shows that the well number 2-6, 8-16, 20 and 21 have low value than the permissible limits. In July 2014, the pH parameter of the well number 2, 5, 6, 10, 11 and 15 is found to be less than the permissible limits and it shows the acidic characteristics. The pH parameter for the month of July 2016 shows that well number 2, 5, 9 and 20-22 are found to have low value than permissible limits. In the HCO_3 parameter for the month of July 2013, the well number 4 shows slightly high concentration than the permissible limits. In July 2014, the HCO_3 parameter of the well number 11 shows the high value than the permissible limits. In July 2016, the HCO_3 parameter for all the wells found to be within the permissible limits. All the other groundwater quality parameters such as EC, TDS and Cl are found to be within the permissible limit for the month of July 2013, 2014 and 2016. Ca, Mg, Total Hardness, Na, K and SO_4 are found to be within the permissible limit for the month of July 2016.

Table 5.9 shows the laboratory groundwater quality parameter result data for the month of August 2013 and August 2014. The pH parameter for the month of August 2013 shows that well number 2, 3, 5, 6, 8-17, 20 and 21 have low value than the permissible limits which indicate the acidic nature. In August 2014, the pH parameter for the well number 2, 6, 13 and 22 have low value than the permissible limits. In the HCO_3 parameter for the month of August 2013, well number 19 and 21 are found to be higher than the permissible limits values. In August 2014, the HCO_3 parameter for all the wells are found to be within permissible limits and good quality. All the other groundwater quality parameters such as EC, TDS and Cl are found to be within the permissible limit for the month of August 2013 and 2014.

The pH parameter for the month of September 2013 represented in Table 5.10 shows well number 2, 3, 5, 8-15, 20, 21 and 25 have low values than the permissible limits which shows the acidic character of groundwater wells. In the month of September 2014, the well number 2, 6 and 11 have low value than the permissible limits of pH parameter. All the other groundwater quality parameters such as EC, TDS HCO_3 and Cl are found to be within the permissible limit for the month of September 2013 and 2014.

Table 5.11 shows the pH parameter for the month of October 2013 in the well number 2-6, 8-17, 20-22 and 25 have low values than the permissible limits. In October 2014, the well number 6 found to be low values of pH parameters than the permissible limits. All the other groundwater quality parameters such as EC, TDS HCO_3 and Cl are found to be within the permissible limit and good groundwater quality for the month of October 2013 and 2014.

In the pH parameter for the month of November 2013, the well number 2, 3, 5, 8-12, 15, 16, 20-22 and 25 from Table 5.12 have low value than the permissible limit value. For pH in November 2014, the well number 6 is low pH value than permissible limits, which shows acidic nature. All the other groundwater quality parameters such as EC, TDS, HCO_3 and Cl are found to be within the permissible limit and good groundwater quality for the month of November 2013 and 2014.

Table 5.13 shows the laboratory results of groundwater quality parameter for the month of December 2013 and 2014. The pH parameter for the month of December 2013, shows that the groundwater well 25 found to be 5.3 which is less than the permissible limit and indicate the acidic nature. In December 2014, well no 6 has low pH value than the permissible limit. All the other groundwater quality parameters such as EC, TDS, HCO_3 and Cl are found to be within the permissible limit and good groundwater quality for the month of December 2013 and 2014.

Table 5.2 Groundwater quality data for the month of January

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.1	6.4	7.0	6.6	6.4	7.2	6.8	6.3	6.4	6.4	5.9	6.5	6.8	6.3	6.6	6.4	6.4	6.7	6.7	5.8	6.2	6.9	-	-	-	6.5 – 8.5
	2014	8.3	7.0	8.3	8.2	7.8	8.2	8.2	7.6	7.8	7.8	7.7	7.7	8.0	7.9	7.9	8.3	7.8	8.3	8.2	7.9	8.1	8.3	8.4	8.1	7.8	
	2017	7.5	7.7	7.7	8.1	7.7	8.2	7.3	7.7	7.6	6.2	8.3	7.7	7.7	7.1	7.3	6.8	6.9	7.2	7.3	7.6	7.6	6.2	7.7	7.1	6.6	
EC (µS/cm)	2013	452.0	99.2	48.6	362.0	196.0	160.0	752.0	184.0	211.0	121.0	59.2	201.0	61.1	140.0	137.0	329.0	306.0	279.0	200.0	156.0	285.0	413.0	-	-	-	700 - 2000
	2014	252.0	352.0	283.0	245.0	155.0	120.0	514.0	140.0	153.0	90.0	41.0	140.0	239.0	109.0	122.0	321.0	189.0	198.0	371.0	116.0	232.0	303.0	253.0	341.0	221.0	
	2017	537.0	261.0	293.0	326.0	166.0	99.0	545.0	141.0	174.0	109.0	65.0	273.0	224.0	127.0	143.0	264.0	163.0	238.0	461.0	149.0	240.0	282.0	278.0	285.0	193.0	
TDS (mg/l)	2013	209.0	64.0	21.8	86.2	88.9	74.7	343.0	31.2	95.3	54.6	27.6	92.1	147.0	44.8	51.6	206.0	139.0	108.0	91.2	70.3	61.9	191.0	-	-	-	500 - 2000
	2014	156.0	218.0	175.0	152.0	96.0	74.0	319.0	87.0	95.0	56.0	25.0	87.0	148.0	68.0	76.0	199.0	117.0	123.0	230.0	72.0	144.0	188.0	157.0	211.0	138.0	
	2017	333.0	162.0	182.0	202.0	103.0	61.0	338.0	87.0	108.0	68.0	40.0	169.0	139.0	79.0	89.0	164.0	101.0	148.0	286.0	92.0	149.0	175.0	172.0	177.0	120.0	
HCO_3 (mg/l)	2013	1785.0	714.0	2034.9	892.5	963.9	928.2	1320.9	1428.0	714.0	714.0	1892.1	1285.2	1428.0	1142.4	535.5	535.5	1892.1	1071.0	678.3	999.6	1249.5	1071.0	-	-	-	200 - 600
	2014	285.6	178.5	357.0	357.0	178.5	249.9	428.4	214.2	392.7	249.9	178.5	285.6	285.6	214.2	214.2	285.6	357.0	357.0	535.5	178.5	357.0	428.4	285.6	357.0	285.6	
	2017	218.0	36.0	142.0	124.0	37.0	79.0	180.0	38.0	49.0	52.0	25.0	106.0	70.0	53.0	49.0	79.0	94.0	118.0	178.0	27.0	70.0	124.0	109.0	144.0	40.0	
Cl (mg/l)	2013	26.3	68.3	26.8	31.7	25.4	16.1	76.6	33.2	22.4	18.0	16.6	29.3	21.9	17.6	21.9	44.9	19.5	24.4	26.3	27.8	38.0	25.4	-	-	-	250 - 1000
	2014	29.3	58.0	51.2	28.3	19.5	12.7	71.7	26.8	32.2	17.5	15.1	21.4	24.4	14.6	18.5	35.1	19.0	16.6	21.0	26.8	34.1	25.0	22.4	26.3	29.7	
	2017	84.1	55.1	57.0	52.3	33.7	21.8	110.7	36.1	53.2	21.9	17.1	45.6	32.8	23.7	24.2	39.0	196.2	23.7	64.1	32.8	46.1	27.1	32.8	42.3	28.5	
Ca (mg/l)	2017	33.6	50.4	35.7	55.7	53.5	31.5	207.9	63.0	33.6	30.5	21.0	87.2	31.5	33.6	48.3	63.0	45.2	112.4	126.0	24.2	51.5	112.4	112.4	120.8	57.8	75 - 200
Mg (mg/l)	2017	15.4	30.6	4.3	13.3	9.5	10.5	32.1	9.0	34.4	17.5	42.0	38.8	8.5	30.4	38.7	72.0	18.8	34.6	54.0	29.8	60.5	5.6	27.6	51.2	32.2	30 - 100
Total hardness (mg/l)	2017	49.0	81.0	40.0	69.0	63.0	42.0	24.0	72.0	68.0	48.0	63.0	126.0	40.0	64.0	87.0	135.0	64.0	147.0	180.0	54.0	112.0	118.0	140.0	172.0	90.0	100 - 500
Na (mg/l)	2017	28.9	19.2	8.2	6.8	0.0	0.0	29.5	0.0	0.0	0.0	0.0	14.4	1.6	0.0	0.0	5.1	2.5	0.0	23.1	0.0	11.0	0.0	5.1	7.0	0.0	10 - 100
K (mg/l)	2017	5.5	6.3	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0	0.0	1.0	1.5	3.2	0.0	9.2	1.5	2.4	0.0	0.0	2.0	25.1	5.1	6.8	4.6	10 - 100
SO_4 (mg/l)	2017	17.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.2	0.0	0.1	23.1	13.8	9.8	30.8	0.0	15.3	20.4	27.0	28.5	11.3	200 - 400

(*Data of Ca, Mg, Total hardness, Na, K and SO_4 for the year 2013 and 2014 are not available)

5.3 Groundwater quality data for the month of February

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	6.8	6.2	6.2	6.2	6.2	6.5	6.4	6.1	6.1	6.3	6.0	6.4	6.5	6.0	5.8	6.2	6.3	6.5	6.4	5.5	6.1	6.4	-	-	-	6.5 – 8.5
	2014	8.3	6.0	8.1	8.2	8.1	8.2	8.6	7.9	8.1	8.2	7.4	8.1	8.2	7.6	7.7	8.3	8.2	8.4	8.4	7.5	8.1	8.3	8.3	8.4	6.7	
	2017	7.1	7.5	7.6	7.3	5.9	8.0	8.0	7.9	7.8	6.4	7.9	7.6	6.9	7.8	6.9	8.0	7.4	6.8	7.6	7.6	7.5	7.8	7.4	7.8	7.1	
EC (µS/cm)	2013	361.0	488.0	764.0	302.0	185.0	121.0	536.0	168.0	168.0	103.0	50.6	200.0	285.0	126.0	122.0	421.0	259.0	320.0	153.0	132.0	271.0	374.0	-	-	-	700 - 2000
	2014	312.0	353.0	426.0	254.0	165.0	126.0	397.0	138.0	163.0	96.0	44.0	143.0	263.0	111.0	122.0	311.0	183.0	209.0	366.0	118.0	228.0	292.0	262.0	320.0	222.0	
	2017	503.0	253.0	309.0	295.0	167.0	76.0	462.0	126.0	169.0	147.0	49.0	245.0	218.0	120.0	137.0	246.0	142.0	234.0	462.0	112.0	243.0	283.0	307.0	301.0	188.0	
TDS (mg/l)	2013	162.0	225.0	345.0	133.0	84.1	55.8	239.0	76.4	75.8	47.4	22.9	92.2	130.0	56.9	55.9	192.0	20.7	141.0	68.9	60.5	123.0	169.0	-	-	-	500 - 2000
	2014	193.0	219.0	264.0	157.0	102.0	121.0	246.0	86.0	101.0	60.0	27.0	89.0	163.0	69.0	76.0	193.0	113.0	130.0	227.0	73.0	141.0	181.0	162.0	198.0	138.0	
	2017	312.0	157.0	192.0	183.0	104.0	47.0	286.0	78.0	105.0	91.0	30.0	152.0	135.0	74.0	85.0	153.0	88.0	145.0	286.0	69.0	101.0	175.0	190.0	187.0	117.0	
HCO_3 (mg/l)	2013	642.6	606.9	285.6	285.6	464.1	357.0	1356.6	249.9	321.3	357.0	535.5	571.2	392.7	249.9	357.0	606.9	571.2	642.6	285.6	249.9	535.5	535.5	-	-	-	200 - 600
	2014	285.6	214.2	249.9	285.6	178.5	357.0	428.4	142.8	285.6	214.2	142.8	214.2	249.9	214.2	178.5	249.9	249.9	285.6	535.5	321.3	285.6	392.7	428.4	357.0	214.2	
	2017	190.0	27.0	129.0	132.0	55.0	52.0	142.0	48.0	58.0	60.0	32.0	93.0	90.0	57.0	48.0	72.0	82.0	120.0	190.0	42.0	72.0	130.0	131.0	131.0	48.0	
Cl (mg/l)	2013	24.4	68.3	156.0	22.0	24.0	11.2	161.0	60.0	56.0	40.0	28.3	25.8	48.8	19.5	22.0	102.4	41.4	80.4	17.1	29.2	39.0	63.4	-	-	-	250 - 1000
	2014	40.0	57.0	94.0	27.8	23.0	14.6	66.8	25.3	30.2	16.6	13.6	20.5	24.4	14.6	20.0	36.0	15.1	17.1	21.4	24.9	35.1	24.4	28.8	29.2	26.8	
	2017	77.0	56.0	64.1	51.0	33.3	16.2	107.0	26.6	50.4	19.0	17.6	52.3	31.0	26.1	27.1	40.0	19.0	24.2	64.1	34.7	47.5	26.6	45.1	53.7	32.3	
Ca (mg/l)	2017	35.7	63.0	70.4	133.4	52.5	39.9	129.2	34.7	115.5	52.5	33.6	65.1	78.8	52.5	59.9	59.9	31.5	110.3	55.7	147.0	59.9	110.3	136.5	177.5	83.0	75 - 200
Mg (mg/l)	2017	54.3	80.0	119.7	66.7	23.5	6.1	49.9	39.4	36.5	23.5	48.4	13.9	49.3	16.5	2.2	49.2	73.5	37.8	91.4	22.0	34.2	51.8	18.5	20.6	14.1	30 - 100
Total hardness (mg/l)	2017	90.0	143.0	190.0	200.0	76.0	46.0	179.0	74.0	152.0	76.0	82.0	79.0	128.0	69.0	62.0	109.0	105.0	148.0	147.0	169.0	94.0	162.0	155.0	198.0	97.0	100 - 500
Na (mg/l)	2017	26.7	17.5	68.2	4.6	0.7	0.0	24.1	0.0	0.0	0.0	0.0	13.4	0.0	0.0	0.0	4.8	2.9	0.0	23.2	0.0	9.7	0.0	4.7	7.9	0.0	10 - 100
K (mg/l)	2017	5.2	6.0	0.0	0.0	1.3	0.0	2.5	0.9	0.0	1.0	0.0	1.1	1.5	3.2	0.0	8.9	0.0	2.5	1.0	0.0	2.0	25.1	5.8	7.8	4.3	10 - 100
SO_4 (mg/l)	2017	745.5	63.9	47.9	52.3	22.7	14.6	33.8	28.4	0.0	1.1	0.0	6.6	38.9	2.4	7.9	22.4	11.4	12.9	29.0	0.0	15.0	19.5	31.1	16.4	31.6	200 - 400

(*Data of Ca, Mg, Total hardness, Na, K and SO_4 for the year 2013 and 2014 are not available)

Table 5.4 Groundwater quality data for the month of March

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.1	6.4	6.7	6.5	6.5	7.1	6.6	6.0	6.2	6.3	5.9	6.8	6.9	6.1	5.8	6.4	6.7	6.8	6.7	5.7	6.1	6.5	-	-	-	6.5 – 8.5
	2014	8.2	6.4	7.9	7.9	7.6	7.6	8.1	7.4	7.6	7.5	7.2	8.0	7.7	7.5	7.5	8.1	8.1	8.0	8.2	6.4	7.8	8.2	8.1	8.2	7.4	
	2017	7.1	7.2	7.5	8.1	7.9	8.0	7.9	7.2	7.2	7.3	7.5	7.2	7.3	7.4	7.1	7.1	7.7	7.1	7.1	7.4	7.1	7.5	7.4	7.4	7.4	
EC (µS/cm)	2013	260.0	380.0	680.0	220.0	147.0	79.0	360.0	133.0	98.0	85.0	39.0	140.0	195.0	102.0	96.0	250.0	180.0	230.0	110.0	91.0	178.0	260.0	-	-	-	700 - 2000
	2014	422.0	412.0	553.0	278.0	198.0	120.0	360.0	169.0	178.0	123.0	58.0	156.0	321.0	131.0	157.0	375.0	228.0	238.0	451.0	142.0	258.0	382.0	308.0	322.0	243.0	
	2017	464.0	264.0	328.0	352.0	191.0	76.0	444.0	137.0	174.0	197.0	53.0	257.0	233.0	139.0	136.0	255.0	147.0	267.0	456.0	128.0	243.0	288.0	274.0	350.0	165.0	
TDS (mg/l)	2013	137.0	149.0	450.0	140.0	96.0	52.0	145.0	87.0	65.0	56.0	26.0	92.0	129.0	68.0	63.0	139.0	119.0	144.0	73.0	60.0	117.0	129.0	-	-	-	500 - 2000
	2014	262.0	255.0	343.0	172.0	123.0	74.0	223.0	105.0	110.0	76.0	36.0	98.0	199.0	81.0	97.0	233.0	141.0	148.0	280.0	88.0	160.0	237.0	191.0	200.0	151.0	
	2017	288.0	164.0	203.0	218.0	118.0	47.0	275.0	85.0	108.0	122.0	33.0	159.0	144.0	86.0	84.0	158.0	91.0	166.0	283.0	79.0	151.0	179.0	170.0	217.0	102.0	
HCO_3 (mg/l)	2013	499.8	535.5	571.2	357.0	357.0	357.0	571.2	285.6	357.0	392.7	249.9	285.6	285.6	214.2	249.9	535.5	285.6	428.4	214.2	214.2	285.6	499.8	-	-	-	200 - 600
	2014	178.5	107.1	107.1	214.2	142.8	285.6	178.5	107.1	107.1	178.5	142.8	357.0	142.8	178.5	142.8	107.1	107.1	214.2	357.0	142.8	107.1	142.8	214.2	178.5	214.2	
	2017	243.0	67.0	152.0	148.0	87.0	52.0	168.0	45.0	60.0	110.0	35.0	95.0	85.0	65.0	48.0	87.0	83.0	125.0	219.0	40.0	82.0	109.0	100.0	110.0	34.0	
Cl (mg/l)	2013	27.3	73.6	268.0	139.0	30.0	14.6	87.8	32.2	73.0	88.3	118.0	79.5	105.3	22.0	81.4	157.5	123.8	114.1	38.0	30.7	97.5	124.3	-	-	-	250 - 1000
	2014	36.0	50.0	102.0	24.0	21.0	9.0	51.0	22.0	25.0	12.0	9.0	21.0	25.0	10.0	18.5	28.3	12.2	14.6	20.0	9.7	28.3	21.0	24.4	25.8	22.4	
	2017	54.6	45.1	55.6	50.4	32.3	16.2	78.9	25.2	43.7	17.6	18.5	37.5	29.5	25.2	27.1	34.2	19.5	31.4	55.1	28.5	42.3	26.1	30.9	48.5	32.3	
Ca (mg/l)	2017	248.9	54.6	80.9	103.0	55.7	39.9	78.8	33.6	42.0	58.8	7.4	84.0	56.7	29.4	41.0	57.8	37.8	37.8	55.7	33.6	48.3	41.0	78.8	106.1	30.5	75 - 200
Mg (mg/l)	2017	61.2	16.4	64.2	47.0	15.4	6.1	156.3	28.4	14.0	31.2	9.7	18.0	32.3	10.6	13.1	27.3	12.2	85.2	129.4	11.4	32.7	54.1	35.3	7.0	16.6	30 - 100
Total hardness (mg/l)	2017	310.0	71.0	145.0	150.0	71.0	46.0	235.0	62.0	56.0	90.0	17.0	102.0	89.0	40.0	54.0	85.0	50.0	123.0	185.0	45.0	81.0	95.0	114.0	113.0	47.0	100 - 500
Na (mg/l)	2017	26.8	21.7	9.7	8.5	1.4	0.0	23.6	0.0	0.0	0.0	0.0	18.3	3.3	0.0	0.0	5.9	6.3	0.0	26.6	0.0	12.1	0.0	1.1	17.9	0.0	10 - 100
K (mg/l)	2017	2.8	5.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	1.6	0.0	10.3	0.0	1.7	0.0	0.0	0.1	27.5	4.7	6.2	2.8	10 - 100
SO_4 (mg/l)	2017	35.3	11.9	0.0	4.7	3.7	14.6	6.1	11.7	0.0	0.0	0.3	7.9	42.8	24.2	31.6	48.3	30.0	31.8	38.9	21.0	15.1	13.8	25.4	16.4	26.0	200 - 400

(*Data of Ca, Mg, Total hardness, Na, K and SO_4 for the year 2013 and 2014 are not available)

Table 5.5 Groundwater quality data for the month of April

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.0	6.1	6.3	6.4	6.6	7.3	6.0	5.9	6.0	6.3	6.1	6.7	6.7	5.9	5.5	6.2	6.3	6.5	6.7	5.6	5.9	6.3	-	-	-	6.5 – 8.5
	2014	8.2	4.6	7.6	7.9	7.6	7.9	8.1	7.6	7.7	7.8	7.2	8.1	7.9	7.7	7.1	7.9	7.9	8.0	8.3	7.8	7.7	7.5	7.7	7.4	7.7	
	2016	6.9	6.4	7.4	6.9	7.0	7.5	7.3	7.4	6.6	7.6	7.7	6.7	6.8	6.8	6.7	6.8	6.7	6.7	7.0	6.6	6.5	6.6	7.0	7.1	6.3	
	2017	7.3	7.5	7.2	7.5	6.4	8.0	6.3	6.4	6.3	6.4	6.3	5.9	6.0	6.3	6.2	6.7	6.4	6.4	6.6	6.7	7.1	6.4	6.7	6.9	6.4	
EC (µS/cm)	2013	132.0	149.0	182.0	115.0	79.0	40.0	155.0	70.0	58.0	45.0	21.0	90.0	119.0	43.0	52.0	159.0	96.0	83.0	76.0	50.0	111.0	148.0	-	-	-	700 - 2000
	2014	388.0	475.0	645.0	289.0	194.0	121.0	422.0	179.0	180.0	140.0	55.0	228.0	302.0	142.0	154.0	345.0	210.0	288.0	360.0	138.0	267.0	392.0	442.0	366.0	279.0	
	2016	500.0	298.0	435.0	235.0	180.0	95.0	407.0	142.0	197.0	102.0	43.0	236.0	257.0	98.0	144.0	358.0	185.0	237.0	451.0	124.0	232.0	322.0	356.0	356.0	171.0	
	2017	600.0	278.0	429.0	347.0	168.0	76.0	443.0	129.0	169.0	206.0	62.0	276.0	249.0	147.0	134.0	272.0	129.0	212.0	445.0	117.0	243.0	276.0	255.0	484.0	164.0	
TDS (mg/l)	2013	82.0	92.0	112.0	71.0	49.0	24.0	96.0	43.0	36.0	28.0	13.0	55.0	74.0	27.0	32.0	99.0	59.0	79.0	47.0	31.0	68.0	92.0	-	-	-	500 - 2000
	2014	241.0	295.0	400.0	179.0	120.0	75.0	262.0	111.0	112.0	87.0	34.0	141.0	187.0	88.0	95.0	214.0	130.0	179.0	223.0	86.0	166.0	243.0	274.0	227.0	173.0	
	2016	310.0	185.0	270.0	146.0	112.0	59.0	252.0	88.0	122.0	63.0	27.0	146.0	159.0	61.0	89.0	222.0	115.0	147.0	280.0	77.0	144.0	200.0	221.0	221.0	106.0	
	2017	372.0	172.0	266.0	215.0	104.0	47.0	275.0	80.0	105.0	128.0	38.0	171.0	154.0	91.0	83.0	169.0	80.0	131.0	276.0	73.0	151.0	171.0	158.0	300.0	102.0	
HCO_3 (mg/l)	2013	714.0	678.3	357.0	464.1	249.9	249.9	535.5	357.0	357.0	214.2	392.7	464.1	571.2	357.0	428.4	535.5	535.5	428.4	535.5	357.0	249.9	464.1	-	-	-	200 - 600
	2014	178.5	499.8	357.0	142.8	214.2	142.8	178.5	142.8	178.5	142.8	142.8	107.1	142.8	107.1	107.1	214.2	178.5	178.5	249.9	357.0	107.1	285.6	178.5	285.6	285.6	
	2016	357.0	71.4	357.0	214.2	71.4	107.1	142.8	142.8	107.1	107.1	107.1	285.6	142.8	107.1	71.4	214.2	107.1	249.9	214.2	107.1	107.1	214.2	178.5	178.5	71.4	
	2017	198.0	50.0	155.0	92.0	42.0	52.0	118.0	41.0	43.0	105.0	33.0	98.0	80.0	50.0	39.0	85.0	65.0	114.0	171.0	35.0	82.0	98.0	93.0	112.0	29.0	
Cl (mg/l)	2013	195.0	164.0	317.0	137.0	107.0	44.0	171.0	91.0	122.0	90.0	78.0	171.0	89.0	83.0	75.0	127.0	96.0	110.0	45.0	111.0	122.0	102.0	-	-	-	250 - 1000
	2014	43.0	49.0	118.0	24.4	20.5	21.0	49.0	24.4	24.9	14.6	8.3	20.5	24.4	13.2	19.5	25.8	12.2	19.5	19.5	20.5	35.6	24.4	49.0	27.3	23.4	
	2016	70.6	60.9	71.1	30.7	34.1	27.3	90.6	30.7	61.4	21.9	32.6	36.5	31.6	31.6	25.3	57.0	21.9	35.5	68.2	34.1	40.9	29.2	41.4	46.7	47.2	
	2017	73.2	46.1	62.7	57.0	29.0	16.2	80.0	26.6	44.7	21.4	16.6	42.8	35.2	22.3	27.6	38.0	19.0	23.8	42.8	27.6	42.3	24.2	26.6	78.9	31.4	
Ca (mg/l)	2016	126.0	34.7	168.0	42.0	41.0	31.5	126.0	21.0	42.0	21.0	10.5	51.5	81.9	25.2	33.6	74.6	37.8	110.3	112.4	26.3	58.8	84.0	121.8	121.8	35.7	75 - 200
	2017	174.3	52.5	147.0	94.5	37.8	39.9	68.3	27.3	31.5	54.6	10.5	41.0	43.1	42.0	42.0	39.9	35.7	52.5	84.0	21.0	48.3	84.0	91.4	65.1	22.1	
Mg (mg/l)	2016	42.0	15.4	32.0	50.0	12.1	16.5	24.0	17.0	22.0	25.0	7.5	21.6	4.1	11.8	10.4	38.5	8.2	8.8	57.7	23.8	4.2	15.0	1.2	0.2	4.3	30 - 100
	2017	59.7	14.5	45.0	38.5	22.2	6.1	101.8	19.7	46.5	55.4	16.5	46.1	49.0	18.0	12.0	65.1	7.3	62.5	98.0	7.0	32.7	12.0	13.7	74.9	16.0	
Total hardness (mg/l)	2016	168.0	50.0	200.0	92.0	53.0	48.0	150.0	38.0	64.0	46.0	18.0	73.0	86.0	37.0	44.0	113.0	46.0	119.0	170.0	50.0	63.0	99.0	123.0	122.0	40.0	100 - 500
	2017	234.0	67.0	192.0	132.0	60.0	46.0	170.0	47.0	78.0	100.0	17.0	87.0	92.0	60.0	54.0	105.0	43.0	115.0	182.0	28.0	81.0	96.0	105.0	140.0	38.0	
Na (mg/l)	2016	36.5	42.4	23.9	18.6	20.0	7.8	35.6	15.5	19.0	11.5	7.3	29.8	20.7	11.4	12.3	31.4	28.7	11.7	41.0	17.4	27.6	15.2	28.8	28.0	19.8	10 - 100
	2017	36.5	22.0	7.6	6.6	1.2	0.0	22.0	0.0	0.0	0.0	0.0	18.3	4.8	0.3	0.0	7.8	0.2	0.0	26.4	0.0	12.1	0.0	4.4	32.3	0.0	
K (mg/l)	2016	10.7	15.7	5.8	7.2	7.4	6.5	8.6	7.4	7.0	7.5	6.9	8.7	8.4	11.4	6.0	19.5	6.9	9.5	8.1	6.5	9.2	39.7	12.1	17.3	12.9	10 - 100
	2017	2.9	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	1.4	0.0	9.3	0.0	0.0	0.0	0.0	0.1	24.8	3.8	6.6	1.8	
SO_4 (mg/l)	2016	11.9	2.8	0.0	9.2	0.0	0.0	0.0	9.1	0.0	0.0	0.0	8.1	32.2	8.3	9.2	28.7	12.7	9.4	25.4	0.0	16.2	13.0	39.1	8.2	10.0	200 - 400
	2017	40.6	12.1	2.5	8.5	0.5	14.6	1.6	8.3	24.1	4.4	2.4	10.6	26.6	5.7	9.9	23.7	7.3	7.4	18.3	0.0	15.1	13.5	23.0	21.4	13.4	

(*Data of Ca, Mg, Total hardness, Na, K and SO_4 for the year 2013 and 2014 are not available)

Table 5.6 Groundwater quality data for the month of May

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.0	6.3	5.9	6.4	6.9	6.8	6.4	6.0	5.7	7.2	6.1	6.7	6.8	6.1	6.3	6.3	6.5	6.3	6.5	5.7	5.5	6.4	-	-	-	6.5 – 8.5
	2014	7.1	5.1	6.7	7.0	6.8	6.7	7.0	6.4	6.7	6.4	6.5	6.8	6.5	6.5	6.9	6.8	6.5	7.1	7.0	6.5	6.7	6.6	6.7	7.0	6.5	
	2016	6.7	5.9	6.4	6.4	6.9	6.8	6.4	6.5	6.2	6.9	6.8	6.6	6.6	6.1	6.1	6.4	6.2	6.4	6.6	6.0	6.1	6.2	6.3	6.6	6.7	
	2017	6.4	6.9	6.4	6.4	7.7	8.0	7.2	7.1	7.1	7.0	7.4	6.8	6.8	6.9	6.8	6.8	6.9	6.7	6.9	7.0	6.8	6.5	6.7	6.6	7.0	
EC (µS/cm)	2013	260.0	440.0	2900.0	220.0	176.0	94.0	360.0	166.0	132.0	190.0	51.0	280.0	290.0	105.0	107.0	370.0	220.0	300.0	210.0	138.0	250.0	320.0	-	-	-	700 - 2000
	2014	419.0	485.0	575.0	374.0	199.0	146.0	582.0	187.0	183.0	84.0	56.0	240.0	303.0	144.0	147.0	370.0	204.0	273.0	312.0	147.0	292.0	379.0	309.0	462.0	262.0	
	2016	597.0	312.0	546.0	272.0	169.0	130.0	490.0	138.0	190.0	196.0	196.0	251.0	248.0	116.0	126.0	347.0	170.0	237.0	454.0	126.0	229.0	292.0	335.0	382.0	164.0	
	2017	674.0	190.0	559.0	417.0	170.0	76.0	515.0	160.0	176.0	217.0	39.0	347.0	323.0	179.0	171.0	375.0	168.0	257.0	317.0	145.0	305.0	320.0	287.0	555.0	199.0	
TDS (mg/l)	2013	160.0	270.0	1800.0	132.0	108.0	57.0	220.0	101.0	80.0	116.0	31.0	140.0	134.0	64.0	66.0	220.0	130.0	180.0	130.0	75.0	150.0	190.0	-	-	-	500 - 2000
	2014	260.0	301.0	357.0	232.0	123.0	91.0	361.0	116.0	114.0	52.0	35.0	149.0	188.0	89.0	91.0	229.0	126.0	169.0	193.0	91.0	181.0	235.0	192.0	286.0	162.0	
	2016	370.0	193.0	339.0	169.0	105.0	88.0	304.0	86.0	118.0	122.0	122.0	156.0	154.0	72.0	78.0	215.0	105.0	147.0	281.0	78.0	142.0	181.0	208.0	237.0	102.0	
	2017	418.0	118.0	347.0	259.0	105.0	47.0	319.3	99.2	109.1	134.5	24.0	215.0	200.0	111.0	106.0	232.0	104.0	159.0	197.0	90.0	189.0	198.0	178.0	344.0	123.0	
HCO_3 (mg/l)	2013	606.9	428.4	606.9	392.7	535.5	428.4	428.4	642.6	357.0	1356.6	785.4	535.5	357.0	464.1	321.3	535.5	642.6	535.5	535.5	714.0	1035.3	606.9	-	-	-	200 - 600
	2014	178.5	178.5	214.2	178.5	214.2	142.8	285.6	214.2	142.8	357.0	249.9	214.2	178.5	357.0	214.2	142.8	285.6	357.0	321.3	214.2	214.2	214.2	178.5	178.5	249.9	
	2016	214.2	142.8	321.3	107.1	214.2	107.1	249.9	142.8	107.1	214.2	249.9	142.8	214.2	214.2	107.1	214.2	107.1	214.2	285.6	107.1	142.8	178.5	178.5	249.9	107.1	
	2017	223.0	65.0	188.0	116.0	48.0	52.0	126.0	30.0	42.0	121.0	20.0	78.0	63.0	47.0	34.0	82.0	58.0	104.0	111.0	29.0	53.0	92.0	73.0	116.0	27.0	
Cl (mg/l)	2013	21.0	66.0	1038.0	28.0	26.0	22.0	61.0	37.5	27.0	11.0	16.0	40.0	25.0	15.0	18.5	42.0	15.0	27.0	17.0	18.5	43.0	29.0	-	-	-	250 - 1000
	2014	39.0	48.3	102.4	29.3	21.0	13.2	50.2	27.8	29.3	13.7	9.8	21.0	25.8	17.1	14.6	31.2	15.1	19.5	22.0	23.4	34.1	25.0	13.7	24.4	22.0	
	2016	109.8	61.0	109.8	38.1	31.7	15.0	85.4	37.1	61.0	24.4	17.6	39.0	34.2	28.3	24.4	51.2	18.1	34.6	67.3	39.5	53.7	29.3	50.0	50.3	41.0	
	2017	96.4	27.1	60.3	49.9	25.7	16.2	76.5	27.6	40.4	15.7	13.8	39.9	33.3	22.3	25.7	41.8	16.6	25.2	25.2	28.5	50.8	26.1	25.2	67.0	24.2	
Ca (mg/l)	2016	189.0	60.9	147.0	54.6	47.3	35.0	148.1	26.3	50.4	58.8	80.9	78.8	65.1	33.6	42.0	101.9	30.5	95.6	126.0	28.4	58.8	94.5	115.5	120.8	30.5	75 - 200
	2017	99.8	50.4	213.2	86.0	20.0	39.9	57.8	21.0	21.0	50.4	13.7	84.0	29.4	54.6	43.1	22.1	33.1	67.2	112.4	8.4	48.3	127.1	104.0	24.2	13.7	
Mg (mg/l)	2016	4.0	19.1	63.0	57.4	7.8	5.0	27.0	18.8	19.6	32.2	1.2	12.3	29.9	3.4	6.0	10.2	5.6	20.5	58.0	8.7	4.2	2.5	9.5	14.3	11.6	30 - 100
	2017	58.3	12.6	25.9	30.0	29.1	6.1	47.3	11.0	79.0	79.6	23.4	74.1	65.6	25.4	11.0	103.0	2.4	39.8	66.7	2.6	32.7	35.0	25.0	90.0	15.4	
Total hardness (mg/l)	2016	193.0	80.0	210.0	112.0	55.0	40.0	175.0	45.0	70.0	91.0	82.0	91.0	95.0	37.0	48.0	112.0	36.0	116.0	184.0	37.0	63.0	97.0	125.0	135.0	42.0	100 - 500
	2017	158.0	63.0	239.0	116.0	49.0	46.0	105.0	32.0	100.0	130.0	37.0	158.1	95.0	80.0	54.0	125.0	35.5	107.0	179.0	11.0	81.0	162.1	129.0	114.2	29.0	
Na (mg/l)	2016	59.5	44.0	48.1	22.1	19.2	0.0	45.3	14.8	16.6	8.7	11.9	31.4	22.6	9.3	12.7	32.9	34.3	12.0	41.2	18.8	27.9	16.5	29.4	35.9	19.6	10 - 100
	2017	46.3	22.3	5.6	4.6	1.0	0.0	20.4	0.0	0.0	0.0	0.0	18.4	6.2	0.6	0.0	9.7	0.0	0.0	26.2	0.0	12.1	0.0	7.7	46.6	0.0	
K (mg/l)	2016	12.6	15.6	5.7	6.9	7.1	0.0	12.4	7.0	6.7	9.4	10.7	7.9	8.1	10.5	5.8	18.5	6.8	9.8	7.4	6.4	9.0	41.6	12.1	17.8	17.3	10 - 100
	2017	3.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	1.2	0.0	8.4	0.0	0.0	0.0	0.0	0.1	22.2	3.0	7.0	0.8	
SO_4 (mg/l)	2016	22.8	3.2	3.3	3.2	0.0	8.5	4.3	0.0	0.0	0.0	31.8	0.2	18.4	0.0	1.0	0.0	8.3	2.1	26.2	0.0	16.2	10.9	33.0	9.8	2.8	200 - 400
	2017	45.8	12.4	4.9	12.2	0.0	14.6	0.0	5.0	48.2	8.8	4.5	13.3	10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.1	13.3	20.5	26.5	0.8	

(*Data of Ca, Mg, Total hardness, Na, K and SO_4 for the year 2013 and 2014 are not available)

Table 5.7 Groundwater quality data for the month of June

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.0	6.1	6.3	6.3	6.3	7.0	6.6	6.3	6.1	7.1	7.4	7.1	6.3	6.3	6.1	6.1	6.4	6.8	6.4	5.9	6.4	6.4	-	-	-	6.5 – 8.5
	2014	6.8	3.9	6.5	6.6	6.5	6.3	7.2	6.5	6.6	6.7	6.4	6.4	6.6	6.7	6.5	6.7	6.9	6.7	6.7	6.3	6.6	6.9	6.5	6.8	6.3	
EC (µS/cm)	2013	330.0	360.0	960.0	280.0	176.0	114.0	410.0	160.0	184.0	60.0	129.0	240.0	260.0	113.0	102.0	350.0	210.0	230.0	173.0	120.0	240.0	320.0	-	-	-	700 - 2000
	2014	477.0	418.0	374.0	313.0	175.0	106.0	637.0	404.0	187.0	98.0	57.0	137.0	374.0	137.0	141.0	407.0	238.0	220.0	404.0	139.0	320.0	365.0	298.0	501.0	248.0	
TDS (mg/l)	2013	200.0	220.0	590.0	170.0	108.0	69.0	50.0	97.0	111.0	36.0	78.0	145.0	150.0	67.0	63.0	143.0	126.0	140.0	105.0	74.0	145.0	190.0	-	-	-	500 - 2000
	2014	296.0	259.0	232.0	194.0	109.0	66.0	395.0	250.0	116.0	61.0	35.0	85.0	232.0	85.0	87.0	252.0	148.0	136.0	250.0	86.0	198.0	226.0	185.0	311.0	154.0	
HCO_3 (mg/l)	2013	214.2	499.8	357.0	464.1	428.4	142.8	499.8	178.5	428.4	321.3	249.9	357.0	214.2	285.6	285.6	464.1	285.6	499.8	285.6	321.3	178.5	499.8	-	-	-	200 - 600
	2014	178.5	107.1	142.8	178.5	142.8	142.8	178.5	107.1	71.4	321.3	142.8	107.1	249.9	142.8	142.8	178.5	142.8	142.8	214.2	142.8	142.8	142.8	214.2	249.9	71.4	
Cl (mg/l)	2013	35.6	68.8	475.4	30.2	26.3	9.8	68.3	37.5	30.7	13.7	14.6	36.1	32.7	18.5	18.0	46.3	21.5	28.8	20.5	24.9	43.9	26.8	-	-	-	250 - 1000
	2014	36.1	43.4	61.0	24.4	20.5	14.6	61.0	22.0	25.4	14.6	13.2	15.6	36.0	12.7	14.6	36.1	17.5	19.0	37.1	21.5	31.7	22.4	20.5	34.1	22.4	

Table 5.8 Groundwater quality data for the month of July

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.3	5.3	6.2	6.4	5.4	5.9	7.6	6.4	6.0	6.2	5.4	6.0	6.1	5.9	5.9	6.3	6.5	7.0	6.8	5.6	5.7	7.7	-	-	-	6.5 – 8.5
	2014	7.1	6.0	6.5	6.8	6.2	6.4	7.0	6.7	6.5	6.3	6.1	6.5	6.7	6.7	6.3	7.0	6.9	6.8	6.9	6.5	6.8	6.9	6.9	7.1	6.6	
	2016	6.5	5.9	7.2	6.7	6.0	7.2	7.0	7.1	6.4	6.7	6.7	6.7	6.6	6.6	6.6	6.6	6.6	6.8	6.7	6.3	6.2	6.2	6.5	6.9	6.7	
EC (µS/cm)	2013	427.0	325.0	326.0	323.0	181.0	110.0	506.0	247.0	159.0	152.0	111.0	181.0	318.0	156.0	139.0	358.0	251.0	178.0	215.0	159.0	235.0	349.0	-	-	-	700 - 2000
	2014	348.0	272.0	240.0	326.0	190.0	94.0	510.0	141.0	187.0	105.0	56.0	118.0	254.0	144.0	150.0	455.0	260.0	174.0	222.0	127.0	190.0	344.0	236.0	490.0	275.0	
	2016	556.0	247.0	204.0	300.0	149.0	75.0	418.0	131.0	126.0	118.0	44.0	178.0	206.0	120.0	136.0	314.0	164.0	154.0	187.0	122.0	384.0	226.0	251.0	390.0	233.0	
TDS (mg/l)	2013	190.0	157.0	149.0	154.0	86.3	51.9	236.0	113.0	76.1	65.2	37.3	82.7	147.0	74.6	58.7	168.0	115.0	81.4	106.0	73.7	108.0	164.0	-	-	-	500 - 2000
	2014	216.0	169.0	149.0	202.0	118.0	58.0	316.0	87.0	116.0	65.0	35.0	73.0	157.0	89.0	93.0	282.0	161.0	108.0	138.0	79.0	118.0	213.0	146.0	304.0	171.0	
	2016	345.0	153.0	126.0	186.0	92.0	47.0	259.0	81.0	78.0	73.0	27.0	110.0	128.0	74.0	84.0	195.0	102.0	95.0	116.0	76.0	238.0	140.0	156.0	242.0	144.0	
HCO_3 (mg/l)	2013	357.0	285.6	357.0	642.6	357.0	464.1	571.2	535.5	499.8	357.0	357.0	321.3	606.9	249.9	285.6	357.0	499.8	392.7	714.0	285.6	285.6	499.8	-	-	-	200 - 600
	2014	178.5	285.6	214.2	142.8	214.2	107.1	214.2	214.2	178.5	178.5	785.4	107.1	107.1	214.2	142.8	214.2	214.2	249.9	392.7	142.8	142.8	178.5	214.2	249.9	178.5	
	2016	195.0	28.0	73.0	125.0	34.0	51.0	161.0	55.0	41.0	49.0	30.0	98.0	70.0	57.0	51.0	114.0	98.0	92.0	101.0	33.0	63.0	102.0	146.0	163.0	44.0	

Cl (mg/l)	**2013**	**27.3**	**53.6**	**73.1**	**40.5**	**28.3**	**20.5**	**68.3**	**33.2**	**20.0**	**21.0**	**14.6**	**17.1**	**37.1**	**14.6**	**19.5**	**40.5**	**15.6**	**16.1**	**19.5**	**23.4**	**30.2**	**24.4**	**-**	**-**	**-**	**250 - 1000**
	2014	**25.0**	**31.2**	**29.3**	**25.4**	**19.5**	**10.7**	**46.8**	**13.7**	**34.1**	**19.5**	**12.2**	**10.7**	**16.6**	**13.7**	**15.6**	**36.6**	**12.7**	**8.8**	**9.8**	**19.5**	**19.5**	**16.1**	**14.6**	**30.2**	**20.5**	
	2016	**78.4**	**59.4**	**41.3**	**44.7**	**36.1**	**20.9**	**76.0**	**28.0**	**37.5**	**27.6**	**21.4**	**28.5**	**31.4**	**22.8**	**29.9**	**42.3**	**17.6**	**18.1**	**28.0**	**31.8**	**119.7**	**27.6**	**26.1**	**46.1**	**34.7**	
Ca (mg/l)	**2016**	**131.3**	**68.3**	**101.9**	**115.5**	**53.6**	**69.3**	**128.1**	**39.9**	**47.3**	**50.4**	**38.9**	**71.4**	**84.0**	**58.8**	**65.1**	**95.6**	**90.3**	**91.4**	**96.6**	**29.4**	**81.9**	**89.3**	**128.1**	**141.8**	**83.0**	**75 - 200**
Mg (mg/l)	**2016**	**93.8**	**33.8**	**3.2**	**26.5**	**10.5**	**36.7**	**28.9**	**9.1**	**12.8**	**0.6**	**5.2**	**1.6**	**12.0**	**21.2**	**24.9**	**23.5**	**4.7**	**7.7**	**0.4**	**0.6**	**28.1**	**0.8**	**1.9**	**2.3**	**2.1**	**30 - 100**
Total hardness (mg/l)	**2016**	**225.0**	**102.0**	**105.0**	**142.0**	**64.0**	**106.0**	**157.0**	**49.0**	**60.0**	**51.0**	**44.0**	**73.0**	**96.0**	**80.0**	**90.0**	**119.0**	**95.0**	**99.0**	**97.0**	**30.0**	**110.0**	**90.0**	**130.0**	**144.0**	**85.0**	**100 - 500**
Na (mg/l)	**2016**	**105.1**	**47.2**	**96.5**	**29.2**	**17.8**	**7.8**	**64.7**	**13.6**	**11.9**	**3.3**	**21.1**	**34.7**	**26.4**	**5.1**	**13.4**	**35.9**	**45.5**	**12.6**	**41.7**	**21.7**	**28.5**	**19.1**	**30.8**	**51.7**	**19.2**	**10 - 100**
K (mg/l)	**2016**	**16.2**	**15.3**	**5.5**	**6.2**	**6.5**	**6.5**	**20.1**	**6.2**	**6.1**	**13.0**	**18.2**	**6.2**	**7.6**	**8.6**	**5.5**	**16.5**	**6.5**	**10.3**	**5.9**	**6.0**	**8.7**	**45.3**	**12.2**	**18.8**	**26.2**	**10 - 100**
SO_4 (mg/l)	**2016**	**44.6**	**4.0**	**9.9**	**0.0**	**0.0**	**0.0**	**12.9**	**0.0**	**0.0**	**0.0**	**95.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**27.8**	**0.0**	**16.2**	**6.7**	**20.7**	**13.1**	**0.0**	**200 - 400**

(*Data of Ca, Mg, Total hardness, Na, K and SO_4 for the year 2013 and 2014 are not available)

Table 5.9 Groundwater quality data for the month of August

Chemical parameters	**Year**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**Permissible limits**
pH	**2013**	**7.5**	**5.2**	**6.2**	**6.9**	**6.1**	**6.1**	**7.0**	**6.3**	**5.6**	**6.0**	**5.2**	**6.0**	**6.4**	**6.3**	**5.6**	**6.3**	**6.4**	**7.2**	**6.9**	**5.3**	**6.2**	**6.7**	**-**	**-**	**-**	**6.5 – 8.5**
	2014	**6.9**	**6.2**	**7.0**	**6.6**	**6.9**	**6.0**	**7.0**	**6.8**	**6.8**	**6.9**	**6.7**	**7.0**	**6.2**	**6.8**	**7.1**	**6.8**	**6.6**	**7.2**	**6.6**	**7.0**	**6.6**	**6.5**	**6.8**	**6.9**	**6.9**	
EC (µS/cm)	**2013**	**390.0**	**250.0**	**190.0**	**270.0**	**160.0**	**75.0**	**430.0**	**158.0**	**115.0**	**81.0**	**50.0**	**153.0**	**230.0**	**126.0**	**124.0**	**300.0**	**210.0**	**122.0**	**130.0**	**125.0**	**178.0**	**280.0**	**-**	**-**	**-**	**700 - 2000**
	2014	**305.0**	**255.0**	**197.0**	**236.0**	**152.0**	**86.0**	**517.0**	**116.0**	**210.0**	**71.0**	**44.0**	**97.0**	**208.0**	**108.0**	**106.0**	**372.0**	**206.0**	**156.0**	**292.0**	**111.0**	**191.0**	**316.0**	**166.0**	**365.0**	**216.0**	
TDS (mg/l)	**2013**	**240.0**	**150.0**	**120.0**	**170.0**	**100.0**	**46.0**	**260.0**	**97.0**	**71.0**	**50.0**	**31.0**	**94.0**	**140.0**	**77.0**	**77.0**	**180.0**	**130.0**	**75.0**	**83.0**	**78.0**	**110.0**	**170.0**	**-**	**-**	**-**	**500 - 2000**
	2014	**189.0**	**158.0**	**122.0**	**146.0**	**94.0**	**53.0**	**321.0**	**72.0**	**130.0**	**44.0**	**27.0**	**60.0**	**129.0**	**67.0**	**66.0**	**231.0**	**128.0**	**97.0**	**181.0**	**69.0**	**118.0**	**196.0**	**103.0**	**226.0**	**134.0**	
HCO_3 (mg/l)	**2013**	**464.1**	**142.8**	**606.9**	**464.1**	**142.8**	**321.3**	**392.7**	**357.0**	**321.3**	**178.5**	**178.5**	**392.7**	**428.4**	**357.0**	**321.3**	**249.9**	**357.0**	**357.0**	**678.3**	**285.6**	**963.9**	**357.0**	**-**	**-**	**-**	**200 - 600**
	2014	**142.8**	**107.1**	**107.1**	**142.8**	**107.1**	**107.1**	**321.3**	**142.8**	**142.8**	**142.8**	**107.1**	**107.1**	**178.5**	**142.8**	**71.4**	**285.6**	**178.5**	**142.8**	**249.9**	**107.1**	**107.1**	**142.8**	**142.8**	**285.6**	**107.1**	
Cl (mg/l)	**2013**	**25.8**	**48.8**	**36.6**	**34.1**	**28.8**	**14.6**	**63.4**	**20.5**	**26.8**	**22.0**	**19.5**	**24.4**	**29.3**	**17.6**	**24.4**	**39.0**	**17.1**	**15.6**	**12.2**	**26.3**	**29.3**	**24.4**	**-**	**-**	**-**	**250 - 1000**
	2014	**23.4**	**39.0**	**32.2**	**20.0**	**19.5**	**7.8**	**59.5**	**16.6**	**46.8**	**12.2**	**12.2**	**10.7**	**14.6**	**10.7**	**12.7**	**36.6**	**12.2**	**10.7**	**10.7**	**19.5**	**17.6**	**14.6**	**12.2**	**26.8**	**19.5**	

Table 5.10 Groundwater quality data for the month of September

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.5	5.2	6.2	6.6	5.9	6.8	6.9	6.2	6.1	6.1	5.5	6.3	6.4	6.0	5.8	7.5	6.6	6.9	6.6	5.5	6.1	6.6	6.9	7.7	6.0	6.5 – 8.5
	2014	6.9	6.3	7.0	6.7	7.1	6.2	7.0	6.8	6.7	6.8	6.3	7.0	6.9	7.0	7.3	6.9	7.3	6.7	6.8	6.7	6.7	6.7	6.9	7.0	7.0	
EC (µS/cm)	2013	410.0	210.0	220.0	240.0	150.0	74.0	460.0	130.0	154.0	72.0	50.0	89.0	210.0	121.0	121.0	280.0	220.0	133.0	270.0	120.0	200.0	300.0	149.0	350.0	210.0	700 - 2000
	2014	343.0	277.0	248.0	234.0	142.0	86.0	518.0	111.0	199.0	68.0	41.0	106.0	199.0	106.0	101.0	315.0	180.0	165.0	268.0	106.0	197.0	286.0	234.0	316.0	197.0	
TDS (mg/l)	2013	230.0	120.0	120.0	130.0	83.0	41.0	250.0	73.0	86.0	41.0	28.0	50.0	120.0	70.0	68.0	160.0	120.0	74.0	150.0	68.0	110.0	160.0	83.0	200.0	120.0	500 - 2000
	2014	213.0	172.0	154.0	145.0	88.0	53.0	321.0	69.0	123.0	42.0	25.0	66.0	123.0	66.0	63.0	195.0	112.0	102.0	166.0	66.0	122.0	177.0	145.0	196.0	122.0	
HCO_3 (mg/l)	2013	428.4	249.9	249.9	214.2	178.5	321.3	392.7	142.8	249.9	142.8	214.2	249.9	178.5	178.5	178.5	249.9	357.0	357.0	428.4	107.1	249.9	357.0	285.6	249.9	178.5	200 - 600
	2014	249.9	178.5	107.1	214.2	142.8	71.4	178.5	107.1	142.8	107.1	142.8	107.1	107.1	142.8	142.8	178.5	71.4	107.1	178.5	71.4	107.1	142.8	107.1	142.8	107.1	
Cl (mg/l)	2013	23.9	48.8	51.7	30.7	25.8	9.8	75.1	21.5	42.4	18.5	14.6	15.6	23.4	18.0	19.0	34.1	16.6	11.2	19.5	25.8	31.2	21.5	15.1	41.0	24.9	250 - 1000
	2014	21.5	50.2	40.0	23.0	22.0	17.0	66.3	19.5	46.3	14.6	14.6	17.6	18.0	15.6	14.6	33.2	14.6	19.5	15.6	23.0	32.2	22.0	25.8	29.3	22.4	

Table 5.11 Groundwater quality data for the month of October

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.2	4.9	5.9	6.2	5.4	6.4	6.7	5.9	5.8	5.7	5.1	6.0	6.2	5.9	5.4	6.1	6.3	7.3	6.6	5.1	5.7	6.4	6.5	7.4	5.6	6.5 – 8.5
	2014	7.0	6.5	7.1	6.6	7.2	6.3	7.1	6.9	6.7	6.9	6.5	7.2	7.2	7.1	7.5	7.0	7.7	6.8	6.9	6.6	6.8	6.8	6.8	6.9	7.3	
EC (µS/cm)	2013	188.0	171.0	141.0	176.0	107.0	58.0	193.0	107.0	126.0	61.0	38.0	183.0	162.0	85.0	89.0	166.0	170.0	94.0	176.0	86.0	142.0	172.0	141.0	189.0	144.0	700 - 2000
	2014	328.0	274.0	242.0	241.0	139.0	87.0	515.0	110.0	202.0	74.0	40.0	110.0	198.0	106.0	101.0	318.0	177.0	167.0	285.0	108.0	202.0	286.0	237.0	312.0	197.0	
TDS (mg/l)	2013	116.0	105.0	86.0	109.0	66.0	35.0	119.0	66.0	78.0	37.0	23.0	112.0	100.0	52.0	55.0	102.0	104.0	58.0	109.0	54.0	88.0	106.0	87.0	116.0	89.0	500 - 2000
	2014	203.0	170.0	150.0	149.0	86.0	54.0	319.0	68.0	125.0	46.0	25.0	68.0	123.0	66.0	63.0	197.0	110.0	104.0	177.0	67.0	125.0	177.0	147.0	193.0	122.0	
HCO_3 (mg/l)	2013	214.2	142.8	285.6	285.6	107.1	107.1	571.2	142.8	142.8	178.5	178.5	214.2	249.9	214.2	142.8	285.6	214.2	178.5	321.3	107.1	142.8	357.0	321.3	249.9	178.5	200 - 600
	2014	214.2	107.1	142.8	178.5	71.4	107.1	142.8	107.1	142.8	71.4	178.5	107.1	107.1	178.5	71.4	142.8	178.5	107.1	71.4	107.1	142.8	71.4	178.5	107.1	107.1	
Cl (mg/l)	2013	22.4	45.3	31.7	25.8	23.4	9.8	59.5	24.4	38.0	15.6	11.7	76.5	27.8	14.1	17.1	36.6	13.2	10.7	16.1	22.9	42.4	16.1	17.5	44.4	21.9	250 - 1000
	2014	23.4	56.6	41.4	25.0	23.0	16.1	66.8	20.5	57.1	18.5	14.6	18.5	20.0	18.0	16.1	33.6	15.1	13.7	16.1	25.0	32.2	21.0	25.0	28.8	21.0	

Table 5.12 Groundwater quality data for the month of November

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	7.8	5.4	6.2	6.5	6.4	7.3	6.9	6.4	6.0	6.1	5.7	6.0	6.6	6.5	5.8	6.1	6.7	6.5	6.9	5.4	6.1	6.4	7.0	7.0	5.8	6.5 – 8.5
	2014	7.0	6.9	7.0	6.7	7.1	6.4	7.0	6.8	7.0	6.5	6.8	6.9	7.1	7.3	7.1	7.2	6.9	6.8	6.9	6.7	6.9	6.9	7.0	7.1	7.3	
EC (µS/cm)	2013	187.0	177.0	169.0	210.0	115.0	70.0	188.0	112.0	133.0	73.0	34.0	90.0	185.0	93.0	92.0	186.0	168.0	116.0	185.0	91.0	193.0	185.0	151.0	196.0	180.0	700 - 2000
	2014	312.0	272.0	238.0	249.0	135.0	92.0	520.0	110.0	203.0	78.0	40.0	113.0	198.0	106.0	101.0	320.0	175.0	167.0	308.0	109.0	204.0	286.0	240.0	310.0	197.0	
TDS (mg/l)	2013	93.0	88.0	85.0	100.0	57.0	35.0	94.0	55.0	66.0	36.0	16.0	44.0	92.0	46.0	47.0	92.0	83.0	58.0	92.0	45.0	96.0	92.0	75.0	98.0	90.0	500 - 2000
	2014	193.0	169.0	148.0	154.0	84.0	57.0	322.0	68.0	126.0	48.0	25.0	70.0	123.0	66.0	63.0	198.0	109.0	104.0	191.0	68.0	126.0	177.0	149.0	192.0	122.0	
HCO_3 (mg/l)	2013	499.8	214.2	178.5	285.6	249.9	392.7	535.5	178.5	249.9	321.3	142.8	285.6	214.2	357.0	178.5	214.2	285.6	321.3	464.1	214.2	214.2	428.4	249.9	357.0	357.0	200 - 600
	2014	178.5	71.4	142.8	142.8	71.4	71.4	142.8	142.8	71.4	142.8	107.1	107.1	178.5	71.4	71.4	178.5	107.1	142.8	214.2	214.2	107.1	142.8	178.5	142.8	107.1	
Cl (mg/l)	2013	26.8	65.8	44.4	31.7	24.4	14.6	87.8	27.8	39.0	16.6	14.1	20.0	21.9	21.0	19.5	41.9	14.6	14.1	16.1	31.7	37.1	21.0	17.6	43.9	30.2	250 - 1000
	2014	29.3	64.4	42.4	25.4	23.4	15.1	65.8	22.0	61.0	20.5	14.6	21.0	19.5	18.5	17.6	34.1	15.6	10.7	17.1	26.8	32.7	20.0	24.0	28.3	20.5	

Table 5.13 Groundwater quality data for the month of December

Chemical parameters	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Permissible limits
pH	2013	8.2	6.6	7.4	7.2	7.3	7.7	7.6	6.8	6.5	7.2	6.3	7.3	7.2	7.0	6.9	7.1	7.7	7.5	7.8	6.1	7.2	7.4	7.4	7.5	5.3	6.5 – 8.5
	2014	7.1	6.8	7.1	6.8	7.1	6.3	7.0	6.8	6.9	6.5	6.9	7.0	7.0	7.4	7.0	7.2	6.8	6.7	6.8	6.6	6.8	6.8	6.9	7.1	7.1	
EC (µS/cm)	2013	276.0	274.0	196.0	236.0	127.0	96.0	578.0	119.0	143.0	77.0	34.0	114.0	213.0	103.0	102.0	288.0	172.0	144.0	296.0	104.0	202.0	282.0	195.0	320.0	213.0	700 - 2000
	2014	322.0	316.0	282.0	251.0	152.0	117.0	534.0	116.0	232.0	81.0	40.0	129.0	221.0	114.0	121.0	385.0	182.0	187.0	415.0	111.0	220.0	316.0	229.0	326.0	200.0	
TDS (mg/l)	2013	171.0	170.0	122.0	146.0	79.0	60.0	358.0	74.0	89.0	48.0	21.0	71.0	132.0	64.0	63.0	179.0	107.0	89.0	184.0	65.0	125.0	175.0	121.0	199.0	132.0	500 - 2000
	2014	200.0	196.0	175.0	156.0	94.0	73.0	331.0	72.0	144.0	50.0	25.0	80.0	137.0	71.0	75.0	239.0	113.0	116.0	257.0	69.0	136.0	196.0	142.0	202.0	124.0	
HCO_3 (mg/l)	2013	392.7	142.8	178.5	321.3	178.5	142.8	249.9	357.0	357.0	285.6	214.2	321.3	214.2	107.1	71.4	357.0	321.3	535.5	357.0	178.5	214.2	357.0	357.0	392.7	214.2	200 - 600
	2014	178.5	214.2	249.9	178.5	142.8	107.1	178.5	142.8	142.8	285.6	142.8	107.1	107.1	142.8	142.8	178.5	214.2	142.8	214.2	142.8	107.1	178.5	214.2	178.5	142.8	
Cl (mg/l)	2013	27.0	57.0	15.6	28.8	24.4	13.7	85.3	30.7	39.0	18.0	16.1	18.5	25.4	18.0	18.5	41.4	15.1	20.5	18.5	29.0	37.0	24.4	20.0	33.2	34.1	250 - 1000
	2014	25.8	52.7	56.1	27.8	23.4	17.1	78.0	22.5	57.1	14.1	19.5	22.0	21.5	18.0	18.5	44.0	16.1	16.1	22.0	27.3	34.6	23.0	19.5	28.3	24.4	

5.4.2 Statistical analysis and results

The statistical analysis for groundwater quality parameters done to understand the quality status of groundwater in each well. Sodium absorption ratio, Piper Plot, Significant Chemical parameter, Factor of sea parameter correlation and Groundwater Quality Status and mapping are the methods used for statistical analysis.

5.4.2.1 Sodium absorption ratio

Sodium absorption ratio (SAR) values for all 25 groundwater wells is plotted and found that the values are less than 6 in both April and May 2016. SAR values for all 25 wells are represented in Fig. 5.2. It can be inferred that there is no significant effect of SAR contamination in the study area since the permissible limit of SAR in water is 10. A statistical correlation of 0.84 (Fig. 5.2) between water quality as observed in both April and May 2016.

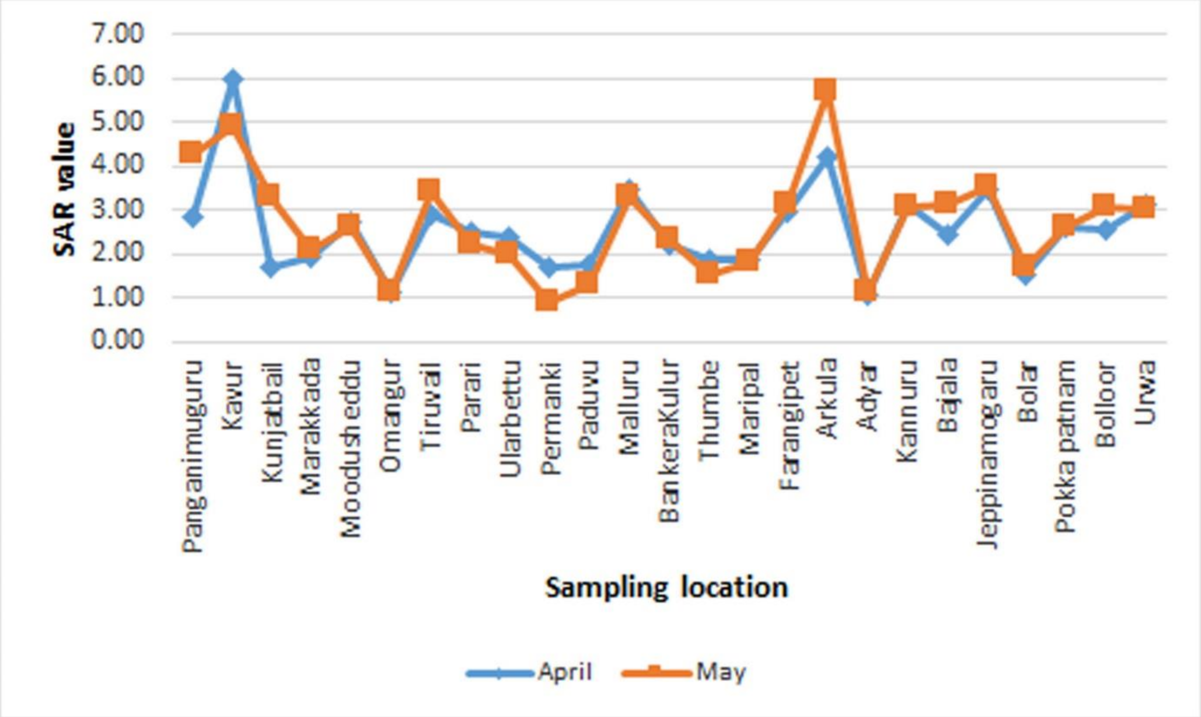


Fig. 5.2 Sodium absorption ratio

5.4.2.2 Piper Plot

Piper plots are prepared for the chemical parameters analysed in the laboratory. Fig. 5.3 and Fig. 5.4 represents the piper plot for the months of April and May 2016 respectively. The inferences of these plots are so essential to take individual decisions. The groundwater quality falls under the conservative mixing of piper plot, which is towards the freshwater zone. However, calcium shows less dominant type in all 25 groundwater samples of piper plot. In the chloride region of the piper plot, most of the groundwater samples found less concentration of chloride and falls safer limits.

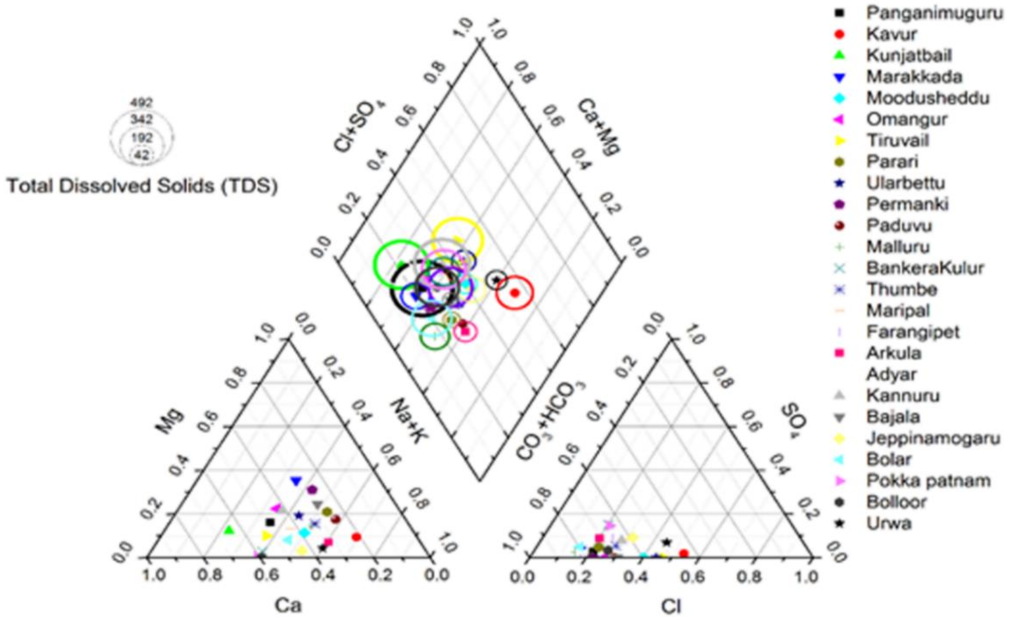


Fig. 5.3 Piper plot for April 2016

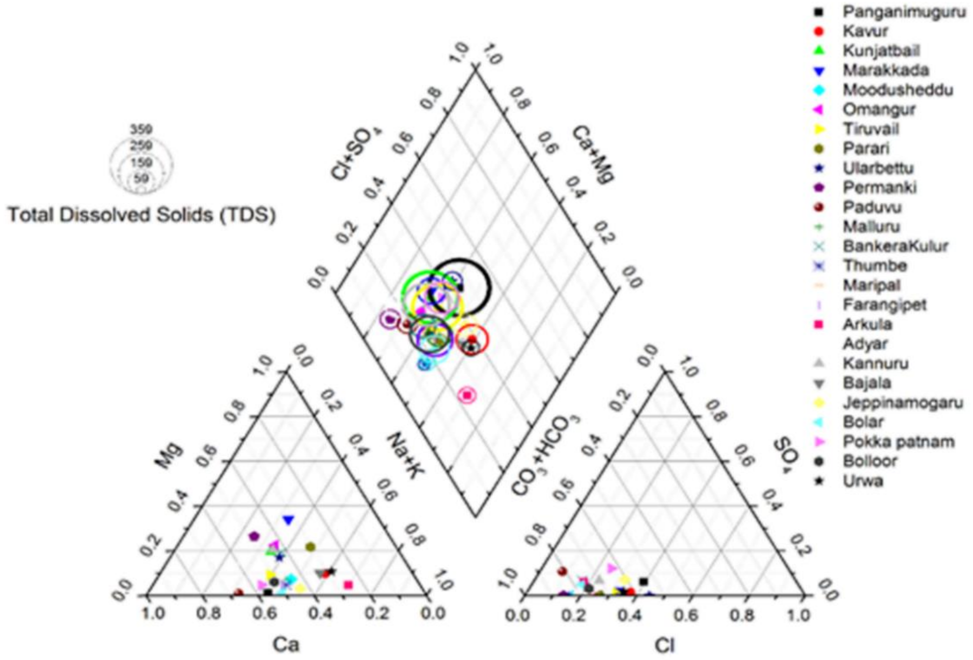


Fig. 5.4 Piper plot for May 2016

5.4.2.3 Significant Chemical parameter

A 2-tailed significant test leading with 0.005 level confidence is carried out for all 25 groundwater samples for the months of April and May 2016. The results are tabulated in Table 5.14 and 5.15. In the month of April, EC, TDS, HCO_3, Cl, Ca and Na have shown a significant correlation with each other. In the month May, the parameter such as Cl and Ca also have a strong correlation at the 0.005 level of the 2-tailed significant test. While HCO_3 and Na show less correlation at the 0.005 level compared to the other parameters. In the month of May, Na has a better correlation with EC, TDS, Cl and Ca. The remaining parameters such as pH, Mg and SO_4 have no significant correlation with other chemical parameters. Based on the 0.005 level of 2-tailed significant test, it can be concluded that EC, TDS, Cl and Ca are the significant parameters in both April and May months.

Table 5.14 Correlations for April 2016

		pH	EC	TDS	HCO_3	Cl	Ca	Mg	Na	K	SO_4
pH	Pearson Correlation	1	-.098	-.098	.133	.004	.076	.150	-.285	-.327	-.272
	Sig. (2-tailed)	-	.642	.642	.525	.985	.718	.473	.168	.111	.188
	N	25	25	25	25	25	25	25	25	25	25
EC	Pearson Correlation	-.098	1	1.000^{**}	$.690^{**}$	$.755^{**}$	$.883^{**}$	$.439^{*}$	$.778^{**}$	.294	.396
	Sig. (2-tailed)	.642	-	.000	.000	.000	.000	.028	.000	.154	.050
	N	25	25	25	25	25	25	25	25	25	25
TDS	Pearson Correlation	-.098	1.000^{**}	1	$.690^{**}$	$.755^{**}$	$.883^{**}$	$.440^{*}$	$.778^{**}$	.294	.396
	Sig. (2-tailed)	.642	.000	-	.000	.000	.000	.028	.000	.153	.050
	N	25	25	25	25	25	25	25	25	25	25
HCO_3	Pearson Correlation	.133	$.690^{**}$	$.690^{**}$	1	.384	$.720^{**}$	$.504^{*}$	.305	.142	.194
	Sig. (2-tailed)	.525	.000	.000	-	.058	.000	.010	.139	.497	.352
	N	25	25	25	25	25	25	25	25	25	25
Cl	Pearson Correlation	.004	$.755^{**}$	$.755^{**}$	.384	1	$.636^{**}$	$.430^{*}$	$.697^{**}$	.001	-.014

	Sig. (2-tailed)	.985	.000	.000	.058	-	.001	.032	.000	.995	.949
	N	25	25	25	25	25	25	25	25	25	25
Ca	Pearson Correlation	.076	.883**	.883**	.720**	.636**	1	.212	.494*	.180	.333
	Sig. (2-tailed)	.718	.000	.000	.000	.001	-	.309	.012	.390	.104
	N	25	25	25	25	25	25	25	25	25	25
Mg	Pearson Correlation	.150	.439*	.440*	.504*	.430*	.212	1	.346	-.098	-.007
	Sig. (2-tailed)	.473	.028	.028	.010	.032	.309	-	.090	.642	.974
	N	25	25	25	25	25	25	25	25	25	25
Na	Pearson Correlation	-.285	.778**	.778**	.305	.697**	.494*	.346	1	.099	.339
	Sig. (2-tailed)	.168	.000	.000	.139	.000	.012	.090	-	.639	.097
	N	25	25	25	25	25	25	25	25	25	25
K	Pearson Correlation	-.327	.294	.294	.142	.001	.180	-.098	.099	1	.239
	Sig. (2-tailed)	.111	.154	.153	.497	.995	.390	.642	.639	-	.249
	N	25	25	25	25	25	25	25	25	25	25
SO$_4$	Pearson Correlation	-.272	.396	.396	.194	-.014	.333	-.007	.339	.239	1
	Sig. (2-tailed)	.188	.050	.050	.352	.949	.104	.974	.097	.249	-
	N	25	25	25	25	25	25	25	25	25	25
**. Correlation is significant at the *0.01 level (2-tailed).*											
*. Correlation is significant at the *0.05 level (2-tailed).*											

Table 5.15 Correlations for May 2016

		pH	EC	TDS	HCO$_3$	Cl	Ca	Mg	Na	K	SO$_4$
pH	Pearson Correlation	1	-.098	-.098	.478*	.004	.229	.274	-.285	-.327	-.272
	Sig. (2-tailed)	-	.642	.642	.016	.985	.272	.185	.168	.111	.188
	N	25	25	25	25	25	25	25	25	25	25

EC	Pearson Correlation	-.098	1	1.000**	.514**	.755**	.868**	.362*	.778**	.294	.396
	Sig. (2-tailed)	.642	-	.000	.009	.000	.000	.076	.000	.154	.050
	N	25	25	25	25	25	25	25	25	25	25
TDS	Pearson Correlation	-.098	1.000**	1	.515**	.755**	.868**	.362*	.778**	.294	.396
	Sig. (2-tailed)	.642	.000	-	.008	.000	.000	.028	.000	.153	.050
	N	25	25	25	25	25	25	25	25	25	25
HCO$_3$	Pearson Correlation	.478*	.514**	.515**	1	.465*	.710**	.368	.222	.063	.096
	Sig. (2-tailed)	.016	.009	.008	-	.019	.000	.070	.285	.763	.647
	N	25	25	25	25	25	25	25	25	25	25
Cl	Pearson Correlation	.004	.755**	.755**	.465*	1	.708**	.335*	.697**	.001	-.014
	Sig. (2-tailed)	.985	.000	.000	.019	-	.000	.102	.000	.995	.949
	N	25	25	25	25	25	25	25	25	25	25
Ca	Pearson Correlation	.229	.868**	.868**	.710**	.708**	1	.258	.542**	.199	.219
	Sig. (2-tailed)	.272	.000	.000	.000	.000	-	.214	.005	.340	.293
	N	25	25	25	25	25	25	25	25	25	25
Mg	Pearson Correlation	.274	.362	.362	.368	.335	.258	1	.189	-.288	-.003
	Sig. (2-tailed)	.185	.076	.076	.070	.102	.214	-	.364	.162	.988
	N	25	25	25	25	25	25	25	25	25	25
Na	Pearson Correlation	-.285	.778**	.778**	.222	.697**	.542**	.189	1	.099	.339
	Sig. (2-tailed)	.168	.000	.000	.285	.000	.005	.364	-	.639	.097
	N	25	25	25	25	25	25	25	25	25	25
K	Pearson Correlation	-.327	.294	.294	.063	.001	.199	-.288	.099	1	.239
	Sig. (2-tailed)	.111	.154	.153	.763	.995	.340	.162	.639	-	.249

	N	25	25	25	25	25	25	25	25	25	25
SO_4	Pearson Correlation	-.272	.396	.396	.096	-.014	.219	-.003	.339	.239	1
	Sig. (2-tailed)	.188	.050	.050	.647	.949	.293	.988	.097	.249	-
	N	25	25	25	25	25	25	25	25	25	25
*. Correlation is significant at the *0.05 level (2-tailed).*											
**. Correlation is significant at the *0.01 level (2-tailed).*											

5.4.2.4 Factor of sea parameter correlation

The factor of the sea (FOS) from Cl parameter is correlated with other groundwater chemical parameters such as EC, TDS, HCO_3, Ca, Mg and Total Hardness for the months April and May 2016 and is presented in Fig. 5.5. The results in Table 5.16 indicates that EC and TDS show a strong correlation of 0.755 and 0.860 compared to other chemical parameters. The parameter such as Ca and Hardness has a correlation within a range of 0.636 to 0.751 and 0.698 to 0.783. A very low correlation is observed in the case of HCO_3 and Mg (< 0.5). Therefore, the results show that there is a significant impact of EC and TDS in the groundwater concerning FOS in April and May months.

Table 5.16 FOS correlation

FOS	R	
	April	May
EC	0.755	0.860
TDS	0.755	0.860
HCO_3	0.384	0.430
Ca	0.636	0.751
Mg	0.430	0.410
Total Hardness	0.698	0.783

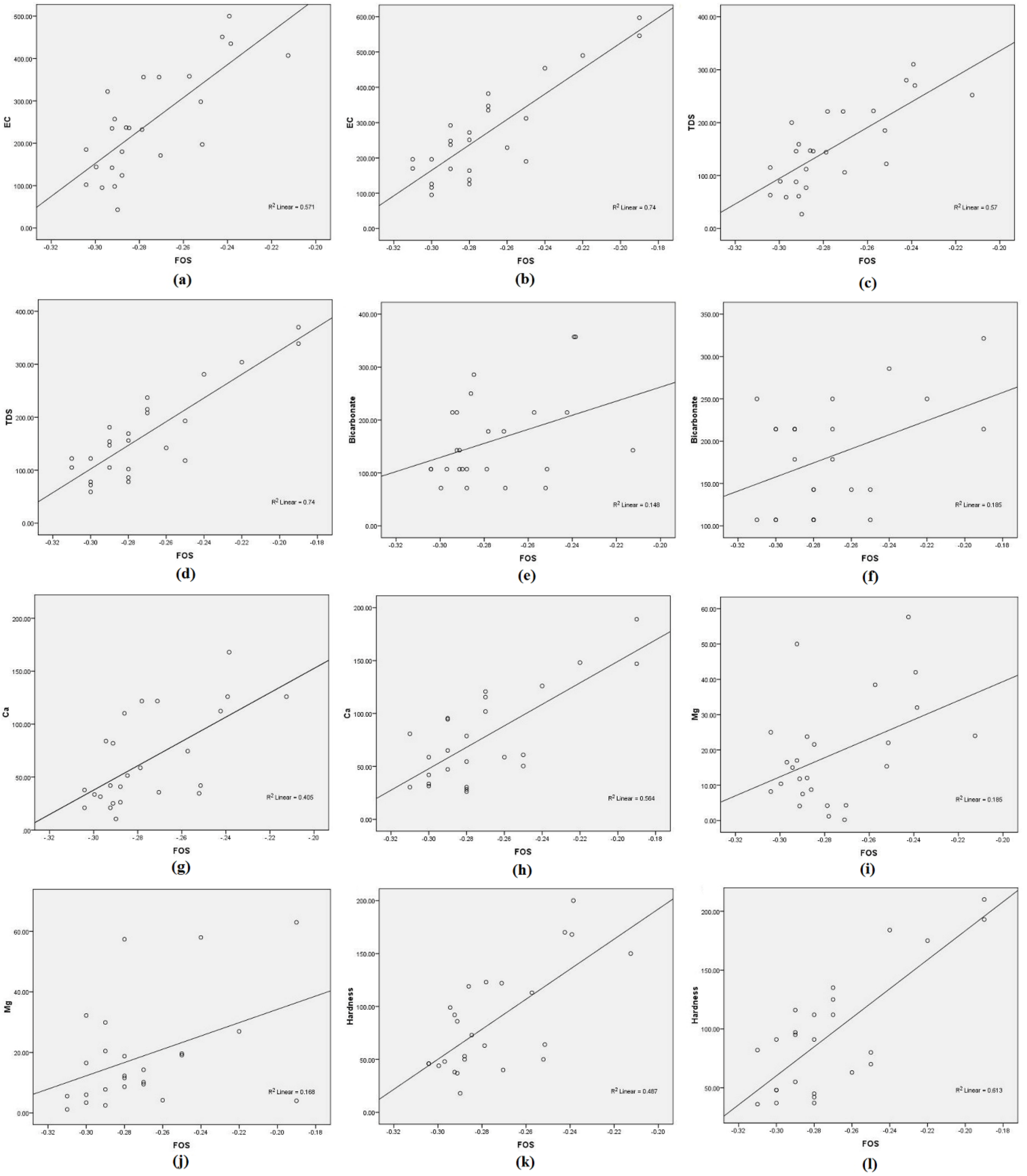


Fig. 5.5 FOS with (a) EC April 2016, (b) EC May 2016, (c) TDS April 2016, (d) TDS May 2016, (e) Bicarbonate April 2016, (f) Bicarbonate May 2016, (g) Ca April 2016, (h) Ca May 2016, (i) Mg April 2016, (j) Mg May 2016, (k) Total Hardness April 2016 and (l) Total Hardness May 2016

5.4.2.5 Groundwater Quality Status and mapping

Groundwater quality status index is assessed for all 25 groundwater wells and categorised into excellent, good, permissible and poor. The groundwater quality status is represented in Table 5.17 and 5.18. In the month of April 2016, TDS is 96% in groundwater well samples which indicates excellent groundwater quality. However, the value reduces to 88% in May due to peak summer. The Cl, TH, EC and Ca parameters shows a decrease in quality from April to May due to peak summer with no or less rainfall to recharge the aquifer. Therefore, water quality status is good.

Table 5.17 Groundwater quality status for April 2016

Index	**I**		**II**		**III**		**IV**	
	Nos	Per (%)	Nos	Per (%)	Nos	Per (%)	Nos	Per (%)
TDS	24	96	1	4	0	0	0	0
Cl	18	72	7	28	0	0	0	0
TH	22	88	3	12	0	0	0	0
EC	23	92	2	8	0	0	0	0
Ca	18	72	7	28	0	0	0	0

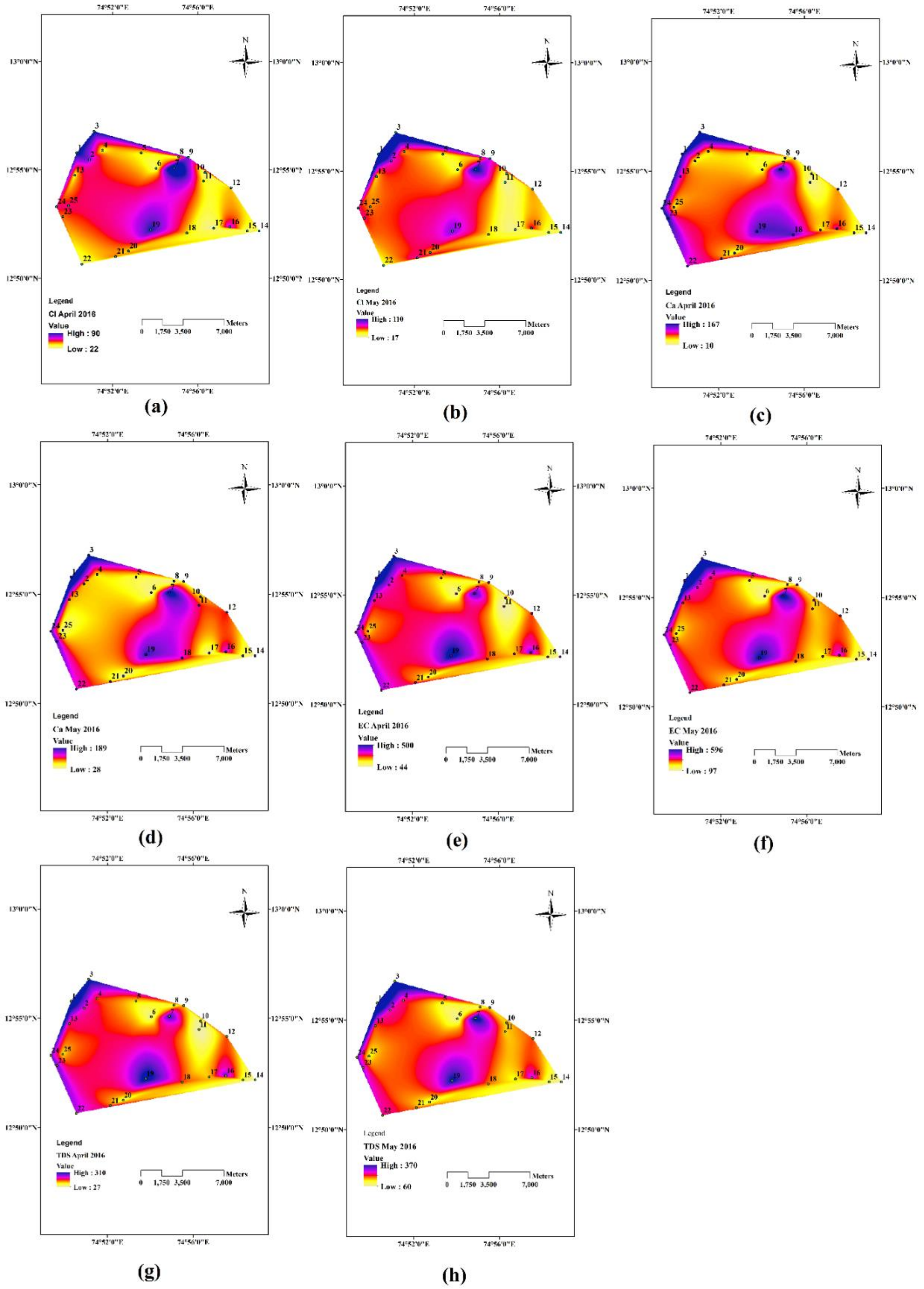
I = Excellent, *II* = Good, *III* = Permissible, *IV* = Poor, *Per* = Percentage, *Nos* = number of samples

Table 5.18 Groundwater quality status for May 2016

Index	**I**		**II**		**III**		**IV**	
	Nos	Per (%)	Nos	Per (%)	Nos	Per (%)	Nos	Per (%)
TDS	22	88	3	12	0	0	0	0
Cl	16	64	9	36	0	0	0	0
TH	21	84	4	16	0	0	0	0
EC	21	84	4	16	0	0	0	0
Ca	18	72	7	28	0	0	0	0

I = Excellent, *II* = Good, *III* = Permissible, *IV* = Poor, *Per* = Percentage, *Nos* = number of samples

The groundwater quality mapping is carried out for significant chemical parameters such as Cl, Ca, EC and TDS as shown in Fig. 5.6. The maps are showing the spatial distribution of groundwater quality good in the regions of Thumbe and Maripal which are away from the coastal region. While the groundwater quality deteriorated in the wells located very close to the coast. The Panganimuguru (well no. 1) and Kunjatbail (well no. 3) shows low quality compared to other wells based on the chemical parameters. It indicates that even though the quality is within the permissible limit, these two wells are vulnerable to groundwater contamination as they are very close to the coastal boundary.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 5.6 Spatial distribution of groundwater quality based on laboratory analysis of (a) Cl April 2016, (b) Cl May 2016, (c) Ca April 2016, (d) Ca May 2016, (e) EC April 2016, (f) EC May 2016, (g) TDS April 2016 (h) TDS May 2016

5.4.3 Prediction of significant chemical parameters

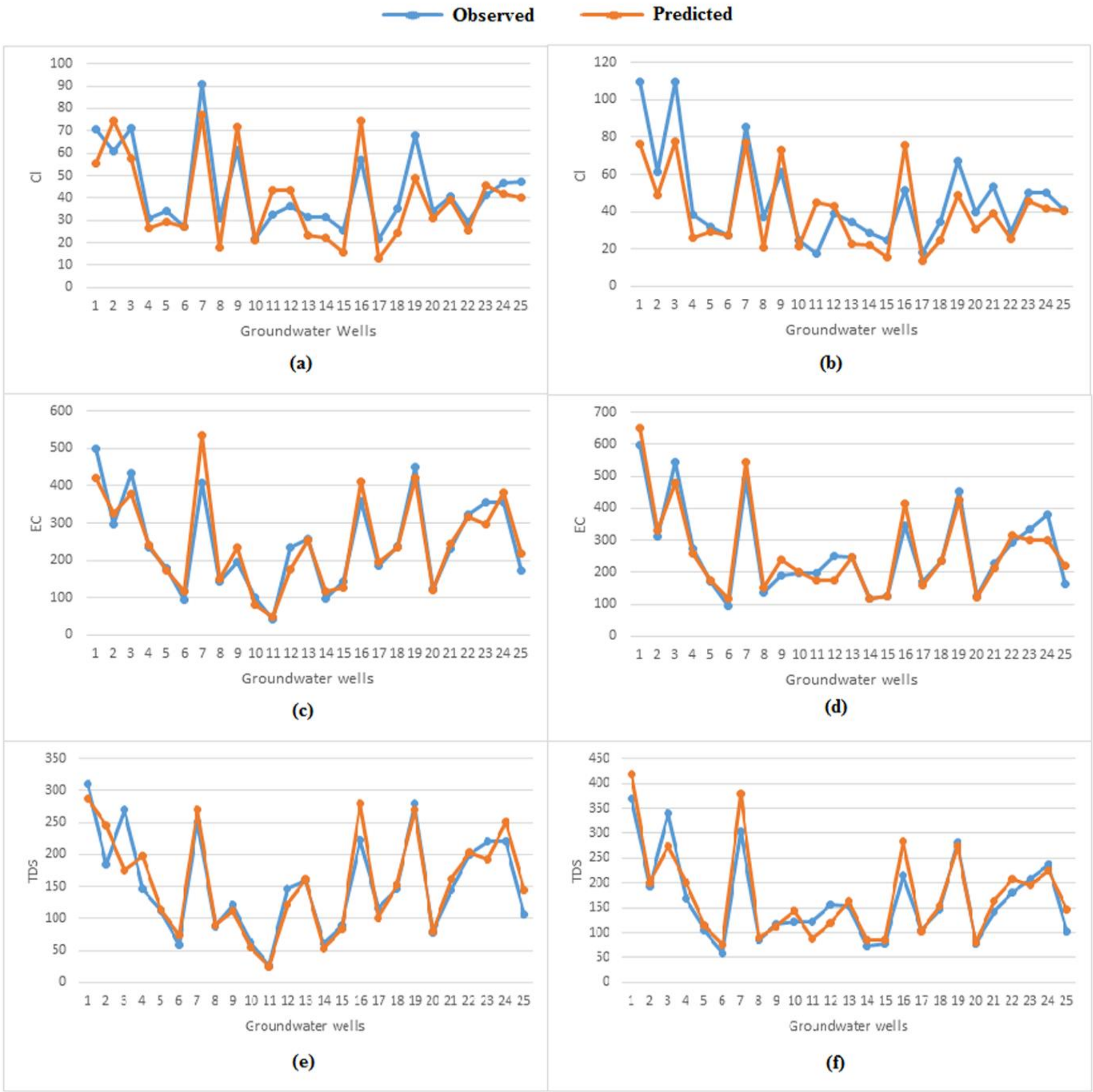


Fig. 5.7 Predicted and observed (a) Cl April 2016, (b) Cl May 2016, (c) EC April 2016, (d) EC May 2016, (e) TDS April 2016 and (f) TDS May 2016

The statistical prediction of the chemical parameter is carried out for three significant groundwater quality chemical parameters such as Cl, EC and TDS. The data used for prediction is the monthly groundwater quality data for the year 2013 to 2014. The strong correlation for Cl, EC and TDS are found at 0.87, 0.94 and 0.92 respectively for the month April 2016. The mean absolute percentage error (MAPE) is found about 0.33%, -0.04% and -0.08% respectively for Cl, EC and TDS which less and acceptable. The Fig. 5.7 represents the observed and predicted results of Cl, EC and TDS for April and May 2016. In the month of

May, Cl has a correlation (R) of 0.83 which is comparatively less than that of EC and TDS and the MAPE is found higher about 0.52%, -0.005% and -0.03% respectively for Cl, EC and TDS which was less and acceptable. Table 5.19 summarises the correlation and MAPE of significant parameters.

Table 5.19 Correlation and MAPE of significant parameters

	R		MAPE (%)	
	April	May	April	May
Cl	0.87	0.83	0.33	0.52
EC	0.94	0.96	-0.04	-0.005
TDS	0.92	0.94	-0.08	-0.23

5.5 CONCLUSIONS

The conclusions of groundwater quality assessment are

1. In pre-monsoon season of 2013, the well number 2-4, 8-11, 14-17 and 20-22 are found to have low concentration value of pH less than the permissible limit value and shows the acidic nature. In the monsoon season of 2013, the pH value is found to be less than the permissible limit value for well numbers 2-6, 8-17, 20 and 21. In post-monsoon season 2013, pH of well number 25 is found to be lo value than the permissible limit.
2. It can be inferred that there is no significant effect of SAR contamination in the study area since all the wells are within the permissible limit of SAR.
3. The groundwater quality falls under the conservative mixing of piper plot, which is towards the freshwater zone. However, calcium shows less dominant type in all 25 groundwater samples of piper plot. In the chloride region of the piper plot, most of the groundwater samples are found with less concentration of chloride and falls within safer limits.
4. In the month of April 2016, EC, TDS, HCO_3, Cl, Ca and Na have shown a significant correlation with each other. In the month May 2016, the parameter such as Cl and Ca also have a strong correlation at the 0.005 level of the 2-tailed significant test.
5. EC and TDS show a strong correlation of 0.755 and 0.860 compared to all other chemical parameters in Factor of sea chemical parameter correlation.
6. The groundwater quality status is represented in Table 5.17 and 5.18. In the month of April 2016, TDS is 96% in groundwater well samples, which indicates excellent groundwater quality. However, the value reduces to 88% in May 2016 due to peak

summer. The Cl, TH, EC and Ca parameters show a decrease in concentration from April 2016 to May 2016 due to peak summer with less or no rainfall to recharge the aquifer. Therefore, water quality status is good but still the quality is getting reduced.

7. The maps are showing the spatial distribution of groundwater quality as good for the regions of Thumbe and Maripal, which are away from the coastal region. While the groundwater quality deteriorated in the wells located very close to the coast. The Panganimuguru (well no. 1) and Kunjatbail (well no. 3) shows low quality compared to other wells based on the chemical parameters. It indicates that even though the quality is within the permissible limit, these two wells are vulnerable to groundwater contamination as they are very close to the coast.
8. In the prediction of Significant chemical parameters, the strong correlation for Cl, EC and TDS are found at 0.87, 0.94 and 0.92 respectively for the month April 2016. The mean absolute percentage error (MAPE) is found about 0.33%, -0.04% and -0.08% respectively for Cl, EC and TDS, which is less and acceptable. Fig. 5.6 represents the observed and predicted results of Cl, EC and TDS for April and May 2016. In the month of May 2016, Cl has a correlation (R) of 0.83 which is comparatively less than that of EC and TDS and the MAPE is found higher about 0.52%, -0.005% and -0.03% respectively for Cl, EC and TDS which was less and acceptable.

CHAPTER 6

DEVELOPMENT OF GROUNDWATER FLOW MODEL

6.1 GENERAL

Numerical model plays a vital role for the past years in the field of Engineering and sciences. In most of the studies, the numerical model simulation used for the analysis of the physical system. In the field of groundwater, the numerical models are used to simulate the groundwater head and contaminants. The numerical model simulation is carried out mainly by two techniques viz, finite difference and finite element method. The transport conditions provide a better understanding of the movement of the contamination. In the finite element method, the FEFLOW and FEMWATER codes are used for both flow and transports. The mesh is generated for the model and elements were created in the finite element methods.

In this study, the FEMWATER code is used to simulate the groundwater flow. The FEMWATER code is a three-dimensional finite element model. It is one of the computational modules of Groundwater Modelling System (GMS) 10.0. It analyses both steady state and transient state flow conditions. The conceptual model for the study area is formulated and the data used for the formulation is elevation, recharge, specific flux, hydraulic conductivity, pumping data and location of groundwater well.

6.2 GOVERNING EQUATION OF GROUNDWATER FLOW

The governing equation of groundwater flow in the FEMWATER code is developed by Lin et al. 1997. Equation 6.1 is the governing equation of groundwater flow which mainly depends on water density, pressure head, potential head, source and hydraulic conductivity.

Governing equations for flow (Lin et al. 1997) is as follows.

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla \cdot \left[K \cdot \left(\nabla h + \frac{\rho}{\rho_0} \nabla z \right) \right] + \frac{\rho^*}{\rho_0} q \tag{6.1}$$

$$F = \alpha' \frac{\theta}{n} + \beta' \theta + n \frac{ds}{dh} \tag{6.2}$$

where

F = storage coefficient

h = pressure head (m)

t = time (s)

K = hydraulic conductivity tensor (m/s)

z = potential head (m)

q = source and/or sink

ρ = water density at chemical concentration C (kg/m^3)

ρ_0 = referenced water density at zero chemical concentration (kg/m^3)

ρ^* = density of either the injection fluid or the withdrawn water (kg/m^3)

θ = moisture content

$\alpha^{'}$ = modified compressibility of the medium

$\beta^{'}$ = modified compressibility of the water

n = porosity of the medium

S = saturation

The hydraulic conductivity K is given by eqn. 6.3

$$\mathrm{K} = \frac{\rho g}{\mu} k = \frac{\left(\rho / \rho_0 \right)}{\left(\mu / \mu_0 \right)} \frac{\rho_0 g}{\mu_0} k_S k_r = \frac{\rho / \rho_0}{\mu / \mu_0} K_{S0} k_r \tag{6.3}$$

where

μ = dynamic viscosity of water at chemical concentration C (P)

μ_0 = referenced dynamic viscosity at zero chemical concentration (P)

k = permeability tensor (m^2)

k_S = saturated permeability tensor (m^2)

k_r = relative permeability or relative hydraulic conductivity (m^2)

K_{SO} = referenced saturated hydraulic conductivity tensor

The referenced value is usually taken at zero chemical concentration. The density and dynamic viscosity of water are functions of chemical concentration and are assumed as follows.

$$\frac{\rho}{\rho_0} = a_1 + a_2 C + a_3 C^2 + a_4 C^3 \tag{6.4}$$

and

$$\frac{\mu}{\mu_0} = a_5 + a_6 C + a_7 C^2 + a_8 C^3 \qquad (6.5)$$

where a_1, a_2, ..., a_8 are the parameters used to define concentration dependence of water density and viscosity and C is the chemical concentration.

The Darcy velocity (v) is calculated as follows,

$$v = -K\left(\frac{\rho_0}{\rho}\nabla h + \nabla z\right) \qquad (6.6)$$

6.3 METHODOLOGY

The field data is collected and used as input data to develop the groundwater flow model. The specific flux is assigned as the boundary condition for the flow model. The mesh is created from the input data and the boundary conditions. Extraction wells with their latitude and longitude are assigned to the model. Further, using scatter point and 2D mesh data, Triangular Irregular Network (TIN) for the study area is created.

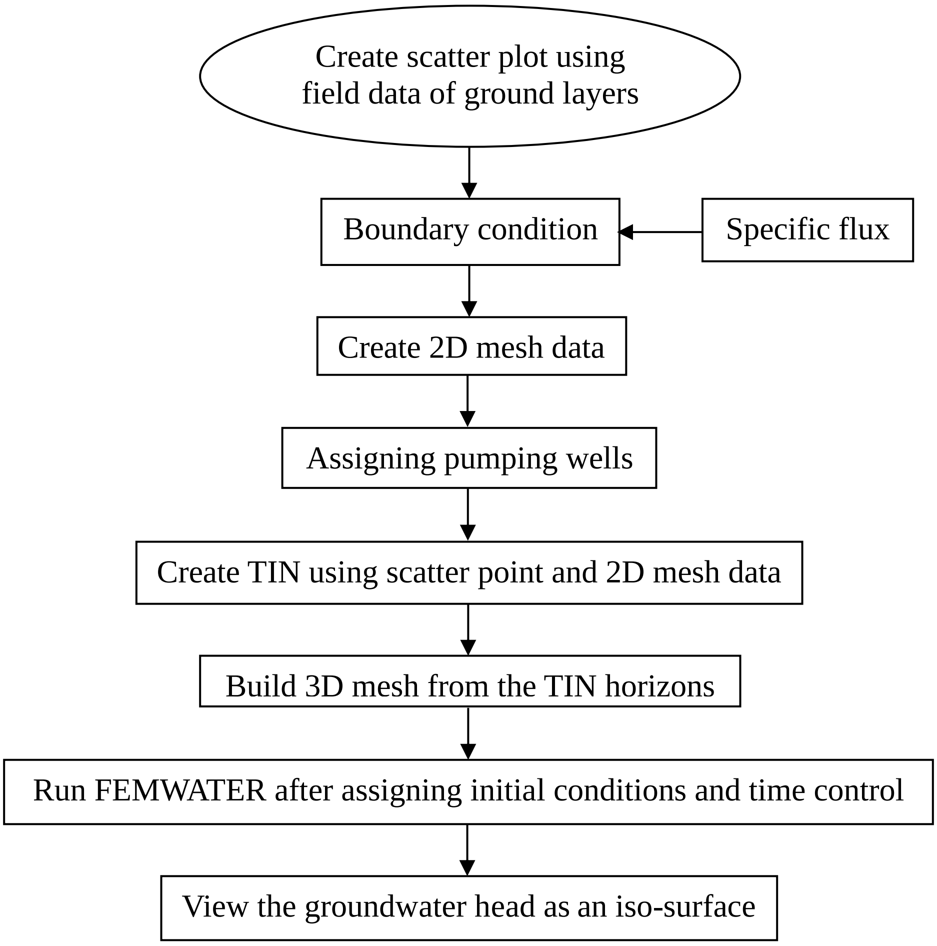


Fig 6.1 FEMWATER flow modelling

From the TIN data and scatter data of groundwater wells, a 3D mesh is created. The flow model is simulated to get the groundwater head result for both steady state and transient state condition. Fig. 6.1 shows the flowchart for FEMWATER groundwater flow modelling.

6.3.1 Conceptual model

The groundwater modelling in the study area carried out based on the conceptual model. In the conceptual model, the boundary condition of the groundwater flow follows the flux condition and precipitation. The initial conditions in the study are followed by the governing equations. Fig 6.2 represents the details of the conceptual model for groundwater modelling in the study area and Fig 6.3 represents the numerical modelling protocol.

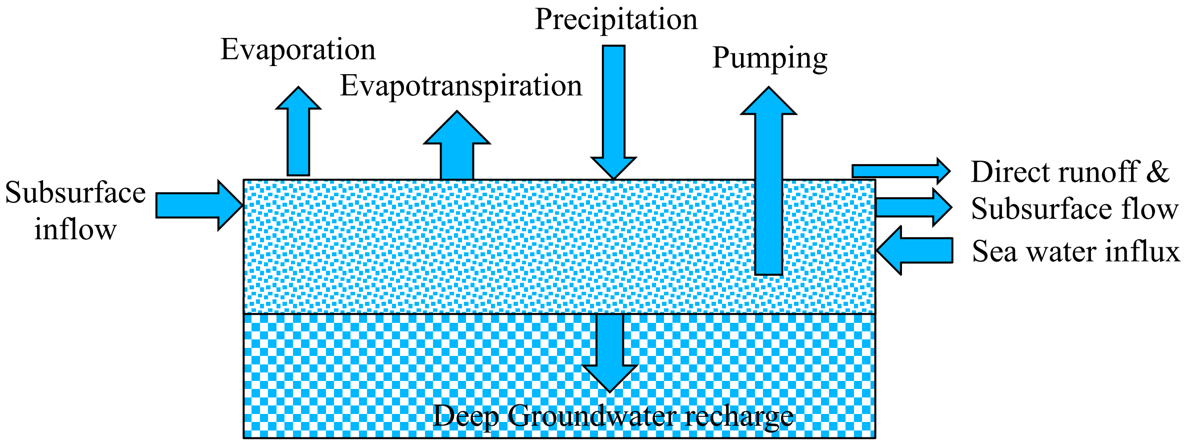


Fig 6.2 Conceptual model

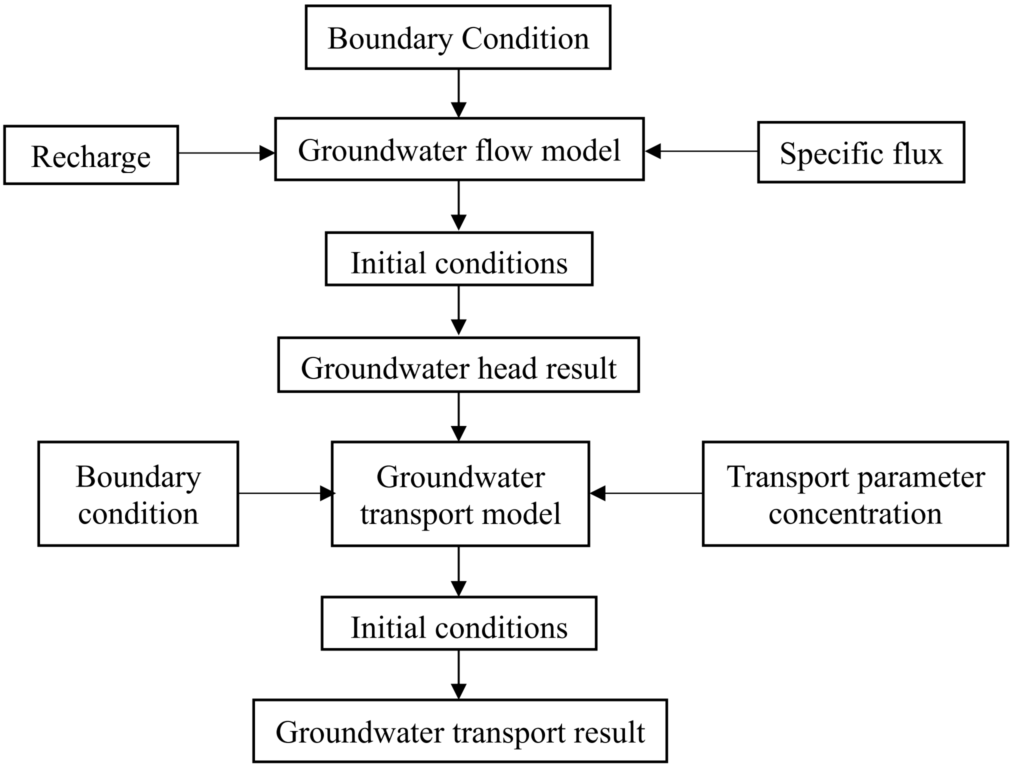


Fig 6.3 Numerical modelling protocol

6.3.1.1 Recharge calculation

The recharge is calculated based on the water balance equation.

6.3.1.1.1 Water balance equation

A general water balance equation is given in Eq. (6.7)

$$P = R + E + \Delta S \tag{6.7}$$

Where

P is precipitation

R is runoff

E is Evapotranspiration

ΔS is change in storage (Recharge)

This equation uses the principles of conservation of mass in a closed system, whereby any water entering a system (via precipitation), must be transferred into either evaporation, surface runoff (eventually reaching the channel and leaving in the form of river discharge), or stored in the ground.

6.3.1.1.2 Precipitation

In meteorology, precipitation is the product of condensation in atmospheric water vapour that falls under gravity. The main forms of precipitation include drizzle, rain, snow, and hail. Precipitation occurs when a portion of the atmosphere becomes saturated with water vapour so that the water condenses and precipitates. Thus, fog and mist are not precipitation but suspensions, because the water vapour does not condense sufficiently to precipitate. Two processes, possibly acting together, can lead to air becoming saturated: cooling the air or adding water vapour to the air. Precipitation forms as smaller droplets coalesce via collision with other rain drops or ice crystals within a cloud. Short, intense periods of rain in scattered locations are called showers.

The study area of Netravathi and Gurpur river confluence consist of six rain gauge stations. The precipitation data of those rain gauge stations have been collected from the Statistical Department of Manguluru and given in Table 6.1. The period of June to October experiences precipitations in all the rain gauge stations. The total average rainfall in the study area was found to be 3000 mm to 4000 mm.

Table 6.1 Precipitation data of Netravathi and Gurpur river confluence

RGS_name	Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Total
Bantwal	2012	0	0	1.6	95.4	20.8	724.1	667.2	1182.6	418.2	135	37	0	3281.9
Bantwal	2013	0	16	3.2	0	38.4	1388.6	1245.32	629.6	323.6	400.5	76	4	4125.22
Bantwal	2014	0	0	0	14.4	148.2	530.6	1277.6	1072.6	332.6	346.4	51.2	47.2	3820.8
Bantwal	2015	0	0	6.1	37.4	180.6	741.5	1059.7	582	241.4	292.1	97.6	3.6	3242
Bantwal	2016	0	0	0.4	0	225.4	905.4	950.6	531	234.42	22	63	9.5	2941.72
Bajpe	2012	0	0	0	54.4	91.2	969.3	584.3	1077.3	322.7	105.8	21.8	0	3226.8
Bajpe	2013	0	34.8	0	0	75.3	1407.9	1090.8	612.7	318.1	234.4	103.2	5.6	3882.8
Bajpe	2014	0	0	0	13	104.2	619.1	1069.7	995.2	330.8	300.8	20.1	35.6	3488.5
Bajpe	2015	0	0	9.2	74.3	129.5	731.4	1018.1	477.8	200.8	272.7	103.2	0.1	3017.1
Bajpe	2016	0	0	0	0	102.1	1254	961.9	474.6	227.1	40.7	15.9	1.5	3076.3
Mangalore RS	2012	0	0	0	79.5	24.1	994.9	715.7	1110.7	423.1	179.6	86.4	0	3614
Mangalore RS	2013	0	70.4	25.4	0	125.5	1495	1002.4	550.1	345	281.5	66.4	1.4	3963.1
Mangalore RS	2014	0	0	0	38.1	190.9	522	943.2	973.3	441.7	211	58	42.8	3421
Mangalore RS	2015	2	0	7.8	123.7	92.4	637.8	1005.2	481.4	216.8	237.4	66.6	16.6	2887.7
Mangalore RS	2016	0	0	0	9.2	192.6	1144.2	1114.6	440.6	192	50.6	11.6	7.2	3162.6
Mangalore DC Office	2012	0	0	1.2	60.2	20.4	873.6	637	965.4	363.9	182.8	61.6	0	3166.1
Mangalore DC Office	2013	0	66.8	53.2	1.6	109.2	1352.2	894.2	501.4	316.1	228.6	45.8	4.8	3573.9
Mangalore DC Office	2014	0	0	0	45	182.4	476.6	827.8	905.9	361.9	200	57	29.2	3085.8
Mangalore DC Office	2015	2	0	8	109.8	96	641.2	976.1	489.3	222.3	215	59.5	16.8	2836
Mangalore DC Office	2016	0	0	0	16.1	193.4	1138.4	1081	434.9	187.4	50	11.6	7.2	3120
Gurupur/ kuppepadhu	2012	0	0	0	108	90	1114	882	1412	483	198	71	0	4358
Gurupur	2013	0	13	2	20	28	1394	1475	583	439	431	112	6	4503
Gurupur	2014	0	0	0	3	152	472.9	1236	1268	367.5	139	28	20	3686.4
Gurupur	2015	0	0	14	28	95	488	796	525	148	164	82	0	2340
Gurupur	2016	0	0	0	0	93	981	941	554	238	56	38	5.2	2906.2

(* Units = mm)

6.3.1.1.3 Evapotranspiration

Evapotranspiration (ET) is the sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and waterbodies. Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapor through stomata in its leaves. Evapotranspiration is an important part of the water cycle. An element (such as a tree) that contributes to evapotranspiration can be called an evapotranspirator. Evapotranspiration for the study area of Netravathi and Gurpur river confluence calculated by downloading the MODIS data. MYD16A2 of MODIS data (Running et al. 2017) used for calculating Evapotranspiration for 8-day time period of each month from

2012 to 2016 as shown in Table 6.2. The average value of Evapotranspiration lies between 3.47 mm/day to 3.96 mm/day.

Table 6.2. Evapotranspiration of Netravathi and Gurpur river confluence

	2012	2013	2014	2015	2016
Jan	2.23	3.09	3.37	3.37	3.75
Feb	2.78	4.2	3.53	3.67	3.66
Mar	2.91	3.81	3.15	3.58	3.77
April	3.5	3.78	2.85	3.78	3.51
May	3.44	2.62	4.43	3.46	4.4
June	2.68	3.27	3.87	1.55	0.95
July	0.96	1.21	1.46	3.66	1.45
Aug	2.81	2.92	3.04	4.17	5.73
Sep	5.79	6.52	7.26	4.47	4.81
Oct	6.42	6.12	5.83	5.44	5.33
Nov	4.59	4.31	4.03	5.43	4.34
Dec	3.53	3.55	3.57	4.94	3.9
Average	3.47	3.783333	3.865833	3.96	3.8

(* Units = mm/day)

6.3.1.1.4 Recharge

Groundwater recharge or deep drainage or deep percolation is a hydrologic process where water moves downward from surface water to groundwater. Recharge is the primary method through which water enters an aquifer. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e., "artificial groundwater recharge"), where rainwater and or reclaimed water is routed to the subsurface. The recharge of the study area Netravathi and Gurpur river confluence is calculated using the Krishna Rao empirical formula. Krishna Rao gave the following empirical relationship in 1970 to determine the ground water recharge in limited climatological homogenous areas is given eq. (6.8).

$$R = K (P - X) \quad \text{(mm)} \tag{6.8}$$

The following relation is stated to hold good for different parts of Karnataka;

$R = 0.20 (P - 400)$ for areas with annual normal rainfall P between 400 and 600mm

$R = 0.25 (P - 400)$ for areas with P between 600 and 1000mm

$R = 0.35 (P - 600)$ for areas with P above 1000mm where,

R & P are expressed in millimetres

R = recharge

P = Precipitation

The major rainfall in the study area mainly occurs during the period of June to October. The average recharge of the study area given in Table 6.3. The unit of rate of recharge is converted from mm to m/d in order to input in model.

Table 6.3 Rate of recharge of Netravathi and Gurpur river confluence

Year	Rate of recharge (m/d)
2012	0.002993
2013	0.003461
2014	0.002973
2015	0.002363
2016	0.002526

6.3.1.2 Specific flux

It is defined as the flow per unit cross-sectional area of the porous medium. In this study, the specific flux is calculated from the Darcy flux. The hydraulic conductivity data is used for the calculation of the specific flux. The obtained specific flux results are assigned in the first coastal stretch, second coastal stretch and freshwater zone in the study area modelling for both steady state and transient state conditions.

6.3.2 Steady state condition

The steady state flow occurs when the magnitude and direction of flow are constant with time throughout the entire domain. In the steady state condition, the hydraulic head does not change with time. The data considered for steady state condition modelling is the April 2013 data. The model parameters of hydraulic conductivity and recharge are adjusted to get acceptable results. The 2D scatter data is created from the field input data of groundwater wells. The groundwater wells input data consist of elevation, groundwater head, first bottom and second bottom, as shown in Table 6.4. The mean sea level (M.S.L) is taken as the benchmark for groundwater wells input data. In the study area, 20 wells are considered for pumping and the details of the pumping wells are shown in Table 6.5. These wells are mostly used for irrigation in agriculture and domestic purposes like drinking and household activities. The specific flux rate is assigned at the boundaries of the study area. The boundaries of the study area are divided into three parts, the first part is the first coastal stream, the second part is second coastal stream and the third part is fresh water stream as shown in Fig. 6.4. The specific flux is calculated based on the Darcy flux. The groundwater table of freshwater stream connecting Gurpur and Netravathi river is shown in dotted line. The TIN data as shown in Fig. 6.5, is created after assigning 2D scatter data, specific flux, pumping wells and recharge in the model. The TIN data is used for the generation of 2D and 3D mesh data. The 3D mesh data for steady state condition is shown in Fig. 6.6., which also gives the head result of flow modelling. In the steady state condition, the number of elements of the model obtained as 17474.

Table 6.4 Input data of groundwater wells for steady state condition

Well No	Latitude	Longitude	Elevation (M.S.L, m)	Groundwater head (M.S.L, m)	First Bottom (M.S.L, m)	Second bottom (M.S.L, m)
1	12° 55' 47"	74° 50' 18"	6	4.76	1.75	-15
2	12° 55' 28"	74° 50' 54"	18	10.7	7.23	-3
3	12° 56' 47"	74° 51' 07"	7	3.11	-0.21	-14
4	12° 55' 54"	74° 51' 31"	40	37.39	34.97	19
5	12° 55' 47"	74° 53' 20"	64	57.28	51.27	43
6	12° 55' 04"	74° 54' 02"	87	74.42	72.53	66
7	12° 55' 05"	74° 54' 53"	11	8.76	6.09	-10
8	12° 55' 36"	74° 55' 06"	19	13.53	10.93	-2
9	12° 55' 35"	74° 55' 33"	29	19.92	17.63	8
10	12° 54' 53"	74° 56' 20"	45	32.2	31.24	24
11	12° 54' 29"	74° 56' 16"	34	22.46	21.83	13
12	12° 54' 10"	74° 57' 34"	45	39.23	38.24	24
13	12° 54' 45"	74° 50' 13"	9	6.66	4.45	-12
14	12° 52' 11"	74° 58' 53"	21	16.95	13.22	-2
15	12° 52' 11"	74° 58' 19"	38	31.1	27.9	15
16	12° 52' 22"	74° 57' 31"	15	12	7.25	-8
17	12° 52' 19"	74° 56' 45"	22	18.87	13.81	-1
18	12° 52' 05"	74° 55' 29"	8	4.01	-0.29	-15
19	12° 52' 14"	74° 53' 47"	10	7.57	6.13	-13
20	12° 51' 15"	74° 52' 44"	32	23.85	18.98	9
21	12° 51' 00"	74° 52' 08"	17	15.36	10.42	-6
22	12° 50' 39"	74° 50' 33"	13	10.31	8.12	-10
23	12° 52' 50"	74° 49' 39"	15	11.5	9.8	-8
24	12° 53' 18"	74° 49' 21"	13	10.7	8.2	-10
25	12° 53' 21"	74° 49' 55"	26	15.58	10.96	3

Table 6.5 Details of the pumping wells

Well No	Latitude	Longitude	Elevation (M.S.L, m)	Flow rate (m^3/hr)
PW1	12° 55' 37"	74° 50' 22"	13	-21.708
PW2	12° 55' 55"	74° 51' 39"	40	-20.556
PW3	12° 55' 09"	74° 56' 05"	30	-12.06
PW4	12° 54' 21"	74° 51' 05"	15	-6.552
PW5	12° 52' 08"	74° 53' 46"	10	-7.308
PW6	12° 52' 04"	74° 58' 22"	30	-10.44
PW7	12° 54' 21"	74°49' 55"	12	-2.5
PW8	12° 52' 49"	74° 49' 52"	15	-2.5
PW9	12° 50' 52"	74° 50' 41"	13	-2.5
PW10	12° 51' 16"	74° 51' 55"	17	-2.5
PW11	12° 51' 16"	74° 52' 56"	30	-2.5
PW12	12° 52' 38"	74° 55' 20"	8	-5
PW13	12° 52' 58"	74° 56' 34"	22	-5
PW14	12° 52' 29"	74° 57' 35"	15	-10
PW15	12° 52' 14"	74° 59' 01"	21	-10
PW16	12° 54' 01"	74° 57' 43"	43	-10
PW17	12° 53' 57"	74° 55' 40"	34	-10
PW18	12° 54' 59"	74° 55' 01"	13	-5
PW19	12° 55' 47"	74° 52' 40"	55	-5
PW20	12° 52' 29"	74° 50' 45"	23	-2.5

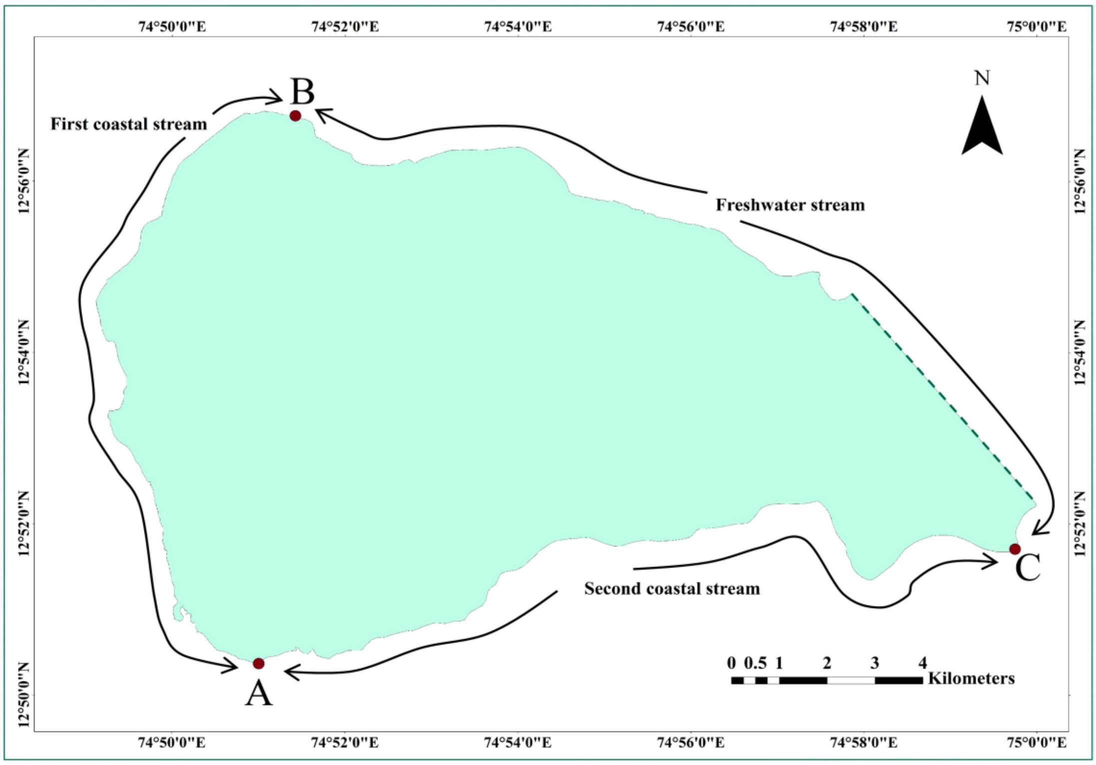


Fig 6.4 Boundary condition

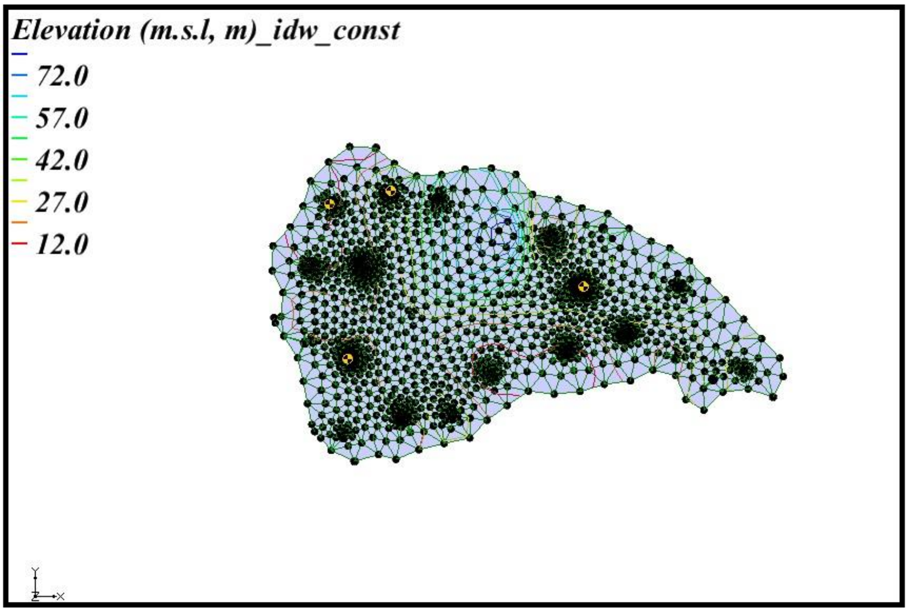
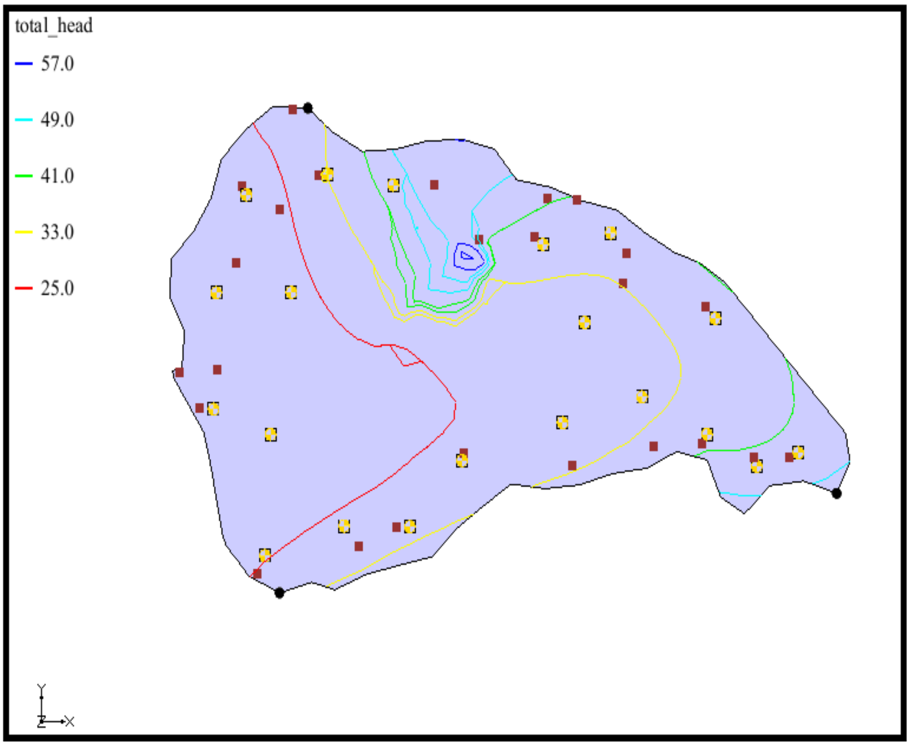


Fig 6.5 TIN model of steady state condition



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 6.6 Flow model of steady state condition

6.3.2.1 Boundary condition

The boundary condition in the study area depends upon the head, specific flux and precipitation. The Fig. 6.4 shows the aquifer delineation of the study area. The boundary of the aquifer is delineated on three streams. They are first coastal stream (AB), second coastal stream

(AC) and freshwater stream (BC). The boundary condition considered for groundwater wells which depends on head is Dirichlet condition and for the study area boundary is Flux condition (Cauchy). The Flux is assigned on three streams of the aquifer. The head dependant is given to the wells of the study area which follows Dirichlet conditions. Based on these boundary conditions the flow equation is given in the following conditions

- Dirichlet conditions
- Gradient flux conditions
- Flux conditions
- Variable conditions during precipitation period
- Variable conditions during the non-precipitation period

a. Dirichlet conditions:

$$h = h_d(x_b, y_b, z_b, t) \quad \text{on } \mathrm{B_d}, \tag{6.9}$$

b. Gradient flux conditions:

$$-n.K.\left(\frac{\rho_0}{\rho}\nabla h\right) = q_n(x_b, y_b, z_b, t) \text{ on } \mathrm{B_n} \tag{6.10}$$

c. Flux conditions:

$$-n.K.\left(\frac{\rho_0}{\rho}\nabla h + \nabla z\right) = q_c(x_b, y_b, z_b, t) \quad \text{on } \mathrm{B_c} \tag{6.11}$$

d. Variable conditions during precipitation period:

$$h = h_p(x_b, y_b, z_b, t) \qquad \text{on } \mathrm{B_v} \tag{6.12}$$

or

$$-n.K.\left(\frac{\rho_0}{\rho}\nabla h + \nabla z\right) = q_p(x_b, y_b, z_b, t) \qquad \text{on } \mathrm{B_v}, \tag{6.13}$$

e. Variable conditions during non-precipitation period:

$$h = h_p(x_b, y_b, z_b, t) \qquad \text{on } \mathrm{B_v} \tag{6.14}$$

or

$$h = h_n \text{ on } \mathrm{B_v} \tag{6.15}$$

or

$$-n.K.\left(\frac{\rho_0}{\rho}\nabla h+\nabla z\right)=q_e\left(x_b,y_b,z_b,t\right) \qquad \text{on } B_v \qquad (6.16)$$

where

(x_b,y_b,z_b) = spatial coordinate on the boundary

n = outward unit vector normal to the boundary

h_d = Dirichlet functional value

q_n = Gradient flux value

q_c = Flux value

B_d = Dirichlet boundary

B_n = Gradient flux boundary

B_c = Flux boundary

B_v = variable boundary

h_p = ponding depth (m)

q_p = throughfall of precipitation on the variable boundary (mm)

h_m = minimum pressure on the variable boundary (m)

q_e = evaporation rate on the variable boundary

Only one of the Eq. (6.12) - (6.16) is used at any point on the variable boundary condition. In this groundwater modelling study, the boundary condition based on the flux and precipitation is considered. The flux and precipitation are mainly considered due to the study area near to the river confluence.

6.3.2.2 Initial condition

The initial condition is specifying the head distribution throughout the system at some particular time. The initial condition is important since based on this model hydrologic inputs and parameters adjusted with correspondence with model heads and field heads is obtained. The initial conditions for the flow equation are shown in Eq. (6.17):

$$h=h_i\left(x,y,z\right) \quad \text{in R,} \qquad (6.17)$$

Where, R is the region of interest and h_i is the prescribed initial condition, which can be obtained by either field measurements or by solving the steady state of eqn. (6.1).

6.3.2.3 Calibration

The model calibration is process which is carried out by comparing the simulated head to observed hydraulic heads at a limited number of observation points. In order to obtain a good fit of observed and simulated heads, the trial and error process is done for model calibration. The model is calibrated for steady state condition. The maximum simulation time taken for model calibration is 30 days with a constant time step interval of 1day. In the calibration analysis, seven well results are considered for both observation and simulation. The vital input data assigned for the model calibration are recharge, hydraulic conductivity and specific flux rate. The recharge and hydraulic conductivity are given as 0.0001m/s and 35 m/s. The specific flux rate is given as input data along the boundary of the study area. In the first coastal stream, it is assigned as 0.0665 m/s, second coastal stream assigned as 0.45 m/s and the freshwater stream assigned as 0.2576 m/s.

The result of the model calibration is represented as the coefficient of determination (R^2). The coefficient of determination is the proportion of the variance in the dependent variable that is predictable from the independent variable(s). The context of the statistical model's purpose is either the prediction of future outcomes or the testing of hypotheses by other related information. It provides a measure of how well-observed data are replicated by the model, based on the proportion of total variation of outcomes explained by the model. The best and acceptable R^2 value is ranging from 0.75 to 1.

6.3.2.4 Validation

The model validation in groundwater modelling is the ability of the model to assess the good fit of observed and the simulated heads. The model is validated for steady state condition considering same time control, recharge, hydraulic conductivity and a specific flux rate of calibration. For validation, coefficient of determination (R^2) is calculated for observed and simulated heads of wells.

6.3.3 Transient state condition

The transient state condition occurs when the magnitude and direction of the flow changes with time. In this condition, the hydraulic head changes with time. In the transient state condition, most of the time control change from steady state condition. The parameters such as 2D scatter data, recharge, hydraulic conductivity and the specific flux rate changes with time as input data. The only parameter which does not change is the location pumping wells, as shown in Table 6.2 assigned in the transient state condition. In the transient state condition, the model is run for both calibration and validation with different field measured groundwater head as the input data.

6.3.3.1 Boundary condition

The boundary condition for the transient state condition for a various factor such as the head, specific flux, recharge and the elements of the model are common but the value of the factors vary from steady state condition. Based on these boundary conditions the flow equation is applied in the following conditions, Eq. (6.7 - 6.14).

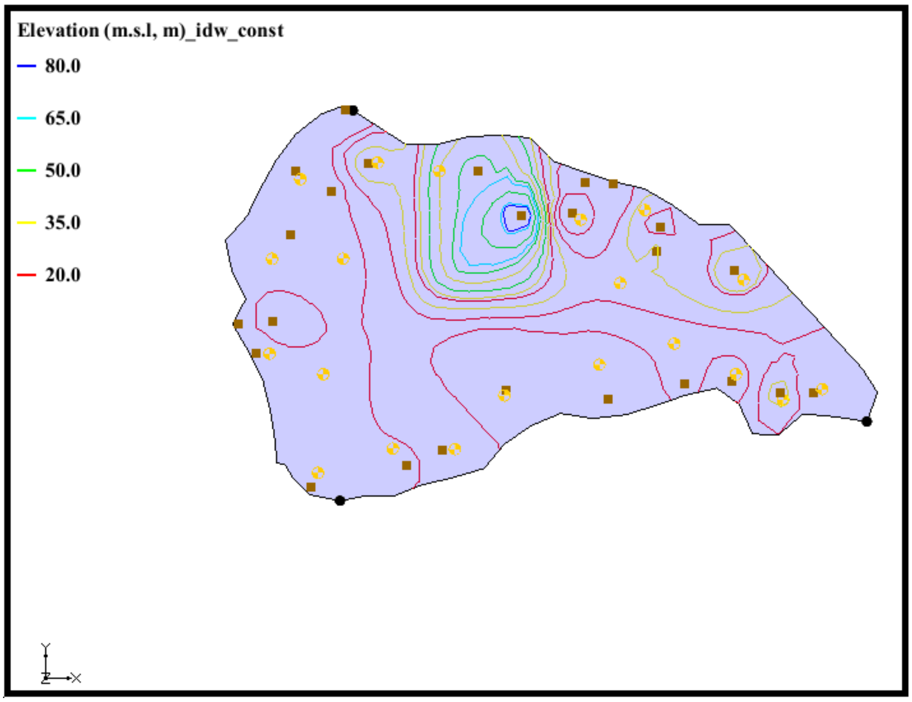
- Dirichlet conditions
- Gradient flux conditions
- Flux conditions
- Variable conditions during precipitation period
- Variable conditions during non-precipitation period

6.3.3.2 Initial condition

In the transient state, the initial conditions are determined through a steady-state simulation of the flow system. An adjustment of model hydrologic inputs and parameters which is acceptably closer values are considered. Steady state model generated heads are used as the initial condition for transient state condition. The initial conditions for the flow equation are given by eqn. 6.17.

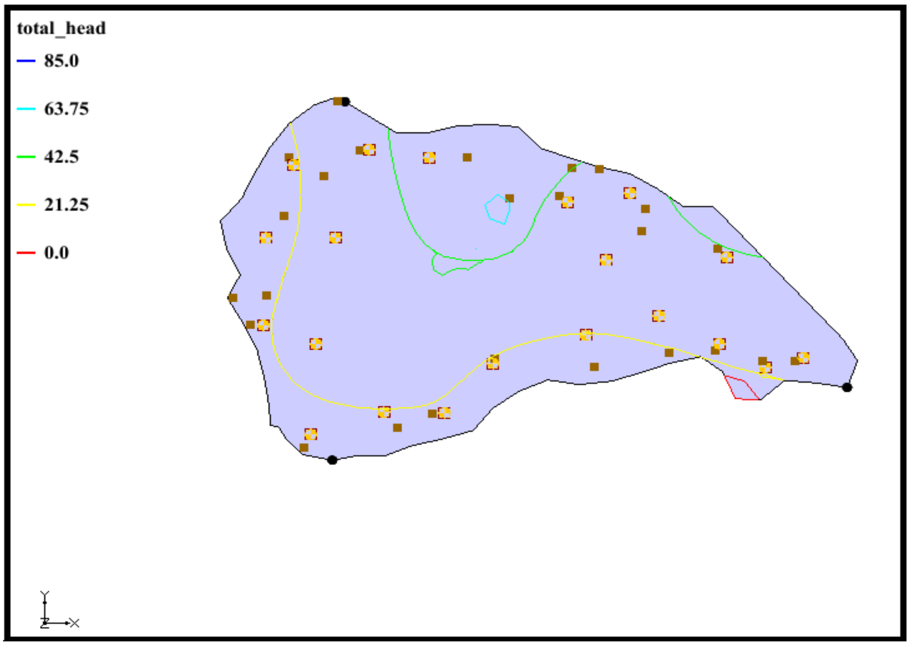
6.3.3.3 Calibration

In the transient state calibration, the input data given to the model are groundwater wells data, recharge, hydraulic conductivity, specific flux rate and details of pumping wells with flow rate. The details of pumping wells and groundwater wells are given in Table 6.5 and 6.6 respectively. The time period taken for model simulation for calibration is 486 days from September 2013 to December 2014) with a constant time interval of 30 days. The recharge and hydraulic conductivity for the model is assigned as 0.003461 m/s and 27.15 m/s respectively. The specific flux assigned for calibration to first coastal stretch, second coastal stretch and the freshwater stretch are -0.0515 m/s, -0.35 m/s and 0.199 m/s respectively. The negative sign in the coastal stretch of specific flux indicates outward flux due to monsoon season. Based on the groundwater data the 2D scatter data is created which is the basic input data for the model. The groundwater head data is created from the 2D scatter data and it is shown in Fig 6.7. The 2D and 3D mesh data is created from TIN data. The 3D mesh data of flow is shown in Fig 6.8. For transient calibration, the number of elements of the model obtained is 17474. The result of the coefficient of R^2 is obtained for 10 representative wells with good performance.



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 6.7 Groundwater head elevation model of transient state calibration



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

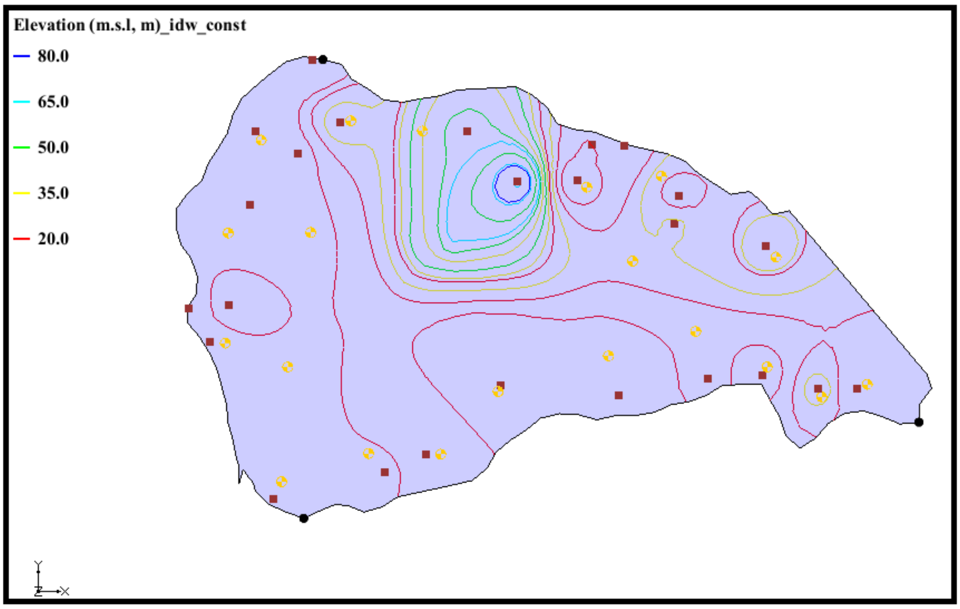
Fig 6.8 Flow model of transient state calibration

Table 6.6 Input data of groundwater wells for transient state calibration

Well No	Latitude	Longitude	Elevation (m.s.l, m)	Groundwater head (m.s.l, m)	First Bottom (m.s.l, m)	Second bottom (m.s.l, m)
1	12° 55' 47"	74° 50' 18"	6	5.34	1.75	-15
2	12° 55' 28"	74° 50' 54"	18	12.68	7.23	-3
3	12° 56' 47"	74° 51' 07"	7	5.05	-0.21	-14
4	12° 55' 54"	74° 51' 31"	40	38.43	34.97	19
5	12° 55' 47"	74° 53' 20"	64	60.33	51.27	43
6	12° 55' 04"	74° 54' 02"	87	79.58	72.53	66
7	12° 55' 05"	74° 54' 53"	11	10.55	6.09	-10
8	12° 55' 36"	74° 55' 06"	19	16.35	10.93	-2
9	12° 55' 35"	74° 55' 33"	29	22.58	17.63	8
10	12° 54' 53"	74° 56' 20"	45	35.93	31.24	24
11	12° 54' 29"	74° 56' 16"	34	29.64	21.83	13
12	12° 54' 10"	74° 57' 34"	45	41.76	38.24	24
13	12° 54' 45"	74° 50' 13"	9	7.18	4.45	-12
14	12° 52' 11"	74° 58' 53"	21	18.14	13.22	-2
15	12° 52' 11"	74° 58' 19"	38	31.2	27.9	15
16	12° 52' 22"	74° 57' 31"	15	14.27	7.25	-8
17	12° 52' 19"	74° 56' 45"	22	19.45	13.81	-1
18	12° 52' 05"	74° 55' 29"	8	6.46	-0.29	-15
19	12° 52' 14"	74° 53' 47"	10	8.47	6.13	-13
20	12° 51' 15"	74° 52' 44"	32	27.38	18.98	9
21	12° 51' 00"	74° 52' 08"	17	15.49	10.42	-6
22	12° 50' 39"	74° 50' 33"	13	10.96	8.12	-10
23	12° 52' 50"	74° 49' 39"	15	13.2	9.8	-8
24	12° 53' 18"	74° 49' 21"	13	11.02	8.2	-10
25	12° 53' 21"	74° 49' 55"	26	18.6	10.96	3

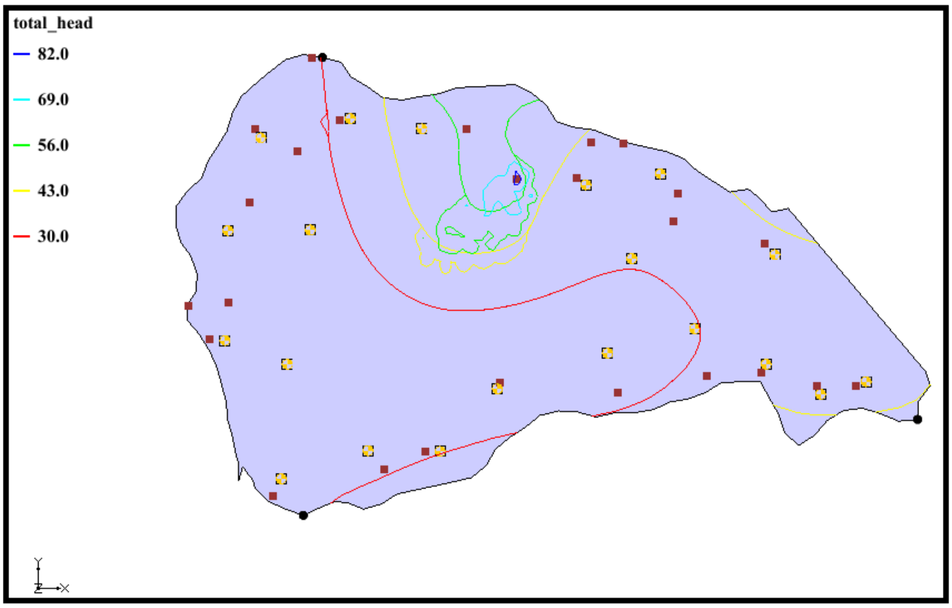
6.3.3.4 Validation

In the transient state condition, the input data given for model validation are similar to calibration. The details of pumping wells and groundwater wells are shown in Table 6.5 and Table 6.7. The recharge and hydraulic conductivity assigned for the model are 0.003461 m/s and 27.15 m/s respectively. The specific flux assigned for validation to first coastal stretch, second coastal stretch and the freshwater stretch are 0.0515 m/s, 0.35 m/s and 0.199 m/s respectively. The positive sign in the coastal stream of specific flux indicates outward flux due to the summer season. Based on the groundwater data the 2D scatter data is created which is the base input data for the model. The TIN data is created from the 2D scatter data and it is shown in Fig 6.9. The 2D mesh data and 3D mesh data is created from TIN data. The 3D mesh data of flow is shown in Fig 6.10. In the transient state validation, the number of elements in the model is 17474. The time control taken for validation is 425 days from April 2016 to May 2017 with a constant time interval of 30 days. R^2 of 9 representative wells is calculated with best result.



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 6.9 Groundwater head elevation model of transient state validation



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 6.10 Flow model of transient state validation

Table 6.7 Input data of groundwater wells for transient state validation

Well No	Latitude	Longitude	Elevation (m.s.l, m)	Groundwater head (m.s.l, m)	First Bottom (m.s.l, m)	Second bottom (m.s.l, m)
1	12° 55' 47"	74° 50' 18"	6	4.08	1.75	-15
2	12° 55' 28"	74° 50' 54"	18	10.33	7.23	-3
3	12° 56' 47"	74° 51' 07"	7	1.39	-0.21	-14
4	12° 55' 54"	74° 51' 31"	40	37.09	34.97	19
5	12° 55' 47"	74° 53' 20"	64	57.27	51.27	43
6	12° 55' 04"	74° 54' 02"	87	76.76	72.53	66
7	12° 55' 05"	74° 54' 53"	11	8.46	6.09	-10
8	12° 55' 36"	74° 55' 06"	19	13.29	10.93	-2
9	12° 55' 35"	74° 55' 33"	29	20.48	17.63	8
10	12° 54' 53"	74° 56' 20"	45	32.29	31.24	24
11	12° 54' 29"	74° 56' 16"	34	22.86	21.83	13
12	12° 54' 10"	74° 57' 34"	45	39.23	38.24	24
13	12° 54' 45"	74° 50' 13"	9	6.08	4.45	-12
14	12° 52' 11"	74° 58' 53"	21	15.78	13.22	-2
15	12° 52' 11"	74° 58' 19"	38	31.07	27.9	15
16	12° 52' 22"	74° 57' 31"	15	12.55	7.25	-8
17	12° 52' 19"	74° 56' 45"	22	17.73	13.81	-1
18	12° 52' 05"	74° 55' 29"	8	4.72	-0.29	-15
19	12° 52' 14"	74° 53' 47"	10	7.07	6.13	-13
20	12° 51' 15"	74° 52' 44"	32	22.58	18.98	9
21	12° 51' 00"	74° 52' 08"	17	15.05	10.42	-6
22	12° 50' 39"	74° 50' 33"	13	10.02	8.12	-10
23	12° 52' 50"	74° 49' 39"	15	11.21	9.8	-8
24	12° 53' 18"	74° 49' 21"	13	10.3	8.2	-10
25	12° 53' 21"	74° 49' 55"	26	14.38	10.96	3

6.4 RESULTS AND DISCUSSION

Groundwater flow model simulates the following results for both steady state and transient state conditions. In the modelling study, it is found out that the hydraulic conductivity and recharge are more sensitive parameters to the model. The slight changes in those parameters have a huge impact in the study area. In the steady state condition, the groundwater head results are shown in Fig. 6.11 and Fig. 6.12. The R^2 value for calibration and validation is obtained as 0.98 and 0.9.

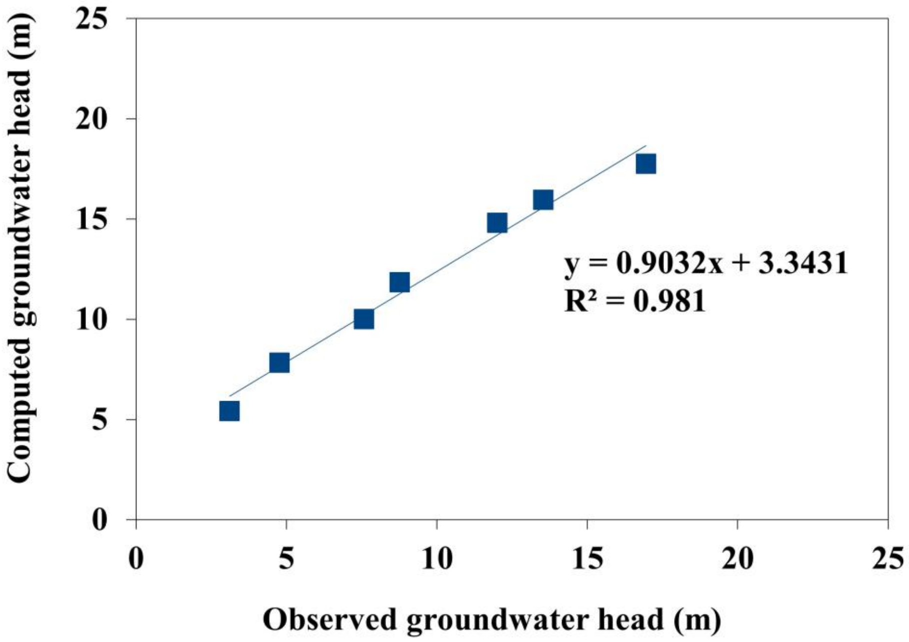


Fig 6.11 Observed and computed groundwater head result for calibration of steady state condition

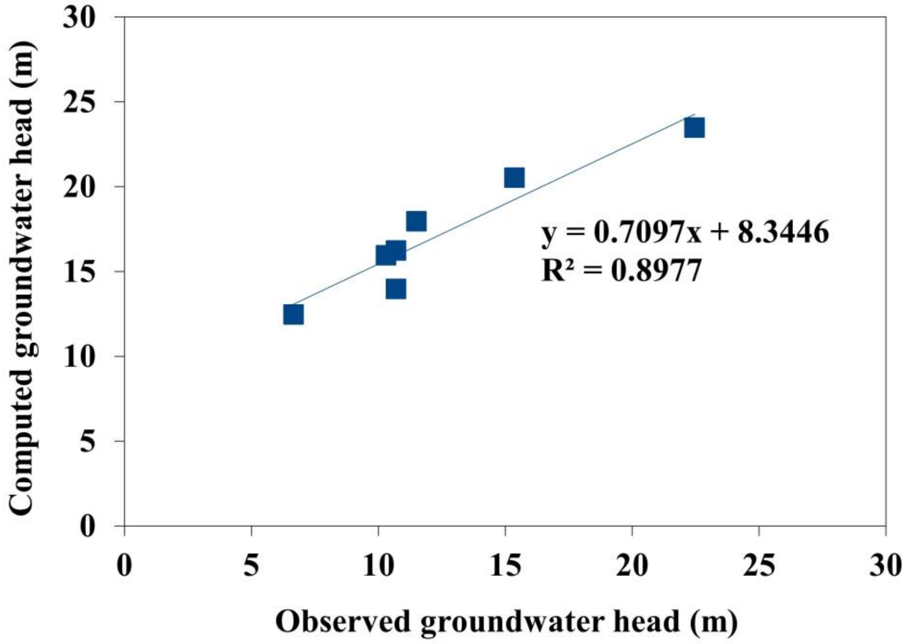


Fig 6.12 Observed and computed groundwater head result for validation of steady state condition

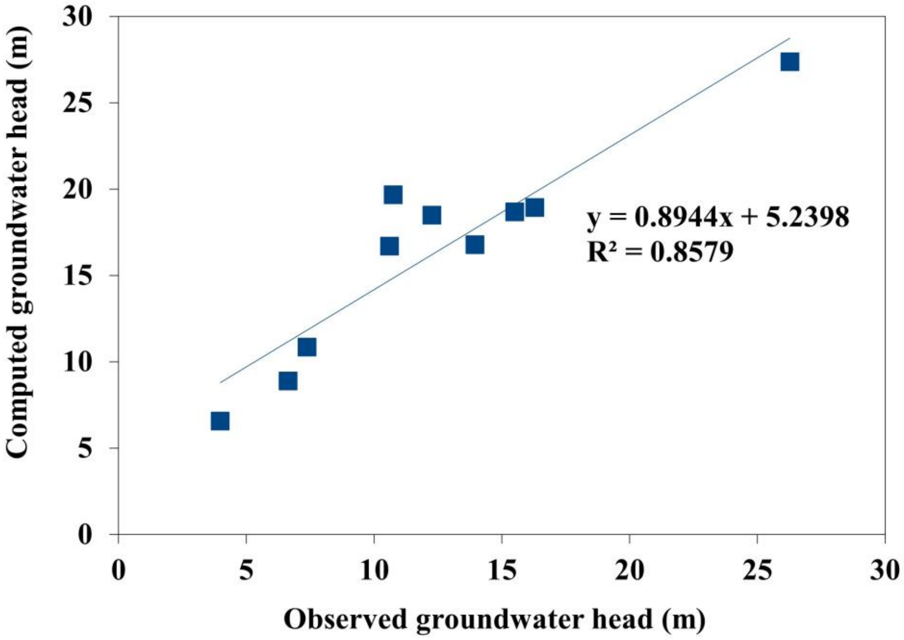


Fig 6.13 Observed and computed groundwater head result for calibration of transient state condition

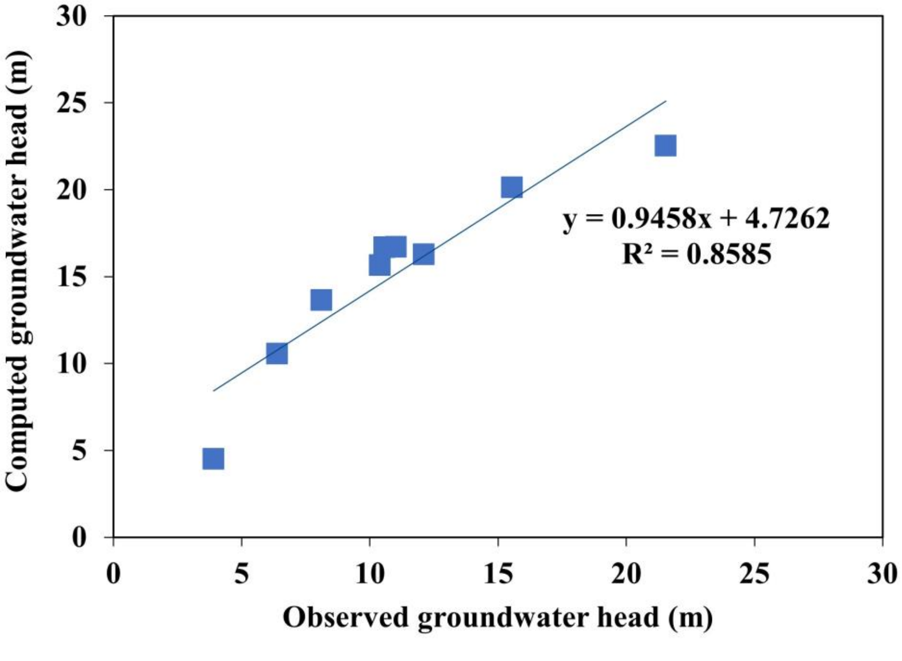


Fig 6.14 Observed and computed groundwater head result for validation of transient state condition

In the transient state, the coefficient of determination R^2 for the calibration and validation are 0.86 and 0.86 and is shown in Fig. 6.13 and Fig. 6.14. The R^2 value for the transient state results is found to be less compared to the steady state since the transient state time control is 486 days for calibration and 425 days for validation, whereas for the steady state the time control is 30 days. The Fig 6.15 shows the time series results of groundwater head for the well numbers 15, 21, 22 and 24 which is found to be the best predicted between observed and simulated groundwater head of the model compared to all other groundwater wells.

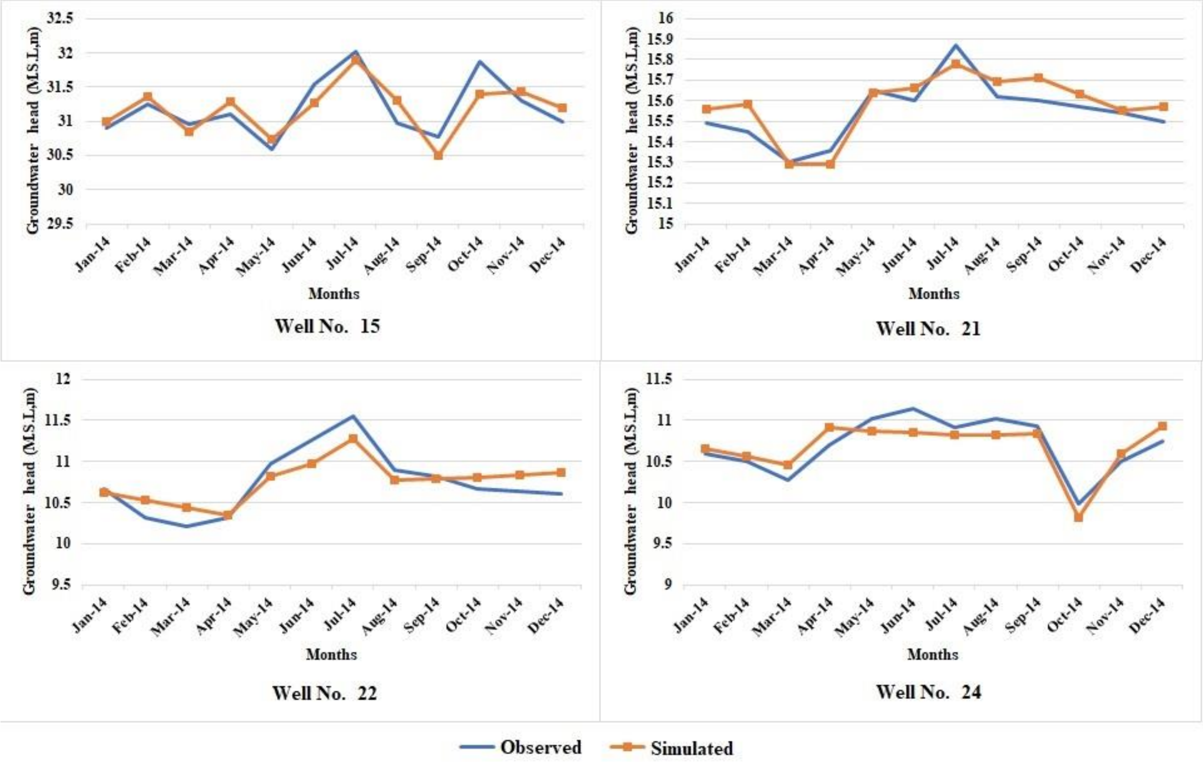


Fig. 6.15 Time series result of groundwater head

6.5 CONCLUSIONS

The conclusions for groundwater flow model are

1. In the steady state condition, the R^2 value between observed and simulated is as 0.98 and 0.90 respectively for calibration and validation and they are in acceptable limit.
2. In the transient state, the coefficient of determination R^2 for the calibration and validation are found to be 0.86 and 0.86 from 2013 year to 2017 year and found acceptable.
3. The time series results of groundwater head for the well numbers 15, 21, 22 and 24 which is found to be the best predicted between observed and simulated groundwater head from the model compared to all other groundwater wells.

CHAPTER 7

DEVELOPMENT OF GROUNDWATER TRANSPORT MODEL

7.1 GENERAL

Groundwater contamination is one of the serious problems facing all over the world which occurs by industries, agriculture land and coastal regions. The industrial waste discharged without proper treatment reaches the groundwater and contaminates the aquifers. In agricultural regions, the fertilisers and insecticides act as the contaminants which degrade the quality of groundwater. The seawater intrusion mostly occurs in the coastal zone contaminating the fresh groundwater due to decline in the freshwater head caused by the excess pumping in the coastal aquifers and tidal variations along with saltwater ingress in the backwater of streams.

In recent years, numerical modelling technique is used to understand the contamination in groundwater for different regions of the world. In most of the studies, it is found that a finite difference or the finite element method is used for numerical modelling (Karatzas 2017). FEMWATER is a three-dimensional finite element groundwater model. It can be used to simulate flow and transport in both the saturated and the unsaturated zone. The FEMWATER model code of GMS is considered for the transport model for the present study. Furthermore, the flow and transport can be coupled to simulate density-dependent problems such as seawater intrusion and groundwater contamination. (Lin et al. 1997).

7.2 GOVERNING EQUATION OF GROUNDWATER TRANSPORT

The governing equation of groundwater transport in FEMWATER is developed by Lin et al. 1997. Eq. 7.1 is the governing equation of groundwater transport, which mainly depends on concentration, time, discharge and pressure head. The governing equation of flow acts as the base equation for the governing equation of transport.

Governing equation for groundwater transport (Lin et al. 1997) is as follows.

$$\begin{aligned}&\theta\frac{\partial C}{\partial t}+\rho_b\frac{\partial S}{\partial t}+V.\nabla C-\nabla.(\theta D.\nabla C)=-\left(\alpha'\frac{\partial h}{\partial t}+\lambda\right)(\theta C+\rho_b S)\\&-(\theta K_W C+\rho_b K_S S)+m-\frac{\rho^*}{\rho}qC+\left(F\frac{\partial h}{\partial t}+\frac{\rho_0}{\rho}V.\nabla\left(\frac{\rho}{\rho_0}\right)-\frac{\partial\theta}{\partial t}\right)C\end{aligned} \tag{7.1}$$

where

θ = moisture concentration

ρ_b = bulk density of the medium (M/L^3)

C = material concentration in the aqueous phase (M/L^3)

S = material concentration in the adsorbed phase (M/M)

t = time (d)

V = discharge (m^3/s)

∇ = del operator

D = dispersion coefficient tensor

α' = compressibility of the medium

h = pressure head (m)

λ = decay constant

m = q C_{in} = artificial mass rate

q = source rate of water

C_{in} = material concentration in the source

K_w = first order biodegradation rate constant through the dissolved phase

K_s = first order biodegradation rate through the adsorbed phase

F = storage coefficient

K_d = distribution coefficient

S_{max} = maximum concentration of medium in the Langmuir nonlinear isotherm

n = power index in the Freundlich nonlinear isotherm

K = coefficient in the Langmuir or Freundlich nonlinear isotherm.

$$S = K_d C \quad \text{for linear isotherm} \tag{7.2}$$

$$S = \frac{S_{\max} KC}{1 + KC} \quad \text{for Langmuir isotherm} \tag{7.3}$$

$$S = KC^n \quad \text{for Freundlich isotherm} \tag{7.4}$$

The dispersion coefficient tensor D in Equation (7.1) is given by

$$\theta D = a_T |V| \delta + (a_L - a_T) \frac{VV}{|V|} + a_m \theta \tau \delta \tag{7.5}$$

where

$|V|$ = magnitude of V

δ = Kronecker delta tensor

a_T = lateral dispersivity

a_L = longitudinal dispersivity

a_m = molecular diffusion coefficient

τ = tortuosity

7.3 METHODOLOGY

The groundwater quality is tested in the laboratory by collecting the groundwater samples from the field. The laboratory results of groundwater quality parameters are compared with the permissible standards of BIS 10500 (2012) and WHO (2008) as given in Table 1.1. The comparative results help us to understand, the status of groundwater wells whether they are safe or contaminated. In this study, the finite element method of numerical modelling is used to understand the contamination in the study area, Nethravathi and Gurpur river confluence.

Groundwater head results from the FEMWATER flow model is taken as the input data for groundwater transport modelling. In the model, the boundaries of the study area which is divided into three parts such as first coastal stretch, second coastal stretch and freshwater stretch, the specific concentration values are assigned for each part as shown in Fig 6.2. Initially, the time control and the initial condition are assigned to the transport model. The output control of the model is assigned to saving the concentration results. In transport modelling, the specific concentration of groundwater quality parameters such as Cl, TDS and Bicarbonate is taken as the input data for the model. The 3D mesh created gives the concentration result of the groundwater transport modelling. The model is run for both steady and transient state conditions with different time intervals. Fig 7.1 shows the flowchart for FEMWATER groundwater transport modelling. The boundary condition has significant importance in the development of groundwater transport model. The specific concentration of different groundwater chemical parameters such as Cl, TDS and Bicarbonate are assigned in the boundary stretch of the study area. In the transient state condition, the model is run for both calibration and validation. The time series analysis is also carried out based on the transport model for the groundwater quality parameters such as Cl, TDS and Bicarbonate. Coefficient of determination (R^2) is calculated for the model simulated versus observed head values.

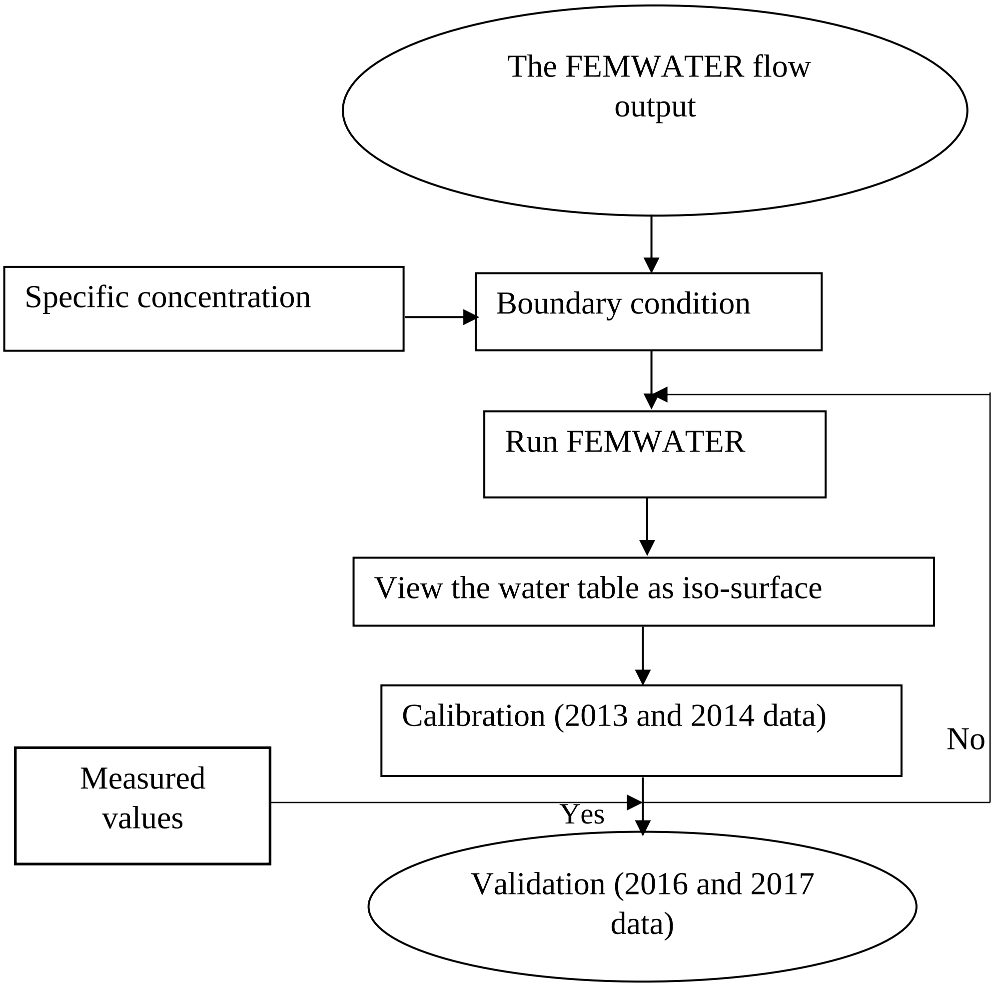


Fig. 7.1 FEMWATER Transport modelling

7.3.1 Steady state condition

In the steady state condition, the specific concentration of different parameters such as Cl, TDS and HCO_3 concentration is assigned at the boundaries of the study area. The Cl parameter input data for the first coastal stretch, second coastal stretch and freshwater stretch are 42.54 mg/l, 20.725 mg/l and 22.9 mg/l respectively. The input data for TDS for the first coastal stretch, second coastal stretch and freshwater stretch are 246.56 mg/l, 147.625 mg/l and 117.75 mg/l respectively. The input data for HCO_3 for the first coastal stretch, second coastal stretch and freshwater stretch are 261.8 mg/l, 187.425 mg/l and 156.19 mg/l respectively. This specific concentration input data gives the 3D mesh data result of Cl, TDS and HCO_3, as shown in Fig 7.2-7.4. The initial condition of Cl, TDS and HCO_3 are considered based on the laboratory result concentration of groundwater samples for the parameters of Cl, TDS and HCO_3.

7.3.1.1 Boundary condition

The boundary conditions for the transport equation of FEMWATER modelling are Dirichlet conditions, variable conditions, flux conditions and gradient flux conditions. In this study, the model depends on Dirichlet conditions and flux conditions. The different boundary conditions are given below

a. Dirichlet conditions:

$$C = C_d\left(x_b, y_b, z_b\right) \quad \text{on } B_d \tag{7.6}$$

b. Variable conditions:

$$n.\left(VC - \theta D.\nabla C\right) = n.VC_v\left(x_b, y_b, z_b, t\right) \quad \text{if } n.V \leq 0 \tag{7.7}$$

$$n.\left(-\theta D.\nabla C\right) = 0 \quad \text{if } n.V > 0 \tag{7.8}$$

c. Flux conditions:

$$n.\left(VC - \theta D.\nabla C\right) = q_C\left(x_b, y_b, z_b, t\right) \quad \text{on } B_C \tag{7.9}$$

d. Gradient flux conditions:

$$n.\left(-\theta D.\nabla C\right) = q_n\left(x_b, y_b, z_b, t\right) \text{on } B_n \tag{7.10}$$

Where,

(x_b, y_b, z_b) = spatial coordinate on the boundary

n = outward unit vector normal to the boundary

C_d = concentration on the Dirichlet boundary

C_v = concentration of water through the variable boundary

B_d = Dirichlet boundary

B_v = variable boundary

q_c = total flux through the boundary B_C

q_n = total gradient flux through the boundaries B_n

Since the hybrid Lagrangian-Eulerian approach is used to simulate Equation (7.1), it is written in the Lagrangian-Eulerian form as

$$\begin{aligned}(\theta+\rho_b K_d)\frac{D_{V_d}C}{Dt} &= \nabla.(\theta D.\nabla C)-\left(\alpha'\frac{\partial h}{\partial t}+\lambda\right)(\theta C+\rho_b S)\\ &-(\theta K_W C+\rho_b K_S S)+m-\frac{\rho^*}{\rho}qC+\left(F\frac{\partial h}{\partial t}+\frac{\rho_0}{\rho}V.\nabla\left(\frac{\rho}{\rho_0}\right)-\frac{\partial \theta}{\partial t}\right)C\end{aligned} \tag{7.11}$$

$$V_d=\frac{V}{\theta+\rho_b K_d} \qquad \text{for linear isotherm model} \tag{7.12}$$

$$\begin{aligned}\theta\frac{D_{V_f}C}{Dt}+\rho_b\frac{dS}{dC}\frac{\partial C}{\partial t} &= \nabla.(\theta D.\nabla C)-\left(\alpha'\frac{\partial h}{\partial t}+\lambda\right)(\theta C+\rho_b S)\\ &-(\theta K_W C+\rho_b K_S S)+m-\frac{\rho^*}{\rho}qC+\left(F\frac{\partial h}{\partial t}+\frac{\rho_0}{\rho}V.\nabla\left(\frac{\rho}{\rho_0}\right)-\frac{\partial \theta}{\partial t}\right)C\end{aligned} \tag{7.13}$$

$$V_f=\frac{V}{\theta} \quad \text{for Freundlich and Langmuir models} \tag{7.14}$$

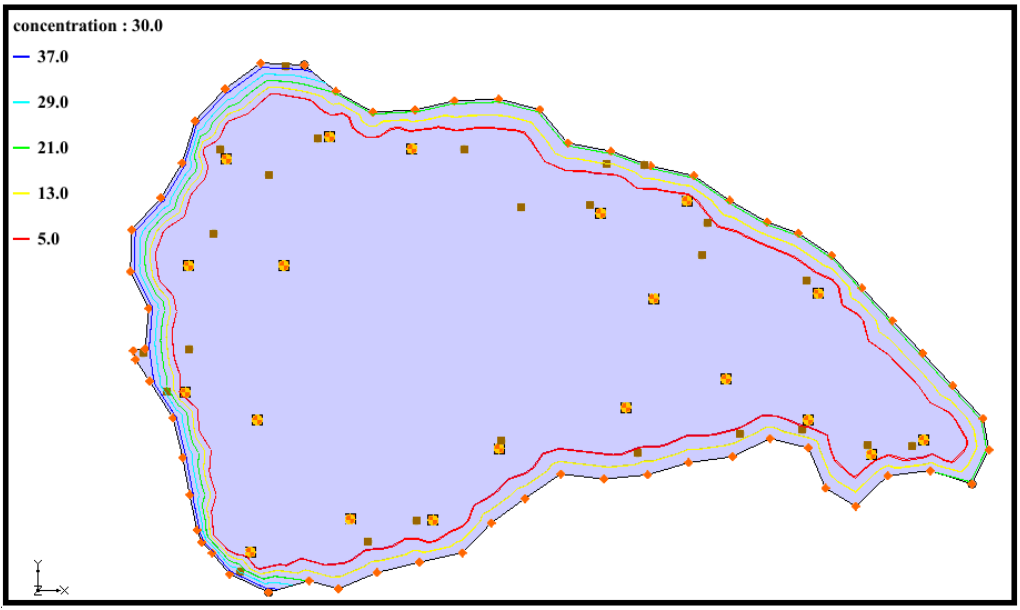
Where V_d and V_f are the retarded and fluid pore velocities, respectively; and D_{vd}/Dt and D_{vf}/Dt denote the material derivative with respect to time using the retarded and fluid pore velocities respectively. The flow equation, (Equation (6.1)), subject to initial and boundary conditions, (Equations (6.7) – (6.14)), is solved with the Galerkin finite element method. The transport equations, (Equations (7.11) and (7.12) or (7.13) and (7.14)), subject to initial and boundary conditions, (Equations (7.6) – (7.10) and (7.15)) are solved with the hybrid Lagrangian-Eulerian finite element methods.

7.3.1.2 Initial condition

The initial conditions for the transport equation are given by Equation (7.1). It is the state of the system variables at the start of the simulation.

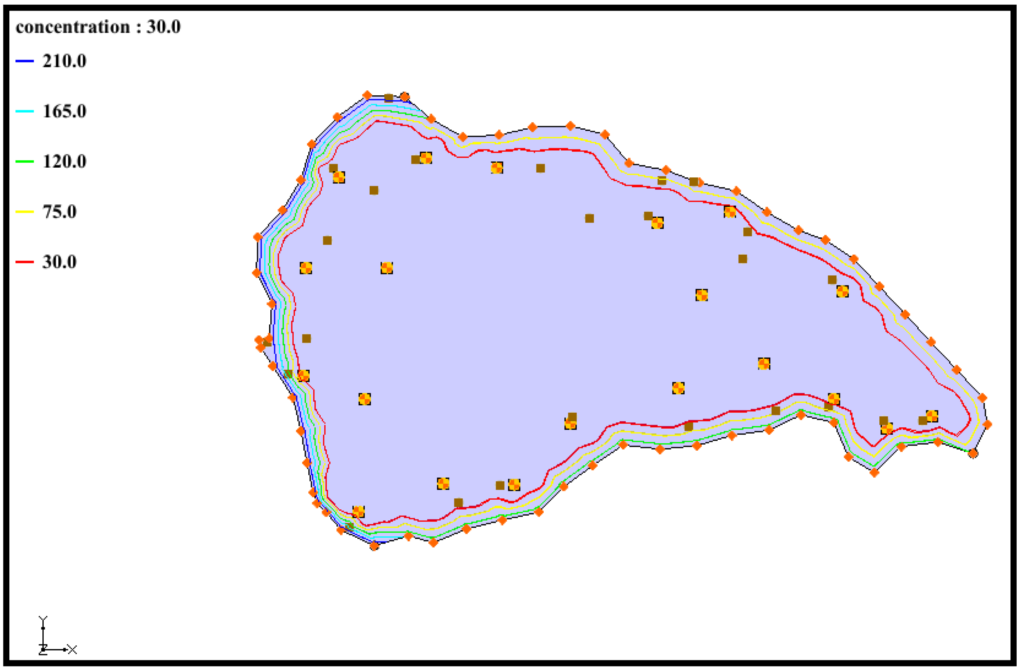
$$C=C_i(x,y,z) \qquad \text{in R} \tag{7.15}$$

Where R is the region of interest and C_i is the prescribed initial condition, which can be obtained by field measurements.



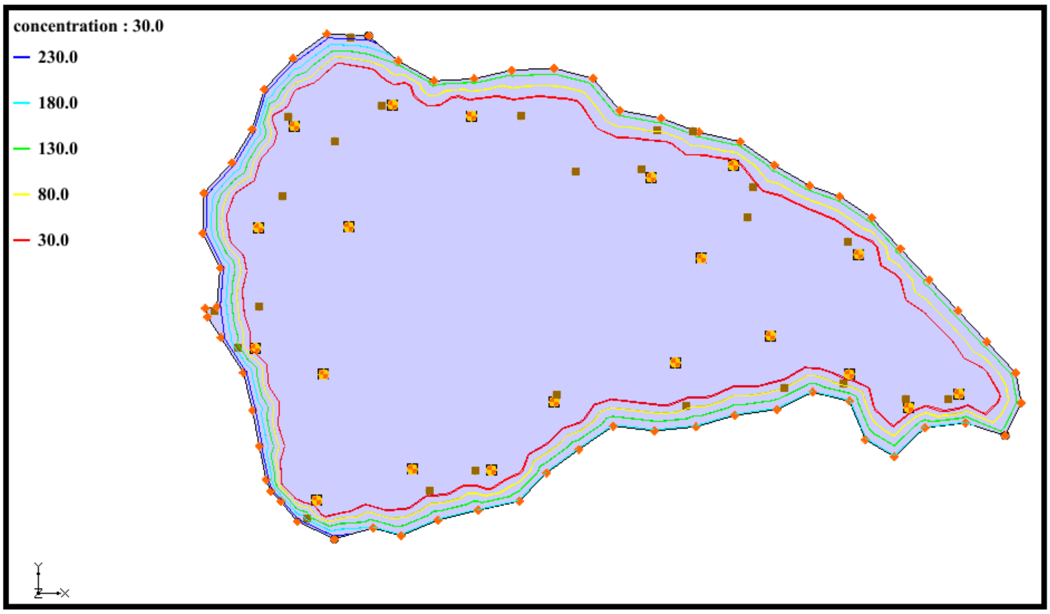
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.2 Simulated Cl for steady state condition



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.3 Simulated TDS for steady state condition



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.4 Simulated Bicarbonate for steady state condition

In the steady state, the concentration of Cl, TDS and HCO_3 are considered for time control of 30 days with a constant time period of 1 day. Fig 7.5-7.7 gives the result of Cl, TDS and HCO_3 of steady state condition with an R^2 value of 0.94, 0.9 and 0.88.

7.3.1.3 Error statistics

The Root Mean Square Error (RMSE) indicates the error between simulated and measured data. RMSE value of 0 indicates a perfect fit (Lathasri, 2016) and it is shown in Eq. 7.16.

$$\text{RMSE} = \sqrt{\frac{1}{\text{n}}\sum_{1}^{n}(Y^{obs} - Y^{sim})^2} \qquad (7.16)$$

Nash-Sutcliffe efficiency (NSE) a method recommended for model evaluation in hydrological applications (Lathasri, 2016). This determines the relative magnitude of the residual variance compared to the measured data variance and it is shown in Eq. 7.17.

$$\text{NSE} = 1 - \left[\frac{\sum_{1}^{n}(Y^{obs} - Y^{sim})^2}{\sum_{1}^{n}(Y^{obs} - Y^{mean})^2}\right] \qquad (7.17)$$

Where Y^{obs} = observed data, Y^{sim} = model simulated data, Y^{mean} = mean of the observed data and n is the total number of observations. NSE values between 0 and 1 are generally viewed as acceptable for model performance and values ≤ 0 indicated unacceptable performance.

Mean Absolute Error (MAE) is a measure of the difference between two continuous variables. Assume *X* and *Y* are variables of paired observations that express the same phenomenon. Examples of *Y* versus *X* include comparisons of predicted versus observed, subsequent time versus initial time, and one technique of measurement versus an alternative technique of measurement. Consider a scatter plot of *n* points, where point *i* has coordinates (x_i, y_i)... Mean Absolute Error (MAE) is the average vertical distance between each point and the identity line. MAE is also the average horizontal distance between each point and the identity line and it is shown in Eq. 7.18.(Pontius et. al. 2008).

$$\text{MAE} = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n} \tag{7.18}$$

The result of R^2, RMSE, NSE and MAE for Cl, TDS and HCO_3 parameters for steady state condition are given in Table 7.1

Table 7.1 Result of R^2, RMSE, NSE and MAE in groundwater quality parameters for steady state condition

Parameter	R^2	RMSE	NSE	MAE
Cl	0.94	17.67	0.96	-6.68
TDS	0.9	82.4	0.97	-31.14
HCO_3	0.88	87.53	0.95	-35.73

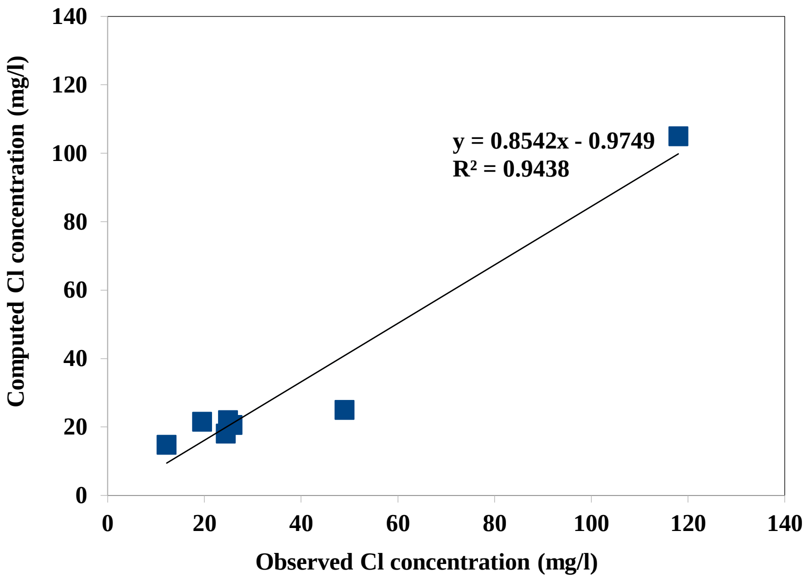


Fig 7.5 Cl concentration result of steady state condition

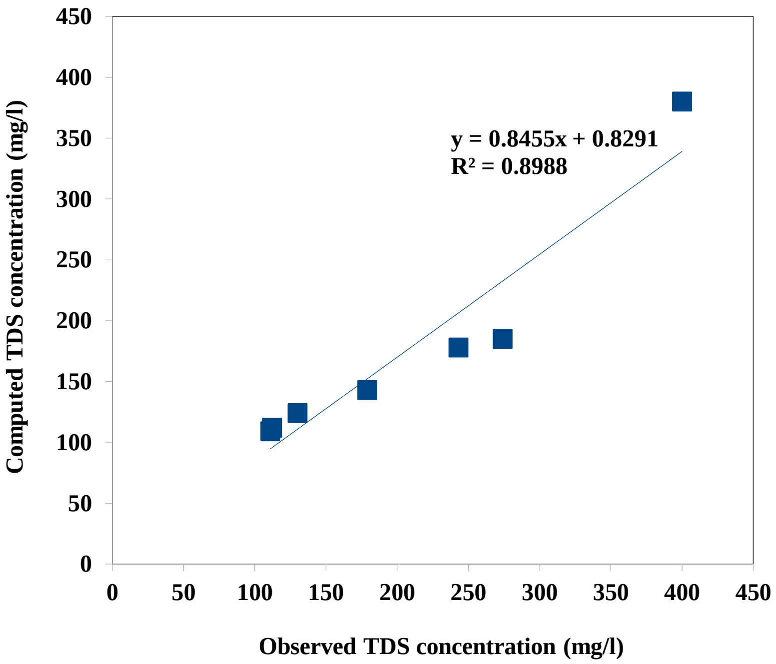


Fig 7.6 TDS concentration result of steady state condition

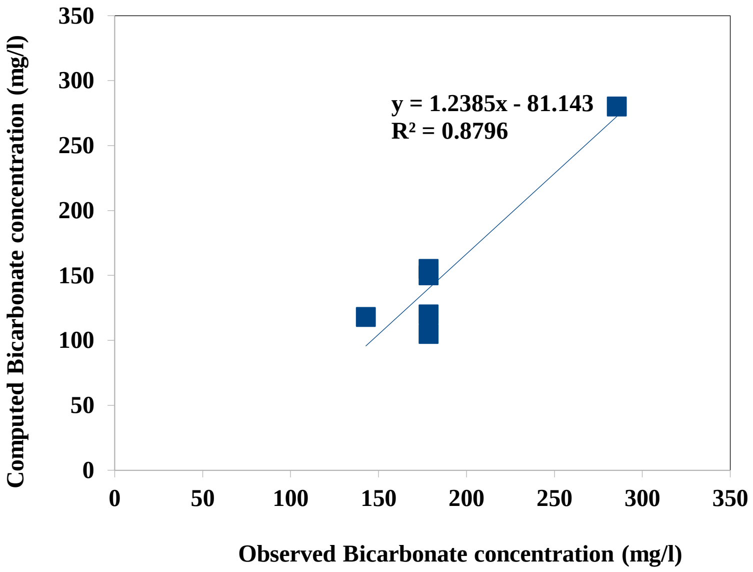


Fig 7.7 Bicarbonate concentration result of steady state condition

7.3.2 Transient state condition

In the transient state, it is run for both calibration and validation. For calibration, the input data of Cl on the first coastal stretch, second coastal stretch and freshwater stretch are 31.2 mg/l, 21.9 mg/l and 27.9 mg/l respectively are given. The input data for TDS on the first coastal stretch, second coastal stretch and freshwater stretch are 142.56 mg/l, 102.5 mg/l and 81.5 mg/l respectively are given. The input data for HCO_3 on the first coastal stretch, second coastal stretch and freshwater stretch are 265.77 mg/l, 263.29 mg/l and 236.51 mg/l respectively are given. The time period assigned for model simulation is 486 days (September 2013 to December 2014) with a constant time interval of 30 days.

For the validation, the input data of Cl on the first coastal stretch, second coastal stretch and freshwater stretch are 47.71 mg/l, 39.31 mg/l and 41.89 mg/l respectively are used. The input data for TDS on the first coastal stretch, second coastal stretch and freshwater stretch are 202 mg/l, 141.88 mg/l and 108.625 mg/l respectively are given. The input data for HCO_3 on the first coastal stretch, second coastal stretch and freshwater stretch are 198.33 mg/l, 147.26 mg/l and 133.875 mg/l respectively are given. The time control taken for validation is 425 days from April 2016 to May 2017 with a constant time interval of 30 days since the data set are separated for both calibration and validation.

7.3.2.1 Boundary condition

The boundary condition for the transient state condition depends on the flux and concentration of groundwater chemical parameters. In the transient state condition, the value of the concentration varies from steady state condition. The following boundary conditions are prescribed all around the boundaries based on the nature of flux and head etc.

- Dirichlet conditions
- Variable conditions
- Flux conditions
- Gradient flux conditions

7.3.2.2 Initial condition

In the transient state, the initial conditions are determined through a steady-state simulation of the observed groundwater head. An adjustment of model hydrologic inputs and parameters which is acceptably closer values are considered. This helps us to generate model concentration in the study area which is used as the initial condition for transient state condition. The initial condition for a transient state considered from equation 7.15.

7.3.3 Time series analysis of wells

Time series analysis is a statistical technique that deals with time series data or trend analysis. In the transport model, the result for the year 2014 is simulated for the time period (month wise). The observed and simulated groundwater quality is plotted to understand the performance of the model with respect to the observed values.

7.4 RESULTS AND DISCUSSION

The result of R^2 value for steady state modelling of the chemical parameters Cl, TDS and HCO_3 are 0.94, 0.9 and 0.88 respectively. The result of transient state modelling consists of both calibration and validation for the same chemical parameters Cl, TDS and HCO_3 are simulated based on the boundary conditions and initial conditions prescribed. The spatial variation of results of simulated Cl, TDS and HCO_3 for transient calibration are shown in the Fig 7.8-7.10 respectively. The result of simulated Cl, TDS and HCO_3 for transient validation are shown in the Fig 7.11-7.13. The transient state calibration of Cl, TDS and HCO_3 have a maximum simulation time of 486 days and validation time of 425 days. The Fig 7.14-7.16 provides the result of Cl, TDS and HCO_3 of transient calibration, which makes R^2 value of 0.92, 0.85 and

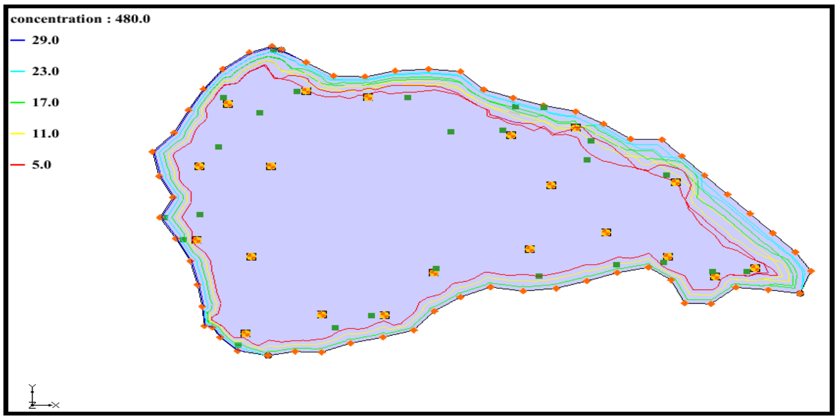
0.87 respectively. Similarly, the Fig 7.17-7.19 provides the result of Cl, TDS and HCO_3 of transient validation and results R^2 value of 0.88, 0.95 and 0.93 respectively. The Table 7.2 and Table 7.3 offers the result of R^2, RMSE, NSE and MAE for Cl, TDS and HCO_3 parameters for transient state calibration and validation. The Fig 7.20 gives the time series result of Cl for the well numbers 5, 10, 13, 15 and 17 which is found to be the best compared to other wells. The Fig 7.21 gives the time series result of TDS for the well number 4, 9, 10, 21 and 24 which is found to be the best compared to other wells. The Fig 7.22 shows the time series result of Bicarbonate for the well numbers 7, 11, 17, 19 and 21 respectively. The quality of water for Cl, TDS and HCO_3 found to be within the permissible limit and it is potable.

Table 7.2 Result of R^2, RMSE, NSE and MAE in groundwater quality parameters for Transient state calibration condition

Parameter	R^2	RMSE	NSE	MAE
Cl	0.92	16.58	0.94	-5.86
TDS	0.85	81.33	0.94	-27.11
HCO_3	0.87	96	0.95	-33.95

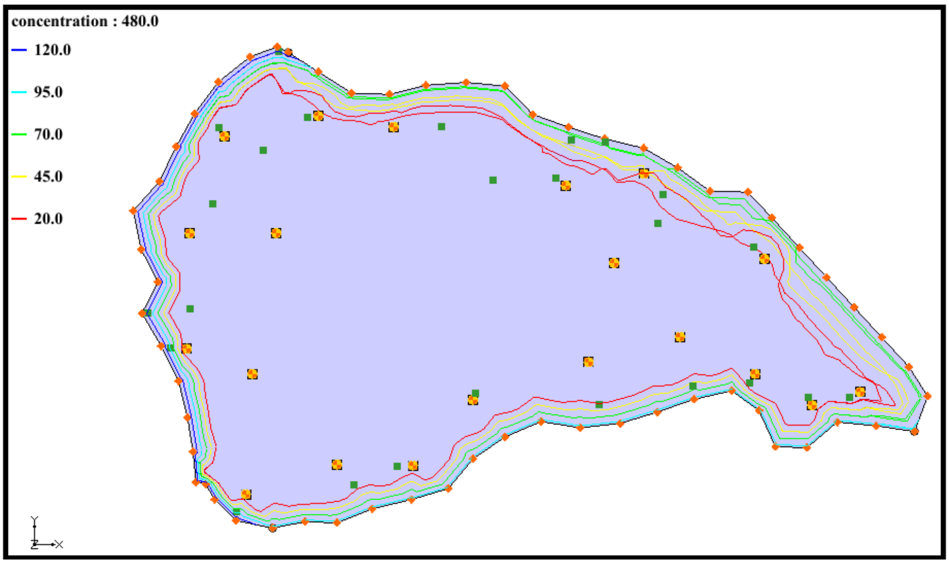
Table 7.3 Result of R^2, RMSE, NSE and MAE in groundwater quality parameters for Transient state validation condition

Parameter	R^2	RMSE	NSE	MAE
Cl	0.88	13.89	0.98	-4.63
TDS	0.95	161.23	0.91	-48.61
HCO_3	0.93	1.41	1	-0.5



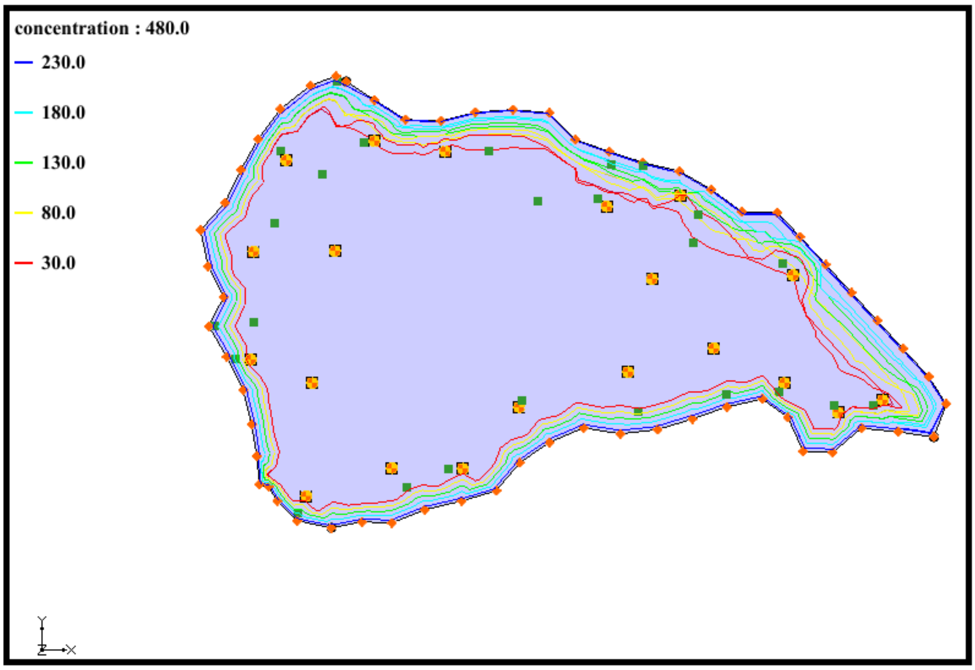
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.8 Simulated Cl for transient state calibration condition



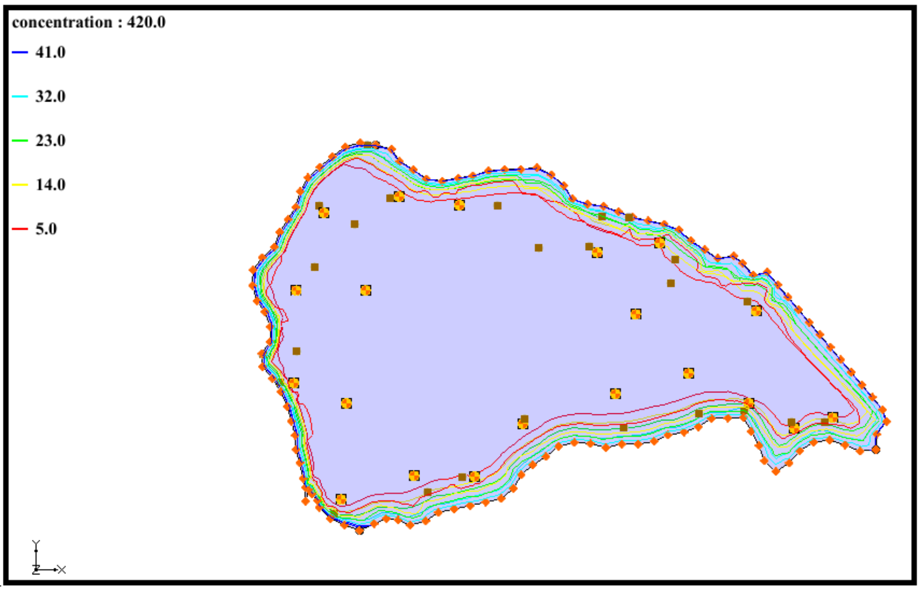
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.9 Simulated TDS for transient state calibration condition



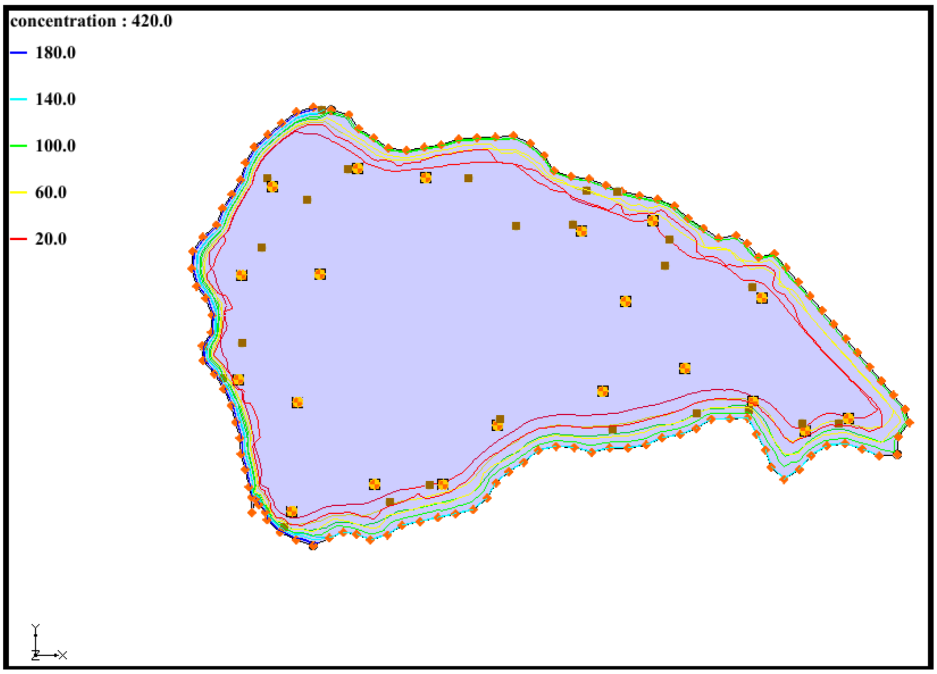
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.10 Simulated Bicarbonate for transient state calibration condition



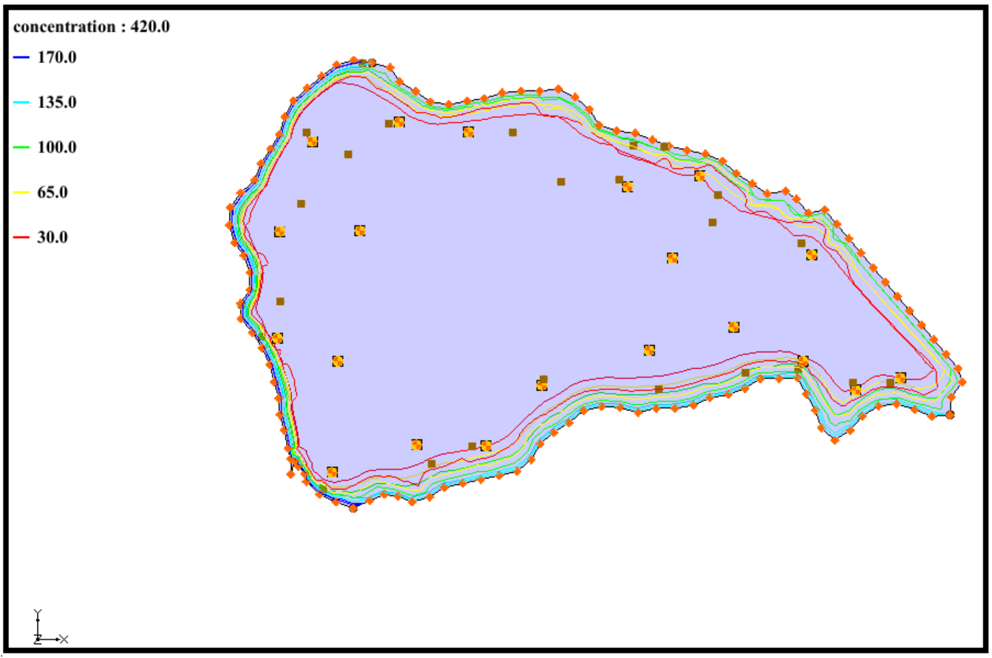
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.11 Simulated Cl for transient state validation condition



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.12 Simulated TDS for transient state validation condition



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 7.13 Simulated Bicarbonate for transient state validation condition

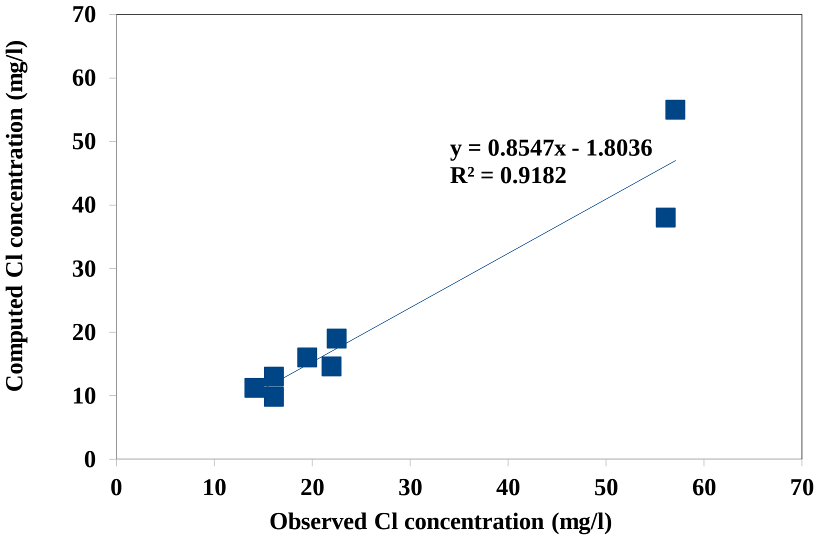


Fig 7.14 Cl concentration result of transient state calibration condition

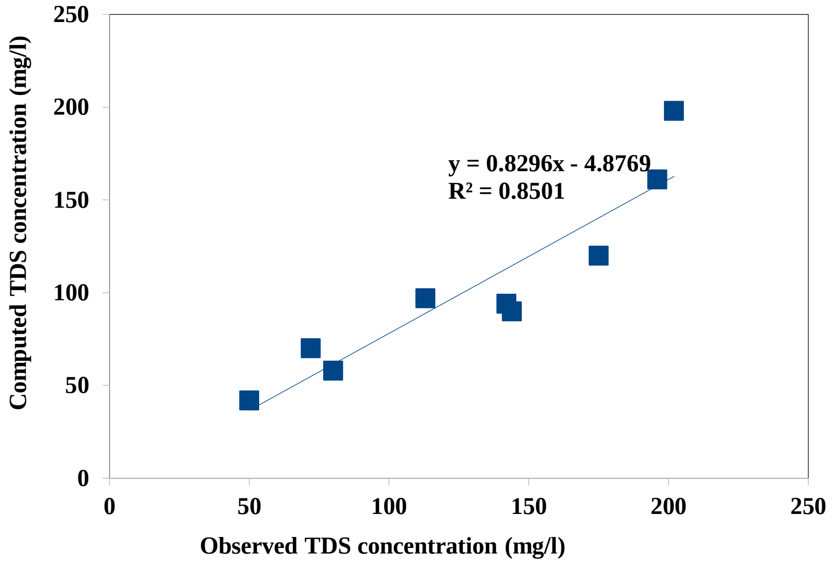


Fig 7.15 TDS concentration result of transient state calibration condition

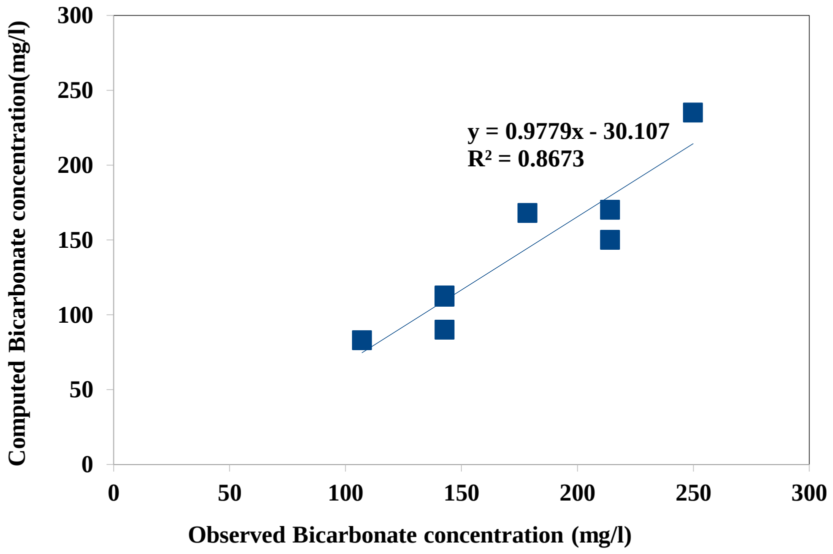


Fig 7.16 Bicarbonate concentration result of transient state calibration condition

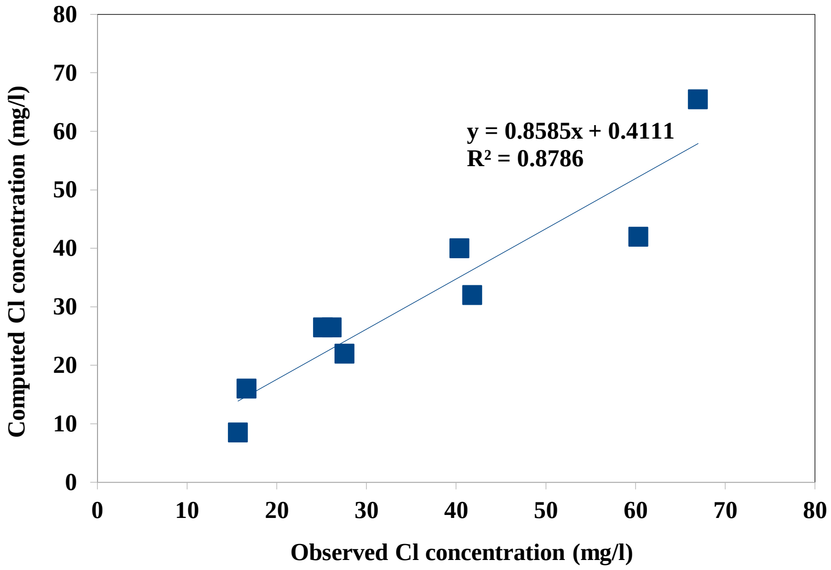


Fig 7.17 Cl concentration result of transient state validation condition

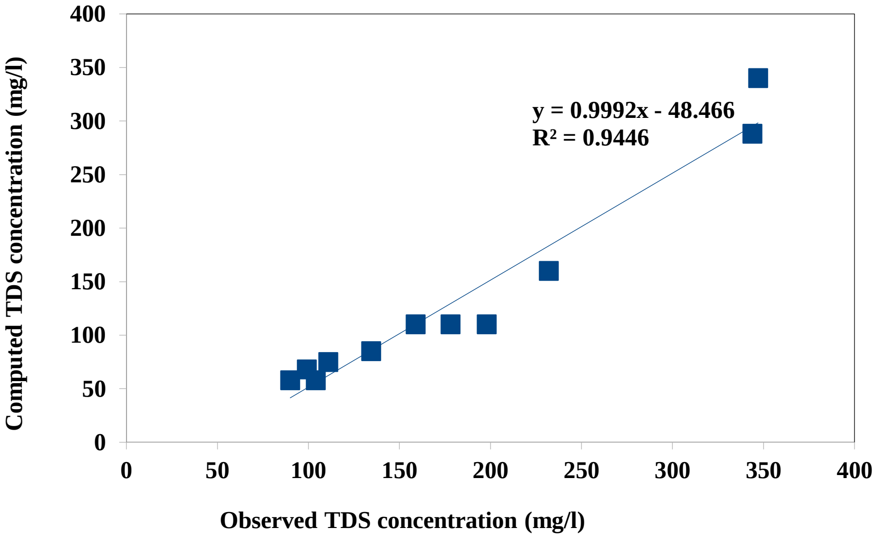


Fig 7.18 TDS concentration result of transient state validation condition

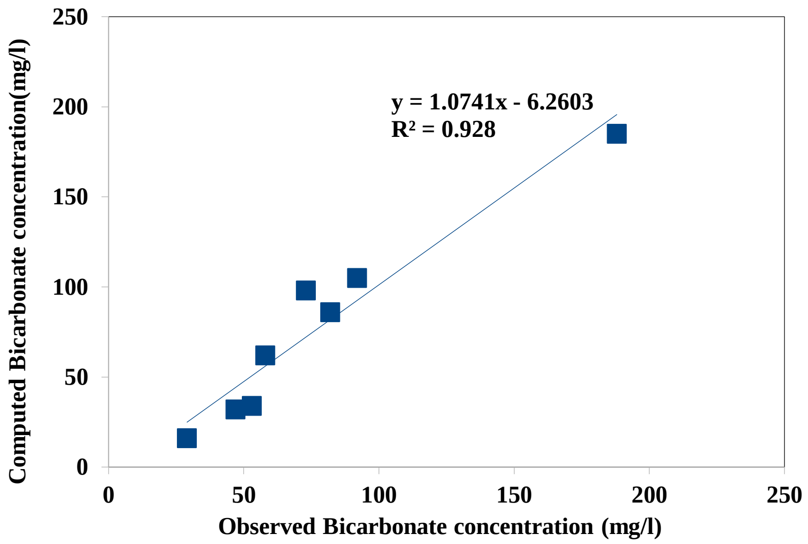


Fig 7.19 Bicarbonate concentration result of transient state validation condition

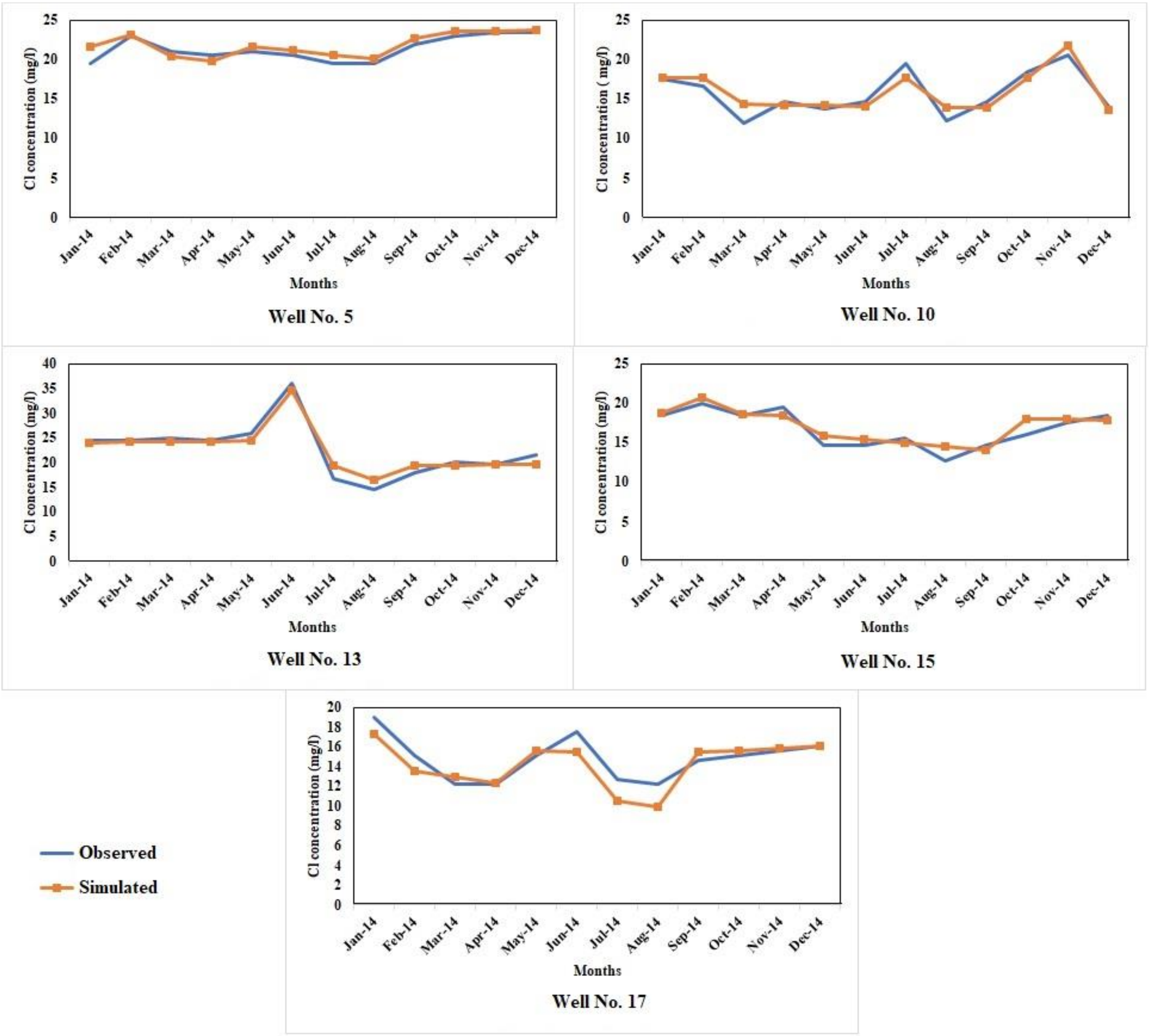
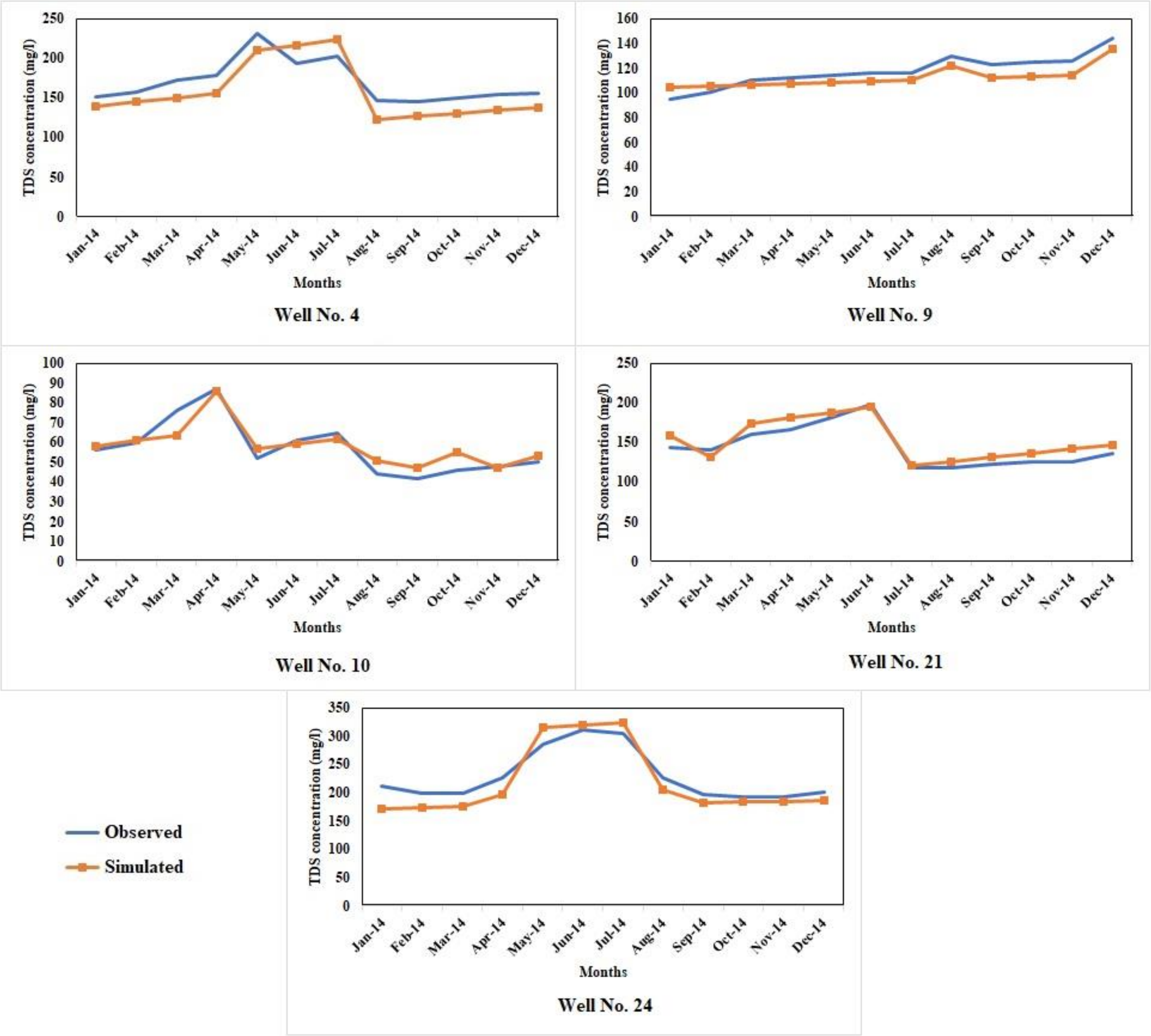


Fig 7.20 Time series result of Cl for well number 5, 10, 13, 15 and 17



Well No. 4

Well No. 9

Well No. 10

Well No. 21

Well No. 24

Fig 7.21 Time series result of TDS for well number 4, 9, 10, 21 and 24

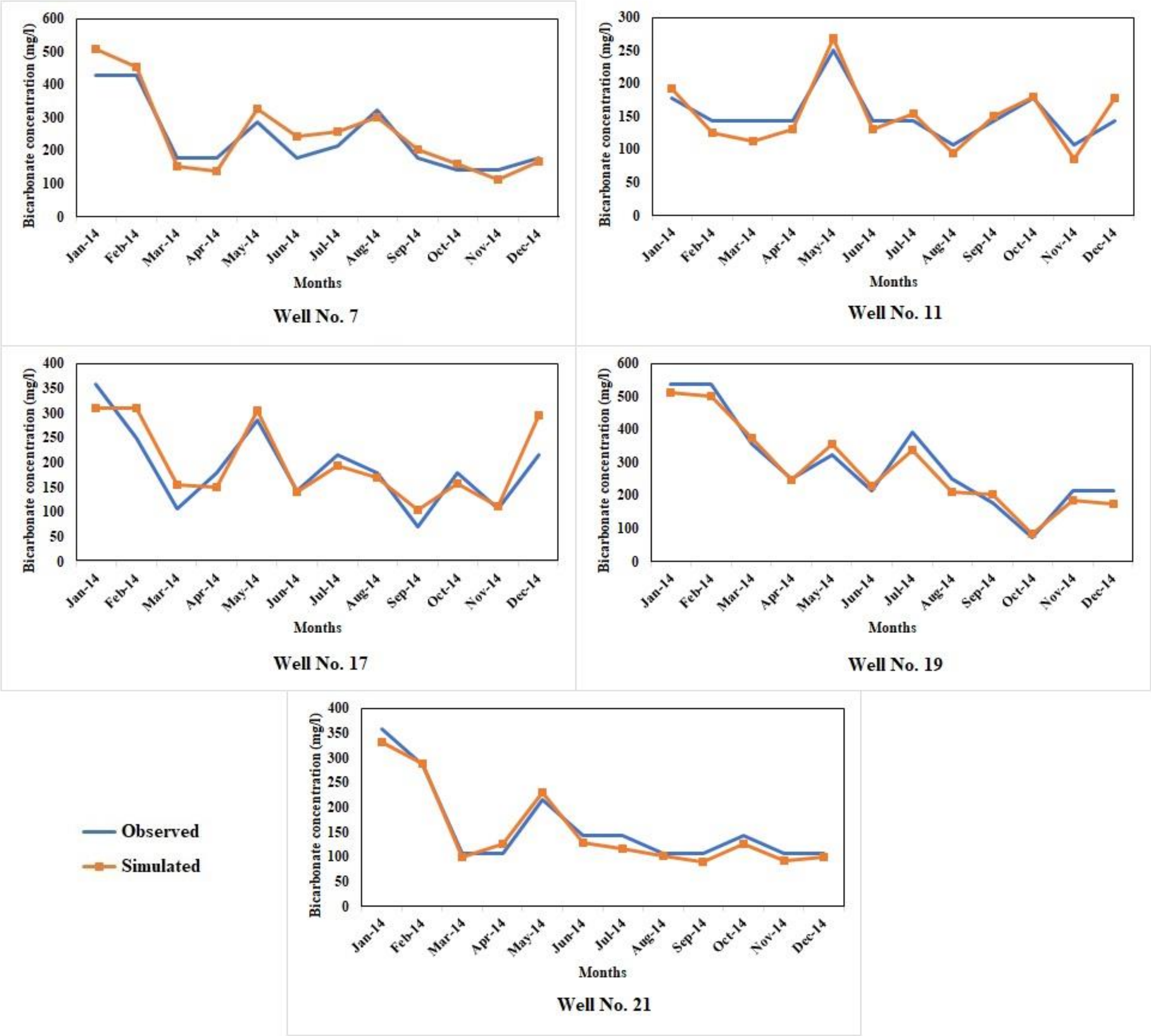


Fig 7.22 Time series result of Bicarbonate for well number 7, 11, 17, 19 and 21

7.5 CONCLUSIONS

The conclusions for groundwater flow and solute transport model are

1. In the steady state conditions, the coefficient of determination (R^2) between observed and simulated groundwater quality parameters are found to be 0.94, 0.9 and 0.88 respectively for Cl, TDS and HCO_3 in the study area and found to be good agreement.
2. In the transient state calibration condition, the coefficient of determination (R^2) between observed and simulated groundwater quality parameters are found to be 0.92, 0.85 and 0.87 respectively for Cl, TDS and HCO_3 in the study area and found to be acceptable.
3. In the transient state validation condition, the coefficient of determination (R^2) between observed and simulated groundwater quality parameters are found to be 0.88, 0.95 and 0.93 from Cl, TDS and HCO_3 in the study area and found to be good.

4. The time series result of Cl for the well numbers 5, 10, 13, 15 and 17 which is found to be the best predicted between observed and simulated groundwater concentrations of the model compared to all other groundwater wells.
5. The time series result of TDS for the well number 4, 9, 10, 21 and 24 which is found to be the best predicted between observed and simulated groundwater concentrations of the model compared to all other groundwater wells.
6. The time series result of TDS for the well number 4, 9, 10, 21 and 24 which is found to be the best predicted between observed and simulated groundwater concentrations of the model compared to all other groundwater wells.

CHAPTER 8

DEVELOPMENT OF PREDICTION SCENARIOS

8.1 INTRODUCTION

Groundwater model is a numerical model representing the groundwater system through which groundwater flow, head and transport of chemical concentration can be simulated and predicted for future time periods. In the present study area, the model is developed for both groundwater flow and transport condition. Once the flow and transport models are calibrated and validated for the study area, the variable recharge scenarios and injection well scenarios are considered in the modelling to find out various groundwater flow and quality status for different conditions. Hence, the scenarios for the model is developed based on variable recharge scenarios and different inflow rate in injection wells.

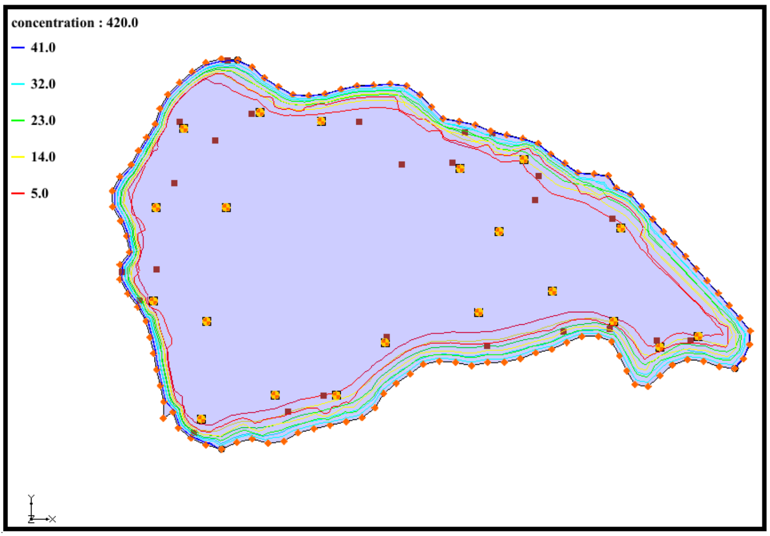
8.2 Variable recharge scenario

The recharge in the model is considered for three different scenarios, they are the minimum recharge, average recharge and maximum recharge which are calculated from previous ten years rainfall data in the study area, collected from the statistical department at Mangaluru. The model is run for the transient state validation condition with a time control of 425 days and with a constant time interval of 30 days. The model result shows that the variation of groundwater quality parameters for different wells with respect to the observed. The scenario results also indicated the change of groundwater quality parameters Cl, TDS and Bicarbonate concentration distance in the study area.

8.2.1 Minimum recharge

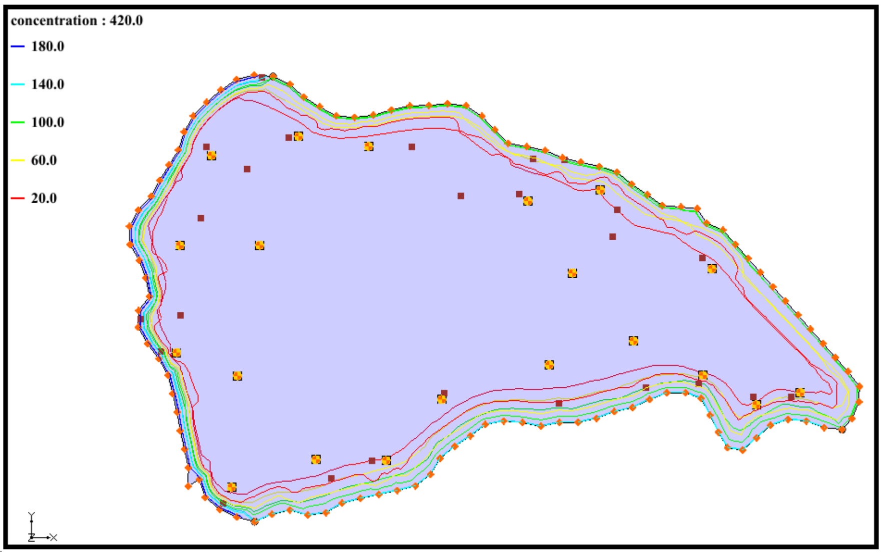
In the first scenario, the minimum recharge of 0.0022 m/d considered, which is calculated from the historical rainfall data. This condition is considered in the study area to understand the changes in groundwater quality status and also the impact of intrusion length compared to the observed groundwater quality result of Cl, TDS and Bicarbonate. The concentration distance of groundwater quality parameters in the model is reduced than the observed groundwater quality concentration of the first coastal stretch and freshwater stretch reduced by 39% and 24% for May 2017. In the second coastal stretch, concentration groundwater quality parameters of Cl, TDS and Bicarbonate in the model shows high concentration than the observed concentration for minimum recharge. The Fig. 8.1-8.3 shows the simulation result under minimum recharge for Cl, TDS and Bicarbonate parameters.

The results of minimum recharge scenario for Cl parameter shows that all the wells give the concentration within the permissible limit 250 mg/l. This shows that groundwater quality is good with respect to the Cl parameter. The well number 3 shows a high Cl concentration of 45 mg/l and well number 12 show a low concentration of 5 mg/l from Table 8.3. For the TDS parameter, the concentration was to be within the permissible limit value of 500 mg/l for all the wells. This indicates that groundwater quality is good with respect to the TDS parameter. The higher concentration of TDS value found in well number 24 at 200 mg/l and the lower concentration of TDS value is 15 mg/l for the well number 12 as shown in Table 8.4. The result of the Bicarbonate parameter for all wells found within the permissible limit values of 200 mg/l. Based on this result, the groundwater quality for all wells is good for Bicarbonate parameter. The higher concentration for this parameter is found as 183 mg/l for well number 3 and the lower concentration is 15 mg/l and 16 mg/l for well number 15 and 12 respectively from Table 8.5. Based on the results obtained it can be inferred that well number 12 has potable groundwater quality in Netravathi and Gurpur river confluence. The well number 3 and 24 found to be higher concentration of Cl, TDS and Bicarbonate parameter which indicates the groundwater quality reduction of two wells but it is well within the permissible limits.



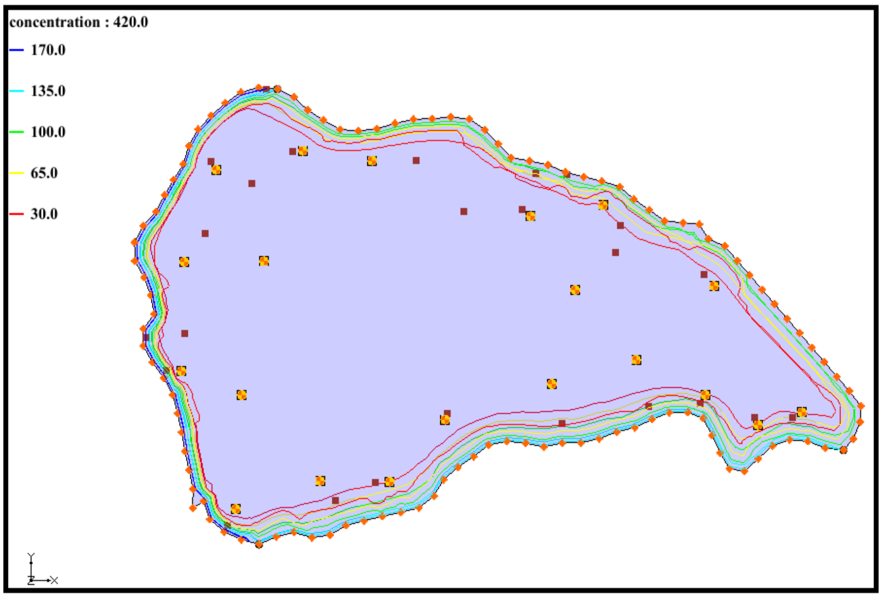
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.1 Simulated Cl concentrations under minimum recharge scenario



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.2 Simulated TDS concentrations under minimum recharge scenario



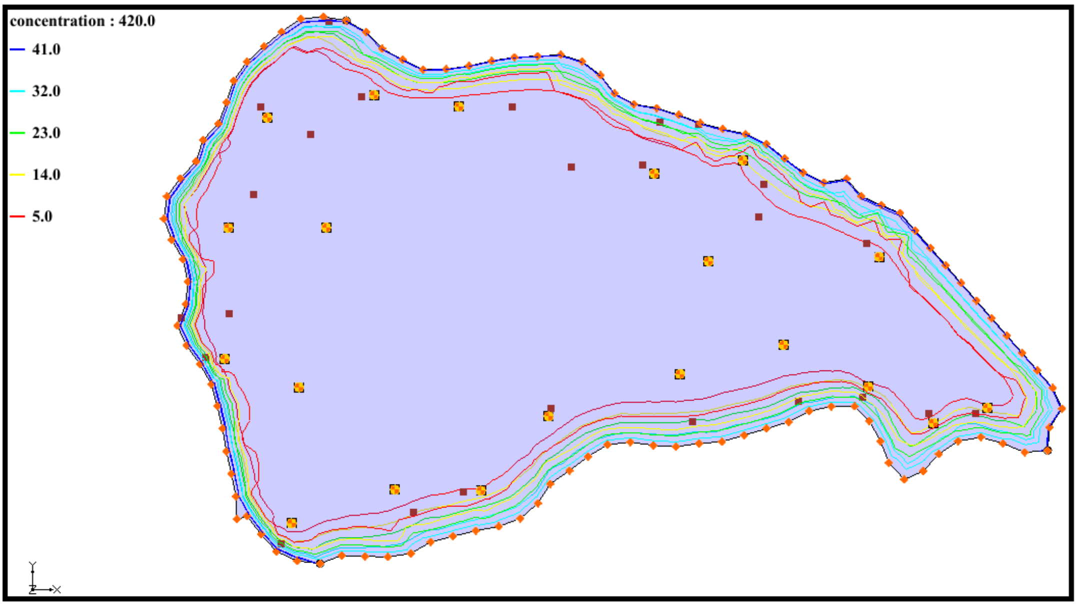
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.3 Simulated Bicarbonate concentrations under minimum recharge scenario

8.2.2 Average recharge

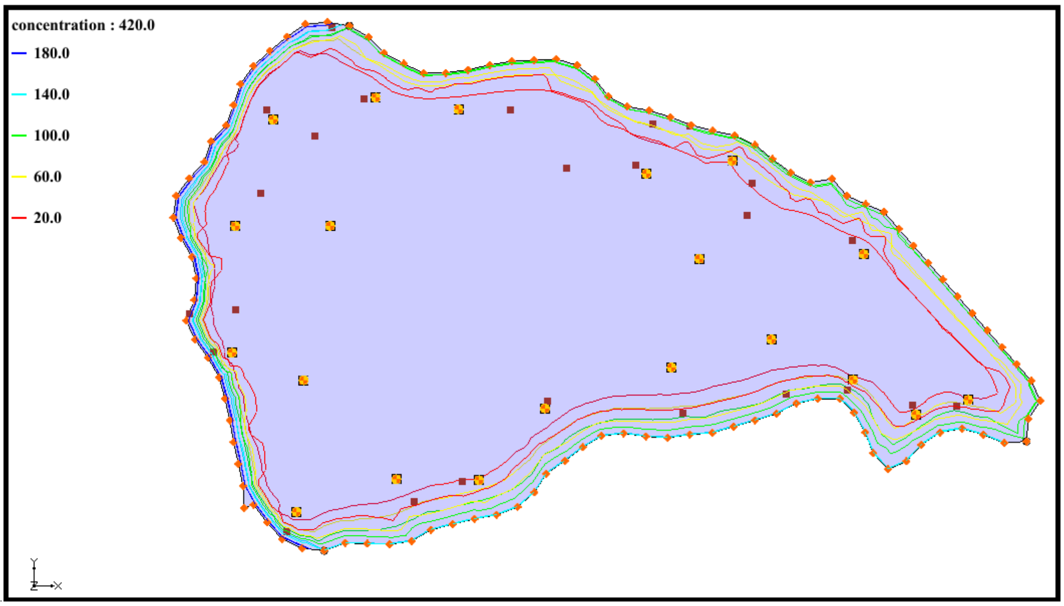
In the second scenario, the average recharge of 0.003 m/d was considered, which is calculated from the historical rainfall data. In this scenario, the result of simulated groundwater quality parameters Cl, TDS and Bicarbonate found to be reduced than the observed groundwater quality parameters from the laboratory result. The groundwater quality parameters Cl, TDS and Bicarbonate concentrations distance in the first coastal stretch of the model is found to be high than the observed model of groundwater quality parameters with a distance up to 1 km. The second coastal stretch and freshwater stretch concentrations distance are found to be reduced than the observed groundwater quality parameters Cl, TDS and Bicarbonate concentrations distance due to average recharge. The Fig. 8.4-8.6 shows the simulation result under average recharge condition for Cl, TDS and Bicarbonate.

The results of this scenario for Cl parameter shows that all the groundwater wells had the concentration within the permissible limit of 250 mg/l. This shows that groundwater well quality is good with respect to the Cl parameter. The well number 3, 9 and 24 show a high Cl concentration of 40 mg/l and well number 12 shows a low concentration of 5 mg/l as shown in Table 8.3. The TDS concentration of the wells is found to be within the permissible limit value of 500 mg/l. This indicates that water quality is good with respect to the TDS parameter. The higher concentration of TDS found to be 200 mg/l from well number 24 and the lower concentration of TDS is 15 mg/l for the well number 12 as given in Table 8.4. The result of the Bicarbonate parameter for all wells found to be within the permissible limit of 200 mg/l. Based on this result, the groundwater quality of Bicarbonate parameter is within the permissible limit of all wells. The higher concentration is found to be 158 mg/l for the well number 3 and the lower concentration is 12 mg/l and 16 mg/l be the well number 15 and 12 (Table 8.5). In Netravathi and Gurpur river confluence the scenario analysis shows that well number 12 has good groundwater quality and the well number 3 and 24 is found to have higher concentration of Cl, TDS and Bicarbonate parameter which indicates the groundwater quality reduction of two wells. The quality of the wells with respect to Cl, TDS and Bicarbonate have improved compared to the minimum recharge scenario.



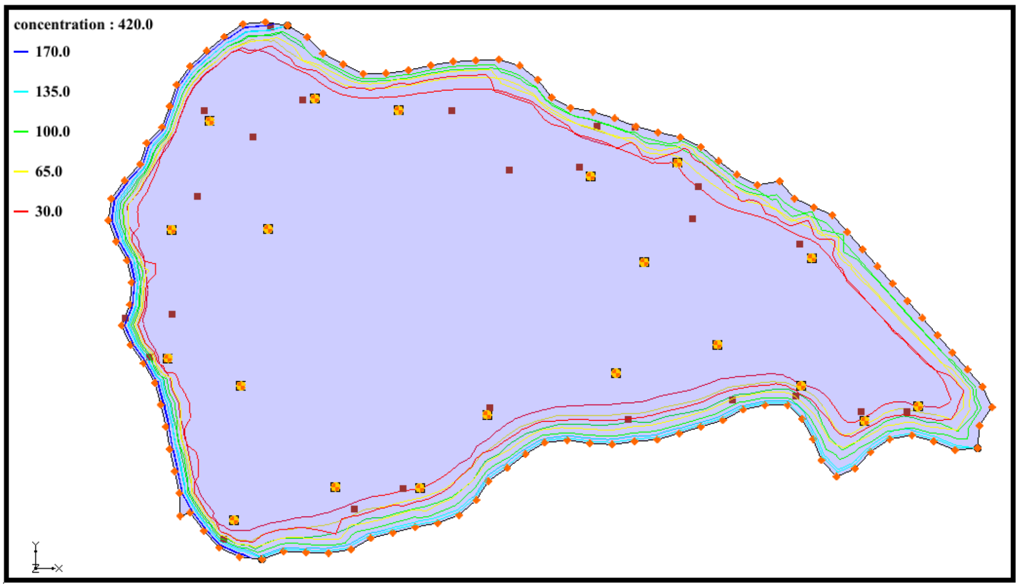
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.4 Simulated Cl concentrations under average recharge scenario



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.5 Simulated TDS concentrations under average recharge scenario



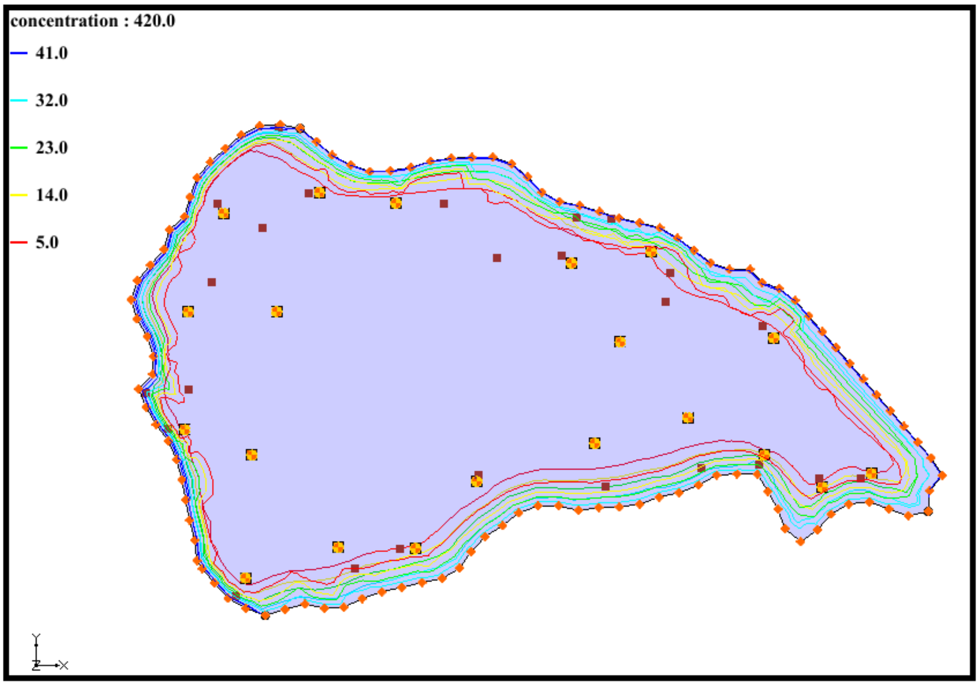
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.6 Simulated Bicarbonate concentrations under average recharge scenario

8.2.3 Maximum recharge

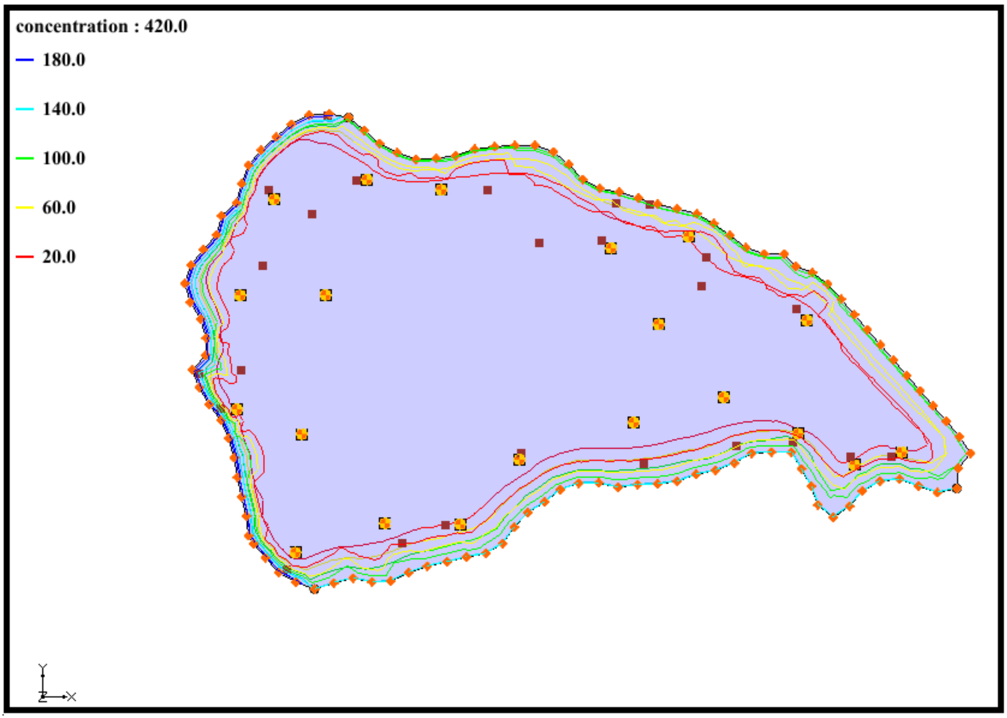
In the third scenario, considered a maximum recharge of 0.0045 m/d considered, which is calculated from the historical rainfall data. In this scenario, the simulated groundwater quality parameters concentrations of Cl, TDS and Bicarbonate are found to be lower than the observed groundwater quality parameters concentrations. The concentration distance of groundwater quality parameters is found to be less in the first coastal stretch and second coastal stretch due to the impact of maximum recharge in the model compared to the observed groundwater quality parameters model. In the freshwater stretch of the model, the concentration distance is found to be higher comparing to the observed groundwater parameters model result. The Fig. 8.7-8.9 shows the 3D mesh simulation result under maximum recharge for Cl, TDS and Bicarbonate.

The results of maximum recharge scenario for Cl parameter shows that all the groundwater wells had the concentration within the permissible limit of 250 mg/l. This shows that groundwater well quality is good with respect to the Cl parameter. The well number 3, 9 and 24 show a high Cl concentration of 40 mg/l, 38 mg/l, 34 mg/l and well number 12 shows a low concentration of 0 mg/l from Table 8.3. The TDS concentration of the wells within the permissible limit of 500 mg/l and indicates that all the wells exhibits good groundwater quality. The higher concentration of TDS value is 150 mg/l for well number 24 and the well number 12 show a lower concentration of 15 mg/l from Table 8.4. The Bicarbonate parameter for all wells is found to be less than the permissible limit values of 200 mg/l and the groundwater quality is found to be good. The well number 3 show a higher concentration of 148 mg/l and the well number 15 and 12 show a lower concentration of 10 mg/l and 16 mg/l from Table 8.5. In Netravathi and Gurpur river confluence, the groundwater well number 12 consist of very good groundwater quality and the well number 3 and 24 found to have higher concentration but it is within the permissible limit based on Cl, TDS and Bicarbonate. The groundwater quality for most of the wells found to be much improved comparing to the average recharge scenario.



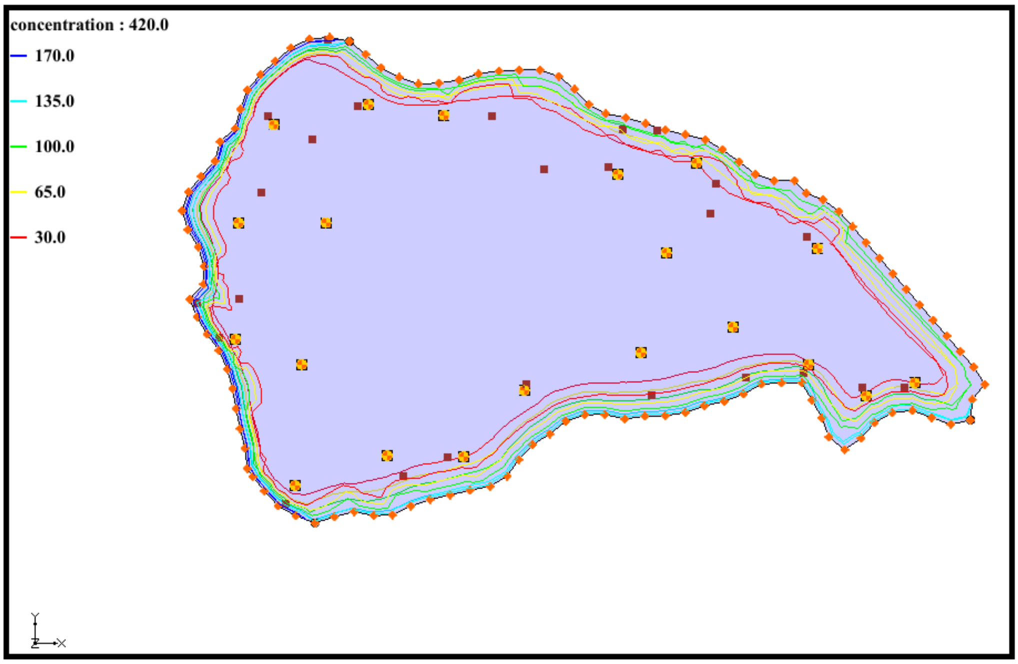
(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.7 Simulated Cl concentrations under maximum recharge scenario



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.8 Simulated TDS concentrations under maximum recharge scenario



(Yellow point data shows the pumping wells and rectangle point data indicate the observed wells)

Fig 8.9 Simulated Bicarbonate concentrations under maximum recharge

8.3 Injection wells

According to the United States Environmental Protection Agency, an injection well is defined as groundwater well used to place fluid underground into porous geologic formations through inflow from an outside source. These underground formations may range from deep sandstone or limestone to a shallow soil layer. Injected fluids may include water, wastewater, brine (saltwater), or water mixed with chemicals. According to Todd and Mays (2005), "This method maintains a pressure ridge along the coast by a line of recharge wells in which injected freshwater flows both seaward and landward. It requires high quality imported water to recharge the wells". The main use of injection wells is to reduce and control seawater intrusion in the coastal aquifers. In this study, the scenarios considered are the injection wells of minimum injection inflow rate of 20 m^3/hr and maximum injection inflow rate of 40 m^3/hr. The model is run for the transient state condition with a time control of 425 days and with a constant time interval of 30 days.

8.3.1 Minimum injection

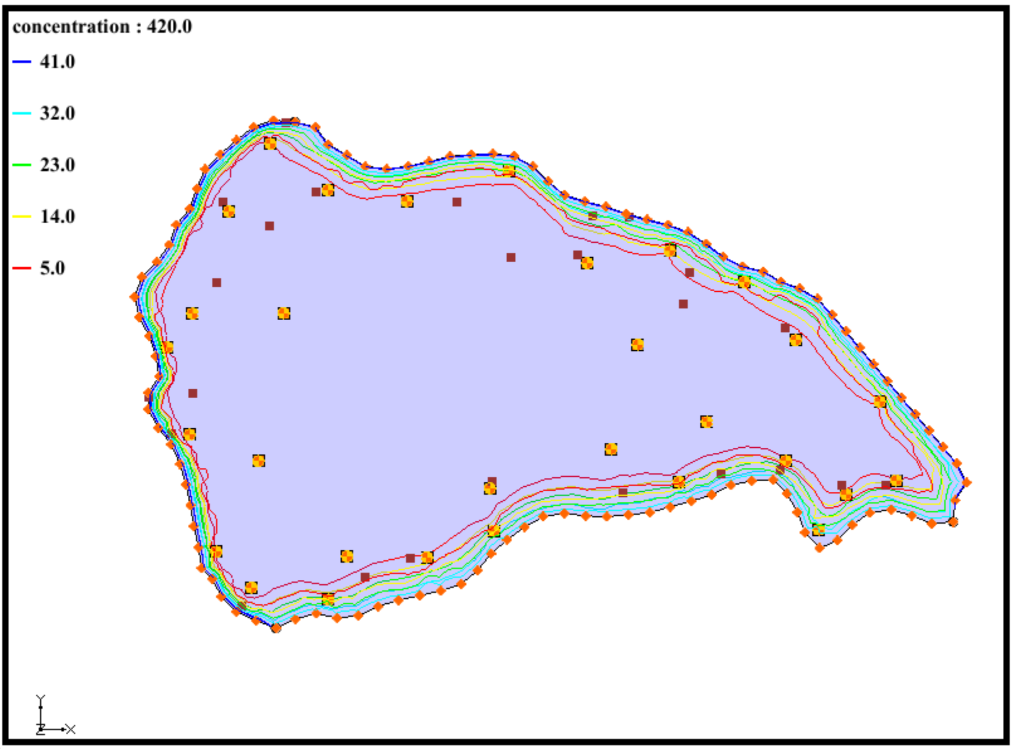
In the fourth scenario, ten injections wells are considered in the study area near the coastal river confluence with a flow rate of 20 m^3/hr. This is set by seeing the normal pumping in different wells of the study area. In order to compensate the pumping in the study area, the flow rate of 20 m^3/hr considered as the minimum injection flow rate in the study area. The ten wells are considered since it gives a good distribution freshwater flow in the coastal river confluence of the study area. In this scenario, it is found that the concentration of Cl, TDS and Bicarbonate is reduced than the observed concentration of Cl, TDS and Bicarbonate. Table 8.1 shows the details of the injection wells. The concentration distance of Cl, TDS and Bicarbonate for the first coastal stretch, second coastal stretch and freshwater stretch is found to be reduced compared to the observed Cl, TDS and Bicarbonate result. The Fig. 8.10-8.12 shows the 3D mesh predicted result under minimum injection wells with an inflow rate 20 m^3/hr for Cl, TDS and Bicarbonate.

The results of this scenario for Cl parameter shows that all the groundwater wells give the concentration within the permissible limit 250 mg/l which show that groundwater well quality is good. The well number 3, 9 and 24 show a high Cl concentration of 40 mg/l, 38 mg/l, 26 mg/l and well number 12 shows a low concentration of 0 mg/l (Table 8.3) which is within the permissible limit. The TDS concentration of the wells is found to be less than the permissible value of 500 mg/l and indicates that groundwater quality is good. The higher concentration of

TDS is 150 mg/l for well number 24 and lower concentration of TDS value is 15 mg/l for well number 12 from Table 8.4. The result of the Bicarbonate parameter for all wells is found to be within the permissible limit values of 200 mg/l and the groundwater quality for all wells is good. The higher concentration is 143 mg/l for well number 3 and the lower concentration is 8 mg/l and 15 mg/l of well 15 and 12 (Table 8.5) As like previous scenarios, in this scenarios the well number 12 has good groundwater quality and well numbers 3 and 24 is found to have higher concentration of Cl, TDS and Bicarbonate parameter which indicates the quality reduction of two wells but it is well within the permissible limit. In all the wells, the injection well flow rate of 20 m^3/hr gives better groundwater quality than maximum recharge scenario.

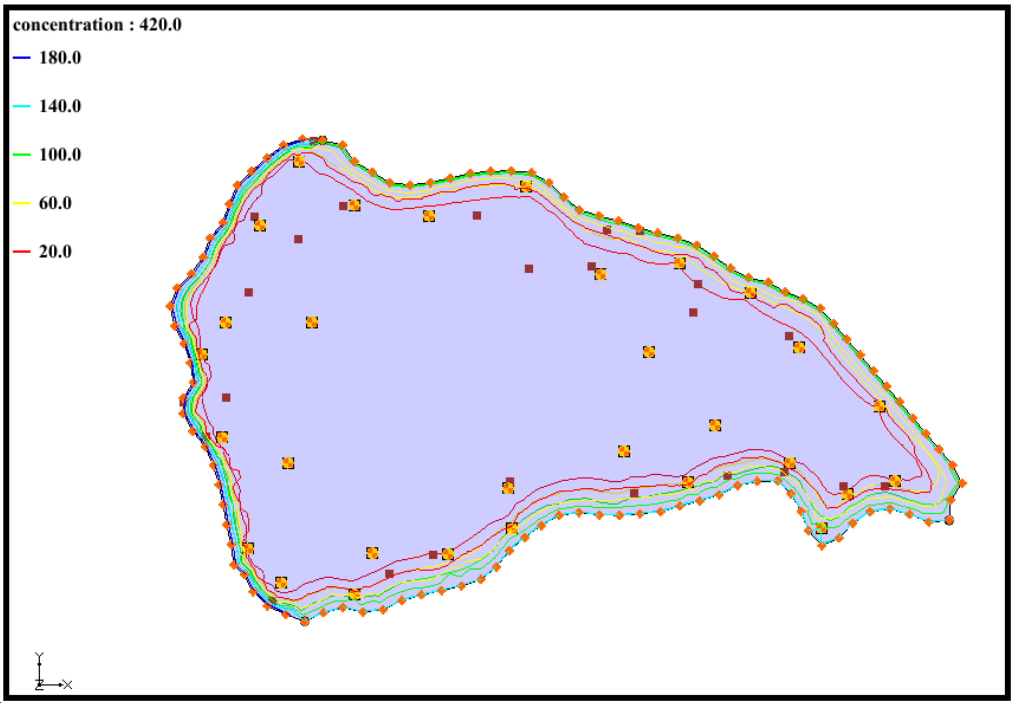
Table 8.1 Details of the injection wells minimum flow rate

Well no	Latitude (Degree Minute second)	Longitude (Degree Minute second)	Elevation (above M.S.L, m)	Flow rate (m^3/hr)
IW1	12° 56' 30"	74° 50' 55"	10	20
IW2	12° 56' 10"	74° 54' 00"	40	20
IW3	12° 54' 45"	74° 57' 03"	46	20
IW4	12° 53' 14"	74° 58' 48"	35	20
IW5	12° 53' 55"	74° 49' 35"	15	20
IW6	12° 51' 19"	74° 50' 13"	14	20
IW7	12° 50' 43"	74° 51' 40"	15	20
IW8	12° 51' 36"	74° 53' 49"	13	20
IW9	12° 52' 13"	74° 56' 12"	16	20
IW10	12° 51' 37"	74° 58' 01"	24	20



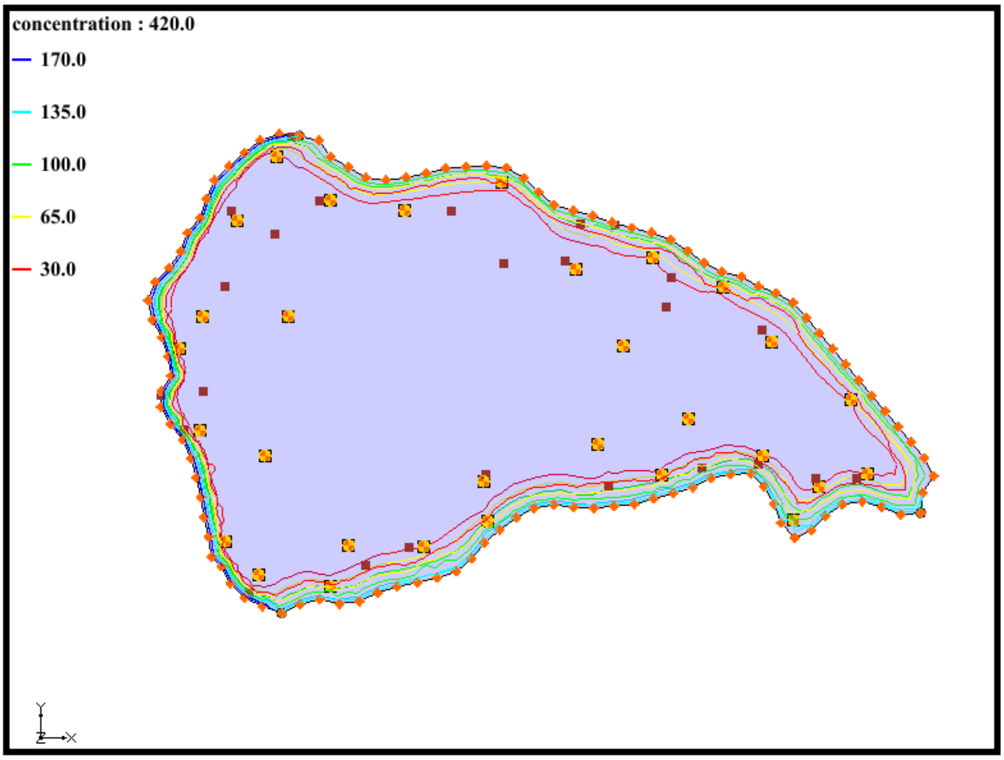
(Yellow point data shows the pumping wells and injection wells and rectangle point data indicate the observed wells)

Fig 8.10 Simulated Cl concentrations under minimum injection flow rate scenario



(Yellow point data shows the pumping wells and injection wells and rectangle point data indicate the observed wells)

Fig 8.11 Simulated TDS concentrations under minimum injection flow rate scenario



(Yellow point data shows the pumping wells and injection wells and rectangle point data indicate the observed wells)

Fig 8.12 Simulated Bicarbonate concentrations under minimum injection flow rate scenario

8.3.2 Maximum injection

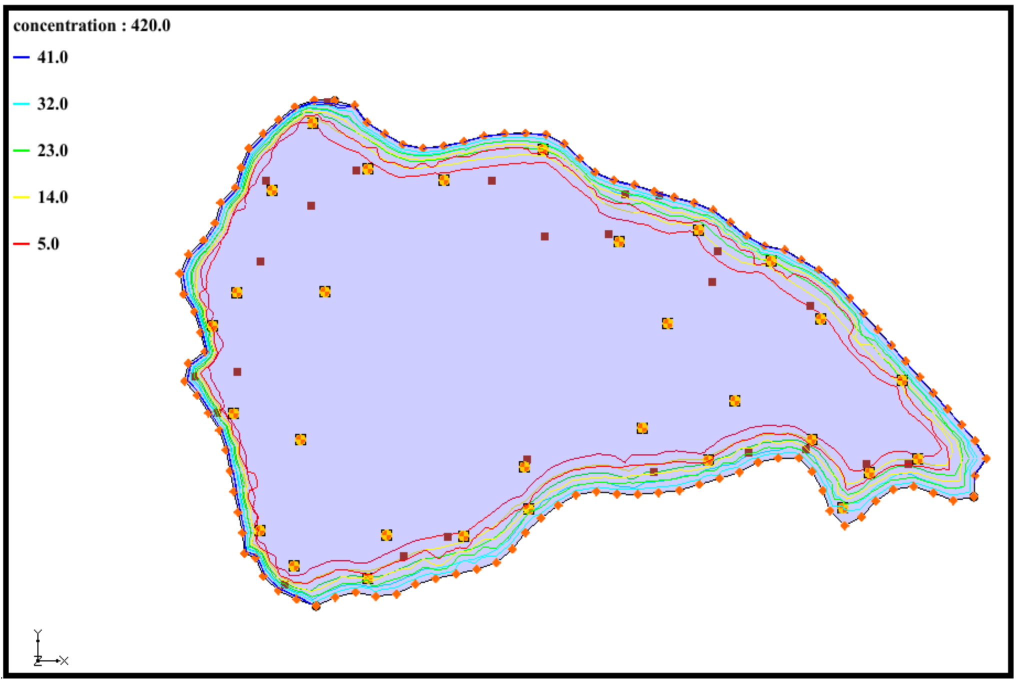
In this scenario, the flow rate of ten injection wells is considered at a maximum inflow rate of 40 m^3/hr in the study area. The inflow rate of 40 m^3/hr is considered mainly to see the impact of the concentration distance. This is set by seeing the normal pumping in different wells of the study area. In order to compensate the pumping in the study area, the flow rate of 40 m^3/hr considered as the maximum injection flow rate in the study area. Table 8.2 shows the details of the injection wells inflow rate for 40 m^3/hr. The well no 24 (Bolloor) have an improved groundwater quality of all three parameters compared to the observed concentrations of Cl, TDS and Bicarbonate and other scenarios in the first coastal stretch. The concentration distance of the first coastal stretch and freshwater stretch is found to be reduced compared to all scenarios and to the observed concentration of Cl, TDS and Bicarbonate. The second coastal stretch has a high concentration distance compared to the observed groundwater quality parameters of Cl, TDS and Bicarbonate. Fig. 8.13-8.15 shows the 3D mesh predicted result under maximum injection wells of inflow rate 40 m^3/hr for concentration Cl, TDS and Bicarbonate.

The results of the maximum injection well flow rate of 40 m^3/hr scenario for Cl parameter shows that all the wells give concentration within the permissible limit of 250 mg/l and the wells quality is good. The well number 3 and 9 shows a high Cl concentration of 40 mg/l and 35.5 mg/l and well number 12 shows a low concentration of 0 mg/l from Table 8.3. In this scenario, the Cl parameter of well number 24 has a concentration of 22mg/l while for the well numbers 22, 9 and 3 has a Cl concentration of 25 mg/l, 35.5 mg/l and 40 mg/l as shown in Table 8.3. The TDS concentration of the groundwater wells is found to be less than the permissible limit value of 500 mg/l and the water quality is good. The higher concentration of TDS is 120 mg/l for well number 3 and the lower concentration is 15 mg/l for the well number 12 from Table 8.4. The well number 24 shows a considerable improvement of quality for TDS comparing other wells such as well number 3, 16, 17, 22 and 23 with concentrations of 120 mg/l, 100 mg/l, 95 mg/l, 110 mg/l and 100 mg/l as shown in Table 8.4. The result of the Bicarbonate parameter for all wells is found to be less than the permissible limit values of 200 mg/l and the quality is good. The higher concentration for this parameter is 133 mg/l from well number 3 and the lower concentration is 6 mg/l and 13 mg/l from groundwater well 15 and 12 from Table 8.5. The well number 12 located in Netravathi and Gurpur river confluence has very good groundwater quality based on Cl, TDS and Bicarbonate parameter similar to previous scenarios. The well number 3 is found to have higher concentration of Cl, TDS and Bicarbonate parameter but it is within the permissible limit (Table 8.3, 8.4 & 8.5). The well number 24 found to have very high improved groundwater quality for the parameters of Cl and TDS. The impact of change in groundwater quality of well number 24 for this scenario indicates the high reduction of intrusion length in the first coastal stretch of the study area.

Table 8.2 Details of the injection wells maximum flow rate

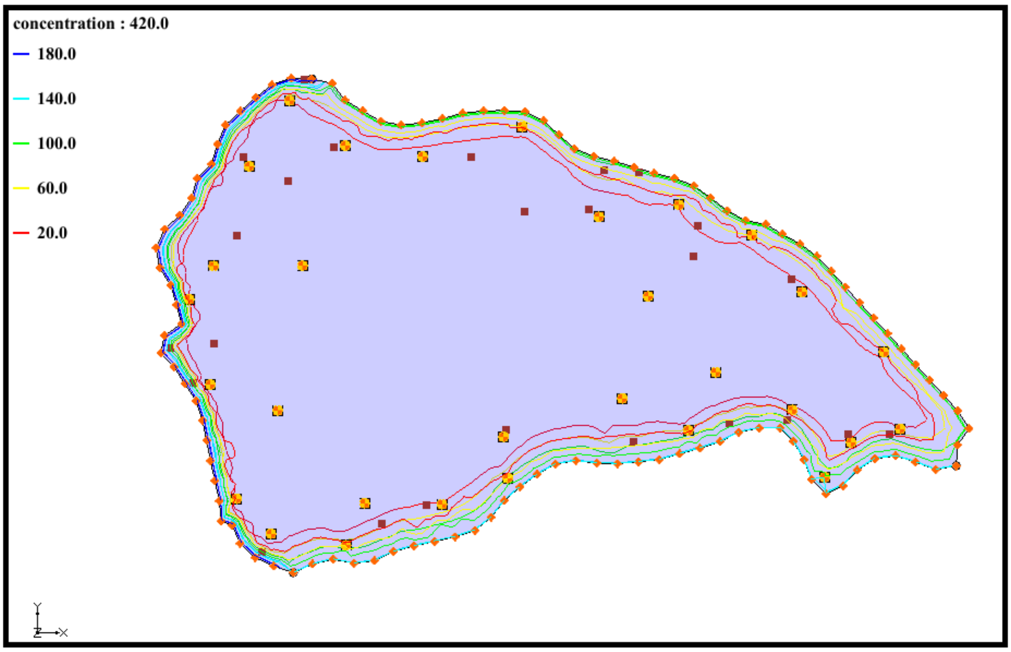
Well no	Latitude (Degree Minute second)	Longitude (Degree Minute second)	Elevation (m)	Flow rate (m^3/hr)
IW1	12° 56' 30"	74° 50' 55"	10	40
IW2	12° 56' 10"	74° 54' 00"	40	40
IW3	12° 54' 45"	74° 57' 03"	46	40
IW4	12° 53' 14"	74° 58' 48"	35	40
IW5	12° 53' 55"	74° 49' 35"	15	40
IW6	12° 51' 19"	74° 50' 13"	14	40
IW7	12° 50' 43"	74° 51' 40"	15	40

IW8	12° 51' 36"	74° 53' 49"	13	40
IW9	12° 52' 13"	74° 56' 12"	16	40
IW10	12° 51' 37"	74° 58' 01"	24	40



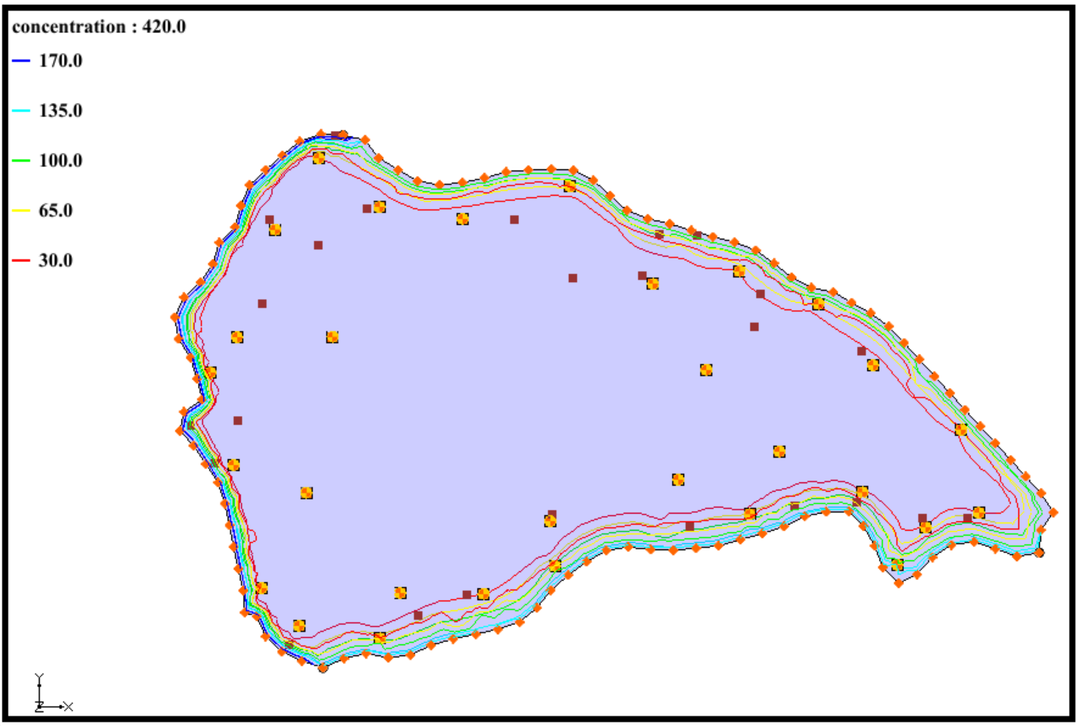
(Yellow point data shows the pumping wells and injection wells and rectangle point data indicate the observed wells)

Fig 8.13 Simulated Cl concentrations under maximum injection flow rate scenario



(Yellow point data shows the pumping wells and injection wells and rectangle point data indicate the observed wells)

Fig 8.14 Simulated TDS concentrations under maximum injection flow rate scenario



(Yellow point data shows the pumping wells and injection wells and rectangle point data indicate the observed wells)

Fig 8.15 Simulated Bicarbonate concentrations under maximum injection flow rate

8.4 RESULTS AND DISCUSSION

The predicted model results incorporating the scenarios for Cl, TDS and Bicarbonate parameters ere compared with the observed data. Table 8.3-8.5 gives the predicted model result of recharge scenario and injection wells results of Cl, TDS and Bicarbonate. Table 8.6 gives a variation of horizontal concentration distance of Cl, TDS and Bicarbonate of the study area for different scenarios. The result of the Cl, TDS and Bicarbonate parameters are considered for the well number 3, 8-10, 12, 14, 16-18 and 20-24. In the recharge scenario and injection wells, results of predicted Cl, TDS and Bicarbonate shows the reduction of concentration from the observed. In this study it shows that groundwater well number 12 consist of very good groundwater quality in Netravathi and Gurpur river confluence based on Cl, TDS and Bicarbonate parameter. In all scenario, except maximum injection well inflow rate of 40 m^3/hr, it is found that the groundwater well number 3 and 24 found to be higher concentration of Cl, TDS and Bicarbonate parameter which indicates the quality reduction of two wells in Netravathi and Gurpur river confluence. In the maximum injection well inflow rate of 40 m^3/hr shows the groundwater well number 24 found to be very high improved groundwater quality in the parameters of Cl and TDS. The impact of change in groundwater quality of groundwater well number 24 indicates the high reduction of intrusion length in the first coastal stretch of the study area. The intrusion length is found to be the reduced from 726.36 m observed first coastal stretch to 441.95 m of maximum injection wells of inflow rate 40 m^3/hr first coastal stretch. This result is found to be more significant since it shows a 39% reduction of an intrusion length in the first coastal stretch from observed to maximum injection wells of inflow rate 40 m^3/hr. The second coastal stretch and freshwater stretch has a reduction of the intrusion length in the first coastal stretch from observed under maximum injection inflow rate of 40 m^3/hr.

Table 8.3 Model results for Cl under variable recharge scenarios and injection well scenarios

Well no	Observed (mg/l)	Min. rec (mg/l)	Avg. rec (mg/l)	Max. rec (mg/l)	IW inflow = 20 m^3/hr (mg/l)	IW inflow = 40 m^3/hr (mg/l)
3	60.33	45	40	40	40	40
8	27.55	25	25	24	17.5	17.5
9	40.38	40	40	38	38	35.5
10	15.68	8.5	8	8	8	8
12	39.9	5	5	0	0	0
14	22.33	21	21	21	20	20
16	41.8	29	25	22	21	19
17	16.63	15	15	14	13	12
18	25.18	12	12	11	9	8.5
20	28.5	6	6	6	6	6
21	50.83	13	13	12	12	12
22	26.13	26.5	26	26	25	25
23	25.18	26.5	25	23	19	12
24	66.98	41	40	34	26	22

rec = recharge, IW = injection wells

Table 8.4 Model results for TDS under variable recharge scenarios and injection well scenarios

Well no	Observed (mg/l)	Min. rec (mg/l)	Avg. rec (mg/l)	Max. rec (mg/l)	IW inflow = 20 m^3/hr (mg/l)	IW inflow = 40 m^3/hr (mg/l)
3	347	150	150	130	130	120
8	99.2	88	85	84	83	82
9	109.12	100	100	100	95	90
10	134.54	25	25	25	25	25
12	215	15	15	15	15	15
14	111	85	75	68	65	65
16	232	120	118	110	100	100
17	104	100	100	100	100	95
18	159	88	85	80	80	80
20	90	25	25	23	22	20
21	189	46	45	45	45	40
22	198	135	130	130	125	110
23	178	110	110	110	108	100
24	344	200	200	150	150	90

rec = recharge, IW = injection wells

Table 8.5 Model results for Bicarbonate under variable recharge and injection well scenarios

Well no	Observed (mg/l)	Min. rec (mg/l)	Avg. rec (mg/l)	Max. rec (mg/l)	IW inflow = 20 m^3/hr (mg/l)	IW inflow = 40 m^3/hr (mg/l)
3	188	183	158	148	143	133
8	30	30	24	23	16	15
9	42	42	38	34	38	24
10	121	27	27	27	27	20
12	78	16	16	16	15	13
14	47	40	36	32	30	25

15	34	15	12	10	8	6
16	82	80	78	68	65	60
17	58	50	42	40	37	30
18	104	92	92	83	82	74
20	29	22	22	22	21	15
21	53	48	48	46	46	46
22	92	84	80	72	68	60
23	73	60	55	55	45	45
24	116	110	102	94	92	88

rec = recharge, IW = injection wells

Table 8.6 Concentration distance for the first coastal stretch, second coastal stretch and freshwater stretch in variable recharge and injection well inflow rate scenarios

Scenarios	First coastal stretch (m)	Second coastal stretch (m)	Freshwater stretch (m)
Observed	726.36	623.80	991.62
Min. rec	704.17	618.29	936.00
Avg. rec	640.51	604.40	918.95
Max. rec	638.50	584.01	889.57
Min. IW flow rate	580.90	579.53	834.13
Max. IW flow rate	441.95	577.46	746.49

rec = recharge, IW = injection wells

8.5 CONCLUSIONS

The conclusion for the prediction scenarios of the model are

1. In the recharge and injection wells scenario, results of predicted Cl, TDS and Bicarbonate shows the reduction of concentration from the observed concentration as additional water recharged into the aquifer and also within the permissible limits showing improved groundwater quality.
2. The well number 12 consist of potable groundwater quality in Netravathi and Gurpur river confluence with respect to Cl, TDS and Bicarbonate parameter for different scenarios. Since well number 12 found to be less chemical parameter value for Cl, TDS

and Bicarbonate parameter, which is within permissible limit and it is very good for potable groundwater quality.

3. In all the scenarios, except maximum injection well inflow rate of 40 m^3/hr, it is found that the well number 3 and 24 are found to be having higher concentration of Cl, TDS and Bicarbonate parameter, within permissible limits, indicating reduced quality of two wells in Netravathi and Gurpur river confluence.
4. In the maximum injection well inflow rate of 40 m^3/hr scenario, the well number 24 is shown improved groundwater quality for the parameters of Cl and TDS and reducing the intrusion length of the first coastal stretch of Netravathi and Gurpur river confluence.
5. A significant reduction of 39% of intrusion length was observed for first coastal stretch, i.e., from 726.36 m to 441.95 m under the maximum inflow rate of injection well scenario.
6. In the maximum (inflow=40 m^3/hr) injection well scenario, the intrusion length reduced to 7% for second coastal stretch, i.e., from 623.80 m to 577.46 m. Even though the intrusion length gets reduced it is not as significant as first coastal stretch. The intrusion length in freshwater stretch is reduced to 25%, i.e., from 991.62 m to 746.49 m. The freshwater stretch intrusion length reduction found to be more significant then second coastal stretch but less significant than first coastal stretch in the study area of Netravathi and Gurpur river confluence.

CHAPTER 9

SUMMARY AND CONCLUSIONS

The groundwater reserves in the coastal area are always sensitive to degradation if both quantity and quality due to dynamic interaction with freshwater and seawater. In this study, the status of the groundwater head and quality in the Netravathi and Gurpur river confluence of Dakshina Kannada district, Karnataka state is taken into consideration. The injections wells are considered in the river confluence as a remedial measure for groundwater quality degradation. The conclusion of the study is presented based on the aquifer characterization, groundwater quality analysis, groundwater flow modelling, groundwater transport modelling and different predictive scenarios.

The aquifer characterized mainly through pumping tests which provide the specific yield and hydraulic conductivity in the study area. The water quality analysis is carried out by field sampling and laboratory testing. Statistical analysis of different groundwater quality parameters has been prepared based on the laboratory analysis of groundwater samples to arrive at the status of the groundwater quality over the entire study area, the groundwater level data monitored acts as the input data for the groundwater flow model. The laboratory analysis of groundwater result is assigned as input data for the transport model. The groundwater flow, groundwater transport and prediction scenario modelled using the FEMWATER of GMS (Groundwater Modelling System)10.0 package.

AQUIFER CHARACTERIZATION

The aquifer characterization is done by pumping tests conducted in three wells for the entire study area. The aquifer parameters of the geological formation of the study area namely, specific storage and transmissivity are obtained through pumping test. This data is used to find out the hydraulic conductivity which is an input to the groundwater flow model. Based on this, the methodology adopted, the following conclusions drawn.

1. The transmissivity in three pumping wells is found between 241.56 m^2/day to 950.4 m^2/day
2. The specific storage in the study area found between 0.000107 to 0.000197. However, the previous studies in the region, the transmissivity ranges from 10 m^2/day to 1440

m^2/day and specific storage ranges from 0.00058 to 0.2805, which shows the aquifer parameters obtained are within the range.

GROUNDWATER QUALITY ASSESSMENT

The groundwater samples are tested for chemical parameters such as Cl, Na, Ca, HCO_3 etc. in the laboratory. According to BIS 10500 (2012) laboratory test, SAR analysis, piper plot, a 2-tailed significant test carried out. Finally, groundwater quality map prepared using GIS. The following are the specific conclusions drawn from this analysis.

1. Based on the laboratory results and statistical analysis, it is concluded that groundwater quality in the study area is good and safe for drinking as per World Health Organisation and Indian standards. Though the laboratory result is within the permissible limits, growing population and summer season would put pressure on groundwater reserves, this in future can cause water shortage and reduction in groundwater quality. In this regard, better management practice can be simulated through groundwater flow and transport modelling.
2. The SAR analysis shows that there is no contamination with respect Na, K and TH. The values of SAR are much lesser than the permissible limit of 10.
3. The piper plot shows the quality of groundwater for the months of April and May is good. Even though it is good, there is still a chance of contamination due to the movement of ions towards the mixing zone.
4. Based on the 2-tailed significant test, the chemical parameters such as EC, TDS, Cl and Ca are found to be more significant in the months April and May as they are strongly correlated with a correlation coefficient greater than 0.7. These chemical parameters are further used for generating groundwater quality map, groundwater quality status, prediction and future scenarios. The prediction of significant chemical parameter results shows that the correlation of the observed and predicted value of significant parameters like Cl, EC and TDS are good as the MAPE was found to be less than 1%. Hence it is concluded that the prediction is acceptable.
5. A strong conclusion is obtained from the groundwater quality maps that the spatial distribution of these parameters shows that the groundwater quality is excellent around Thumbe and Maripal region of the study area. The samples at Panganimuguru (well no. 1) and Kunjatbail (well no. 3) have indicated low quality for all chemical parameters. But these groundwater wells could be vulnerable to an increase in groundwater quality concentration and quality degradation, even though the quality is under the permissible

limit. This observation is also further supported and confirmed by the groundwater quality status index for the months of April and May 2016. Mapping results show the reduction of groundwater quality within 850m from the coast.

GROUNDWATER FLOW

The groundwater flow model developed in FEMWATER which is a three-dimensional finite element model and one of the computational modules of Groundwater modelling system (GMS) 10.0. The flow model is run for both steady state and transient state conditions. The following conclusions are obtained based on the numerical model analysis.

1. The coefficient of determination (R^2) between observed and simulated groundwater heads found to be 0.98 and 0.9 for calibration and validation respectively for steady state condition. The R^2 value shows a better agreement between observed and simulated values for the steady state condition.
2. In the transient state condition, R^2 value for simulated groundwater head found to be greater than 0.86 for both calibration and validation in the groundwater flow model. The R^2 value is found to be less compared to the steady state condition. Since, steady state time control is for a single time step of a month whereas the time control for the transient state is 486 days for calibration and 425 days for validation with an interval of 30 days.
3. The groundwater flow model is highly sensitive to hydraulic conductivity and groundwater recharge parameters. The pumping wells flow rate in the study area is not as sensitive compared to hydraulic conductivity and recharge parameters.

Based on the groundwater flow model results, it is found that the model performs reasonably good for both steady state and transient state condition. So the calibrated model is then be used for predicting future scenarios.

GROUNDWATER TRANSPORT

The groundwater transport model is developed using FEMWATER, which is a three-dimensional finite element model and one of the computational modules of Groundwater Modelling System (GMS) 10.0. The transport model is run for both steady state and transient state conditions for three groundwater quality parameters such as Cl, TDS and Bicarbonate. The following conclusions are obtained based on the result of groundwater quality parameters.

1. The R^2 between observed and simulated concentration was obtained as 0.94, 0.9 and 0.88 respectively for the groundwater quality parameters of Cl, TDS and Bicarbonate for steady state condition.
2. The Root Mean Square Error (RMSE) between observed and simulated concentration is obtained as 17.67, 82.4 and 87.53 respectively for the groundwater quality parameters of Cl, TDS and Bicarbonate for steady state condition.
3. The Nash-Sutcliffe efficiency (NSE) between observed and simulated concentration is obtained as 0.96, 0.97 and 0.95 respectively for the groundwater quality parameters of Cl, TDS and Bicarbonate for steady state condition.
4. The Mean Absolute Error (MAE) between observed and simulated concentration is obtained as -6.68, -31.14 and -35.73 respectively for the groundwater quality parameters of Cl, TDS and Bicarbonate for steady state condition.
5. The R^2 between observed and simulated concentration obtained as 0.92, 0.85 and 0.87 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state calibration condition. R^2 between observed and simulated concentration obtained as 0.88, 0.95 and 0.93 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state validation condition.
6. The RMSE between observed and simulated concentration obtained as 16.58, 81.33 and 96 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state calibration condition. RMSE between observed and simulated concentration obtained as 13.89, 161.23 and 1.41 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state validation condition.
7. The NSE between observed and simulated concentration obtained as 0.94, 0.94 and 0.95 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state calibration condition. NSE between observed and simulated concentration obtained as 0.98, 0.91 and 1 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state validation condition. The results show that the model performance is acceptable.
8. The MAE between observed and simulated concentration obtained as -5.86, -27.11 and -33.95 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state calibration condition. MAE between observed and simulated concentration obtained as -4.63, -48.61 and -0.5 respectively for the

groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state validation condition.

Based on the groundwater transport model, calibration, validation and error statistics, the model performs good for both steady state condition and transient state condition as per groundwater quality is concerned.

PREDICTION SCENARIO

The prediction scenario results are based on the cases from recharge of groundwater and injection wells. The recharge conditions considered are minimum recharge, average recharge and maximum recharge conditions based on rainfall conditions. The inflow rate considered in the injection wells are 20 m^3/hr and 40 m^3/hr.

1. For the groundwater recharge scenario of minimum, average and maximum and injection wells rates of 20 m^3/hr and 40 m^3/hr, results of predicted Cl, TDS and Bicarbonate shows the reduction of concentration from the observed wells and also are found within the permissible limit showing good groundwater quality.
2. In this study, well number 12 consist of potable groundwater quality which is located in Netravathi and Gurpur river confluence exhibits acceptable value of Cl, TDS and Bicarbonate parameter under all scenarios.
3. It is found that well number 3 and 24 has the parameter Cl, TDS and Bicarbonate high concentration approaching the permissible limit except the maximum flow rate (40m^3/hr) injection well scenario.
4. The concentration of Cl and TDS have found to be very much below the permissible limit indicating improved groundwater quality and reduction of seawater intrusion along the coast for well number 24 under the maximum injection well inflow rate (40m^3/hr) scenario.
5. The model results indicate an overall improvement in groundwater quality and reduction of seawater intrusion distance along the coastal stretch for the scenario of maximum injection well inflow rate (40m^3/hr).
6. Inspite, of the recharge scenario (Average and maximum) improved groundwater quality compared to observed quality parameters, injection wells are effective in improving groundwater quality and reducing seawater intrusion comparing to recharge scenarios.

9.1 SUMMARY

Groundwater contamination is one of the major problems in the 21st century due to increased population, irrigation and industrial activities. According to the UNESCO report, nearly 60% of the world population lives in coastal regions due to many benefits such as health, transportation, navigation, trade and recreation etc. However, these regions face many hydrological problems like flood due to cyclones, wave surge and drinking water scarcity due to seawater intrusion therefore, the coastal aquifers are under pressure both in terms of quantity and quality of water. Change in groundwater levels with respect to mean sea level along the coast largely influences the extent of seawater intrusion in the freshwater aquifers. Water quality modelling is essential to know the temporal and spatial changes and also to take the necessary preventive measures to reduce the seawater intrusion.

The important objectives of the study are to assess the status of groundwater quality parameters and mapping spatial and temporal distribution of groundwater quality over Netravathi and Gurpur river confluence. The second objective is to assess the vulnerable area for groundwater quality parameters and to investigate seawater intrusion through geochemical analysis of groundwater. The third objective to simulate the groundwater flow and contaminants in the urban coastal aquifer of Nethravathi and Gurpur river confluence through a numerical model. The fourth objective is the development of contaminant remedial scenarios based on historical rainfall recharge and injection wells.

The groundwater quality assessment the approach followed to assess the status of groundwater quality by mapping the spatial and temporal distribution of groundwater quality parameters. This helps us to understand the vulnerable area in the study area. The groundwater flow and transport model is developed using FEMWATER from the computational modules of Groundwater Modelling System (GMS) 10.0.

The groundwater quality assessment carried out by collecting groundwater samples from the field and laboratory testing. The laboratory test gives the different groundwater quality parameter results such as pH, EC, TDS, HCO_3, CO_3, Ca, Na, K, Mg and Cl. These results are further considered for the statistical analysis such as SAR, Piper plot, Significant chemical parameter, Factor of sea parameter correlation, groundwater quality status and mapping. This statistical analysis helps us to understand the status of the groundwater quality. Further, the flow and transport model is developed in order to understand the groundwater head status and effect of concentrations of groundwater quality parameters in the study area. In the development of the flow model, the field measured data of groundwater head used as input data. In the transport model, the laboratory result of the concentration of Cl, TDS and HCO_3 was used as the input data for the model. Further, the groundwater modelling also carried out for the different prediction scenarios.

The aquifer characterization using field pumping test shows the transmissibility parameter ranges from the 241.56 m^2/day to 950.4 m^2/day and the specific storage ranges from 0.000107 to 0.000197. Based on the laboratory results and statistical analysis, the groundwater quality in the study area is good and safe for drinking by Indian and World Health Organisation standards. However, it is observed by results that deterioration of groundwater quality is continued to increase during summer, for this reason, necessary management steps in the form of recharge structures, coastal reservoirs and injection wells should be constructed to increase groundwater storage. The samples at Panganimuguru (well no. 1) and Kunjatbail (well no. 3) have indicated low quality for all groundwater quality chemical parameters in laboratory results during the summer season. These wells could be vulnerable due to groundwater abstraction, even though the quality at present under the permissible limit.

The groundwater flow model performance is found to be good since it gives the R^2 value above 0.85 for groundwater head both in steady state and transient state condition. The R^2 value above 0.85 for groundwater quality parameters Cl, TDS and Bicarbonate show that groundwater transport model performing better for both steady state and transient state condition. The prediction scenarios modelled with injection wells resulted in increasing groundwater quality at an optimum inflow rate of 40 m^3/hr and also reduced the groundwater quality concentration length towards the coast.

Based on the overall summary it is found that most of the laboratory results of groundwater quality parameters are within the permissible limit at present status. In future, there is always the vulnerability of contamination as the climate changes in summer season found to be drastically higher in year basis from 2013 to 2017. In this concern, the injection wells near the coastal river confluence can help to reduce the intrusion length considerably and save the freshwater.

9.2 CONCLUSIONS

The important conclusions of this study are

1. The spatial distribution of groundwater quality parameters shows that the groundwater quality is excellent around Thumbe and Maripal region of the study area. The samples at Panganimuguru (well no. 1) and Kunjatbail (well no. 3) have indicated low groundwater quality for all chemical parameters. But these groundwater wells could be vulnerable to an increase in groundwater quality degradation, even though the quality is under the permissible limit. This observation is also further supported and confirmed by the groundwater quality status index for the months of April 2016 and May 2016. Mapped results show the reduction of groundwater quality within 850m from the coast of Netravathi and Gurpur river confluence.
2. The R^2 between observed and simulated concentration was obtained as 0.94, 0.9 and 0.88 respectively for the groundwater quality parameters of Cl, TDS and Bicarbonate for steady state condition. Similarly, the R^2 between observed and simulated concentration obtained as 0.92, 0.85 and 0.87 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state calibration condition. R^2 between observed and simulated concentration obtained as 0.88, 0.95 and 0.93 respectively for the groundwater quality parameters of the Cl, TDS and Bicarbonate for transient state validation condition. This means the model performance is more than 86% and can be used for predicting the future scenarios with artificial recharge and injection well.
3. Inspite, of the recharge scenario (Average and maximum) improved groundwater quality compared to observed quality parameters, injection wells are effective in improving groundwater quality and reducing seawater intrusion as compared to recharge scenarios. A significant reduction of 39% of intrusion length was observed for first coastal stretch, i.e., from 726.36 m to 441.95 m under the maximum inflow rate of injection well scenario. In the maximum (inflow=40 m^3/hr) injection well scenario, the intrusion length reduced to 7% for second coastal stretch, i.e., from 623.80 m to 577.46 m. Even though the intrusion length gets reduced it is not as significant as first coastal stretch. The intrusion length in freshwater stretch is reduced to 25%, i.e., from 991.62 m to 746.49 m. The freshwater stretch intrusion length reduction found to be more significant then second coastal stretch but less significant than first coastal stretch in the study area of Netravathi and Gurpur river confluence.

4. In this study, well number 12 comprises of potable groundwater quality which is located in Netravathi and Gurpur river confluence exhibits acceptable value of Cl, TDS and Bicarbonate parameter under all scenarios with observed values. The parameters Cl, TDS and Bicarbonate for the wells 3 and 24 have shown high concentration approaching to exceed the permissible limit except for the maximum flow rate (40 m^3/hr) injection well scenario.
5. The concentration of Cl and TDS have found to be very much below the permissible limit indicating improved groundwater quality and reduction of seawater intrusion (i.e., from 726.36 m to 441.95 m) along the coast for well number 24 under the maximum injection well inflow rate of 40 m^3/hr scenario.

9.3 RESEARCH CONTRIBUTIONS

The important research contributions of this study are

1. The status of the groundwater quality was identified through sampling and laboratory testing as per standard procedure and analysed statistically to understand the vulnerable locations due to pumping and other anthropogenic cause. This acts as primary data generation for calibration and validation of groundwater flow and quality model for Mangalore area in river confluence subjected to freshwater on one side and tidal saltwater on three sides.
2. The model helps us to identify the water head and water quality of different chemical concentration of groundwater. The model also helps us to understand the reduce recharge under climate change and also the effect of the injection wells in improving groundwater quality.
3. The model also identifies the vulnerable areas due to seawater intrusion in summers.

9.4 LIMITATIONS OF THE STUDY

The limitations of this study are

1. The aquifer is considered to be single unconfined.
2. Since the whole study area is considered as single layered unconfined aquifer, pumping tests have been conducted in open wells at various locations and found transmissivity values and storativity values. These are presented in the Table 4.1, 4.5-4.6. From these results, there is not much variation is observed in transmissivity in the study area. Also, the geographical extent of the study area being small, a single average k value is used

for the modelling study and later this value is calibrated during steady state calibration of numerical model.

3. The agricultural fertilizer contamination in the groundwater is not considered in the groundwater modelling.

9.5 SCOPE FOR FURTHER STUDY

The scope for the further study is

1. Multilayer could be considered and modelled for both flow and transport parameters. This can be achieved through geophysical test, water level and water quality monitoring at different layers.
2. An artificial recharge structure such as a “subsurface barriers” along the coast and backwater course could be proposed wherever saltwater intrusion exists. This will aid both saltwater intrusion reduction and recharge of water in wells.
3. A complete 3D aquifer characterization and mapping could be carried out based on lithology or borelogs.
4. Anthropogenic activities of the study area and climate change scenarios could be simulated and it impact on groundwater and solute transport in the study area for sustainable management of coastal aquifer.

REFERENCES

Ahmed, A.A. (2011). "Seasonal variations in water quality of al-wehda dam north of jordan and water suitability for irrigation in summer." *Arab. J. Geosci.*, 6, 1131-1140.

Andrade, F., Aravinda, H.B. and Puttaiah, E.T. (2011). "Studies on Mangalore coastal water pollution and its sources", *Indian J. Sci. Technol.,* 4, 553-557.

APHA, (1999). "Standard methods for the examination of water and wastewater", *American Public Health Association*, Washington DC.

APHA, (2005). "Standard methods for the examination of water and wastewater", 21st Ed., *American Public Health Association*, New york, USA.

Askri, B. (2015). "Hydrochemical processes regulating groundwater quality in the coatal plain Al Musanaah, Sultanate of Oman", *J. Afr. Earth Sci.*, 106, 87-98.

Avvannavar, S.M. (2007). "Studies on pollution of river Nethravathi, Karnataka." *Nat. Environ. Pollut. Technol.,* 6(3), 541-542.

Balakrishnan, S., Chelladurai, G., Mohanraj, J. and Poongodi, J. (2015). "Seasonal variations in physico-chemical characteristics of Tuticorin coastal waters, southeast coast of India." *Appl. Water Sci.,* 7(4), 1881-1886.

Bhat, G.H. and Subrahmanya, K.R. (2000). "Shoreline changes and evolution of the coastal zone in southern Karnataka, India-an analysis based on multi-temporal data", *Int. Arch. Photogramm. Remote Sens.,* 33(PART B7), 191-197.

BIS (Bureau of Indian Standards). (2012). "Specification for drinking water." IS 10500:2012, New Delhi, India.

BIS (Bureau of Indian Standards). (1998). "Sampling and test." IS 3025:1998, New Delhi, India.

Boateng, T.K., Opoku, F., Acquaah, S.O. and Akoto, O. (2016). “Groundwater quality assessment using statistical approach and water quality index in Ejisu-Juaben Municipality.” Ghana. *Environ. Earth Sci., 75*(6), 1-14.

Canales, A., Gonzalez, R. and Islas, L. (2001). “Saltwater Intrusion Risk Assessment in the Boca Abierta Valley, Sonara, Mexico.” *First International Conference on Saltwater Intrusion and Coastal Aquifers,* Morocco.

Chen, L., Shen, Z., Yang, X., Liao, Q. and Shaw, L.Y. (2014). “An Interval-Deviation Approach for hydrology and water quality model evaluation within an uncertainty framework.” *J. Hydrol.*, 509, 207-214.

CGWB (2012), Central Groundwater Board. “Groundwater information booklet, Dakshina Kannada district, Karnataka.” *Govt. of India, Ministry of Water Resources,* South western region, Bangalore, 11.

Cooper. H.H. and Jacob. C.E. (1946). “A generalized graphical method for evaluating formation constants and summarizing well field history.” *Trans. Am. Geophys. Union,* 27(4), 526-534.

Dahanukar, N., Raut, R., & Bhat, A. (2004). Distribution, endemism and threat status of freshwater fishes in the Western Ghats of India. *Journal of Biogeography, 31*, 123-136.

Datta, B., Vennalakanti, H. and Dhar, A., (2009). “Modeling and control of saltwater intrusion in a coastal aquifer of Andhra Pradesh, India.” *J. Hydro. Environ. Res.*, 3, 148-159.

Dhakate, R., Sankaran, S., Kumar, V.S., Amarender, B., Harikumar, P. and Subramanian, S.K. (2016). “Demarcating saline water intrusion pathways using remote sensing, GIS and geophysical techniques in structurally controlled coastal aquifers in Southern India.” *Environ. Earth Sci.,* 75(363), 1-19.

Edet, A. (2016). “Hydrogeology and groundwater evaluation of a shallow coastal aquifer, southern Akwa Ibom State (Nigeria).” *Appl. Water Sci.,* 7(5), 2397-2412.

Fitta, C. R. (2010). “Modelling aquifer systems with analytic elements and subdomains.” *Water Resour. Res.,* 46, 1-10

Forcada, E. G. (2014). “Space/time development of seawater intrusion: A study case in Vinatoz coastal plain (Eastern Spain) using HFE-Diagram, and spatial distribution of hydrochemical facies.” *J. Hydrol.,* 517, 617-627.

Harshendra, K. (1991). “Studies on water quality and soil fertility in relation to crop yield in selected river basins of D.K. District of Karnataka state.” Ph.D. Thesis, Mangalore University, Karnataka, India.

Jeevanandam, M. (2007). “Hydrogeochemistry and groundwater quality assessment of lower part of the Ponnaiyar river basin, Cuddalore District, South India.” *Environ. Monit. Assess.*, 132, 263-274.

Johnson, T. (2007). “Battling seawater intrusion in the Central and west coast basins. Water Replenishment district of Southern California.” Technical Bulletin, 13, 1-2.

Kanagaraj, G., Elango, L., Sridhar, S.G.D. and Gowrisankar, G. (2018). “Hydrogeochemical processes and influence of seawater intrusion in coastal aquifers south of Chennai, Tamil Nadu, India.” *Environ. Sci.* 25(9), 8989-9011.

Karanth, K. R. (1987). “Ground water assessment: development and management.” Tata Mcgraw-Hill Education, India.

Karatzas, G. P. (2017). “Developments on modeling of groundwater flow and contaminant transport.” *Water resour. manage*., 31, 3235–3244.

Khadri, S.F.R. and Pande, C. (2016). “Ground water flow modeling for calibrating steady state using MODFLOW software: a case study of Mahesh River basin, India.” *Model. Earth Syst. Environ.,* 2(39), 1-17.

Khashogi, M.S. and Magdy, M.S. (2013). “Evaluation of groundwater resources for drinking and agricultural purposes, Abar Al Mashi area, south Al Madinah Al Munawarah city, Saudi Arabia.” *Arab. J. Geosci.,* 6(10), 3929-3942.

Khorasani, M., Ehteshami, M., Ghadimi, H. and Salari, M. (2016). “Simulation and analysis of temporal changes of groundwater depth using time series modelling.” *Model. Earth Syst. Environ*., 2(90), 1-10.

Kim, S.D., Lee, H.J. and Park, J.S. (2012). “Simulation of seawater intrusion range in coastal aquifer using the FEMWATER model for disaster information.” *Mar. Georesour. Geotec.,* 30, 210- 221.

Krishna, R.K. (1987). “Groundwater assessment, development and management.” Tata McGraw-Hill Publishing Co. Ltd., New Delhi, 576–657.

Krishna, R. (1970). Hydrometeorological aspects of estimating ground water potential. Seminar on ground water potential in hard rock areas, Bangalore. Geological Society of India. 1(1): 99.1-18.

Kumar, K.S., Rammohan, V., Sahayam, J.D. and Jeevanandam, M. (2008). “Assessment of groundwater quality and hydrogeochemistry of Manimuktha River basin, Tamil Nadu, India.” *Environ. Monit. Assess.,* 159, 341-351.

Kumarasamy, P., Dahms, H.U., Jeon, H.J., Rajendran, A. and James, R.A. (2014). “Irrigation water quality assessment—an example from the Tamiraparani river, Southern India.” *Arab. J. Geosci., 7*(12), 5209-5220.

Lathasri, U.A. (2016). “Predictive simulation of flow and solute transport for managing the coastal aquifer of Dakshina kannada district, Karnataka, India”, Ph.D thesis, National Institute of Technology Karnataka, Surathkal, India.

Lin, C.Y., Abdullah, M.H., Praveena, S.M. and Yahaya, A.H.B. (2012). “Delineation of temporal variability and governing factors influencing the spatial variability of shallow groundwater chemistry in a tropical sedimentary Island”, *J. Hydrol.*, 432, 26-42.

Lin, H.C.J., Richards, D.R., Yeh, G.T., Cheng, J.R. and Cheng, H.P. (1997). "FEMWATER: a three-dimensional finite element computer model for simulating density-dependent flow and transport in variably saturated media." Technical Report, *U.S. Army Engineer Waterways Experiment Station*, Fort Belvoir, Virginia.

Liu, F., Anh, V.V., Turner, I., Bajracharya, K., Huxley, W.J. and Su, N. (2006). "A finite volume simulation model for saturated-unsaturated flow and application to Gooburrum, Bundaberg, Queensland, Australia." *Appl. Math. model.*, 30(4), 352-366.

Lopez, A. and Vurro, M. (2008). "Planning Agricultural Wastewater Reuse in Southern Italy: The case of Apulia Region", *Desalination*, 218(1-3), 164-169.

Lu, C. and Werner, A.D. (2013). "Timescales of seawater intrusion and retreat." *Adv. water Resour.,* 59, 39-51.

Mahesha, A. and Nagaraja, S.H. (1996). "Effect of Natural Recharge on Sea Water Intrusion in Coastal Aquifers." *J. Hydrol.,* 174, 211-220.

Mawlood, D.K. and Mustafa, J.S. (2016). "Performing pumping test data analysis applying Cooper-Jacob's method for estimating of the aquifer parameters." *Math. Model. Civil Eng.,* 12(1), 9-20.

Milnes, E. (2011). "Process-based groundwater salinisation risk assessment methodology: Application to the Akrotiri aquifer (Southern Cyprus)." *J. Hydrol.*, 399(1), 29-47.

Mishra, A.K., Arya, M. and Mathur, R. (2011). "Assessment of pre-monsoon and post-monsoon ground water quality with special reference to fluoride concentration in Narwar, Shivpuri, Madhya Pradesh, India." *J. Environ. Res. Dev.,* 6(1), 77-81.

Mondal, N.C., Singh, V.P., Singh, V.S. and Saxena, V.K. (2010). "Determining the interaction between groundwater and saline water through groundwater major ions chemistry." *J. Hydrol.*, 388(1), 100-111.

Mohan, S. and Pramada, S.K. (2005). “Management of South Chennai coastal aquifer system- A multi objective approach.” *Jalvigyan Sameeksha,* 20, 1-14.

Narany, T.S., Ramli, M.F., Aris, A.Z., Sulaiman, W.N.A. and Fakharian, K. (2015). “Groundwater irrigation quality mapping using geostatistical techniques in Amol–Babol Plain, Iran.” *Arab. J. Geosci.,* 8(2), 961-976.

NBSS & LUP. (1998). “National Bureau of soil survey and land use planning (Indian council of agricultural research). Soils of Karnataka for optimising land use.” *State soil survey, department of agriculture,* Bangalore, Karnataka, NBSS Publ. 47.

Nosrati, K. (2015). “Application of multivariate statistical analysis to incorporate physico-chemical surface water quality in low and high flow hydrology.” *Model. Earth Syst. Environ*., 1(19), 1-13.

Obe, I., Fashanu, T.A., Idialu, P.O., Akintola, T.O. and Abhulimen, K.E. (2016). “Produced water re-injection in a non-fresh water aquifer with geochemical reaction, hydrodynamic molecular dispersion and adsorption kinetics controlling: model development and numerical simulation.” *Appl. Water Sci.,* 7(3), 1169-1189.

Ojha, R., Ramadas, M. and Govindaraju, S.R. (2013). “Current and future challenges in Groundwater I: Modelling and management of resources.” *J. Hydrol. Eng.,* 20(1), 1-24.

Paldor, A., Shalev, E., Katz, O. and Aharonov, E. (2019). “Dynamics of saltwater intrusion and submarine groundwater discharge in confined coastal aquifers. A case study in Northern Israel.” *Hydrogeo. J.,* 1-15.

Panaskar, D.B., Wagh, V.M., Muley, A.A., Mukate, S.V., Pawar, R.S. and Aamalawar, M.L. (2016). “Evaluating groundwater suitability for the domestic, irrigation, and industrial purposes in Nanded Tehsil, Maharashtra, India, using GIS and statistics.” *Arab. J. Geosci*., 9(615), 1-16.

Parmar, K.S. and Bhardwaj, R. (2014). “Water quality management using statistical analysis and time-series prediction model.” *Appl. Water Sci*., 4(4), 425-434.

Prasanth, S.V.S., Magesh, N.S., Jitheshlal, K.V., Chandrasekar, N. and Gangadhar, K. (2012). “Evaluation of groundwater quality and its suitability for drinking and agricultural use in the coastal stretch of Alappuzha district, Kerala, India.” *Appl. Water Sci.*, 2, 165-175.

Polemio, M., Dragone, V. and Limoni, P.P. (2009). "Monitoring and methods to analyse the groundwater quality degradation risk in coastal karstic aquifers (Apulia, Southern Italy)". Environmental Geology. 58 (2): 299–312.

Pontius, R.G., Thontteh, O. & Chen, H. (2008). “Components of information for multiple resolution comparison between maps that share a real variable”. *Environ Ecol Stat* 15, 111–142.

Pulido-Leboeuf, P. (2004). “Seawater intrusion and associated processes in a small coastal complex aquifer (Castell de Ferro, Spain).” *Appl. Geochem.*, 19(10), 1517-1527.

Rajagopal, B., Shrihari, S. and Dwarakish, G.S. (2010). “Global water quality indices for River Gurpur, Karnataka State, India.” *Int. J. Earth Sci. Eng.*, 3(6), 833-840.

Raju, J.N. (2007). “Hydrogeochemical parameters for assessment of groundwater quality in the upper Gunjanaeru river basin, Cuddapah District, Andhra Pradesh, South India.” *Environ. Geol.,* 52, 1067-1074.

Raghunath, H.M. (1987). Groundwater, 2" edition. *New Age International Publishers, New Delhi*. 246-247.

Ramadas, M., Ojha, R. and Govindaraju, S.R. (2013). “Current and future challenges in Groundwater II: Water quality modelling.” *J. Hydrol. Eng.*, 20, 1-24.

Ranganna, G., Gurappa, K,M., Gajendragad, M,R. and Chandrakantha, G. (1986). “Hazardous effects of groundwater pollution and mitigative measures thereof.” *Report submitted by Department of Applied Mechanics and Hydraulics,* National Institute of Technology Karnataka, Surathkal to the Department of Environment, Government of India, 128.

Rao, G.T., Rao, V.G., Rao, Y.S. and Ramesh, G. (2013). "Study of hydrogeochemical processes of the groundwater in Ghatprabha river sub-basin, Bagalkot District, Karnataka, India." *Arab. J. Geosci., 6*(7), 2447-2459.

Reghunath, R., Murthy, S.R.T. and Raghavan, B.R. (2005). "Time series analysis to monitor and assess water resources: A moving average approach." *Environ. Monit. Assess.*, 109(1), 65-72.

Revelle, R. (1941). "Criteria for recognition of seawater in ground waters." *Eos, Trans. Amer. Geophys. Union*, 22(3), 593-597.

Running, S., Mu, Q., Zhao, M. (2017). *MYD16A2 MODIS/Aqua Net Evapotranspiration 8-Day L4 Global 500m SIN Grid V006* [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2020-03-10 from https://doi.org/10.5067/MODIS/MYD16A2.006

Sebri, M. (2016). "Forecasting urban water demand: A meta-regression analysis." *J. Environ. Manage.*, 183, 777-785.

Senthilkumar, M. and Elango, L. (2011). "Modelling the impact of a subsurface barrier on groundwater flow in the lower Palar River basin, southern India." *Hydrogeology J.,* 19, 917-928.

Sharma, S.K. (2008). "Imfluence of sea water ingress: A case study from East coast aquifer in India." *20th Saltwater intrusion meeting,* Naples, Florida, USA, 250-253.

Shetkar, R.V. (2008). "Studies on the efficacy of vented dams as water harvesting structures across the river Netravathi of D.K. district, Karnataka." Ph.D. thesis, National Institute of Technology, Karnataka, Surathkal, India.

Shivanagouda, H.S. (2015). "Studies on aquifer characterization and seawater intrusion vulnerability assessment of coastal Dakshina Kannada district, Karnataka." Ph.D. Thesis, National Institute of Technology Karnataka, Surathkal, India.

Sindhu, G., Ashitha, M., Jairaj, P.G. and Raghunath, R. (2012). "Modelling of coastal aquifers of Trivandrum." *P. Eng.*, 38, 3434-3448.

Sotirios, K., Sakellari, A., Nikolaos, M., Manos, D. and Scoullos, M.J. (2008). "Evaluation of the Quality of Drinking Water in Regions of Greece." *Desalination,* 204, 317-329.

Sun, L. and Gui, H. (2014). "Hydro-chemical evolution of groundwater and mixing between aquifers: a statistical approach based on major ions." *Appl. Water Sci.,* 5, 97–104.

Suribabu, C.R., Ravinder, S., Ananadapadmanaban, S., Seshadri, S. and Bhaskar, J. (2012). "Tracing the evidence of seawater intrusion in the coastal aquifer of Adhirampattinam, India, using Hydro-chemical analysis." *ISH J. Hydraul. Eng.*, 18, 90-100.

Tay, C.K., Hayford, E.K. and Hodgson, I.O.A., (2017). "Application of multivariate statistical technique for hydrogeochemical assessment of groundwater within the Lower Pra Basin, Ghana." *Appl. Water Sci.,* 7(3), 1131-1150.

Teikeu, W. A., Meli'i, J. L., Nouck, P. N., Tabod, T. C., Nyam, F. E. A. and Aretouyap, Z. (2016). "Assessment of groundwater quality in Yaounde area, Cameroon, using geostatistical and statistical approaches." *Environ. Earth Sci*., 75(21), 1-15.

Theis, C.V. (1963). "Estimating the Transmissivity of a water-table aquifer from the specific capacity of a well." U. S., Geological survey water supply paper, 1536-I, 332-336.

Todd, D.K. and Mays L.W., (2005). "Groundwater Hydrology.", John Wiley and sons, New York.

Tomaszkiewicz, M., Najm, A.M. and Fadel, E.M. (2014). "Development of a groundwater quality index for seawater intrusion in coastal aquifers." *Environ. Model. Softw.*, 57, 13-26.

Tuong, T.P., Kam, S.P., Hoanh, C.T., Dung, L.C., Khiem, N.T., Barr, J. and Ben, D.C. (2003). "Impact of Seawater Intrusion Control on the Environment, Land use and Household Incomes in a Coastal Area." *Paddy Water Environ.*, 1, 65-73.

Udayakumar, G. (2008). “Subsurface barrier for water conservation in lateritic formations.” Ph.D. thesis, Department of Applied Mechanics and Hydraulics, National Institute of Technology, Karnataka, Surathkal, India, 88-92.

UNESCO-WWAP (World Water Assessment programme). 2009. Water in a Changing World. World Water Development Report 3. Paris/London, UNESCO/ Earthscan.

Victor, R., Amina, A.I. and Al-Farsi. (2000). “Water Quality and Invertebrate Fauna of Farm Wells in an area affected by Salinization in Oman.” *J. Arid Environ.*, 48, 419-428.

Vyshali. (2008). “Studies on saltwater intrusion in the coastal D.K district, Karnataka. Ph.D. Thesis, Department of Applied Mechanics and Hydraulics, National Institute of Technology Karnataka, Surathkal, Mangalore, India. 52-72.

Vyshali, P.M, Palchaudhury, M. and Mahesha, A. (2008). “Simulation of saltwater intrusion in the Pavanje-Gurpur basins of Karnataka.” *J. Hydraul. Eng.*, 14(2), 49-60.

Web, M. D. and Howard, K.W. (2011). “Modelling the transient response of saline intrusion to rising sea-levels.” *Ground water*, 49(4), 560-569.

Werner, A.D., Bakker, M., Post, E.A.V., Vandenbohede, A., Lu, C., Ashtiani, B., Simmons, T.C. and Barry, D.A. (2012). “Seawater intrusion processes, investigation and management: Recent advances and future challenges.” *Adv. Water Resour.,* 51, 1-26.

White, I., Falkland, T., Perez, P., Dray, A., Metuter, T., Metai, E. and Overmars, M. (2006). “Challenges in freshwater management in low coral atolls.” *J. Clean. Prod.*, 15, 1522-1528.

WHO (World Health Organization), (1996). “Guidelines for drinking water.” Geneva.

WHO (World Health Organization), (2008). “Guidelines for drinking water quality”. World Health Organization, 20 Avenue Appia, 1211 Geneva 27, Switzerland. 324-445.

Yang, Y.J. (2008). “A case study of Finite-Element Numerical modelling on saltwater intrusion for the Ping- Tung Plain”, 20th Saltwater intrusion meeting, 325-327.

Yang, Q., Li, Z., Ma, H., Wang, L. and Martin, D.J. (2016). “Identification of the hydrogeochemical processes and assessment of groundwater quality using classic integrated geochemical methods in the South Eastern part of Ordos basin, China.” *Environ. Pollut.*, 1-10.

Zalidis, G., Stamatiadis, S., Takavakoglou, V., Eskridge, K. and Misopolinos, N. (2002). “Impacts of Agricultural Practices on Soil and Water Quality in the Mediterranean Region and Proposed Assessment Methodology.” *Agric. Ecosyst. Environ.*, 88(2), 137-146.

Zekri, S. (2008). “Using Economic Incentives and Regulations to reduce Seawater Intrusion in the Batinah Coastal area of Oman.” *Agric. Water Manage.*, 95(3), 243-252.

Zhou, X., Xia, Y., Juan, L., Jinmei, Y. and Wenyu, D. (2006). “Evolution of the Groundwater Environment under a Long-term Exploitation in the Coastal area near Zhanjiang, China.” *Environ. Geol.*, 55(5), 847-856.

Zhan, N., Huang, Y., Rao, Z. and Zhao, X.L. (2016). “Fast detection of carbonate and bicarbonate in groundwater and lake water by coupled ion selective electrode.” *Chin. J. Anal. chem.*, 44(3), 355-360.

http://www.miwaterstewardship.org/residents/environmentalterms/filter/s

http://landweb.nascom.nasa.gov/cgi-bin/QA_WWW/qaFlagPage.cgi?sat=aqua&ver=C6

https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php

https://www.epa.gov/uic/general-information-about-injection-wells

https://www.eskawater.com/the-importance-of-ph-2/

APPENDIX

Fig. 1 Pumping well no 1

Fig. 2 Pumping well no 2

Fig. 3 Pumping well no 3

PUBLICATIONS

International Journal Papers

- **Sylus, J.K** and Ramesh, H (2014), “Statistical analysis of water quality and water Level of Netravathi and Gurpur river basin, Mangalore, India for non- monsoon season”, ***J. Environ. Res. Develop.***,8, 747-750.
- **Sylus, J.K** and Ramesh, H (2017), “Modelling of groundwater quality using Chloride and Total dissolved solids parameters in Nethravathi and Gurpur river confluence, India”, ***Int. Academic Res. J. Eng. Sci.***, 2(1), 15-31.
- **Sylus, J.K** and Ramesh, H (2018), “Geo-statistical analysis of groundwater quality in an unconfined aquifer of Nethravathi and Gurpur river confluence, India”, ***Model. Earth Syst. Environ***. 4:1555-1575**. SPRINGER,** DOI 10.1007/s40808-018-0488-z (SCOPUS)

International Conference Papers

- **Sylus, J.K** and Ramesh, H (2013), “The Study of seawater intrusion in coastal aquifer by chemical parameter ratio method”, ***International conference on Hydraulic and water resources*** - **HYDRO’2013**, 456-461.
- **Sylus, J.K** and Ramesh, H (2015), “The study of sea water intrusion in coastal aquifer by electrical conductivity and total dissolved solid method in Gurpur and Netravathi river basin”, ***International conference on water resources, coastal and ocean engineering – ICWRCOE’2015***. DOI:10.1016/j.aqpro.2015.02.009**.**
- **Sylus, J.K** and Ramesh, H (2017), “Modelling of groundwater quality using Bicarbonate parameter in Nethravathi and Gurpur river confluence, India”, ***International conference on Electrical, Electronics, Materials and Applied science***, 315-324. DOI: 10.1063/1.5032006

BIODATA

Name : Konstantin sylus J

Date of Birth : 25-10-1986

Mobile : (+91) 9743850767

Email : ksylus@gmail.com

Qualification : B.E. (Civil), M.E. (WREM)

Journal Publications : 3

No. of Conference Publications : 3