ANALYZING THE SEASONAL VARIATION OF GROUNDWATER CHARACTERISTICS IN THE ATTANAGALU OYA BASIN

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“The undersigned hereby certify that the thesis has been read and recommended for acceptance in partial fulfilment of the requirements for the Degree of Bachelor of Science of Engineering”

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DEDICATION

We here by dedicate our thesis entitled "Analyzing The Seasonal Variation Of Groundwater Characteristics In The Attanagalu Oya Basin" especially to the **people of Gampaha** district who cooperated and helped us to finish this research successfully. And especially, we state our sincere dedication and thanks to our **beloved parents** who were our moral support in our every activity.

We hereby declare our dedication of this thesis to the people of Gampaha district which will be very useful to them to know about the quality of the water they use for drinking and other purposes. We also dedicate this study to the all the **researchers** who spend their time to improve the quality of life of humans in Sri Lanka.

Finally, we dedicate our thesis to all who helped to finish our research successfully and a special dedication to our supervisor **Dr. S.P. Chaminda** who was the main pillar behind our success.

Thank you.

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ABSTRACT

Sri Lanka is considered as a country with little or no water scarcity when considering the whole country as one unit. However, several regions with temporal water scarcities have been identified by past studies in Sri Lanka. Gampaha district which has the second largest population in the country consist of many industrial establishments and residential areas. Attanagalu Oya basin which covers almost entirely the Gampaha district is a major hydrologic feature in determining the seasonal variations of groundwater characteristics in the region.

In this study, the ground water characteristics in the Attanagalu Oya basin was analyzed both quantitatively and qualitatively to identify variations in the pre and post monsoon periods. The qualitative parameters such as pH, conductance, turbidity, calcium, magnesium, nitrate, phosphorous, ferrous, and heavy metal concentrations were analyzed for samples taken throughout the entire basin for the two time periods pre and post monsoons.

The ground water quantity variations were observed through data loggers and field surveys of water wells in the Attanagalu Oya basin. These recorded values were used to model the ground water resources in the region using two numerical models, MODFLOW by USGS and a self-written Fortran code.

The qualitative and quantitative variations were then analyzed spatially and temporally to correlate with the upstream to downstream flow and the monsoonal recharging impacts. The possible reasons for the observed trends and variations were also studied to provide recommendations for the sustainable management of the groundwater resources in the Attanagalu Oya basin.

Key words: Attanagalu Oya basin, Groundwater quality, Groundwater modelling, Seasonal variations, MODFLOW, Fortran

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LIST OF ABBREVIATIONS

Abbreviation	Description
USGS	United States Geological Survey
WRB	Water Resources Board
NWS & DB	National Water Supply and Drainage Board
GWF	Ground Water Flow
Sq.km	Square kilometers
GAB	Great Artesian Basin
RMS	Root Mean Square
3D	Three-dimensional
EBT	Eriochrome Black T
ASTM	American Society for Testing and Materials
UV	Ultra Violet
GUI	Graphical User Interface
DEM	Digital Elevated Map
CRIP	Climate Resilience Improvement Project

ASCII	American Standard Code for Information Interchange
LAT	Latitude
LON	Longitude
WHO	World Health Organization
SLS	Sri Lankan Standard
NTU	Nephlometric turbidity units

CHAPTER 1: INTRODUCTION

Water plays a major role in human's everyday life routine. Getting pure water for drinking is very important. The cleanest water is groundwater rather than surface water. Considering the scarcity of water, if the scarcity of water is high the water resources should be saved carefully, and the quality should be maintained in a better level. Groundwater, which is in an aquifer below the surface of the earth, is one of the nation's most important natural resource. Groundwater is the source of about 37 percent of the water that country and city water departments supply to households and businesses worldwide (public supply). It provides drinking water for more than 90 percent of the rural population who do not get their water delivered to them from a county/city water department or private water company. (UN DESA, 2015). Withdrawals of groundwater are expected to rise as the population increases and available sites for surface reservoirs become more limited.

Sri Lanka has less or no water scarcity. But there are spatial and temporal scarcities in water within the country. Gampaha district has the 2nd largest population in Sri Lanka, categorized from moderate - severe going from 1991 to 2025 according to Falkenmark indicator. (Amarasinghe et. al, 1998)

The Urbanization and the industrialization are causing the scarcity of water in Sri Lanka.

Sri Lanka is rich in groundwater resources. There are many types of aquifers found in Sri Lanka. The recharge and discharge cause the variation in the rate of groundwater levels.

"The seasonal variations involve in the ground water level changes due to the recharge and discharge rates changes depending on the seasonal variations and also the characteristics of the ground water is also changed by the seasonal variations."(IWMI,*2005*)

Sri Lanka is a developing country where, there is no water supply service provided everywhere. So, most of the rural areas are served by the domestic wells for the daily routines. As, there is enough ground water resource in Sri Lanka, if it would be developed quantitatively and qualitatively it should be economically preferable and the rural areas would be developed to use the ground water for industrial applications too by the effective management of groundwater.

In Sri Lanka, groundwater development is moderating small-scale agriculture and improving the living standards of poor farmers in many areas. "Over the last 20 years there is a sharp increase in the number of wells, but groundwater use has so far been completely unregulated. This is a cause for concern. Unless the use of groundwater is managed in a sustainable way, it will have adverse effects on the environment and could destabilize the rural economy as other countries have found, to their cost." (IWMI, 1985)

It would be very useful if a regional scale model is developed to simulate ground water responses to changing rates of recharge and extraction and determine the seasonal variation of ground water characteristics. "Groundwater modelling has been the most commonly used tool for decision making process. Groundwater modelling aids the mitigation and determination of adverse effects beforehand successfully." (Yangxiao Zhou and Wenpeng Li, 2011). While groundwater modelling gives an idea for proper management of water, regular monitoring and testing should be done to analyze the quality of groundwater systems.

To determine the seasonal variations of groundwater characteristics some water quality tests should be done to groundwater samples collected during various seasonal periods. These water quality parameters should be tested and compared with international standards and permissible limits so that even minor variations can be detected.

1.1 Problem Statement

Gampaha district is having the second most population in Sri Lanka and many new industries are coming there recently. Due to the urbanization and industrializations the need of the water is increasing in Gampaha district. Attanagalu Oya is the major river basin flowing covering almost entirely the Gampaha district. At present, there is inadequate data for policy making and ground water management of Attanagalu basin in Gampaha District which is the second most populated district of Sri Lanka, to mitigate seasonal scarcities of ground water is taken into consideration.

1.2 Aims and Objectives

The aim of this research project is to analyze the seasonal variation of ground water characteristics in the Attanagalu Oya basin using numerical models.

This research project has been broken down into several specific, achievable objectives, which include;

- Determine the seasonal variation of ground water quality in the Attanagalu Oya basin.
- Develop a regional scale model to determine the amount of groundwater available in the basin.
- Identify the impact of industrialization moving from upstream to downstream of Attanagalu Oya basin.

1.3 Significance of the Study

The research will provide useful information on;

- Seasonal variation of ground water quality which will help the general public to be ready for seasonal groundwater variations.
- Different regions with varying stress levels of ground water scarcities with seasons.
- Influence due to urbanization and industrialization from upstream to downstream on the variation of ground water characteristics.

CHAPTER 2: LITERATURE REVIEW

The Literatures were studied under the topics of the water resources present in Gampaha district, the water demand of Gampaha district, the factors that cause the demand for water in Gampaha district, the supply of water to fulfill the demand, Ground water availability and characteristics and the factors affecting the groundwater characteristics in Attanugalu Oya basin.

2.1 Water Supply

In Gampaha, only a very small percentage of the population (8.7%) is served by a water supply scheme and the balance obtain their domestic water from shallow wells (Central Environmental Agency, 1996). The aquifers presumably have an abundance of good quality water. However there had been instances of contamination of this water due to untreated affluent discharge from factories as well as the crude oil pipeline springing leaks on its way to the refinery at Sapugaskanda. This has however been attended to by carrying out due repairs to the pipeline. Residents however feel uneasy as it could happen again.

A groundwater survey has been implemented for Gampaha district by the National Water Supply and Drainage Board in the course of the Minuwangoda Town Water supply Project. According to the survey, wells of 60m depth and 15 in. diameter yield a discharge of 270-540 c/min. Although boring logs are not available, these wells appear to be dug in alluvial formation judging from their location. As alluvial deposits are greater in the western half of the district, this area would be expected to offer more extensive groundwater development as the eastern sector. Wells will provide an effective means of water supply given the current state of water service infrastructure in rural area. A groundwater survey merits implementation in this regard.

Table 2.1: Number of tube wells constructed by Water Resources Board (WRB) and National Water Supply & Drainage Board (NWS&DB) in Gampaha district

District	No. of tube wells constructed by WRB	No. of tube wells constructed by NWS & DB	Total tube Wells
1)Ampara	321	716	1037
2)Anuradhapura	329	4693	5022
3)Badulla	114	925	1039
4)Batticaloa	136	9	145
5)Colombo	190	152	342

6)Galle	158	239	397
7)Gampaha	272	618	890
8)Hambantota	989	1494	2483
9)Jaffna	260		260
10)Kegalle	6	163	169
11)Kilinochchi	14		14
12)Kalutara	32	1099	1131
13)Kandy	23	1731	1754
14)Kurunegala	264	3420	3684
15)Mannar	99	34	133
16)Monaragala	371	1961	2332
17)Mullaithivu	44	30	74
18)Matale	51	1509	1560
19)Matara	11	398	409
20)Nuwaraeliya	49	134	183
21)Polonnaruwa	189	1648	1837
22)Puttalam	1563	1705	3268
23)Ratnapura	70	1054	1124
24)Trincomalee	21	248	269
25)Vavuniya	503	498	1001
Total	6079	24478	30557

Source: (Panabokke and Perera 2005)

The Attanagalu Oya has its headwaters in the hilly area of Galapitamada of the neighbouring Kegalle district to the east. The river flows westward, confluxing with the Diyaella Oya in the vicinity of Gampaha Urban Council. At its further lower reaches it joins with the Mapalam and Kimbulapitiya Oyas and at this, point the river name changes to Dandugan Oya.

Table 2.2: Comparison of surface and groundwater supplies in districts

District	Total supply of surface and groundwater resources(10^3m^3/year)	Supply of groundwater resources(10^3m^3/year)	Percentage of total supply from groundwater (%)
1)Ampara	4547	120	2.6
2)Anuradhapura	7652	1199	15.7
3)Badulla	8111	0	0
4)Batticaloa	529	529	100
5)Colombo	205090	0	0
6)Galle	9580	360	3.8
7)Gampaha	18883	1774	9.4
8)Hambantota	9920	373	3.8

9)Jaffna	76	76	100
10)Kegalle	5799	0	0
11)Kalutara	11170	203	1.8
12)Kandy	16088	4830	30
13)Kurunegala	4191	657	15.7
14)Mannar	201	201	100
15)Monaragala	1543	4	0.3
16)Matale	4786	261	5.4
17)Matara	28281	479	1.7
18)Nuwaraeliya	3184	1643	51.6
19)Polonnaruwa	2794	122	4.4
20)Puttalam	3173	3075	96.9
21)Ratnapura	7172	0	0
22)Trincomalee	523	3	0.6
23)Vavuniya	283	283	100
Total	353577	16191	4.6

Source: (WRB and NWS&DB databases, 2004)

The river subsequently meanders northward and southward to finally debouche into Negombo lagoon. The Uruwal Oya flows parallel to the Attanagalu Oya, joining it at one portion, undergoing a name change to Ja Ela and ultimately emptying into Negombo lagoon as well. A river gauge station is located at Karasnagala on the upper reaches of the Attanagalu Oya.

2.2 Water demand

There is a huge demand for water globally due to the population increases and the need of water increases with it. Water demand is the volume of water required by a population in an area for a definite period of a time.

World population increased by 1.3% and the water withdrawal increased by 1.8% per year. The Global water withdrawal increased 1.7 times faster than world population as described in the Figure 2.1.

Global water withdrawal can be divided by the three major sectors,

- Agriculture
- Industries
- Municipalities

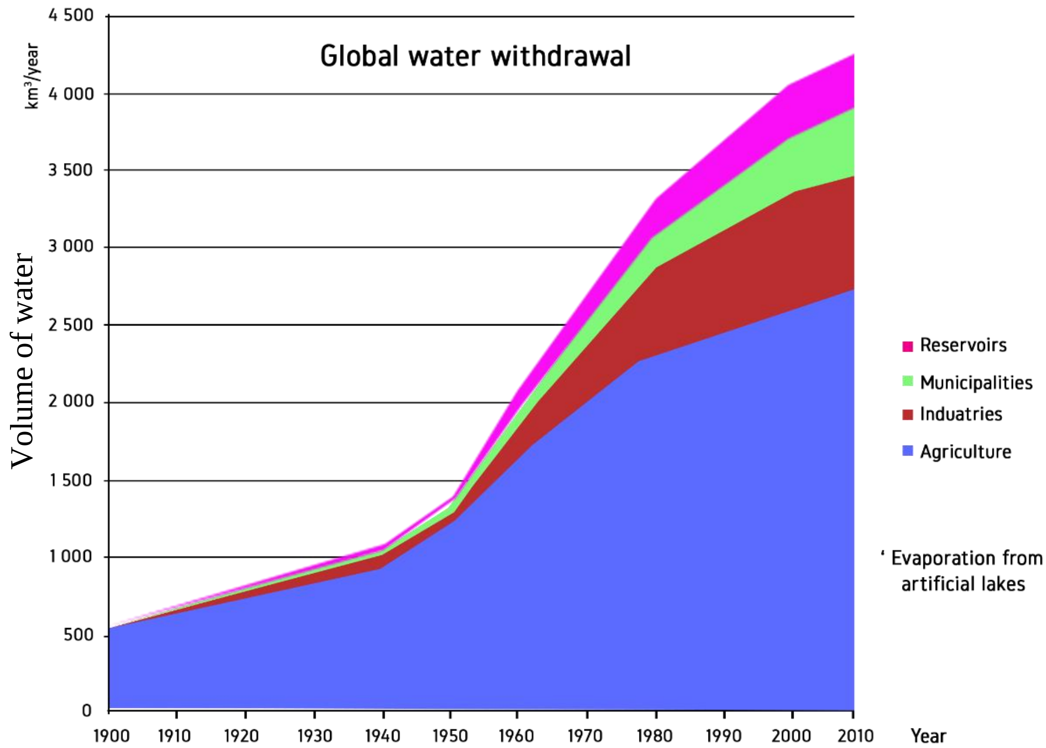


Figure 2.1: The variation of Global water withdrawal for a 110 years period from 1900 to 2010

Source: (Food and Agriculture Organization of the United Nations (FAO))

Attanagalu Oya basin is situated between Ma-Oya basin and Kelani river basin. Its Catchment area is 737 km^2. Mainly, the basin gets water from the rain water and ground water. Water from Attanagalu Oya River is mainly used for domestic, irrigation and industrial purposes. Because of the water demand of Gampaha district is increasing with the population increases and the industrializations, a suitable groundwater management scheme is required to fulfill the need of water.

When considering the population variation of Gampaha district from 1981 to 2012, the population has been increased and the total population of Gampaha district was 2,294,641 in 2012. The domestic water usage has increased with the population (Census of Population & Housing,2013).

The Attanagalu Oya basin has a total area of 200 square miles and its extent is shown in Figure 2.2. The river's source is 40 miles from the sea at an elevation of about 400 feet above sea level. The main river drains directly west and empties into Negombo Lagoon. There is one existing gauging station, station 68, and a synthetic station, station 131, located on the river system in order to define a runoff regime. The entire catchment of Attanagalu Oya is divided into five (5) sub basins in accordance with the terrain and distribution of stream paths. (Jayarathna, 2013).

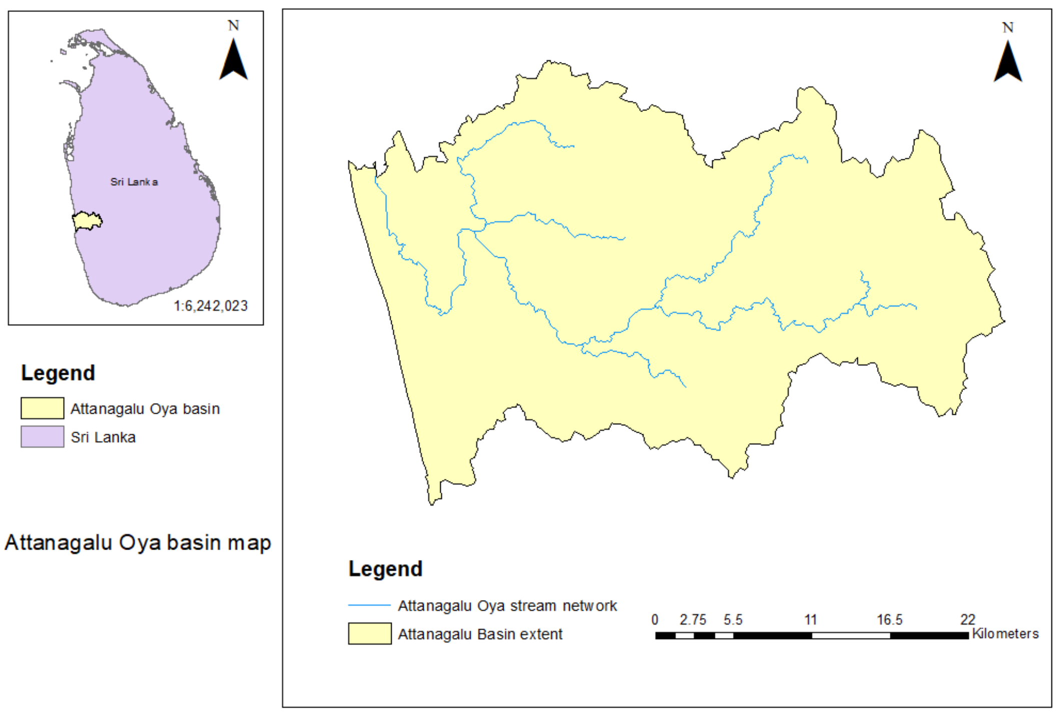


Figure 2.2: Attanagalu Oya basin and stream network

2.2.1 Domestic water usage

Urban population is served around 31000m^3 water per day by Attanagalu Oya basin. There are 7 supply schemes from this basin. When considering the people in Gampaha district, in the urban areas 83% of people use pipe borne water and 17% use ground water (wells) and in the rural areas 8% of people use pipe borne water and 92% use traditional supplies. (National water supply and drainage board, 2004.)

2.2.2 Water usage for irrigation

Water from Attanagalu Oya is widely used for the irrigation. Majority irrigation systems are in lower part of the basin. Those are entirely dedicated for paddy production fed by anicuts. 84.61 MCM of water is extracted annually with 50.77 MCM return to the river. Monthly rate of water usage varies from around 0.2 MCM to 3.5 MCM from September to January, which is the main irrigation season. (Department of Irrigation, 2003).

2.2.3 Industrial usage

Minuwangoda,Ja-Ela, Wattala, Katana and Attanagalla are the main industrial centres in the basin. There are four industrial parks in the basin; Katunayaka, Malwatta, Wathupitiwala and Ekala. About 10. 17 MCM of water is extracted annually for industrial usage while 7.12 MCM is returned to the river. (National water supply and drainage board, 2004)

The Major industries in Attanagalu Oya basin are,

- Apparel
- Food processing
- Steel
- Iron making
- Chemicals
- Plastic and rubber etc.

(Industrial development board, 2008)

2.3 Groundwater

Ground water is a hidden resource where water can be found underground in the cracks and spaces in soil, sand and rock. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers.

Aquifers are the soil or rock layers which have both permeability and porosity. Mainly the water of rivers, lakes and maybe reservoirs are considered as fresh water. Yet even when the huge lakes of North America or mighty rivers like the Amazon and the Ganges are considered, over 97% of the planet's fresh water is to be found under the surface of the earth in the form of groundwater (IWMI, 1985).

Groundwater is widely used as the main source of daily use water in many parts of the world. Water for irrigation and urban use is taken by driving down boreholes into the saturated layer under the ground. At least 1,500 million urban inhabitants are provided with water from groundwater reserves. It is also widely used as a low-cost rural water supply. (International Association of Hydrogeologists, 2008) Ground water is very beneficent as it is inexpensive to develop since it is naturally good quality and extensive existence. During the drought times also, the groundwater is dependable due to the large amounts deposited below the surface. It is also protected against catastrophic events - if natural disasters or war disrupt surface water distribution, then groundwater reserves can easily be developed. Some near surface may not be saturated with water and only have an intermittent supply of water. But, numerous areas deeper below the surface are saturated with water accumulated over hundreds or even thousands of years. These areas often supply permanent springs and can be tapped with boreholes to provide water. When groundwater is drawn from deep aquifer supplies, we are tapping into water locked away under the surface and filtered through layer upon layer of rock. This is one of the reasons why groundwater is so reliable. Groundwater may even be protected against recent surface pollution, providing a high-quality supply where none was previously available. (International Association of Hydrogeologists, 2008)

The rocks and the structures that are formed over a long period of time ago are studied under the topic of geology. Hydrogeology is a branch of geology. Water interaction methods with geological systems are looked under hydrogeology. Water is a dynamic natural resource for people all around the world - whether it is piped to homes or drawn out of wells. It is important to understand where it is and how it moves beneath the ground to protect this resource. Commonly hydrogeology is affected by the following factors such as climate, rainfall (recharge), temperature (evaporation), soil type, types of aquifers present and water resources and the main components of the hydrogeological cycle is shown in Figure 2.3.

Only some parts of the world get frequent rainfall and have plentiful surface water resources. Most of the countries use the water that is stored in the aquifers to fulfill their needs. Hydrogeologists can help by pinpointing suitable reserves and by assessing how much water it is possible to be extracted without enduring damage to underground aquifers or surrounding ecosystems.

Hydrogeologists can also identify when it is at danger from pollution and how we can protect it by careful planning and land-use by looking at the mode that groundwater flows. Hydrogeology plays a major role in predicting what will happen to the water resources or the future effects on the environment of water extraction.

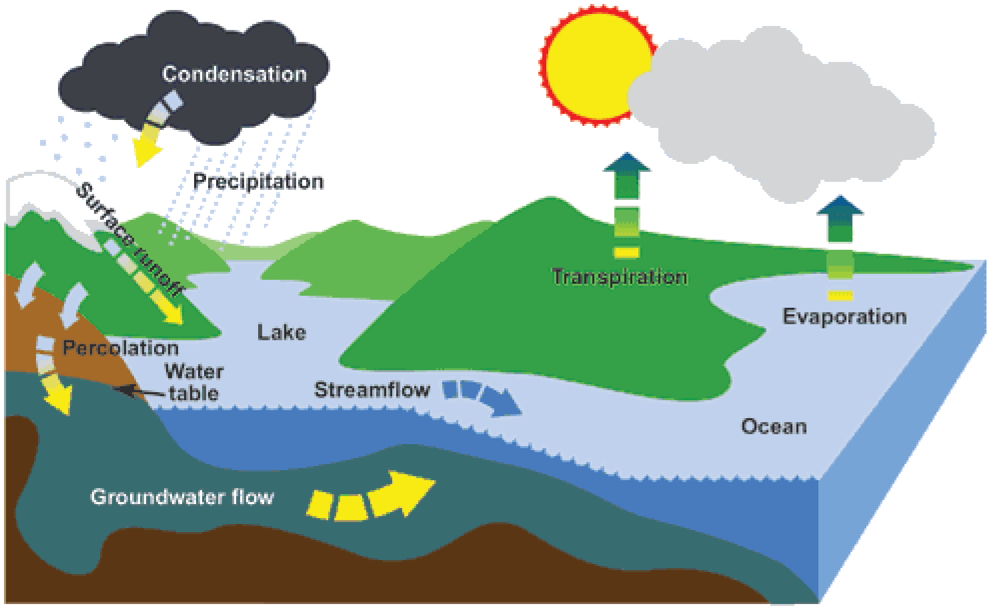


Figure 2.3: Hydrological cycle
Source: (Environment and Climate change Canada)

Key element of a groundwater system like topography, climate, rainfall, temperature, and aquifer systems available relevant to Attanagalu Oya basin will be discussed in the following sub sections.

2.3.1 Topography

Topographically Sri Lanka has,

- A mountainous region in central part rising to about 2,500 m above mean sea level, with the highest elevations covered by virgin forests and grasslands.
- The surrounding plains, which rise to about 50 to 100 m above sea level, are largely used for agriculture and homesteads, but still have virgin scrubland where the population distribution is lower. (Meteorological department, 2000)

Gampaha district:

- Gampaha District is in the North of Colombo and has a land area of 1,399 kilometers.
- Gampaha district is bounded by,

  The South - Kelani River

  North - MahaOya

  East - mountainous Zone of Kegalle

  West- Indian Ocean
- In Gampaha district The Eastern Highland Series, South Western Group and the Northern Vijayan Series are all represented.
- For the agricultural purposes about 70% of the land area of the district is used where coconut, paddy, rubber and few other cash crops are cultivated.
- It shows the need of water in Gampaha district is high and essential.

2.3.2 Climate

Sri Lanka is divided into three different climatic zones based on amount and pattern of rainfall received. (Burt and Weerasinghe, 2014). In general, rainfall in the island mainly occurs during the southwest and northeast monsoons and during the inter-monsoons. Gampaha District falls within the wet zone with an annual rainfall of 2000 - 2600 milliliters occurring during two monsoonal periods April-June and October- December. The temperature ranges from 23 - 31 degrees c and the mean. Relative humidity is, on the average, 73% during the day and 90% at night. Attanagalu Oya flows through the Gampaha District and is the main source of water for irrigated lands.

Table 2.3: Water gauge statistics of Attanagalu Oya basin, Dunamale station

Basin	Station Name	Catchment Area (km^2)	Alert Level (m)	Minor Flood Level (m)	Major Flood Level (m)	Recorded Highest Water Level (m)	Condition
Attana galu Oya	Dunamale	153	3.3	4.4	5.5	5.93	Normal

Source: (Gampaha District Water Resources Management and Sustainable Development Program Technical, 2017)

2.3.3 Rainfall

Groundwater is recharged naturally by rainfall (C.P. Kumar, 2014). In a year, the average rainfall in Gampaha is 2398 mm. Gampaha district is situated in the wet zone, both monsoons provide almost equal amounts of precipitation and its proportions are shown in Figure 2.4. (Prof.N.T.Sohan Vijesekara, Flood Mitigation and drainage study, 2011)

- Southwest-Monsoon Season (May – September)
- Northeast-Monsoon Season (December – February)

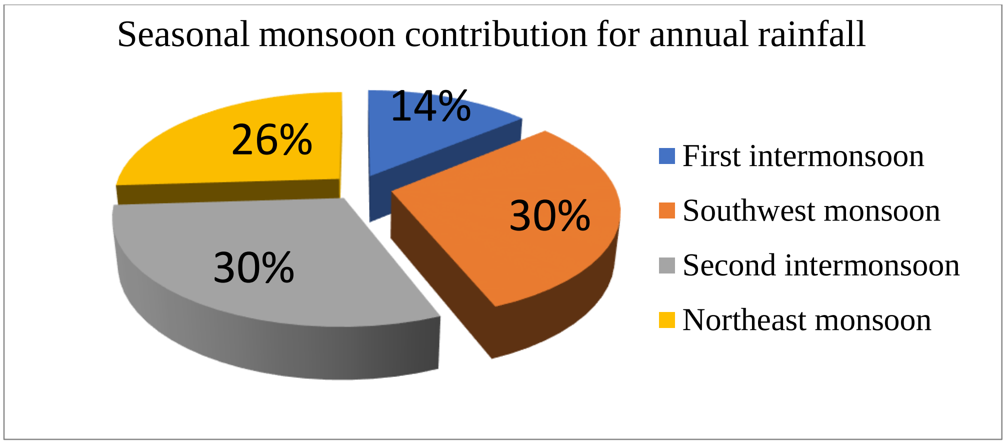


Figure 2.4: Seasonal monsoon contribution for annual rainfall in Gampaha district
Source: (Meteorological Department, Sri Lanka)

The annual average of rainfall over Sri Lanka has been decreased by an amount of 144 millimeters, about seven percent, during 1961 to 1990 period compared to 1931 to 1960 period and this variation is shown in the Figure 2.5 (Chandrapala, 1997)

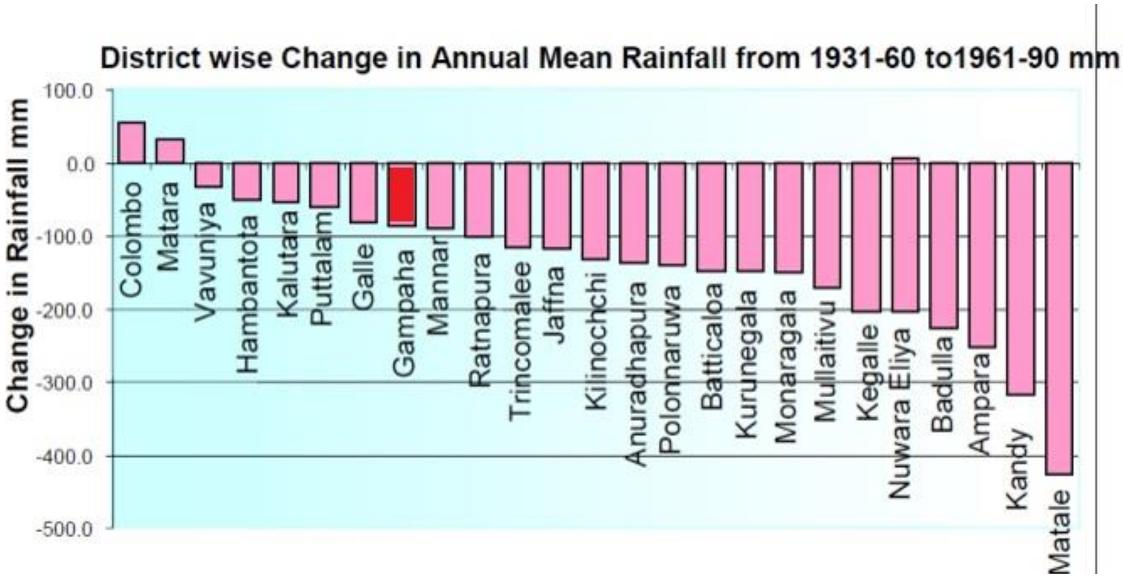


Figure 2.5: Change of rainfall contours 1931-1960 and 1961-1990
(Source: SLNWDR (2006))

2.3.4 Temperature

The average temperature of Sri Lanka usually ranges from 28 – 32 degrees Celsius which may differ due to global weather conditions. Average daily sunshine of Sri Lanka is 7.2 hours/day. April is warmest month in Gampaha, with an average temperature of 28.4 °C (83.1 °F) and December is the coldest month, with temperatures averaging 26.1 °C (79 °F). Throughout the year, temperatures vary by 2.3 °C. The average temperature in Gampaha is about 27.3 °C. (Burt and Weerasinghe, 2014)

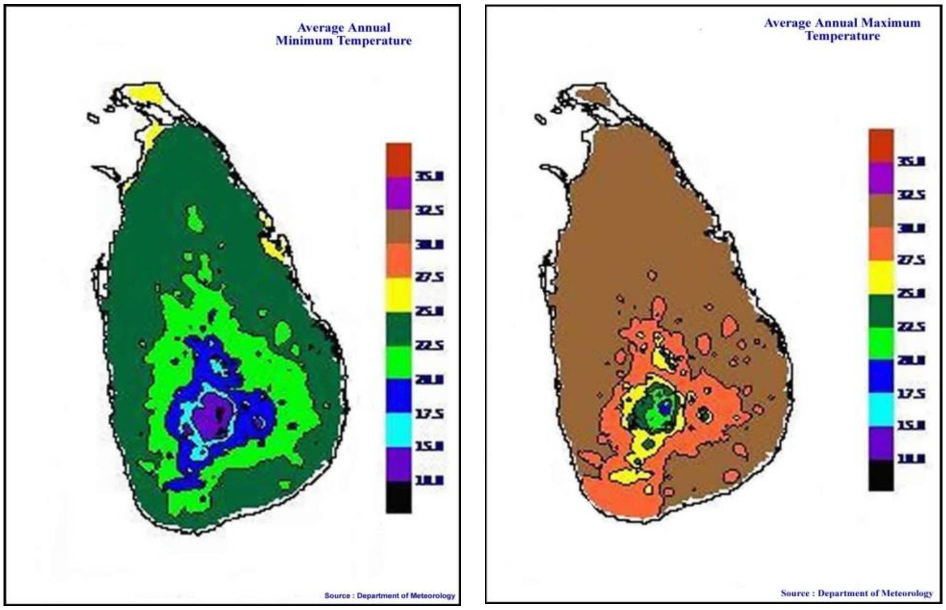


Figure 2.6: Average annual maximum and minimum rainfall in Sri Lanka

Source: (Meteorological Department, Sri Lanka)

2.3.5 Soil

Five major soil types are identified in, the district, these being, Regosols, Latosols, Red-Yellow Podzolic Soils, Bog and Half-Bog Soils and Alluvial Soils. The Red-Yellow Podzolic Soils form the major group, with Regosols and Latosols found on the coastal areas and Bog and Half-Bog Soil is adjacent to the Muthurajawela swamp. Alluvial Soils are present along the rivers and streams of the district.

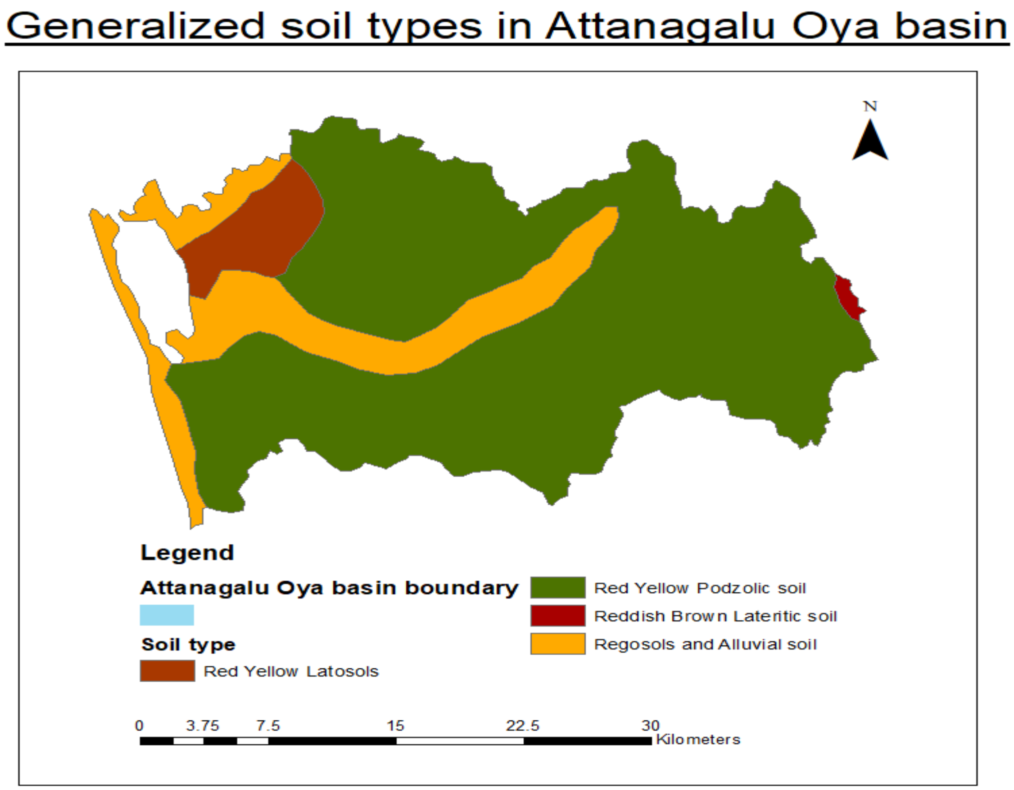


Figure 2.7: Generalized map of different soil types available in the Attanagalu Oya basin

Source: (Panabokke and Perera, 2007)

The soil types can be identified as the Regosols (very weakly developed mineral soil in unconsolidated materials), Latosols (soils found under tropical rainforests with a relatively high content of iron and aluminium oxides),Red-Yellow Podzolic soil (any of a group of acidic, zonal solids having a leached, light colored surface layer and a subsoil containing clay and oxides of aluminium and iron, varying in colour from red to yellowish red to a bright yellowish brown.),Bog and Half-Bog Soils (a bog is a wetland that accumulates peat, halfbog-having mucky or peaty surface soil underlain by gray mineral soil) and Alluvial Soils (a fine-grained fertile soil deposited by water flowing over flood plains or in river beds) (Panabokke and Perera, 2007)

2.3.6 Aquifer Types in the Attanagalu Basin

The major aquifer types identified in the Attanagalu Oya basin according to the past studies are: lateritic, alluvial, coastal sand and fractured crystalline basement aquifers and they are given in the Table 2.3.

Table 2.4: Aquifer types and occurrence in Attanagalu Oya basin

Aquifer type	Occurrence and description
Shallow unconfined karstic aquifers	Occur in the channels and cavities (karsts) of the Miocene limestone formation
Deep confined sandstone and Miocene limestone aquifers	Occur within sedimentary limestone and sandstone formations
Shallow Quaternary unconfined coastal sand aquifers	Consist of different types, i.e. raised beaches, coastal spits, and bars. Occurs along long, but narrow stretches of the sand aquifers coastal line
Alluvial aquifers of variable depth	Occur in coastal and inland flood plains, inland river valley sand old buried riverbeds
Shallow regolith aquifers of the hard rock region	Groundwater in these formations is found as separate pockets formed in the shallow weathered mantel rock (regolith) or in deeper fracture zones of the un weathered material.
Confined or semi-confined lateritic (cabook) aquifers	Occurs in the south-western low-lying parts of the country.

2.4 Groundwater modelling concept

Models are basically used to predict the response of a system when factors influencing their dynamics (variables) change over time. In the case of groundwater modelling, many possible variables of nature can be included so as to influence the final system. However, due to practical impossibility of accounting for each and every aspect of nature that influence the groundwater conditions, many assumptions and simplifications are established at the start of the modelling process (Mclean and Bledsoe, 1992).

Groundwater modelling has been identified by many scientists to be a major tool in groundwater management. It is a simple and cheap solution compared to establishing projects and achieving information in reality. Since groundwater models can simulate response under different conditions, information gained through varying model runs can help decision makers justify their decisions about future (Franklın and Zhang, 2003). The International Ground Water Modelling Center defines a model as a non-unique, simplified, mathematical description of an existing groundwater system, coded in a programming language. The generation of computer-based groundwater modelling began in the mid 1960's and has been evolving for many years due to their vast applications. With the improvement of computers and their processing power, running groundwater models has become a priority in any hydrogeological assessment (Heijde and Elnawawy, 1993).

The world-famous statistician George Box has once said "All models are wrong, but some are useful". The objective of any model is to bring the complex real-world scenario to a simplified form without compromising the accuracy and making invalid assumptions. The assumptions made depending on the objectives of the model will result in unique model structures according to their own set of simplifications which makes no two models in the world identical nor equal to the real world scenario. (Barnett et al, 2012).

2.4.1 Physical models

Physical models are the most primitive type of modeling approach that gave birth to the science of modeling. They depend on physically constructed laboratory models to study specific problems of groundwater flow or contamination for a specific scenario. These models are highly case specific and therefore the adjustment of parameters to simulate varying scenarios is difficult. Although they are relatively easy to set-up, physical models cannot handle complicated real-world problems.

2.4.2 Analogue models

Analogue models use the behavior of a physical parameter like heat flow and electricity to interpret the movement of groundwater. The electric analogue is the most commonly used analogue for groundwater and it uses the similarity between Ohm's law of current flow and Darcy's law on groundwater movement (Leenhouts, 2013).

2.4.3 Mathematical models

Mathematical models are based on the conceptualization of the groundwater system into a set of equations. These equations are formulated based on boundary conditions, initial conditions, and physical properties of the aquifer. Unlike physical models and analogue models, mathematical models allow the manipulation of the groundwater systems more rapidly and easily (McCranie et al., 2011).

2.5 Groundwater modeling process

Groundwater modeling process involves the following steps as shown in Figure 2.8

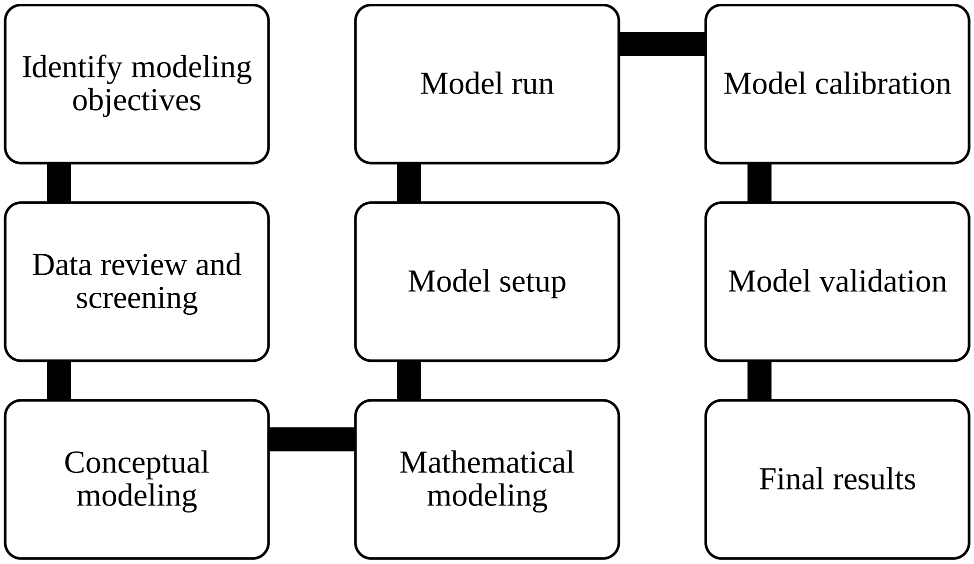


Figure 2.8: Modelling steps
Source: (Mclean and Bledsoe, 1992)

2.5.1 Conceptual modeling

The modelling approach starts with these simplifications and set of assumptions established prior to the model setup. However, the modelling objectives should be always in the mind while arriving at possible assumptions and simplifications. The collection of these initial assumptions and simplifications will constitute the conceptual model (Zhou and Li, 2011). It also includes a descriptive interpretation of the groundwater system along with geological and hydrological conditions. Conceptual model can be considered as the foundation on top of which the model will be built upon. The following list of key details either measured or assumed should be included in a conceptual model of groundwater (Franklın and Zhang, 2003).

- Model region and its domain
- Boundary conditions
- Aquifer properties
- Groundwater recharge
- Water balance

2.5.2 Mathematical modeling

Once the conceptual model is established, the elements of the conceptual model should be transformed into a mathematical format according to their inter relationships so that they can be solved either analytically or numerically. In this step, several fluid flow equations and laws are used to interpret the groundwater conditions conceptualized in the conceptual model. A mathematical model should include a minimum of 4 basic governing equations as mentioned below (Mclean and Bledsoe, 1992).

1. An equation that expresses the balance of the considered extensive quantity.
2. An equation that define the behavior of the solids and fluids involved.
3. An equation that expresses initial conditions that describe the known system at some initial time.
4. An equation that defines boundary conditions that describes the interaction of the considered domain with its environment.

The governing equation for groundwater flow is derived by combining the mass balance equation and Darcy's law (Kumar, 2014).

$q = -K\ grad\ h$

$q_x = -K_x \frac{\partial h}{\partial x}$

$q_y = -K_y \frac{\partial h}{\partial y}$

$q_z = -K_z \frac{\partial h}{\partial z}$

h = head

K = hydraulic conductivity

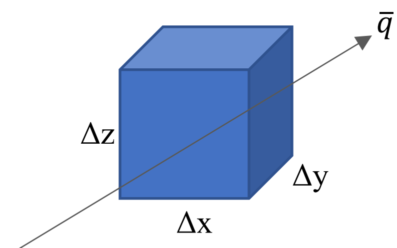


Figure 2.9: Representative elementary volume for groundwater flow medium

Transient water balance equation

Inflow = Outflow +/- Change in storage

$s = \Delta V / A \Delta h$

S = storativity

$s = s_s \Delta z$

S_s = specific storage

$$Out - In = \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} - W\right) = -s_s \frac{\partial h}{\partial t}$$

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) = s_s \frac{\partial h}{\partial t} - W$$

$$div\ q = -s_s \frac{\partial h}{\partial t} + W$$

$$div\ (K\ grad\ h) = s_s \frac{\partial h}{\partial t} - W$$

2.5.3 Types of solution for the mathematical model

1. Analytical solutions

   Analytical solutions can be only used for simplified groundwater models since they use several assumptions and estimations that do not exist in reality. They assume that an aquifer is isotropic and homogeneous which is not the case in reality. Therefore use of analytical solutions to solve the mathematical model of a complex groundwater problem will perform less effectively (Franklın and Zhang, 2003).

   Ex: Theis equation

2. Numerical solutions

   In the solution of a differential equation by a numerical method, the equation is put into an equivalent weighted-integral form and then the approximate solution over the domain is assumed to be a linear combination of appropriately chosen approximation functions and undetermined coefficients. The most commonly used numerical solutions for groundwater modelling are finite element method and finite difference method (J.N. Reddy, 1988).

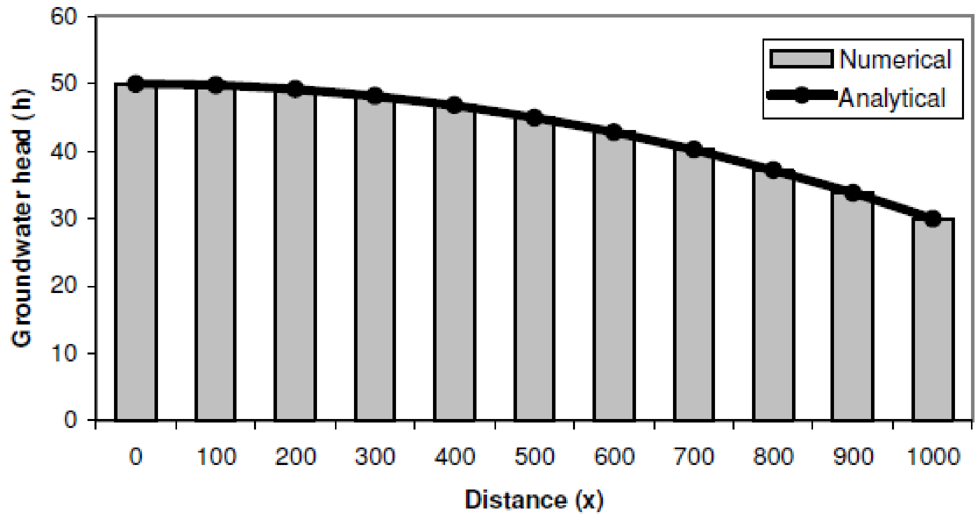


Figure 2.10: Difference between the analytical solution and the numerical solution
Source: (An introduction to the finite element method by J.N.Reddy)

2.5.4 Model calibration

After the initial run of any model, the possibility of results to vary from the field measurements is very high. This is due to the fact that the modeling process is a mere simplification of reality and therefore the room for approximations and computational errors is unavoidable. Model calibration serves as a fine tuning procedure to match the model results with the field measurements. The calibration process in many groundwater models is carried out by forcing the resulting groundwater heads to match the head at measured points. By doing so, other parameters like hydraulic conductivity and recharge will be adjusted. In general, calibrations involves an optimization process to minimize the root mean square error of the residual given below (Franklın and Zhang, 2003).

Equation 1: Root mean squared error for observed and simulated values

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (h_{ob} - h_{sim})^2 \right]^{1/2}$$

h_{ob} = Observed head

h_{sim} = Model simulated head

2.5.5 Model validation

The next step in modeling process after model calibration is the model validation step. The objective of model validation is to check if the calibrated model works well on any given set of input data. Since calibration involves changing different parameter like hydraulic conductivity, recharge, pumping rates etc. there may be several combinations of parameter values that give the same solution. This means a good calibration does not necessarily imply a good prediction. Therefore, model validation process is conducted to test the model's stability and precision with different data sets. Usual procedure in model validation is to use half of the field measured data for model calibration and to use the rest for model validation (McCreery, 2000).

2.6 MODFLOW by United States Geological Survey (USGS)

The most popular groundwater modelling software among hydro geologists, MODFLOW was first developed in 1983. It was created as a result of the necessity to consolidate all the commonly used simulation capabilities which were available at that time into a single code. The code was originally called Modular Three-Dimensional Finite Difference Ground Water Flow Model and later it became commonly known as MODFLOW. MODFLOW was developed using Fortran 66 computer language. Within a period of a decade, MODFLOW became the most widely used groundwater flow model worldwide. Initially, the developers of MODFLOW focused on the code to be solely a groundwater flow model. However by the late 1990s, due to the broadened application of MODFLOW, it was decided to expand the capabilities of MODFLOW to allow the code perform tasks such as solute transport and parameter estimation (Harbaugh, 2006). The evolution of the MODFLOW code from the start is given below in Figure 2.11

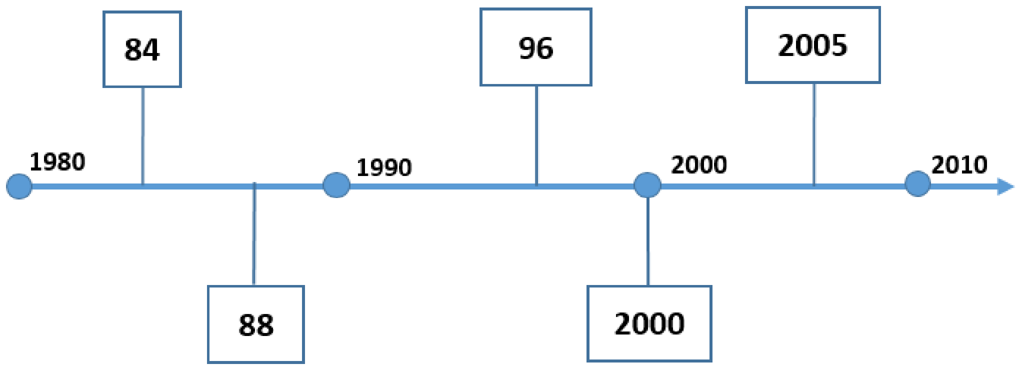


Figure 2.11: MODFLOW releases from 1980 to 2010
Source: (USGS publications)

The latest stable version of the code which is MODFLOW 2005 is written in Fortran 90 language. As in all the other previous version of MODFLOW, MODFLOW 2005 has no graphical user interface. This makes it challenging for users with less programming knowledge to manipulate and setup the model as necessary. However, several third-party developments both open source and commercial software for visualizing MODFLOW 2005 are readily available in the market. This software gives the user the freedom to incorporate GIS data files from other popular software like ArcMap into the model setup.

In the model architecture, The Groundwater Flow (GWF) process is broken down into several pieces called procedures. Each of these procedures are invoked in an order to solve the groundwater flow equation. The period of simulation is divided into stress periods where stress data are constant. Each stress period is further divided into time steps. A system of finite difference equations is formulated and solved to obtain the head at each node at the end of each time step. The whole program is divided into several packages. Various parts of the code that deals with defining the groundwater flow equation are called hydrologic packages. The two main types of hydrologic packages are internal flow package and stress package.

The internal flow package simulates the flow between adjacent cells while the stress package simulates individual types of stresses like rivers, wells and recharge.(Harbaugh, 2006) MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. It is the most widely groundwater modelling software all around the world. Many case studies have been conducted in USA, China, India, etc. using MODFLOW.

2.7 Applications of MODFLOW for groundwater modeling

2.7.1 Death Valley, California, USA

The Death Valley region of southeastern California has an approximate land cover of 100 000 sq. km. Groundwater flow in the Death Valley region is composed of several interconnected, complex groundwater flow systems. Most groundwater recharge results from the infiltration of precipitation and run off on the high mountain ranges. The underground nuclear test and disposal of nuclear wastes in the Death Valley region resulted in numerous intensive groundwater studies from 1982 to the present. In 1998, the Department of Energy requested the USGS to develop an improved groundwater flow model of the Death Valley region. The purpose of this modeling was;

a) Understand the groundwater flow paths and travel times associated with potential migration of radioactive materials from nuclear test sites.
b) Characterize the groundwater system in the vicinity of the proposed nuclear waste disposal site in Yucca Mountain.
c) Address various effects on users down gradient from the two sites.

A transient groundwater flow model was constructed using MODFLOW-2000. The finite difference model consisted of 194 rows and 160 columns and 16 layers. A 3D digital hydrogeological framework model was created which defined physical geometries and materials of hydrogeological units. The final calibrated model was evaluated by comparing measured and computed groundwater heads and discharges. Good fit to observed groundwater heads occurs in areas of flat hydraulic gradients. Poor fit to the observed groundwater heads is visible in areas with steep hydraulic gradient (Zhou and Li, 2011).

2.7.2 Great Artesian Basin (GAB), Australia

The Great Artesian Basin is a confined groundwater basin that extends upto 1.7 million sq. km. The basin is comprised of a multi-layer system of five major confined aquifers separated by aquitards. These aquifers are largely continuous across the extent of the Basin and extend down to 3000 m below land surface in the central depressions. Groundwater resources are increasingly exploited for drinking water supply, agricultural irrigation, and water supply for oil, gas and mining developments in the region.

MODFLOW-88 was used to construct the groundwater flow model of the GAB. The basin was discretized with a uniform grid 369 columns. There are more than 60,000 active cells, covering size of 5 km * 5 km, resulting in a model grid of 359 rows and a model area of 1.54 million sq. km. The total recharge from rainfall in the model is then 1,937,394 m3/day. The recharge was simulated with the MODFLOW recharge package.

The model was calibrated with a trial-and-error method to reduce the difference between the modeled and measured groundwater head surface. During model calibration, hydraulic conductivities of the modeled aquifer and recharge from precipitation were adjusted. The Root Mean Square (RMS) error was used to measure the accuracy of the model calibration. The RMS error of the final model is 4.5 m with individual values ranging from -13.1 to +12.8 m. The model was used to evaluate the effectiveness of the GAB Sustainability Initiative with the aim to restore the pressure heads under different management scenarios (Zhou and Li, 2011).

2.8 Advantages of using MODFLOW for groundwater modeling

- Numerous facilities for data preparation.
- Modular structure allows the modification of the code for different applications.
- Relative ease in exchange of data in standard form.
- Extended worldwide users and continuous development.
- MODFLOW can be applied as a one dimensional, two-dimensional, or full three-dimensional model.

(Moeeni and Ahsan, 2017)

CHAPTER 3: METHODOLOGY

3.1 Seasonal variations of groundwater quality

Ground water samples collected from the study area in the pre-monsoon and post monsoon periods of year 2018 were tested for analyzing the following parameters and their concentrations in ground water samples.

3.1.1 Selection of sampling locations

The sampling locations were selected so that a representative measurement can be arrived for the whole Attanagalu Oya basin as shown in the Figure 3.1. In this process, two sampling locations on either side of main stream flows were obtained as given in the diagram below. Special consideration was given to collect samples from locations to depict the upstream – downstream transition.

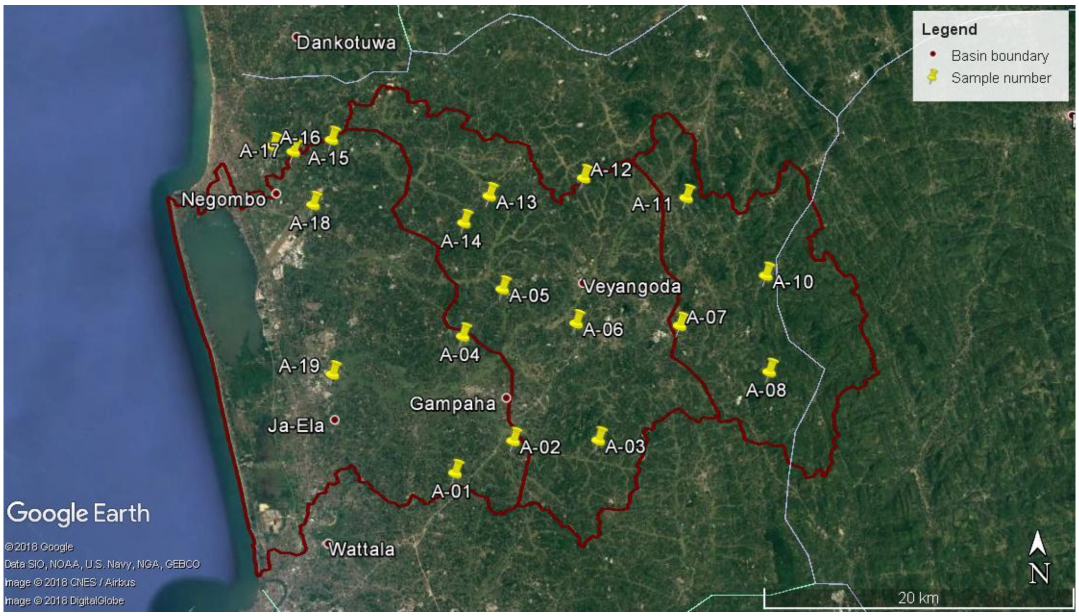


Figure 3.1: Sampling locations for the field surveys 1 and 2

3.1.2 Data obtained at each location of the survey

- Water sample from a well (one liter).
- Depth to the water level from the ground level.
- GPS coordinates of the location.
- Estimate of water extracted from the well per day.

Two field surveys were carried out in the pre and post monsoon periods of 2018. Same locations were sampled and tested in both surveys for water quality parameters.

Field survey 1 – 29th of June (South West monsoon)

Field survey 2 – 18th of October (Second inter monsoon)

3.1.3 Spatial distribution of pH

Instrument used: pH meter (Advanced method- A digital pH meter can be used to obtain the most accurate reading of the pH level.)

Model name: HACH Portable pH meter and Sension2 electrode, ranging 0-14 pH units, electrode type is pH combination with temperature probe

The samples were taken in the small beakers washed well with the distilled water and the pH meter tip was washed with distilled water and then with the sample. Washed pH meter was put into the sample in the beaker and allowed to stabilize and the pH reading was taken.

The accuracy of the reading is obtained by the electrode's proper response when the calibration slope is 58±3 mV per pH unit.

The precision of the pH readings was ensured by measuring the pH of sample several times and calculate the average pH.

3.1.4 Turbidity

Instrument used- Nephelometer or turbidimeter {Loviband TB 300IR (machine model) which measures the intensity of light scattered at 90 degrees as a beam of light passes through a water sample. 3 turbidity readings were taken from the machine for each sample and the average was taken.

Measurement ranging 0.01-1100 NTU

Sample was taken into the sample containers of the machine and placed in the machine and then the readings were taken from the machine itself.

Turbidity is measured in NTU

3.1.5 Conductivity

The electrical conductivity in a solution is measured by an electrical conductivity meter (EC meter)

Model: HACH HQ 14d

Measuring range:0.01-200 μS/cm

It is commonly used in hydroponics, aquaculture and freshwater systems to monitor the amount of nutrients, salts or impurities in the water.

The conductivity meter was used to measure the conductivity. The meter was directly input into the sample taken in the washed beakers after the tip was well washed with distilled water and the sample itself and allowed to the stabilization. There after the readings were taken from the meter itself.

The accuracy was confirmed by eliminating the air bubbles in the probe tip before getting to read and to get a faster stabilization. Multiple readings were got, and the average was calculated to get a precise reading.

Conductivity is measured in the μS/cm unit.

3.1.6 Fluoride and Nitrate

Both Fluoride and Nitrate concentrations are from the HQ40d Multi (ISENo 3181/ ISEF121) model meter. Both Nitrate and Fluoride electrodes are connected to the meter. Fluoride reading ranging 0.01mg/L to 19000 mg/L and the Nitrate reading ranging from 0.1mg/L to 14000 mg/L. Both Fluoride and Nitrate tips were well washed with distilled water and then with the sample and then put into the sample and left to stabilize. Both Fluoride and Nitrate readings were taken at once from the meter itself.

To get a fast stabilization and accurate result, if the air bubbles present under the probe tip when submerged were removed by gently shaking the probe until the bubbles are removed.

3.1.7 Calcium and Magnesium

For the Calcium and magnesium, the same titration was done using the reagents EDTA, KOH and EBT and Pattern and Reader indicators.

Titration method-Complexometric Titration

Standard: ASTM D511-14

Color changes observed is shown in Figure 3.2:

- Titration with EBT indicator to the identification of the reaction of both Magnesium and Calcium ions.
- Titration with Pattern and Reader indicator for the identification of Calcium ions.

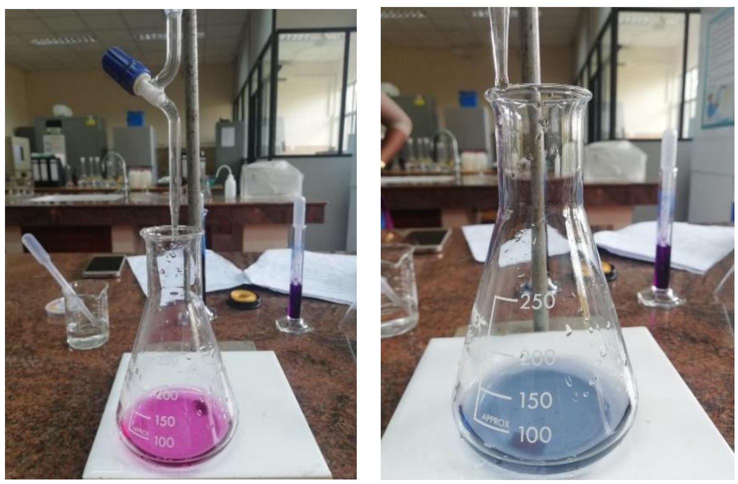


Figure 3.2: Color changes observed during the Calcium and Magnesium test

3.1.8 Phosphorous

Instrument used - UV spectrophotometer, Model- HACH, DR2700, Operating mode is from transmittance. Absorbance and concentration. Source lamp used in the instrument is Gas-filled Tungsten lamp, Wavelength range of the instrument is 400-900 nm.

The wavelength accuracy is ±1.5nm.

The spectrophotometric method was used, and the absorbance readings were got for each sample and the standard graph (Absorbance vs Concentration) was plotted and the concentration of Phosphorus in each sample was found.

The accuracy of the concentration reading was determined considering the representing absorbances.

0.5% of absorbance accuracy at 0.0-0.5 Absorbance.

1.0% of absorbance accuracy at 0.5-2.0 Absorbance

3.1.9 Heavy minerals

Atomic Absorption Spectrometry method (ASTM D1687 Standard method) was used to determine the Heavy mineral concentrations.

Instrument used: Atomic Absorption Spectrophotometer

The representing samples from entire Gampaha district were tested for Cr and Pb concentrations.

Reference: Standard methods for the examination of water and wastewater APHA, AWWA & WEF 22nd Edition 2012

3.1.10 Total iron content

Instrument used - UV spectrophotometer, Model- HACH, DR2700, Operating mode is from transmittance. Absorbance and concentration. Source lamp used in the instrument is Gas-filled Tungsten lamp, Wavelength range of the instrument is 400-900 nm.

The wavelength accuracy is ±1.5nm.

The spectrophotometric method was used, and the absorbance readings were got for each sample and the standard graph (Absorbance vs Concentration) was plotted and the concentration of Iron in each sample was found.

The accuracy of the concentration reading was determined considering the representing absorbance.

0.5% of absorbance accuracy at 0.0-0.5 Absorbance.

1.0% of absorbance accuracy at 0.5-2.0 Absorbance.

3.2 Seasonal variation of groundwater quantity

3.2.1 Self written Fortran code for run off modeling

Unlike in the case of Visual MODFLOW which has a GUI, the self-written Fortran code runs in a command prompt and has no GUI. The model can read only text file inputs and therefore all the required variables were created as text files using ArcMap and Envi software.

3.2.1.1 Preparation of input files

a. Elevation data input

2m resolution Lidar DEM of Attanagalu Oya Basin was obtained from the Climate Resilience Improvement Project (CRIP). This data was highly accurate but the processing power of the computers available could not handle high resolution data which would result in larger amount of grids. Therefore the data was resampled up to 75m size cells. The resulting grid covering the entire Attanagalu Oya basin consisted of 421 rows and 614 columns.

b. Model region (Catchment)

The model region was created in the format of 1 and 0 to allow the model only to compute values for the land regions. The region was extracted using the DEM file by using the reclassifying tool in ArcMap to mask out the external regions beyond the model domain. The same grid specs of 421 rows and 614 columns were maintained.

c. Stream network

A binary file with 1 for the stream and 0 for other regions were created using ArcMap. The stream lines were generated using the high-resolution DEM with Hydrology tools in ArcMap. Once the flow accumulation was obtained using the Hydrology tool, the range of pixel values for the stream network was identified. This pixel value range was then reclassified in ArcMap to give 1 to the stream and 0 to the other. The same grid specs were maintained.

d. Latitude of each cell

The latitude of each cell is required for the calculation of the evapotranspiration. Therefore the latitude of each cell was prepared for the whole grid using excel. A constant value for the change in latitude corresponding to a change in 75m was added proceeding from the first row.

e. Daily rainfall and temperature code

This code was written in Fortran language and used to create an intermediate file format from the observed meteorological data in excel files. This code will extract daily rainfall from each station and write separate files with unique identity. The same code can be used to extract minimum and maximum temperatures of each station form excel files.

```
! Write value to file in different month

        DO IMONTH=8,12
            WRITE(MUP,202)IMONTH
 202        FORMAT(I2.2)


        IF(IMONTH.EQ.8)THEN

                 OPEN(21,FILE=STA//'rain2016'//MUP//'.TXT')

                    DO J=1,31
                        WRITE(21,100)(HR(STID,J))
                    ENDDO
                    ENDIF
                    CLOSE(21)
        IF(IMONTH.EQ.9)THEN

                 OPEN(22,FILE=STA//'rain2016'//MUP//'.TXT')

                    DO J=32,61
                        WRITE(22,100)(HR(STID,J))
                    ENDDO
                    ENDIF
                    CLOSE(22)
```

Figure 3.3: Code snippet for preparing rainfall files for each month for different stations

	A	B	C	D	E	F	G	H
1	Station_ID	Station_Name	Element_Cod	Element_Nan	Year	Month	Day	obs_val(mm)
2	01KE0064	CHESTERFORD	5	PRECIP	2015	1	1	0
3	01KE0064	CHESTERFORD	5	PRECIP	2015	1	2	0
4	01KE0064	CHESTERFORD	5	PRECIP	2015	1	3	0
5	01KE0064	CHESTERFORD	5	PRECIP	2015	1	4	0
6	01KE0064	CHESTERFORD	5	PRECIP	2015	1	5	0
7	01KE0064	CHESTERFORD	5	PRECIP	2015	1	6	0
8	01KE0064	CHESTERFORD	5	PRECIP	2015	1	7	0
9	01KE0064	CHESTERFORD	5	PRECIP	2015	1	8	0
10	01KE0064	CHESTERFORD	5	PRECIP	2015	1	9	0
11	01KE0064	CHESTERFORD	5	PRECIP	2015	1	10	0
12	01KE0064	CHESTERFORD	5	PRECIP	2015	1	11	0
13	01KE0064	CHESTERFORD	5	PRECIP	2015	1	12	0
14	01KE0064	CHESTERFORD	5	PRECIP	2015	1	13	0
15	01KE0064	CHESTERFORD	5	PRECIP	2015	1	14	0
16	01KE0064	CHESTERFORD	5	PRECIP	2015	1	15	0
17	01KE0064	CHESTERFORD	5	PRECIP	2015	1	16	0
18	01KE0064	CHESTERFORD	5	PRECIP	2015	1	17	0
19	01KE0064	CHESTERFORD	5	PRECIP	2015	1	18	0
20	01KE0064	CHESTERFORD	5	PRECIP	2015	1	19	0
21	01KE0064	CHESTERFORD	5	PRECIP	2015	1	20	0
22	01KE0064	CHESTERFORD	5	PRECIP	2015	1	21	0
23	01KE0064	CHESTERFORD	5	PRECIP	2015	1	22	0
24	01KE0064	CHESTERFORD	5	PRECIP	2015	1	23	17.7
25	01KE0064	CHESTERFORD	5	PRECIP	2015	1	24	0
26	01KE0064	CHESTERFORD	5	PRECIP	2015	1	25	0
27	01KE0064	CHESTERFORD	5	PRECIP	2015	1	26	0
28	01KE0064	CHESTERFORD	5	PRECIP	2015	1	27	0
29	01KE0064	CHESTERFORD	5	PRECIP	2015	1	28	22.2
30	01KE0064	CHESTERFORD	5	PRECIP	2015	1	29	29.7
31	01KE0064	CHESTERFORD	5	PRECIP	2015	1	30	0
32	01KE0064	CHESTERFORD	5	PRECIP	2015	1	31	0

Arain201501 - Notepad

File Edit Format View Help

```
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
 0.00000
17.70000
 0.00000
 0.00000
 0.00000
 0.00000
22.20000
29.70000
 0.00000
 0.00000
```

Figure 3.4: Rainfall of one station in excel and its output

f. Binary map making code

This code was written in Fortran language and used to create binary maps for recharge and evapotranspiration for each cell in the model domain. This code uses the following data to calculate the precipitation and evapotranspiration for each cell in the model domain.

a. Elevation data

b. Model region (catchment)

c. Latitude file

In this code, once the rainfall stations and temperature stations are set, values from these readings will be read and used to interpolate for the whole model grid. The resulting output will be binary files for each day for evapotranspiration value and rain. Inverse distance method is used for the interpolation of values for all the cells in the grid. The following equation was used for the calculation of the evapotranspiration for each cell. (Hargreaves et al, 1985)

$$ET_O = 0.0023\left(T_m + 17.8\right)\left(\sqrt{T_{\max} - T_{\min}}\right)R_a$$

- T_m is daily mean air temperature [°C]
- T_{max} is daily maximum air temperature [°C]
- T_{min} is daily minimum air temperature [°C]
- R_a is extraterrestrial radiation [MJ m^{-2} day^{-1}].
- R_a is computed from information on the location of the site and time of the year.

Extraterrestrial Radiation for Daily Periods (Ra)

The extraterrestrial radiation, Ra, for each day of the year and for different latitudes is estimated from the solar constant, the solar declination and the time of the year by:

$$Ra = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(\omega_s)\right]$$

Where;

Ra = extraterrestrial radiation (MJ m−2 day−1)

G_{sc} = solar constant = 0.0820 MJ m−2 min−1

d_r = inverse relative distance Earth–Sun

ω_s = sunset hour angle

ϕ = latitude (rad)

δ = solar decimation

```
C--------- Evapotranspiration calculations ------------------------


            TMAX(I,J)=RMTEMP(I,J)
            TMIN(I,J)=RTEMP(I,J)

            TAVG(I,J)=  (TMAX(I,J)+TMIN(I,J))/2

            LATRAD(I,J)=(3.141*LAT(I,J))/180

            INVREDIS(I,J)=1+0.033*COS(2*3.141*(JDAY(I,J))/365)



            SOLADECI(I,J)=0.409*SIN(2*3.141*(JDAY(I,J))/365-1.39)
            SUNSETAN(I,J)=ACOS(-TAN( LATRAD(I,J))
     &      *TAN(SOLADECI(I,J)))
            SINCAL(I,J)  =SIN(LATRAD(I,J))*SIN(SOLADECI(I,J))
              COSCAL(I,J)    =COS(LATRAD(I,J))*COS(SOLADECI(I,J))
            TERINCH(I,J)=((24*60/3.141)*0.082*INVREDIS(I,J)
     &                     *(SUNSETAN(I,J)*(SINCAL(I,J))+COSCAL(I,J)*
     &                     SIN(SUNSETAN(I,J))))*0.408



          ET(I,J)=0.0023*(TAVG(I,J)+17.8)*SQRT(ABS(TMAX(I,J)-TMIN(I,J)))
     &                *TERINCH(I,J)
             RET(I,J)=ET(I,J)/1000.0/3600/24


         ENDIF
             RETM(I,J)=  RETM(I,J)+ RET(I,J)
          ENDDO
```

Figure 3.5: Code snippet for the calculation of evapotranspiration using latitude of each cell

The final output of the program will be binary files for each month with daily records of rainfall and evapotranspiration for corresponding cells in the grid.

g. Flow direction preparation

This code was written in c language and used to extract the x and y components of the flow directions. The input file for the code is given as a binary file which then produce two separate direction files for x and y corresponding to each cell in the grid. The direction of flow is calculated initially using hydrology tool in ArcMap. ArcMap uses the following convention for denoting the direction as a floating point raster.

There are 8 valid output directions relating to the eight adjacent cells into which flow could travel as shown in the Figure 3.6.

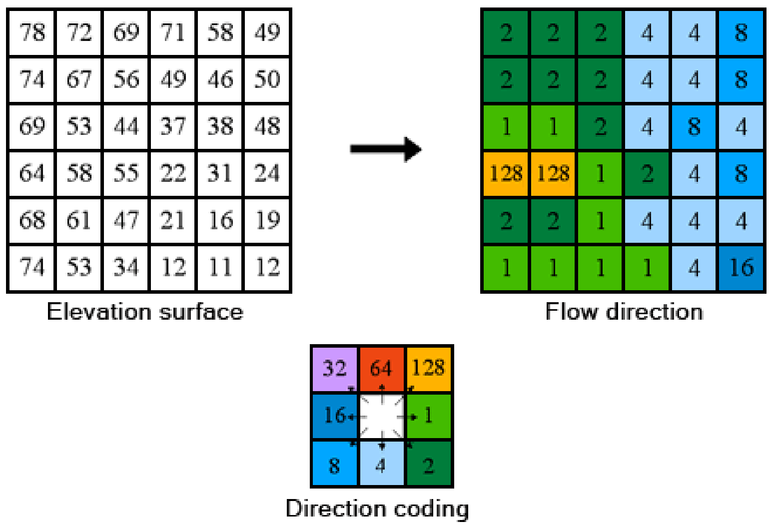


Figure 3.6: 8 direction convention used in ArcMap for denoting the flow direction

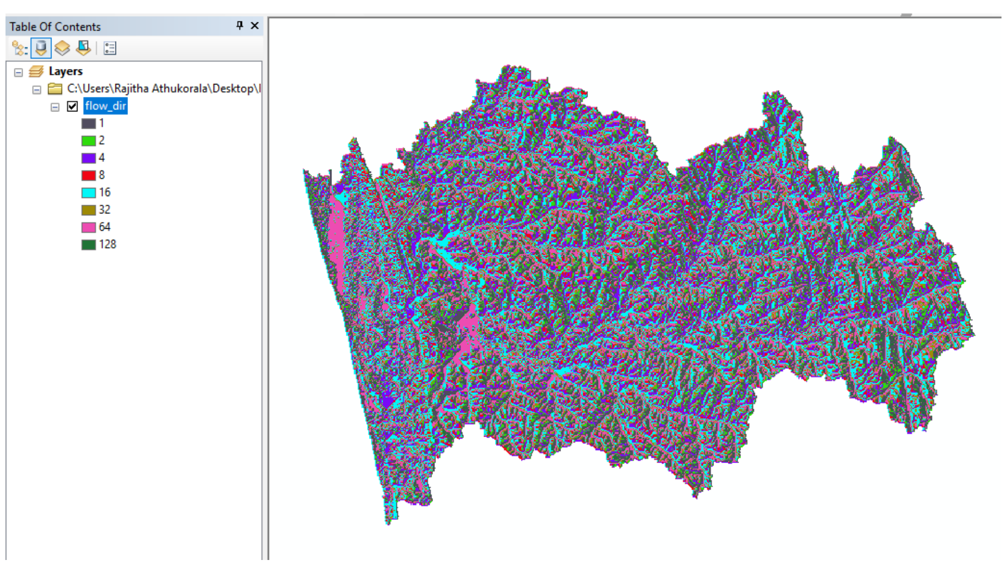


Figure 3.7: Flow directions from Hydrology tool in ArcMap for Attanagalu Oya basin

The ASCII file generated from ArcMap for flow direction was then converted into binary format using the software ‘Transform’. The binary file is then read by the code and the direction for each cell is assigned for respective x and y directions.

```
/*llevar de flowdir a fxd y fyd*/
for( i=1; i<FILA; i++){          /*inicializar las matrices*/
    for( j=1; j<COLU; j++){
        fxd[i][j]=500;
        fyd[i][j]=500;
    }
}

for( i=0; i<FILA; i++){
    for( j=0; j<COLU; j++){
        if(flowdir250[i][j]==128||flowdir250[i][j]==1||flowdir250[i][j]==2) fxd[i][j]=j+2;
        else if(flowdir250[i][j]==32||flowdir250[i][j]==16||flowdir250[i][j]==8) fxd[i][j]=j;
        else if(flowdir250[i][j]==64||flowdir250[i][j]==4) fxd[i][j]=j+1;
        else fxd[i][j]=fxd[i][j];
    }
}

for( i=0; i<FILA; i++){
    for( j=0; j<COLU; j++){
        if(flowdir250[i][j]==8||flowdir250[i][j]==4||flowdir250[i][j]==2) fyd[i][j]=i+2;
        else if(flowdir250[i][j]==32||flowdir250[i][j]==64||flowdir250[i][j]==128) fyd[i][j]=i;
        else if(flowdir250[i][j]==16||flowdir250[i][j]==1) fyd[i][j]=i+1;
        else fyd[i][j]=fyd[i][j];
    }
}

fp = fopen("fxd.bin","wb");
fwrite(fxd,sizeof fxd,1,fp);
fclose(fp);

fp = fopen("fyd.bin","wb");
fwrite(fyd,sizeof fyd,1,fp);
fclose(fp);
```

Figure 3.8: Code snippet for preparing the direction files for x and y directions

3.2.2 MODFLOW-2005 engine with Visual MODFLOW interface

The basic engine used was MODFLOW 2005 by USGS. The model setup procedure was done through the third party software Visual MODFLOW Flex Version 2015.1 by Waterloo Hydrogeologic. The model was setup to start from 2018/1/1.

3.2.2.1 Preparation simple polygon for model boundary.

The domain boundary of the MODFLOW model needs to be defined at the preliminary stages of the model setup. However, a complex polygon or a polygon which contains multiple polygons cannot be used for the domain boundary as shown in Figure . A complex polygon is a polygon that intersects with itself and/or contains holes. Although sink tool in hydrology fills low lying sudden varying pixels, when it comes to the domain boundary, intersecting polygon features extracted from basin tool of ArcMap cannot be imported.

Therefore a refining process was carried out to ensure such intersecting polygons are not present by manually digitizing the basin extent extracted from ArcMap hydrology tools.

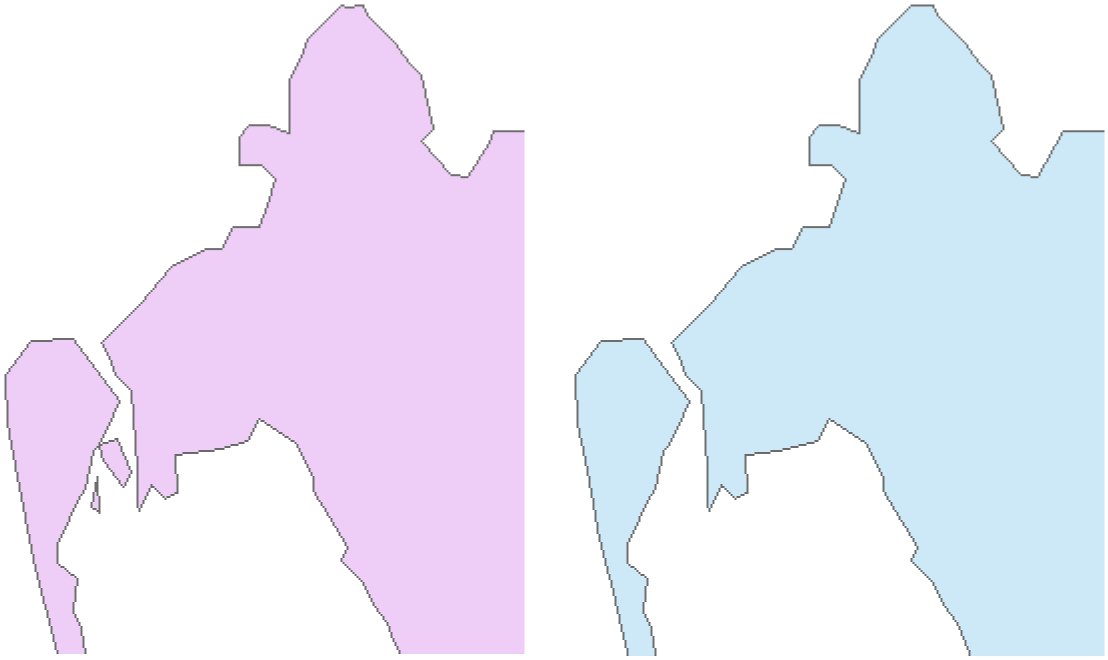


Figure 3.9: Complex polygon (on the left) and the simple polygon (on the right)

3.2.2.2 Defining model structure.

The vertical profile and model structure needs to be setup properly at the conceptual modelling stage in Visual MODFLOW. For the determination of the vertical structure of the Attanagalu Oya basin, well log data for 361 well all around the Attanagalu Oya basin were analyzed.

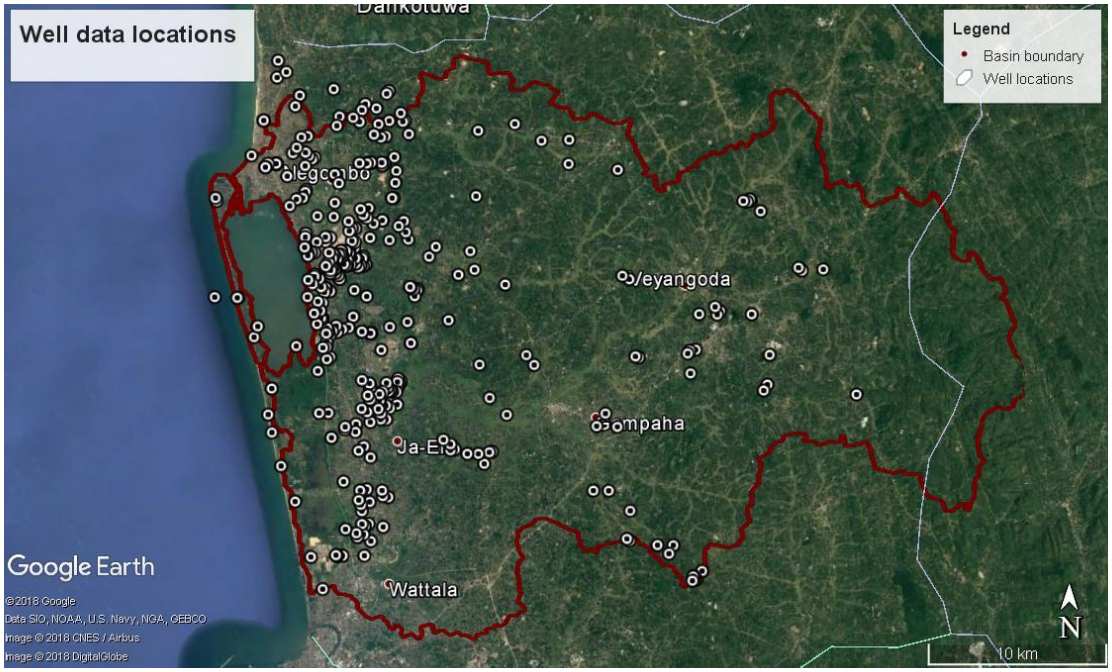


Figure 3.10: Location of well data

In order to determine the most general trend and layers of different types of soil, a conditional if statement was written for the different lithology classes in excel. The results obtained for the mostly occurring soil types for each layer with their frequency are given below.

Table 3.1: Occurrence of the soil types in different well locations

Layer	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Top soil	115	0	0	0	0
Clay	13	33	35	28	27
Sand	38	39	22	20	10
Weathered rock	1	7	17	31	33
Rock	0	3	17	16	43

The results suggested that there are 5 major layers in the region as follows

1. Layer 1 – Top soil
2. Layer 2 – Sand
3. Layer 3 – Clay
4. Layer 4 – Weathered rock
5. Layer 5 – Rock

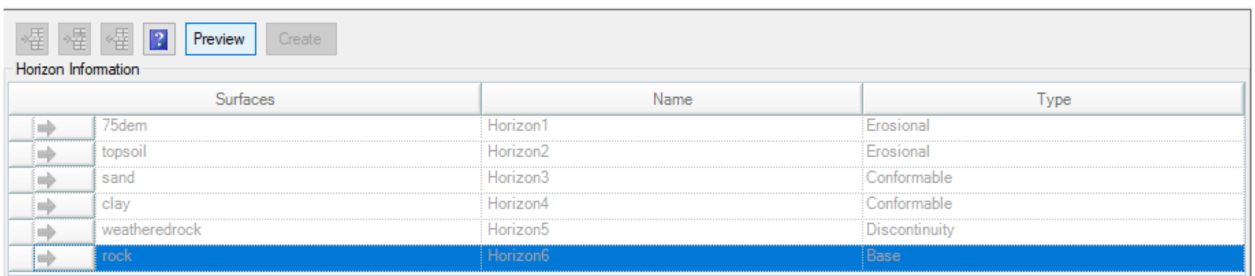
The corresponding depths of each layer was then generalized using the same conditional if statement in Excel to give the most frequently occurring depth ranges for each layer. The results obtained were as follows.

Table 3.2: Vertical profile of layers (mbgl-meters below ground level)

Layer	From (mbgl)	To (mbgl)
Top soil	0	3
Sand	3	10
Clay	10	13
Weathered rock	13	20
Rock	20	60

The layers were assumed to have no local variations and uniform throughout the basin extent. The horizons of each layer was obtained by reducing a fixed value from the 75m resolution DEM using the raster calculator in ArcMAp.

The surfaces were imported to Visual MODFLOW Flex and the horizons and structures were defined as given below.



Surfaces	Name	Type
75dem	Horizon1	Erosional
topsoil	Horizon2	Erosional
sand	Horizon3	Conformable
clay	Horizon4	Conformable
weatheredrock	Horizon5	Discontinuity
rock	Horizon6	Base

Figure 3.11: Horizons and zones with their types

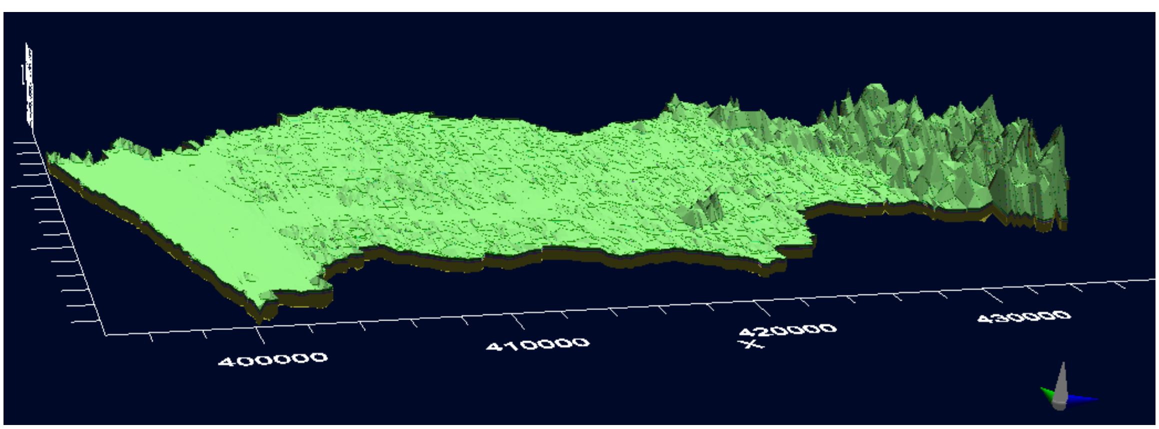


Figure 3.11: The model structure with vertical exaggeration of 10

The hydraulic conductivities of each layer in x, y and z layers were assigned by referring to past literature on soil data.

Table 3.3: Relevant conductivity values assigned for each layer

Layer	Kx	Ky	Kz
Top soil	0.02525	0.02525	0.002525
Sand	0.001	0.001	0.0001
Clay	2.40E-09	2.40E-09	2.40E-10
Weathered rock	2.80E-05	2.80E-05	2.80E-06
Rock	1.00E-10	1.00E-10	1.00E-11

3.2.2.3 Defining boundary conditions

a. Recharge

The daily rainfall data for 11 stations in the Attanagalu Oya basin was obtained from the meteorological department from 2015 to 2018.

Table 3.4: Station list with co-ordinates for Attanagalu Oya basin

Station	District	Lat	Lon	Elevation
Chesterford	Kegalle	7.07	80.18	198.2
Henarathgoda bot grdns	Gampaha	7.1	79.98	9.1
Katunayaka	Gampaha	7.17	79.88	8.5
Kelepitimulla	Gampaha	7.23	79.95	0
Negombo	Gampaha	7.22	79.83	3.1
Nittambuwa	Gapaha	7.13	80.1	16
Paysala	Gampaha	7.15	80.13	16
Thammita	Gampaha	7.1	79.95	0
Vincit estate	Kegalle	7.08	80.22	16
Warakapola(niyadurupola)	Kegalle	7.15	80.22	280
Welisara-navy	Gampaha	7.02	79.9	0

However, to distribute the rainfall for the whole Attanagalu Oya basin, the Thiessen polygon method was used to assign representative values for the whole region. The Thiessen polygon tool in ArcMap was used for this task.

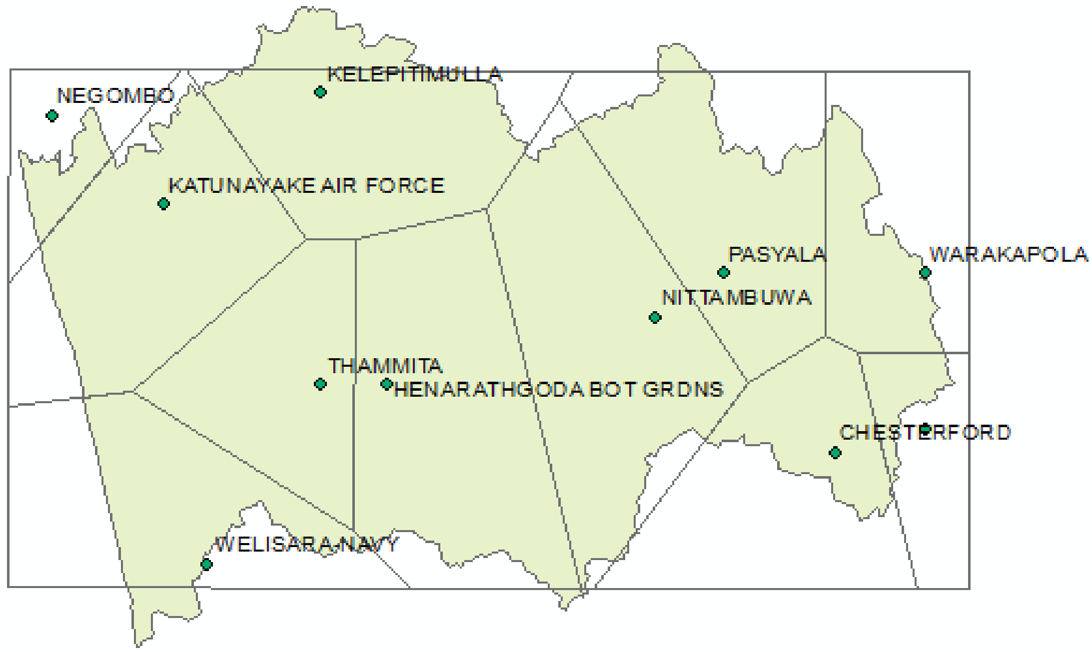


Figure 3.12: Thiessen polygon method for distribution of rainfall

These 11 zones were imported to Visual MODFLOW Flex as a polygon shape file deduced from the Thiessen polygons.

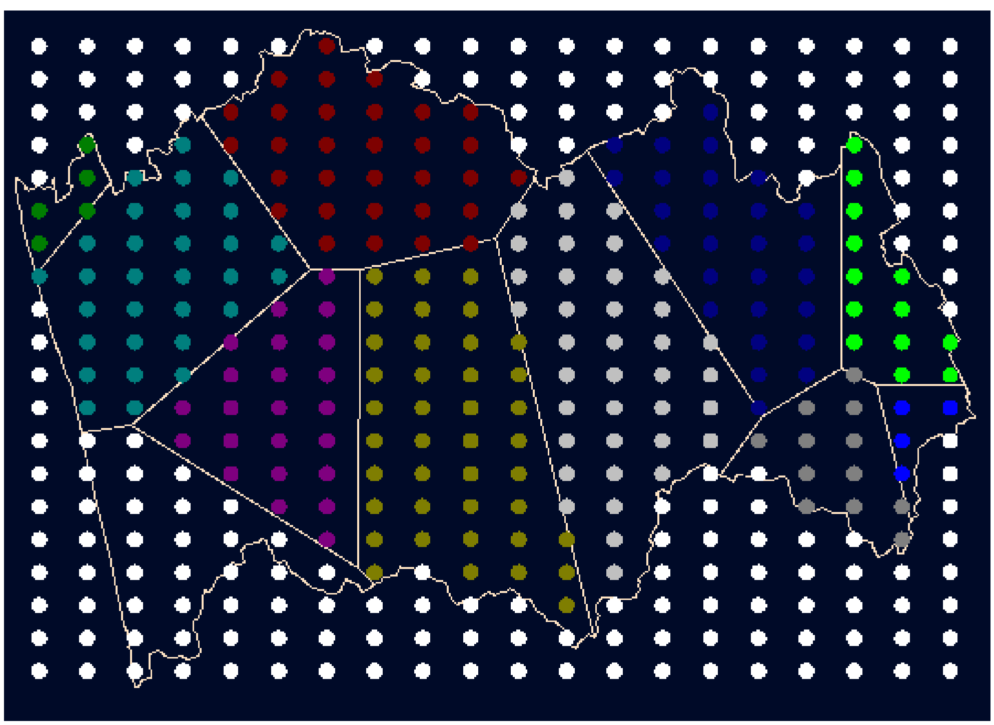


Figure 3.13: Recharge zones in MODFLOW

Each zone was then assigned recharge values on a daily basis using time schedule data objects created using Visual MODFLOW Flex.

b. Observation wells

The survey data of the field surveys 1 and 2 were used to create a tme schedule data object for varying head conditions for two stress periods of the year

3.2.2.4 Grid settings

A finite difference grid type was selected with 20 rows and 20 columns. The vertical grids were maintained as uniform thickness layers consisting 10 layers for the entire model domain.

- Cell height – 1578.75 m
- Cell width - 2302.5 m

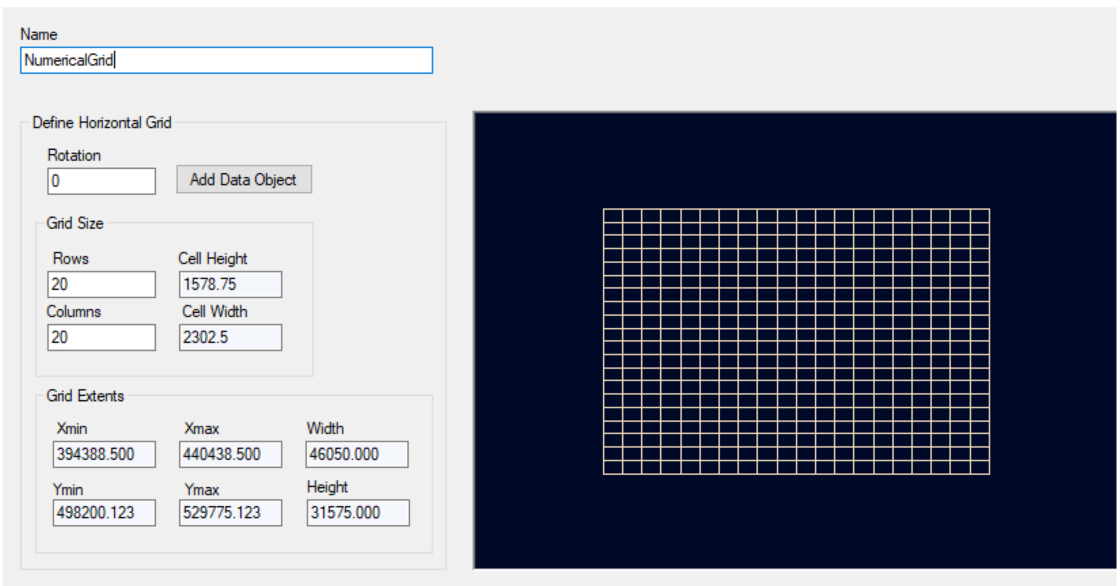


Figure 3.14: Horizontal grid settings used in the steady state model run

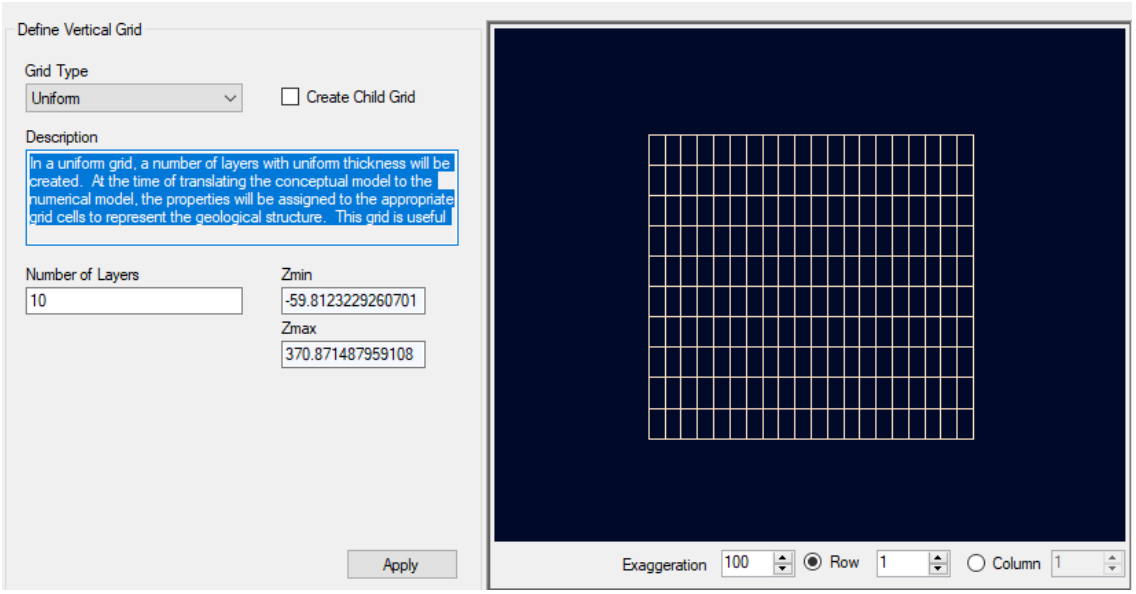


Figure 3.15: Vertical grid settings used in the steady state model run

3.2.2.5 Translation parameters

- Run type – Steady state
- Selected solver – Conjugate Gradient Solver

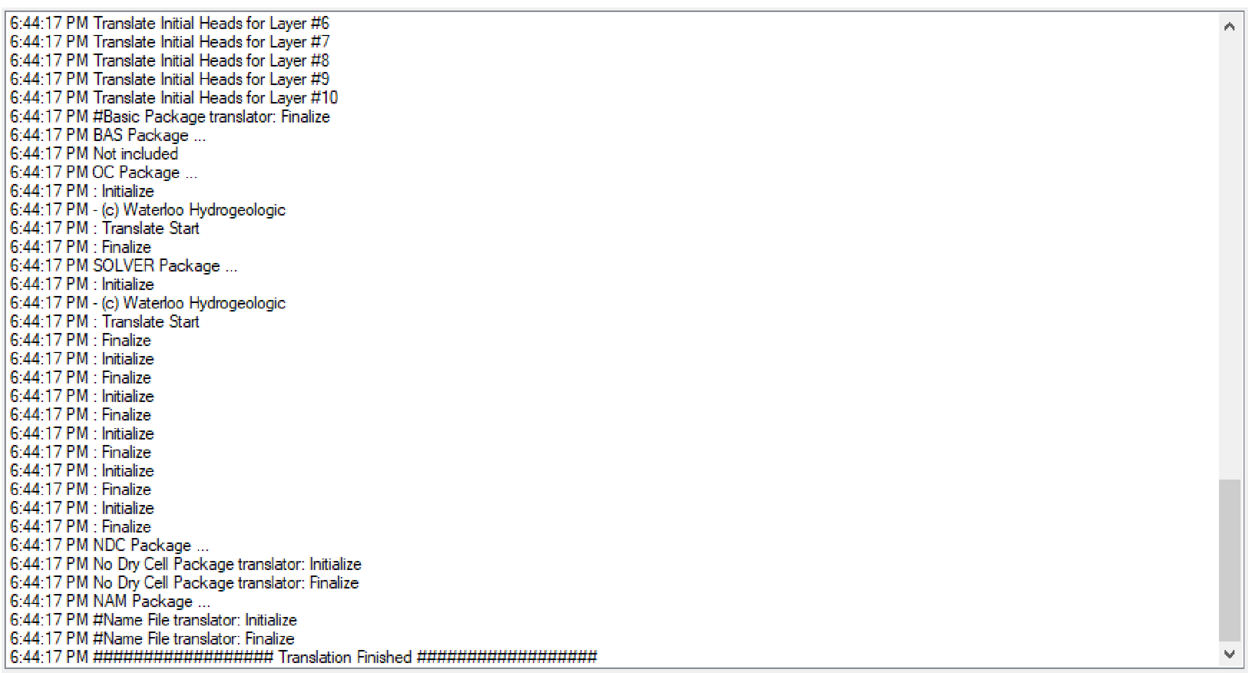


Figure 3.16: Model translation log for the steady state model run

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Seasonal variations of Groundwater quality

4.1.1 Calcium and Magnesium content for survey 1

Table 4.1: Chemical analysis results of Calcium and Magnesium in survey 1

SAMPLE NO / TOLERANCE LIMIT	Elevation	Calcium (mg/l)	Magnesium (mg/l)
WHO		100	30
SLS		100	30
A-04	Down stream	16	4.8
A-05	Middle stream	8	2.4
A-06	Middle stream	0	2.4
A-12	Middle stream	0	2.4
A-07	Up stream	0	4.8

Because there is no any significant or abnormal variation and concentration of calcium and magnesium over the seasonal change, a few number of representative samples were tested to get the results. There were negligible amount of magnesium and calcium concentrations identified.

4.1.2 Calcium and Magnesium content for survey 2

Table 4.2: Chemical analysis results of Calcium and Magnesium in survey 2

SAMPLE NO / TOLERANCE LIMITS	Elevation	Calcium (mg/L)	Magnesium (mg/L)
WHO		100	30
SLS		100	30
A-15	Down Stream	8	2.4
A-16	Down Stream	28	19.2
A-17	Down Stream	28	12
A-18	Down Stream	24	7.2
A-04	Down Stream	16	24
A-03	Middle Stream	24	12
A-05	Middle Stream	28	2.4
A-06	Middle Stream	20	21.6
A-12	Middle Stream	4	4.8

A-13	Middle Stream	20	9.6
A-14	Middle Stream	0	9.6
A-07	Up Stream	28	28.8
A-08	Up Stream	24	12
A-10	Up Stream	24	7.2

After rain, the number of samples analyzed for calcium and magnesium was increased to determine and confirm the increment and considerable concentration of calcium and magnesium after raining.

4.1.3 Heavy metal content (Lead and Chromium) for survey 1

Table 4.3 Chemical analysis results of Lead and Chromium in survey 1

SAMPLE NO / TOLERANCE LIMIT	Elevation	Lead (mg/L)	Chromium (mg/L)
WHO		0.01	0.05
SLS		0.05	0.05
A-15	Down Stream	<0.01	<0.01
A-16	Down Stream	<0.01	<0.01
A-17	Down Stream	<0.01	<0.01
A-18	Down Stream	<0.01	<0.01
A-03	Middle Stream	<0.01	<0.01
A-13	Middle Stream	<0.01	<0.01
A-14	Middle Stream	<0.01	<0.01
A-08	Up Stream	<0.01	<0.01
A-10	Up Stream	<0.01	<0.01

4.1.4 Heavy metal content (Lead and Chromium) for survey 2

Table 4.4: Chemical analysis results of Lead and Chromium in survey 2

SAMPLE NO / TOLERANCE LIMIT	Elevation	Lead (mg/L)	Chromium (mg/L)
WHO		0.01	0.05
SLS		0.05	0.05
A-15	Down Stream	<0.01	<0.01
A-16	Down Stream	<0.01	<0.01
A-17	Down Stream	<0.01	<0.01
A-18	Down Stream	<0.01	<0.01
A-03	Middle Stream	<0.01	<0.01
A-13	Middle Stream	<0.01	<0.01
A-14	Middle Stream	<0.01	<0.01

A-08	Up Stream	<0.01	<0.01
A-10	Up Stream	<0.01	<0.01

The heavy metals were analyzed because there is a possibility for the heavy metals due to the industrializations in the downstream regions.

Here also some representing samples were analyzed for the verification in the pre-monsoon and post monsoon seasons. The results obtained shows no any contamination due to the heavy metals.

4.1.5 Turbidity, Conductivity, fluoride, Nitrate, Phosphorous and Ferrous content in the survey 1

Table 4.5: Chemical analysis results of Turbidity, Conductivity, Fluoride, Nitrate, Phosphorous and Ferrous in survey 1

SAMPLE NO / TOLERANCE LIMIT	Elevation	Turbidity(ntu)	Ph	Conductivity (µs/cm)	Fluoride (mg/l)	Nitrate (mg/l)	Phosphorus (mg/l)	Ferrous (mg/l)	Depth (feet)
WHO		5	7-8.5	50-500	1	50	5	0.3	
SLS		2	6.5-8.5	3500	1.5	50	2	1.0	
A-15	Down Stream	0.64	6.26	465	0.07	6.5	0.1	0.04	3.25
A-16	Down Stream	0.69	5.7	210.6	0.03	0.08	0.63	<0.01	1.5
A-17	Down Stream	1.93	6.24	405	0.15	2.1	0.18	<0.01	4.83
A-18	Down Stream	0.53	6.39	166.2	0.02	0.1	0.23	<0.01	3.83
A-04	Down Stream	0.21	6.73	223	0.03	2.3	0.06	<0.01	3.25
A-03	Middle Stream	0.07	6.47	73.1	0.01	1.8	0.43	<0.01	11.75
A-05	Middle Stream	0.51	6.12	681	0.16	15	0.43	<0.01	24.5
A-06	Middle Stream	0.29	6.38	75.2	0.02	1.5	0.26	0.06	20.17
A-12	Middle Stream	0.05	6.45	122.6	0.02	4.1	0.13	<0.01	12.75

A-13	Middle Stream	0.23	5.47	98.7	0.02	1.6	0.1	<0.01	10
A-14	Middle Stream	0.31	6.18	163.6	0.15	2.2	0.15	0.06	13.25
A-07	Up Stream	0.23	6.56	58.5	0.02	1.3	0.53	<0.01	18.75
A-08	Up Stream	0.2	6.46	56.5	0.04	1.3	0.15	7.71	16.83
A-10	Up Stream	0.14	6.66	55.1	0.15	0.03	0.83	<0.01	8.83

4.1.6 Turbidity, Conductivity, fluoride, Nitrate, Phosphorous and Ferrous content in the survey 2

Table 4.6: Chemical analysis results of Turbidity, Conductivity, Fluoride, Nitrate, Phosphorous and Ferrous in survey 2

SAMPLE NO / TOLERANCE LIMITS	Elevation	Turbidity(ntu)	Ph	Conductivity (µs/cm)	Fluoride (mg/l)	Nitrate (mg/l)	Phosphorus (mg/l)	Ferrous (mg/l)	Depth (feet)
WHO		5	7.0-8.5	50-500	1	50	5	0.3	
SLS		2	6.5-8.5	3500	1.5	50	2	1	
A-15	Down stream	0.82	6.1	329	0.02	5.1	<0.01	<0.01	4.33
A-16	Down stream	0.7	5.6	280	0.18	0.16	0.15	<0.01	6.75
A-17	Down stream	0.44	6.2	336	0.01	2.8	0.01	0.44	6
A-18	Down stream	1.55	6.3	312	0.25	0.13	0.09	0.99	4.42
A-04	Down stream	0.45	5.4	250	0.05	3.6	0.04	1.31	2.83
A-03	Middle stream	0.09	5.5	82.5	0.01	2.5	0.21	<0.01	12.58
A-05	Middle stream	0.58	5.5	677	0.32	15	0.13	2.09	24
A-06	Middle stream	0.31	5.9	128.5	0.12	1.1	0.24	2.37	23.58
A-12	Middle stream	0.67	6.2	265	0.16	4.2	0.13	<0.01	11.5
A-13	Middle stream	2.5	6.4	106.3	0.16	2.4	0.22	0.01	14.67

A-14	Middle stream	2.31	6.7	63	0.13	0.63	0.36	0.15	17.33
A-07	Up stream	0.4	5.9	143.1	0.08	1.4	0.18	<0.01	18
A-08	Up stream	0.3	5.8	135.1	0.12	1.9	0.12	<0.01	12.83
A-10	Up stream	0.11	6	113.8	0.23	0.02	0.51	0.16	8.58

4.1.7 Qualitative analysis of groundwater in the upstream wells.

Table 4.7: Comparative analysis of water quality parameters of the upstream wells in the pre monsoon and post monsoon periods

Parameters	Pre-monsoon	Description	Conclusion	Post-monsoon	Description	Conclusion
pH	Within limits	Nearly neutral pH	Suitable for drinking	Less than the minimum pH (variation is high)	Acidic elements have been transported by runoff or chance of acidic rain	Less suitable for drinking
Turbidity	Within limits	Good quality of water (high transparency)	Suitable for drinking	Increase in turbidity but within limits	Particles has been picked up by runoff and settled in water bodies	Still suitable for drinking
Conductivity	Within limits	Good quality of water	Suitable for drinking	Increased but within limits	Salinity increased, more ions are added due to raining or from runoff	Still suitable for drinking
Fluoride	Within limits (less comparatively)	Good Quality of water	Suitable for drinking	Increased but within limits	Will be good if increased more (less comparatively)	Still suitable for drinking
Nitrate	Within limits	Good quality of water	Safe to drink and good for water living species	Increased within limits (little increment)	Nitrate level is low and safe	Suitable for drinking
Phosphorus	Within limits	Good Quality of water	No harm for drinking	Decreased but	Within limits	Suitable for drinking

				within limits		
Ferrous	Within limits (no measurable amounts in most places)	Suitable for drinking	Suitable for drinking and safe	No any considerable changes	Within limits	Suitable for drinking
Calcium	Within limits (soft water)	Good Quality water	Suitable for drinking	Increased within limits	Rain water contains calcium or from runoff	Soft water Suitable for drinking
Magnesium	Within limits (soft water)	Good Quality water	Suitable for drinking	Increased within limits	Rain water contains Magnesium or from runoff	Still soft water Suitable for drinking
Chromium	No considerable amount	Good Quality water	Suitable for drinking	No contamination	Good Quality water	Still suitable for drinking
Lead	No considerable amount	Good Quality water	Suitable for drinking	No contamination	Good Quality water	Still suitable for drinking

4.1.8 Qualitative analysis of groundwater in the middle stream wells.

Table 4.8: Comparative analysis of water quality parameters of the middle stream wells in the pre monsoon and post monsoon periods

Parameters	Pre-monsoon	Description	Conclusion	Post-monsoon	Description	Conclusion
pH	Lower than the minimum limit	Nearly acidic pH	Less suitable for drinking Became acidic from neutral on the direction of flow (Upstream to middle stream)	Less than the minimum pH	Water is acidic due to rain water is generally acidic and Acidic elements have been transported by runoff	Less suitable for drinking

Turbidity	Within limits but increased than the upstream	Good quality of water (high transparency)	Suitable for drinking	Increase in turbidity but within limits	Particles has been picked up by runoff and settled in water bodies	Still suitable for drinking
Conductivity	Within limits but increased than the upstream	Good Quality of water	Suitable for drinking	Increased, increment is higher than the upstream	Salinity increased, more ions are added due to raining or from runoff	Still suitable for drinking
Fluoride	Within limits (less comparatively) No any considerable change than the upstream	Good Quality of water	Suitable for drinking	Increased within limits	Will be good if increased more (less comparatively)	Still suitable for drinking
Nitrate	Within limits	Good quality of water	Safe to drink and good for water living species	Increased within limits (little increment)	Nitrate level is low and safe	Suitable for drinking
Phosphorus	Within limits	Water quality is good	Suitable for drinking	Decreased but within limits	Good water quality	Suitable for drinking

Ferrous	Within limits (no considerable amount in most places)	Suitable for drinking	Suitable for drinking and safe	No any considerable changes	Within limits	Suitable for drinking no any harm
Calcium	Within limits (soft water)	Good Quality water	Suitable for drinking	Increased within limits More than upstream	Rain water contains calcium or from runoff	Still soft water Suitable for drinking
Magnesium	Within limits (soft water)	Good Quality water	Suitable for drinking	Increased within limits More than upstream	Rain water contains Magnesium or from runoff	Still soft water Suitable for drinking
Chromium	No considerable amount	Good Quality water	Suitable for drinking	No contamination	Good Quality water	Still suitable for drinking
Lead	No considerable amount	Good Quality water	Suitable for drinking	No contamination	Good Quality water	Still suitable for drinking

4.1.9 Qualitative analysis of groundwater in the downstream wells

Table 4.9: Comparative analysis of water quality parameters of the downstream wells in the pre monsoon and post monsoon periods

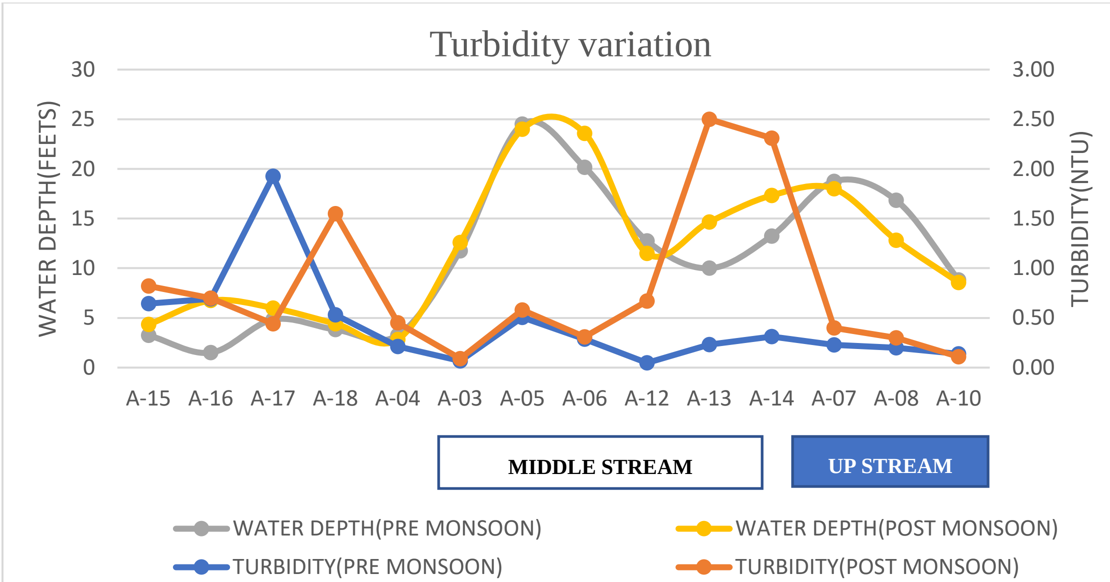
Parameters	Pre-monsoon	Description	Conclusion	Post-monsoon	Description	Conclusion
pH	Lower than the minimum limit More acidic	Nearly acidic pH Became more acidic from neutral on the direction of flow (Upstream to middle stream to downstream)	Less suitable for drinking Acidic Chemicals from the nearer industries have contaminated groundwater flow	Less than the minimum pH	Acidic water Acidic elements have been transported by runoff And also, generally the rain water is slightly acidic	Less suitable for drinking Acidic Chemicals from the nearer industries have contaminated groundwater flow and transported by the runoff
Turbidity	Within limits But increased than the upstream and middle stream	Good quality of water (high transparency)	Suitable for drinking	Increase in turbidity but within limits	Particles has been picked up by runoff and settled in water bodies	Still suitable for drinking
Conductivity	Within limits But increased than the upstream and middle stream	Good Quality of water	Suitable for drinking	Increased in some places and also decreased in some places within limits	Salinity increased, more ions are added due to raining or from runoff	Still suitable for drinking
Fluoride	Within limits (less	Good Quality of water	Suitable for drinking	Increased within limits	Will be good if increased more (less	Still suitable

	comparatively)				comparatively)	for drinking
Nitrate	Within limits	Good quality of water	Safe to drink and good for water living species	Increased within limits (little increment)	Nitrate level is low and safe	Suitable for drinking
Phosphorus	Within limits	Water quality is good	Not harm for drinking	Decreased but within limits	Water quality is good	Suitable for drinking
Ferrous	Within limits (no measurable amounts in most places)	Suitable for drinking	Suitable for drinking and safe	No any considerable changes	Within limits	Suitable for drinking no any harm
Calcium	Within limits (soft water)	Good Quality water	Suitable for drinking	Increased within limits Upstream has more increment	Rain water contains calcium or from runoff	Still soft water Suitable for drinking
Magnesium	Within limits (soft water)	Good Quality water	Suitable for drinking	Increased within limits	Rain water contains Magnesium or from runoff	Still soft water Suitable for drinking
Chromium	No considerable amount	Good Quality water	Suitable for drinking	No contamination	Good Quality water	Still suitable for drinking
Lead	No considerable amount	Good Quality water	Suitable for drinking	No contamination	Good Quality water	Still suitable for drinking

8.1.3 Analysis of spatial variation of groundwater quality parameters in the Attanagalu Oya basin.

The variations are plotted in graphs are from the downstream to upstream and the spatial variations are shown in the maps.

Figure 4.1: Turbidity variation with the change of water depth in the upstream, downstream and middle stream for pre and post monsoon



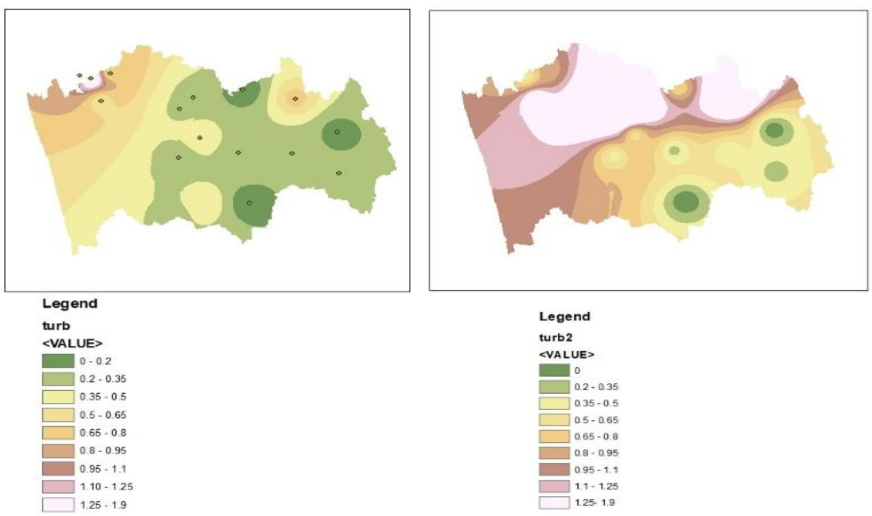


Figure 4.2: Spatial variation of turbidity in the Attanagalu Oya basin from pre monsoon (left) to post monsoon (right)

In the pre-monsoon the turbidity is within permissible limits. And the turbidity is high in downstream wells and low in upstream wells, after raining the post monsoon period shows an increment in the turbidity generally. The spatial map shows the increment in turbidity in the wells over the seasonal changes from pre-monsoon to post monsoon. According to the turbidity the quality of water is good, having high transparency and suitable for drinking.

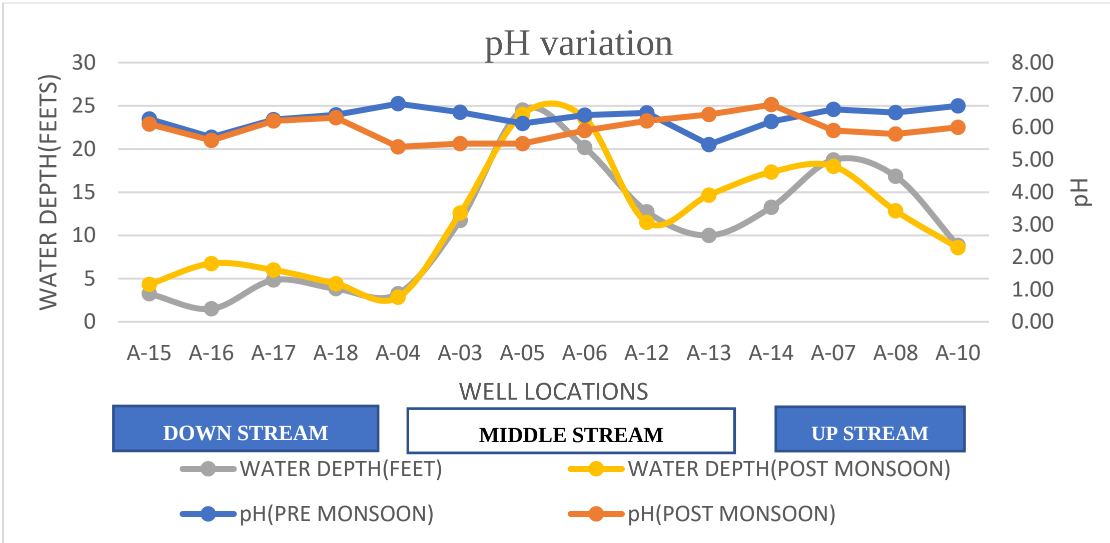


Figure 4.3: pH variation with the change of water depth in the upstream, downstream and middle stream for pre and post monsoon

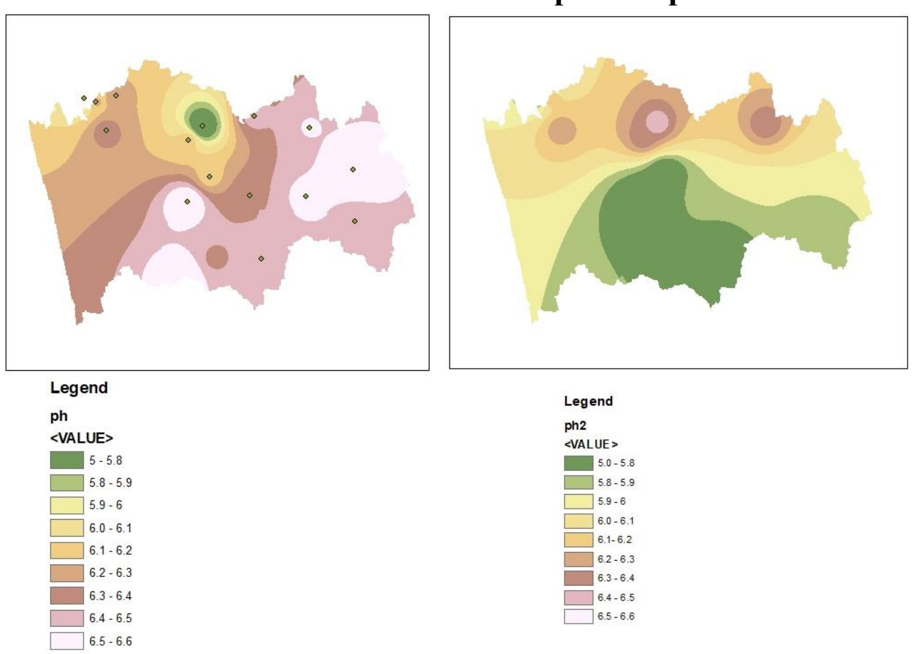


Figure 4.4: Spatial variation of pH in the Attanagalu Oya basin from pre monsoon (left) to post monsoon (right)

In the pre-monsoon the pH is lower than the allowable least limit. The water is slightly acidic. And the pH is decreased, and the average is 5.5 which is the representing pH of rain water. But before the rain also the water is acidic, and the acidity is high in the downstream wells due to the industrial discharges. The spatial map shows the decrease in pH with the seasonal change over the representing wells in the entire Gampaha district. Water is not suitable for drinking in both pre-monsoon and post monsoon seasons.

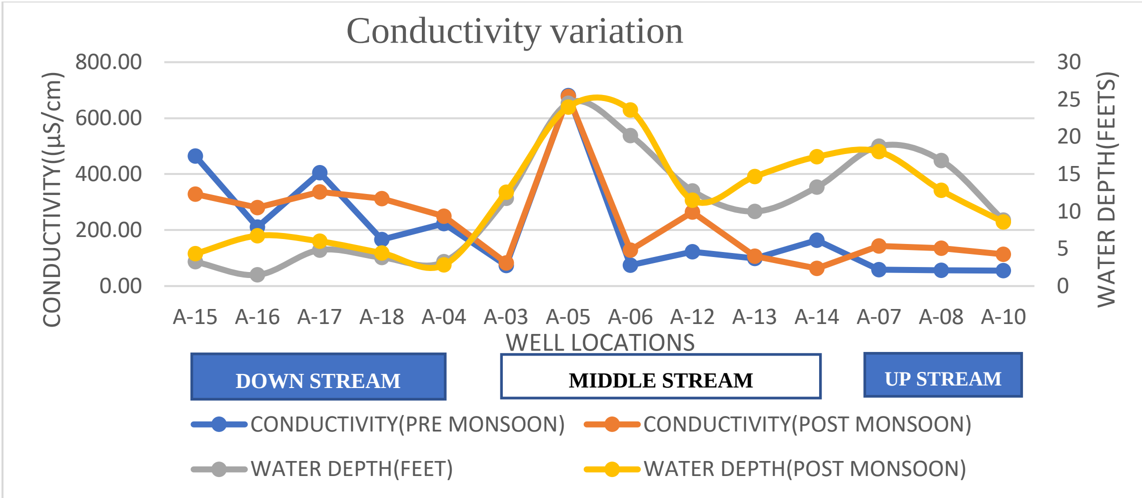


Figure 4.5: Conductivity variation with the change of water depth in the upstream, downstream and middle stream for pre and post monsoon

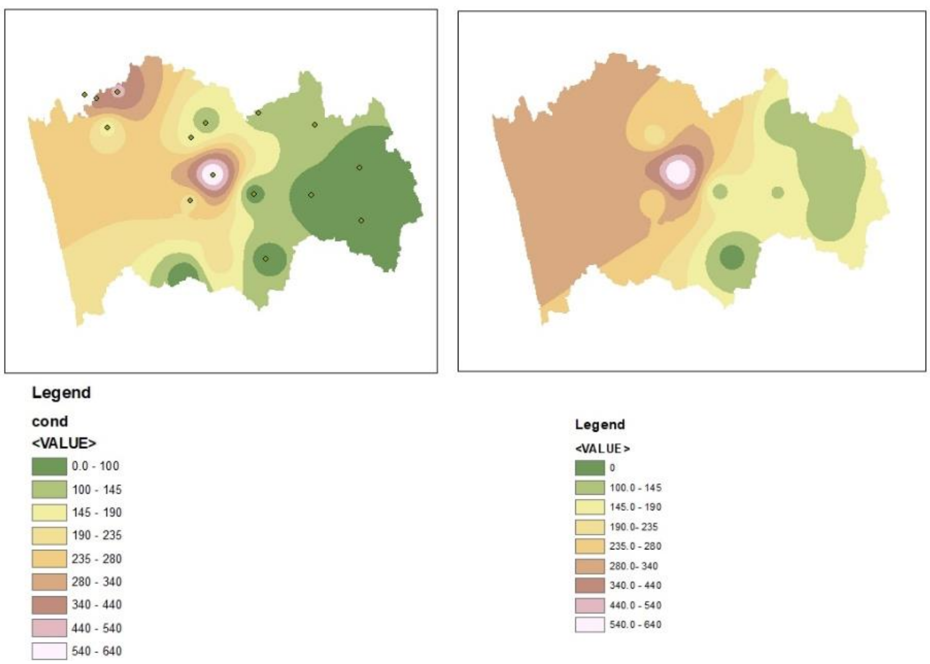


Figure 4.6: Spatial variation of conductivity in the Attanagalu Oya basin from pre monsoon (left) to post monsoon (right)

The conductivity implies the salinity of the water. In both pre-monsoon and post monsoon periods the conductivity is within the allowable limits. After raining the conductivity is increased generally. The increase in the conductivity over the seasonal change in the representing wells in the entire catchment area of the Gampaha district is given in the figure above. Conductivity is high in the downstream compared to the middle stream and upstream. The water is suitable for drinking considering the conductivity.

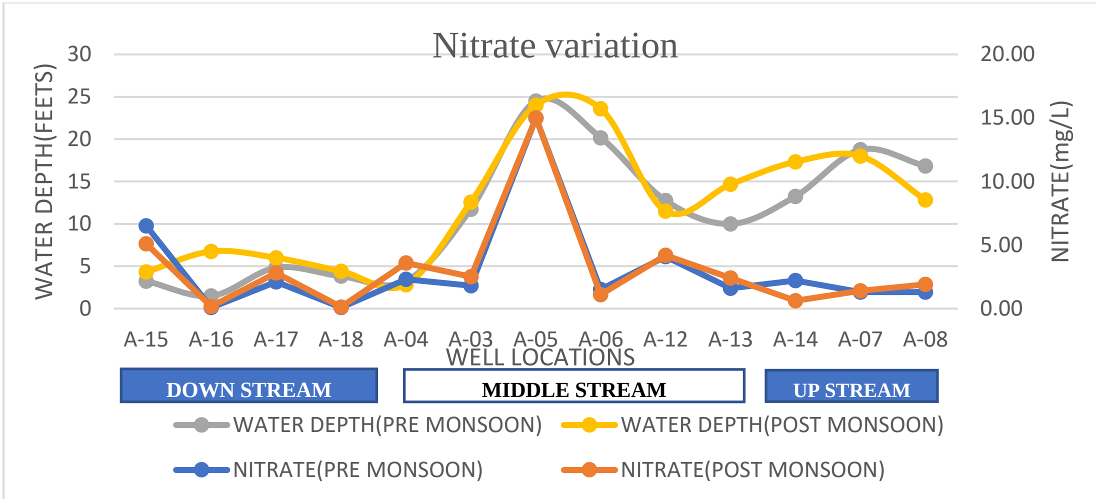


Figure 4.7: Nitrate variation with the change of water depth in the upstream, downstream and middle stream for pre and post monsoon

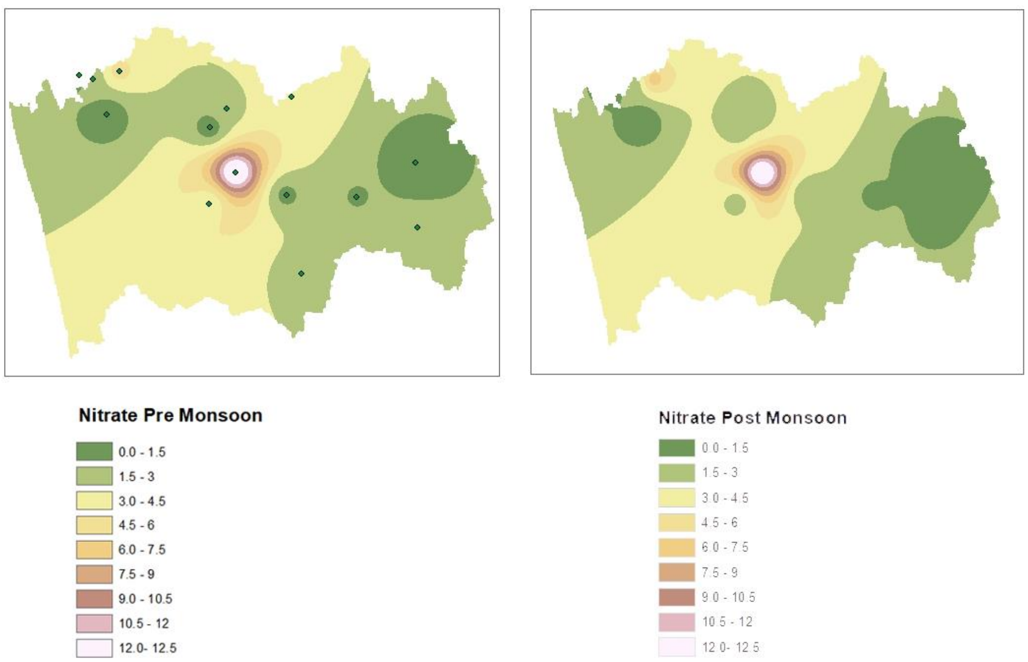


Figure 4.8: Spatial variation of Nitrate concentration in the Attanagalu Oya basin from pre monsoon (left) to post monsoon (right)

Nitrate concentration is within limits in both pre-monsoon and post monsoon periods. But after raining the nitrate has been increased generally. The increment can be clearly identified from the spatial map. Water is safe for drinking.

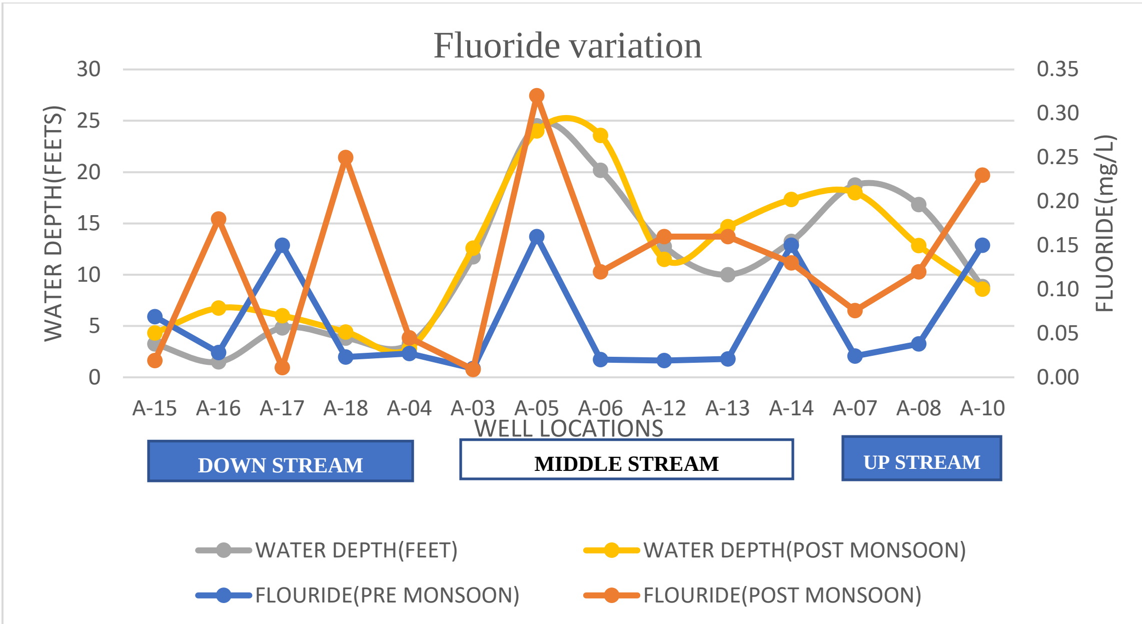


Figure 4.9: Fluoride variation with the change of water depth in the upstream, downstream and middle stream for pre and post monsoon

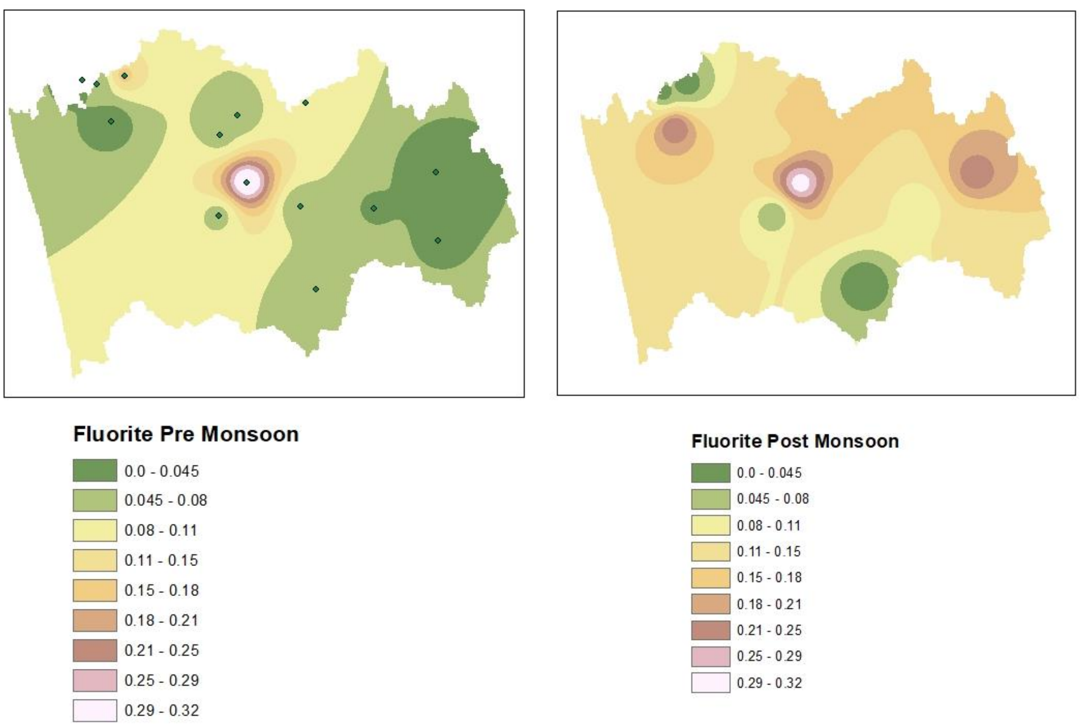


Figure 4.10: Spatial variation of Fluoride concentration in the Attanagalu Oya basin from pre monsoon (left) to post monsoon (right)

During both pre-monsoon and post-monsoon periods, fluoride concentration is within the permissible limits. After raining fluoride has been increased generally. The spatial map shows the increment on the fluoride concentration after raining and the seasonal variation of fluoride over the representing wells in the entire catchment of Gampaha.

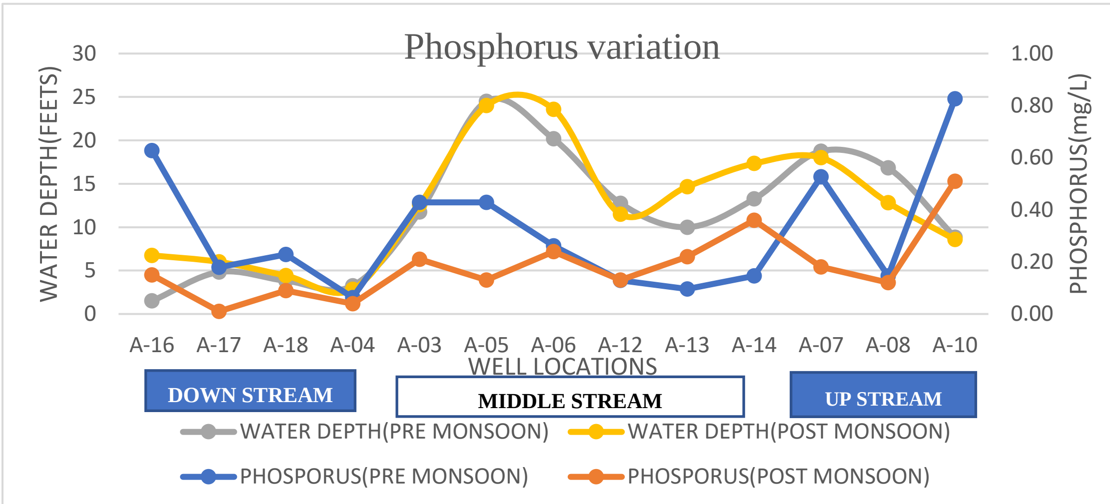


Figure 4.11: Phosphorous variation with the change of water depth in the upstream, downstream and middle stream for pre and post monsoon

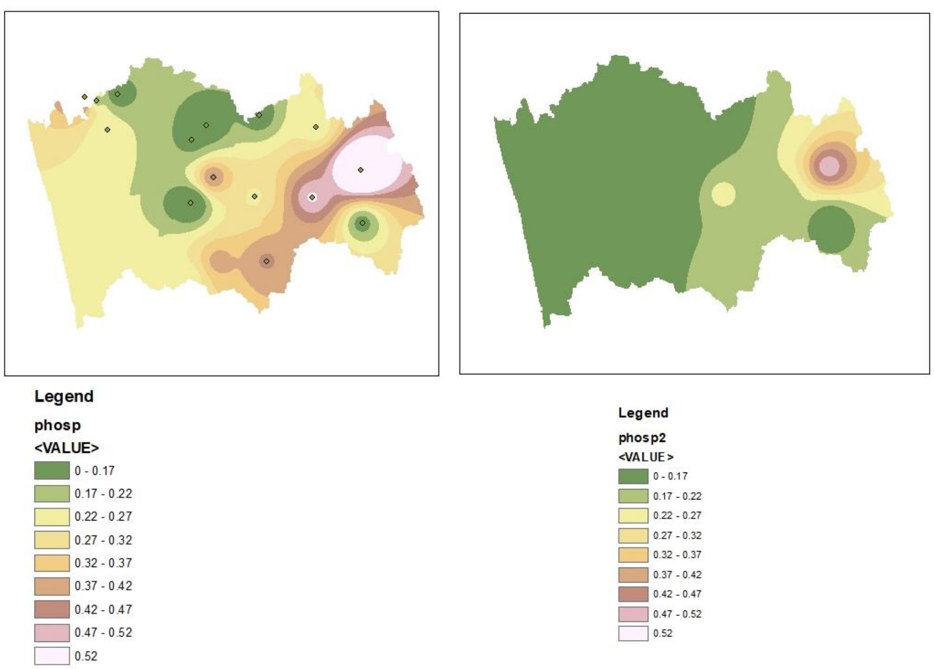


Figure 4.12: Spatial variation of Phosphorous concentration in the Attanagalu Oya basin from pre monsoon (left) to post monsoon (right)

The phosphorus concentration is within permissible limits in both pre-monsoon and post monsoon periods. After raining the phosphorus concentration has been decreased generally due to the dilution. The spatial variation of the phosphorus concentration over the Gampaha district can be observed from the spatial map in Figure 4.12.

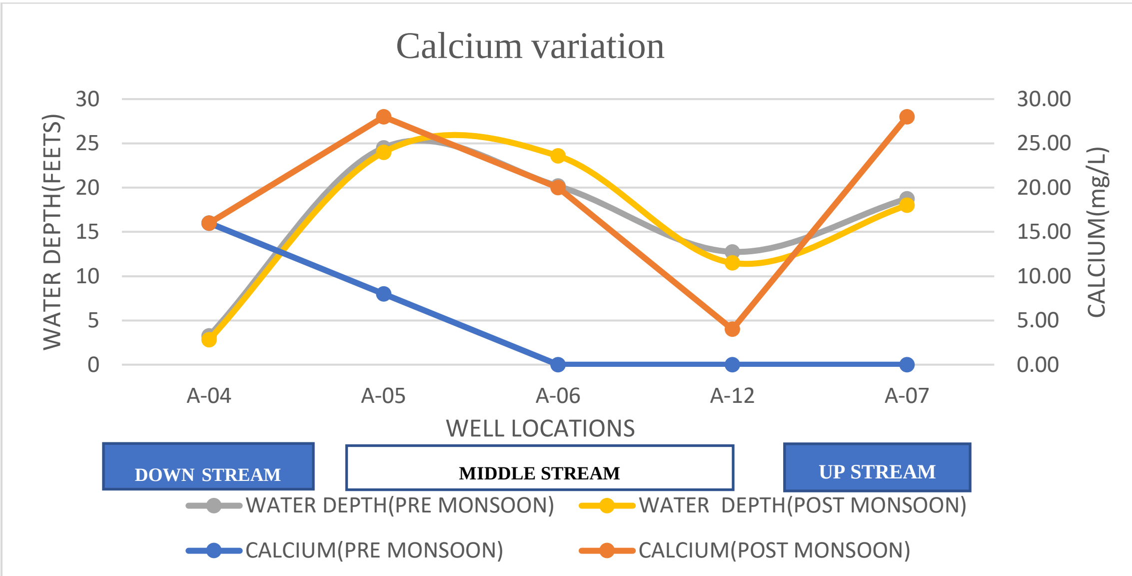


Figure 4.13: Calcium variation with the variation of water depth in the upstream, downstream and middle stream for pre and post monsoon

Calcium concentration implies the hardness of water. During both pre-monsoon and post monsoonal seasons the calcium concentration is within limit and the water is soft water. After raining calcium increases generally.

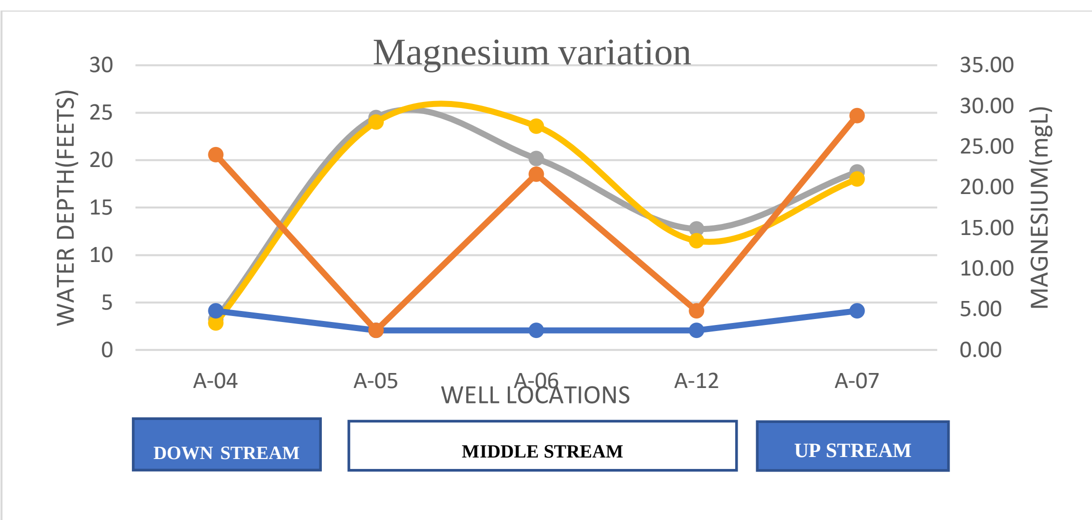


Figure 4.14: Magnesium variation with the variation of water depth in the upstream, downstream and middle stream for pre and post monsoon

The Magnesium concentration implies the hardness of water. During both pre-monsoon and post monsoonal seasons the magnesium concentration is within limit and the water is soft water. After raining magnesium increases generally.

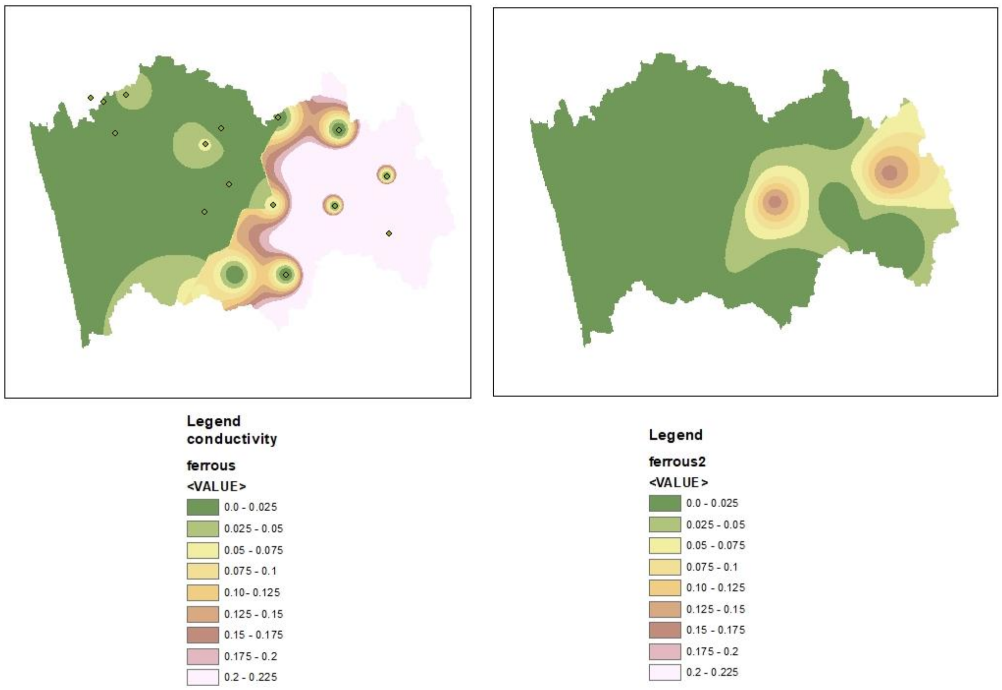


Figure 4.15: Spatial variation of Ferrous concentration in the Attanagalu Oya basin from pre monsoon (left) to post monsoon (right)

The spatial map above shows no any significant variation in the ferrous concentration over the seasonal variation. A slight decrease can be identified and the concentration of ferrous in both seasons is negligible from the results obtained. So, there is no any need of the detailed comparative analysis graph for the ferrous concentration.

4.2 Seasonal variations of Groundwater quantity

4.2.1 Results from MODFLOW

Steady state model run results:

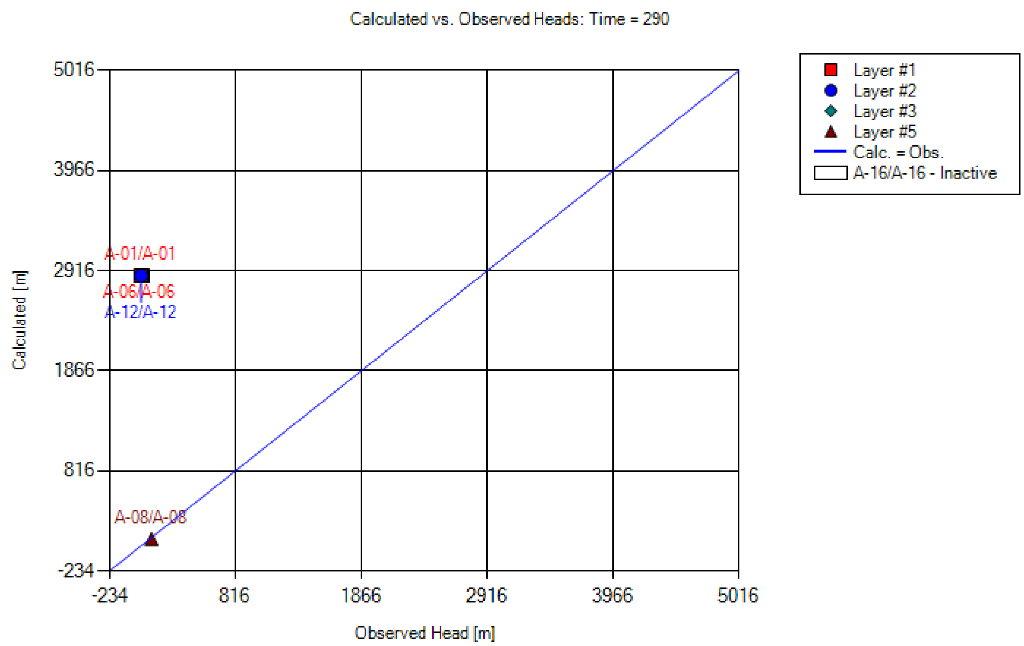


Figure 4.16: Comparison of the steady state model simulation results for head values and the observed head values during the field survey 1 and 2

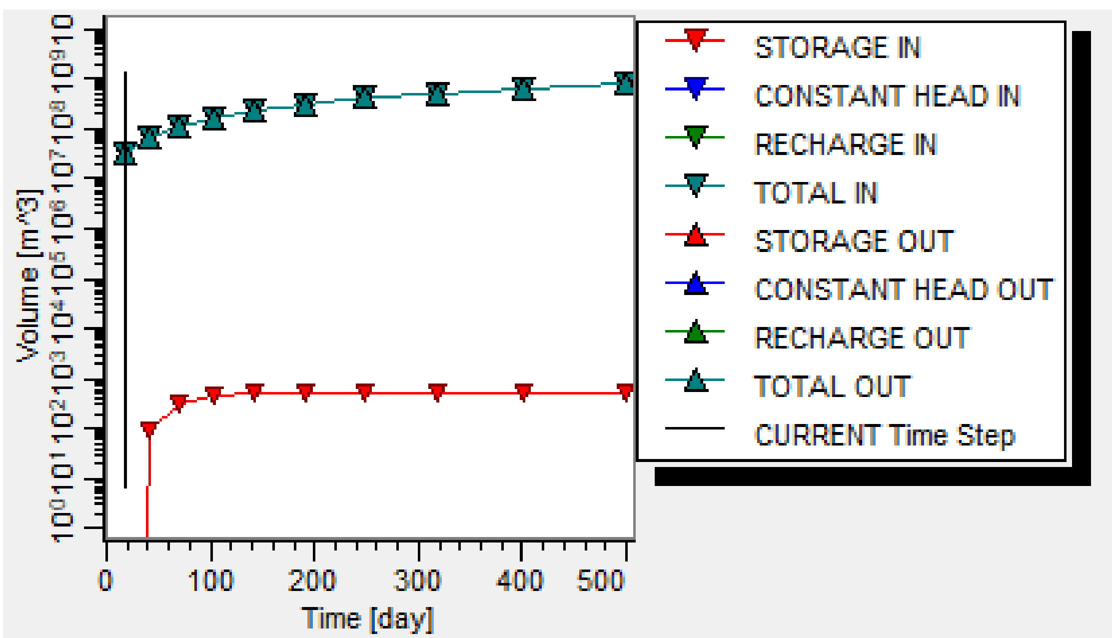


Figure 4.17: Accumulated volumes for the steady state model run during each time step

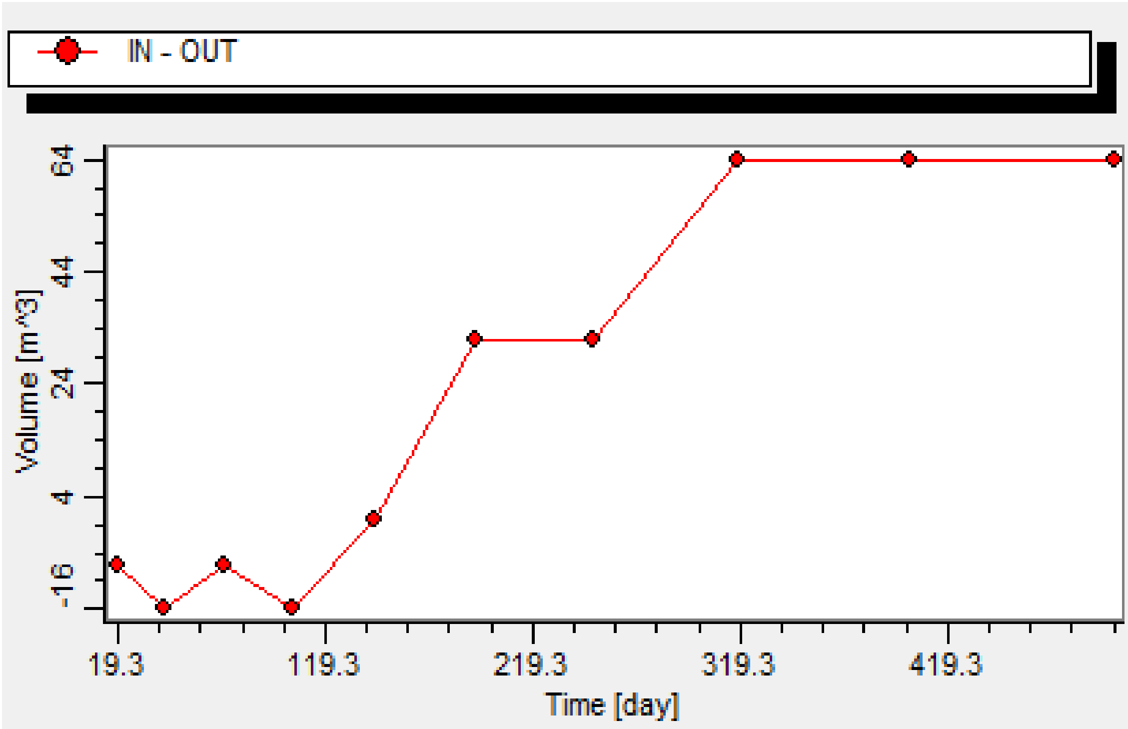


Figure 4.18: The variation of the (In–Out) volumes for each time step of the steady state model run

Error statistics

- Minimum Residual: -14.2 m at Well A-08
- Maximum Residual: +2840.15 m at Well A-06
- Residual Mean: +2122.3 m
- Absolute Residual Mean: 2129.41 m
- Standard Error of the estimate: 712.18 m
- Root Mean Squared: 2454.74 m
- Normalized RMS: 2691.67 %
- Correlation Coefficient: -0.99

Transient state model run results

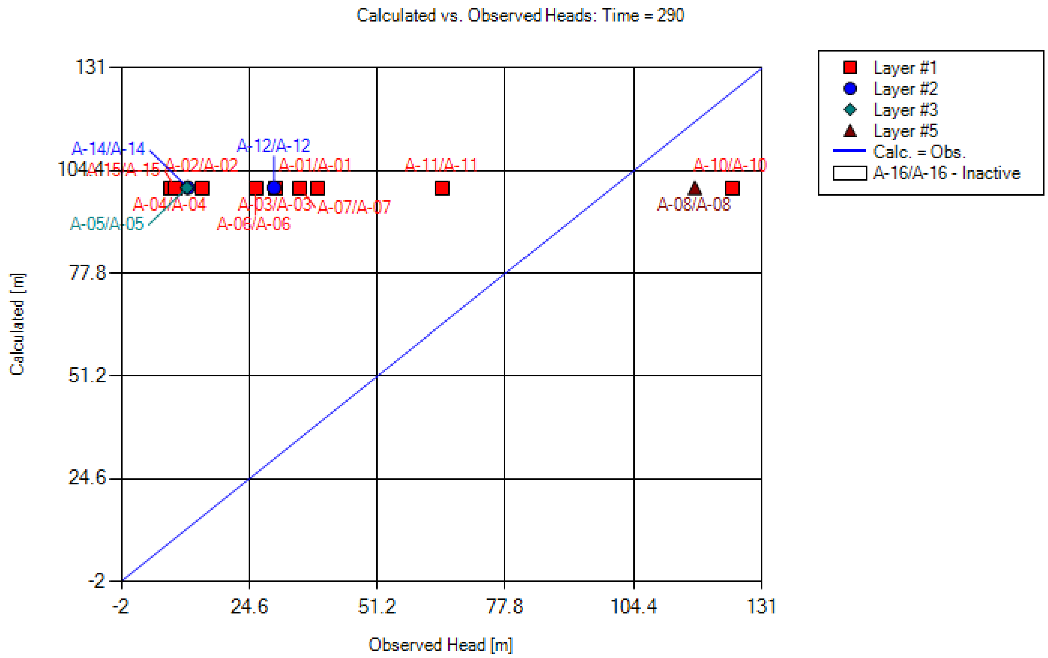


Figure 4.19: Comparison of the transient model simulation results for head values and the observed head values during the field survey 1 and 2

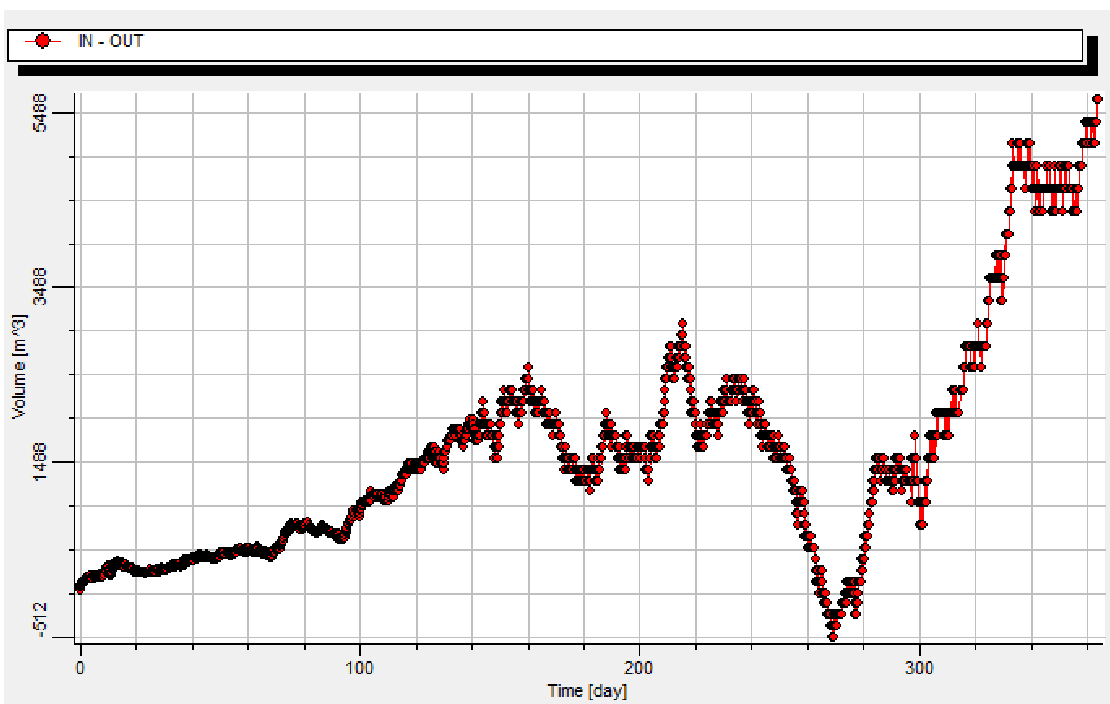


Figure 4.20: The variation of the (In–Out) volumes for each time step of the transient state model run

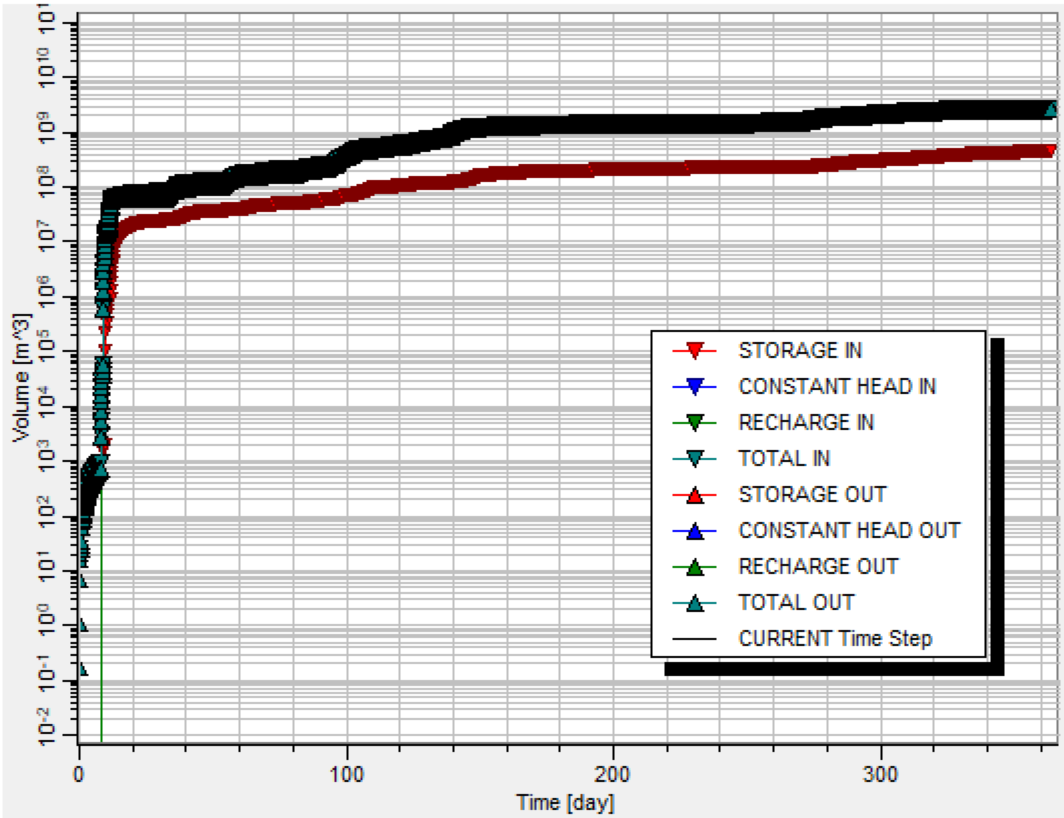


Figure 4.21: Accumulated volumes for the transient state model run during each time step

Error statistics

- Minimum Residual: -17.1 m at Well A-08
- Maximum Residual: +91.6 m at Well A-04
- Residual Mean: +59.83 m
- Absolute Residual Mean: 66.27 m
- Standard Error of the estimate: 10.84 m
- Root Mean Squared: 70.65 m
- Normalized RMS: 60.7 %
- Correlation Coefficient: 0

4.2.2 Results from the self-written Fortran code

When the Fortran code program executed, the daily run-off for each cell was calculated and the map files were saved as bin files. The output contains the RAINT (rainfall intensity m/s), RS (Tank 2 Water storage), RH (Tank 1 water height - meters), RQOUT (tank 1 out flow m3/s). The model was calibrated using the Tank 1 water height which represents the surface water height. The groundwater head values denoted by RS for tank 2 should be used for groundwater model calibration but since there are no available records for past groundwater observations, the surface water recordsfor 2015 from the Dunamale river gauge had to be used.

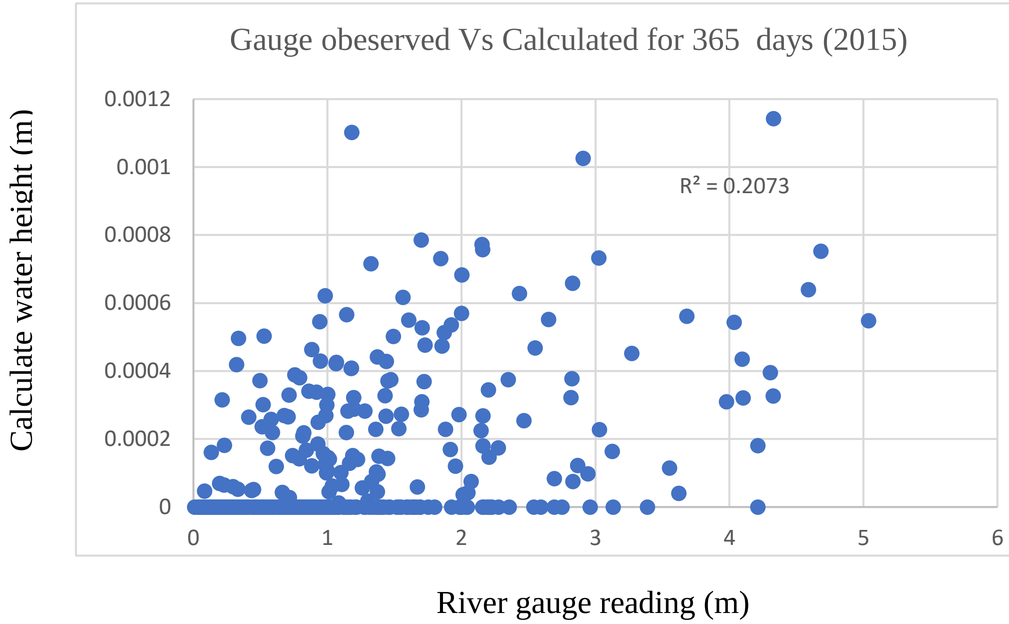


Figure 4.22: Dunamale river gauge data for 2015 compared with the model outputs

As the result the R^2 value was obtained as 0.2073 which means the observed and calculated values for the river gauge location correlates 20%. It is not enough for a good numerical model. So Furthermore, improvements and calibration needed. The land classification roughness values and less accurate temperature and rainfall data should be calibrated.

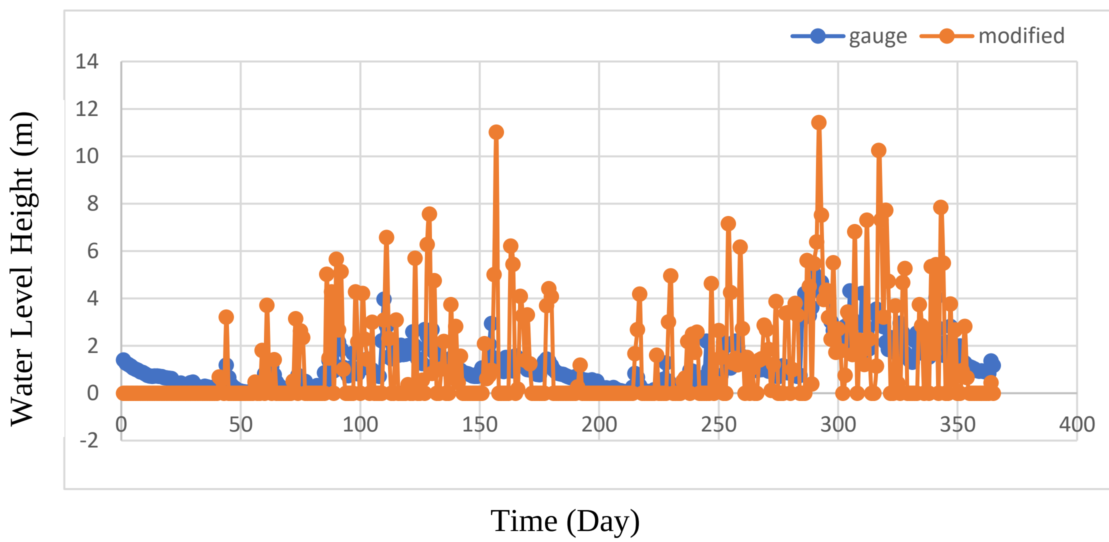


Figure 4.23: Modified water level heights from the model compared with the Dunamale river gauge data for the model run period

Model result statistics

Table 4.10: The regression statistics and ANOVA test for the observed river gauge data from Dunamale station and the model output

Regression Statistics	
Multiple R	0.455340567
R Square	0.207335032
Adjusted R Square	0.205151382
Standard Error	0.000186951
Observations	365

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.32E-06	3.32E-06	94.94883691	4.4024E-20
Residual	363	1.27E-05	3.5E-08		
Total	364	1.6E-05			

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The general groundwater quality of the Attanagalu Oya basin in the pre monsoon period is more suitable and safe for drinking while the quality deteriorates with the monsoon rainfall. The prolonged infiltration through the subsoil with the cease of surface run-off tend to buffer and re-clean the groundwater resources in the region. This trend of temporal variation in post monsoon groundwater quality emphasize the requirement for pre-treatment of groundwater used for drinking followed by the monsoon rainfall. The general public should be made aware to use suitable pre-treatment techniques especially for drinking water following the monsoon period.

The water quality parameters like turbidity, pH, and conductivity increase, following the monsoon rainfall period for the whole Attanagalu Oya basin. The trends in the levels of contamination observed from upstream to downstream suggest that the variations depend on the type of contaminant.

The levels of Nitrate and Phosphate which are major agricultural byproducts of groundwater contaminants are much more prominent in the upstream regions of the Attanagalu Oya basin. This observation emphasize the requirement for the proper monitoring of run-off from agricultural fields in the Attanagalu Oya basin and the locals in the vicinity of such agricultural fields should be made aware to be vigilant about such contaminations of their drinking water resources.

The downstream regions were much more influenced by turbidity and pH which are associated with effluents from industrial establishments. However, the content of heavy metals like Lead and Chromium in the vicinity of highly industrialized downstream regions of the Attanagalu Oya basin is below 0.01 ppm level which concludes that these regions are yet to be contaminated. Further sampling is required to identify localized contaminations from the industries and their impacts on the groundwater resources.

The study of groundwater modelling for the region should be continued with more field surveys and observation well data in order to achieve satisfactory levels of valid results. The use of self-written codes like the Fortran code used in the study can be easily adjusted for Sri Lanka conditions unlike in the case of complex modelling software like MODFLOW. The required data for inputs like constant heads and subsurface layers are difficult to access in Sri Lanka. A collection of groundwater level observation data along with their qualitative analysis would provide compulsory information for successful modelling of groundwater resources in the Attanagalu Oya basin. The inadequacy of data for model calibration and validation is a major problem faced in the process of groundwater modelling which can be overcome by the maintenance of a national level groundwater head observation and well record.

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