URBAN DEVELOPMENT DIRECTORATE (UDD)

Ministry of Housing and Public Works

Government of the People's Republic of Bangladesh

FINAL REPORT
ON
HYDRO-GEOLOGICAL SURVEY UNDER PREPARATION OF PAYRA-KUAKATA COMPREHENSIVE PLAN FOCUSICNG ON ECO-TOURISM

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Executive Summary

Scarcity of potable water is severe in many areas in coastal Bangladesh. This is primarily due to inferior quality of surface water and scarcity of suitable freshwater aquifers. The situation is getting worst due to climate change induced frequent storm surges and coastal inundation. In many areas in the coast, freshwater is available at shallower depth during rainy season; however, it turns to brackish during the dry period. Deep aquifer, where exist, is the main sources of potable water in coastal Bangladesh. Therefore, characterizing the deep aquifer and assessing its sustainability in coastal area is an important issue. The study aims to characterize the aquifer system based on field data and assess the sustainability of potable water using a numerical groundwater flow model in south-central coastal areas.

Lithological data collected from seven monitoring well installed during this study as well as thirty-six monitoring well installed by Bangladesh water Development Board (BWDB) suggests that there are mainly three aquifer depth zones namely, shallow, intermediate and deep aquifer zones. They exist at an average depth of about 80 m, 150 m, and 258 m, respectively. The hydraulic conductivity value measured by grain size analysis and slug test data analysis ranges from 0.1 m/d to 30 m/d. Aquifer pump test was carried out at the depth of 283.5 m and the transmissivity was calculated 600 m^2/min and storativity 0.003.

The shallow aquifer zone is highly active hydraulically and well connected with the surface water system. It receives about 300 mm of rainfall recharge every year. It also continuously exchanges water with rivers and streams in the study area due to seasonal variation in groundwater level and river stage. The intermediate aquifer is also seemed to be connected with the shallow system. However, the degrees of connection vary from place to place. In contrast, the deep aquifer is completely isolated from the overlying aquifers.

To assess water quality, groundwater samples from 70 locations covering different depths were collected from seven upazilas of Patuakhali (Kalapara, Galachipa, Rangahali, Amtoli) and Barguna (Taltoli, Patharghata and Barguna Sadar) districts during pre-monsoon (2018) and post-monsoon (2019) seasons. Analysis of all hydrochemical data and their spatial distribution maps reveal that the northwestern and southern part of the study area contains higher amounts of dissolved solids compared to the northern part. Shallow and intermediate aquifers show very high salinity compared to the deep aquifer. Hydrochemical facies analysis shows that, most of the shallow and intermediate aquifer contain Na-Cl type water and indicate influence of saline water. In contrast most of the deep aquifer shows Na-K-HCO3 type water and indicate fresh water with the exception in Patharghata.

Water Quality Index (WQI) has been calculated to assess suitability of water for drinking purpose. Results from WQI assessment shows that deep aquifer contains good quality water compared to the shallow and intermediate aquifers. Comparisons with the WHO and Bangladesh drinking water standards also reveal the same situation as most parameters of shallow and intermediate aquifer exceed the permissible limits while for deep aquifer all parameters are within safe limit.

A groundwater flow model was developed using MODFLOW to simulate groundwater flow at various depths. The model was calibrated using long term hydraulic head (2005-2013) data at 7 locations at shallow depth (<50 m), and 1 year of head data at 7 locations at deeper depth (>280m). Since, there is no groundwater irrigation in the study area; population based estimated domestic groundwater pumping was assigned in the model for the deep aquifer. One future scenario was simulated by increasing the domestic pumping rate by 10, considering future development in this region. The model result suggests that the aquifer reach a new dynamic steady-state after a sharp decline of groundwater by about 0.5 m, indicating the high possibility of both saltwater intrusion from the south and downward migration of brackish water from shallower depth. Further modelling studies

including variable density should be to quantify the risks before going for full phase development of the deep aquifer in this region. Additional investigations including isotopic age dating is necessary to understand the recharge mechanisms and long-term sustainability of deep groundwater.

Surface water and Ground water interaction can be a gain to the river or loss from the river; the latter is considered an important source of recharge to the groundwater aquifer. Surface water bodies are represented in the ground water model as constant head boundary condition, allowing groundwater to enter and exit the aquifer system depending on the dynamics of the groundwater level relative to river level. In this context, the model already includes the surface water component within it. The surface water in the study interacts mostly with the shallow groundwater system; it has no influence on the deep groundwater system.

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SECTION-1: INTRODUCTION

1 Introduction

Any development work requires water. Assessment of the availability of water and its quality is a prerequisite in any development work. This is even more important in the coastal area because of the limited availability of fresh water and their high contamination risk. It is highly appreciated that the Urban Development Directorate of the Government of Bangladesh included a hydrogeological study in the Payra-Kuakata comprehensive plan for Eco-Tourism development. Bangladesh is very risk prone country for safe drinking water because shallow aquifers here are mostly contaminated by various poisonous elements like Arsenic, Iron, Chloride, Magnesium, Sulfates etc and recharge deep groundwater is rarely quantified.

Urban Development Directorate (UDD) has planned to identify safe water source and proper water supply for the development plan of the project area. Accordingly UDD initiated a project, titled '*Hydrogeological Survey in Kalapara, Galachipa & Rangahali Upazila under Patuakhali Districts and Amtoli, Taltoli, Patharghata & Barguna Sadar under Barguna District (Figure 1), an area of approximately 3322.77 sq, km*' which includes 59 unions and 5 municipalities. "***Center for Geoservices and Research***" has been entrusted to conduct this project work. This project work comprises of Hydro-geological and geophysical investigations, groundwater modeling, and water quality mapping.

1.1 Background of the Project Area

We learn from the Terms of Reference (ToR) that, Barguna District (barisal division) area 1831.31 sq km, located in between 21°48' and 22°29' north latitudes and in between 89°52' and 90°22' east longitudes. It is bounded by jhalokati, Barisal, pirojpur and patuakhali districts on the north, Patuakhali district and Bay of Bengal on the south, Patuakhali district on the east, Pirojpur and bagerhat districts on the west. Amtoli, Patharghata and Barguna Sadar upazila are selected as a project area from Barguna district.

On the other hand, Patuakhali District (Barisal division) area of 3220.15 sq km, located in between 21°48' and 22°36' north latitudes and in between 90°08' and 90°41' east longitudes. It is bounded by Barisal district on the north, Bay of Bengal on the south, bhola district on the east, barguna district on the west. The land of the district is composed of alluvial soil of the meghna basin and of a number of small char lands. Galachipa (Including New Created RangabaliUpazila) and Kalapara upazila are selected as a project area from Patuakhali District.

Kuakata a scenic sea beach on the south of Bangladesh. The most important attraction of the beach is that one can see both sunrise and sunset from some of its locations. Situated 320 km from DHAKAand 70 km from the PATUAKHALIdistrict headquarters, *Kuakata* is part of *Latachapli* and *Dhulasar* unions of *KALAPARA*upazila. On the other hand, Amtaliupazila of Bargunazila is on the way to *Kuakata* from Barisal. The only highway towards Kuakata from Barisal is running through *Amtali*upazila. Due to the reason, both *Kalapara* and *Amtali*upazila have been undertaken for "Preparation of Eco-Tourism Development Plan for Kuakata Coastal Region" to develop tourism in the area in an integrated and comprehensive manner on a regional planning concept. The best way to reach *Kuakata* from Dhaka is to first travel to BARISALby road, water, or air, and then to take the bus or boat/launch for the destination. The Bangladesh Road Transport Corporation introduced a direct bus service from Dhaka to *Kuakata* via Barisal. Besides, on the west of Kuakata, there is a reserve forest, *Fatrar Char* by name, which is part of Sundarbans and is a unique location for tourism development. *Sonar char* of Rangabaliupazila is also a place of panoramic beauty. There is ample opportunity for tourism development in the area. Moreover, Paira Bandar, the third sea port is going to establish at Ravnabad Channel near Kuakata, which would act as catalyst for radical change in the overall urbanization in the area.

A detailed description of the Project Area is given below:

Table 1: Area, Population and Density of the Project Area:

Name of District	Name of the Upazila	Area		Population[1]	Density of total Population per Sq.Km
		Sq. Km	Acre		
Barguna	BargunaSadarUpazila	454.39	112284.31	237613	523
Barguna	PathargataUpazila	387.36	95720.53	162025	418
Patuakhali	Galachipa (Including New Created RangabaliUpazila)	1267.89	313308.30	325235	257
Patuakhali	KalaparaUpazila (Excluding Dulashar and Latachapli Union)	380.81	94101.96	159875	420
Barguna	AmtaliUpazila	720.76	178107.00	259757	360
Total		3211.21	793522.10	1144505.00	356

1.2 Objectives of the Project

The objective of the project is to optimize coastal resources and activities for sustenance of marginal people. The coastal activities and resources are very important to the economy and life of the people of Bangladesh whose living conditions are inextricably linked to the productivity and sustainability of coastal zone. There is no long term Holistic Development Plan for the coastal zone. Coastal zone needs to be integrated with the mainstream of development process of the country. So, an interdisciplinary development planning approach is urgent to optimize livelihood of coastal zone. The physical development planning problems, needing attention, are as follows:

i. To integrate coastal zone with the mainstream of development process of the country.
ii. To frame policies for the best use of land and its control for the Payra-Kuakata Coastal Region.
iii. To optimize coastal environment for sustenance of marginal people.
iv. Formulation of Policies and plans for mitigation of different types of hazards, minimizing the adverse impacts of climate change and recommend possible adaptation strategies for the region.

[1] BBS, 2001

v. Formulation of Policies and Plans for gradual nucleation of settlements with policies and plans for development of growth centers of the area.
vi. Formulation of a planning package for development of turism in Payra-Kuakata Coastal Region, and also to accommodate future changes in existing land use pattern, socio-economic condition of the area and quality of life of the people due to establishment of the third sea port in the region in an integrated and comprehensive manner.

1.3 Scope of Works

The aim of hydro-Geological study for urban area of Payra-Kuakata Coastal Region is to identify the aquifer of the region including its seasonal variation. The study is also intended to identify the availability of fresh ground water, which would be required for the additional people including tourists after implementation of the project. The hydro-geological data and information shall have to integrate with both spatial and attribute data of output of other components of planning package of **"Preparation of Payra-Kuakata Comprehensive Plan Focusing on Eco-Tourism"** in order to keep the hydrological system of the region sustainable.

With a view to attain the aim of hydrological and hydro-geological study of Payra-Kuakata Coastal Region including (a) Barguna Sadar Upazila (b) Pathargata Upazila (c) Galachipa Upazila (including Newly Created Rangabali Upazila), (d) Kalapara Upazila, and (e) Amtali Upazila, the objectives of the work comprise the following:

i. To identify the aquifer level of the region including its seasonal variation.
ii. To identify the potential area of groundwater recharge.
iii. To identify the areas potential for drawing fresh ground water.
iv. To develop a model for interfacing between surface water and ground water.
v. To identify the areas of interruption including probable change in the hydrological cycle due to human intervention and climate change.
vi. To suggest the remedial measures to make the hydrological system of the region sustainable.
vii. To develop a water quality map.
viii. Finally, development of an interactive digital model comprising of interfacing between surface water and ground water, and interruption in the hydrological system along with the mitigation measures.

SECTION-2: MATERIALS AND METHODS

2 Methodology

2.1 Aquifer characterization

The first step in any hydrogeological study is to identify the aquifers and characterize groundwater flow system. A number of investigations are required to achieve that. Following investigations have been carried out in this study for aquifer characterization.

2.1.1 Piezometer Installation

Since the groundwater quality in the study area varies with depth, monitoring wells at multiple depth intervals is essential. A total of 21 monitoring wells have been installed at seven locations (one set of 3 wells in each Uapzila, Figure 2-1). At each location a cluster/nest[2] of three wells (one at around 1000±100 feet depth, one at around 300 feet depth and the other at around 100 feet depth, each well will be within 10-50 ft from the other) have been installed as shown in Figure 2-2.

2.1.1.1 *Site Selection*

Monitoring well locations were selected first on the basis of Geological, Geomorphological, and hydro-geological variability, and the location of existing data in the study area. Later on, the locations were verified by physical observation and shifted a bit on the basis of local access and available space for the investigation as well as the permission of the land owners. All the locations are verified finally and permission is also obtained from the land owners. Locations of the monitoring wells are shown in Figure 2-1 and details are given in a Table in Appendix-A.

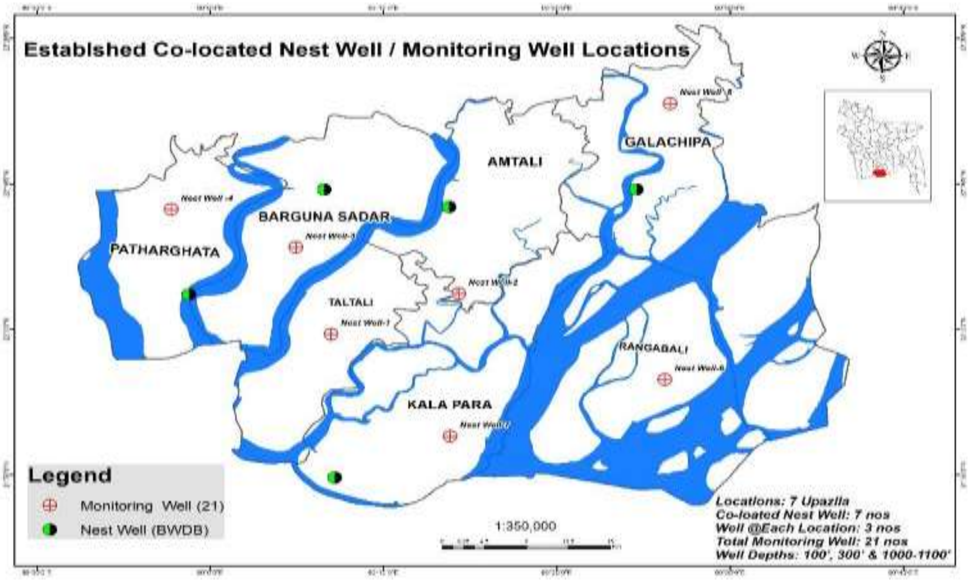

Figure 2-1: Location map of the monitoring nests

[2] Nest well: A cluster of wells where tubes or pipes are constructed in separate (10-50 feet distance to each other), individual boreholes that are drilled and completed at different depths.

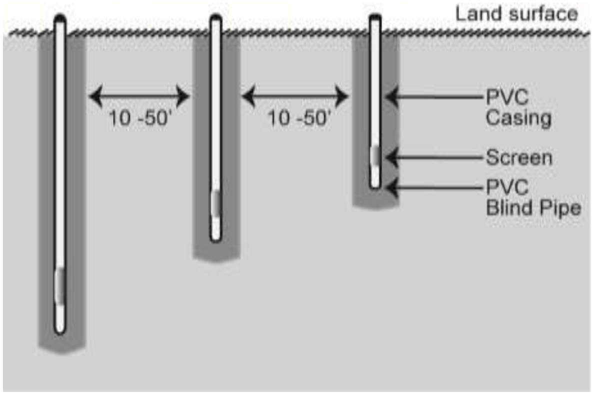

Figure 2-2: Cross Sectional View of Well Nest/Cluster

2.1.1.2 ***Drilling of Monitoring Wells***

Reverse circulation conventional drilling method (Figure 2-3) was used for drilling the monitoring wells. In this method drilling fluid enters the hole through the drill pipe and comes up to the surface with a mixture of drill cuttings through the annulus. Fluid was piped through the pipe using a high speed mechanical pump. A mixture of water and cow dung was used as drilling fluids. For the deepest piezometer drilling was continued for at least 1000 feet, at some places where suitable layer could not be found around 1000 feet drilling was carried out for 1100 feet.

Figure 2-3: Drilling Procedure of Monitoring well.

2.1.1.3 *Lithological Sampling and Logging*

A well site Geologist was present at each site during drilling and prepared lithological logs based on the drill cut samples in standard format provided by CGR. Drill cuts were collected at every 10 feet interval. After logging, the drill cuttings were also preserved in polyethylene bag for grain size analysis in laboratory.

2.1.1.4 *Installation of Monitoring Wells*

After the drilling was completed a monitoring well was installed at every drill hole. The deepest monitoring wells have 20 feet screen at the bottom of the well but above 5 to 15 feet blind pipes. The shallower monitoring wells have 10 feet screen above 5 to 10 feet blind pipe. Both the well casing and screen consists of PVC materials (Figure 2-4). After installing the pipes a gravel packing was done around the well screen. The well annulus was back filled by clays collected during the drilling.

Figure 2-4: Installation of Monitoring Well

2.1.1.5 *Development of Monitoring Wells*

After installation, each monitoring well was developed by both manual pumping and by an electrical compressor for duration of several hours for the shallow wells to tens of hours for the deep well until the EC of the well water was stable. A local hand pump was used for the manual pumping for well development.

2.1.2 Aquifer Pump Test

The goal of a aquifer pump test, as in any aquifer test, is to estimate hydraulic properties of an aquifer system and to determine the yielding capacity of an aquifer. One pump test well was carried out in the study area. A pumping test is a field experiment in which a well is pumped (Figure 2-5) at a controlled rate and water-level response (drawdown) was measured in three surrounding observation wells and optionally in the pumped well (control well) itself; response data from pumping tests were used to estimate the hydraulic properties of aquifers, evaluate well performance and identify aquifer boundaries.

Figure 2-5Aquifer pump test in field

Aquifer properties were estimated from a constant-rate (0.5 cusec) pumping test by fitting Theis mathematical models (type curves) (Figure 2-7) to drawdown data (Figure 2-6) through a procedure known as curve matching. Diagnostic tools such as derivative analysis are useful for identifying flow regimes and aquifer boundaries from a pumping test prior to performing curve matching. The test results are given in Table 2.

Table 2 Aquifer Pump test data

Pump Test Result	
Description	**Value**
Well Depth	283.5 m
Transmissivity T	600 m2/min
Storativity S	0.003

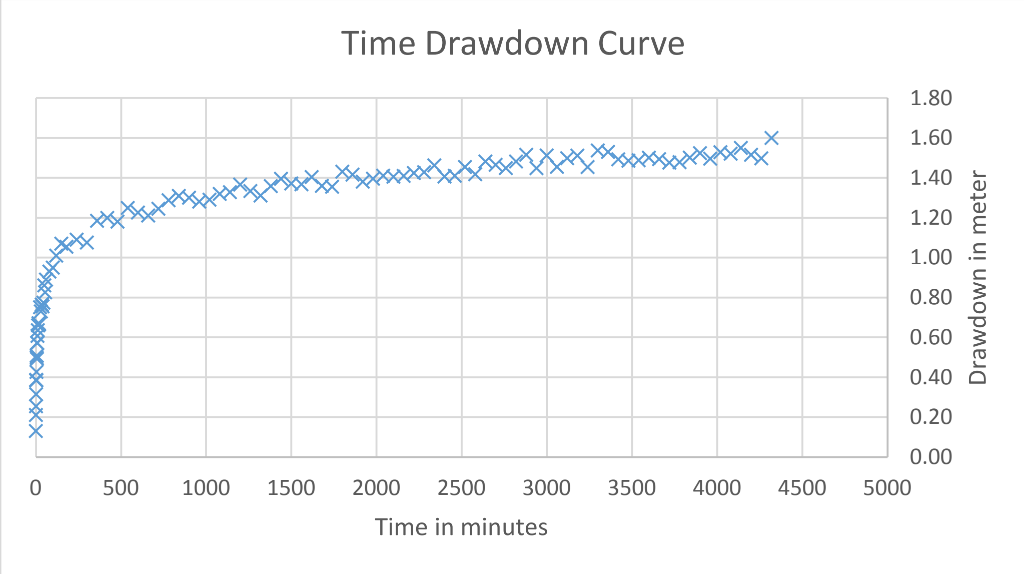

Figure 2-6Time Drawdown Curve

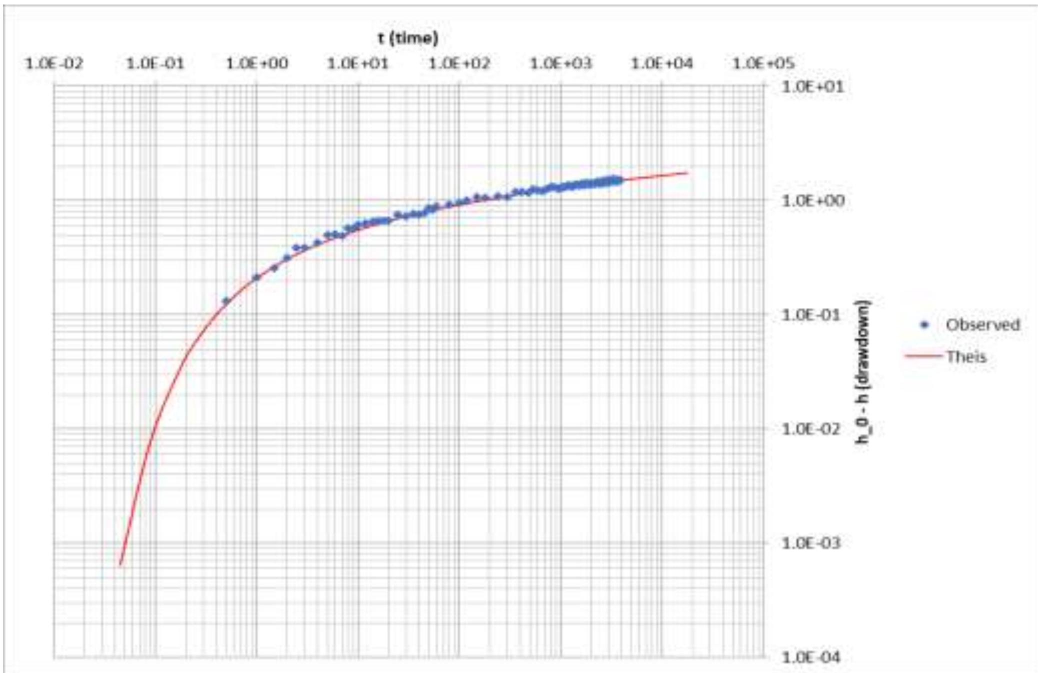

Figure 2-7Theis Curve Matching

2.1.3 Geophysical Investigation (Vertical Electrical Sounding)

Boreholes provide direct information about the subsurface. However, drilling of boreholes is expensive and their density in an area is usually low resulting in a sparsely distributed point data on the subsurface geology. Interpolation of these sparse data for mapping subsurface geology/aquifers can be erroneous because of high degree of spatial variability of subsurface geology in deltaic region, such as Bangladesh. Geophysical methods can be very useful in minimizing the data gap. In this study, vertical electrical survey (VES) has been carried out in a total of 21 locations (3 at each upazila, Figure 2-8). Seven of these 21 points are collocated with the nested monitoring wells and the rest are distributed in between these nested wells.

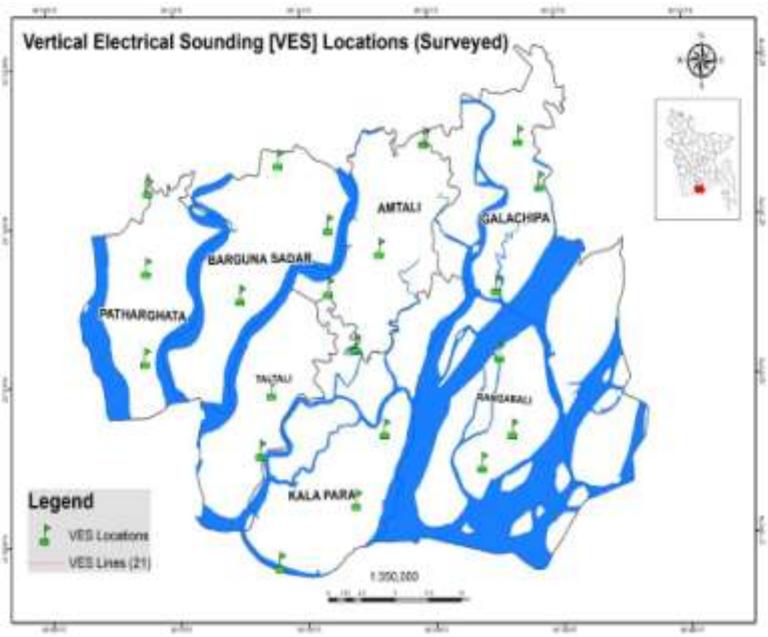

Figure 2-8: Location Map of VES

Procedure: The resistivity of a material is defined as the resistance in ohms between the opposite faces of a unit body of the material. The SI unit of resistivity is ohm-meter. A series of measurements of resistivity are made by increasing the electrode spacing in successive steps about a fixed point. This method of vertical exploration is known as the expanding electrode method, “Resistivity sounding” or “Depth probing” or vertical electrical sounding (VES). The apparent resistivity values obtained with increasing values of electrode separation are used to estimate the thickness and resistivity of the subsurface formations. VES mainly employed in groundwater exploration to determine the disposition of the aquifers.

Electrical resistivity methods rely on measuring subsurface variations of electrical current flow which is exhibited by an increase or decrease in electrical potential (voltage) between two electrodes. It is commonly used to map lateral and vertical changes in subsurface material.

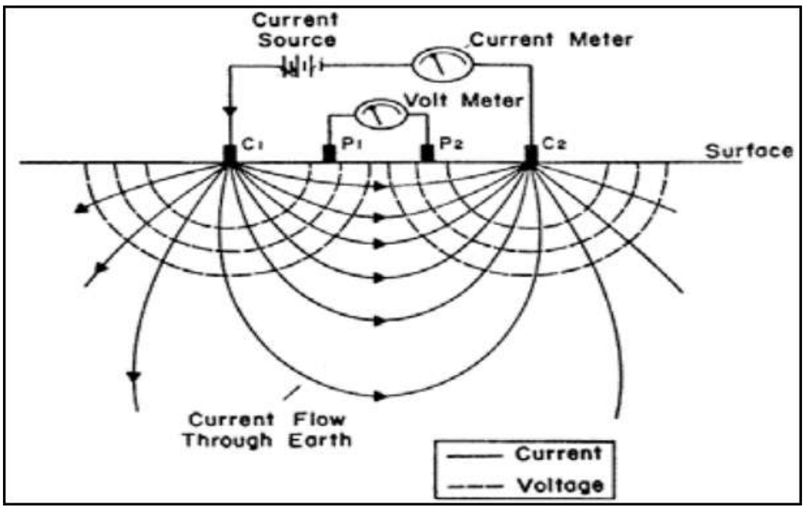

Figure 2-9: Basic Concept of Resistivity Measurement. [Source: Abstracted from Benson et al. (1988)]. Note: C1 and C2, P1 and P2 refer to the current and voltage/potential electrodes respectively.

According to the following formula which is based on Ohm's Law: k ($\Delta V/I$)=ρ ……….. eq 1

Where ρ = Electrical resistivity, ΔV = Potential difference (voltage), I = Applied current, and k = Geometric factor. There are several standard combinations of electrode geometries which have been developed. The value of the geometric factor, k would depend on the particular electrode geometry used. ASTM D6431-99 (2005) indicates that the most common electrode geometries used in engineering, environmental and ground-water studies are the Wenner, Schlumberger and dipole-dipole arrays. These arrays are shown in Figure 2-10.

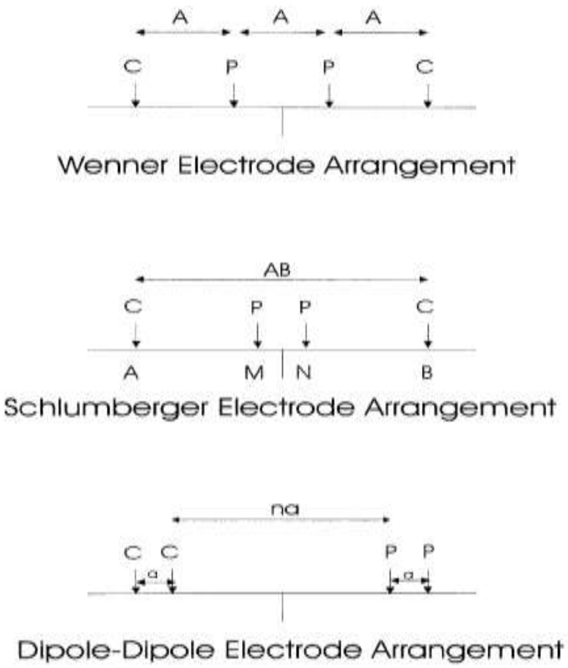

Figure 2-10: Standard Electrode Geometries. Source: Abstracted from ASTM D6431-99 (2005)

Wenner array mainly used for resistivity imaging/profiling and Schlumberger array provide better result in Vertical Electrical Sounding (VES). Dipole-Dipole array is used when survey line is very large with a view to getting greater depth of penetration. In this survey Wenner electrode configuration has been used. The geometric factor (k) for Wenner array of equation-1 is K= 2πa, Where, 'a' is spacing between two electrodes. Hence the equation become ρ =2πa x ΔV/I.

Depth of Penetration: In homogeneous ground the depth of current penetration increases as the separation of the current electrodes is increased. Figure 2-11 shows the proportion of current flowing beneath a given depth Z as the ratios of electrode separation L to depth Z increases. When L=Z about 30% of the current flows below Z and when L=2Z about 50% of the current flows below Z. The current electrode separation must be chosen so that the ground is energized to the required depth, and should be at least equal to this depth (Figure 2-11). Fraction of current penetrating below a depth Z for a current electrode separation AB Proportion of current flowing below depth Z. For Wenner Configuration expected depth of penetration is about one third of the array length (AB/3).

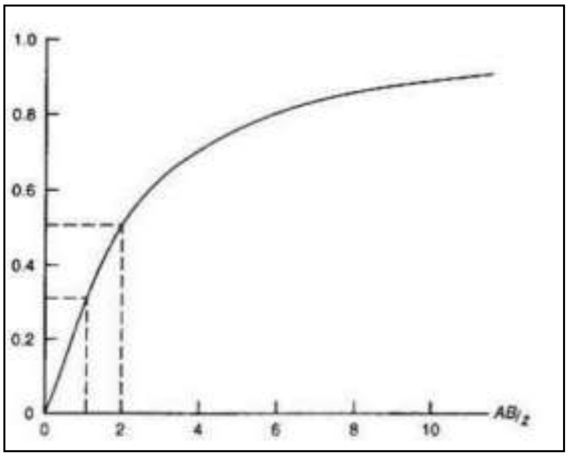

Figure 2-11: Fraction of current penetrating below a depth Z for a current electrode separation AB Proportion of current

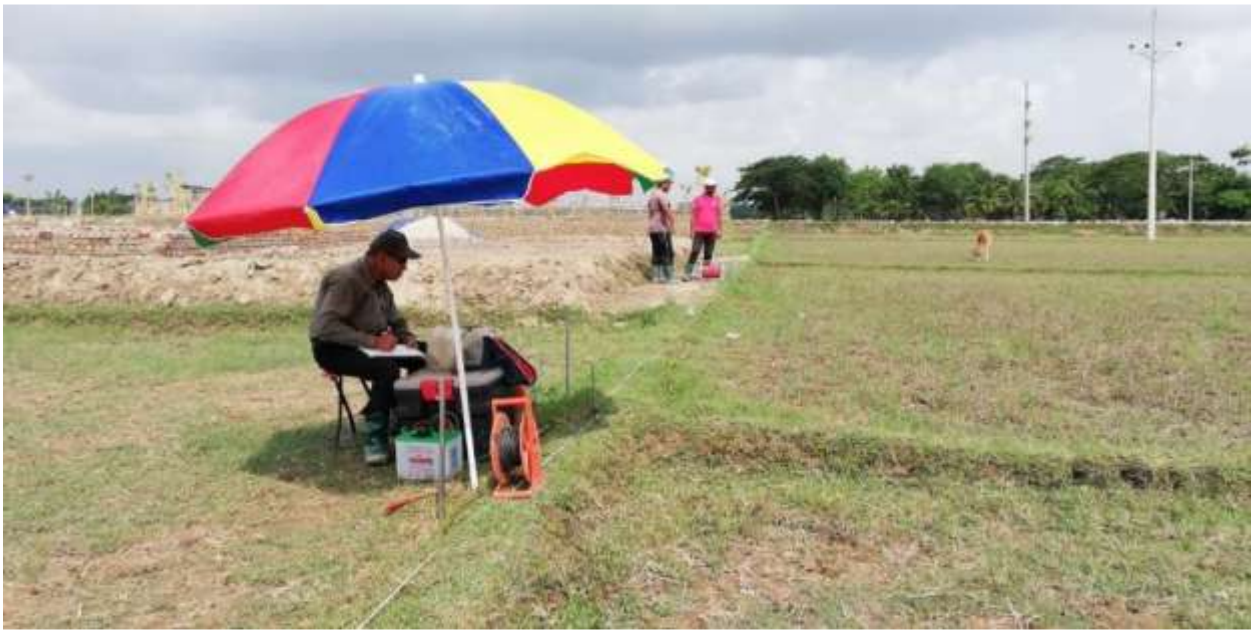

Figure 2-12: Resistivity Survey [Vertical Electrical Sounding (VES)

Interpretation Techniques of Data: When electrical resistivity measurements are conducted in the field, the values obtained are referred to as the apparent resistivity. These apparent resistivity values must be inverted in order to determine the true resistivity. The process of inversion entails comparing plots of apparent resistivity versus depth with master or theoretical curves. This process not only determines the true resistivity, but it also gives an estimate of the respective layer thickness. For the case studies outlined later, the inversion process was conducted using the computer program RES2DINV. The final model obtained through software is taken to be the layered geo-electric image of the subsurface. The field procedure of VES is given in Figure 2-13

Interpretation Steps of VES interpretation: There are two types of procedures of VES data interpretation. 1. Manual Interpretation of Sounding Curves by Complete Curve Matching and 2. Interpretation by Software. The steps of VES interpretation are given below-

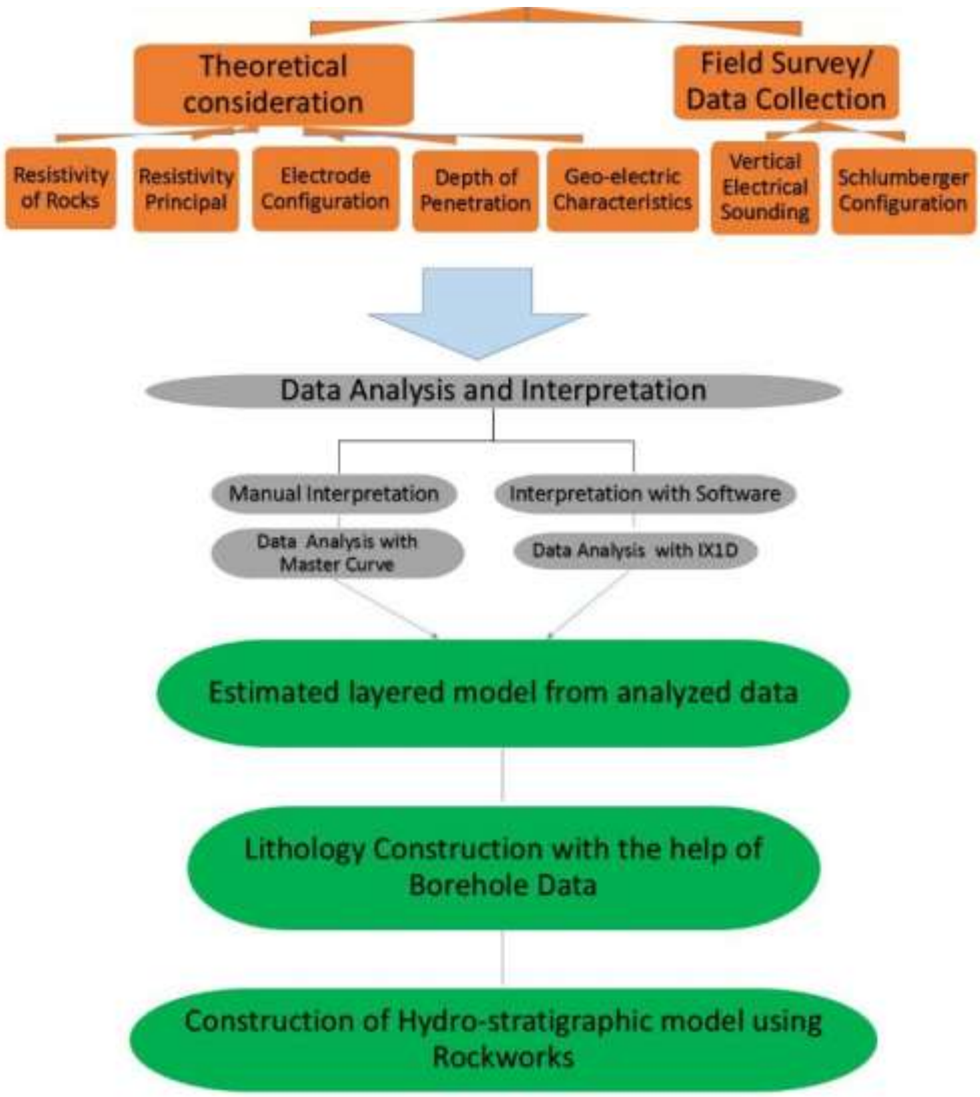

Figure 2-13: Flow chart shows all basic steps followed in methodology

Details of the locations, field data of VES and master curves & interpreted data are given in Appendix-B.

2.1.4 Aquifer Flow Properties Estimation

2.1.4.1 *Grain Size Analysis:*

Grain size analyses were performed to determine the percentage (%) of different grain sizes in the aquifer sediments. It was used both for grain size distribution and sediment classification. Hundred grams (100 gm) of dry and crushed sediment samples were sieved according to the standard method using 35, 60, 120 and 230 mesh size and a pan (Figure 2-14). From the sieving data histogram and cumulative curve (Appendix-C) were prepared and different statistical parameters were computed using the formula in Folk (1966).

Hydraulic Conductivity (K) Estimation from Grain Size Analysis: Hydraulic conductivity of aquifer materials was calculated using modified Hazen formula from grain size distribution curves (Appendix-2). The empirical formula (Hazen, 1911) used for the calculation of hydraulic conductivity is $K = C*(d_{10})^2$. Where, K is hydraulic conductivity in cm/s, d_{10} is the effective grain size in cm, C is a coefficient (for well sorted fine to medium grained sand which varies from 100 to 150) (Fetter, 2014).

Figure 2-14: Photograph showing the grain size analysis in laboratory

2.1.4.2 ***Slug Test***

Since pump test is very expensive, they are usually carried out at only a few locations, providing very sparse data on the aquifer properties. A cheap alternative of pump test is slug test. For high density coverage of hydraulic conductivity data slug test was performed in a large number of wells throughout the study area. During the analysis of the slug test data, it was found that good quality data was available for 87 wells distributed within the study area (Figure 2-15).

Slug test is a field method where a slug (usually a rod) is inserted in a well below the water table (Figure 2-16a), which causes an instantaneous rise of water level in the well. Dissipation of the water level in the well is then recorded, usually; by an automatic water level logger (Figure 2-16b).The temporal rate of this water level declination provides information on the hydraulic conductivity and specific yield/storage of the aquifer surrounding the well. This is a quick but accurate method of estimating hydraulic conductivity in any small diameter tube wells.

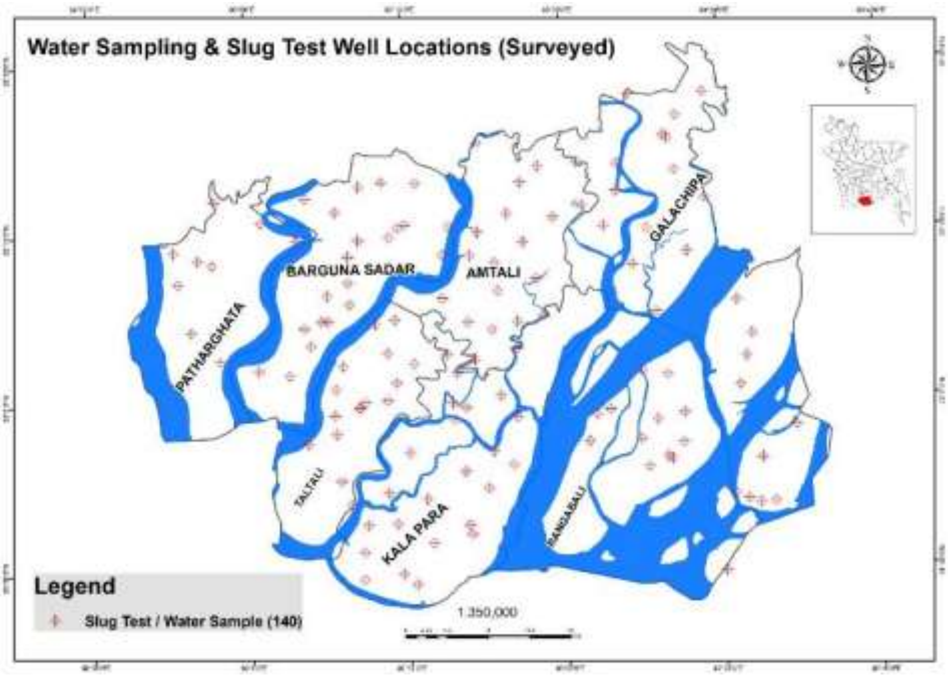

Figure 2-15: Water Sampling and Slug test Location Map

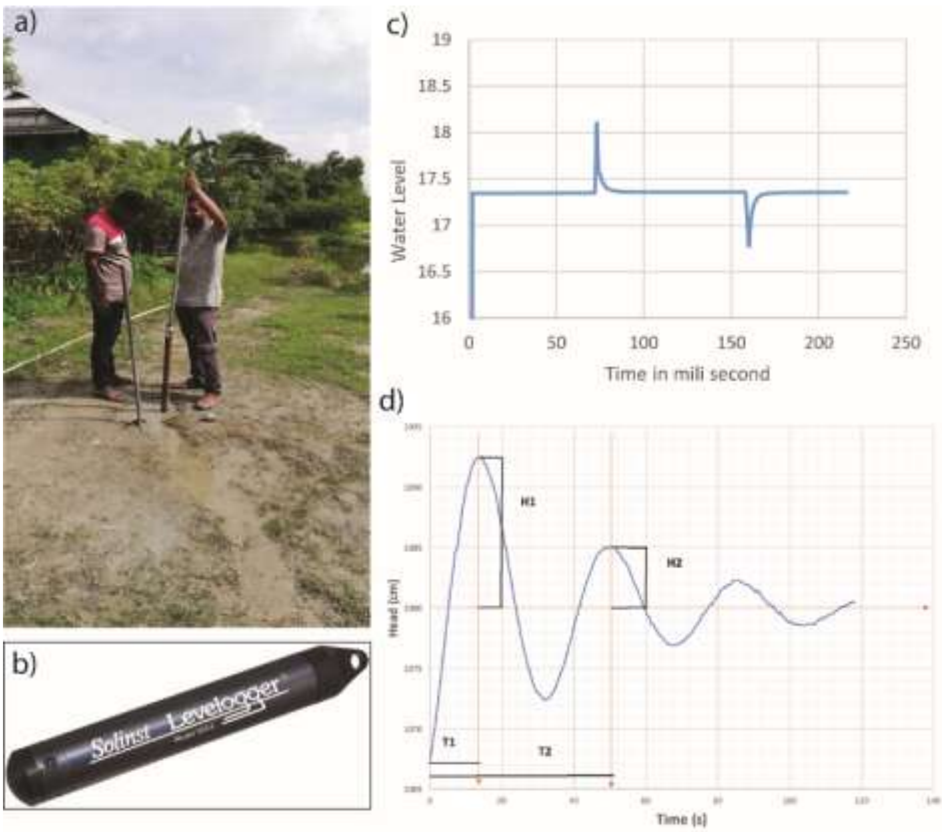

Figure 2-16: Slug Test in Monitoring Well. a) Lowering of a slug in the well, b) automated groundwater level logger pre-installed in the well to record the changes water level after inserting and removing the slug in the well, c) typical overdamped response of groundwater level due to inserting the slug and removing the slug, d) typical underdamped response.

A slug test is a controlled field experiment, performed by groundwater hydrologists to estimate the hydraulic properties of aquifers and aquitards, in which the water level in a control well is caused to change suddenly (rise or fall) and the subsequent water-level response (displacement or change from static) is measured through time in the control well and one or more surrounding observation wells (Figure 2-16).

Slug tests are frequently designated as rising-head or falling-head tests to describe water-level recovery in the control well following test initiation (Figure 2-16b). Other terms sometimes used instead of slug test include baildown test, slug-in test and slug-out test. The goal of a slug test, as in any aquifer test, is to estimate hydraulic properties of an aquifer system such as hydraulic conductivity.

Depending on the groundwater level response (overdamped as in Figure 2-16c or underdamped as in Figure 2-16d), there are analytical methods for estimating hydraulic conductivity from the time vs. groundwater level data. In this study, the Hvorslev method is used for overdamped response and Van Der Kamp method are used for underdamped response. Details of this method can be found in (Fetter, 2014)

2.2 Estimation of Groundwater Recharge Potential

Groundwater recharge may be explained as the process where water moves downward from surface water to groundwater. The amount of water that may be extracted from an aquifer without causing depletion is primarily depends upon the groundwater recharge. Rainfall is the principal sources for groundwater recharge most importantly for shallow aquifer. Estimating the rate of aquifer replenishment is probably the most difficult of all measures in the evaluation of groundwater resources. There are a number of methods or techniques for estimating groundwater recharge. In this research, Chaturvedi formula are used for groundwater recharge estimation. Based on the water level fluctuation and the rainfall amounts on the Ganga-Yamuna doab, Chaturvedi (1973) derived the following empirical relationship to calculate recharge as a function of annual precipitation.

$$R = 2.0\,(P-15)^{0.4}$$

Where, R= Net recharge due to precipitation during the year, in inches and P= Annual precipitation in inches.

Daily and monthly total rainfall data of the study area (Patuakhali-Barguna district) was collected from Bangladesh Meteorological Department (BMD). BMD had four (4) stations in and around the study area at Patuakhai, Khepupara, Bhola and Barisal. Monthly total rainfall data from all four station was averaged to calculate/estimate monthly recharge using Chaturvedi formula.

2.3 Groundwater Quality Assessment

Field work was conducted to collect water samples in 7 upazillas (Amtoli, Rangabali, Golachipa, Patharghata, Kolapara, Taltoloi and Barguna Sadar) of Patuakhali and Barguna districts. Seventy groundwater samples were collected from different locations of study area. Six monitoring wells were sampled for 3 different depth intervals (one at around 100 feet depth, one at around 300 feet depth and the other at around 1000 feet depth) in six upazilas for two different seasons (pre-monsoon and post-monsoon). Groundwater levels at the monitoring wells were measured using an electronic groundwater level meter. Sampling site geo-positions were fixed by using hand held GPS equipment. Afterwards the wells were pumped and water samples were collected for onsite field measurements and laboratory analysis. Location of water samples collected from various depths is shown in Figure 2-17.

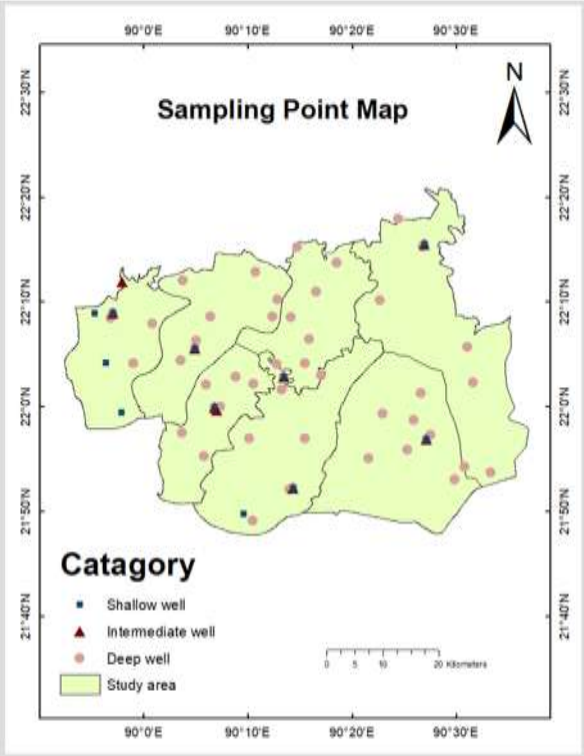

Figure 2-17: Sampling point location map

Figure 2-18: Water Sampling and Field Test.

2.3.1 On-Site Field Measurement

A number of important on-site physical parameters were measured in the field during water sampling, using field test kits for assessing on field water quality (Figure 2-18). It is important assess these parameters to have a fast, comparatively easy and reliable field survey to know the field condition. These parameters include pH, Electrical conductivity (EC), Eh, temperature and Arsenic. For measuring these parameters following field kits were used-

Digital pH and Eh meter (HANNA HI98121): Water sample's pH (Hydrogen ion concentration) and OPR (Oxidation Reduction potential) were measured on spot using water proof pocket pH meter and Eh meter, (Figure 2-19a).

EC meter (HANNA HI98312): EC (Electrical Conductivity) of groundwater and surface water samples were measured by using water proof pocket EC meter. Temperature was also measured simultaneously using the same EC meter, (Figure 2-19b).

Arsenic Field Kit (ITS Arsenic Econo-Quick Test Kit): Used to measure Arsenic concentration in groundwater samples, (Figure 2-19c).

(a)

(b)

(C)

Figure 2-19: (a) Digital pH meter, (b) EC meter, (c) Arsenic Field Kit

2.3.2 Laboratory Analysis:

After field work collected water samples were transported to the Geochemistry Laboratory and preserved in refrigerator for avoiding any chemical changes. After that chemical analysis were carried out in a well-equipped lab with necessary facilities. Sophisticated instruments and established analytical methods were employed for this analysis.

2.3.2.1 *Analytical Method:*

Analytical methods are used to detect and measure all the natural elements and their inorganic compounds and some organic chemical species. Concentration of major, minor and trace ions in collected water sample were determined by using different instruments at the Geochemistry lab of Department of Geology, University of Dhaka. Analytical methods used in the laboratory study is given in Table 2-1, whereas Figure 2-20 shows various analytical equipment used.

Figure 2-20: Instrument used in laboratory analysis. a) Atomic absorption spectrometry, b) ion chromatography, and c) acid based titration

Table 3: Methods and Instruments used for different chemical constituents

Serial No	**Chemical Constituents**	**Methods & Instruments**
1	Calcium (Ca^{2+})	Atomic Absorption Spectrometer (GBC Sens AA)
2	Magnesium (Mg^{2+})	Atomic Absorption Spectrometer (GBC Sens AA)
3	Sodium (Na^{+})	Atomic Absorption Spectrometer (GBC Sens AA)
4	Potassium (K^{+})	Atomic Absorption Spectrometer (GBC Sens AA)
5	Bicarbonate (HCO_3^{-})	Titration Method (Standard H_2SO_4)
6	Chloride (Cl^{-})	Ion Chromatography (Dionex ICS 1100)
7	Sulphate (SO_4^{2-})	Ion Chromatography (Dionex ICS 1100)
8	Nitrate (NO_3^{-})	Ion Chromatography (Dionex ICS 1100)
9	Iron (Fe^{2+})	Atomic Absorption Spectrometer (GBC Sens AA)
10	Manganese (Mn^{2+})	Atomic Absorption Spectrometer (GBC Sens AA)

2.3.2.2 *Analytical Accuracy and Reliability Check:*

To determine the acceptance of analysis, analytical accuracy was checked for each sample. Ionic Balance of analytical data was used to check the accuracy of analysis. Nearly all the data showed a well acceptable value for the accuracy check. The formula for determining ionic balance is-

$$Ionic\ Balance\ (\%) = [\ \Sigma\ Cations - \Sigma\ Anions) / (\Sigma\ Cations + \Sigma\ Anions)] * 100$$

Here, concentrations are expressed in meq/l. If the calculated ionic balance is within 5%, the analysis is assumed to be good (Hounslow, 1995). However, balance up to 10% is acceptable. When values are outside the ±10% range then there is a possibility that some part of the analysis is wrong. It may be for one or all of the following reasons:

- Poor or inaccurate analysis.
- Significant amounts of less common species which were not taken into consideration for ionic balance.
- Very acidic water and H+ was not included

2.3.2.3 *Data Processing and Analysis:*

Excel spread sheet was used to organize all sorts of data. Then these data were processed by using various software and statistical methods such as-

- Microsoft Excel was used for creating water chemistry database and generating graphs and tables.
- Location map, EC and ion distribution maps were done by using ArcGIS 10.3 software.
- Rockworks 15 was used to create lithological cross-sections, fence diagram, 3-D lithological model, piper diagram and stiff diagram.

2.3.2.4 *Data Presentation and Interpretation:*

To evaluate general chemical characteristics of groundwater of the aquifer system various graphical and geospatial analysis system were used. Results from this analysis were used to display the trend, spatial, vertical and seasonal variations of dissolved chemical constituents in groundwater throughout the study area. Figures, tables and graphs were used to present the analysis result. Finally, interpretation and evaluation were made based on the analysed data and graphical representations. All the interpretations were made from geological, hydro-geological, hydrological and hydro-chemical point of view.

2.3.2.5 *Water Quality Index:*

Water quality index (WQI) is a method of summarizing a vast amount of complex water quality data by using a numerical expression to define a certain level of quality indicator (Miller *et al.*, 1986). It is an important parameter to determine the quality and suitability of groundwater for drinking purpose (Tiwari and Mishra, 1985). Horton (1965) proposed the first WQI.

Basically, WQI calculate an index value for each water quality parameters by using a mathematical equation to express the overall quality of water at a certain location and time (Yongera and Puttaiah, 2008).

There are a number of methods for calculating WQI, in which weighted arithmetic index method is one of the most widely used methods. In this method water quality is classified according to the degree of purity by using the most commonly measured water quality parameters (Brown, 1972). In this study for calculating WQI of water samples 13 parameters are taken into consideration which are- Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^-, NO_3^-, Fe, Mn (all in mg/l), EC, pH and TDS. Standards of drinking water quality standards for Bangladesh were used to calculate WQI (DoE, 1997). Equation for calculating WQI is-

$$WQI = \Sigma WiQi / \Sigma Wi$$

Where, Wi = Relative weight of ith parameter, Qi = Quality rating of ith parameter.

Firstly, to calculate relative weight each of the 13 parameters have been assigned with a weight (wi) according to its relative importance in the overall quality of water for drinking purpose such as-parameters having health effects are assigned 4, those which are responsible for decreasing the physical characteristics of water and have slight effects on quality are assigned 3 and parameters with less effects are assigned 2.

Now, Wi can be calculated by using following equation-

$$W_i = w_i / \Sigma w_{,I,} \text{ Here, wi = Weight of each parameter.}$$

The calculated relative weight (Wi) values of each parameter are shown in Table 2-2.

Table 4: Relative weights of the parameters used in WQI calculation

Parameter	BD Standard (Si)	Weight (wi)	Relative Weight (Wi)
Na^+	200	4	0.1
K^+	12	2	0.05
Ca^{2+}	75	3	0.075
Mg^{2+}	35	2	0.05
HCO_3	200	3	0.075
Cl^-	600	4	0.1
SO_4^{-}	400	3	0.075
NO_3	10	4	0.1
Fe	1	3	0.075
Mn	0.1	3	0.075
pH	8.5	2	0.05
TDS	1000	3	0.075
EC	1000	4	0.1
		wi=40	Wi=1

Equation for calculating Qi is –

$$Qi = (Ci/Si) * 100$$

Here, Ci = estimated Concentration of ith parameter in analyzed water sample measured in mg/l (except pH), Si = Recommended standard value for Ith parameter (according to Bangladesh Standard). By summing the WiQi value for each parameter within a sample, value of WQI of that sample can be obtained. After computing WQI, values are classified into five categories according to Vasanthavigar (2009) in Table 2-3.

Table 5: WQI classification (Vasanthavigar, 2009)

WQI (Range)	Water Quality
< 50	Excellent
50-100	Good
100-200	Poor
200-300	Very poor
> 300	Water unfit for drinking

2.4 Groundwater Level Monitoring

After the successful development of the monitoring wells groundwater level at the monitoring wells were measured using an electronic groundwater level meter. A total of Twelve (12) months of groundwater level fluctuations data has been collected.

2.4.1 Manual monitoring of groundwater level

Monthly manual measurement was done in the shallow and in the intermediate wells using an electronic water level measuring instrument (Figure 2-21a).

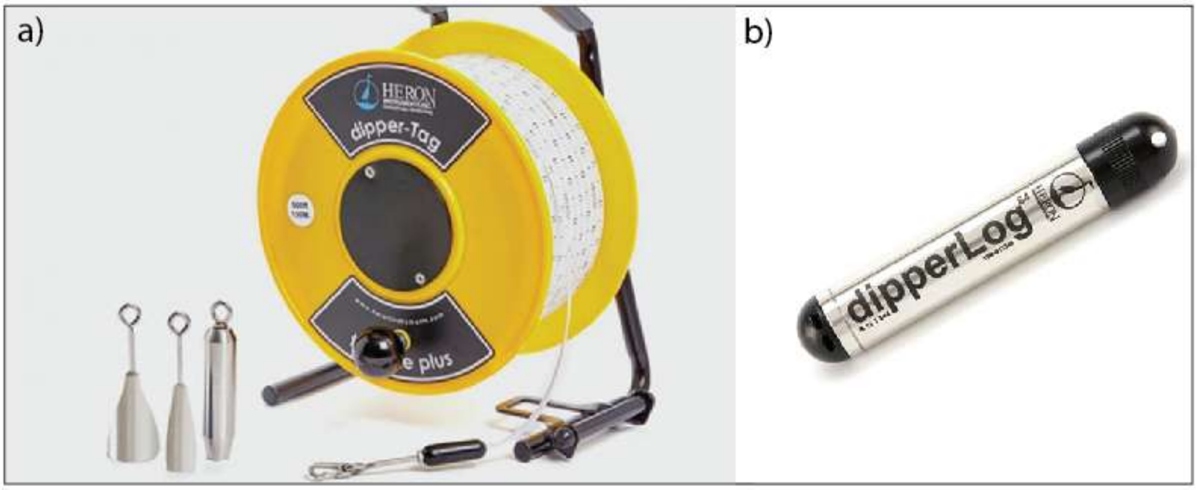

Figure 2-21:a) Heron water level meter, b) Heron dipperLog for automated groundwater level monitoring

2.4.2 Automated monitoring of groundwater level

Automated data logger (Figure 2-21b) is used for measuring the groundwater level fluctuation in the deep wells in half hourly interval. The loggers were installed in the wells and left for one year. Data from the loggers were collected every month by going to the field.

2.5 Estimation of current groundwater abstraction

Like many other areas in Bangladesh there is no reliable data on the current groundwater abstraction in the study area. Data on groundwater abstraction is essential for development of groundwater model that will be used for various scenario analyses. However, it is well known that groundwater in the entire study area is used only for domestic purposes; irrigation in the study area is mainly based on surface water. Therefore, the groundwater abstraction is calculated in this study based on population. The assumption is that per capita groundwater consumption is 50 litres per day. Figure 2-22 shows the population distribution[3] in the study area along with surrounding regions.

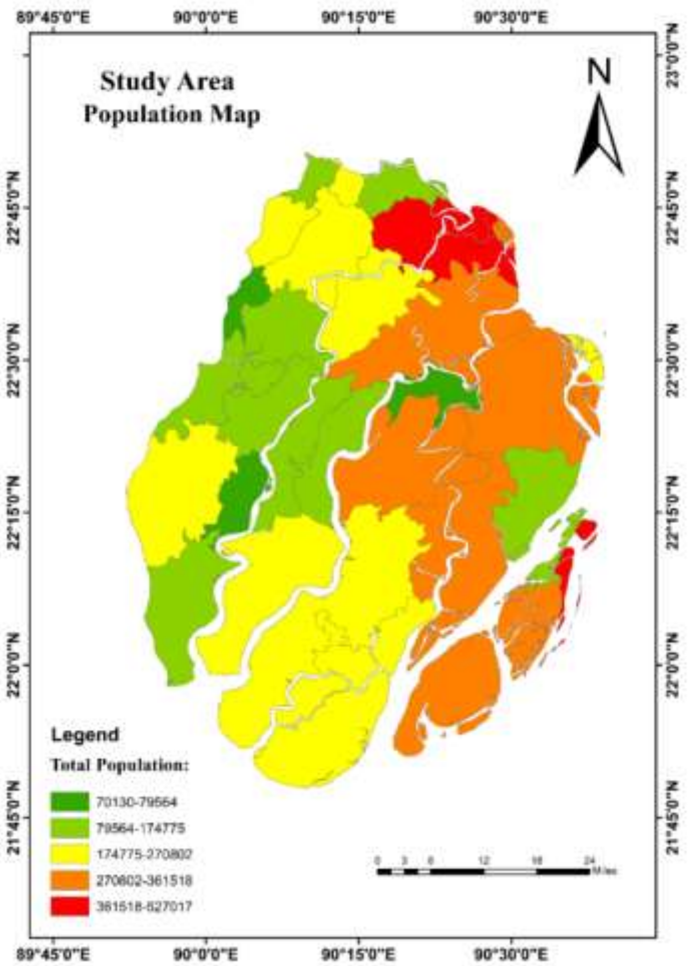

Figure 2-22: Map showing the total population (per Upazila) in the study area

2.6 Groundwater Model Development and Sustainability Analysis

A MODFLOW based 3-D groundwater flow model was developed to characterize the current groundwater flow system, and analysis of the effect of future development in the study area. Detail of the model development, model calibration, and parameterization is discusses in section-6.

[3] Bangladesh Bureau of Statistic (Bangladesh Bureau of Statistics, 2011

SECTION-3: CHARACTERISTICS OF THE AQUIFER SYSTEM

3 Characterization of Subsurface Geology

3.1 Subsurface Geology Depicted from VES

Vertical Electrical Sounding (VES) data were converted to standard lithology. Using these data four lithogical cross sections A-A', B-B', C-C' and D-D' are drawn to observe the vertical and lateral variation of the subsurface geology in the study area. Directions of this cross-section are shown in the Figure 3-1. More lithological cross-sections are shown in the Appendix-B.

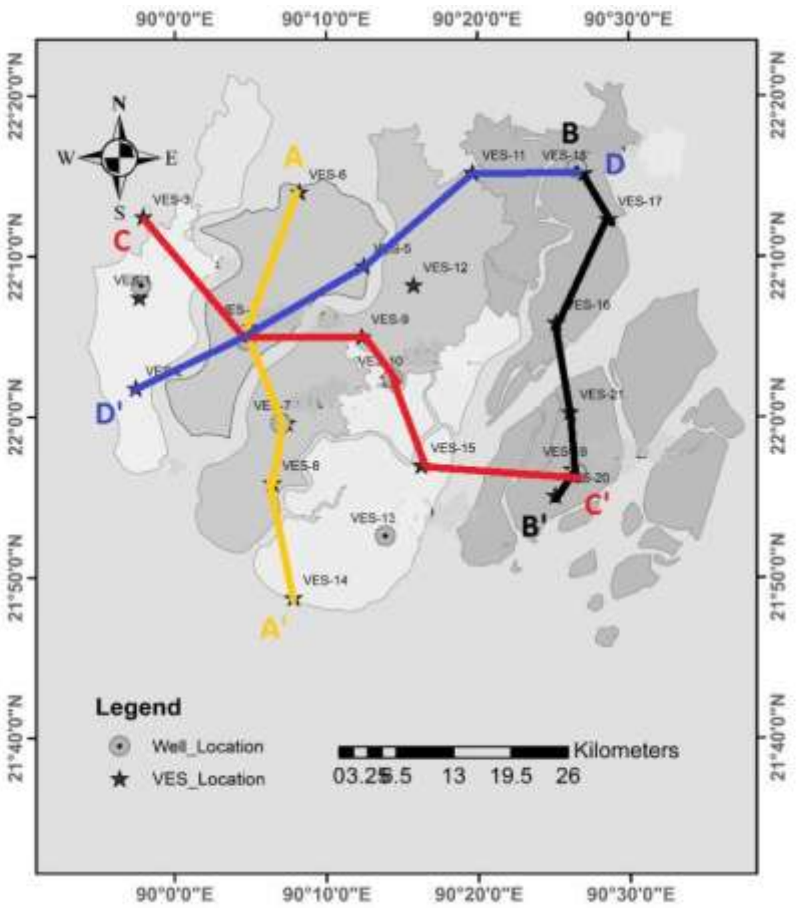

Figure 3-1: Selected lines through the corresponding VES points with respect to their position for lithological cross section.

Cross section along A-A': Cross section AA' along North-South covers five VES points named VES-06, VES-04, VES-07 VES-08 and VES-14 shows non-uniformity in the lithological distribution especially in the grain size (Figure 3-2). Several tidal rivers and channels are in the middle of these VES points such as, Pyra River between VES-4 and VES-07, Andharmanik River between VES-08 and VES-14. Surface is covered by 1-1.5m thin soil layer along the cross section. A uniformly thick clay layer with 10-12 m thickness is found below the top soil layer of Barguna Sadar upazilla. But, at the same depth at taltoli and kolapara upazilla a sand layer of similar thickness is found. A major facies change occurs between VES-04 and VES-07 where Pyra River situated and a thick clay layer exists below this sand layer and thickness of clay layer increases towards south. Headed for further south, textural change occurs to the lithology and establish as a thick silty clay unit. Alternating sand and clay layers occur in the subsurface. There is a great variation in the grain size of sand, finer grains are in the northern part medium and coarse grains at the middle and medium grains at southern part of the cross section. Inter bedded clay layers are non-continuous and indicate frequent changes in the depositional environment.

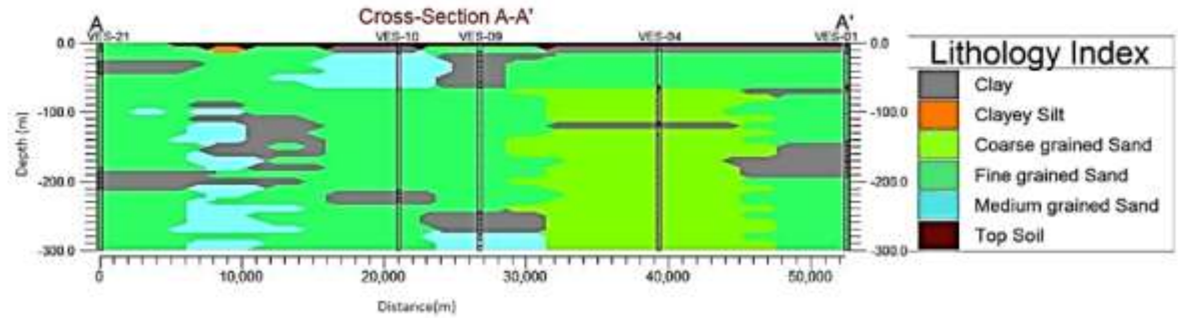

Figure 3-2: Lithological cross section along A-A'

Cross section along B-B': Cross section along BB' across six points VES-18, VES-17, VES-16, VES-21, VES-19 and VES-20 approximately north to south in the eastern part of the study area over Golachipa and Rangabali Upazilla accordingly. A 5-10m thick clayey silt layer is underlying the top soil and almost continuous and uniformly distributed over the northern part (Golachipa) of the cross section. Top soil and clay layer are absent over a large area between VES-16 and VES-19 where Golachipa River flows dividing Golachipa and Rangabali upazilla. Underlying sediments are dominated by fine grained sand, medium grained sand has found in the middle portion of the section below 70 to 80 m depth and a little amount of coarse grained sand observed under VES-17 greater than 100-120 m depth. Lithology along the cross section indicates that upper clay layers are discontinuous and alternating with the sand layers. Continuous clay has found at depth 170 to 180 meters which is thin at northern part and gradually get thicker towards south. Thickness of the clay layers varies from 10 to 40 meters. More than 200 m depth a continuous sand layer with varying grain size act as potential zone for groundwater development (Figure 3-3).

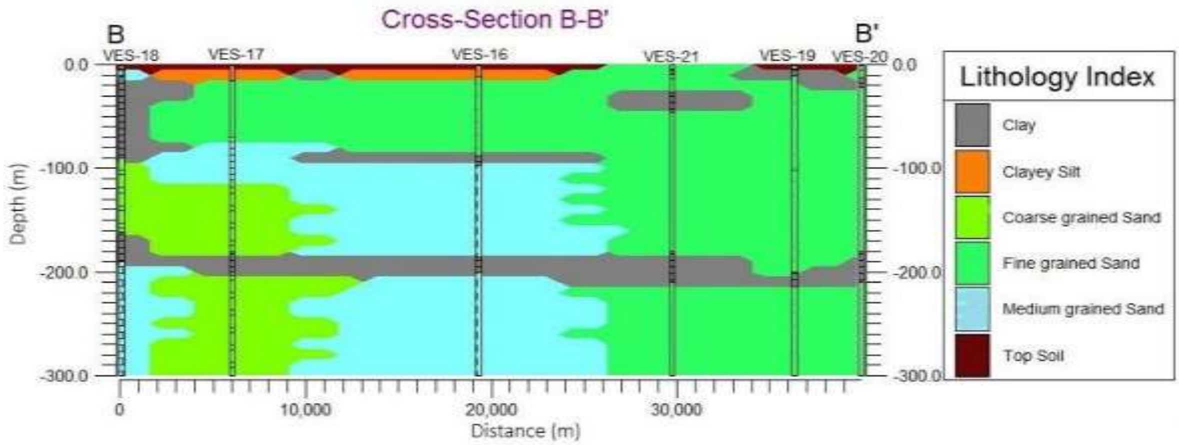

Figure 3-3: Lithological cross section along B-B'

Cross section along C-C': This cross section along C-C' is taken from northwest to southeast and goes through six VES points, VES-03, VES-04, VES-09, VES-10, VES-15 and VES-20 (Figure 3-4). First clay layer beneath the top soil is continuous from northwest part to central part along the cross section and then extinguishes towards south. Thickness of this clay layer is about 40 m to the northwest and middle part but very much thin (5-10 m) between these two thick portions. Cross shows abrupt change in the underlying lithology both laterally and vertically. Distribution of underlying sediments especially clay layers frequently changes throughout the section. Thus any trend for thickness and grain sizes cannot be establish. Subsurface lithology is dominated by sand grains particularly fine grained sand. A thick deposition of coarse grained sand is spotted at 65 m depth with inter-bedded thin clay layer. Clayey silt deposition is coexisted with clay layer at 130 m depth in the northern part of the section.

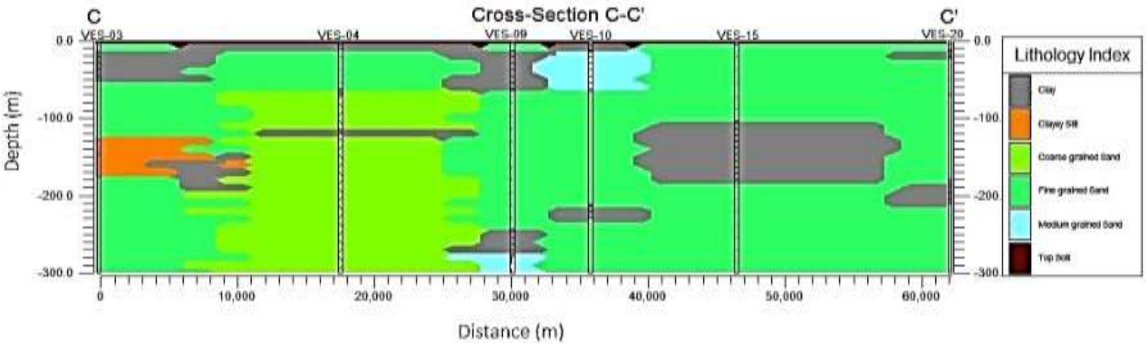

Figure 3-4: Lithological cross section along C-C'

Cross section along D-D': Cross section is taken from northeast to west over following five sounding points, VES-18, VES-11, VES-05, VES-04 and VES-02. Underlying lithology is predominantly composed of alternating sand and clay layers with varying thickness. Clay layer below top soil unit is almost 80 m thick in the northeast part and decreases on the way to western direction. The layer is discontinuous at several places and shows no uniformity in thickness variation (Figure 3-5). Such uneven distribution is also found for other underlying layers. Subsurface sand dominated lithology shows great variation in the sand grain sizes. It displays medium to course to fine grained sand from northeast to western direction.

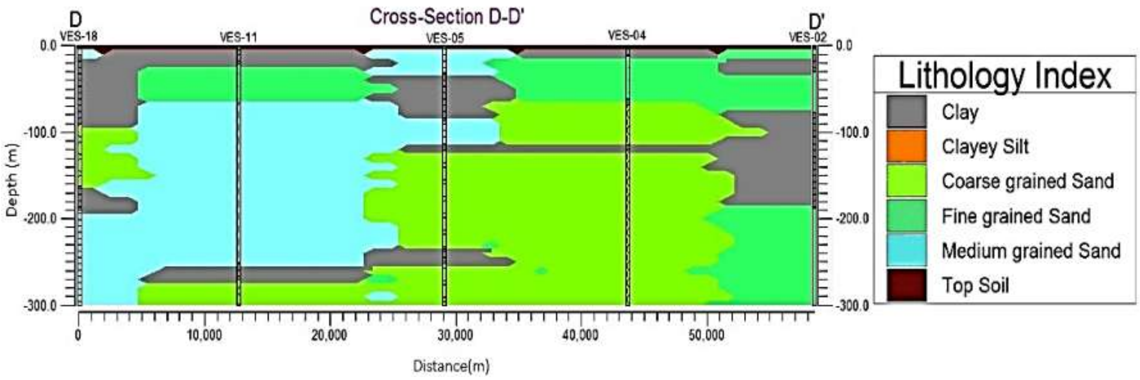

Figure 3-5: Lithological cross section along D-D'

3.2 Subsurface Geology Depicted from Borehole Data

A total of 34 borehole data (Figure 3-6) is used in this study to delineate the subsurface lithology distribution. These boreholes include 7 deep monitoring wells drilled under this study and the remaining data is from Bangladesh Water Development Board (BWDB) and Department of Public Health Engineering (DPHE).

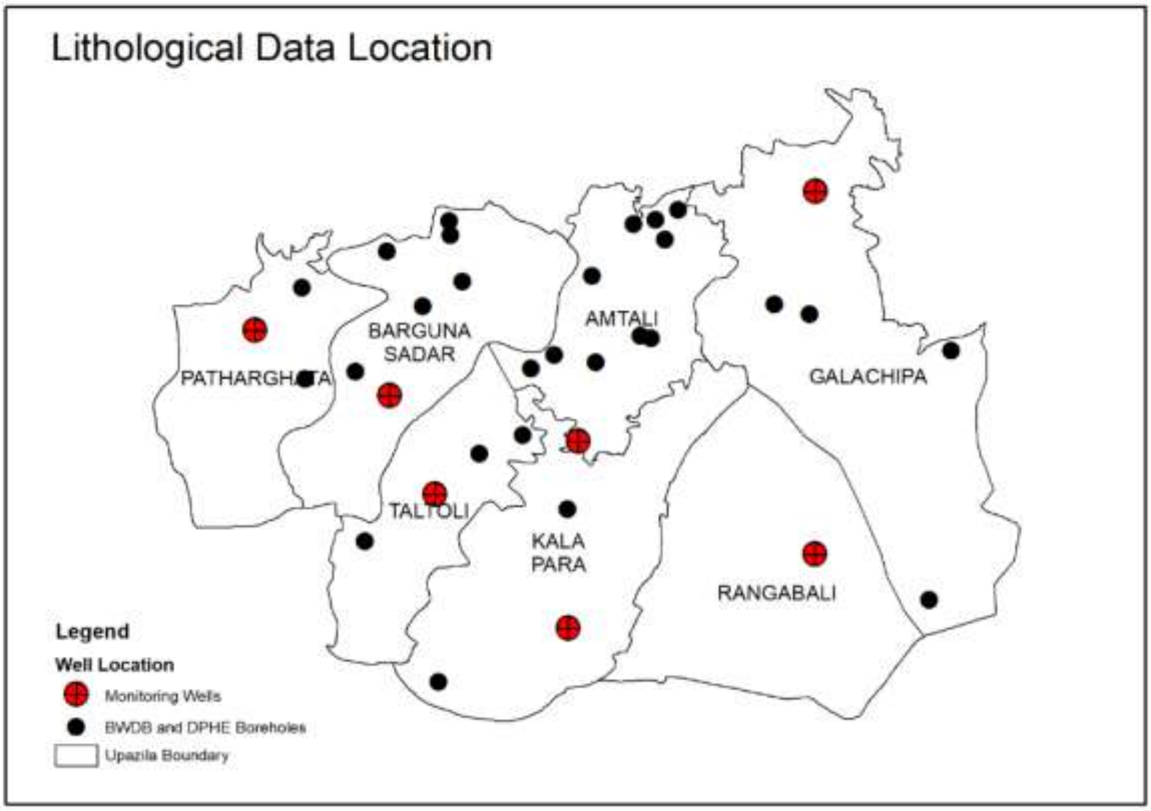

Figure 3-6: Location map of borehole logs used in lithological modelling

A three dimensional lithological model and fence diagrams are prepared in Rockworks software using the above mentioned lithological data (Figure 3-7 and 3-8). The lithological model and fence diagram reveals the complex subsurface distribution of sands and muds. Although individual sands and mud layers are rather discontinuous and can't be traced over the entire region, some simplifications can be made. Specially, the depth interval from land surface down to 300 m can be subdivided into three aquifer zones, namely the shallow aquifer zone, the intermediate aquifer zone, and the deep aquifer zone. The shallow aquifer zone exist between the land surface and to a depth of about 100 m (Figure 3-7 and 3-8).

There is a 20-30 m thick occasionally discontinuous clay underlying the shallow aquifer zone, which separate the shallow aquifer from the intermediate aquifer. Occasional breaks in this clay layers connected the shallow and the intermediate aquifers in some areas. The shallow aquifer is composed of mostly fine to very fine sands. The intermediate aquifer zone extends about 200 m below land surface. This intermediate zone is highly heterogeneous and variable in terms of thickness and lithology. In some areas, there is only one thick aquifer at this intermediate depth where as in other areas there might be multiple aquifers at this depth interval. Lithology of the intermediate aquifer is also variable. It varies from fine to coarse sands. There is 30-50 m thick clay separating the deep aquifer from the intermediate aquifer. Although the thickness of the clay layer is variable, it is rather ubiquitously present in the region. The deep aquifer exists between 200 and 300 m depth interval. This aquifer is composed of fine to medium sands and occasionally coarse sands. In some places the deep aquifer is bifurcated by local clay layers into two separate aquifers. The deep aquifer zone is completely separate from the intermediate aquifer zones. There seems to be no hydraulic connection between these two aquifers.

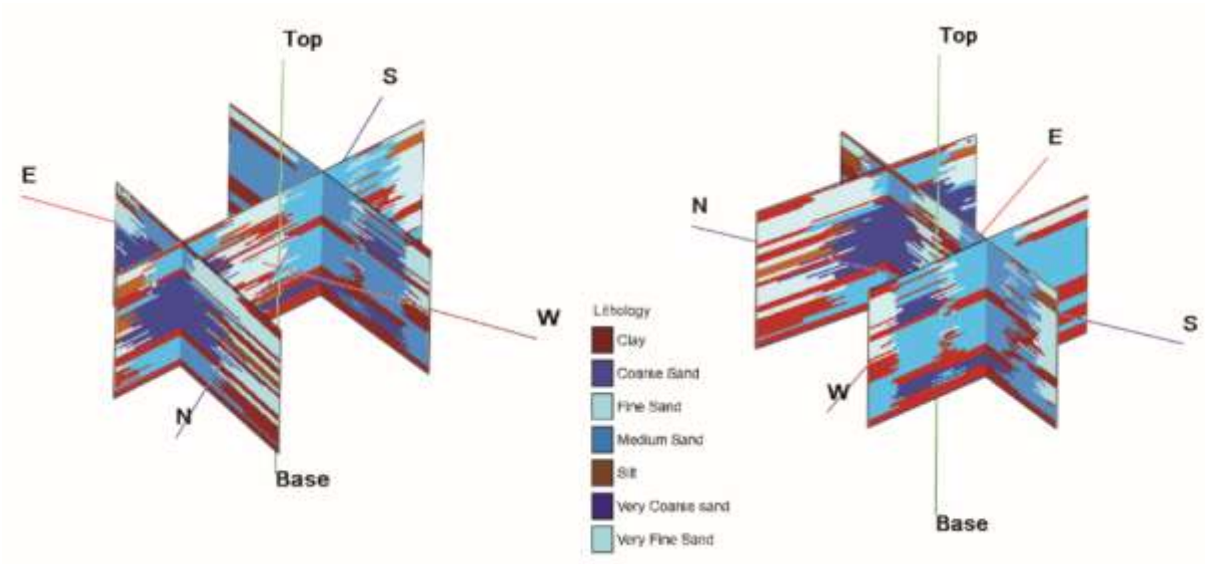

Figure 3-7: Lithological fence diagram

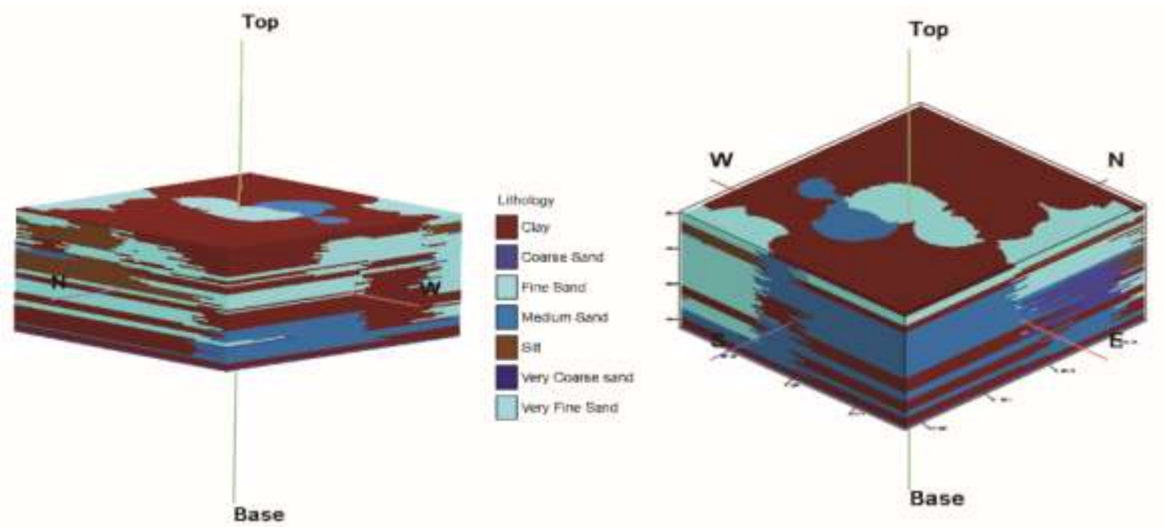

Figure 3-8: 3-D lithological model

3.3 Simplified Layered Aquifer System

Groundwater systems are bounded by natural hydrologic boundaries, they rarely coincide with administrative boundaries. Selection of appropriate model boundary is the most important task in groundwater modelling. Therefore, in order to develop a reliable groundwater flow model, the study area was extended following big rivers as shown in Figure 3-9.

Conversion of the subsurface lithological information into simplified aquifer layers or hydrostratigraphic model is essential for groundwater model development. Since, the model area needs to be bounded by natural hydrologic boundaries; the selected area extends beyond the area of investigation. Although there is no primary data of the subsurface in areas beyond the study area, there are existing lithologic data in department of public health engineering (DPHE) deep borehole database. We have selected a subset of existing data in the larger study area for developing Hydrostratigraphic model. Locations of all boreholes are shown in Figure 3-10.

Figure 3-9: Study area extended to match natural hydrologic boundary. This area was considered for model development

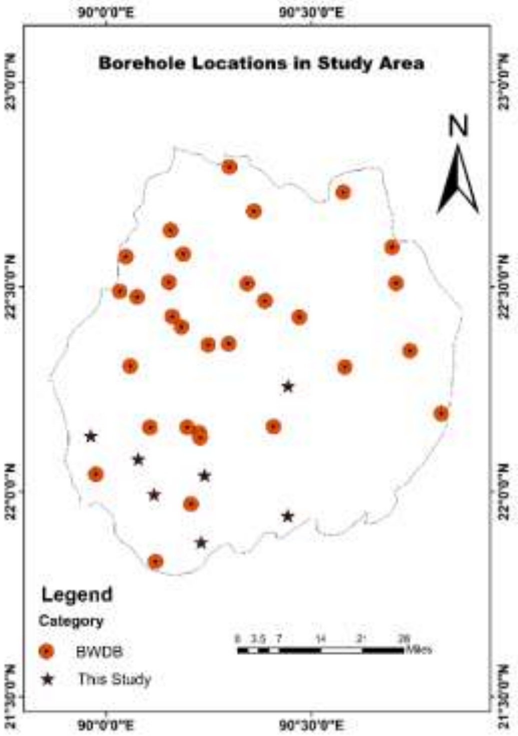

Figure 3-10: Map showing the borehole locations along with BWDB boreholes

In the hydro-stratigraphic model, six (6) stratigraphic layers are shown (Figure 3-11). The upper 50 m of the hydro-stratigraphic model are fallow because this 50 m is considered as the model-Top (upper unconfined aquifer) in groundwater model. In the hydro-stratigraphic model, first layer is identified as aquitard-1 which is composed of mainly clay, silt and silty clay. The layer immediately below the first layer (aquitard-1) is shown as aquifer-1 or 1st aquifer which is composed of fine or medium grained sand with an average thickness of about 37 m. below the aquifer-1, second aquitard (aquitard-2) exist. Below the aquiterd-2, the fourth layer of the model are aquifer-2 occurs at an average depth 150 m with an average thickness of about 36 m. The fifth layer of the model is shown as aquiterd-3 and below which the bottom layer of the model is aquifer-3 at an average depth of about 258 m with an average thickness of about 27 m.

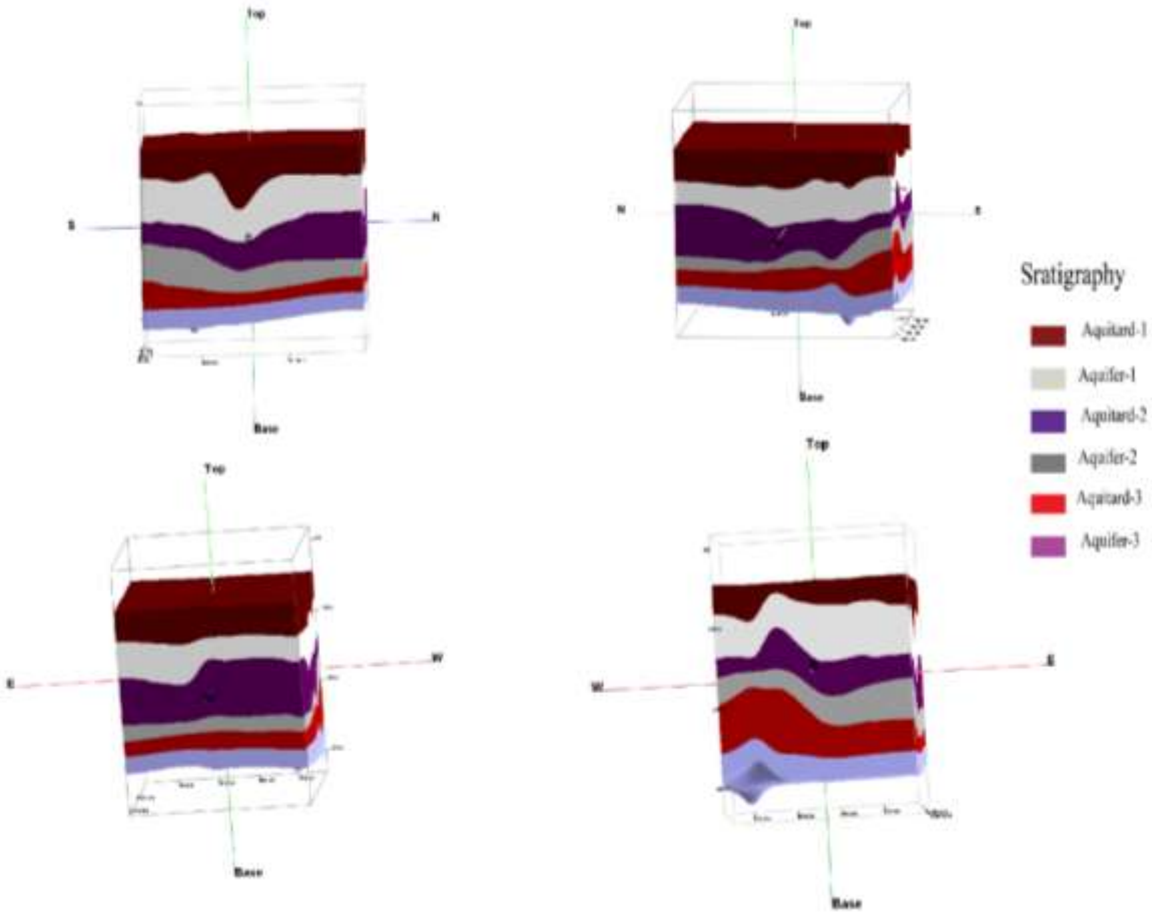

Figure 3-11: 3-D hydro-stratigraphic model of the study area

3.3.1 Aquifer Depth

Three major aquifers are identified in the study area except the uppermost unconfined aquifer which is assigned as upper aquifer in modelling. The first aquifer occurs at shallower depth and in some places the first shallow aquifer is exposed to the ground. Most of the places the first aquifer is covered by a thin layer of top soil.

First aquifer occurs at a depth ranges from 0-180 m and an average depth of about 80 m. In some locations of Galachipa, Mirzaganj, Amtoli, Barguna Sadar and in kalapara upazila the first aquifer is almost exposed to the surface. In northern and southern part of the study area, there are top soil cover ranges from 30-80 m. Top soil cover is maximum at Lalmohon upazila at Bhola and at Bhandaria upazila in Pirojpur district ranges from 150-180 m (Figure 3-12).

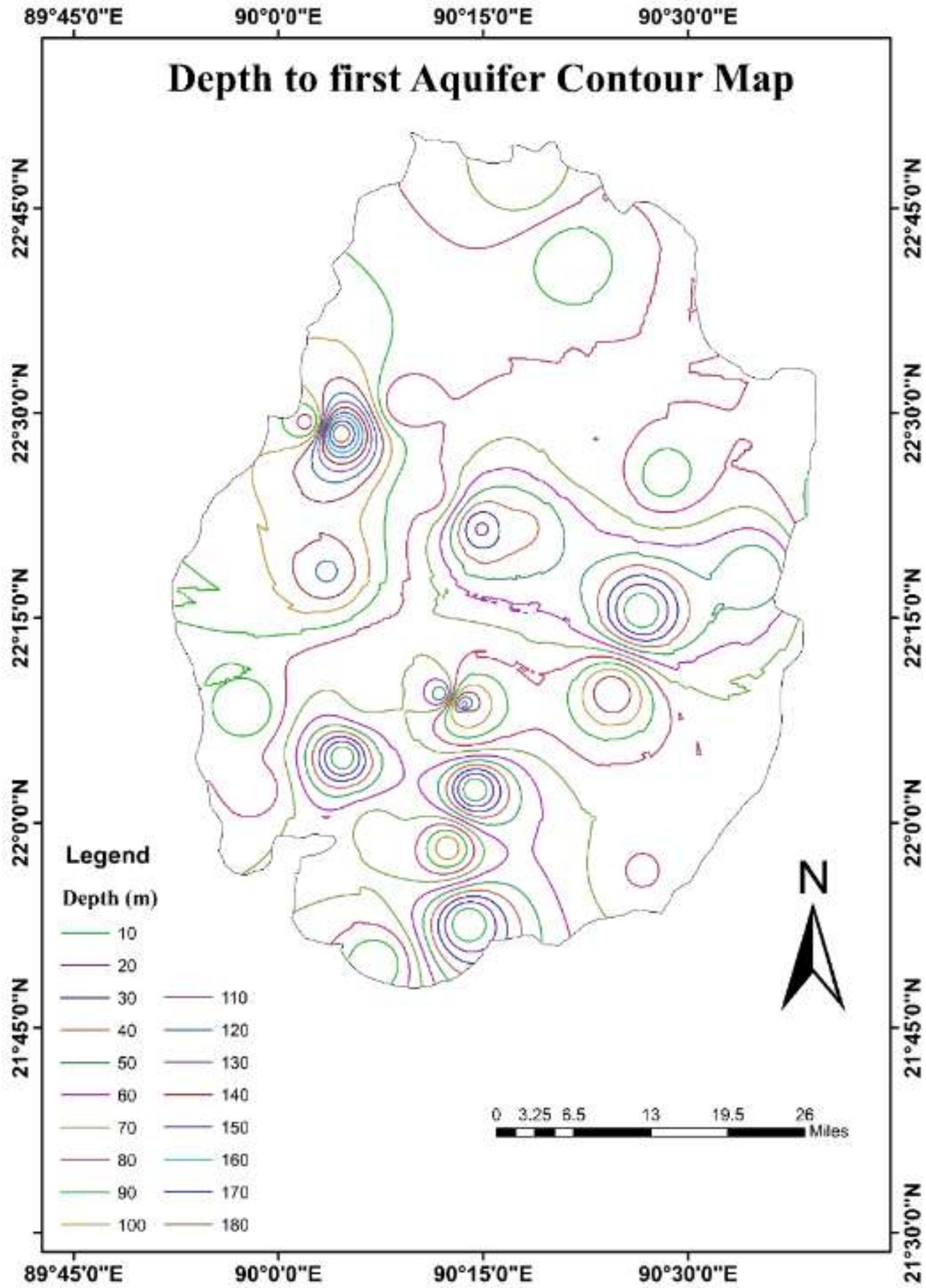

Figure 3-12: Map showing the first aquifer depth contour

Second aquifer occurs at a depth ranges from 70-250 m and an average depth of about 150 m. In the central part of the study area, second aquifer occurs at the lowest depth ranges from 70-130 m. In Lalmohon, Bhandaria, Patharghata, Barguna sadar, Galachipa and in Rangabali upazila the second aquifer occurs at the highest depth, ranges from 160-250 m (Figure 3-13).

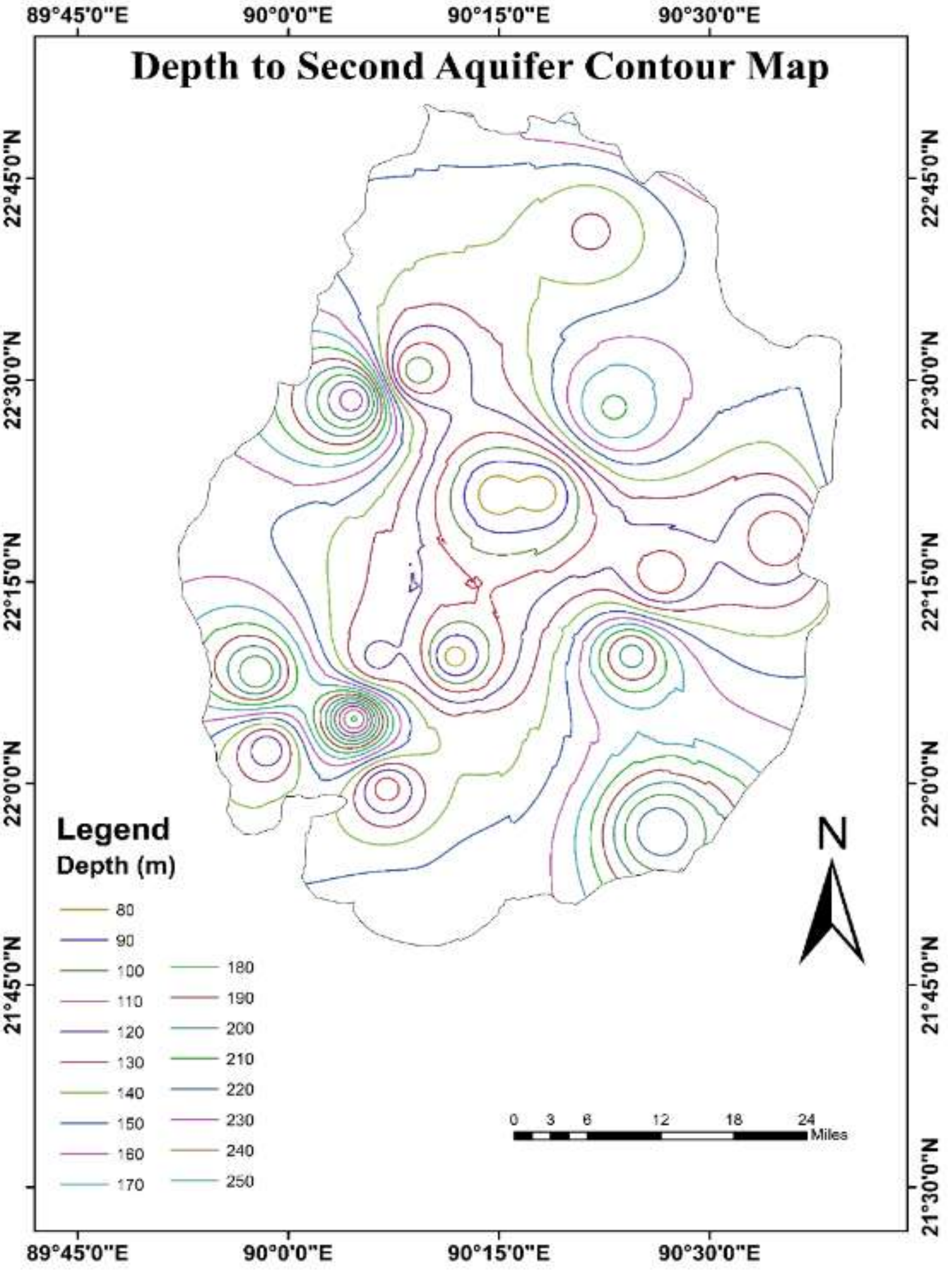

Figure 3-13: Map showing the second aquifer depth contour

Third aquifer occurs at a depth ranges from 229-315 m and an average depth of about 258 m. In the northern part of the study area the depth of the third aquifer are lowest and in the southern part of the study area depth are highest except in Kolapara upazila. In Barguna Sadar, Kalapara, Taltoli and Amtoli upazila the depth of third aquifer are lowest and it ranges from 229-250 m and in Barisal Sadar, Taltoli, Rangabali, Patharghata, Muladi, Dumki upazila the depth are highest which ranges from 265-315 m (Figure 3-14). It is usually considered as the main aquifer here for fresh water exploitation.

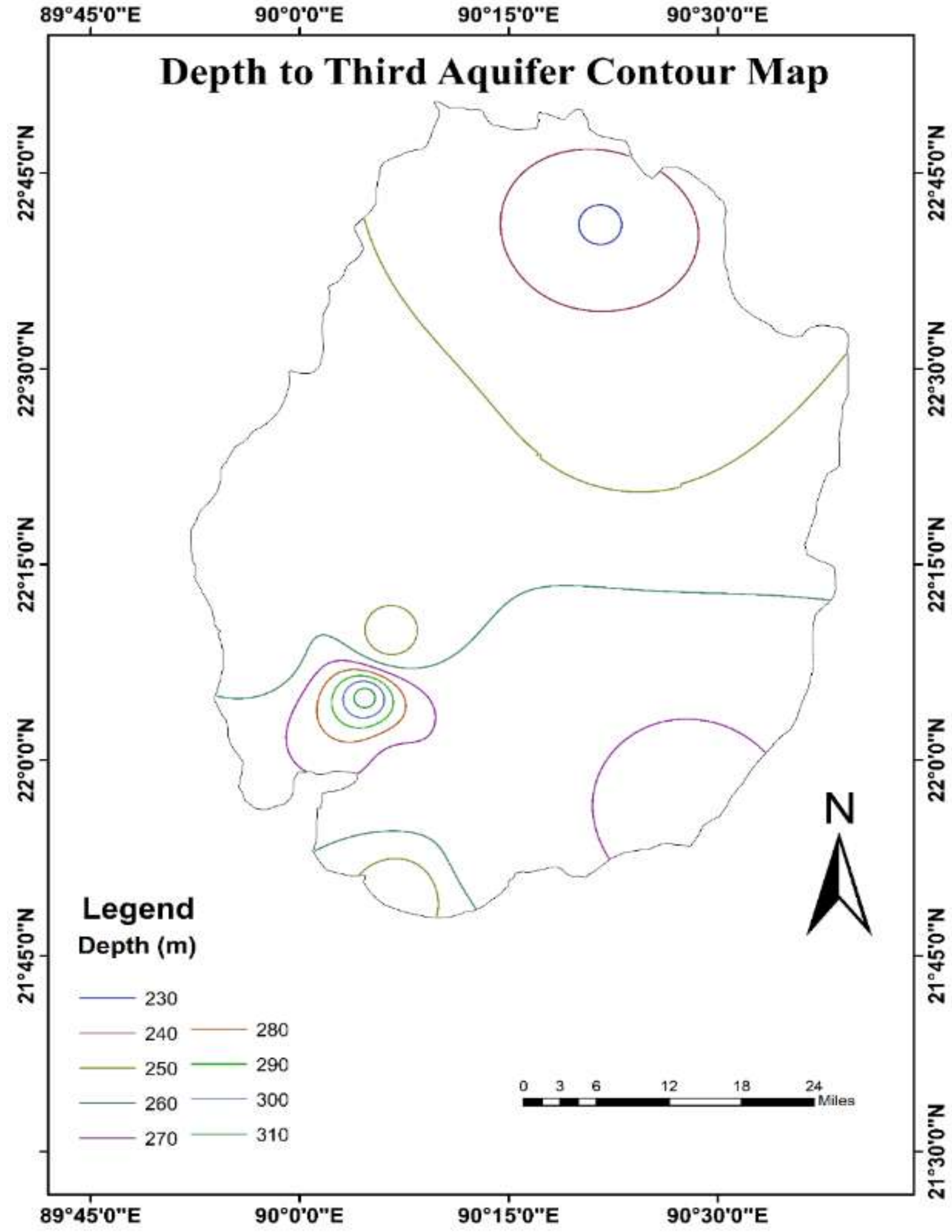

Figure 3-14: Map showing the third aquifer depth contour

3.3.2 Aquifer Thickness

The thickness of the first aquifer of the study area ranges from 6 m to 235 m with an average thickness of about 35 m. Aquifer thickness gradually increases towards the south-east and south-western part of the study area. Maximum thickness occurs at Barguna Sadar upazila, ranges from 200-235 m and most of the other parts have thickness ranges from 6-50 m (Figure 3-15).

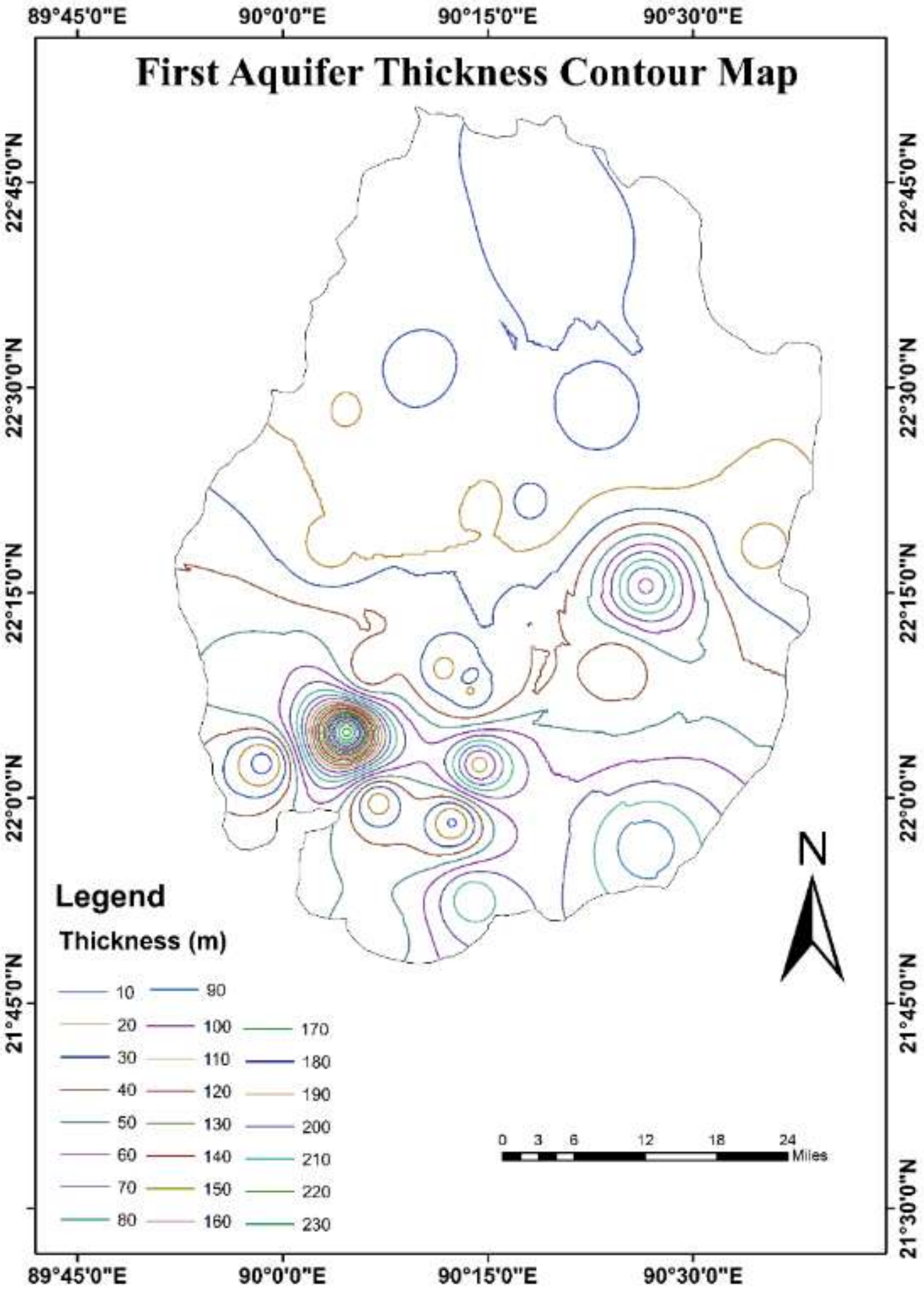

*Figure 3-15***:** *Map showing the first aquifer thickness contour*

The second aquifer is separated from first aquifer by a thick aquitard. The thickness of second aquifer ranges from 9-175 m with an average thickness of about 38 m. Maximum thickness occurs at Galachipa upazila ranges from 140-175 m. In the northern, north-west, north-east, south-central and south-western part of the study area second aquifer thickness ranges from 9-35 m (Figure 3-16).

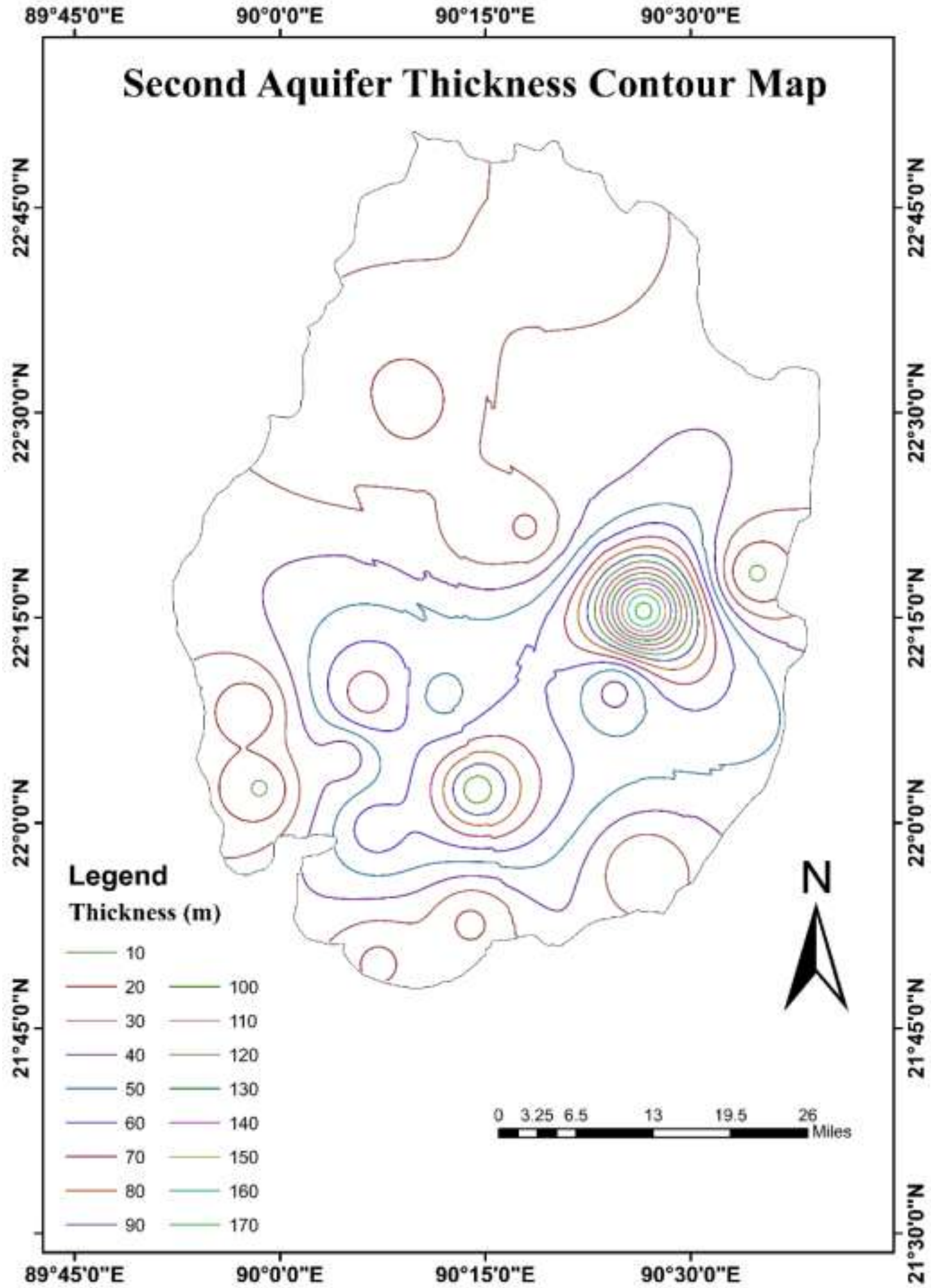

Figure 3-16: Map showing the second aquifer thickness contour

The third aquifer is also separated from second aquifer by thick aquitard. The thickness of third aquifer ranges from 9-50 m with an average thickness of about 27 m. In the northern part of the study area the thickness is lowest which ranges from 9-15 m and it gradually increases towards east, west and southern part. Patharghata upazilla shows the maximum third aquifer thickness which ranges from 43-50 m (Figure 3-17).

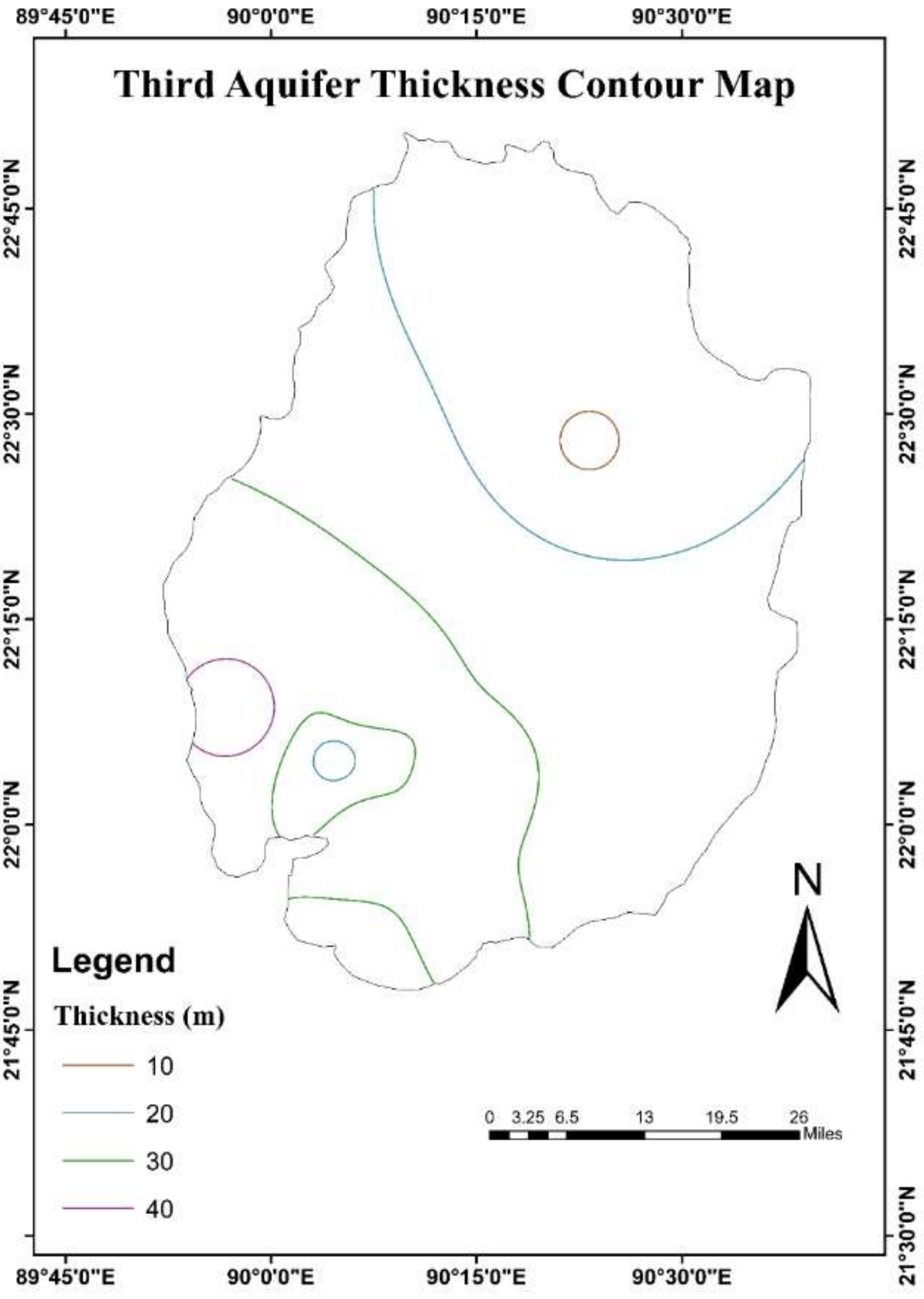

Figure 3-17: Map showing the third aquifer thickness contour

3.4 Groundwater Flow properties of the Aquifer

Hydraulic conductivity (K) is the ability of sediment to transmit water through a unit width of aquifer under a unit hydraulic gradient (Fetter, 2014). In general, hydraulic conductivity varies with particle sizes; finer particles exhibit lower values of hydraulic conductivity whereas coarser particles exhibit higher values. Hydraulic conductivity values measured by the empirical equation (Hazen, 1911) ranges between 3.51 and 8.53 and 5.26 and 12.79 m/day for C=80 and C=120 (the constant in the Hazen formula) respectively (Table 3-1). The average of all grain size derived hydraulic conductivity is about 6.95 m/day. This is similar to the average hydraulic conductivity value of 3.41 m/day determined by slug test at various locations. Though the ranges of hydraulic conductivity value are narrow, there are some variations in hydraulic conductivity in both vertical and lateral directions. Highest hydraulic conductivity is found by grain size analysis in Amtoli, Taltoli and Rangabali upazila. Hydraulic conductivity of individual sample is given in (Appendix-C)

Hydraulic conductivity is also measured from slug test data at eighty-five locations in the study area. Hydraulic conductivity measured from slug test data varies from 0.31 to 8.46 m/day (Figure 3-18). Hydraulic conductivity is low in Kalapara upazila which is in the south-central part of study area and some parts of Galachipa upazila. Rangabali and Barguna Sadar upazila shows the highest hydraulic conductivity ranges from 5.5 to 8.5 m/day. Rest parts of the study area shows hydraulic conductivity ranges from 1 to 5.5 m/day (Figure 3-18). Hydraulic conductivity value measured by slug test is provided in (Appendix-C).

Table 6: Summary of hydraulic conductivity from grain size analysis

Depth Zone	No. of Samples	Hydraulic conductivity [m/d]		
		Maximum	Minimum	Mean
Shallow	21	6.6	0.09	2.26
Intermediate	35	13.5	0.16	3.5
Deep	35	28.6	0.1	10.4

Among the monitoring well, MW-4 (Monitoring well-4) at Patharghata represents the highest hydraulic conductivity of about 8.46 m/day and this is the highest hydraulic conductivity in the study area measured from slug test data. Conversely MW-1 (Monitoring Well-1) at Taltoli shows the lowest hydraulic conductivity of about 2.38 m/day. The deep aquifer of MW-2 (Monitoring Well-2) at Amtoli upazila shows the hydraulic conductivity about 5.19 m/day, whereas the deep aquifer of MW-3 (Monitoring Well-3) at Barguna Sadar upazila shows the hydraulic conductivity of about 6.16 m/day and the deep aquifer of MW-7 (Monitoring Well-7) at Taltoli Upazila shows the hydraulic conductivity of about 3.85 m/day (3-18).

In the study area (Patuakhali-Barguna district) shallow wells shows the lower hydraulic conductivity ranges from 0.68 to 4.71 m/day with an average of about 2.26 m/day. Within the shallow wells MW-4 (Monitoring Well-4) at Patharghata upazila shows the lowest hydraulic conductivity of about 0.68 m/day and MW-1 (Monitoring Well-1) at Taltoli upazila shows the highest hydraulic conductivity of about 4.71 m/day. The intermediate wells show hydraulic conductivity ranges from 1.55 to 6.21 m/day with an average of about 3.52 m/day where MW-1 (Monitoring Well-1) at Taltoli upazila shows the lowest hydraulic conductivity of about 1.55 m/day and MW-4 (Monitoring well-4) at Patharghata upazila shows highest hydraulic conductivity of about 6.21 m/day. The deep wells of the study area show hydraulic conductivity ranges from 4.56 to 18.41 m/day with an average of about 10.41 m/day. MW-2 (Monitoring Well-2) at Amtoli Upazila shows lowest hydraulic conductivity of about 4.56 m/day whereas MW-1 (Monitoring Well-1) at Taltoli Upazila shows highest hydraulic conductivity of about 18.41 m/day.

The Deep well of the study area shows highest hydraulic conductivity with an average of 10.41 m/day conversely Shallow wells shows the lowest hydraulic conductivity with an average of about 2.26 m/day and the intermediate wells shows the moderate hydraulic conductivity with an average of about 3.52 m/day. A comparison of hydraulic conductivity measure by two methods in deep wells is shown in Figure 3-19.

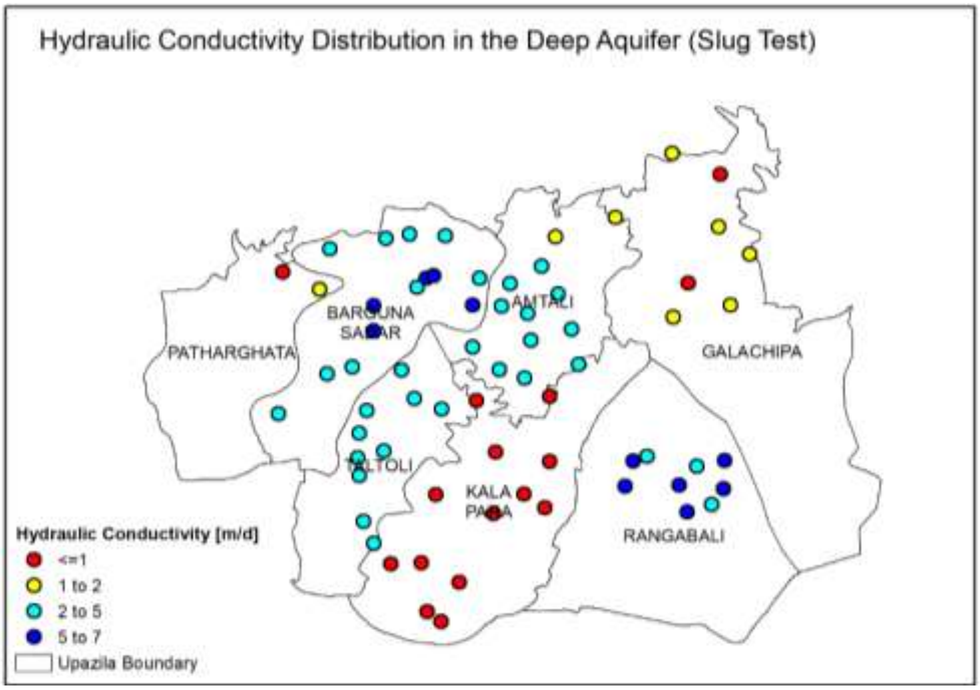

Figure 3-18: Hydraulic conductivity distribution in the deep aquifer measured by slug test

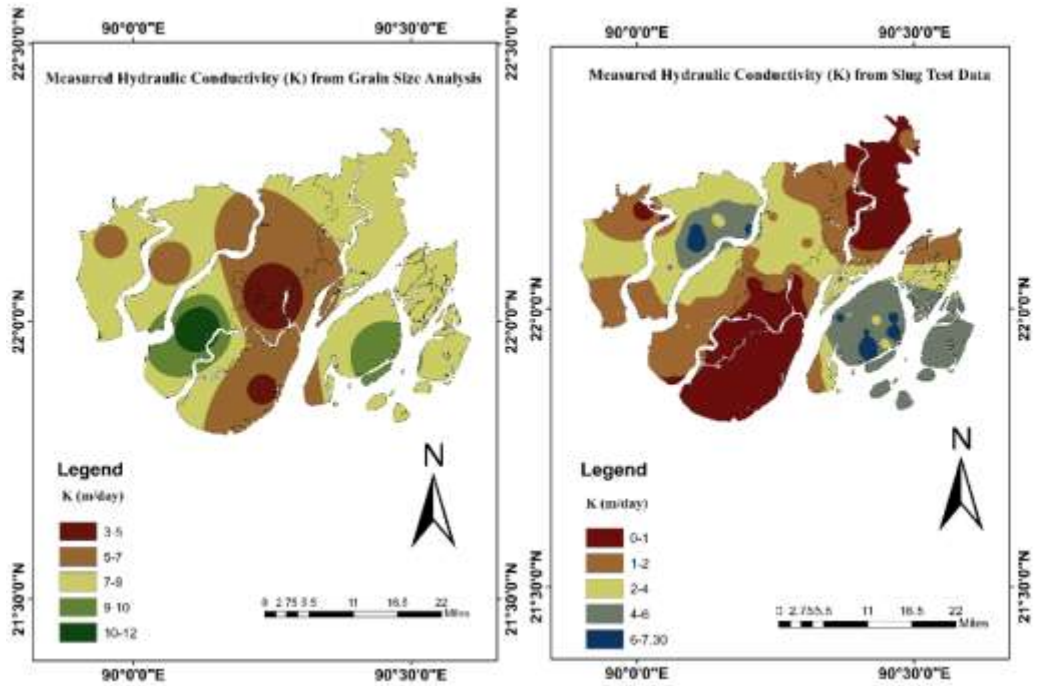

Figure 3-19: Map showing the measured hydraulic conductivity in the study area both from grain size analysis and slug test data

SECTION-4: GROUNDWATER LEVEL DYNAMICS

4 Groundwater Level

A total of Twelve (12) months of groundwater level fluctuations data in all of the monitoring wells has been collected. Automated data logger is used for measuring the groundwater level fluctuation in the deep well in half hourly interval. Monthly manual measurement was done in the shallow and in the intermediate wells.

4.1 Groundwater Level in Deep Aquifers

Among the three aquifer zones, the deep aquifer exhibits the least variation in groundwater level with time. Except in Galachipa, the differences between the dry and wet season depth to water vary between 0.4 and 0.8 m. In Galachipa groundwater in deep well fluctuated about 1.5 m within the same time period. The least seasonal variability is found in the Amtoli well.

Since early November deep groundwater level in this area shows a steady decrease. One striking feature about the deep groundwater level in this area is that in all 7 upazilas the deep aquifer has almost exactly same water level response, all small fluctuations have been observed at the same time at all locations except in Amtoli. The characteristics of the water level data of the Amtali well are completely different than all other monitoring wells. This suggests that probably the Amtoli monitoring well is screened in an isolated pocket aquifer. The deep aquifer seems to respond to tides but the tidal effect is only a few centimeters. Low seasonal fluctuations and minimum tidal effect on the deep aquifer water level suggest that this aquifer is rather isolated from the shallow aquifers and surface water bodies. Also, this aquifer may not receive any vertical groundwater recharge in this area; the small seasonal fluctuation is probably due to the loading and unloading (recharge/discharge) effect of the shallow aquifer.

Our groundwater monitoring data of a year is suggesting potential aquifer level declination regionally. Except in Amtoli, post-monsoon groundwater levels in all other monitoring wells did not recovered to the previous year’s level (Table 4-1). All of those wells lagged by an amount of 20 to 50 cm to the previous year’s level. This could be an indication of regional scale groundwater resource declination in the deep aquifer. However, it should be noted that we have only one year of data, and no concrete conclusion can be made based on this.

Station ID	Location	Maximum depth to water [m]	Minimum depth to water [m]	Seasonal Fluctuation [m]	Annual Recovery deficiency	Annual Recovery deficiency %
MWTT-1	Taltoli	2.8	2	0.8	30 cm	10.71%
MWAT-1	Amtoli	4.2	3.8	0.4	0 cm	0%
MWKP-7	Kalapara	1.9	1.2	0.7	30 cm	23%
MWBS-3	Barguna Sadar	2.5	2	0.5	30 cm	9.50%
MWPG-4	Patharghata	3.3	2.9	0.4	20 cm	6.60%
MWRB-6	Rangabali	1.8	1.1	0.7	30 cm	23%
MWGC-5	Galachipa	4.5	3	1.5	50 cm	10%

Table 7: Summary of deep groundwater level

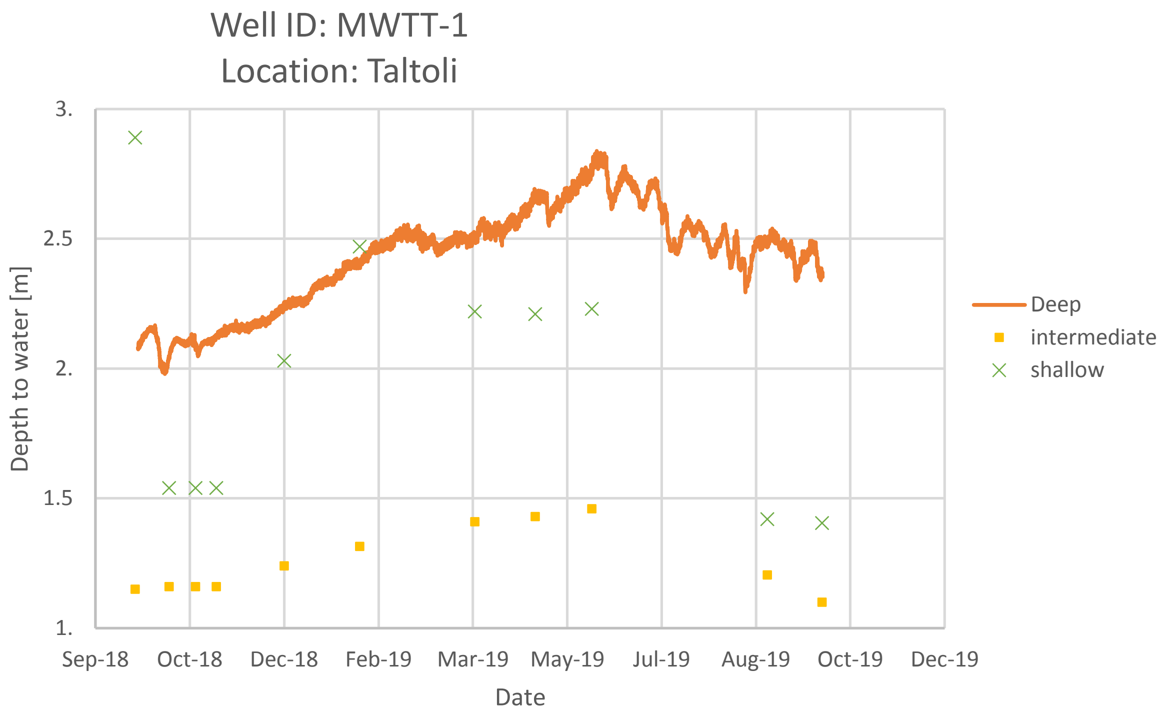

Figure 4-1: Groundwater Level in Taltoli Upazila

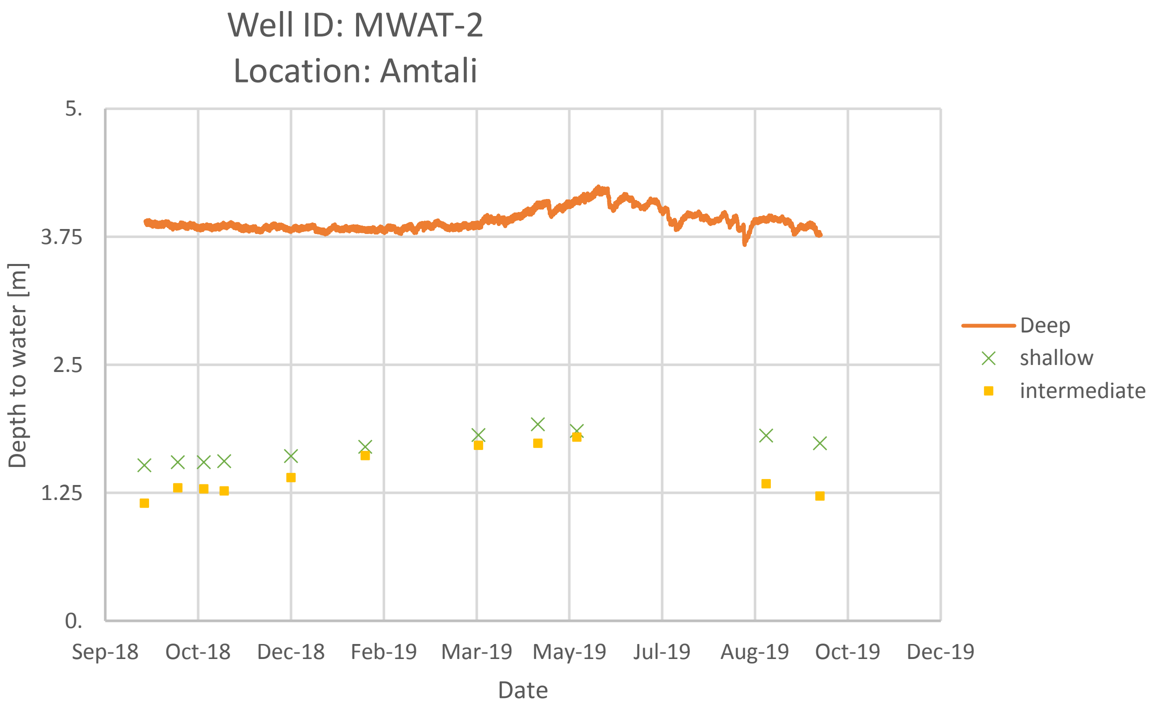

Figure 4-2: Groundwater level in Amtali upazila

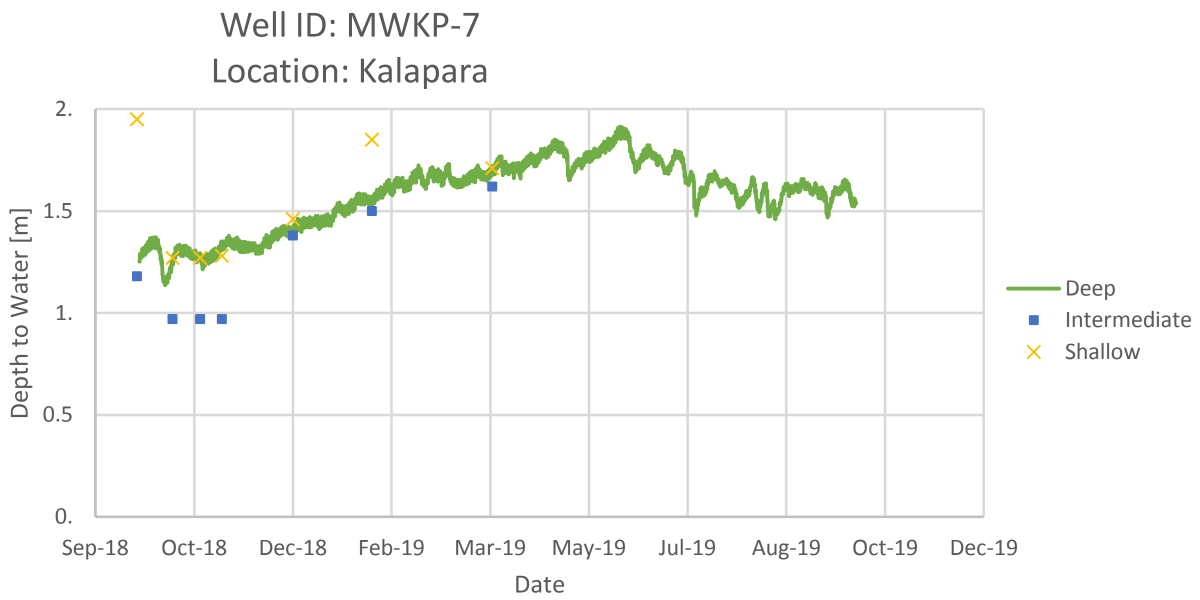

Figure 4-3: Groundwater level in Kalapara Upazila

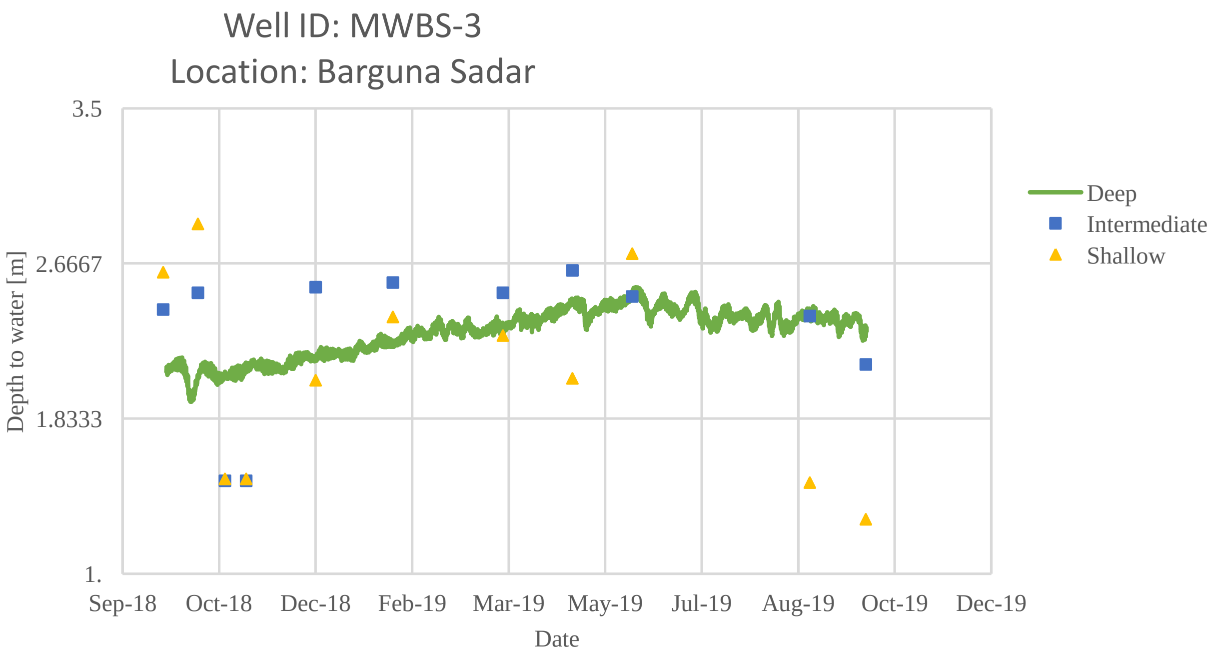

Figure 4-4: Groundwater Level in Barguna Sadar Upazila

4.2 Groundwater Level in Shallow and Intermediate Aquifer

Groundwater in the shallow and intermediate zone in this region is highly affected by tide as evidenced by their high fluctuations within short time. There can be a few meter variations in groundwater level daily. Manual measurement of these two aquifers produced rather chaotic data (Figure 4-1 to 4-7). Although, seasonal trend from scattered manual measurement can be identified. In most of the area except Kalapara, Barguna Sadar and Rangabali upazila groundwater level in the shallow and intermediate depth zones seems to be always above the deep groundwater level. In Barguna Sadar and Kalapara upazilas the shallow and intermediate groundwater level has almost the same mean value as the deep aquifer groundwater level but with higher daily fluctuations due to tide. In Rangabali upazila groundwater level in the deep aquifer seems to be always higher than that in the shallow and intermediate zone. Higher Tidal fluctuation in the shallow and intermediate depth interval indicates that these two depth zones are well connected with the tidal rivers in these areas.

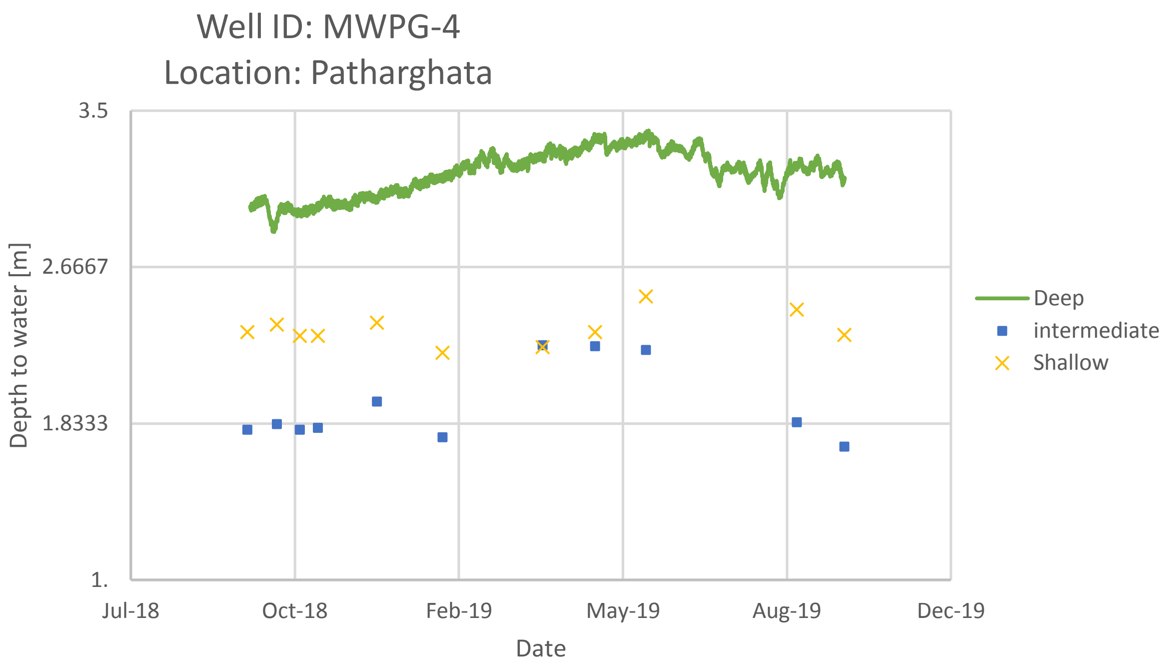

Figure 4-5: Groundwater level in Patharghata Upazila

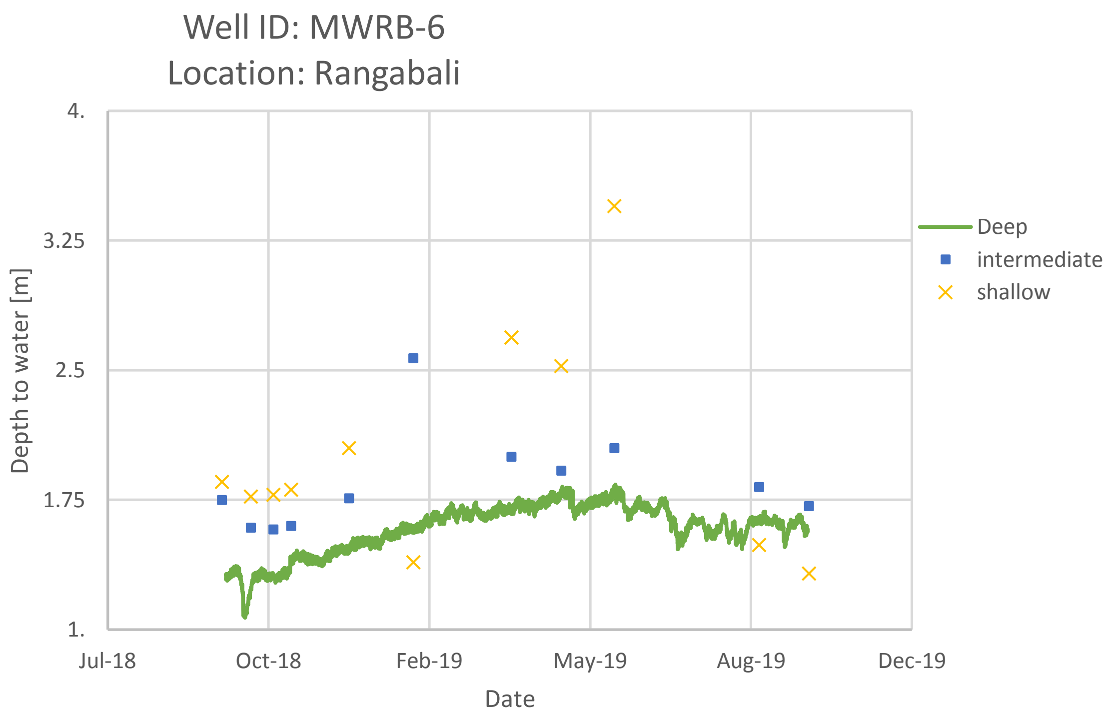

Figure 4-6: Groundwater level in Rangabali Upazila (30 cm)

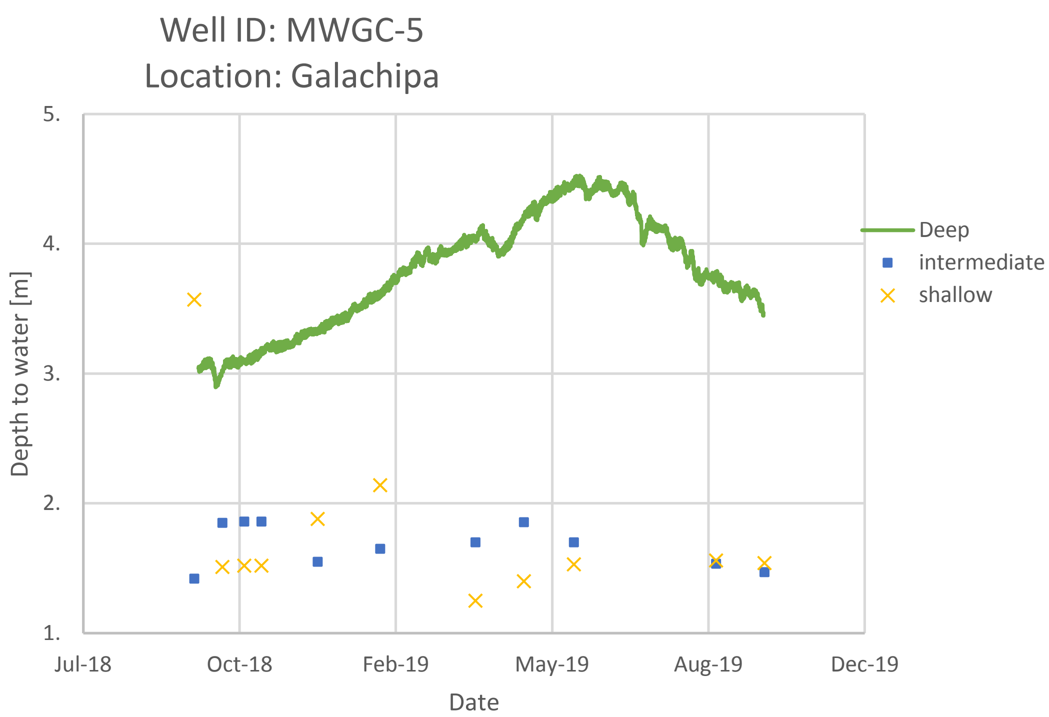

Figure 4-7: Groundwater level in Galachipa Upazila

All the water level data and baro log data are supplied by a CD.

4.3 Significance of Groundwater Level Fluctuation and Groundwater Flow

Groundwater level in the study area is controlled by a number of factors including rapid recharge during the rainy reason, natural discharge along the periphery of the aquifer, evapotranspiration and finally by groundwater pumping for domestic purposes.

Bangladesh Water Development Board (BWDB) has a good resources of groundwater level data all over the Bangladesh. They have a number of monitoring well (MW) in my study area (Patuakhali-Barguna district). The variation of groundwater level data was recorded by BWDB through data logger from January 2000 to December 2013 at Swarupkati, Banaripara, Babuganj, Charfassion, Barguna Sadaar, Mirzaganj, Patuakhali Sadar, Daulatkhan, Barisal Sadar, Jhalokati Sadar, Kawkhali, Bhandaria and Patharghata Upazilla. There were also seven monitoring wells by this study which recorded the variation of groundwater level from 30 Sep. 2018 to 27 Sep. 2019 at Patharghata, Kalapara, Rangabali, Galachipa, Taltoli, Amtoli and Barguna Sadar upazila. Rainfall data of my study area was collected from Bangladesh Meteorological Department (BMD) to observe the seasonal response of the aquifer.

Groundwater level data in the study area represents an interesting hydrogeological characteristic of the aquifer system. The highest groundwater level very close to the ground surface of about 1.1 m during the rainy season and the lowest groundwater level is at 2.6 m from the ground surface during the dry period. During the rainy season groundwater level remains close to the ground surface and after that the level start to decline spontaneously as a result of discharge along periphery, evapotranspiration and pumping for domestic and industrial purposes and again during the rainy season the groundwater level Strat to rise back close to the surface (Figure 4-8).

As the groundwater level during the rainy season remain close to the surface, the direction of groundwater flow typically, follow the topography like - groundwater flows from topographic high to topographic low (Figure 4-9). During this time the direction of groundwater flow is towards the river or sea. Conversely during the dry season, when groundwater level start to decline due to high abstraction of groundwater for domestic, industrial purpose and by evapotranspiration, groundwater from the surrounding areas flow towards the pumping section in all over the study area (Figure 4-9).

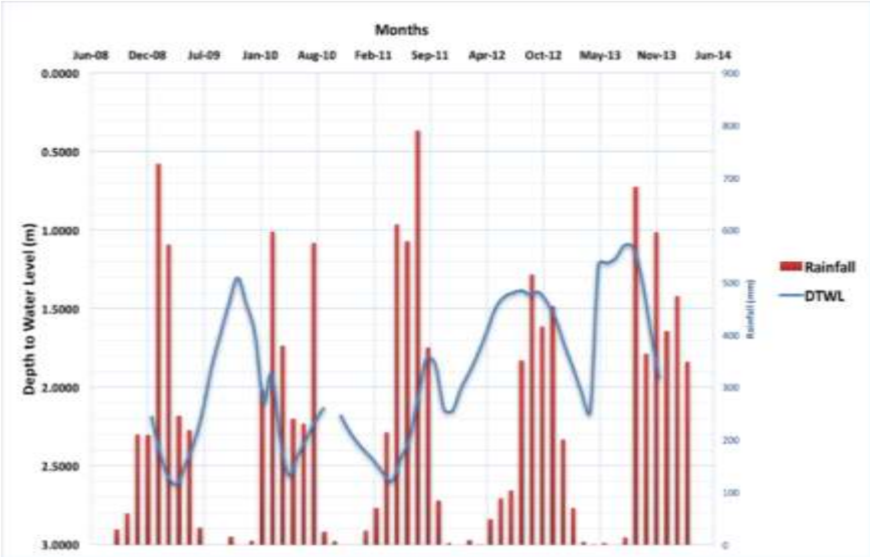

Figure 4-8: Graph showing the water level change with rainfall in study area

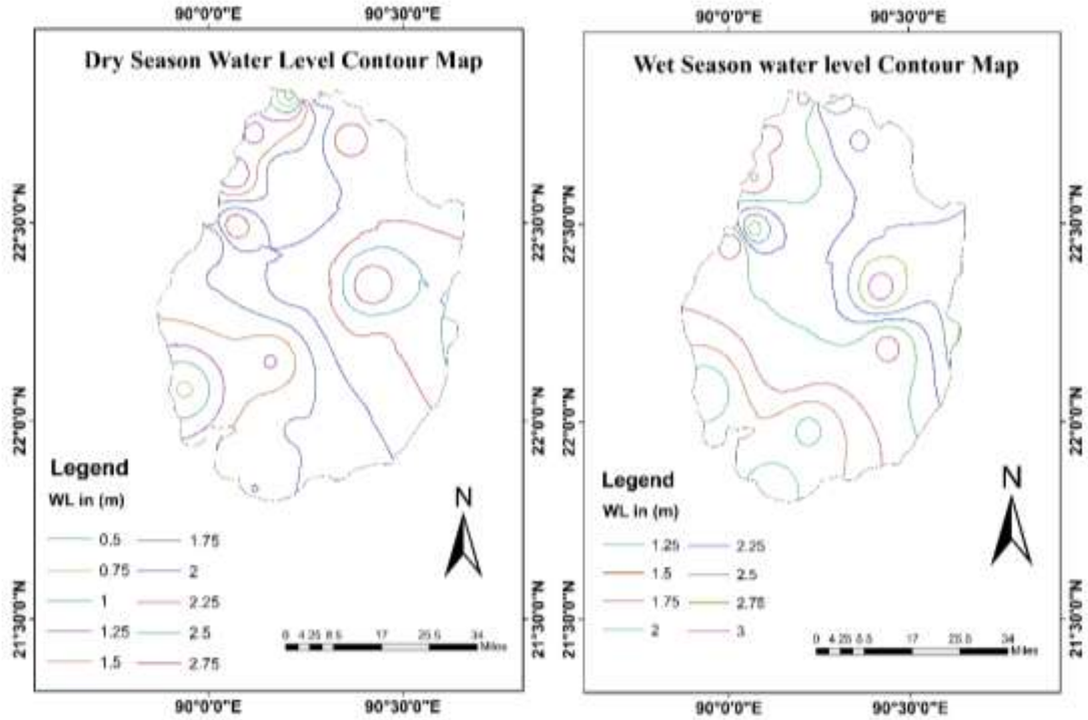

Figure 4-9: Map showing the water level contour in the study area both at dry and wet season at shallow depth

SECTION-5: WATER QUALITY

5 *Water Quality Data*

5.1 Hydro-Chemical Analysis:

Groundwater usually contains a range inorganic & organic constituent and dissolves gasses. Most of these chemical constituents incorporate in water by the dissolution of rock and minerals through which water flows (Freeze and Cheery, 1979). The quality of water mainly depends on the dissolved constituent present in it. That's why it is important to evaluate the hydro-chemical analysis of major minor and trace elements to determine its quality and suitability.

For this research work total 70 samples have been collected during pre-monsoon season, in which 50 samples were from deep wells, 9 samples were from intermediate wells and 11 samples were from shallow wells. Among these samples 7 samples were from 7 monitoring wells located at 7 upazillas from which samples have been collected again in post-monsoon season. Physicochemical parameters such as- temperature, pH, electrical conductivity (EC), Eh were measure on spot using field kits and concentration of major, minor and trace elements were analyzed at the laboratory using standard analytical procedures.

Results from these hydro-geochemical analyses of collected groundwater samples are graphically presented and interpreted in this chapter. On the basis of this result a quality index for drinking water also provided here.

5.1.1 Physico-Chemical Parameter Analysis:

On-site field parameters can give an immediate idea about the natural condition of water sample. Among these parameters -temperature, electrical conductivity (EC), pH were measured in field during sampling. These parameters are usually measured on-site in the field during sampling. Summary finding of each of these parameters are given below while field data of these parameters are given in Appendix-D.

5.1.1.1 *Temperature:*

Temperature is an important physicochemical parameter as it influences the chemical reaction rate in water. In high temperature mineral dissolution rate increases in groundwater. Seasonal variation in groundwater deeper than 50 to 75 feet is less than 1^0 C (Heath, 1989).

In study area groundwater temperature varies from 26˚C to 30.6˚C in shallow aquifer, from 27.3˚C to 29.7˚C in intermediate aquifer and from 27 °C to 32.2 °C in deep aquifer.

Figure 5-1 shows that, all the sample collected from study falls within a temperature range from 26 ˚C recorded in a deep aquifer to 32.2 ˚C recorded in a shallow aquifer. Deep aquifer shows slightly high temperature than shallow aquifer. Otherwise, any significant variation in groundwater temperature with respect to depth is not noticeable.

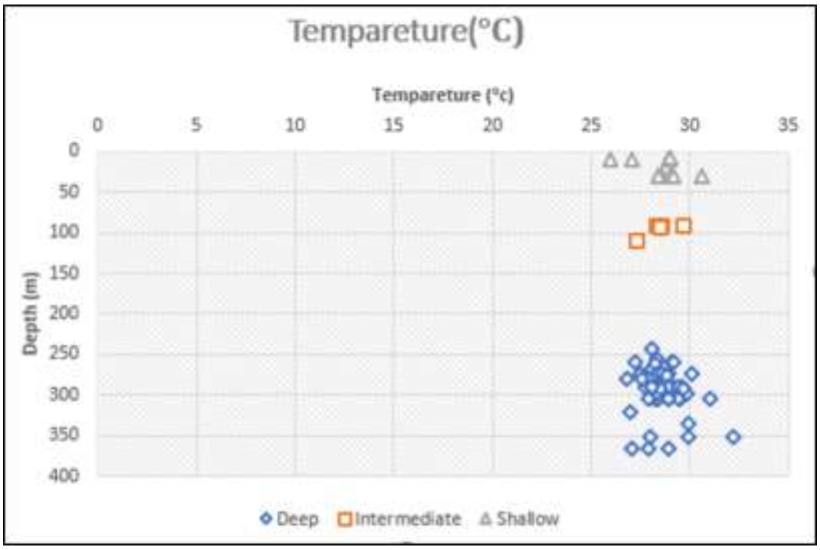

Figure 5-1: Depth profile of temperature in groundwater

5.1.1.2 ***Hydrogen Ion Concentration (pH)***

Negative logarithm of the hydrogen ion concentration (pH) is a measure of how acidic/basic water is, and can be considered as a good indicator of how water changes chemically as it is highly influenced by the chemicals present in the water. Although pH usually has no direct impact on water consumers, it is one of the most important operational water quality parameters. Excessively high or low pH's can be detrimental for the use of water. Bangladesh drinking water standard value for pH is between 6.5 and 8.5.

Maximum pH recorded in a deep well that is 8.5 and minimum pH recorded in an intermediate well that is 6.7 (Figure 5-2).

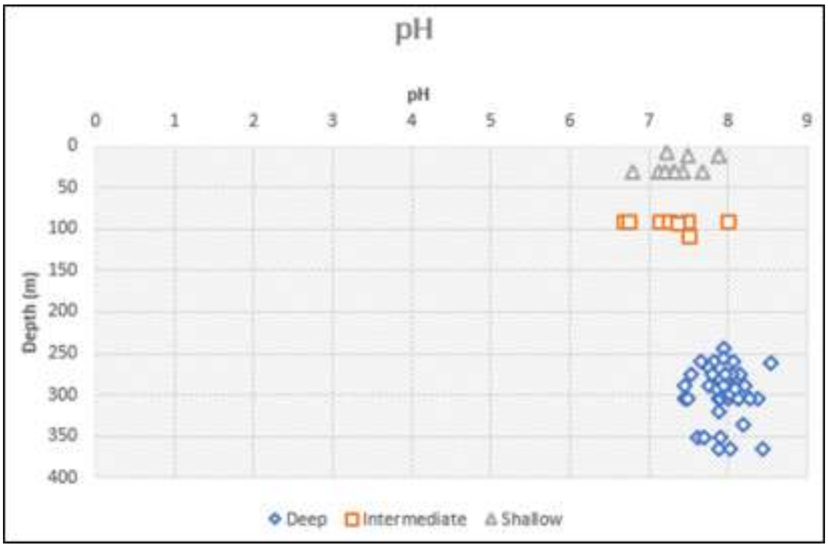

Figure 5-2: Depth profile of pH in groundwater

5.1.1.3 ***Oxidation Potential (Eh):***

Oxidation Potential (Eh) is commonly refereed as oxidation potential of solution, also called Oxidation Reduction Potential (OPR). It is a measure of the tendency of a chemical species to acquire electrons and thereby reduced.

In water sample Eh ranges from -184 to 142 in shallow aquifer, -151 to 130 in intermediate aquifer and -189 to 183 in deep aquifer. Figure 5-3 shows, in water samples Eh varies in a wide range from -200 to 200. There is no variation in Eh value of samples in relation to depth.

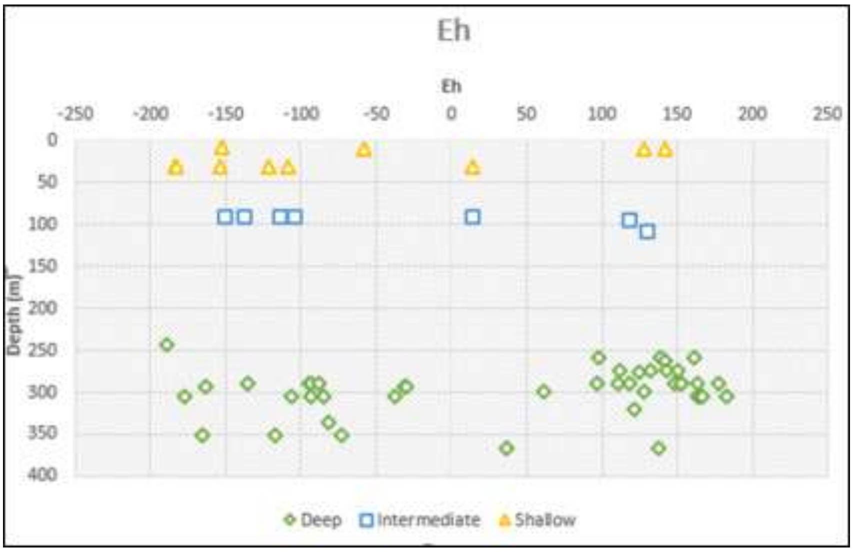

Figure 5-3: Depth profile of Eh in groundwater

5.1.1.4 ***Electrical Conductivity (EC):***

Electrical Conductivity (EC) reflects the sum of the contribution from all the dissolved ions; it is a good proxy measurement of salinity. Plots of lab measured TDS vs EC shows that EC = 1.4 x TDS. Both Bangladesh drinking water standard and WHO guideline value for TDS is set to a maximum of 1000 mg/L, which is equivalent to an EC value of 1400 µS/cm.

Depth profile: A depth profile has been plotted to show the variation of EC with aquifer depth. The plot (Figure 5-4) illustrates that, shallow and intermediate wells show very high EC than deep wells. In shallow well EC ranges up to 35000 µS/cm whereas in deep aquifer most of the samples fall within an EC cluster of 2500 µS/cm at depth between 250m to 350m.

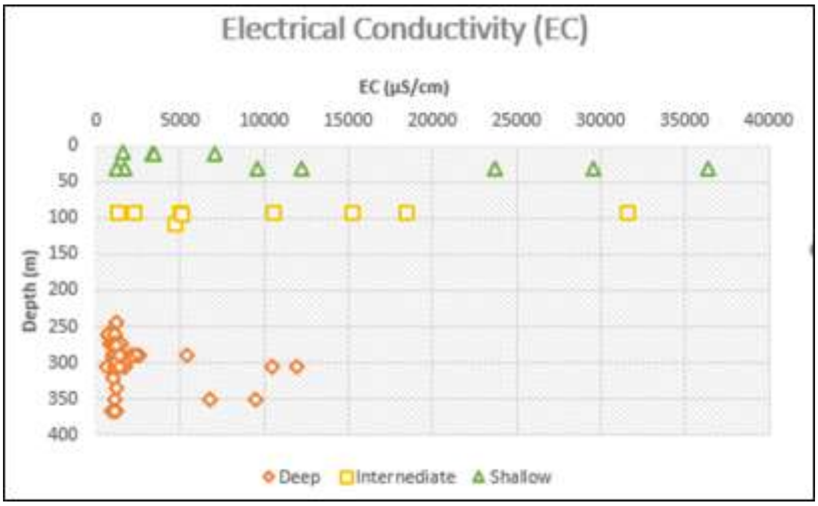

Figure 5-4: Depth profile of EC in groundwater samples

Spatial Variations: In the groundwater sample of the study area EC ranges from 1240 µS/cm to 36490 µS/cm in shallow well, 1260 µS/cm to 31620 µS/cm in intermediate well and 630 µS/cm to 11920 µS/cm in deep well. Highest EC found in a shallow well at Taltoli that is 36490 µS/cm and lowest EC found in a deep well at Golachipa (Figure 5-5).

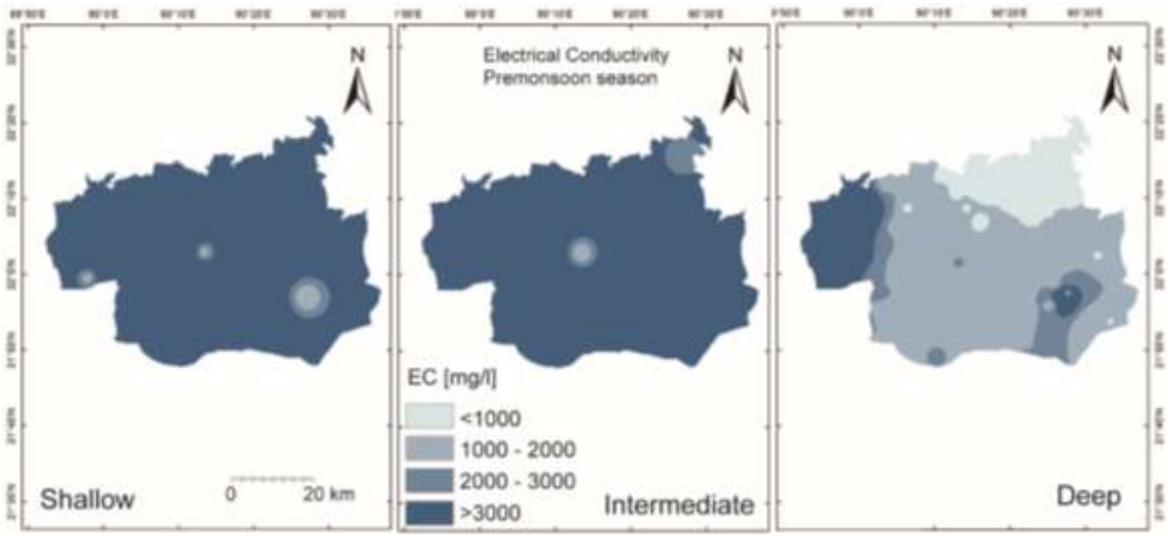

Figure 5-5: Spatial variation of EC in groundwater of shallow, intermediate and deep aquifer

From the spatial distribution map (Figure 5-5) it is clear that, shallow and intermediate aquifers show a higher EC than the deep aquifer. Both of these aquifers contain EC higher than 2000 µS/cm and the possible cause of this high EC is possibly saline water intrusion in shallow and intermediate aquifers. Most of the EC values are within 2000 µS/cm in deep aquifer. In deep aquifer the northern part shows lowest EC and gradually increases towards south and northwest due to proximity of these areas to sea. In some locations EC is recorded below 1000 µS/cm.

Seasonal Variations: Figure 5-6 shows that except sample from monitoring well 4D other samples have EC lower than 2000 µS/cm and indicate fresh water. EC in monitoring well 4D is recorded more than 10000 µS/cm and indicate presence of saline water. No significant seasonal variation occurs in the EC value of other water sample.

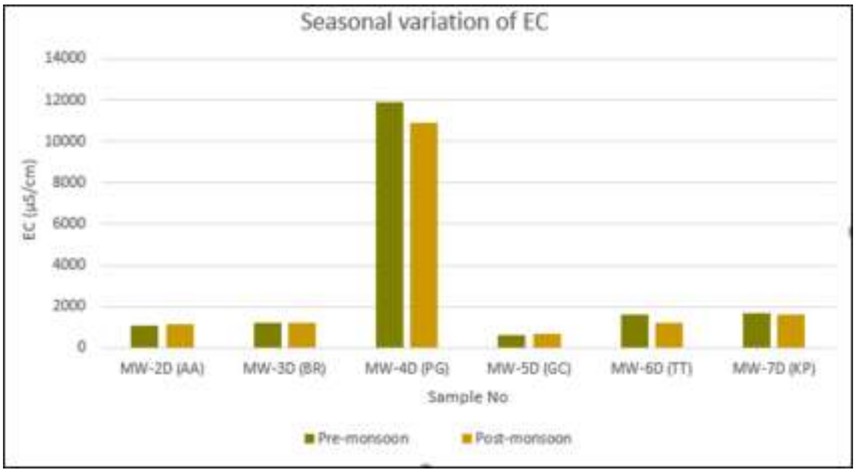

Figure 5-6: Seasonal variations of EC in deep groundwater

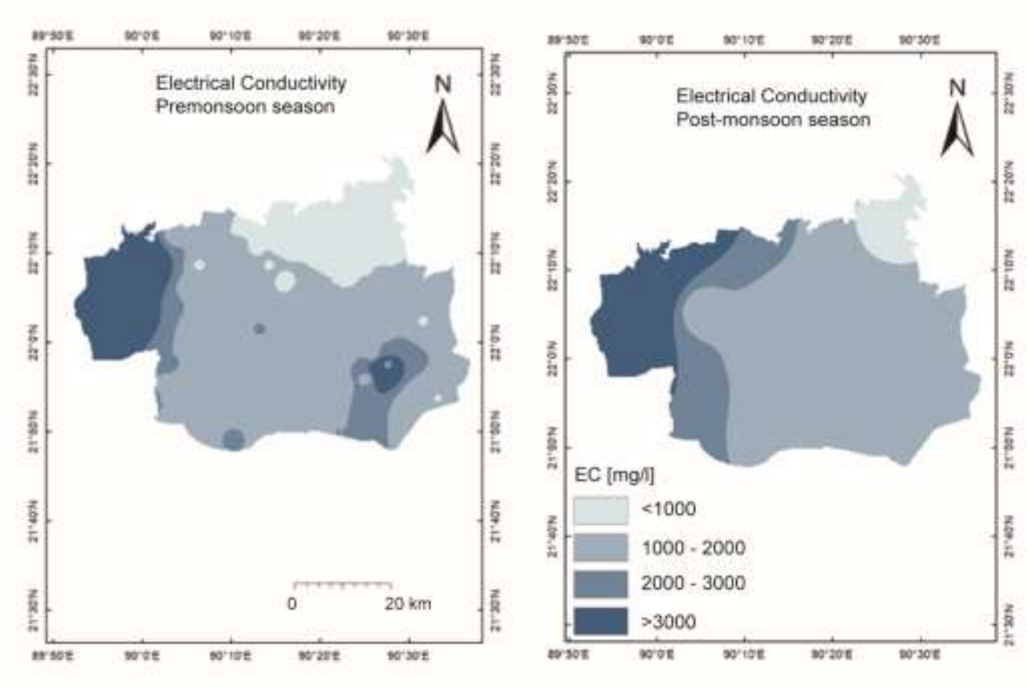

Figure 5-7: Spatial variation of EC in deep groundwater of pre-monsoon and post-monsoon period

Figure 5-7 Shows, in both seasons EC in deep groundwater is lower in northern and northeastern side of the study area and gradually increases towards northwestern part. Most of the part of the study area show EC lowers than 2000 µS/cm and safe for drinking. High EC in northwestern part particularly in Patharghata upazila as this area is closest to the sea.

5.2 Major Ion Chemistry

The chemical constituents that found in groundwater in concentration greater than 1 mg/l is termed as major constituents. They are- sodium, potassium, calcium, magnesium, bicarbonate, chloride, sulphate, silicon and carbonic acid. Major constituents that occur mainly in ionic form are refereed as major ions (Na^{+}, Ca^{2+}, Mg^{2+}, HCO_3^{2-}, Cl^{-} and SO_4^{2-}). Total concentration of these 6 major ions comprises more than 90% of the TDS in water (Fetter, 2001). Major Ion concentration of the collected sample from the study area is presented in Appendix-D.

5.2.1 Sodium (Na+):

Sodium is one of the most common cations present in groundwater. It is commonly derived from seawater, aerosols, rock weathering and ion exchange where it is released from clay in exchange for Calcium and Magnesium ions. The only common sink for sodium is reverse ion exchange (regeneration) that occurs when saline water comes in contact with calcium rich clay (Hounslow, 1995). Both the Bangladesh standard and WHO guideline set 200 mg/L limit of Na+ in drinking water.

Depth Profile: To evaluate the relationship of Sodium concentrations with respect to well depth a depth profile has been plotted (Figure 5-8). The plot (Figure 5-8) depicts, water samples from deep wells have lower concentrations of sodium than shallow and intermediate wells. Up to 100 meters most of the samples show sodium concentration above 1000 mg/L. However, samples from deep wells mostly show concentration below 500 mg/L.

Spatial Variations: Maximum sodium concentration in groundwater of the study area was found in a shallow well at Taltoli which is 6593.55 mg/L and minimum concentration found in a deep well at Barguna Sadar which is 131.07 mg/L. In deep well sodium concentration ranges from 131.07 mg/l to 2380.88 mg/l (Figure 5-9).

Generally, there is a relation between sodium concentration and EC distribution in groundwater. The spatial distribution map (Figure 5-9) shows that in shallow aquifer Na^+ concentration is very high and not safe for drinking except two locations (Pathorghata and Amtoli). In intermediate aquifer northwestern and eastern part have Na^+ concentration more than 1000 mg/l and in the central and northern part have concentration lower than 250 mg/l. Deep aquifer shows much less concentration than the shallow and intermediate aquifer. The norther part of deep aquifer shows sodium concentration within permissible limit whereas in southern and northwestern part of the study area, most of the sample exceeds the Bangladesh drinking water standard for Na (200 mg/l). In these areas higher sodium values may be result from saline water intrusion in groundwater.

Overall, the northwestern part of the study area (Patharghata) shows high sodium concentration possibly due to saline water intrusion and shallow aquifer is not suitable for drinking.

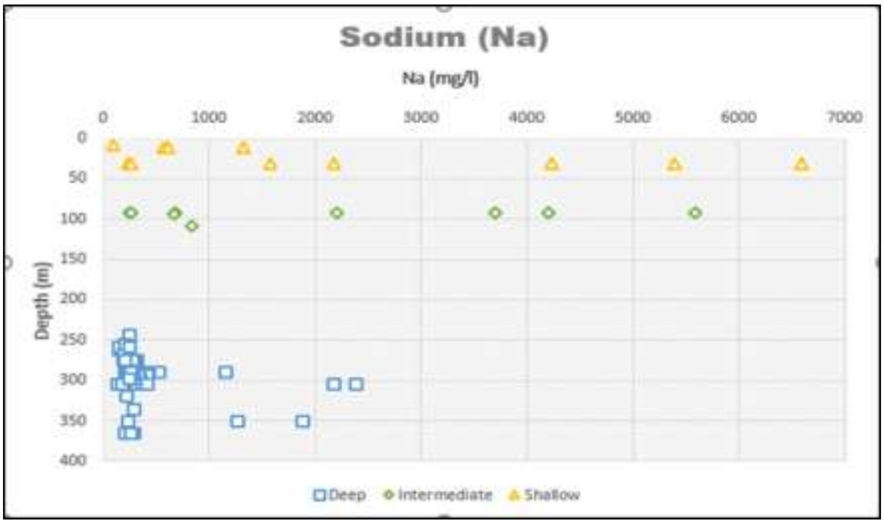

Figure 5-8: Depth profile of Na+ concentration in groundwater samples

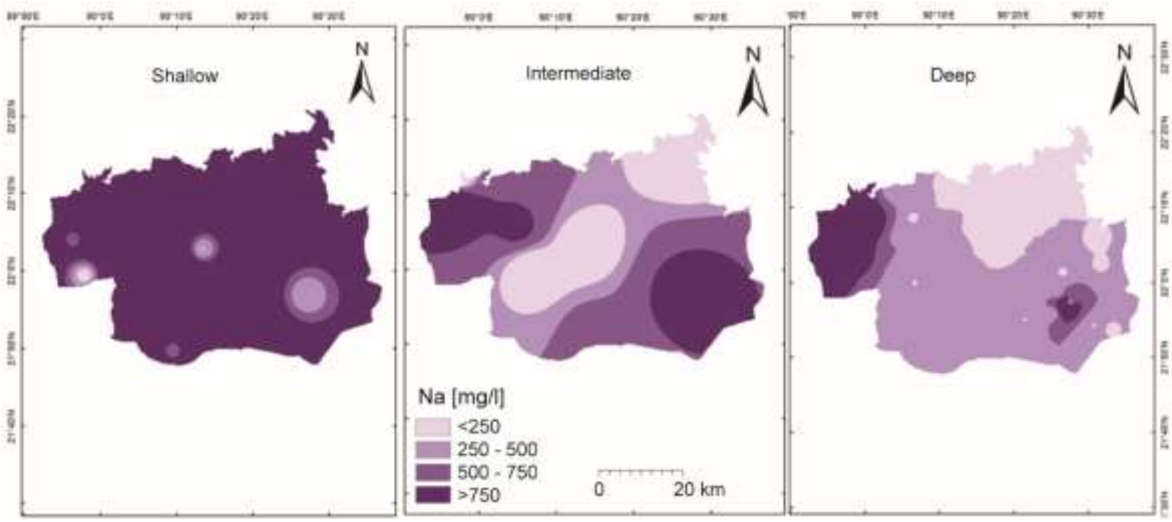

Figure 5-9: Spatial variation of Na+ in groundwater of shallow, intermediate and deep aquifer

Seasonal Variations: The graph (Figure 5-10) shows, all the water samples, except Monitoring well 4D have a sodium concentration below 500 mg/l. Monitoring well 4D is located in Pathorghata and shows sodium concentrations greater than 2000 mg/l in both seasons. Post-monsoon sample shows higher concentration than pre-monsoon sample may be due to brackish water flow from tide dominated Baleshwar River after Monsoon period as river water level may rises up during heavy monsoon rainfall. Overall, other samples do not show much significant seasonal variations.

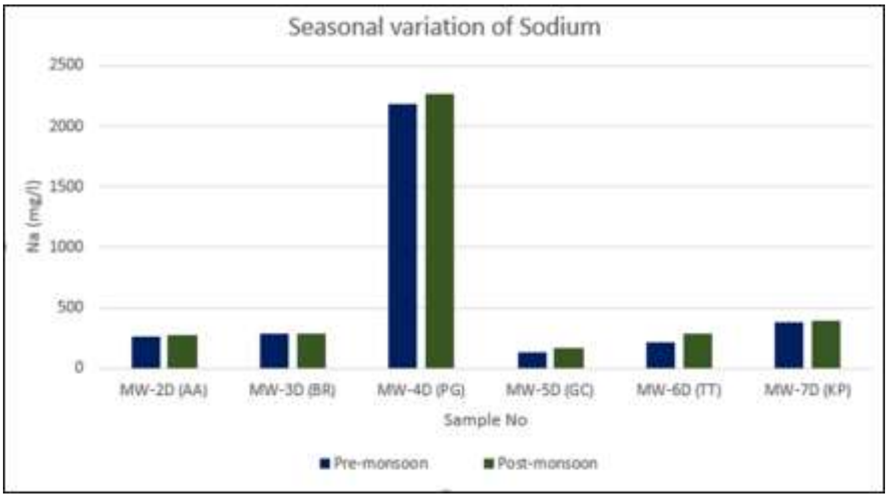

Figure 5-10: Seasonal variations of Na+ ion

5.2.2 Potassium K+:

In comparison with Sodium, Potassium is less common in groundwater due to the slower weathering process of the K+ bearing minerals than those containing Na+. The source of K+ in groundwater is same as Na+ (Hem, 1989). In most fresh water aquifers, if the Na+ concentration substantially exceeds 10 mg/l, the K+ concentration commonly is half or a tenth of that of Na+ (Hem, 1989). Bangladesh drinking water standard limit for potassium is 12 mg/L.

Depth Profile: A depth profile of potassium has been constructed, shown in Figure 5-11. The plot shows, higher potassium concentration found in shallower aquifer whereas lower concentration found in deeper aquifer. 6 samples in shallow and intermediate aquifers show very high k^+ concentration, over 50 mg/l. Generally, there is a relationship between potassium and sodium distribution in groundwater. If Na^+ concentration exceeds 10 mg/l then K^+ concentration commonly will be half or a tenth of that of Na^+ (Hem, 1989). Higher values of potassium and its correlation with sodium indicate mixing of groundwater with sea water. Most samples in deep aquifer falls in the cluster found within 20 mg/L in concentration.

Spatial Variations: In the study area potassium concentration in shallow aquifer ranges from 1.66 mg/l to 201.45 mg/l and in deep aquifer concentration varies from 2.79 mg/l to 46.36 mg/l. Figure 5-12 shows, in shallow and intermediate aquifer most of the sample contain high potassium concentration and exceed permissible limit for potassium in drinking water. In intermediate aquifer, water samples from north-western part and eastern part shows high potassium concentration, more than 48 mg/l. In deep aquifer, most of the samples show low concentration than shallow and intermediate aquifer and do not exceed Bangladesh drinking water guideline value of 12 mg/l.

Seasonal variations: The graph (Figure 5-13) depicts, all the samples have potassium concentration below 5 mg/l except monitoring well 4D. Sample MW-4D shows concentration greater than 15 mg/l in both seasons and not suitable for drinking water. Monitoring well 5D shows concentration of 5 gm/l in pre-monsoon period which falls in 2 mg/l in post-monsoon season. Similar pattern shows monitoring well 7D. Overall, all samples show lesser concentration in post-monsoon period than in pre-monsoon period.

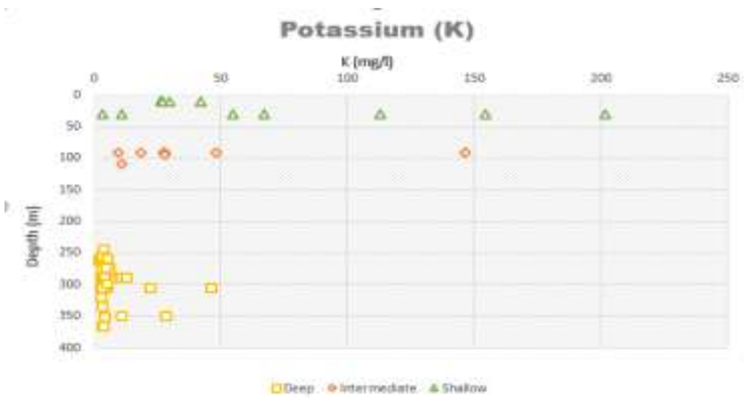

Figure 5-11: Depth profile of potassium concentration in groundwater

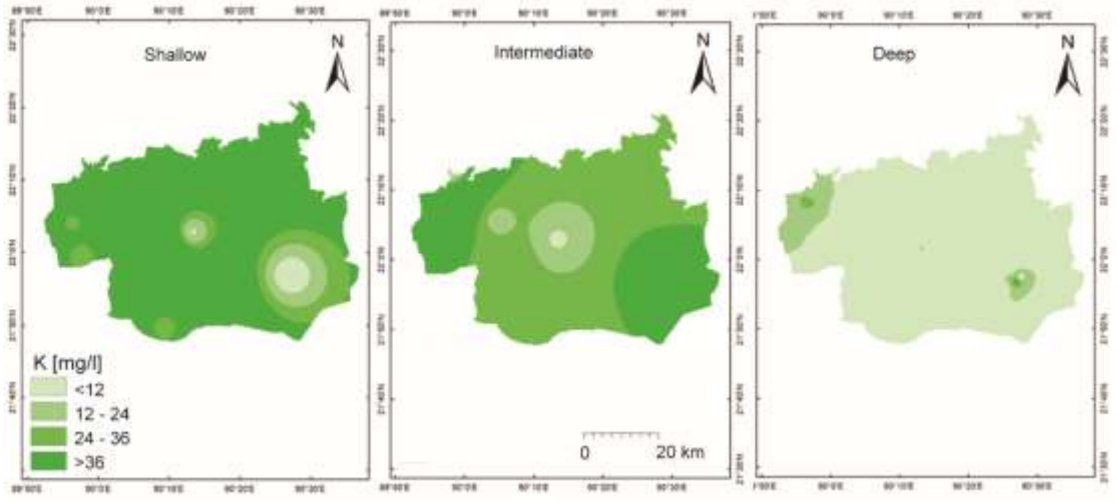

Figure 5-12: Spatial variations of K+ concentration in deep aquifer

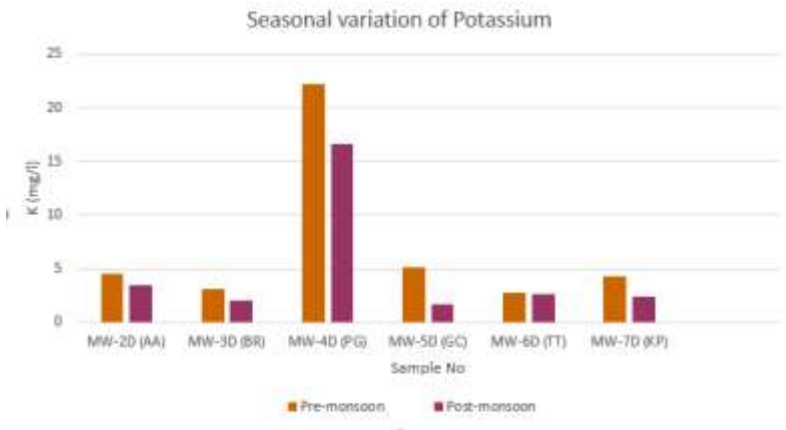

Figure 5-13: Seasonal Variations of K+ ion

5.2.3 Calcium (Ca^{2+}):

Calcium has a high level of solubility and is one of the major ion components in groundwater and in combination with magnesium ions is responsible for the hardness of groundwater. Bangladesh drinking water standard for calcium is set to 75 mg/L. WHO set the same limit from aesthetic point of view and set a higher limit of 200 mg/l for health concern.

Depth Profile: The relation of Calcium concentrations with respect to depth is represented in the depth profile plot (Figure 5-14). The plot (Figure 5-14) shows that, deep wells have lower concentration and most of the samples found in a cluster fall within concentration below 50 mg/l. In shallow and intermediate wells samples show higher concentration than deep well and fall within 150 mg/l except 3 samples. Those 3 samples showing very high calcium ion concentration around 350-400 mg/l.

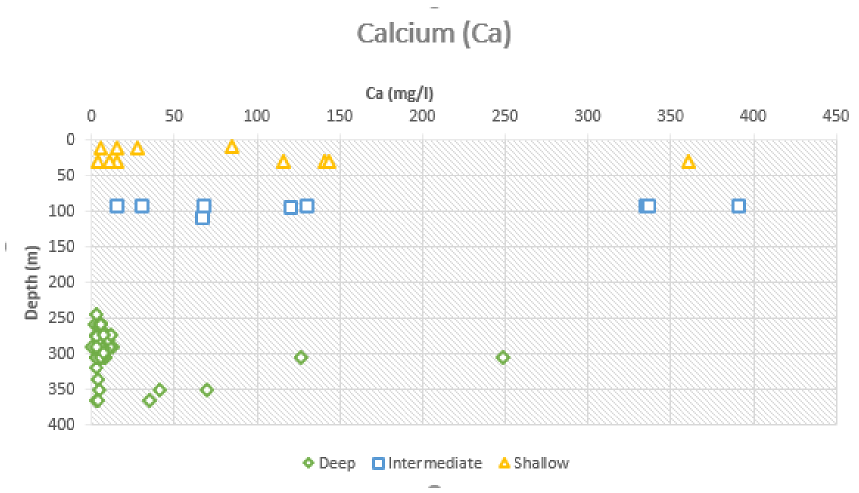

Figure 5-14: Depth profile of Ca^{2+} concentration in groundwater samples

Spatial Variations: Maximum Ca^{2+} concentration in groundwater of the study area was found in a shallow well at Taltoli which is 361.06 mg/L and minimum concentration found in a deep well at Barguna Sadar which is 2.14 mg/L. In deep well Ca^{2+} concentration ranges from 3.903 mg/l to 361.06 mg/l (Figure 5-15).

Calcium concentration is high in both the shallow and intermediate aquifer and low in the deep aquifer. In shallow aquifer northeastern part shows concentration within 60 mg/l but in southwestern part particularly Taltoli upazilla shows concentration greater than 180 mg/l. In intermediate aquifer except small part in the northern side all other areas show very high ca concentration. Most of the samples in the shallow and intermediate aquifer exceed Bangladesh drinking water guideline value. All samples in deep aquifer showing lower Ca^{2+} concentration value and occur within the Bangladesh drinking water guideline value of 75 mg/l (5-15).

Seasonal variations: From the graph (Figure 5-16) it is evident that only the water samples from Monitoring well 4D possess high Ca concentration that is 120 mg/l in pre-monsoon and further increases to 140 mg/l in post-monsoon period. All other samples show Ca^{2+} concentration below 10 mg/l and suitable for drinking purpose. Only monitoring well 6D shows high Ca concentration in pre-monsoon season than in post monsoon season. All other wells show reverse pattern.

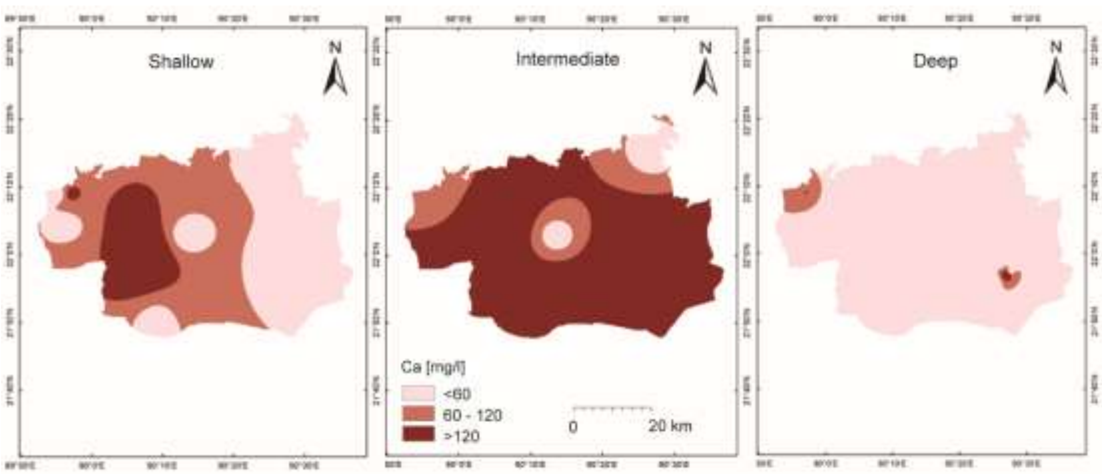

Figure 5-15: Spatial variation map of Ca^{2+} in groundwater of shallow intermediate and deep aquifer

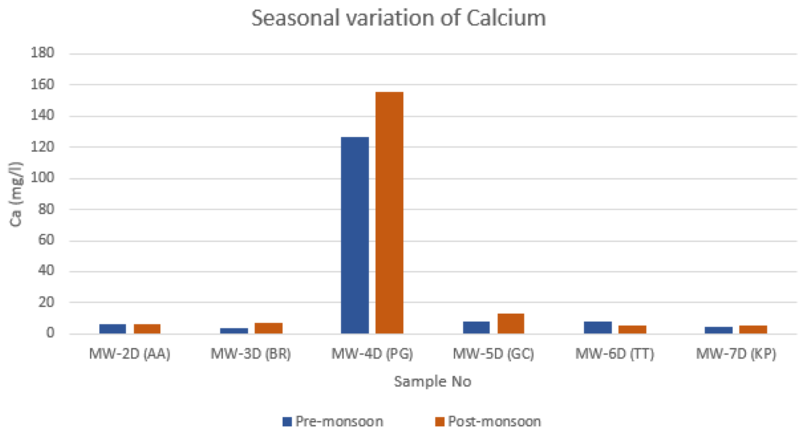

Figure 5-16: Seasonal variations of Ca2+ ion

5.2.4 Magnesium (Mg^{2+})

Magnesium ions also contribute to the hardness of water. A large number of minerals contain magnesium, for example Dolomite (Calcium Magnesium-Carbonate; CaMg(CO3)2 and Magnesite (magnesium carbonate; MgCO3). In Bangladesh, it probably comes from micas and amphibolites. Bangladesh drinking water standard for magnesium is 30mg/l for aesthetic and 50mg/l for health concern.

Depth Profile: A concentration VS depth profile has been plotted to identify the relationship of Mg concentration with well depth (Figure 5-17). The plot illustrates that, Mg concentration is lower in deeper aquifer and most of the sample occur within concentration below 60 mg/l. Both shallow and intermediate wells show high concentration and except 4 samples others found in a cluster falls within 200 mg/l.

Spatial Variations: Highest Mg concentration found in an intermediate well located in Pathorghata which is 590.95 mg/l and lowest concentration found in a deep well at Golachipa which is 2.31 mg/l. In shallow well Mg concentration ranges from 3.9 mg/l to 361.06 mg/l whereas in deep well it varies from 2.31 mg/l to 146.4 mg/l. The spatial distribution of Mg^{2+} concentration for shallow aquifer (Figure 5-18) shows that concentration is lowest in the - part of the area and considerably increased towards south-western part. In case of intermediate well, map shows; apart from small portion in northern and central parts other areas have high Mg concentrations.

Deep aquifer contains lesser concentration than both shallow and intermediate aquifers. Most of the samples from deep aquifer contain Mg concentration below the Bangladesh drinking water guideline value of 35 mg/l whereas, about 60% of the samples from shallow and intermediate aquifer exceeds safety limit for drinking water.

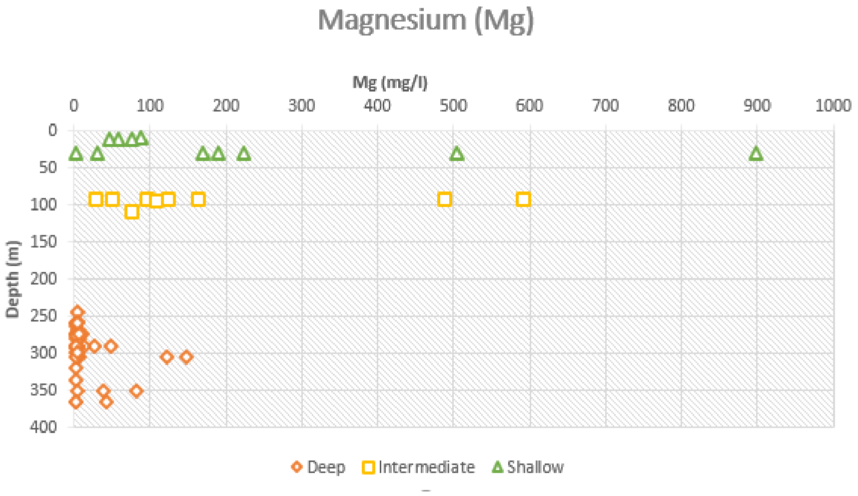

Figure 5-17: Depth profile of Mg2+ concentration in groundwater samples

Seasonal Variations: All the monitoring well sample shows Mg concentration lower than 10 mg/l except one monitoring well in Pathorghata (MW-4D). MW-4D sample shows high concentration in post-monsoon season than in pre-monsoon season and always having concentration higher than 120 mg/l. Other samples do not show any significant seasonal variations (Figure 5-19)

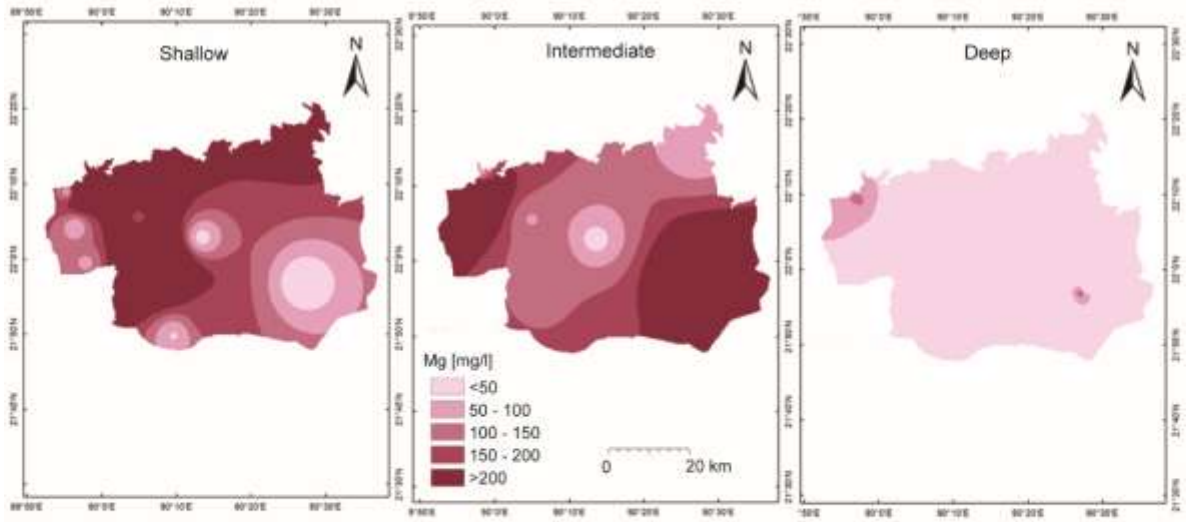

Figure 5-18: Spatial variation of Mg2+ in groundwater of shallow, intermediate and deep aquifer

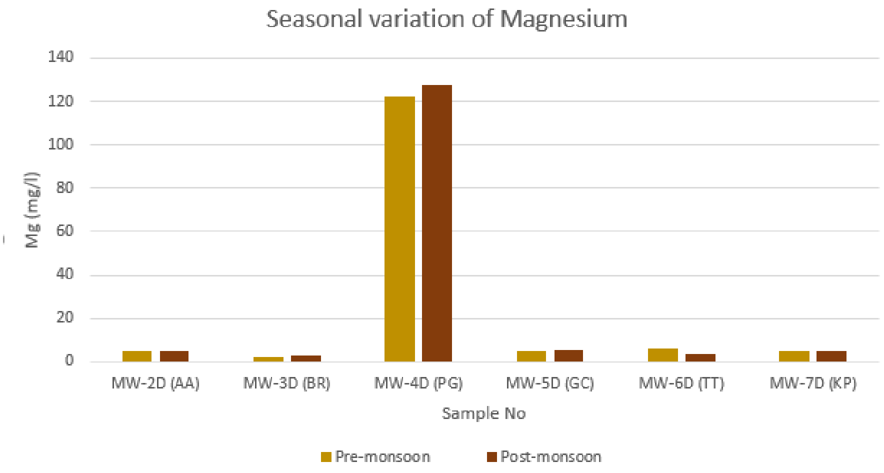

Figure 5-19: Seasonal variations of Mg2+ ion

5.2.5 Chloride (Cl^-)

Chloride occurs in all natural water in widely varying concentration. The chloride content normally increases as the mineral content increases. Groundwater receives chloride from various sources like halite (NaCl), sea spray (Hounslow, 1995). Chloride concentrations are generally low in groundwater but where the groundwater receives effluent, industrial waste or experiences seawater intrusion a higher Cl- concentration result. Bangladesh drinking water standard for chloride is 150 mg/l for aesthetics and 600 mg/l for health. WHO guideline value is 200 mg/l.

Depth Profile: To evaluate the relationship of chloride concentrations with respect to well depth a depth profile has been plotted (Figure 5-20). The plot shows, shallow and intermediate wells having much higher chloride concentrations compared to deep well which ranges up to 16000 mg/l. in deep well most of the samples are within a concentration of below 1000 mg/l.

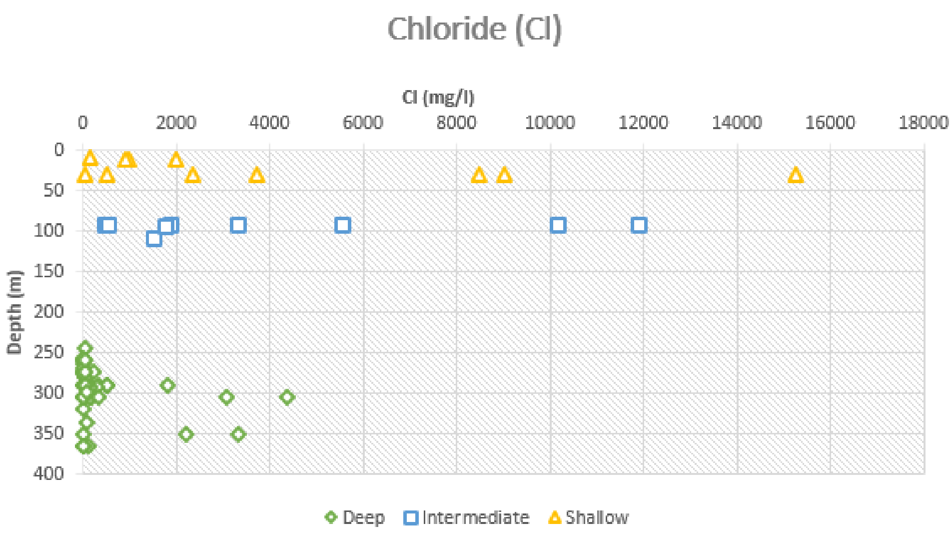

Figure 5-20: Depth profile of Cl- concentration in groundwater samples

Spatial Variations: Maximum chloride concentration recorded in a deep well located at Pathorghata which is 4720.136mg/l and minimum concentration found in another deep well at Golachipa which is 5.94 mg/l. In shallow well chloride concentrations varies from 37.57 mg/l to 15252.07mg/l. From

Figure 5-21 it can be seen that, shallow and intermediate aquifer show high chloride concentration than deep aquifer. In shallow aquifer the southern and western part shows high chloride concentrations. In intermediate aquifer western and south-eastern part show high concentration. Most of the sample collected from both these wells exceed permissible limit of drinking water according to Bangladesh. In deep well northern and central part shows lower chloride concentrations and remains within safe drinking water limit of 250 mg/l according to Bangladesh and concentration gradually increases towards north-western part. High concentration of chloride in north-western part indicates mixing of groundwater with sea water.

Seasonal Variations: The graph (Figure 5-22) shows, a significant seasonal variation is noticeable in monitoring well 4D where, chloride concentration raises from 2400 mg/l in pre-monsoon to 4720 mg/l in post-monsoon. All the other wells have low chloride concentration in both seasons and show limited seasonal variations.

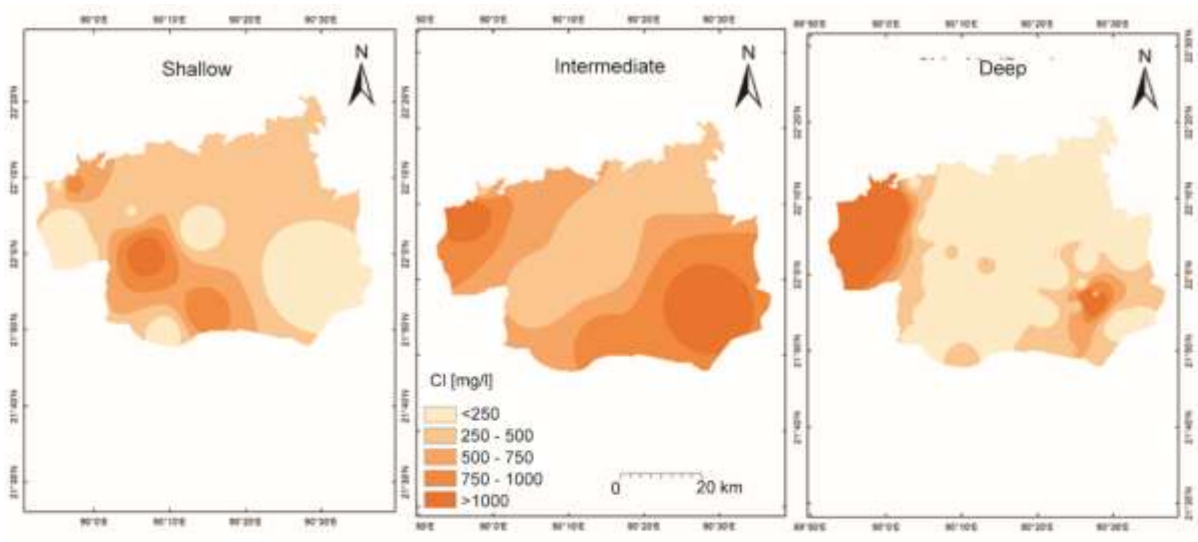

Figure 5-21: Spatial variation of Cl- in groundwater of shallow, intermediate and deep aquifer.

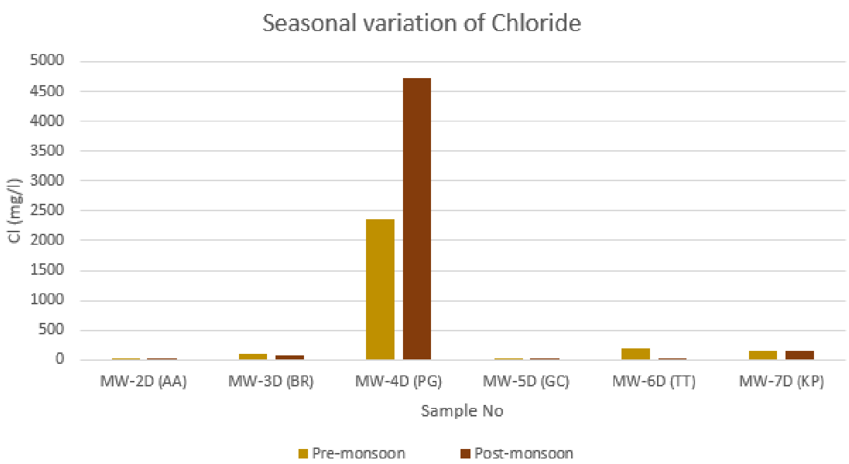

Figure 5-22: Seasonal variations of Cl- ion

5.2.6 Bicarbonate (HCO_3^-)

Bicarbonate is a major ion and has a strong influence on the pH (alkalinity) of groundwater. Sources of bicarbonate are mainly carbon dioxide, calcite, dolomite and sulphate reduction. Breakdown of organic matter also causes higher HCO3- in groundwater. The concentration of Bicarbonate in natural water is held within a moderate range by the effect of carbonate equilibria (Hem, 1985). Concentrations of HCO3- of more than 200 mg/l are common in Bangladesh groundwater, especially its deeper aquifers. Both the Bangladesh drinking water standard and WHO guideline value for bicarbonate in drinking water is set to 200 mg/l.

Depth Profile: A depth profile is shown in Figure 5-23 to see the relationship between bicarbonate concentration and well depth. From the plot it is observable that, deeper aquifer shows higher bicarbonate concentration compared to in shallow and intermediate wells. In deep well bicarbonate concentration ranges within a cluster of concentration from 400 mg/l up to 1000 mg/l. In shallow and intermediate well most of the samples have concentration lower than 600 mg/l.

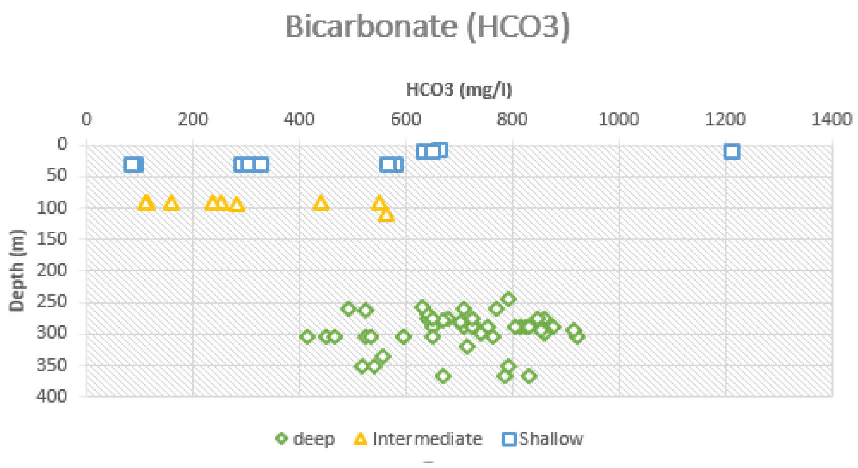

Figure 5-23: Depth profile of HCO3- concentration in groundwater sample

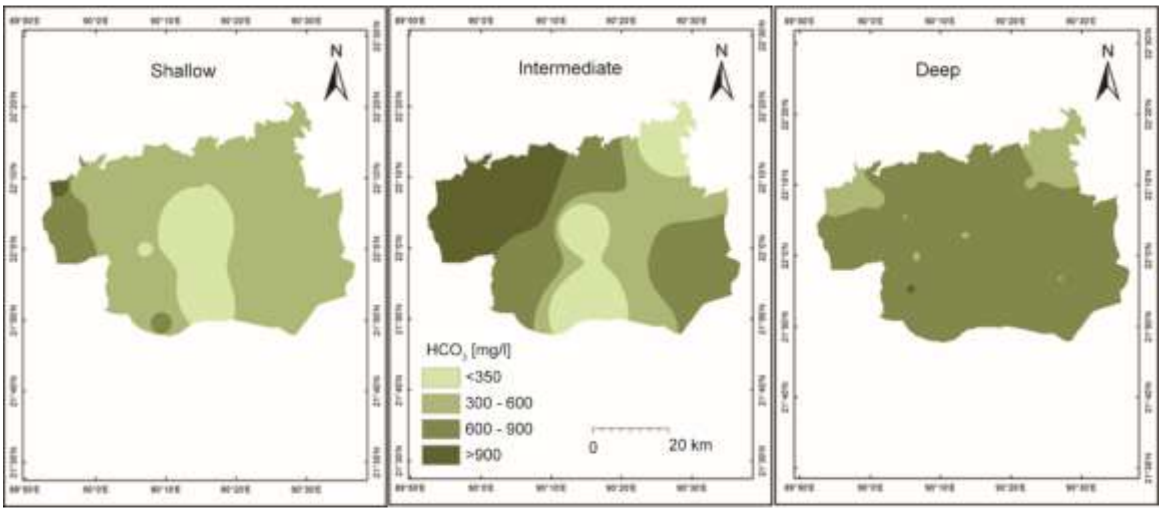

Figure 5-24: Spatial variation of HCO3- in groundwater of shallow, intermediate and deep aquifer

Spatial Variations: Bicarbonate concentrations of the water samples collected from the study area vary widely. Highest concentration of 1212.35 5mg/L is found a shallow well at Ptharghata and lowest concentration of 90.5 mg/l is found in another shallow well at Amtoli. In deep well concentration varies from 415.25 mg/l from 922.63 mg/l. The Figure 5-24 shows that, in shallow and intermediate aquifer southern part of the area exhibit concentration lower than 250 mg/l and other parts of the area shows higher concentration. In deep well most of the area shows high bicarbonate concentration except northern part of the study area. In all case most of the sample exceed permissible limit for drinking water of 250 mg/l according to Bangladesh.

Seasonal Variations: The graph (Figure 5-25) shows high bicarbonate concentrations in all well and significant seasonal variation is also noticeable. Samples from post-monsoon shows higher concentrations than pre-monsoon samples. Highest variation shows sample that is collected from Rangabali upazila.

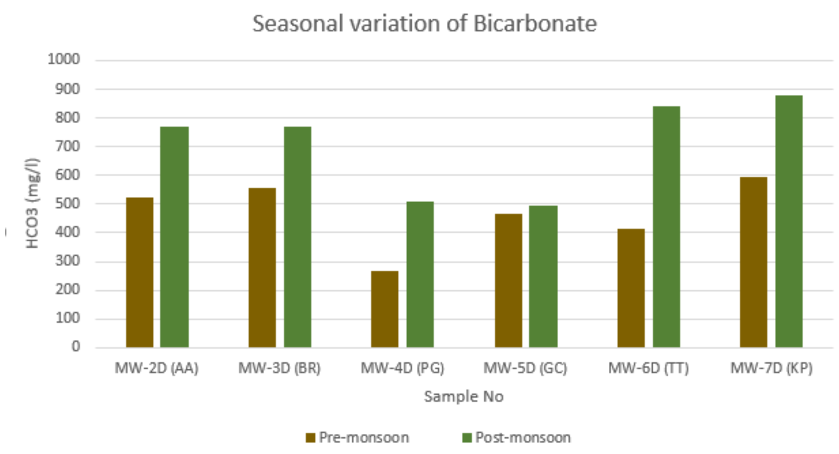

Figure 5-25: Seasonal variations of HCO3- ion

5.2.7 Sulphate (SO_4^{2-}):

Sulphate ions are less significant than chloride ions in controlling the chemical behaviour of groundwater. Sulphur is released into groundwater from the oxidation of sulphide minerals such as marcasite and pyrite, sea water intrusion, and agricultural and industrial effluents. Bangladesh drinking water standard for sulphate is 400 mg/l, while the WHO guideline value is 250 mg/l.

Depth Profile: A sulphate concentration VS well depth scatter plot has been shown in Figure 5-26. The plot shows that, all the samples have sulphate concentration below 200 mg/l except two samples in shallow aquifer. Deep well samples show lesser concentration than shallow and intermediate wells.

Spatial Variations: Maximum sulphate concentration has been found in a shallow well located in Taltoli that is 2046 mg/l and minimum concentration found in an intermediate well located in Patharghata that is 15 mg/l. The spatial distribution map (Figure 5-27) shows that shallow aquifer contains higher concentration of sulphate than intermediate and deep aquifer. In shallow aquifer only 2 samples contain high sulphate concentration recorded from Barguna Sadar and Taltoli which may result from leaching of agricultural wastewater into groundwater. All the other samples show low sulphate concentrations and do not exceed Bangladesh drinking water standard for sulphate (400 mg/l).

Seasonal Variations: Figure 5-28 shows there is significant concentration variations between two seasons. Samples from pre-monsoon season show high concentration than samples from post-monsoon season. Overall, all the sample having concentration below 4 mg/l and safe for drinking.

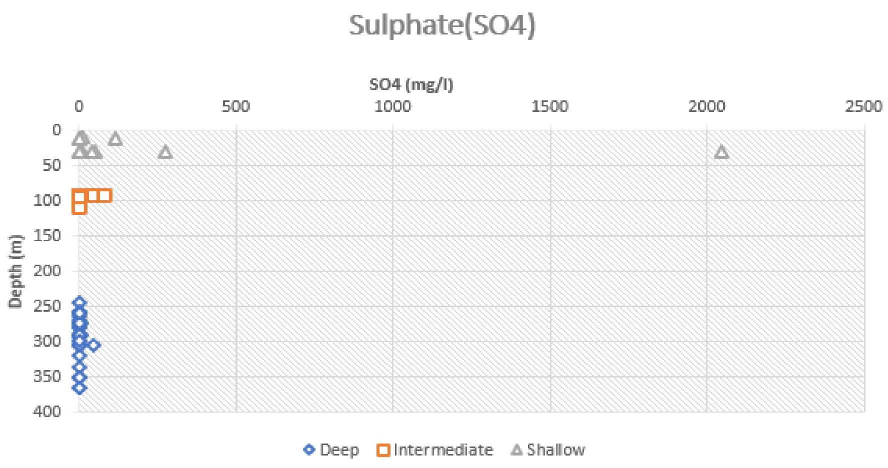

Figure 5-26: Depth profile of SO42- concentration in groundwater samples

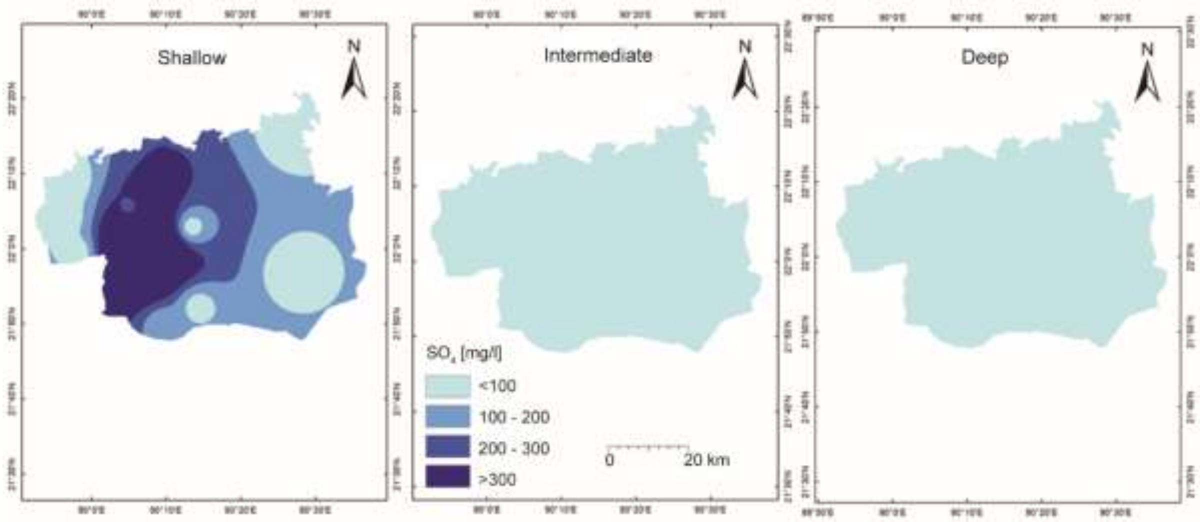

Figure 5-27: Spatial variation of SO_4^{2-} in groundwater of shallow, intermediate and deep aquifer

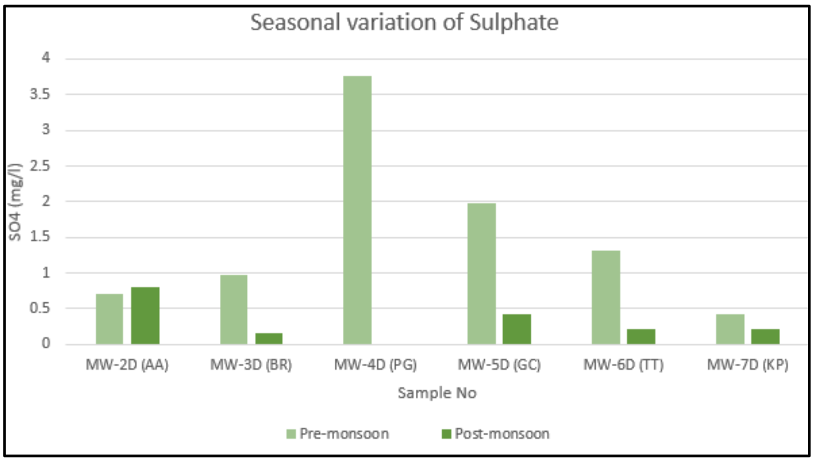

Figure 5-28: Seasonal variations of SO42- ion

5.3 Minor and Trace Constituents

The chemical constituents which found in groundwater within a concentration range from 0.01 to 10 mg/l, is termed as Minor constituents such as- Boron, Strontium, Fluoride, Nitrate, Iron etc. Trace constituents are those which occur in concentration less than 0.01 mg/l. These constituents are very important in the groundwater the study of groundwater chemistry as they can degrade water quality and can have health effect. Presence of trace elements like Lead and Cadmium indicate pollution of water from toxic wastes and have an importance from medical point of view (Trieff, 1980). Other trace element like- Barium, Cobalt, Chromium, Manganese, Copper and Radioactive elements are also important from the same concern (Maroof *et al.*, 1986).

Among a number of minor constituents and trace elements, concentrations of Nitrate (NO_3^-), Iron (Fe) and Manganese (Mn^{2+}) are determined in this study.

5.3.1 Nitrate (NO_3^-)

Nitrate is an inorganic compound that occurs under a variety of conditions in the environment, both naturally and due to anthropogenic influences. It is one of the most common groundwater contaminants in rural areas. Nitrate in groundwater can originate from fertilizers, septic systems, and manure (Hem, 1989). High concentrations of nitrate in drinking water can lead to health problems. Nitrates form compounds in the body that change haemoglobin to methemoglobin, decreasing the ability of blood to carry oxygen. In infants, this can cause what is known as Blue baby Syndrome (methemoglobinaemia). Bangladesh drinking water standard for nitrate is 50 mg/l which is the same as the WHO guide line.

Depth Profile: To evaluate the relationship of nitrate concentrations with respect to well depth a depth profile has been plotted (Figure 5-29). The plot depicts, shallow and intermediate wells show high nitrate concentration than deep well. All samples collected from shallow and intermediate well show concentration below 100 mg/l except 1 sample. In deep well, all samples fall in a concentration cluster within 25 mg/l.

Spatial Variations: The spatial variation map (Figure 5-30) shows that, in shallow aquifer northern and southern side of study area contain high nitrate concentration. Intermediate aquifer shows high nitrate concentration than shallow and deep aquifer. Most of the samples from shallow and intermediate aquifer exceed standard value for nitrate concentration (10 mg/l) in drinking water according to Bangladesh. In deep aquifer 90% sample shows concentration lower than 10 mg/l and safe & suitable for drinking.

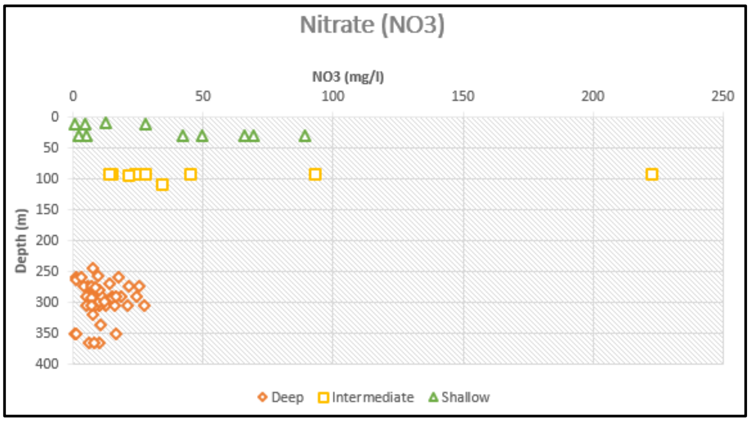

Figure 5-29: Depth profile of NO3- concentration in groundwater samples

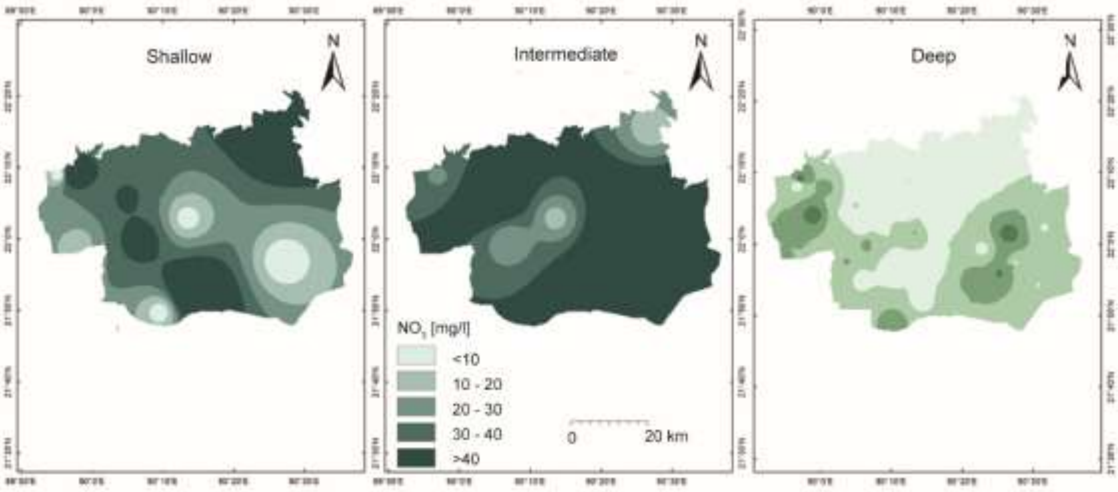

Figure 5-30: Spatial variation of NO3- in groundwater of shallow, intermediate and deep aquifer

Seasonal Variations: Figure 5-31 shows that, except sample MW-4D and, MW-6D other samples have concentration within 10 mg/l and do not exceed permissible limit. Sample MW-4D shows highest concentration that rises from 27 mg/l in pre monsoon to over 100 mg/l in post monsoon. In all other well show lower nitrate concentration in post-monsoon season.

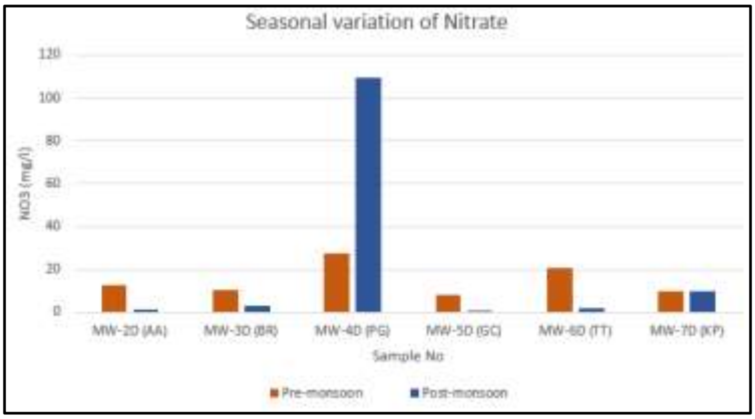

Figure 5-31: Seasonal variations of NO3- ion

5.3.2 Iron (Fe)

Iron (Fe) is one of the most abundant elements in the Earth's crust forming many minerals that are present in groundwater. Two types of inorganic iron exist in nature: ferrous iron (reduced [Fe+2]) in oxygen poor conditions and ferric iron (oxidized [Fe+3]) in oxygen rich conditions. When groundwater is reduced, ferrous iron is fully dissolved and colourless. Under reducing conditions, ferrous iron levels range from 0.1-10 mg/L and can be as high as 50 mg/L (WHO, 2003; McMahon and Chapelle, 2008).

Colourless, dissolved ferrous iron will react with oxygen and form ferric iron oxide or rust. This ferric iron forms particles or precipitates on grain surfaces. When iron oxide particles are suspended in water, it gives the water a rusty orange, brown, red, or yellow color.

Bangladesh has drinking water standards for Iron of 0.3 mg/l and 1.0 mg/l and a guideline of 3 mg/L. There is currently no health-based guideline value for iron in drinking water (WHO, 2003). The

United States Environmental Protection Agency recommends a secondary maximum contaminant level (MCL) of 0.3 mg/L because iron concentrations exceeding 0.3 mg/L water can have an unpleasant metallic taste and can produce water with a rusty or yellow colour. However, millions of hand tubewells in Bangladesh contain several mg/L of iron.

Depth Profile: Fe concentration VS depth profile has been plotted in Figure 5-32. The plot illustrates that, shallow and intermediate wells contain higher Fe concentrations than deeper wells. In shallow well iron concentration varies up to 8 mg/l whereas in deep well most of the sample show concentration within 1 mg/l.

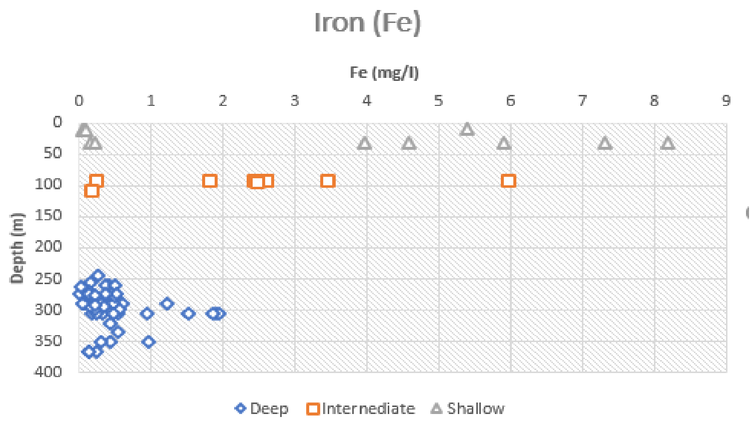

Figure 5-32: Depth profile of Fe concentration in groundwater samples

Spatial Variations: Highest iron concentration found in a shallow well at Taltoli (8.19 mg/l) and lowest concentration found in another shallow well at Kolapara (0.052 mg/l). In shallow well concentration ranges from 0.052 to 8.19 mg/l whereas in deep aquifer it ranges from 0 to 0.949 mg/l. in intermediate well concentration varies in between 0.17 to 5.9 mg/l. The spatial variation map (Figure 5-33) shows that, deep aquifer has low iron concentration than shallow and intermediate aquifers. Most of the area in shallow and intermediate aquifer show iron concentration greater than 1.5 mg/l and exceed permissible limit for drinking water except northern side of the study area. On the other hand, in deep aquifer except 2 samples, all other sample show iron concentration within 1 mg/l which is the standard value for iron concentration in drinking water according to Bangladesh.

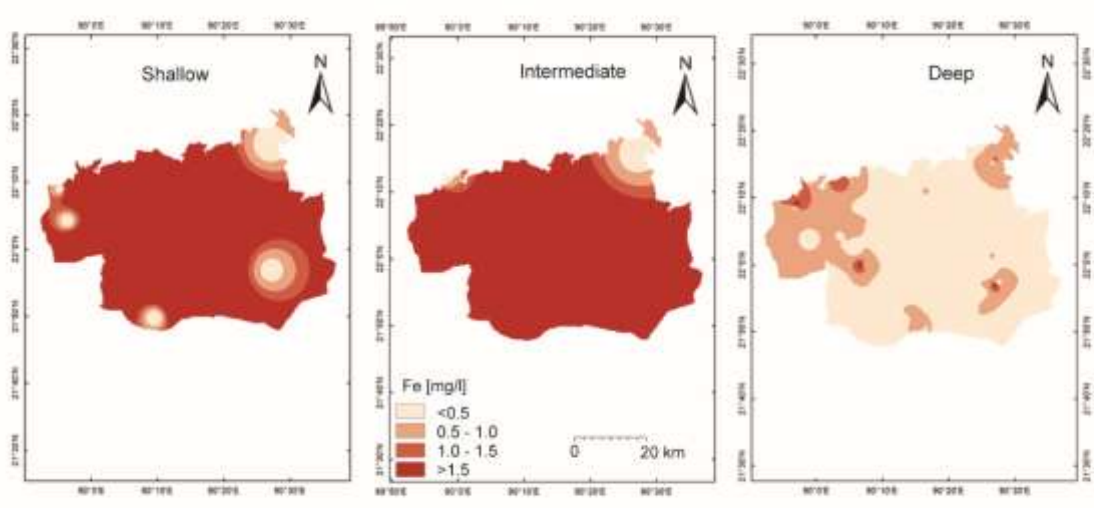

Figure 5-33: Spatial variation of Fe in groundwater of shallow, intermediate and deep aquifer

Seasonal Variations: The graph (Figure 5-34) represents that, a significant variation of concentration is noticeable between the samples from two seasons and pre-monsoon samples always contain higher concentration of iron than post-monsoon samples. In post-monsoon concentration of all samples remain within safety limit for drinking but in pre-monsoon 3 samples exceed the limit.

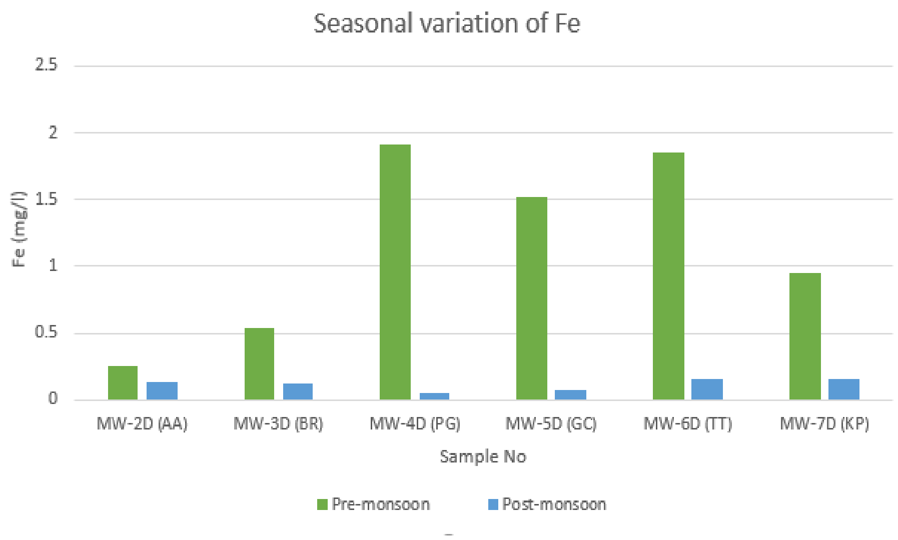

Figure 5-34: Seasonal variations of Fe

5.3.3 Manganese (Mn):

Manganese is not currently included in the list of health-based parameters of WHO drinking water quality standards. Previously WHO standards (2008) included 0.4 mg/L as health-based limit which has been removed in the latest guideline (2017). The current Bangladesh drinking water standard for Mn is 0.1mg/L which is based on WHO's aesthetic guideline value. In general, natural Mn concentration is high in Bangladesh groundwater (BGS and DPHE, 2001) and some studies reported the neuro-toxic impacts of high Mn on children (Wasserman et al, 2006). A recent study in Canada proposed 0.1 mg/L as maximum allowable concentration (MAC) value for Mn in drinking water. The same study reported that Mn can cause a clinical neurological disease referred to as manganism, characterized by generalized cognitive and motor disturbances, including bradykinesia, widespread rigidity, gait disturbances, falling, dystonia, difficulty walking backwards, and speech difficulties (Health Canada, 2016).

Depth Profile: A depth profile has been plotted to show the relationship of Mn concentration with respect to well depth (Figure 5-35). The plot shows in shallow well Mn concentration ranges up to 1.5 mg/l except up 1 sample. Intermediate and deep wells show lower concentration than shallow well and fall within a cluster of concentration below 0.5mg/l, except three samples.

Spatial Variations: Maximum Mn concentration found in an intermediate well at Kalapara that is 4.35 mg/l and minimum concentration recorded in a deep well at Amtoli that is 0.004 mg/l. The spatial map (Figure 5-36) shows that, in the study area manganese concentrations are not very high in deep aquifer as most of the wells have concentrations less than 0.1 mg/l and within the limit of safe drinking water Bangladesh standard guide line. But in shallow and intermediate aquifer most of the sample have concentration more than 0.3 mg/l and exceed safety limit.

Seasonal Variations: Figure 5-37 shows that, except sample from monitoring well 4D, other samples contain very low Mn concentration in both seasons and remain within Bangladesh standard for Mn 0.1 mg/l. Mn concentration of sample MW-4D falls from 0.45 mg/l in pre-monsoon to 0.15 mg/l in post-monsoon. Except sample MW-2D, all other samples possess low concentration in post-monsoon.

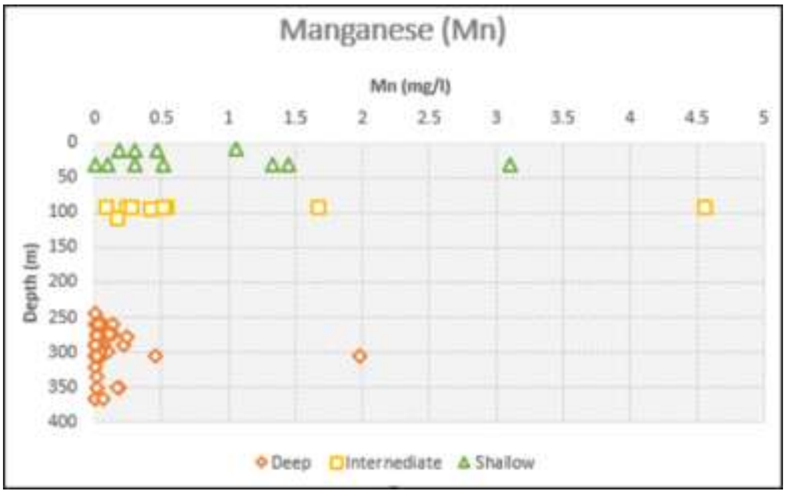

Figure 5-35: Depth profile of Mn concentration in groundwater samples

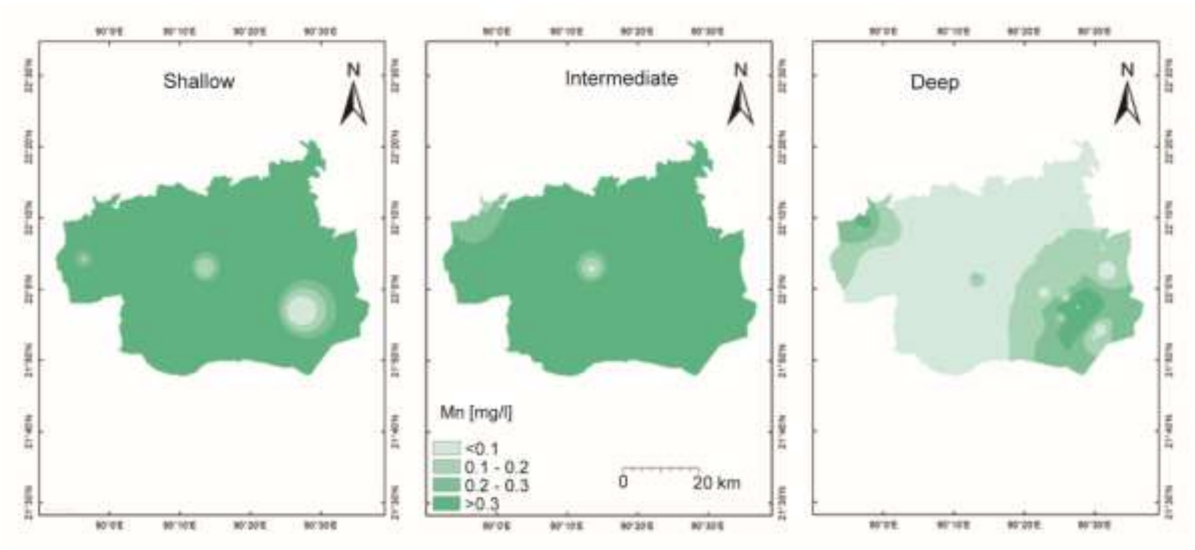

Figure 5-36: Spatial variation of Mn in groundwater of shallow, intermediate and deep aquifer

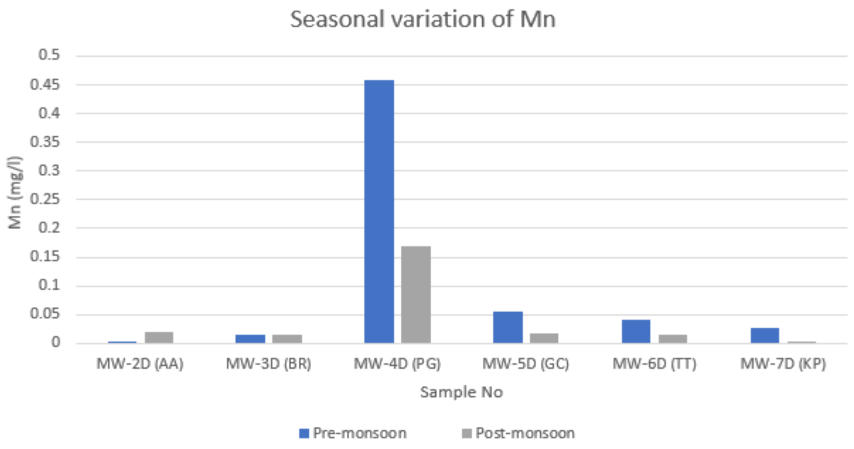

Figure 5-37: Seasonal variations of Mn

5.3.4 Arsenic (As)

Arsenic is a naturally occurring element widely distributed in soil, water and in biota. It releases to water from a variety of natural and manmade sources such as- erosion, dissolution and weathering of As containing rocks, geothermal waters, woodl preservatives etc. Microbially mediated reductive dissolution of iron oxyhydroxide (FeOOH) is the major mobilization process of arsenic into shallow aquifer (Ravenscroft *et al.*, 2001; Ahmed *et al.*, 2004; Bhattacharya *et al.*, 2008). Higher arsenic concentration possess threat to human health.

The water samples collected from the study area do not possess any threat to high level of Arsenic concentration. The Arsenic content was measured on site by using field arsenic kit and only 3 samples shows the presence of arsenic in water. None of the 3 samples exceed World Health Organization (WHO) guideline value for arsenic concentration (10 ppb).

5.4 Hydrochemical Facies Analysis:

Analysis of Hydro-chemical facies is important to understand the composition and type of water. Based on the concentration of dominant cation and anion, hydrochemical facies divide water into distinct compositional zone and classify water according to it, which provide an idea about the origin and flow path history of water.

5.4.1 Piper Diagram

Piper diagram is universally used as a trilinear diagram to present hydro-chemical data. It is commonly used to determine hydro-chemical facies and water type. It shows a graphical presentation of water composition by using concentration of dissolved ion in water. This diagram is helpful to understand any changes in water composition during its flow through any geological formation (Piper, 1944).

Piper Diagram consists of two triangles, one of which is for cations and another for anions and a central diamond shaped figure whose diameter is proportional to the total dissolved solids (TDS). To construct this diagram cations are plotted on the Ca-Mg-(Na+K) triangle and anions are plotted on the HCO_3-SO_4-Cl triangle as percentage. Concentrations are expressed in meq/l. Total cations and anions are each considered as 100%. On the basis of position of ion on the diagram a speculation can be made about the origin of the water. From the plotting on piper diagram 4 basic conclusions can be made which are- water type, precipitation or solution, mixing, and ion exchange (Hounslow, 1995).

A piper diagram has been constructed to understand the dominant water type and hydrochemical facies of the ground water of the study area.

Piper plot (Figure 5-38) clearly shows that, in most of the water samples collected from shallow and intermediate well dominant cation is Na+K type and dominat anion is cl type, which means Na-Cl facies and indicate saline water. Only a few water samples from those aquifers show Na-HCO_3 facies and indicate fresh water.

In deep aquifer most of the sample shows Na-K-HCO_3 type water which represent alkali carbonate water. Alkali carbonate water is an indication of fresh deep groundwater which is influenced by ion exchange. Only one deep water sample shows Ca-Mg-HCO_3 type water and indicates water of temporary hardness. Some deep groundwater sample also indicates mixed type of water.

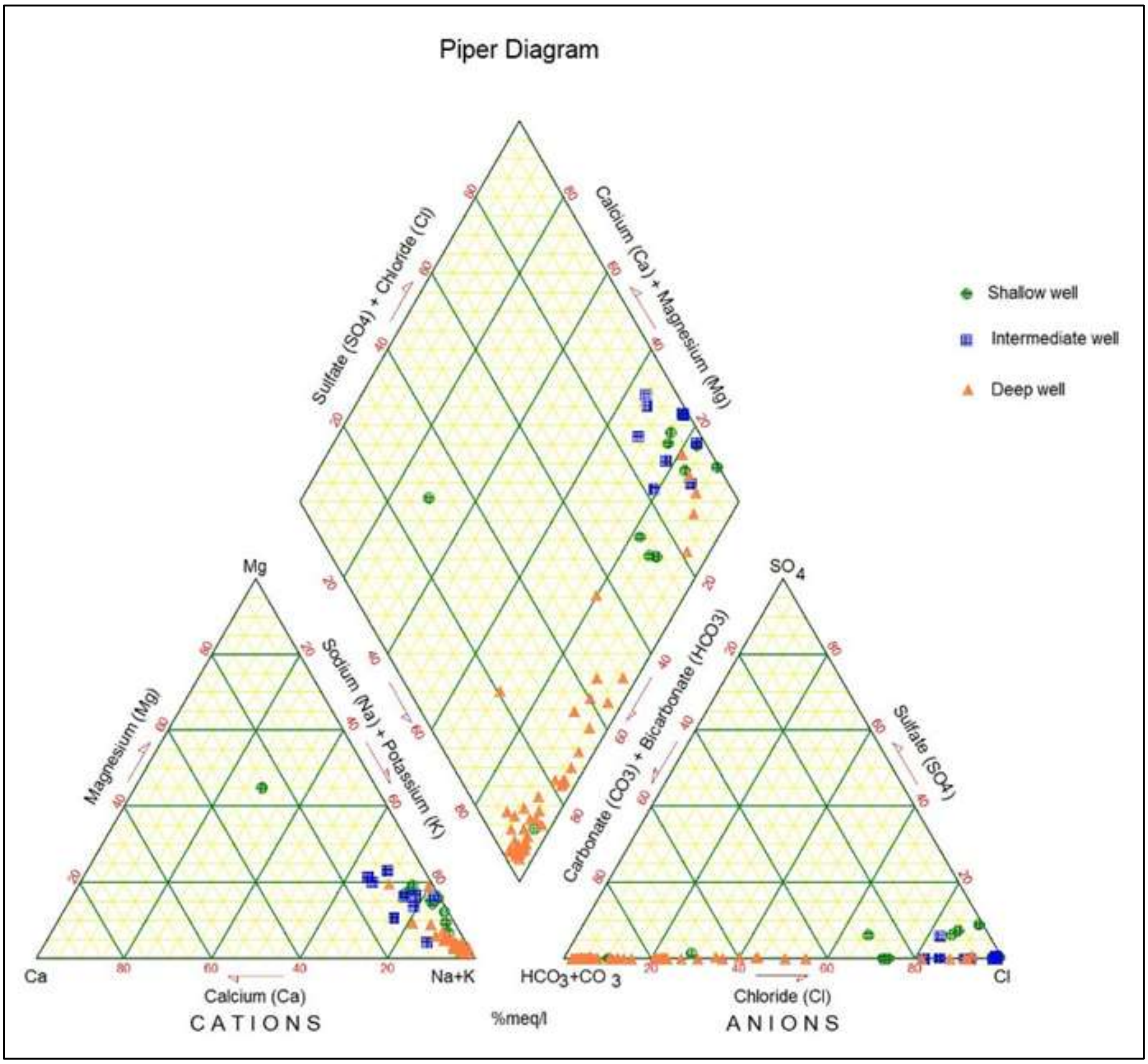

Figure 5-38: Piper Diagram

5.4.2 Stiff Diagram

A Stiff diagram or Stiff pattern is a graphical representation of chemical analyses of water samples (Stiff, 1951). This diagram is used widely by hydro-geologists and geochemists to display the variations of major ions of water samples, either spatially or vertically. Polygonal shapes are created using three or four parallel horizontal axes extending on either side of a vertical zero axes. Cations are plotted in meq/L on the left side of the zero axis and anions are plotted on the right side.

In order to depict the vertical variations in groundwater composition of the study area collected from three aquifer depths, seven piper diagrams have been plotted for the seven piezometer nests placed at different locations. Samples from all seven locations show considerable variations in size and shape of the Stiff pattern diagrams.

Figure 5-39 and 5-40 illustrates stiff diagrams for water samples from four piezometer nests- MW-1 at a depth of 30.48m (1S), 91.44m (1I) and 304.8m (1D), MW-2 at a depth of 30.48m (2S), 91.44m (2I) and 304.8m (2D), MW-5 at a depth of 30.48m (5S), 91.44m (5I) and 304.8m (5D) and MW-7 at a depth of 30.48m (7S), 91.44m (7I) and 304.8m (7D). This figure revealed that, water from shallow aquifer have high Na^+ and Cl^- concentrations indicating Na-Cl type water at the shallower depths indicating modern day saline water intrusion in the aquifer. In the intermediate aquifer, water is still Na-Cl type but with much lower concentrations. Concentrations decrease further in the deep aquifer and water type changes to $NaHCO_3$-type. Fresh water at the deeper depths might have been recharged during geological past; also, lateral regional recharge might contribute to the fresh water at depths.

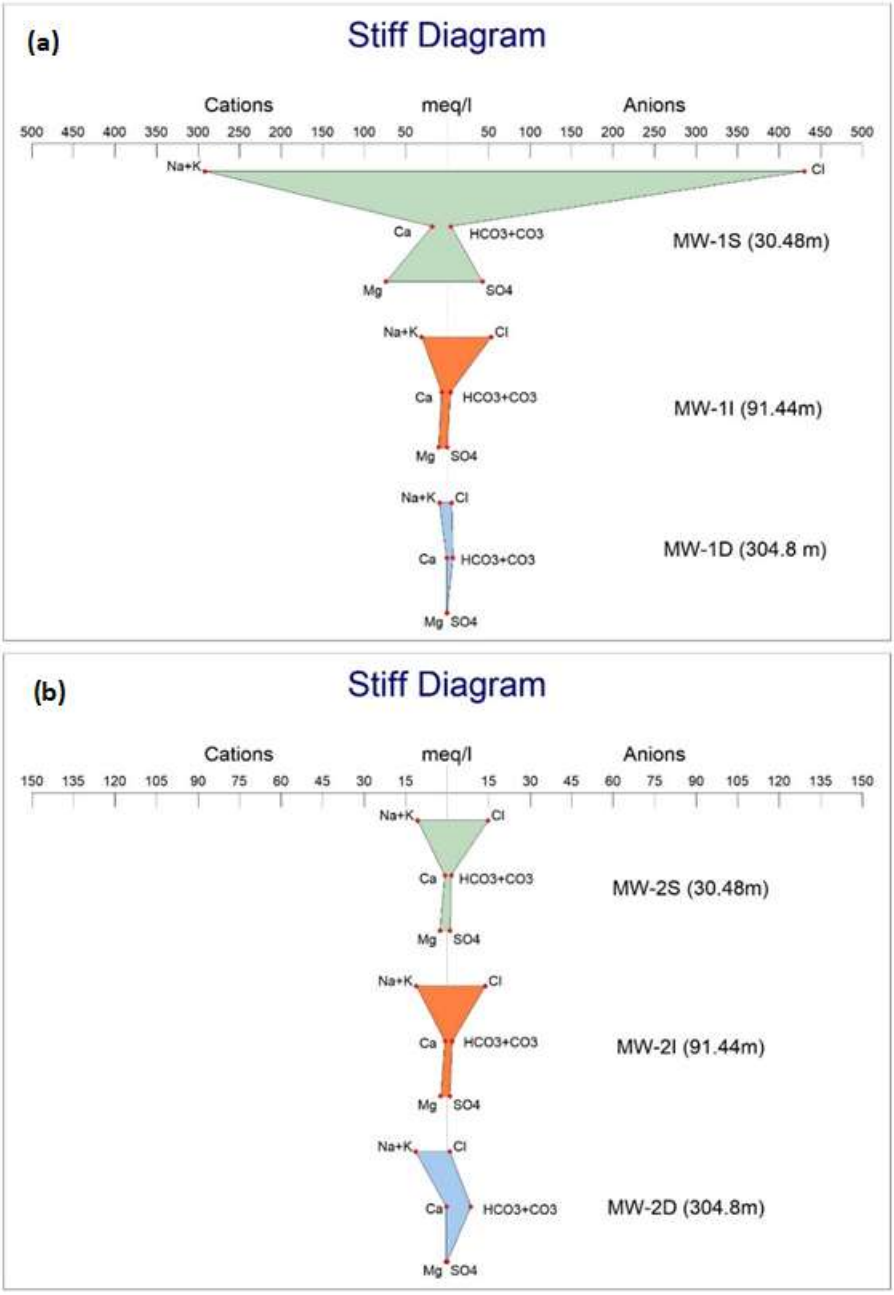

Figure 5-39: Stiff diagram of water samples from piezometer nest (a) MW-1S, MW-1I, MW-1D, (b) MW-2S, MW-2I, MW-2D

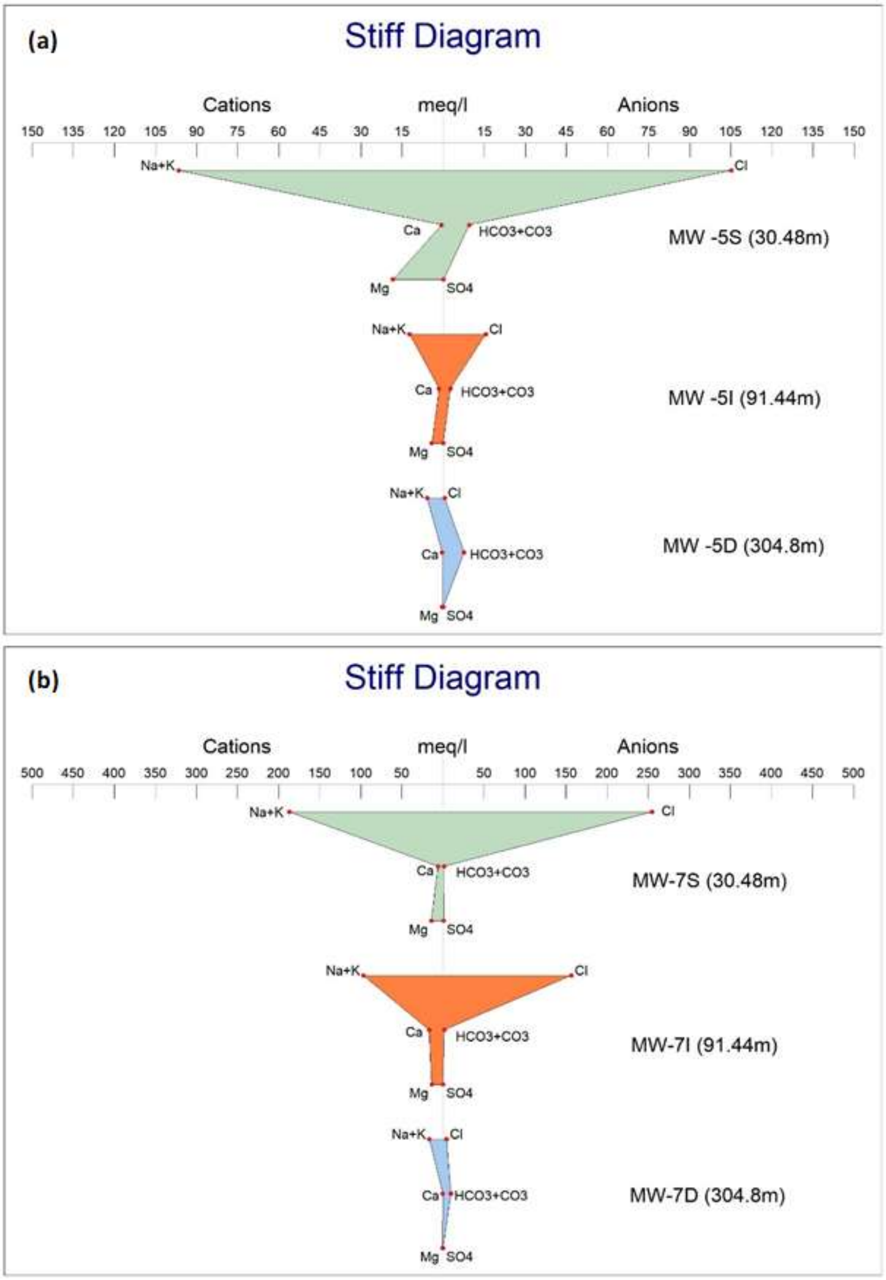

Figure 5-40: Stiff diagram of water samples from piezometer nest-(a) MW-5S, MW-5I, MW-5D, (b) MW-7S, MW-7I, MW-7D

Figure 5-41 and 5-42 illustrates stiff diagrams for water samples from three piezometer nests MW-3 at a depth of 30.48m (3S), 91.44m (3I) and 335.28m (3D), MW-4 at a depth of 30.48 (4S), 91.44m (4I) and 304.8m (4D) and MW-6 at a depth of 30.48m (6S), 91.44m (6I) and 304.8m (6D). This figure shows that, water from intermediate aquifer have higher Na^+ and Cl^- concentrations than shallow and deep aquifers. Shallow and intermediate both aquifers indicate Na-Cl type of water and presence of saline water. Except in Patharghata, deep aquifer shows relatively fresh Na-HCO_3 type water.

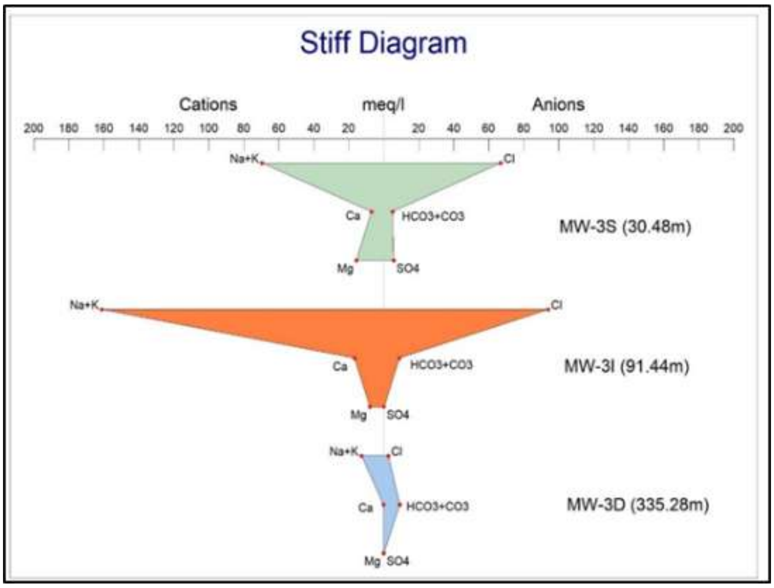

Figure 5-41: Stiff diagram of water samples from piezometer nest (a) MW-3S, MW-3I, MW-3D

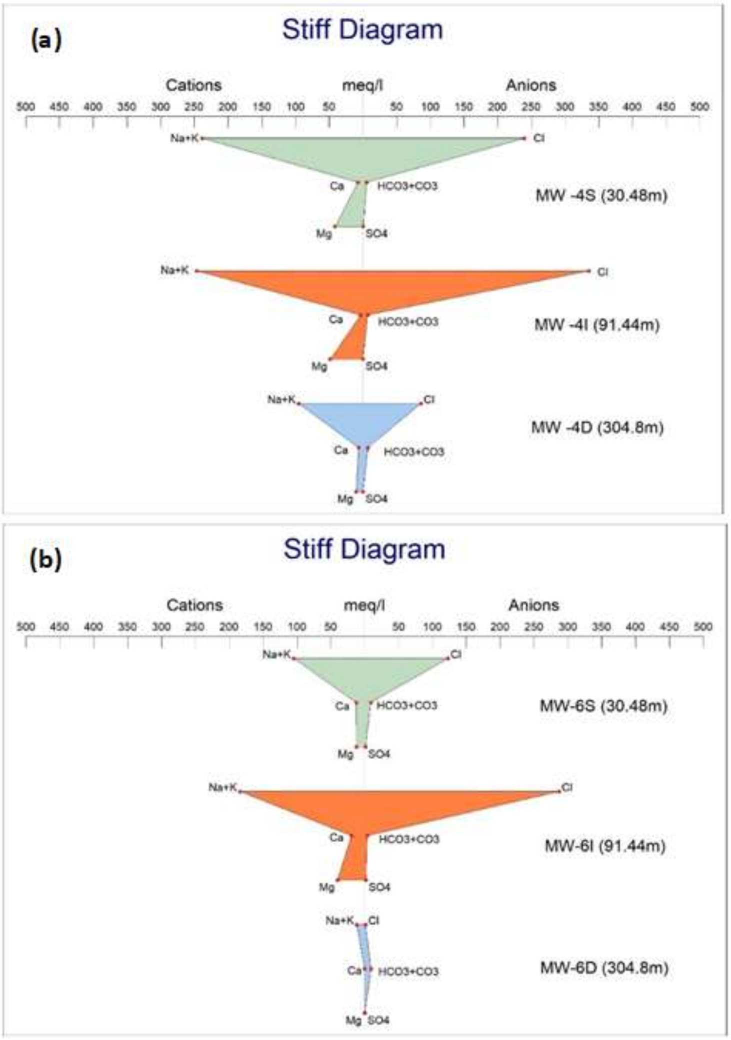

Figure 5-42: Stiff diagram of water samples from piezometer nest (a) MW-4s, MW-4I, MW-4D, (b) MW-6S, MW-6I, MW-6D

5.5 Drinking Water Quality:

Safe and easily accessible water is one of the basic needs for human and an essential step for improving life standards. Universal and equitable access to safe and affordable drinking water is also one of the main targets of Sustainable Development Goal (SDG) (target 6.1). Safe drinking water is a prior to prevent and control waterborne diseases. That's why, assessment of groundwater quality has been given a special emphasis in this research.

To assess the quality of ground water of the study area and determine its suitability or deinking purpose a comparison has been made between the results of collected water quality analysis and guideline values. A water quality index is also provided by using one of the most widely used WQI methods.

5.5.1 Comparison with Drinking Water Standards

Comparison of the concentration of different water quality parameters of analyzed samples with World Health Organization (WHO, 2008) and Department of Environment, Government Republic of Bangladesh (DoE, 1997) has been made in Table 5-1.

5.5.1.1 *Major, Minor and Trace Elements:*

The Table 5-1 shows that, concentration of the major anions and cations in most of the samples remain within the acceptable limit recommended by WHO and DoE except sodium and chloride. Groundwater samples of the study area show the presence of very high concentration of sodium and chloride. In some places nitrate and potassium also found in higher concentrations.

Table 8: Comparison of the concentration of different water quality parameters with WHO standards (2011) and BDWS (DoE, 1997)

Parameters		WHO Standards (2011)	BDWS (DoE, 1997)	No of Samples exceeds WHO limits			No of Sample exceeds BDWS limits		
				STW (out 0f 11)	ITW (out of 9)	DTW (out of 50)	STW (out of 11)	ITW (out of 9)	DTW (out of 50)
pH		6.5-8.5	6.5-8.5	None	None	None	None	None	None
Major Cations	Na^+	200	200	9	9	45	9	9	45
	K^+	-	12	-	-	-	9	4	3
	Ca^{2+}	75	75	3	2	2	3	2	2
	Mg^+	35	30-50	7	5	5	5	5	5
Major Anions	Cl^-	200	150-600	10	9	10	9	9	5
	SO_4^{2}	250	400	None	None	None	None	None	None
	NO_3^-	50	10	None	None	None	5	9	14
Minor & Trance Constituents	Fe^{2+}	0.3-3	0.3-1	None	None	None	6	3	5
	Mn^{2+}	.01	0.5	3	None	4	3	2	4
	As	.01	0.05	None	None	None	None	None	None

Concentration of Na ion in almost 90% sample exceed the WHO and DoE standard (1997) recommended limit of 200 mg/L. Increased dietary sodium ingestion can contributes to the risk of hypertension, congenial heart diseases and kidney problems. In case of chloride concentrations mostly in shallow and intermediate well show higher value, where almost 90% sample exceed the recommended limit of WHO and DoE. On the other hand, deep well samples show low concentration and only 6% samples exceed the limit.

5.5.1.2 *Electrical Conductivity (EC):*

Based on amount of EC in groundwater some authors divided water quality in 3 groups (Deshpande and Aher., 2011). The classification is shown in following Table 5-2

Table 9: Classification of groundwater based on EC (Deshpande S.M. and Aher K.R., 2011) and comparison with samples

EC (µS/cm)	No of Sample			Classification
	Shallow	Intermediate	Deep	
<1500	2	4	40	Permissible
1500-3000	3	1	9	Not Permissible
>3000	5	4	1	Hazardous

The table shows shallow well sample has very high EC and 70% sample is above permissible limit. 50% intermediate well also exceed safety limit. Deep wells contain lot safer water than shallow and intermediate wells and more than 60% remain within safety limit.

Around 10% sample in shallow well and 7% sample in deep well exceed recommended limit for calcium and magnesium. In case of potassium, 82% shallow, 36% intermediate and 6% deep groundwater samples exceeding standard limit.

None of the sample exceed acceptable value of nitrate prescribe by WHO but 45% shallow and 20% of deep well exceed DoE prescribed value.

Around 30% shallow well and 5% deep well exceeds the standard value of Fe and Mn given by WHO DoE. The study area is free from sulphate and arsenic contamination and all of the samples show concentration within standard value.

5.5.1.3 *Total Dissolved Solids (TDS):*

EC values can give an indication about TDS in water. TDS can be calculated from EC value by using following formula (Hem, 1970).

$$TDS = EC \times A$$

Where, ‘A’ is a conversion factor. For most ground water ‘A’ is between 0.55 and 0.75 (usually 0.66). EC is expressed in µS/cm and TDS is expressed as mg/L.

Table 10: TDS classification of drinking water (Freeze & Cherry, 1979) and comparison with samples

TDS (mg/l)	No of Sample			Types of Water
	Shallow	Intermediate	Deep	
<1000	1	2	40	Fresh
1001-10000	5	4	10	Brackish
10001-100000	2	2	None	Saline
>100000	None	None	None	Brine

Table 5-3 shows that 80% sample from deep well is fresh and others fall in brackish category. But sample from shallow and intermediate mostly brackish and even some samples fall in saline category.

5.5.1.4 ***Total Hardness:***

Hardness is normally expressed as the total con centration of Ca^{2+} and Mg^{2+} as mg/l equivalent $CaCO_3$. It can be calculated by using following equation (Freeze and Cherry, 1979)

$$Total\ Hardness = 2.5(Ca^{2+}) + 4.1(Mg^{2+})$$

Here, hardness is expressed as mg/l.

Harness (mg/l) After Sawyer & McCarty)	No of Sample			Types of Water
	Shallow	Intermediate	Deep	
<75	2	None	43	Soft
75-150	None	None	1	Moderately Hard
150-300	4	4	2	Hard
>300	5	5	4	Very Hard

Table 11: Hardness classification of drinking water and comparison with samples

According to classification samples from shallow and intermediate wells are hard to very hard. In deep well 60 % samples are soft and others are hard to very hard.

5.5.2 Water Quality Index (WQI):

WQI provide an idea about the overall quality of water and asses it's reliability for drinking purposes (Avvannavar and Shrihari, 2008). That's why WQI range is measured for each sample and classifies water quality according to range value (Table 5.1).

From table it can be seen that, 60% samples from deep aquifer shows excellent quality and 32% samples show good quality and only 2 samples from pre-monsoon and 1 sample from post-monsoon season show very poor quality. But in the case of sample from shallow and intermediate aquifer, most of them are not very good in quality. Around 50% samples from pre monsoon have good quality but others are not suitable for drinking. On the other hand, in post monsoon 85% sample show good quality.

Table 12: Classification of WQI range and type of water (Vasanthavigar, 2009)

WQI Range	No of Sample (pre-monsoon)			No of Sample (post-monsoon)	Percentage				Water Type
					Pre-monsoon			Post-monsoon	
	STW	ITW	DTW		STW	ITW	DTW		
<50	1	2	30	4	9	23	60	85	Excellent
50-100	5	2	16	1	45	23	32	15	Good
100-200	2	2	3	1	1	23	1	None	Poor
200-300	2	4	2	1	1	40	1	15	Very Poor
>300	2	None	None	None	1	None	None	None	Water Unfit for Drinking

Figure 5-44 shows that, deep well samples show lower WQI value than shallow and intermediate wells and contain fresh water. WQI range in deep well is low in almost throughout the area. In shallow and intermediate aquifer most of the area have high WQI value and indicate poor quality water. In these aquifers lowest value found in northern part and gradually increases towards north-western and southern part. Figure 5.45 shows that, in both season northern parts indicate highest quality of water and in north-western and southern part water quality decreases.

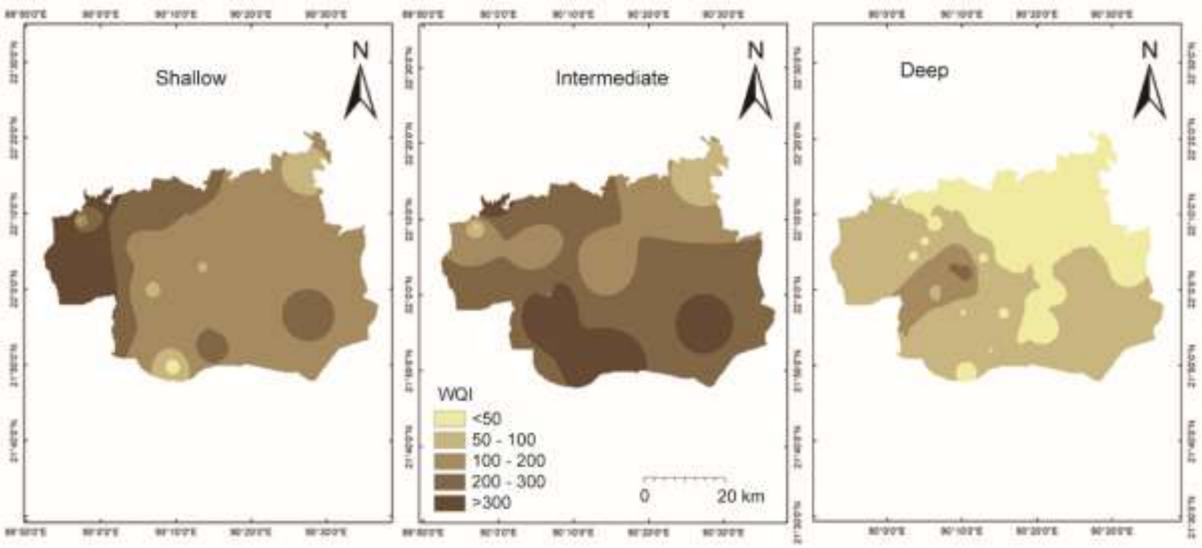

Figure 5-43: Spatial variation of WQI range in shallow, intermediate and deep aquifer

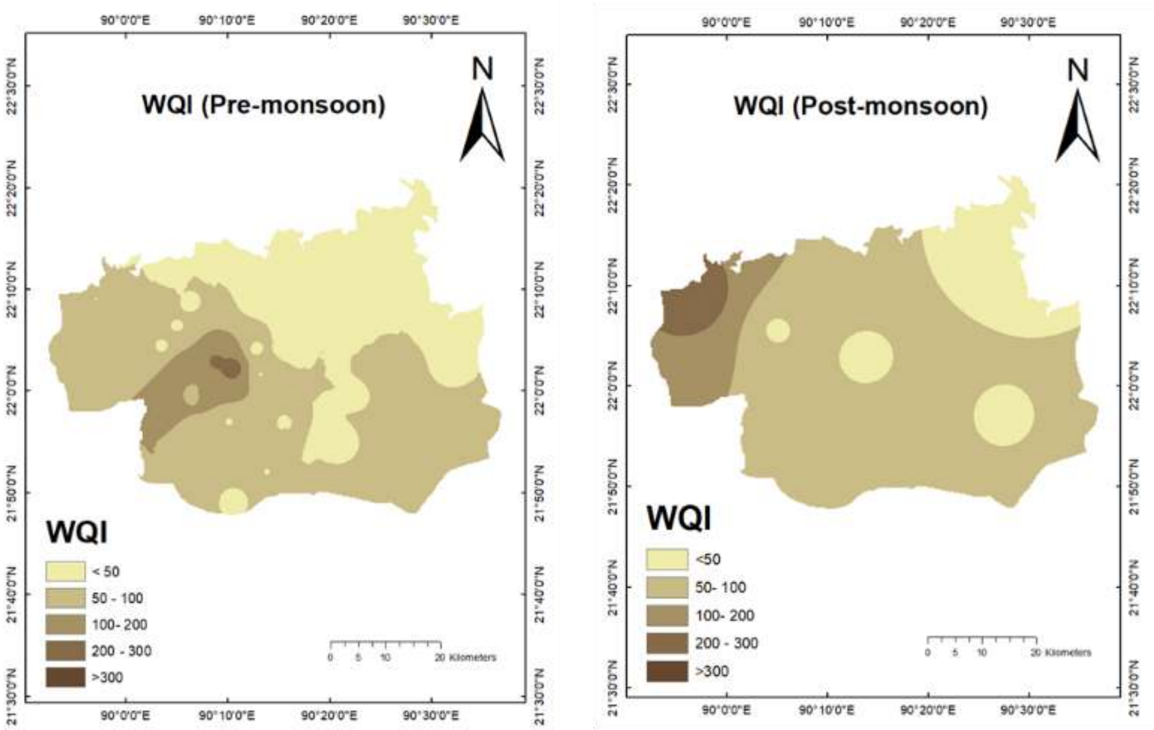

Figure 5-44: Seasonal Variation of WQI

SECTION-6: GROUNDWATER MODEL DEVELOPMENT

6 Groundwater modelling

For groundwater management, groundwater modelling is an effective tool. Model is the simplification of reality to predict future scenario (Gorelick, 1983). Though it is very difficult to imitate the natural condition in model input but it gives a reliable insight about present condition and to predict future scenarios and possibilities.

A groundwater flow model was constructed for the study by using MODFLOW-6 (Langevin et al., 2017). MODFLOW is the USGS's modular hydrologic model and is considered as an international standard for simulating and predicting groundwater conditions.

6.1 Description of the Model

6.1.1 Selection of model area

Groundwater systems are bounded by natural hydrologic boundaries, they rarely coincide with administrative boundaries. Selection of appropriate model boundary is the most important task in groundwater modelling. Therefore, in order to develop a reliable groundwater flow model, the study area was extended following big rivers as shown in Figure 3-9. These boundary rivers are large and expected to act as natural hydraulic barriers for the shallow aquifer, which is well connected with the rivers.

6.1.2 Model Grids:

There are a total 3,861 cells in the model among them 3,124 are active cells and rest of the cells are inactive and the scenario is similar for all the layers of the model. Among the active cells, 1,173 are 2 km in length and width whereas, rest of the 1,951 cells are 2 km in length and width. The finer grids were usually assigned along the major river systems.

6.1.3 Model Layers:

There are total seven (7) layers in the model (Figure 6-1). The surface of the model is considered as model top. The first 50 m of the model are considered upper aquifer. The second layers of the model are aquitard-1 which extends from -50 m to -70 m. The third layers are aquifer-2 and extend from -70 m to -140 m. After aquifer-1, there is aquitard-2 which extends from -140 m to -160 m. The fifth layer of the model are aquifer-3 and it extend from -160 m to -190 m. Aquitard-3 exist immediately after the aquifer-3 which extend from -190 m to -260 m and the bottom layer of the model are aquifer-4 and it extend from -260 m to bottom (-300 m) of the model. Here, thickness and depth of each layer are calculated from the hydro-stratigraphic model.

6.1.4 Model Parameters:

Hydraulic conductivity of various layers of the study area are calculated by grain size analysis and slug test analysis which are already discussed (section 3.4). Though the measured /calculated hydraulic conductivity (K) sometimes underestimate the natural conductivity, the model began with exact average value of measured hydraulic conductivity for all layers. The value of specific storage and specific yield was initially same in all layers and later all these parameters were changed in varying degree but obviously within plausible ranges to get a good match between model simulated head data with observed head data. It should be noted that, the observed head data is highly affected by the areal topography and the revelation of well head. Due to the dearth of good topographic data the exact match between model simulated and observed head data were not possible. Here, more attention was given to match the overall trend in flow direction and the ranges of fluctuation in model simulated and observed head data.

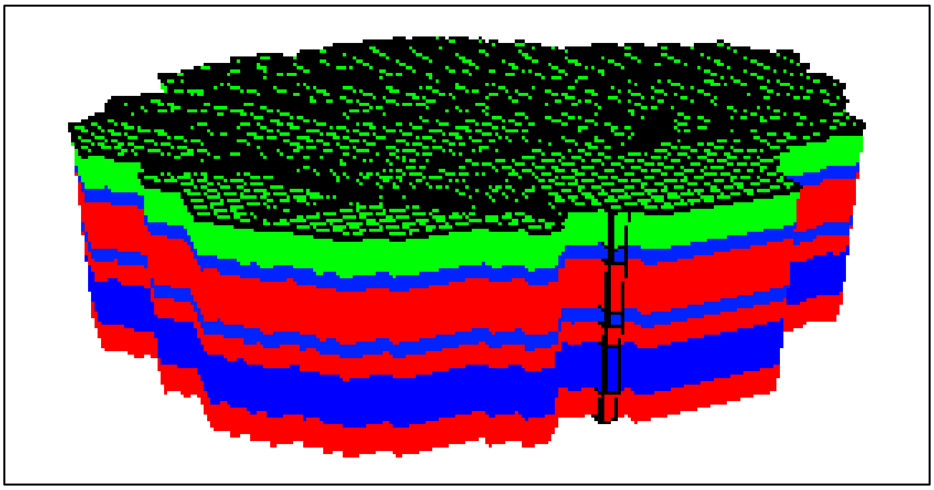

Figure 6-1: Figure showing the layers of the model

6.1.5 Assignment of Pumping Rate:

Groundwater abstraction/pumping for domestic purposes was assigned with the WEL package with an appropriate spatial distribution. The exact value for quantifying the per capita water consumption in the study area is a convoluted task. Michel and Voss (2009) considered 50 liters of water consumption per person per day in rural area of Bangladesh and this rate is used in this research. Various future scenarios can be estimated by multiplying water consumption with estimated population of each upazila. Industrial pumping is not considered in this research. Payra port is another largest sea port at kalapara, Patuakhali which in under construction. When it will start its activity, various industries will develop around the port and the abstraction/pumping of water will be increased. We can assess the future scenario of water head in the study area by adding industrial pumping with this model. All pumping are assigned at the deepest layer of the layer, which is the fresh water aquifer.

6.1.6 Boundary Condition:

The boundary condition of the model is constant head (CHD) in south-central, south-west and south-eastern part due to the presence of Kuakata Sea beach in south, Tetulia river in the south-east, Balaswar River in south-west and the northern boundary of the model are general head boundary. There are a number of rivers within the model among them the major rivers are also considered as constant head (CHD) boundary connected to the top model layer.

The top boundary of the model was approximated a constant value of recharge with drain package (DRN) allowing model to accept as much recharge as required and reject the access recharge water through the drains. The drain package was used in the model because the accurate estimation of recharge is so difficult and never gives reliable estimation.

6.1.7 Model Time Discretization:

The model was run in steady state condition in 1st period and then it was run in transient condition. Finally, the model was run for twenty-one (21) years from 2005 to 2025. Initially the time discretization was 1.2 meaning there are 11 stress period for each month. Finally, for long term simulation, the time discretization was 1.3 meaning there are 9 stress period for each month.

6.1.8 Model Sensitivity Analysis Procedure:

Sensitivity analysis usually means the changes in output owing to changes in the input parameters. In sensitivity analysis various input parameters are changed at varying degree to evaluate how the model result changes with this variation. Sensitivity analysis provides a valuable understanding about the behaviour of the model. In sensitivity analysis, horizontal and vertical hydraulic conductivity, specific storage was increased and decreased by times, respectively to understand how much the model are sensitive to each parameter.

Assessment of the subsurface water resources, groundwater flowing trend, flow direction, water level fluctuation range, recharge and discharge rate are the essential part to get better understanding about the sustainability of subsurface water bearing zones. Groundwater modelling is a highly recommended tool to assess those properties of groundwater resources. Furthermore, a calibrated model can be used to predict a number of future scenarios to glean about the sustainability of aquifer.

6.2 Model Calibration

A model never able to magically replicate or imitate the reality. In reality the subsurface environment is too much convoluted and it varies greatly even within the smaller distance. For this reason, here comes the calibration issue immediately after finishing model simulation. It is very important for increasing model accuracy and hydraulic conductivity, specific storage, specific yield is need to changes at various ranges but obviously in between the plausible and realistic ranges. After changing hydraulic properties at a number of times, when model simulated result best match with the observed result then we can consider it as base case. In this research, the model is calibrated with the observed groundwater level data at fourteen (14) different locations. Among them, in Bhandaria upazila, model simulated result slightly differed from the observed data. From the observed data water level graph in Bhandaria, the breaking in water level rise and fall indicate that domestic pumping in Bhandaria upazila is much higher. Observation wells located very close to the major river shows higher water level value than the model simulated data. This is because of their location. Due to their location very close to the river, the recovery rate on those area is higher than the others surrounding area. The observation well in Patharghata and Amtoli upazila are located at very close to the river and they show higher water level than the model simulated data. Except the observation well data from Bhandaria, Patharghata and Amtoli upazila, all others observation well data represents the similar trend and satisfactory match with the model simulated data (Figure 6-12). Model Calibration graphs of all fourteen locations are provided in (Appendix-E).

The sets of hydraulic properties by which the best match obtained between model simulated data and observed data was considered base case model. In base case model, the horizontal hydraulic conductivity value for first aquifer was 5.0 m/day, for all other aquifers the hydraulic conductivity value was 10 m/day. The vertical hydraulic conductivities of all aquifer layers were 100 time lower than the horizontal hydraulic conductivity. Both the horizontal and and vertical hydraulic conductivities of the aquitard layers were 0.01 m/day. The specific storage value for first aquifer was $7.0x10^{-04}$ and for second, third, fourth aquifer it was $7.0x^{10-6}$. Specific yield value was 0.2 m/d for the top model layer.

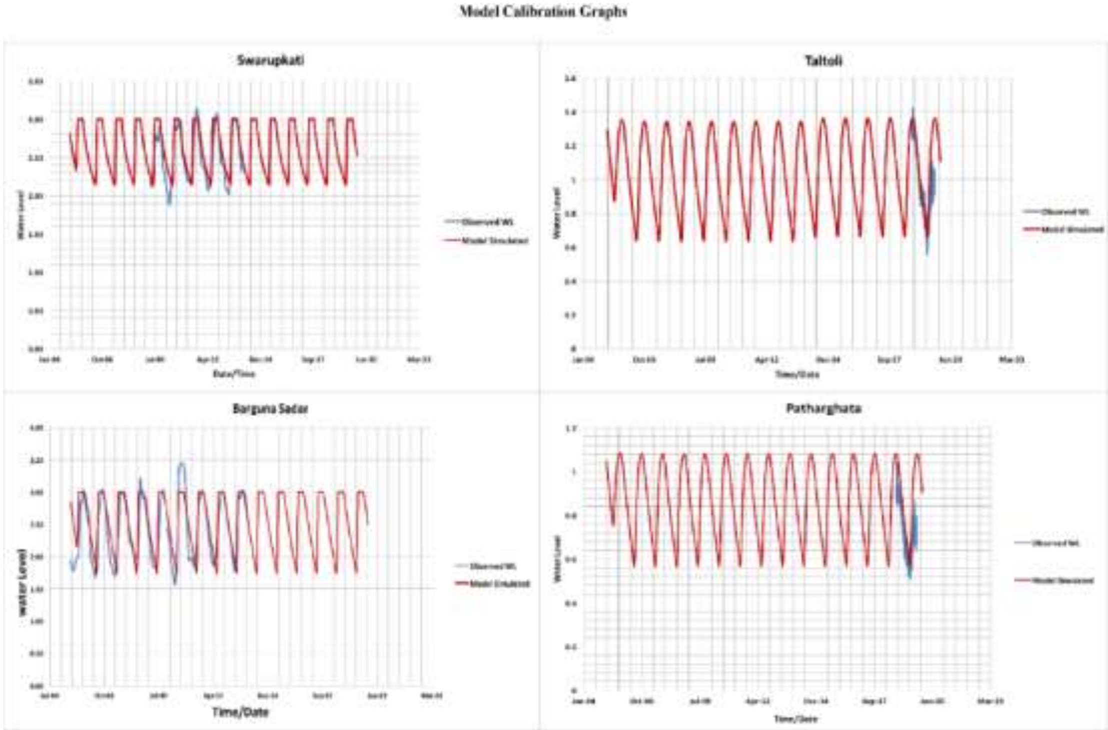

Figure 6-2: Above graphs showing the model calibration at different location at shallow depth (left) and deep (right) in study area

6.3 Base-Case Model simulated Result

The groundwater hydraulic head of the study area at present state were simulated in transient condition. The time ranges from 2005 to 2025. Both the shallow and deep aquifer show similar trend of hydraulic head which increases during the rainy season and decreases during the dry season (Figure 6-3). In the upper aquifer, the water head ranges from 0 m to 2.9 m. Water head is lowest or zero along the river which we assigned as constant head (CHD) in the model and the water head are highest at the area close to river ranges from 2 m to 2.9 m. In the second, third and fourth aquifer water head ranges from ~0-2.1, ~0-2.7 and ~0-2.3 m respectively. In second and third aquifer, water head is higher close to the major rivers. In the fourth aquifer, water head is higher in the northern part and gradually decreases towards the southern coastal part (Figure 6-4 and Figure 6.5).

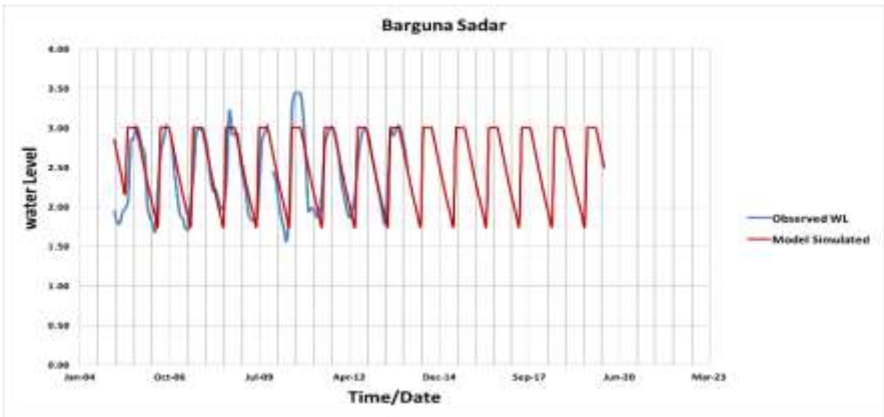

Figure 6-3: Graph showing the model simulated water level at Barguna Sadar upazia in December, 2019

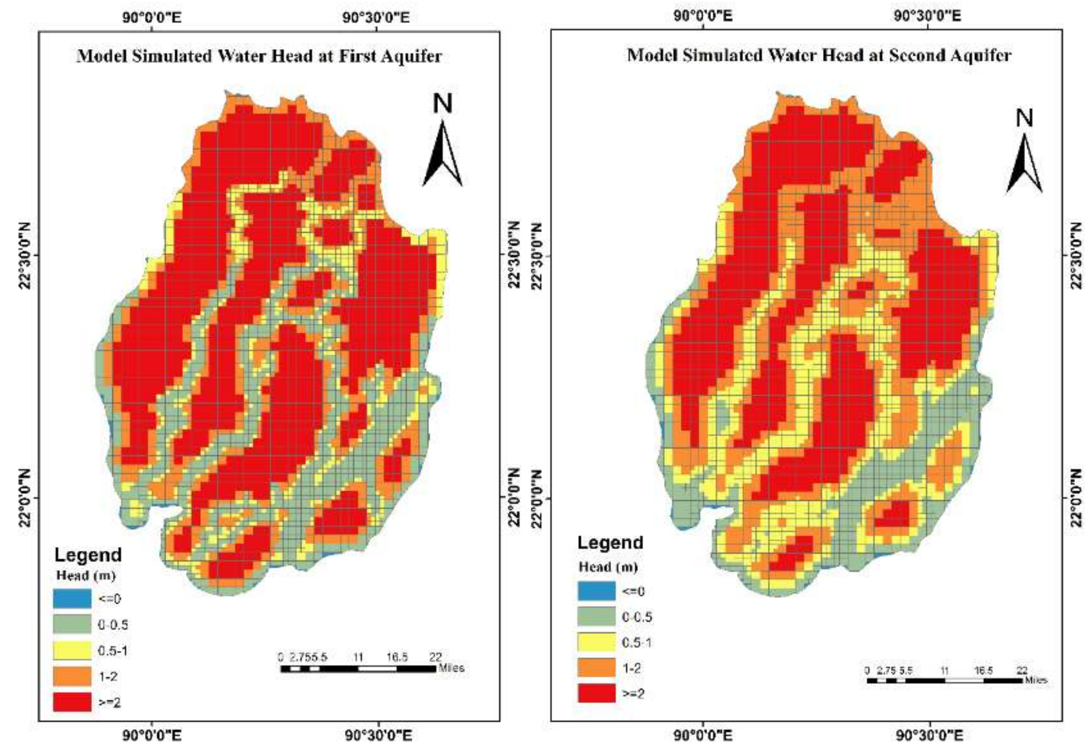

Figure 6-4: Map showing the model simulated water head at first and second aquifer in December, 2019

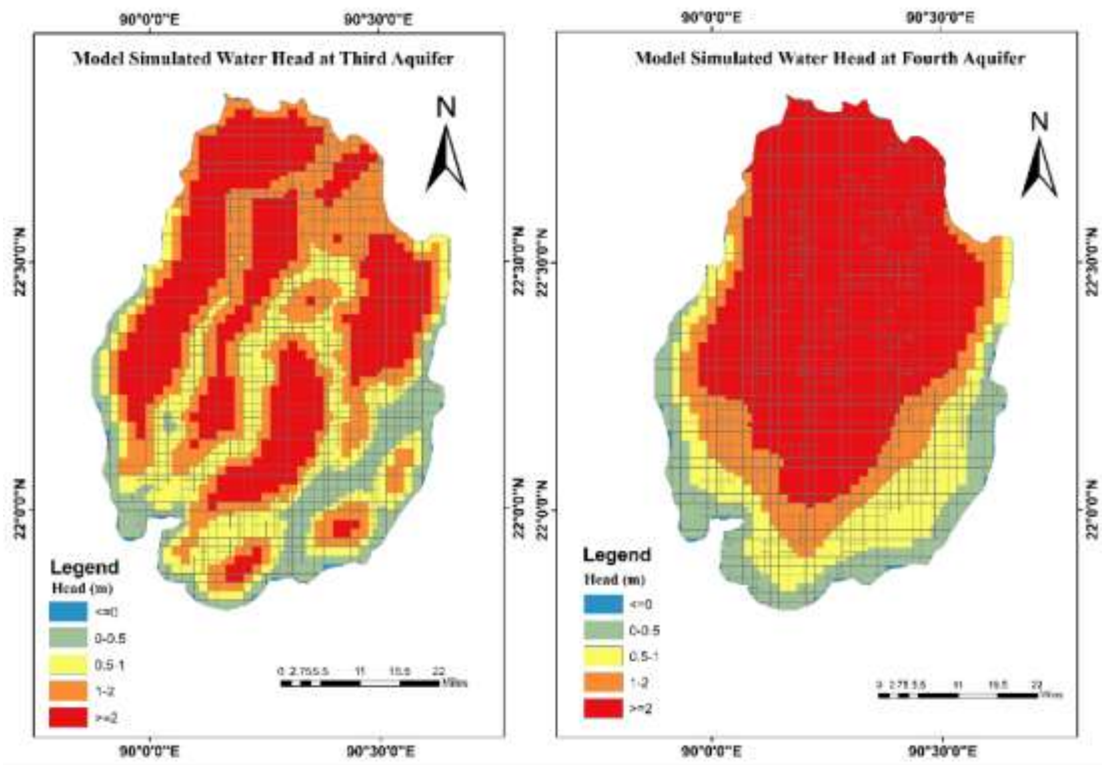

Figure 6-5: Map showing the model simulated water head at third and fourth aquifer in December, 2019

6.4 Sensitivity Analysis of the Model

Sensitivity analyses indicate that if the horizontal hydraulic conductivity is increased by ten (10) times from the base case condition, water level drops greatly both in shallow and deep aquifer. Here shallow aquifer shows high fluctuation whereas deep aquifer represents moderate fluctuation. Conversely, if the horizontal hydraulic conductivity is decreased by ten times from the base case condition, water level rises greatly in both aquifers. In case of vertical hydraulic conductivity, when the vertical hydraulic conductivity is increased by ten times from the base case condition, in shallow aquifer water level decreases whereas in deep aquifer water increases with noticeable fluctuations. At the same time when vertical hydraulic conductivity is decreased by ten times in deep aquifer water level decreased without showing any fluctuations and in shallow aquifer water level increased with moderate fluctuations (Figure 6-6). Both the shallow and deep aquifer are highly sensitive to specific storage value. When the specific storage value increased by ten times from the base case condition, both in shallow and deep aquifer water level increased largely and the opposite scenario occurs when specific storage value decreased by ten times from the base case condition. Here fluctuations of water level are very high in both aquifers from the base case (Figure 6-7). All sensitivity analysis graphs are provided in (Appendix-9).

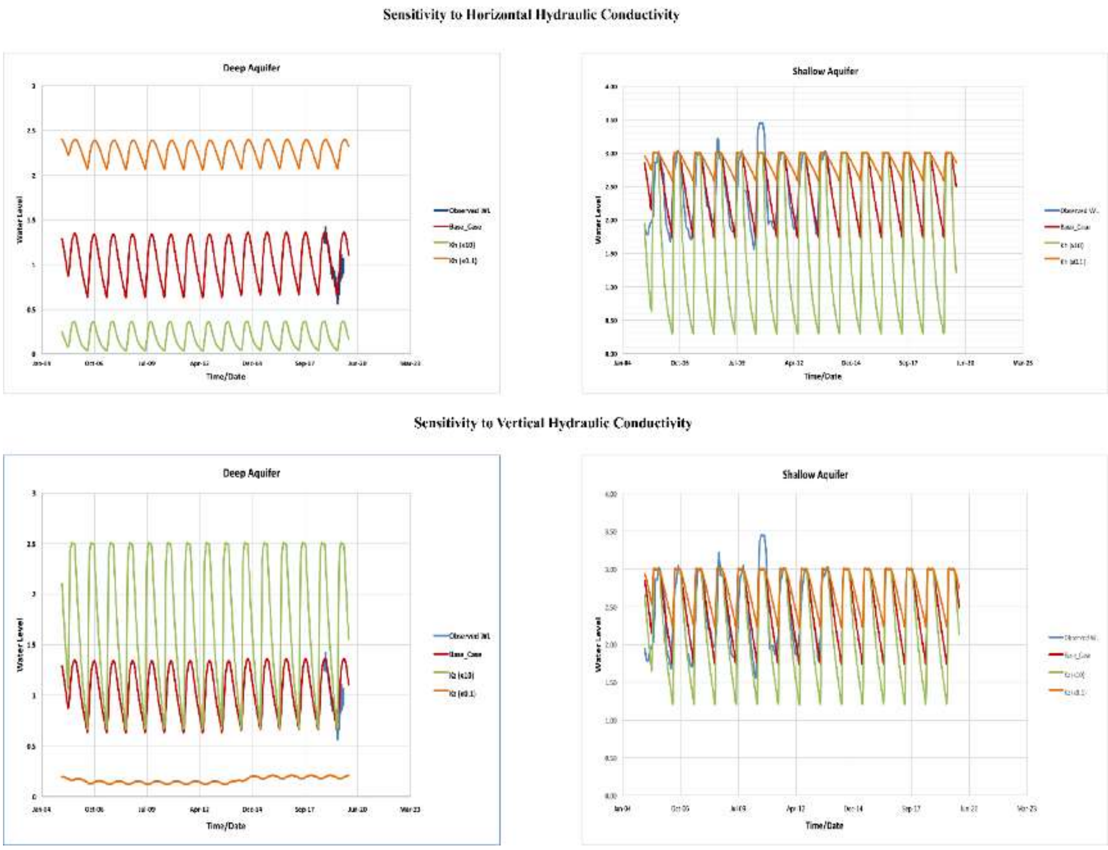

Figure 6-6: Above graphs showing the sensitivity of the model to horizontal and vertical hydraulic conductivity

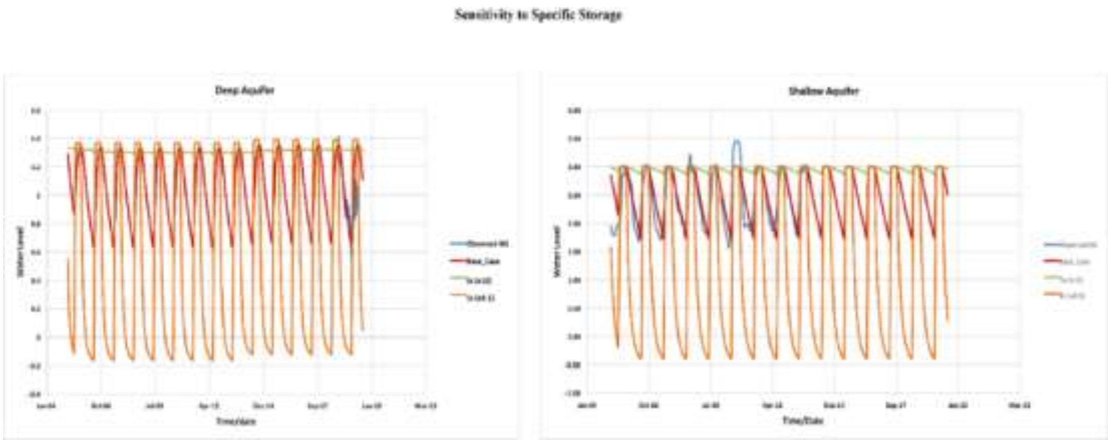

Figure 6-7: Above graphs showing the sensitivity of the model to specific storage

6.5 Potential areas for recharge and groundwater withdrawal

Groundwater recharge was estimated by Chaturvedi (1973) formula which was potential recharge (Figure 6-9). Potential recharge is too much greater than the actual recharge. Model simulated actual recharge was estimated by subtracting drained water from recharged water. Model simulated actual recharge value ranges from 0 to ~1500 mm/year. Actual recharge is the lowest along the model boundary and the river where constant head (CHD) was assigned. Along the side of the river recharge rate are higher and it is highest at very close to the river, this is because rainwater infiltrating at river banks can quickly flow out to the river. Recharge gradually decreases away from the river. Actual recharge is comparatively higher at the southeast and southwestern part of the study area than the northeast and northwestern part. In most part of the study area, actual recharge ranges from 0 to 300 mm/year (Figure 3.21). This spatial recharge map is off course would be affected by the permeability variation of the top soil, which has not been considered here because of lack of data.

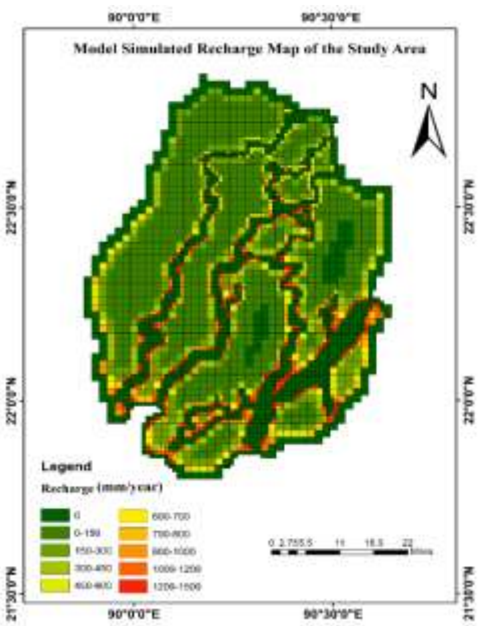

Figure 6-8: Map showing the model simulated actual recharge in the study area in 2019

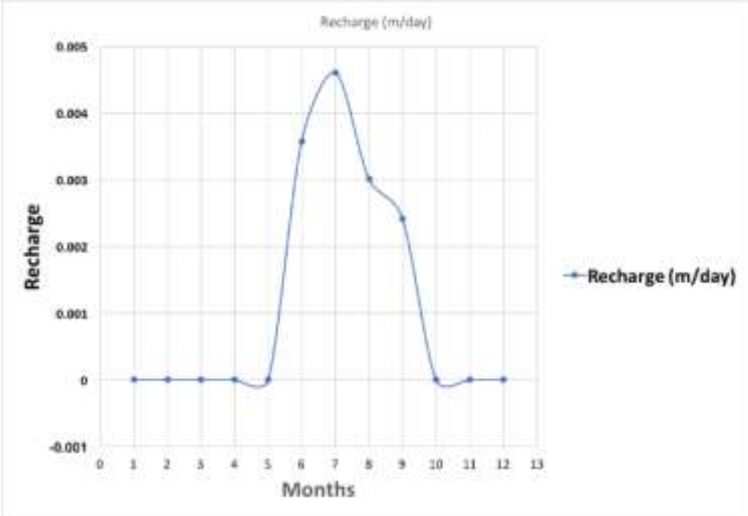

Figure 6-9: Above graph showing the potential recharge measured by Chaturvedi (1973) formula

6.6 Future scenario prediction

Once we have a calibrated model, we can do many future scenario analyses. This is generally the purpose of a model. The most important concern in this area is potential rise of water demand in near future, therefore, one future scenario of higher pumping is considered using this calibrated model. We all are concerned and excited about the Pyra port at Kalapara, Patuakhali another large sea port in Bangladesh. When various activities through this port will start, this area will become a large commercial area. Large number of people will go there daily for business purposes. Various industries will develop in this area in general. So, it’s conspicuous that, the demand of water will increase greatly. As groundwater is the only source of freshwater on this area, people will start to pump groundwater at a higher rate than present day. A ten times higher abstraction than the present abstraction rate was considered in the entire model area. The model simulated result shows that water level drops greatly from the base case condition and goes down to the MSL (mean sea level) (Figure 6-10 and 6-11) which indicate that, there are a very high possibility for salt water intrusion during the dry season.

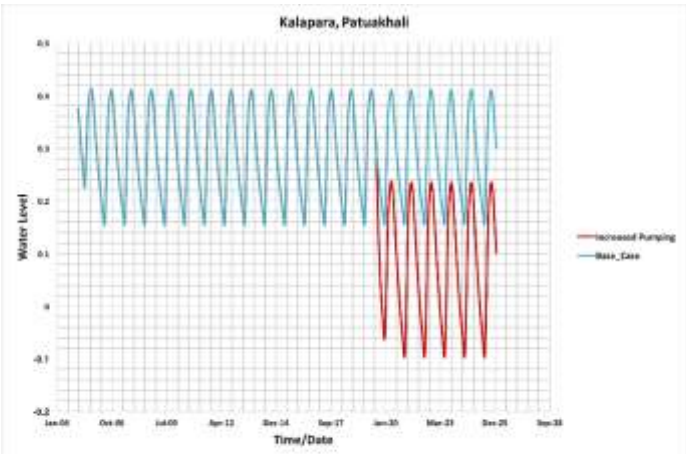

Figure 6-10: Above graph showing the effect of high pumping at Kalapara, Patuakhali

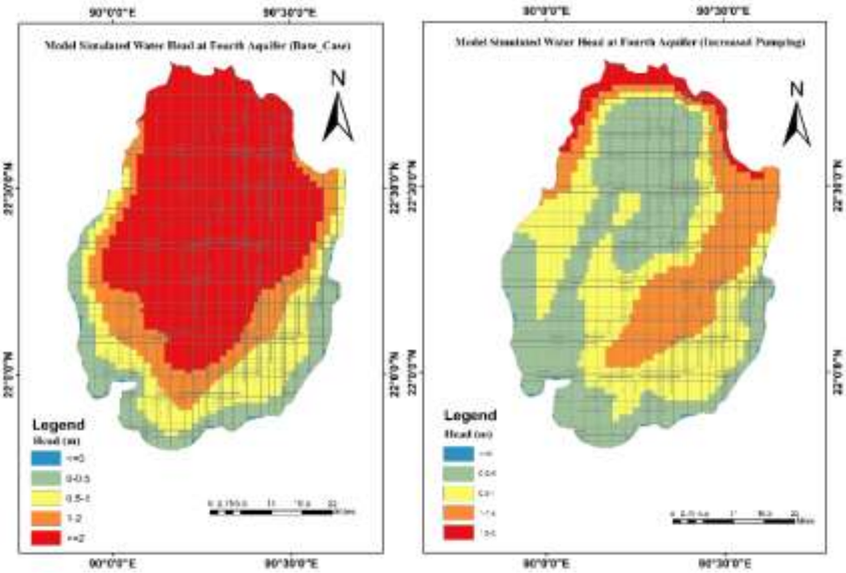

Figure 6-11: Map showing the comparison between deep aquifer in Base Case condition at December, 2019 (left) and in increased pumping condition at December, 2025 (right).

6.7 Surface water and Groundwater interaction

In many river systems, the extraction of large volumes of groundwater in close proximity to major streams and rivers has the potential to reduce stream flows. Basin-scale prediction tools that simulate these complex groundwater-surface water (GW-SW) interactions are required to assist in providing sustainable allocation of water. In unregulated upland streams, the primary impacts are on low-flow conditions that are crucial to ecosystem health. In regulated rivers, the primary impacts are on water security as the rivers interact with the underlying groundwater system in a spatially and temporally varying manner. This interaction can be a gain to the river or loss from the river; the latter is considered an important source of recharge to the groundwater aquifer.

One of the key challenges in modelling GW-SW interactions is the significant time-scale differences between surface water and groundwater processes. Because groundwater movement can be slower than surface water movement, the responses of groundwater systems to hydrological and management drivers such as climate variability, land use change, and groundwater extraction can be very damped and lagged. Hence, a key requirement in modelling GW-SW interactions in river system models is to account for these time lags.

Extensive analyses should be conducted to justify the need for a new model to estimate the GW-SW exchange fluxes. For example, if good quality groundwater head data is available in close proximity to the river of interest, and the period and frequency of the groundwater data record correspond to those of the river model calibration/prediction period, then the fluxes can be calculated using Darcy's Law.

Alternatively, a groundwater model that encompasses the reaches of interest might be available. In such cases, the GW-SW exchange fluxes predicted by the groundwater model can be imported into the river model. However, prior to this process, one needs to ensure that the groundwater model satisfies some critical criteria. Firstly, the calibration period and the time steps of the groundwater model need to correspond to those of the river model.

Secondly, the groundwater model has been purpose-built to provide reliable predictions for GW-SW exchange fluxes; for example, one of the crucial requirements is a suitable boundary condition such as the River boundary in MODFLOW. Due to the dependence of the GW-SW exchange fluxes on the river stage height, it may be necessary to calibrate the groundwater and river models simultaneously.

Surface water bodies are represented in the current model as constant head boundary condition, allowing groundwater to enter and exit the aquifer system depending on the dynamics of the groundwater level relative to river level. In this context, the model already includes the surface water component within it. However, there is scope for further improvement of the current model by adding the time variation of the river stage in the model. It couldn't be done because data was not available at the time of the model's development. Nevertheless, the surface water in the study interacts mostly with the shallow groundwater system; it has no influence on the deep groundwater system. Since the shallow groundwater is brackish and the deep groundwater is utilized mostly in this area, accurate assessment of surface water groundwater interaction is not crucial for this area.

6.8 Limitations of the Model

- All models are wrong, some are useful. A model can never imitate the subsurface conditions.
- Constant head (CHD) boundary is considered in the southern part of the study area and along the main river but in reality, the aquifer specially the deeper one may not expose to the rivers. However, since the deep aquifer is vast in size the constant head boundary around the side of the model may not have much effect near the center of the model area, which is the focus area of this study.
- The model is a constant density model. As being a coastal region, the saline water density may vary throughout the study area. This calibrated model can be used by assigning variable density in future.
- Populations are uniformly distributed over the study area in model but in reality, the population density may be much greater.
- Water level fluctuation data in the study area from data logger contained data from 2000 to 2013 and September 2018 to August 2019. Data from 2014 to 2017 are missing. There was only one- year deep aquifer water level fluctuation data. Water level flections data of deep aquifer for whole year (least 2010 to 2019) will able to provide mode detail scenarios.

SECTION-7: EFFECT OF CLIMATE CHANGE ON WATER RESOURCES IN COASTAL AREA

7 Effect of Climate Change

The coastal zone of Bangladesh sustains the livelihoods of over 40 million people with a diversity of natural resources that include fisheries, shrimp farms, forests, and deposits of salt and minerals. It also provides sites for export-processing zones, harbors, airports, land ports, and tourism. However, the coast of Bangladesh is vulnerable. A combination of natural events, including storm surges, cyclones, flooding, high groundwater arsenic levels, and anthropogenic hazards such as erosion, water logging, soil salinity, pollution, and increasing population pressures, have adversely affected the pace of social and economic development in this region. Compounding these issues are increasing risks from climate change, particularly sea-level rise. There is strong evidence that global sea level has risen during the last century at an increased rate (approximately 1.7 millimeters per year). Sea level is not rising uniformly around the world. The two major causes of sea-level rise are thermal expansion of the oceans (water expands as it warms) and the loss of land-based ice due to increased melting.

A 1-meter rise in sea level will inundate an estimated 18% of the total land in Bangladesh, directly threatening about 11 % of the population. Moreover, the indirect effects of climate change, such as changes in river flows and drainage and the nature of extreme events, could have a large impact on the population, with disproportionate impacts on the rural poor. Sea-level rise may also alter the salinity in groundwater and surface water, with corresponding impacts on soil salinity. Saltwater intrusion in groundwater means the gradual or sudden change from freshwater conditions in the ground to saline conditions. Saltwater intrusion can adversely impact the quality and potability of groundwater pumped from wells and the suitability of such water for irrigation. Saltwater intrusion can also cause soil salinization, which may adversely impact crop yields.

Saltwater intrusion may occur from saline waters that naturally move up rivers under tidal or storm surge pressures, or from surface flooding associated with storm surges, or from natural processes such as long-term rise in sea level, driving saltwater already underground farther inland. There are three primary paths of salinization in the coastal aquifer: (a) classical lateral seawater intrusion within the aquifer, with the Bay of Bengal as the saltwater source, caused by a rising sea level or falling inland groundwater levels; (b) vertical downward seawater intrusion from saline surface water carried inland by repeated storm saltwater surges and by possible future transgression of the coast; and (c) migrating preexisting pockets of subsurface saline water from vertical intrusion, lateral intrusion, or relic seawater that was deposited with the aquifer sediment. The rate of saltwater intrusion along all of these paths may be greatly increased by pumping. Climate change-driven sea-level rise would provide sources of saltwater in new places inland of the current coastal zone, and new saltwater intrusion would occur along these paths.

The direct impacts of sea-level rise on coastal inundation and extent of storm surges is of greater concern for groundwater conditions than classical lateral seawater intrusion. Moreover, pumping in the coastal zone, even without climate change, is an important determinant of salinization rate, and pumping-induced salinization rate is dependent on the pattern of the various sediment types that compose the aquifer fabric. Sea-level rise may shorten the lifetime of the fresh groundwater resource in the current coastal zone.

SECTION-8: SUMMARY, DISCUSSION AND RECOMMENDATIONS

8 Summary, Discussion and recommendations

This research work is done by an extensive field and laboratory analysis, and groundwater modelling to assess the groundwater resources and its sustainability in Patuakhali-Barguna district, Barisal division. In the study area both surface and groundwater are available but surface water are not suitable for drinking purpose. So, peoples are largely dependable on groundwater for drinking purpose.

8.1 Groundwater Occurrence

Groundwater in the study area occurs in porous deltaic sediments. Our geophysical investigation and borehole data suggest that the aquifer system in this area is highly heterogeneous. Individual layers of sands and clays cannot be traced over vast distances. However, depending on the relative sandiness and clayeyness the aquifer system down to a depth of 300 m can be subdivided in to three depth zones. The shallowest depth zone extends around 70 m on average. The intermediate zone is the thickest and lies between 70 m and 250 m. The deepest zone lies below 250 m. It is very difficult to pin point the exact depth intervals of these various zone everywhere in the study area based on sparse point data. Therefore, these reported depths should be considered as average and in particular area exact depths of these three zones may vary considerably.

The shallow aquifer is hydraulically very dynamic and is well connected with the surface water bodies. Most of the groundwater recharge and discharge occurs through this aquifer. Model suggests that the shallow aquifer receives less than 300 mm recharge annually from rainfall. As the groundwater level during the rainy season remain close to the surface, the direction of groundwater flow typically, follow the topography like - groundwater flows from topographic high to topographic low. During this time the direction of groundwater flow is towards the river or sea. Conversely during the dry season, when groundwater level start to decline due to high abstraction of groundwater for domestic, industrial purpose and by evapotranspiration, groundwater from the surrounding areas flow towards the pumping section in all over the study area.The intermediate aquifer seems to have some connection with the shallow aquifer as the water quality of this aquifer resembles that of the shallow aquifer. With some exception, the deep aquifer seems to be completely isolated hydraulically from the overlying aquifers. Its hydraulic behaviour as well as the quality of water differs completely from that of the overlying aquifers. The deep aquifer is likely not getting any vertical local recharge through the overlying aquifers. This deep aquifer seems to be connected to the regional aquifer system and may get recharged further upland.

In general groundwater level in Bangladesh fluctuates 3 to 4 meters between wet and dry season. This area is in complete contrast. Among the three aquifer zones, the deep aquifer exhibits the least variation in groundwater level with time. Except in Galachipa, the differences between the dry and wet season depth to water vary between 0.4 and 0.8 m. In Galachipa groundwater in deep well fluctuated about 1.5 m within the same time period. The least seasonal variability is found in the Amtoli well. Automatic recording of groundwater levels in the deep well also show daily tide effects on a scale of centimetres. Moreover, groundwater level in the deep aquifer zone is also almost always lower than the shallow and intermediate zone. There is only one year of observation made in this study. Based on this short time observation it is really difficult to comment on any long term trend. Nevertheless, over this one year the deep groundwater level seem to have not got back to its original position in almost every piezometer, potentially suggesting a regional declination of deep groundwater head. Groundwater levels of the shallow and intermediate depth zones were measured manually once every month. In most cases these data seem to be very chaotic. This is either because of high tidal influence on these wells or due to poor measurement. However, some trends can be depicted from these rather chaotic data. With the exception of Amtali, the seasonal fluctuations in both shallow and intermediate depth zones seem to be higher than the deep zone. Except Taltoli, groundwater level in the shallow and intermediate depth zone also seem to be similar in magnitude and variation.

8.2 Groundwater Quality

In general the deep aquifer zone contains potable groundwater in the study area with the exception of Patharghata. Our analysis of groundwater quality index suggests that 92% samples from deep aquifer have excellent to good drinking water quality. 8% samples from pre-monsoon and 1 sample from post-monsoon season show very poor but drinkable quality. The exceptional well is located in Patharghata. The deep groundwater is not only fresh; it is also free from other contaminant such as arsenic, iron, nitrate, and manganese. The deep groundwater is also mostly soft in nature.

In contrast to the deep aquifer water quality of both the shallow and intermediate depth zone are mostly undrinkable. This is largely because of high salinity. Determination of the source of the salinity at these depth intervals is out of the scope of this study. However, previous study (Agarwal et al., 2001) suggests that the salinity probably resulted from connate water entrapped during the deposition of the sediments in shallow marine condition. There are some pocket areas in both the shallow and intermediate aquifer depth zones that contain drinkable groundwater. However, identification of these freshwater pockets is really challenging and requires detail geophysical survey over the entire area.

8.3 Groundwater Sustainability

A groundwater flow model using MODFLOW 6 by USGS has been developed to assess the sustainability of aquifer. The model was calibrated to match the observed data. One major groundwater abstraction scenario was simulated in this study by increasing the current pumping by a factor of 10. The model simulated increased pumping scenario show that, due to over pumping, water level drops sharply close to sea level, although reaches a dynamic steady state condition. So, there is high possibility of salt water intrusion either from shallow aquifer by vertical down flow or adjacent saline water bodies by lateral flow due to over pumping in deep aquifer. This is particularly important for the southern part of the study area adjacent to the Bay of Bengal. However, the model suggests that the current groundwater abstraction is sustainable in the study area. Further scenario analysis can be done using this model.

8.4 Recommendations

As a coastal region various natural disaster as well as various anthropogenic activities are deteriorating the water quality at shallow aquifer and heavy pumping for industrial and domestic purposes decreasing the aquifer sustainability. As the population increasing day by day, water demand is also increasing very obviously. The only economically reasonable alternative of groundwater is rainwater. The most important advantage of rainwater harvesting is that it has no connection with sanitation problem and it requires no or minimal treatment for drinking. If peoples of the study area get interested about the rainwater harvesting and do it spontaneously then it will largely decrease the groundwater abstraction pressure from subsurface water bearing zones.

To ensure the sustainability of aquifer, water resource management plays vital role. For proper water resource management, the following aspects should be considered:

1. Improving the efficiency of water supply.
2. Prevent groundwater from anthropogenic contaminant sources.
3. Planning for proper disaster management
4. Raising public awareness and encouraging local community in the water management process.
5. Recycling water for industrial uses.
6. Improved sanitation system.
7. Continuous monitoring of the study groundwater quality for domestic use.
8. Develop a model to identify the potential zones of saltwater and fresh water interaction.

9 Social Contribution by the Consulting Farm

Center for Geoservices and Research is always commited about responsibilities to the society. In this context the farm handed over all the monitoring wells to the land owners as the safe and fresh water sources in the study area. These wells are being used by the land owner and their neighbouring families. All the seven monitoring wells in seven upazilas of the project area are serving about 140 families as the safe and fresh water sources. Credit goes to Urban Development Directorate for arranging such project for the wellbeing of the people in the root level where fresh drinking water is not available in shallow depths and are beyond the reach of poor people.

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APPENDICES

11 APPENDIX-A: Monitoring wells

Table A-1: Location of Monitoring Wells.

Well ID	Total Depth [m]	Screen Depth [m]	District	Upazila	Union	Village	Latitude	Longitude	Land Owners Name
MWTT1a	300	279-285	Barguna	Taltoli	Choto Bogi	Zakir Tobog	21.9941	90.116659	Abdur Rahman
MWTT1b	93	87-90							
MWTT1c	30	27-30							
MWAT2a	300	282-288	Patuakhali	Amtoli	Chakamayia	rbo Chakama	22.039163	90.236445	Abdul Quader Hawlader
MWAT2b	102	81-84							
MWAT2c	30	24-27							
MWBS3a	330	318-324	Barguna	Barguna Sadar	Nimtoili	M. Baliatoli	22.089582	90.071306	Abdul Kuddus
MWBS3b	102	75-78							
MWBS3c	30	9-12							
MWPG4a	300	273-279	Barguna	Pathorghata	Geyanpara	Nachnapara	22.13704	89.96286	Romen Chandra Hawlader
MWPG4b	102	93-96							
MWPG4c	30	27-30							
MWGC5a	300	267-273	Patuakhali	Galachipa	Kalaraja	Chiknikandi	22.25836	90.44239	Motiur Rahman Sarder
MWGC5b	87	84-87							
MWGC5c	30	24-27							
MWRB6a	300	285-291	Patuakhali	Rangabali	Rangabali	Majh Neta	21.94229	90.43747	Gazi Mostafa
MWRB6b	102	84-87							
MWRB6c	30	24-27							
MWKP7a	300	279-285	Patuakhali	Kalapara	Bara Baliatoli	Baliatoli	21.87726	90.231089	Moinuddi Hawlader
MWKP7b	96	84-87							
MWKP7c	30	24-27							

12 APPENDIX-B: Aquifer Pump Test

Time Since Pumping Started in minute	Depth to Water in meter	Drawdown in meter	Q = 1200 m3/day	Distance of the obesrvation well = 10 meter
0	1.15	Static Water Level		
0.5	1.28	0.13		
1	1.36	0.21		
1.5	1.40	0.25		
2	1.47	0.32		
2.5	1.54	0.39		
3	1.53	0.38		
4	1.58	0.43		
5	1.65	0.50		
6	1.66	0.51		
7	1.64	0.49		
8	1.72	0.57		
9	1.72	0.57		
10	1.76	0.61		
12	1.79	0.64		
14	1.81	0.66		
16	1.82	0.67		
18	1.82	0.67		
20	1.82	0.67		
25	1.90	0.75		
30	1.88	0.73		
35	1.91	0.76		
40	1.91	0.76		
45	1.92	0.77		
50	2.01	0.86		
55	1.98	0.83		
60	2.04	0.89		
80	2.08	0.93		
100	2.10	0.95		
120	2.16	1.01		
150	2.22	1.07		
180	2.20	1.05		
240	2.24	1.09		
300	2.23	1.08		
360	2.33	1.18		
420	2.35	1.20		
480	2.33	1.18		
540	2.40	1.25		
600	2.38	1.23		
660	2.36	1.21		
720	2.39	1.24		
780	2.44	1.29		
840	2.46	1.31		
900	2.45	1.30		
960	2.43	1.28		
1020	2.44	1.29		
1080	2.47	1.32		
1140	2.48	1.33		
1200	2.52	1.37		
1260	2.48	1.33		
1320	2.46	1.31		
1380	2.51	1.36		
1440	2.55	1.40		
1500	2.52	1.37		
1560	2.52	1.37		
1620	2.55	1.40		
1680	2.51	1.36		
1740	2.51	1.36		
1800	2.58	1.43		
1860	2.57	1.42		
1920	2.53	1.38		
1980	2.55	1.40		
2040	2.56	1.41		
2100	2.56	1.41		
2160	2.56	1.41		
2220	2.57	1.42		
2280	2.58	1.43		
2340	2.61	1.46		
2400	2.56	1.41		
2460	2.56	1.41		
2520	2.60	1.45		
2580	2.57	1.42		
2640	2.63	1.48		
2700	2.62	1.47		
2760	2.60	1.45		
2820	2.63	1.48		
2880	2.67	1.52		
2940	2.60	1.45		
3000	2.66	1.51		
3060	2.61	1.46		
3120	2.65	1.50		
3180	2.66	1.51		
3240	2.60	1.45		
3300	2.69	1.54		
3360	2.68	1.53		
3420	2.64	1.49		
3480	2.64	1.49		
3540	2.64	1.49		
3600	2.65	1.50		
3660	2.64	1.49		
3720	2.63	1.48		
3780	2.63	1.48		
3840	2.65	1.50		
3900	2.67	1.52		
3960	2.65	1.50		
4020	2.68	1.53		
4080	2.67	1.52		
4140	2.70	1.55		
4200	2.67	1.52		
4260	2.65	1.50		
4320	2.75	1.60		

13 APPENDIX C: VES location and field data

ID				Final		Location		
ID	SI No.	Name	Length(Meter)	Mid_Lat	Mid_Long	District	Upazila	Details
1	1	VES_1	800	22.12422	89.9615	BARGUNA	PATHARGHATA	From Patharghata UP HQ to the North, Kalipur, Turag Filling Station before Keramotpur Bazar, Patharghata-Mothbaria Road (South to Nest Well-4), Patharghata
2	2	VES-2	800	89.958089	22.029888			SW from Patharghata Upazila Sadar, Korailla Sorok, End of Poyrosova, Patharghata
3	3	VES-3	800	89.965792	22.207939			South to C&B Bazar, Patharghata-Mothabaria Road, End of Patharghata, Beside Jora Mobile Tower, Patharghta
4	4	VES-4	800	22.09347	90.08417		BARGUNA SADAR	From Borguna Sadar to the North (Nishanbaria Road), Before Hujurbari Bus Stand, (After Nest Well-3), Borguna
5	5	VES-5	800	90.200428	22.165396			From Borguna (from Amtali) Purakata Ferry Ghat to Purakata Bazar then Northward then to Eastbefore Kadamtal Bazar,(Alternative to east from Purakata Bazar to Katherpul-Ayla Road), Barguna
6	6	VES-6	800	90.136435	22.234505			From Boruna Sadar to Barisal Subidkhali Road, Near Shikdarbari Satnd , Borguna
7	7	VES-7	800	21.99382	90.12302		TALTALI	Bogi Rastar Matha, Amtali-Taltali Road after Harinbaria, (Before Nest Well-1), Taltali
8	8	VES-8	800	90.107238	21.930807			From Taltali UP HQ Bazar to the South till Baroghar More then East (Left turn) towards Charbazr/Kheya Ghat, Taltali
9	9	VES-9	800	22.09925	90.19996			400 m NE (Right) of Arpangasia Bazar, from Dhk-Kuakata Highway (Manikjuri More) to West to the Taltali Road, Taltali
10	10	VES-10	800	22.04012	90.23406		AMTALI	Charghat More/Bazar, 300m West of Barisal-Kuakata Highway at 10 km South from Amtali, Amtali
11	11	VES-11	800	90.327893	22.253984			Shakharia Bazar, Potuakhali-Kuakata Road before Amtali, Amtali
12	12	VES-12	800	90.267193	22.139450			Chandra/Baunia, Potuakhali- Kuakata Highway—From Amtali A K High School More to the East through Mohila College Road towards Talukdar Bazar Road, Amtali
13	13	VES-13	800	90.231461	21.876393	PATUAKHALI	KALA PARA	Baliatali Mredha Bari, Near MP Road & Baliatali Road Junction, Entrance From Highway: Mahipur Bridge to the NE towards Baliatali Bazar Road (VES-13,15), Kalapara
14	14	VES-14	800	90.130296	21.812706			Kuakata Beach, From East of Bus Stopage to the Berbadh Road, After Grand Hotel, South (Right Turn) from Road, Kalapara
15	15	VES-15	800	21.95007	90.27002			NE of VES-13, Baliatali-Banati Bazar Rd, Behind Power Station, NE of Banati bazar, Entrance From Highway: Mahipur Bridge to the NE towards Baliatali Bazar Road , Kalapara
16	16	VES-16	800	22.09796	90.41947		GALACHIPA	Majhighat Boalia Bazar – Boalia Bazar, Way to Panpotti Launch Ghat, Golachipa
17	17	VES-17	800	90.477903	22.205288			North of Ulania Bazar, Vill: Dakua, Backside of Home of Delwar Kha, Left to the Road, Golachipa
18	18	VES-18	800	22.20522	90.47796			East of Kalaraza Bazar (Before Nest Well-5), From Golachipa North to Ulania Bazar , Golachipa
19	19	VES-19	800	21.94682	90.43726		RANGABALI	NW to Neta Bazar , Before/West of Majh Neta More/School/Bridge, (460 m West of Nest Well-6, Rangabali
20	20	VES-20	800	90.396565	21.911188			Shaner Haola, East of Rajabazar towards Neta Bazar-opposite to the Saw Mill , Alternative: North of Raza Bazar-Katcha Rasta, Back side of Hiron Haoladar's Home, Rangabali
21	21	VES-21	800	90.429572	22.028066			East of Koralia Ferry Ghat, North of Koralia Bazar (Left Tun), Near Shop of Md. Billal Hossain/Mosque, Rangabali

VES-01		
AB/2	**MN**	**Apparent Resistivity(ohm-m)**
1	0.5	3.95
2	0.5	6.54
4	0.5	2.47
6	0.5	2.31
8	0.5	2.2
10	0.5	2.19
10	1	2.19
12	1	2.02
15	1	2.46
20	1	1.87
25	1	1.95
25	2	1.95
30	2	1.4
40	2	1.5
50	2	0.78
50	5	0.77
60	5	1.34
80	5	1.4
100	5	1.25
100	10	1.24
120	10	1.57
150	10	1.4
200	10	2.19
200	20	2.19
250	20	2.43
300	20	2.46
400	20	2.5

VES-02		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	10.53
2	0.5	13.27
4	0.5	7.07
6	0.5	5.16
8	0.5	3.6
10	0.5	2.81
10	1	2.8
12	1	1.8
15	1	1.75
20	1	1.87
25	1	1.95
25	2	1.94
30	2	4.22
40	2	6.26
50	2	1.55
50	5	1.55
60	5	1.34
80	5	1.6
100	5	3.13
100	10	3.1
120	10	2.02
150	10	1.75
200	10	1.87
200	20	1.86
250	20	1.46
300	20	1.4
400	20	1.25

VES-03		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	4.33
2	0.5	8
4	0.5	4.89
6	0.5	4.49
8	0.5	5.6
10	0.5	3.26
10	1	3.26
12	1	2.46
15	1	1.76
20	1	2.5
25	1	2.93
25	2	2.92
30	2	1.41
40	2	1.25
50	2	1.77
50	5	1.7
60	5	1.79
80	5	1.6
100	5	1.25
100	10	1.25
120	10	8.08
150	10	3.52
200	10	2.5
200	20	2.49
250	20	4.38
300	20	5.62
400	20	5.011

VES-04		
AB/2	MN	Apparent Resistivit y(ohm-m)
1	0.5	11.06
2	0.5	23.9
4	0.5	15.08
6	0.5	70.72
8	0.5	11.009
10	0.5	12.21
10	1	12.2
12	1	3.81
15	1	2.81
20	1	3.38
25	1	2.93
25	2	2.9
30	2	3.51
40	2	3.75
50	2	3.52
50	5	3.5
60	5	1.12
80	5	1.2
100	5	1.4
100	10	1.39
120	10	1.79
150	10	3.16
200	10	7.2
200	20	6.83
250	20	3.89
300	20	4.22
400	20	11.27

VES-05		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	3.95
2	0.5	3.03
4	0.5	2.62
6	0.5	2.35
8	0.5	1.8
10	0.5	2.48
10	1	2.48
12	1	2.02
15	1	1.76
20	1	1.87
25	1	2.43
25	2	2.43
30	2	2.81
40	2	2.51
50	2	1.96
50	5	1.94
60	5	2.02
80	5	3
100	5	1.25
100	10	1.25
120	10	2.02
150	10	2.11
200	10	3.13
200	20	3.1
250	20	3.89
300	20	4.92
400	20	7.51

VES-06		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	2.54
2	0.5	36.27
4	0.5	38.08
6	0.5	6.39
8	0.5	5.004
10	0.5	3.44
10	1	3.41
12	1	4.04
15	1	2.81
20	1	2.5
25	1	6.85
25	2	6.8
30	2	896.08
40	2	679.05
50	2	758.12
50	5	746.06
60	5	987.84
80	5	1575.37
100	5	21.86
100	10	15.54
120	10	22.22
150	10	24.61
200	10	5.01
200	20	5
250	20	48.74
300	20	70.33
400	20	1.13

VES-07		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	0.44
2	0.5	0.38
4	0.5	0.25
6	0.5	1.12
8	0.5	1.8
10	0.5	1.72
10	1	1.69
12	1	5.83
15	1	4.92
20	1	5.63
25	1	6.84
25	2	6.82
30	2	4.22
40	2	5.01
50	2	2.74
50	5	2.72
60	5	2.46
80	5	2.4
100	5	2.5
100	10	2.48
120	10	3.14
150	10	2.81
200	10	3.75
200	20	3.75
250	20	4.874
300	20	5.62
400	20	5.01

VES-08		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	0.296
2	0.5	0.54
4	0.5	1.68
6	0.5	2.02
8	0.5	5.2
10	0.5	6.26
10	1	6.21
12	1	5.38
15	1	8.08
20	1	6.89
25	1	4.89
25	2	4.87
30	2	0.703
40	2	31.32
50	2	7.83
50	5	7.77
60	5	16.83
80	5	6.01
100	5	4.69
100	10	4.66
120	10	89.03
150	10	14.06
200	10	6.26
200	20	1.87
250	20	1.94
300	20	1.4
400	20	5.01

VES-09		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	0.44
2	0.5	0.38
4	0.5	0.25
6	0.5	1.12
8	0.5	1.8
10	0.5	1.72
10	1	1.69
12	1	5.83
15	1	4.92
20	1	5.63
25	1	6.84
25	2	6.82
30	2	4.22
40	2	5.01
50	2	2.74
50	5	2.72
60	5	2.46
80	5	2.4
100	5	2.5
100	10	2.48
120	10	3.14
150	10	2.81
200	10	3.75
200	20	3.75
250	20	4.874
300	20	5.62
400	20	5.01

VES-10		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	5.47
2	0.5	4.98
4	0.5	4.15
6	0.5	3.47
8	0.5	2.8
10	0.5	2.19
10	1	2.33
12	1	2.24
15	1	2.11
20	1	2.5
25	1	1.95
25	2	2.43
30	2	2.81
40	2	5.01
50	2	4.89
50	5	4.66
60	5	5.61
80	5	10.01
100	5	9.39
100	10	6.4
120	10	8.98
150	10	15.83
200	10	9.77
200	20	9.33
250	20	11.69
300	20	11.25
400	20	12.528

VES-11		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	4.97
2	0.5	6.95
4	0.5	8.46
6	0.5	8.87
8	0.5	8.41
10	0.5	7.83
10	1	7.62
12	1	6.73
15	1	5.97
20	1	4.38
25	1	3.95
25	2	3.89
30	2	3.51
40	2	2.5
50	2	1.96
50	5	2.33
60	5	2.24
80	5	1.6
100	5	1.87
100	10	1.87
120	10	2.25
150	10	2.81
200	10	3.75
200	20	3.74
250	20	4.38
300	20	4.92
400	20	7.51

VES-12		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	5.95
2	0.5	8.71
4	0.5	11.17
6	0.5	14.25
8	0.5	16.01
10	0.5	17.85
10	1	17.72
12	1	7.18
15	1	4.92
20	1	6.89
25	1	4.89
25	2	4.87
30	2	9.14
40	2	12.52
50	2	15.67
50	5	15.54
60	5	1.68
80	5	2.01
100	5	1.56
100	10	1.55
120	10	1.79
150	10	2.11
200	10	2.5
200	20	2.48
250	20	4.63
300	20	5.62
400	20	6.26

VES-13		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	5.85
2	0.5	10.56
4	0.5	7.32
6	0.5	6.62
8	0.5	5.6
10	0.5	5.01
10	1	3.9
12	1	3.37
15	1	2.81
20	1	3.13
25	1	3.42
25	2	2.92
30	2	2.1
40	2	1.88
50	2	1.95
50	5	1.94
60	5	1.68
80	5	2
100	5	1.25
100	10	1.24
120	10	1.23
150	10	1.23
200	10	1.25
200	20	1.4
250	20	1.46
300	20	1.75
400	20	2.5

VES-14		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	4898.4
2	0.5	27.5
4	0.5	1393.64
6	0.5	190.38
8	0.5	48.84
10	0.5	83.32
10	1	72.43
12	1	56.35
15	1	28.83
20	1	25.68
25	1	25.47
25	2	19.5
30	2	17.58
40	2	13.78
50	2	9.79
50	5	9.32
60	5	4.49
80	5	6.2
100	5	20.45
100	10	20.2
120	10	8.98
150	10	10.55
200	10	8.77
200	20	9.01
250	20	424.11
300	20	84.4
400	20	25.05

VES-15		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	6.68
2	0.5	5.08
4	0.5	4.95
6	0.5	3.93
8	0.5	3.6
10	0.5	3.45
10	1	3.42
12	1	3.14
15	1	2.81
20	1	2.63
25	1	2.94
25	2	2.44
30	2	2.46
40	2	2.51
50	2	2.94
50	5	1.92
60	5	2.24
80	5	4.6
100	5	1.87
100	10	2.49
120	10	2.69
150	10	2.81
200	10	2.06
200	20	4.04
250	20	4.39
300	20	4.22
400	20	5.01

VES-16		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	7.1
2	0.5	5.9
4	0.5	5.59
6	0.5	5.61
8	0.5	5.81
10	0.5	5.32
10	1	5.75
12	1	5.38
15	1	4.92
20	1	4.39
25	1	3.92
25	2	3.89
30	2	3.52
40	2	2.51
50	2	2.94
50	5	2.72
60	5	2.25
80	5	2.8
100	5	3.19
100	10	3.42
120	10	3.14
150	10	2.11
200	10	2.51
200	20	2.49
250	20	3.9
300	20	3.52
400	20	5.01

VES-17		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	7.5
2	0.5	8.16
4	0.5	8.4
6	0.5	8.41
8	0.5	7.6
10	0.5	7.83
10	1	8.08
12	1	6.95
15	1	7.03
20	1	7.51
25	1	6.85
25	2	4.38
30	2	3.51
40	2	2.5
50	2	2.93
50	5	2.87
60	5	1.68
80	5	2
100	5	1.86
100	10	1.86
120	10	2.24
150	10	2.81
200	10	3.75
200	20	3.73
250	20	4.87
300	20	5.62
400	20	6.89

VES-18		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	16.45
2	0.5	15.54
4	0.5	17.25
6	0.5	18.03
8	0.5	18.62
10	0.5	19.41
10	1	19.27
12	1	18.86
15	1	17.23
20	1	15.66
25	1	13.72
25	2	12.18
30	2	9.84
40	2	6.26
50	2	3.92
50	5	3.88
60	5	3.92
80	5	4.003
100	5	3.13
100	10	3.1
120	10	3.59
150	10	5.62
200	10	5.32
200	20	5.28
250	20	6.33
300	20	7.03
400	20	8.77

VES-19		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	8.4
2	0.5	10.56
4	0.5	8.9
6	0.5	8.08
8	0.5	6.61
10	0.5	5.64
10	1	5.6
12	1	4.71
15	1	3.87
20	1	2.82
25	1	3.43
25	2	2.92
30	2	3.38
40	2	4.26
50	2	4.7
50	5	1.78
60	5	1.57
80	5	1.6
100	5	2.5
100	10	1.7
120	10	1.8
150	10	1.76
200	10	2.5
200	20	2.49
250	20	2.93
300	20	3.52
400	20	3.13

VES-20		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	6.04
2	0.5	6.74
4	0.5	5.69
6	0.5	5.05
8	0.5	4.4
10	0.5	3.75
10	1	3.57
12	1	3.14
15	1	2.46
20	1	2
25	1	1.96
25	2	2.19
30	2	2.1
40	2	1.87
50	2	0.75
50	5	1.55
60	5	1.46
80	5	1.6
100	5	1.25
100	10	1.4
120	10	1.57
150	10	1.41
200	10	1.88
200	20	1.87
250	20	2.44
300	20	2.49
400	20	2.4

VES-21		
AB/2	MN	Apparent Resistivity (ohm-m)
1	0.5	8.95
2	0.5	8.84
4	0.5	11.47
6	0.5	7.52
8	0.5	6.41
10	0.5	5.63
10	1	5.75
12	1	5.16
15	1	4.33
20	1	3.76
25	1	2.94
25	2	3.41
30	2	2.81
40	2	1.88
50	2	1.95
50	5	1.82
60	5	3.37
80	5	4
100	5	4.7
100	10	3.73
120	10	2.69
150	10	2.11
200	10	1.38
200	20	2.33
250	20	2.43
300	20	2.46
400	20	3.13

Resistivity range of different rock types established by correlating surface resistivity results to bore log data

Resistivity Range (Ω-m)	**Corresponding Rock type**
6-15	Top Soil
1-6	Clay
6-9	Clayey Silt
9-20	Fine grained Sand
20-100	Medium grained Sand
>100	Coarse grained Sand

VES 01		
Thickness(m)	Lithology	Resistivity
0-1.4	Top Soil	4.025
1.4-15	Clay	2.13
15-60	Fine grained Sand (saline water)	0.93
60-141	Fine grained Sand with clay	6.34
141-194	Clay with thin fine sand	3.12
194-300	Fine grained Sand (Brackish)	1.5
VES 02		
Thickness(m)	Lithology	Resistivity
0-0.5	Top Soil	11.432

0.5-3.5	Clayey Silt	8.4749
3.5-11	Fine grained Sand (saline water)	0.96386
11-30	Clay	4.3921
30-77	Fine grained Sand (saline water)	1.2715
77-187	Clay	2.0707
187-300	Fine grained Sand (saline water)	0.78066
VES 03		
Thickness(m)	Lithology	Resistivity
0-0.4	Top Soil	4.0529
0.4-4	Clay	5.6180
4-14	Fine grained Sand (Brackish)	2.1936
14-52	Clay	1.2095
52-127	Fine grained Sand	19.612
127-175	Clayey Silt	8.6936
175-300	Fine grained Sand (Brackish)	2.8496
VES04		
Thickness(m)	Lithology	Resistivity
0-1	Top Soil	12.98
1-2.5	Medium grained Sand	35.35
2.5-11.5	Clay	3.68

11.5-62	Fine grained Sand (Brackish)	1.86
62-115	Coarse grained Sand	177.34
115-300	Coarse grained Sand	374.97
VES 05		
Thickness(m)	Lithology	Resistivity
0-1	Top Soil	4.044
1-31	Fine grained Sand (Brackish)	2.156
31-87	Clay	1.369
87-121	Fine grained Sand	9.20
121-235	Medium grained Sand	22.7
235-300	Medium grained Sand	40.593
VES 06		
Thickness(m)	Lithology	Resistivity
0-1	Top Soil	2.295
1-3	Fine grained Sand	11.59
3-18	Clay	2.295
18-84	Medium grained Sand	27.67
84-188	Medium grained Sand with clay and saline water	1.1097
188-300	Fine grained Sand (Saline)	0.656
VES 07		
Thickness(m)	Lithology	Resistivity
0-1.5	Top Soil	0.4088

1.5-4	Clay	1.533
4-13	Fine grained Sand	8.91
13-48	Clay	0.9247
48-126	Fine grained Sand	17.35
126-152	Clayey Silt	8.73
152-300	Fine grained Sand (Brackish)	3.966
VES 08		
Thickness(m)	Lithology	Resistivity
0-1	Top Soil	0.4558
1-2.5	Clay	4.23
2.5-10	Fine grained Sand	28.4
10-64	Clay	2.87
64-160	Fine grained Sand with clay	6.99
160-300	Fine grained Sand (Brackish)	3.75
VES 09		
Thickness(m)	Lithology	Resistivity
0-1	Top Soil	0.351
1-3	Clay	1.876
3-13	Fine grained Sand with Clay	7.741
13-64	Clay	1.384
64-243	Fine grained Sand	13.64
243-300	Fine grained Sand with clay	6.45

VES10		
Thickness(m)	Lithology	Resistivity
0-2	Top Soil	5.4
2-5.5	Fine grained Sand (Brackish)	3.132
5.5-15	Clay	1.156
15-65	Medium grained Sand	46.53
65-212	Fine grained Sand	9.943
212-300	Fine grained Sand with clay	5.875
VES11		
Thickness(m)	Lithology	Resistivity
0-0.5	Top Soil	3.238
0.5-5	Fine grained Sand	10.074
5-21	Clay	3.809
21-66	Fine grained Sand (saline water)	0.912
66-251	Medium grained Sand	86.521
251-300	Coarse grained Sand	193.51
VES 12		
Thickness(m)	Lithology	Resistivity
0-1	Top Soil	4.748
1-3	Medium grained Sand	23.35
3-23	Clay	4.914

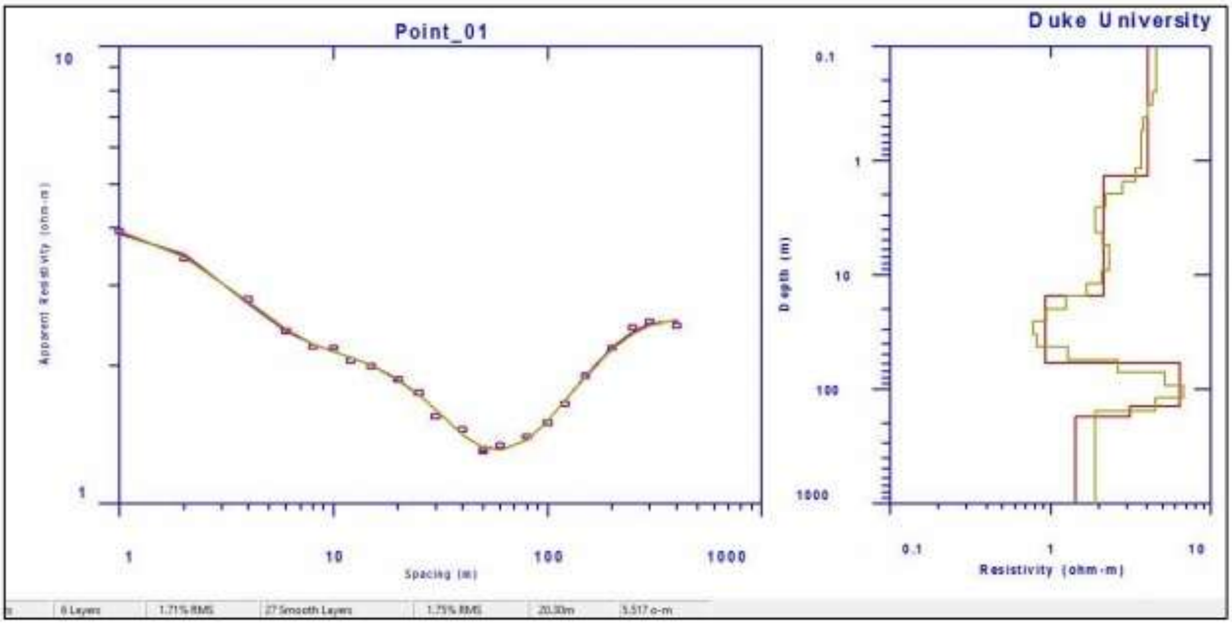
23-69	Fine grained Sand (saline water)	0.983
69-219	Medium grained Sand with clay	21.281
219-300	Medium grained Sand	62.146
VES13		
Thickness(m)	Lithology	Resistivity
0-0.5	Top Soil	3.2869
0.5-2.5	Fine grained Sand	12.389
2.5-30	Clay	2.3119
30-126	Fine grained Sand (saline water)	0.85651
126-226	Clay	4.6687
226-300	Fine grained Sand with clay	6.8549
VES14		
Thickness(m)	Lithology	Resistivity
0-1.5	Top Soil	3147.5
1.5-4.5	Clay	169.27
4.5-17	Fine grained Sand	29.670
17-111	Clayey Silt	6.8261
111-240	Medium grained Sand	51.333
240-300	Coarse grained Sand	109.24
VES15		

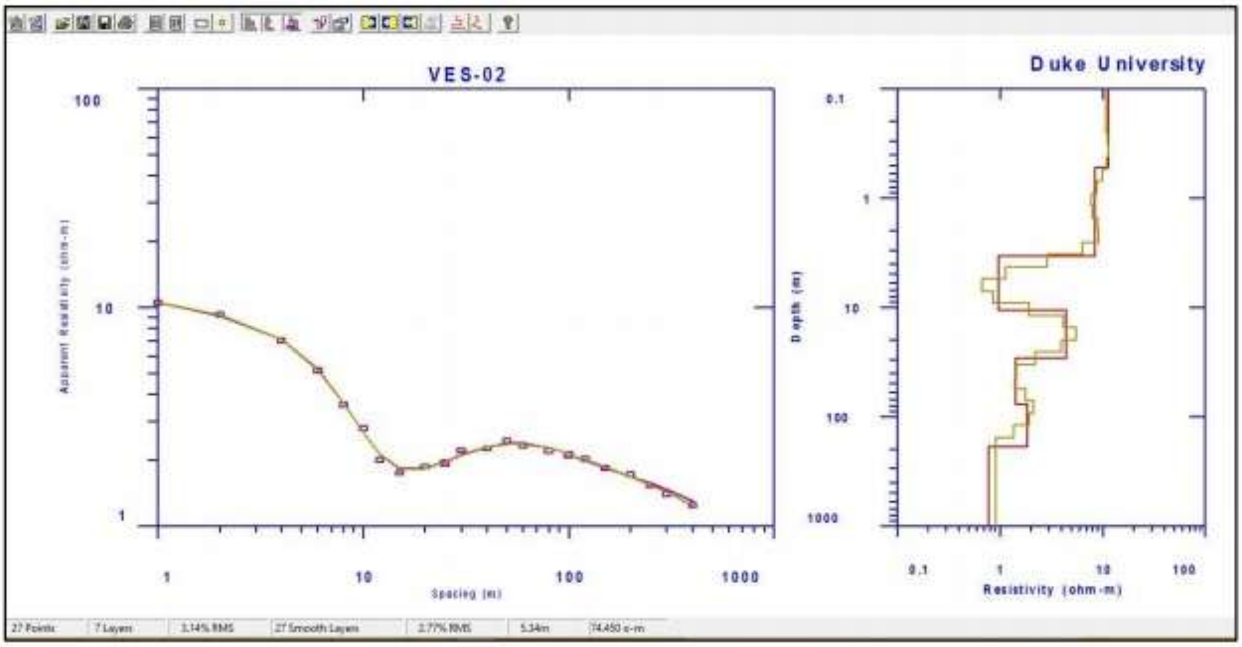
Thickness(m)	Lithology	Resistivity
0-0.5	Top Soil	8.3875
0.5-5	Clay	4.4190
5-104	Fine grained Sand (Bracklish)	2.3158
104-182	Clay	4.9292
182-300	Fine grained Sand	13.332
VES16		
Thickness(m)	Lithology	Resistivity
0-0.5	Top Soil	6.808
0.5-11	Clayey Silt	8.745
11-88	Medium grained Sand with clay and saline water	1.616
88-186	Medium grained Sand with clay	23.9
186-300	Coarse grained Sand	119.38
VES17		
Thickness(m)	Lithology	Resistivity
0-0.5	Top Soil	6.896
0.5-15	Clayey silt	8.318
15-70	Fine grained Sand (Saline)	1.079
70-111	Medium grained Sand	44.537
111-180	Coarse grained Sand	119.33
180-300	Coarse grained Sand	344.58

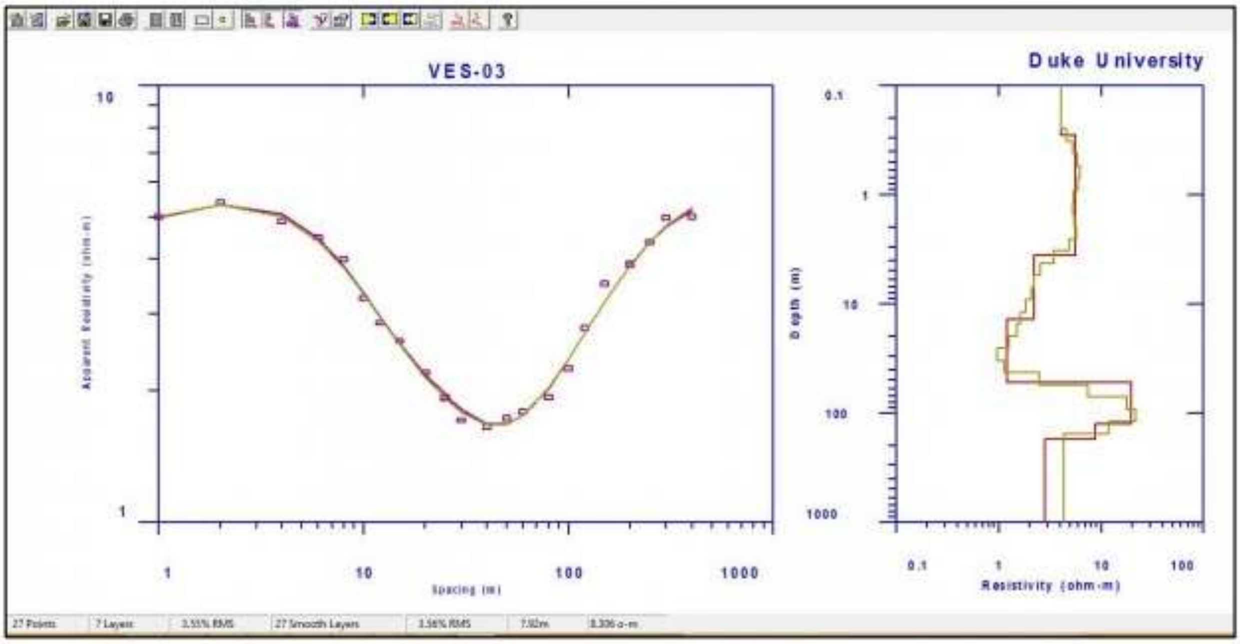
VES 18		
Thickness(m)	Lithology	Resistivity
0-.5	Top soil	18.055
.5-3.5	Clayey Silt with coarse sand	15.229
3.5-10	Medium grained Sand	29.528
10-90	Clay	2.8042
90-162	Fine grained Sand	11.992
162-300	Medium grained Sand with Clay	27.163
VES 19		
Thickness(m)	Lithology	Resistivity
0-0.5	Top Soil	6.053
0.5-3.5	Fine grained Sand	10.829
3.5-10	Clay	3.9166
10-102	Fine grained Sand (Saline)	1.392
102-214	Fine grained Sand with clay	8.41
214-300	Fine grained Sand	16.195
VES 20		
Thickness(m)	Lithology	Resistivity
0-1	Top Soil	7.196
1-5	Fine grained Sand with Clay	6.131
5-12	Fine grained Sand (Saline)	1.42
12-22	Clay	2.856

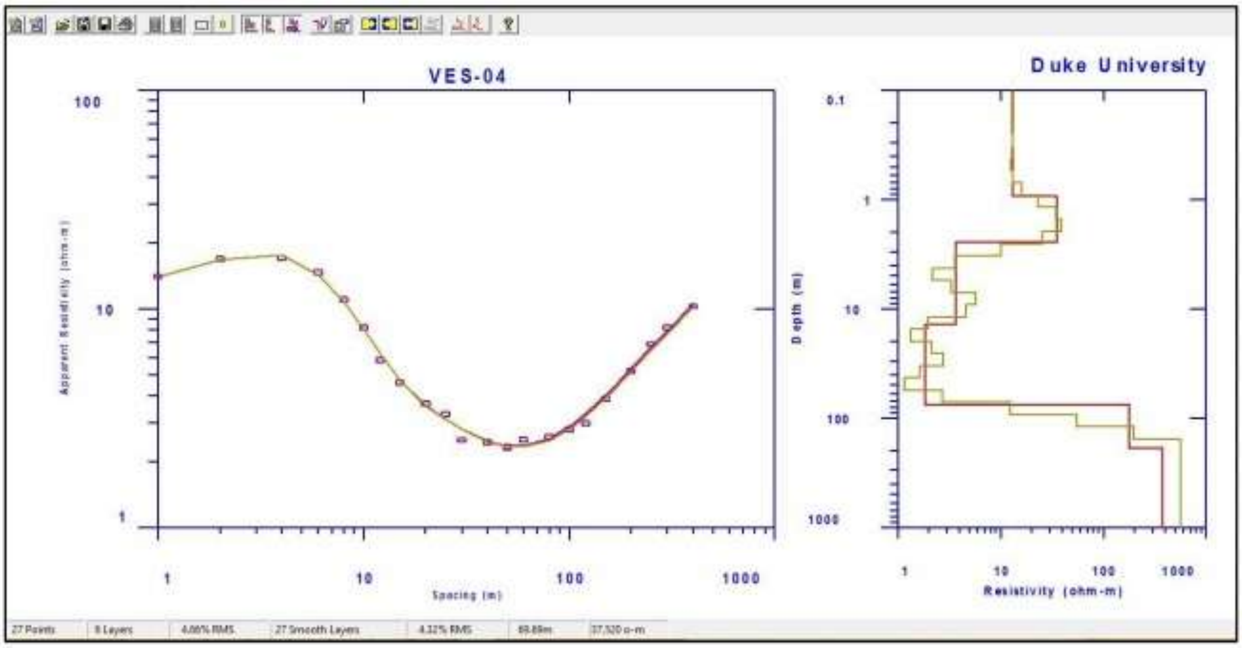
22-70	Fine grained Sand (Saline)	0.847
70-190	Fine grained Sand with clay	5.993
190-300	Fine grained Sand (Brackish)	1.581
VES 21		
Thickness(m)	Lithology	Resistivity
0-4	Fine grained Sand	9.1234
4-9	Clay	3.416
9-13	Fine grained Sand with Clay	7.996
13-27	Fine grained Sand (Saline)	0.7445
27-46	Clay	3.362
46-180	Fine grained Sand (Brackish)	2.0078
180-300	Fine grained Sand with Clay	7.629

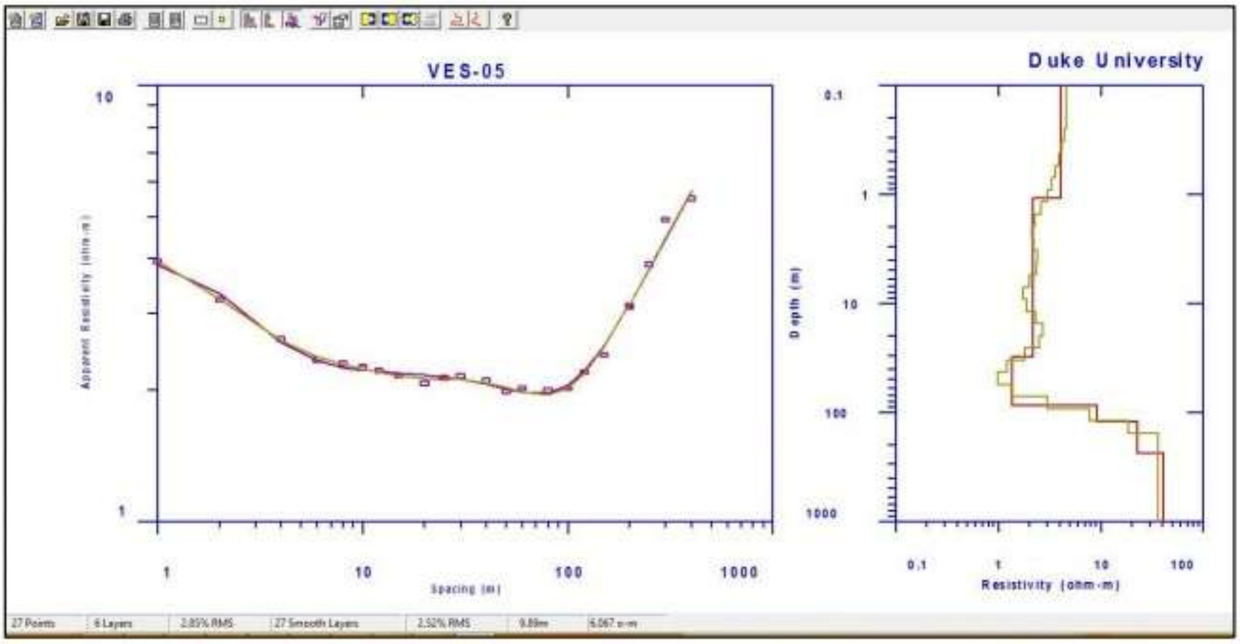
Resistivity sounding curve

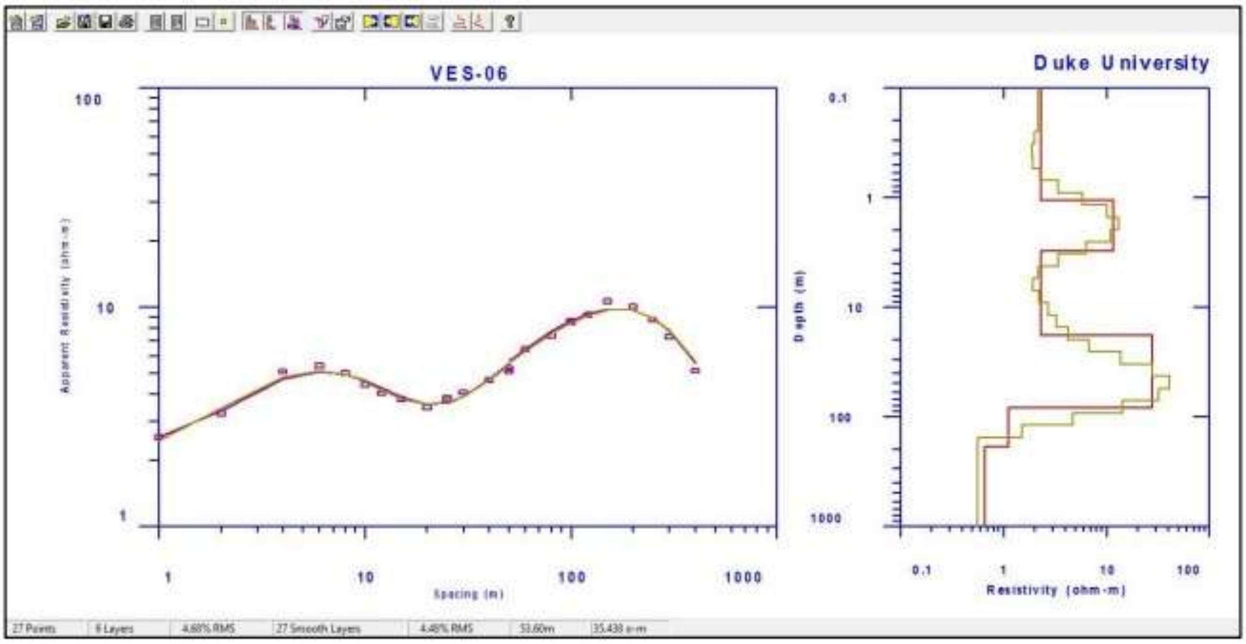


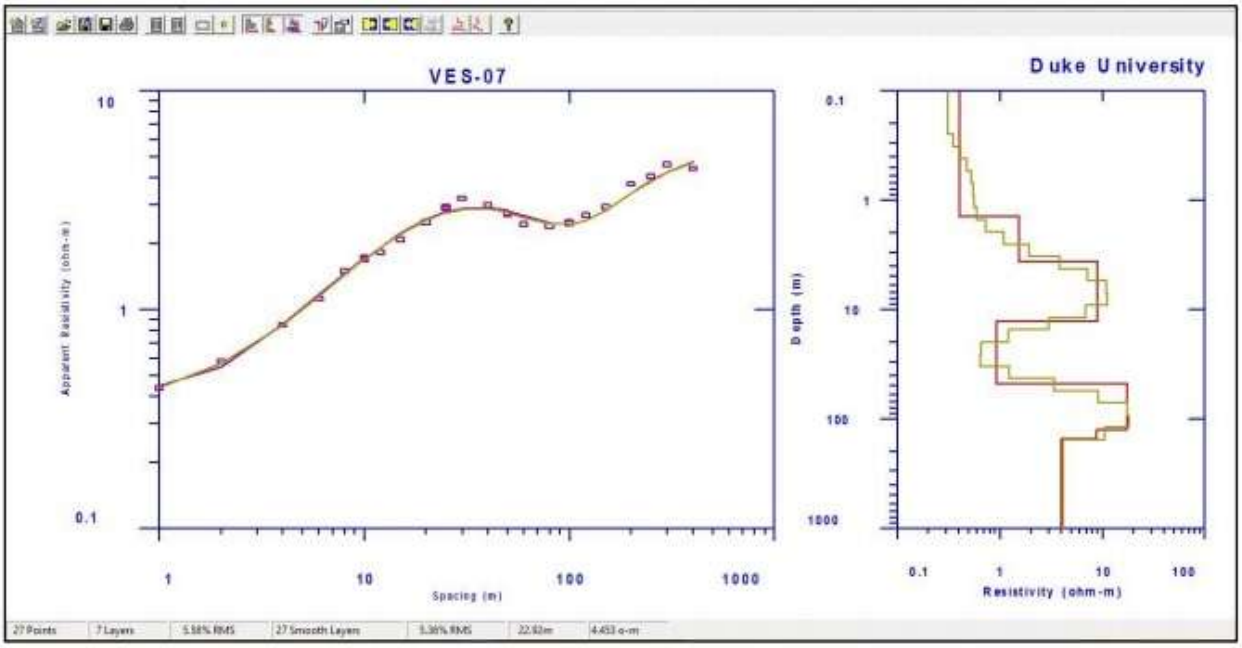


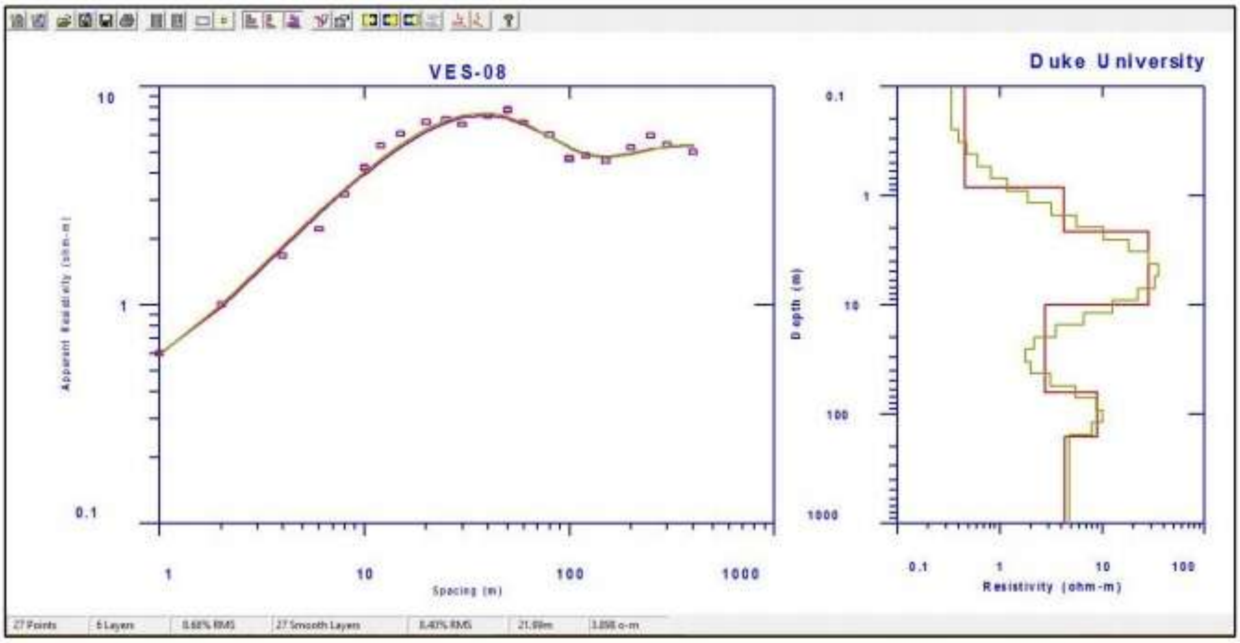

VES-03
Duke University
Apparent Resistivity (ohm-m)
10
1
1
10
100
1000
Spacing (m)
Depth (m)
0.1
1
10
100
1000
0.1
1
10
100
Resistivity (ohm-m)

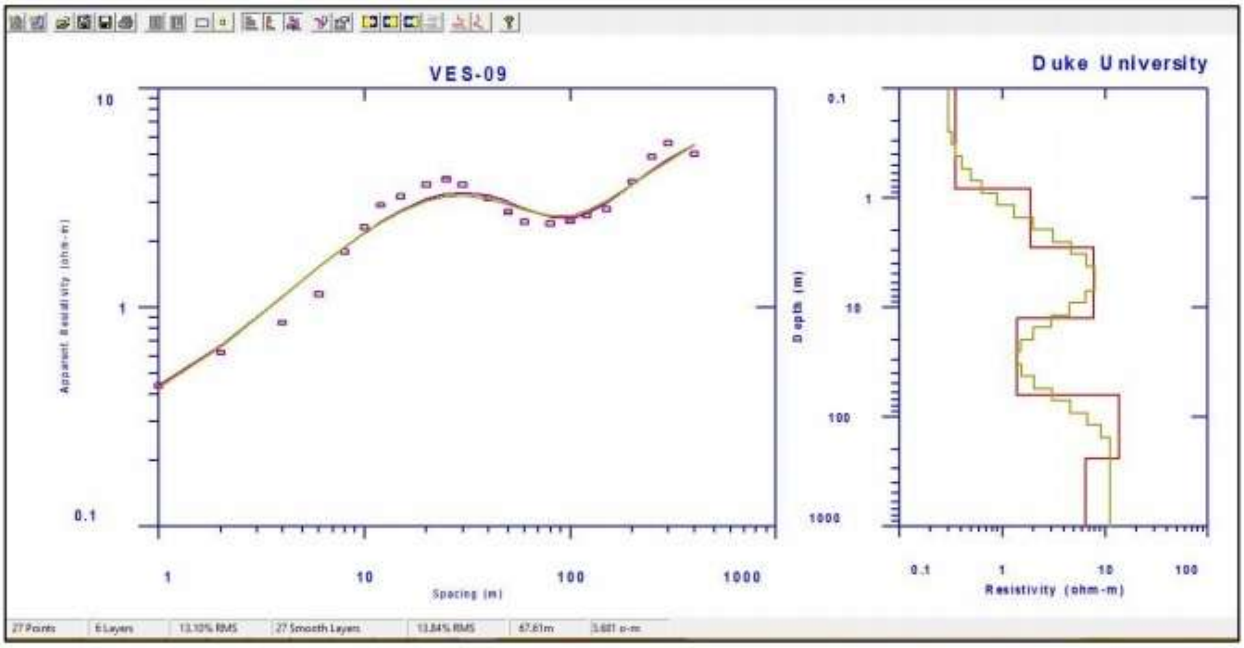

VES-04
Duke University
Apparent Resistivity (ohm-m)
100
10
1
1
10
100
1000
Spacing (m)
Depth (m)
0.1
1
10
100
1000
1
10
100
1000
Resistivity (ohm-m)

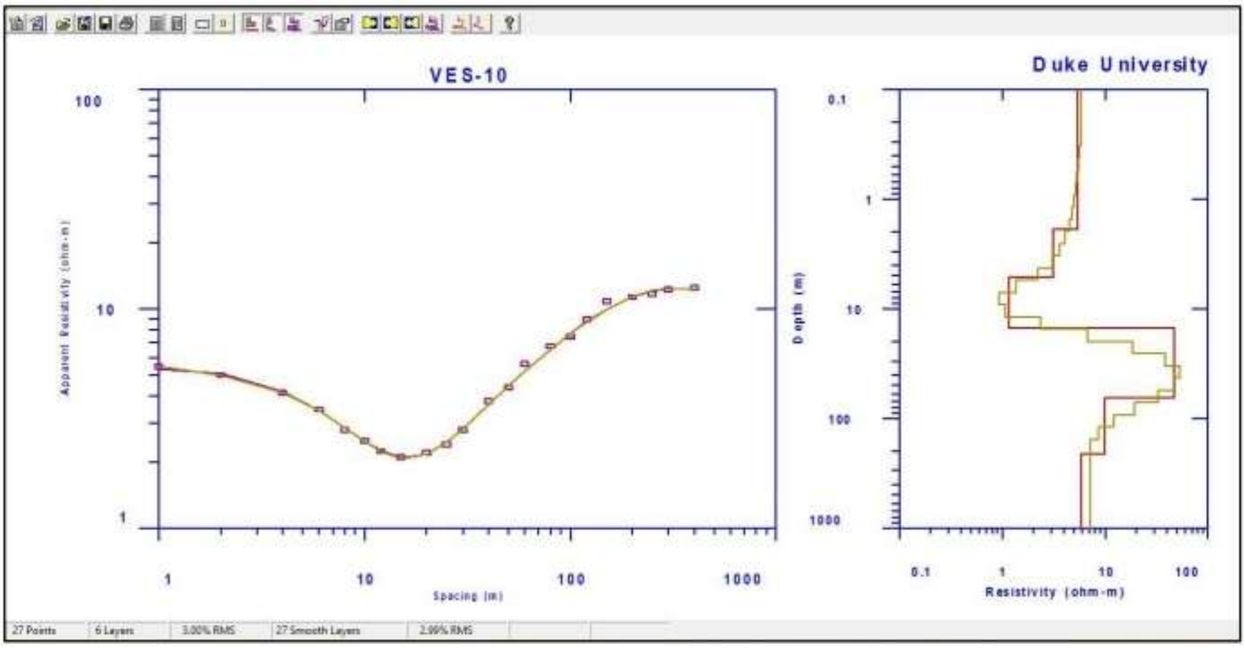

VES-05
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
27 Smooth Layers

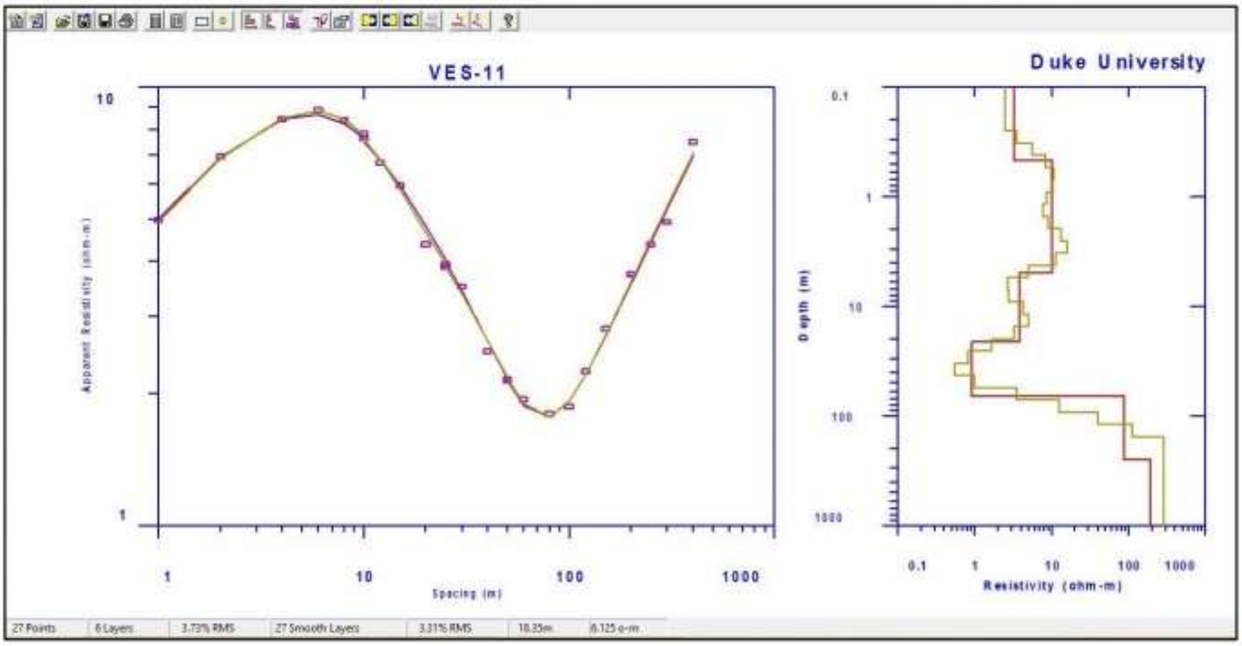

VES-06
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
27 Smooth Layers

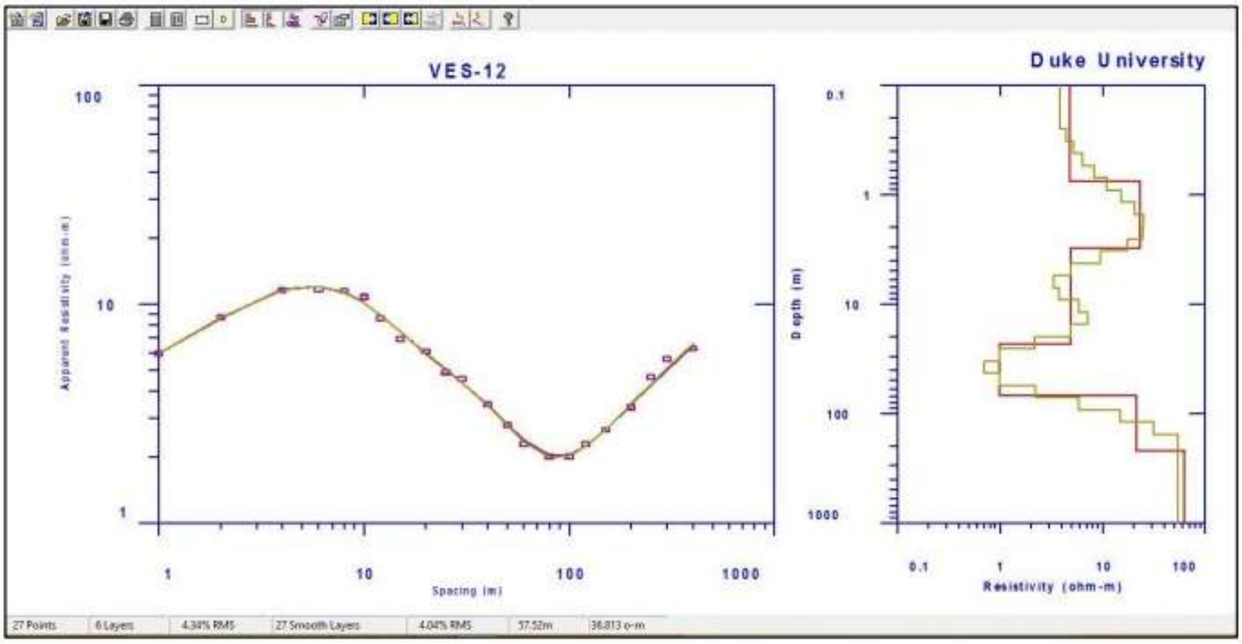

VES-07
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
7 Layers
5.58% RMS
27 Smooth Layers
5.36% RMS
22.92m
4.453 o-m

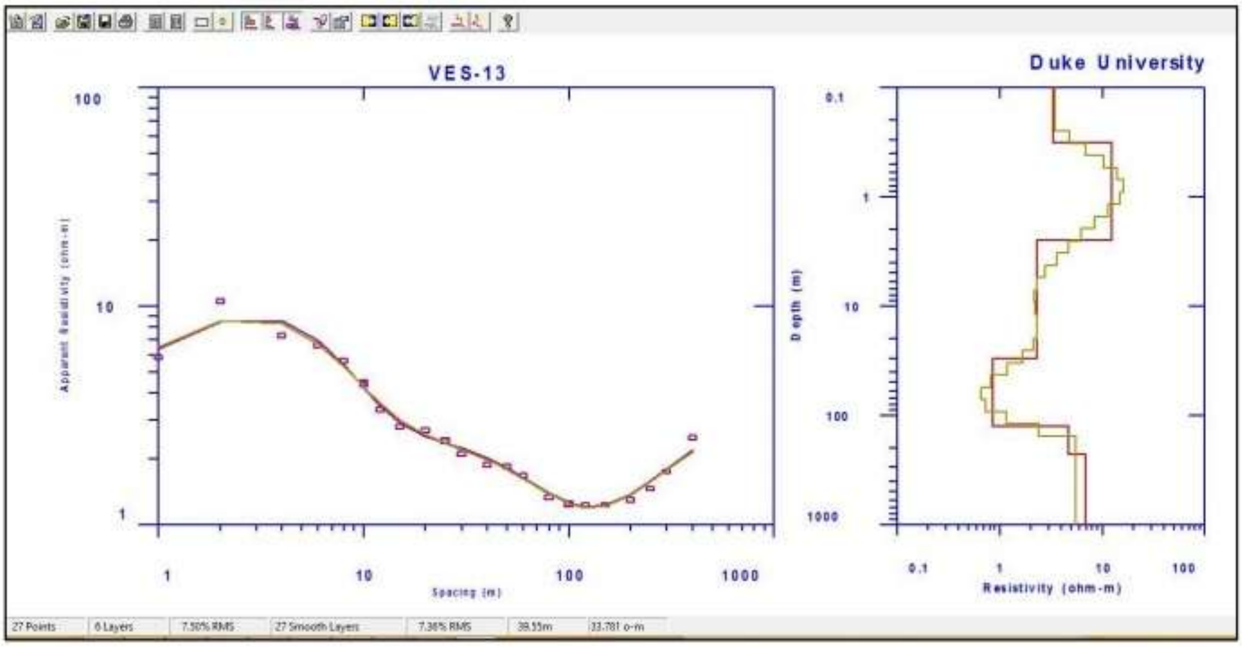

VES-08
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
8.68% RMS
27 Smooth Layers
8.40% RMS
21.89m
3.898 o-m

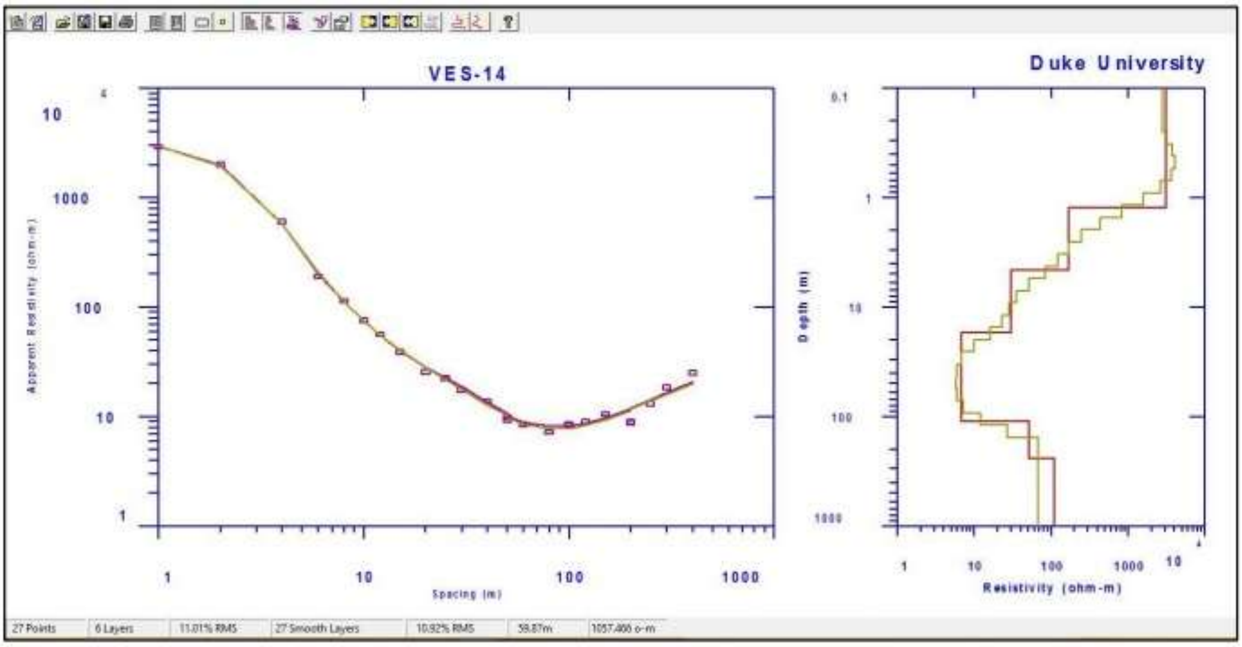

VES-09
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
27 Smooth Layers

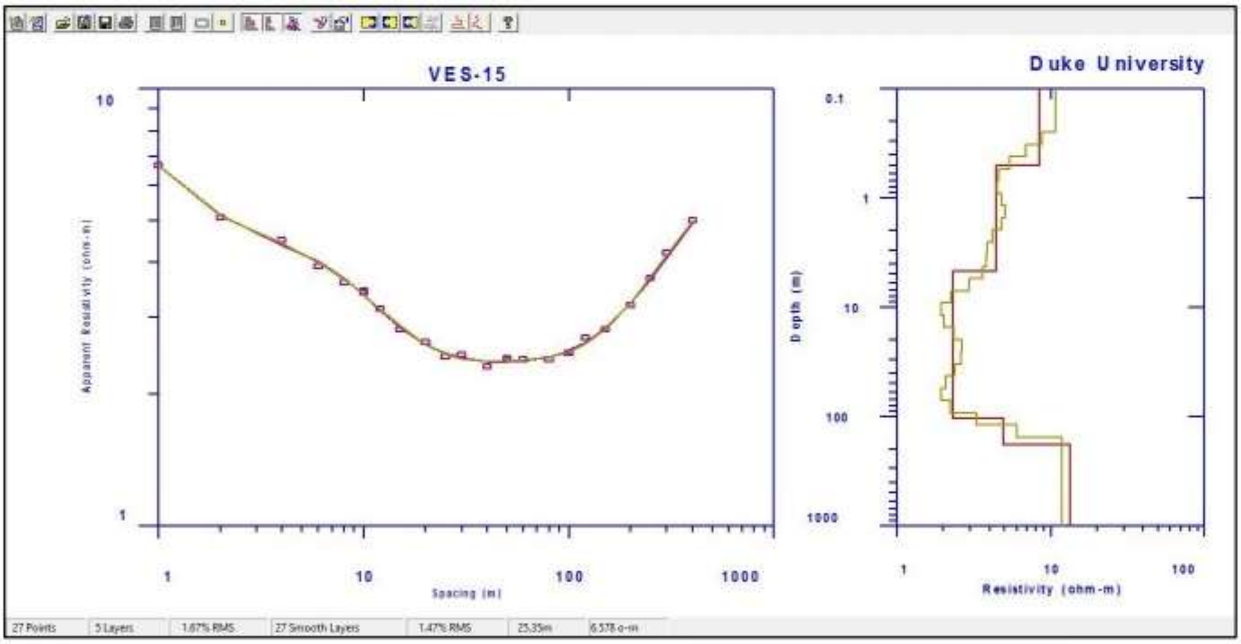

VES-10
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
27 Smooth Layers

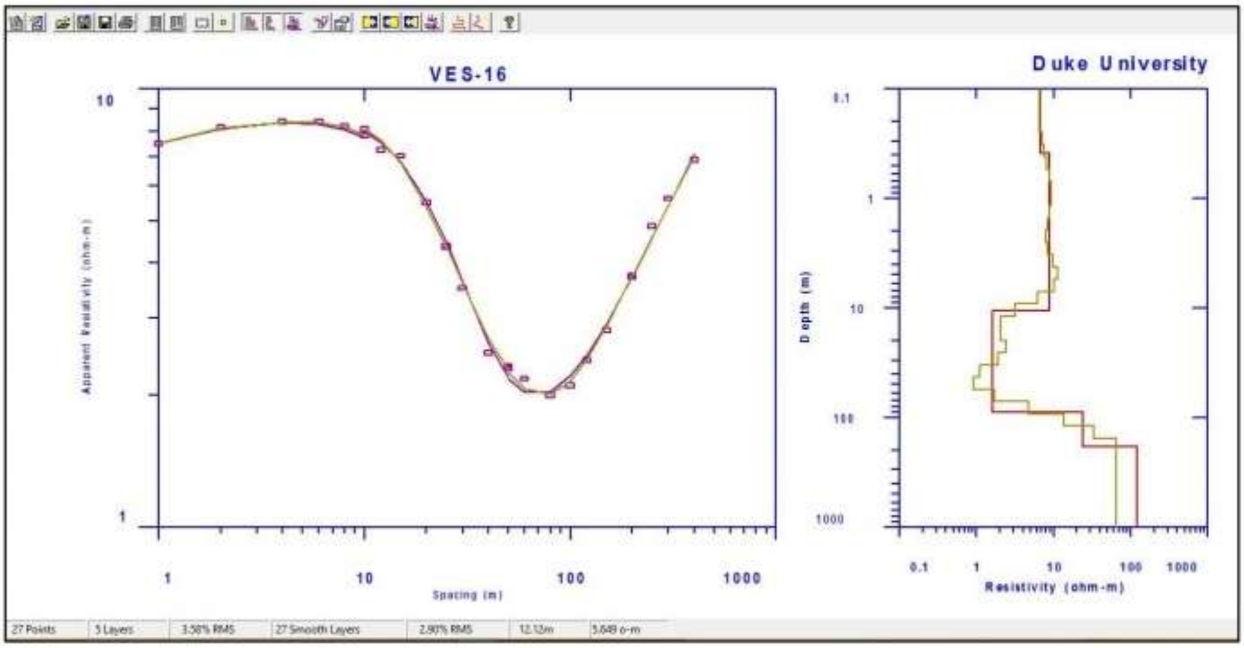

VES-11
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
3.73% RMS
27 Smooth Layers
3.31% RMS
18.35m
6.125 o-m

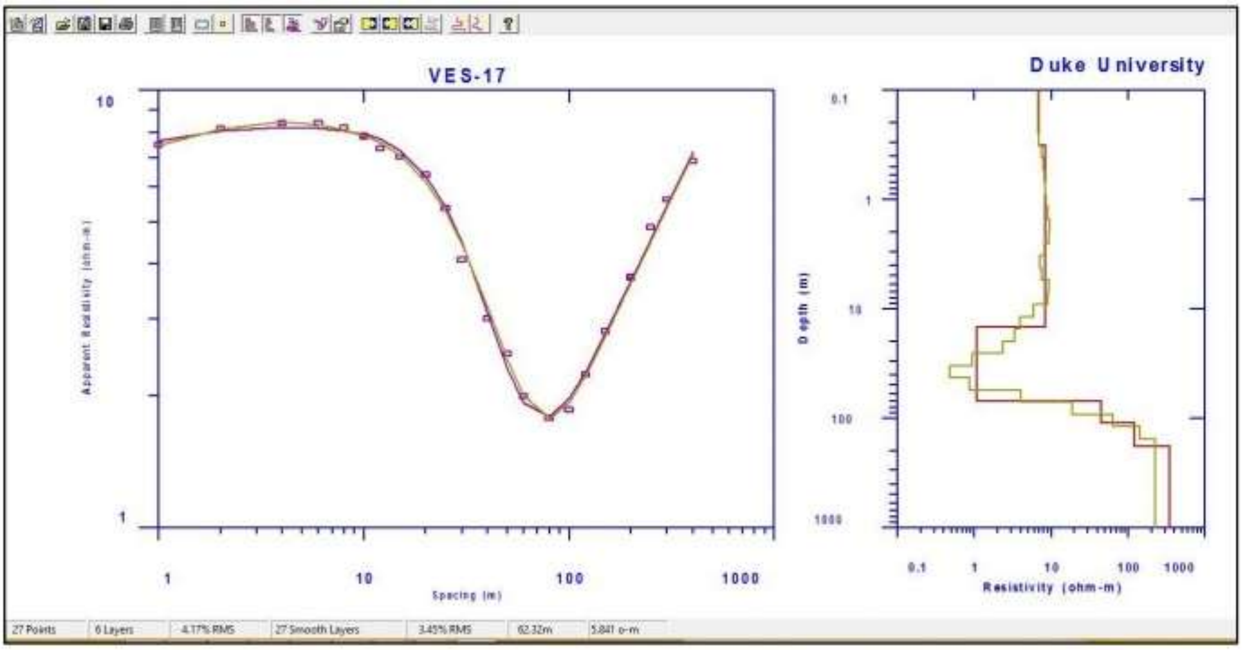

VES-12
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
4.34% RMS
27 Smooth Layers
4.04% RMS
57.52m
36.813 o-m

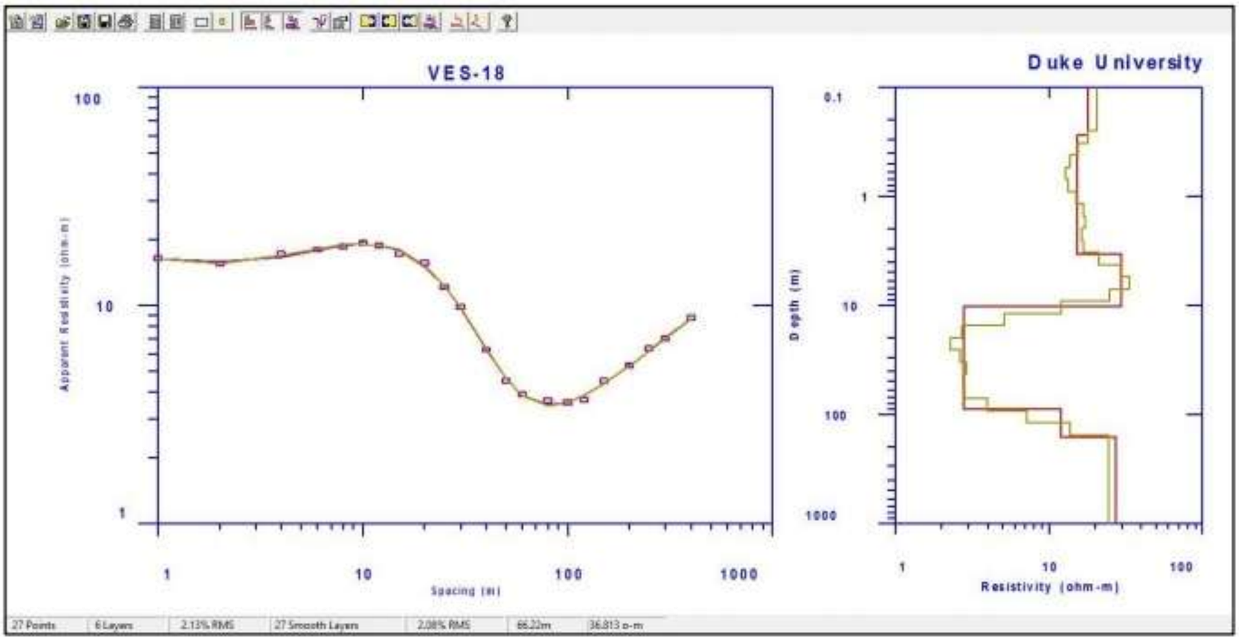

VES-13
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
7.50% RMS
27 Smooth Layers
7.36% RMS
39.55m
33.781 o-m

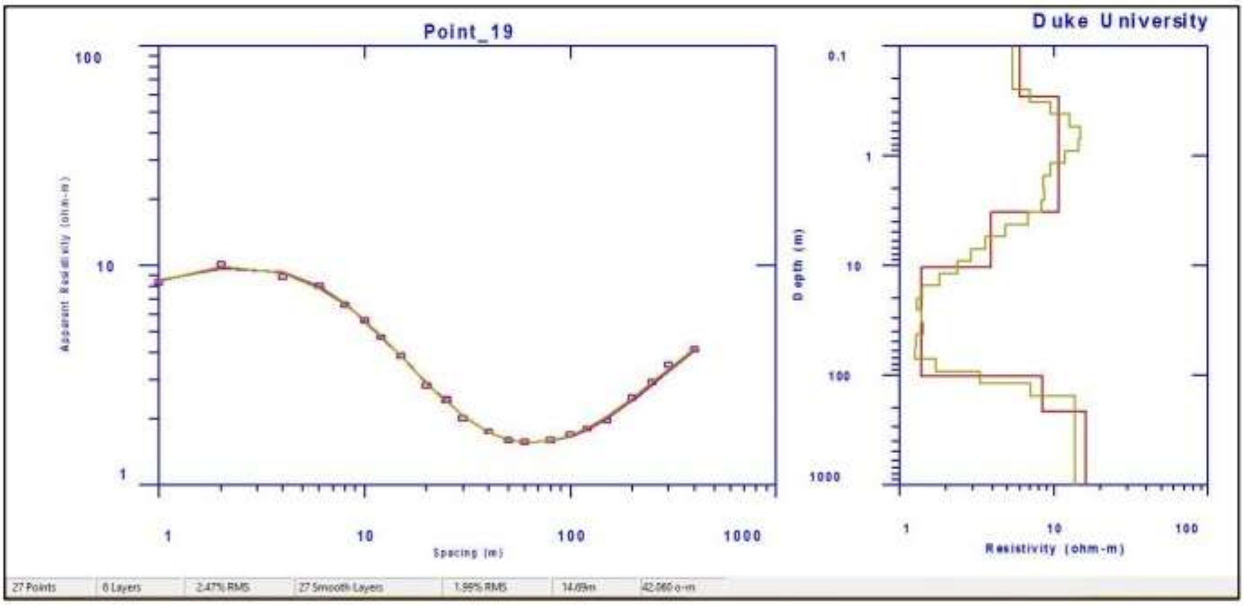

VES-14
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
11.01% RMS
27 Smooth Layers
10.92% RMS
59.87m
1057.466 o-m

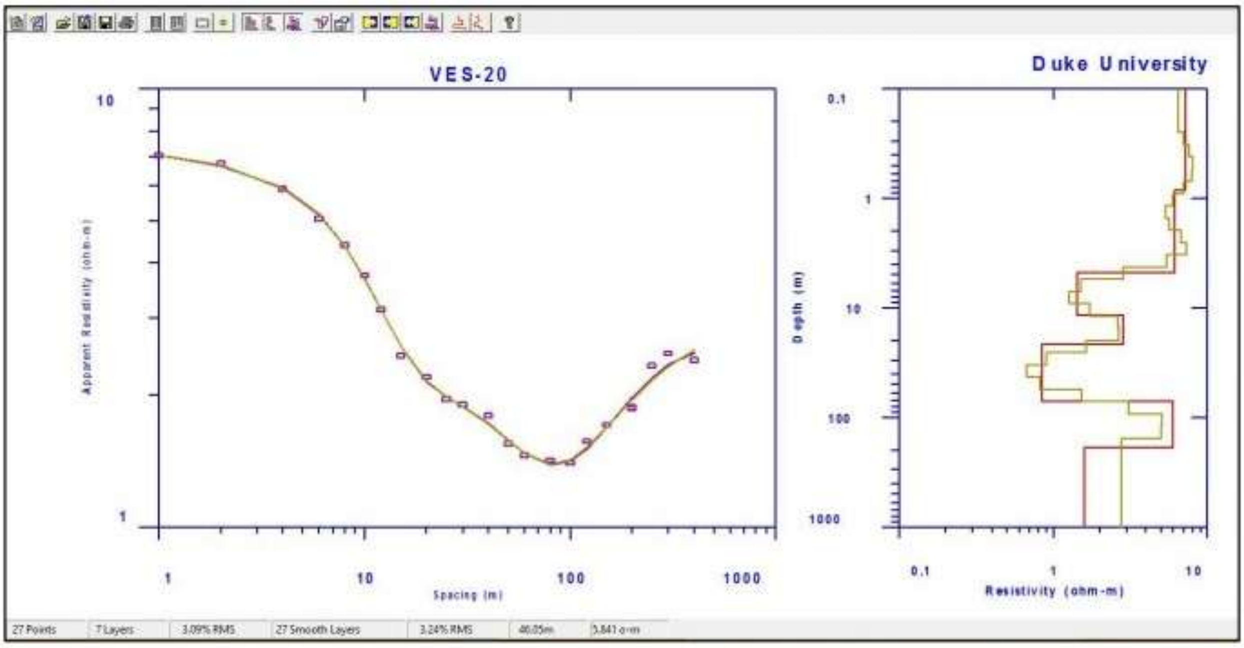

VES-15
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
5 Layers
1.67% RMS
27 Smooth Layers
1.47% RMS
25.35m
6.578 o-m

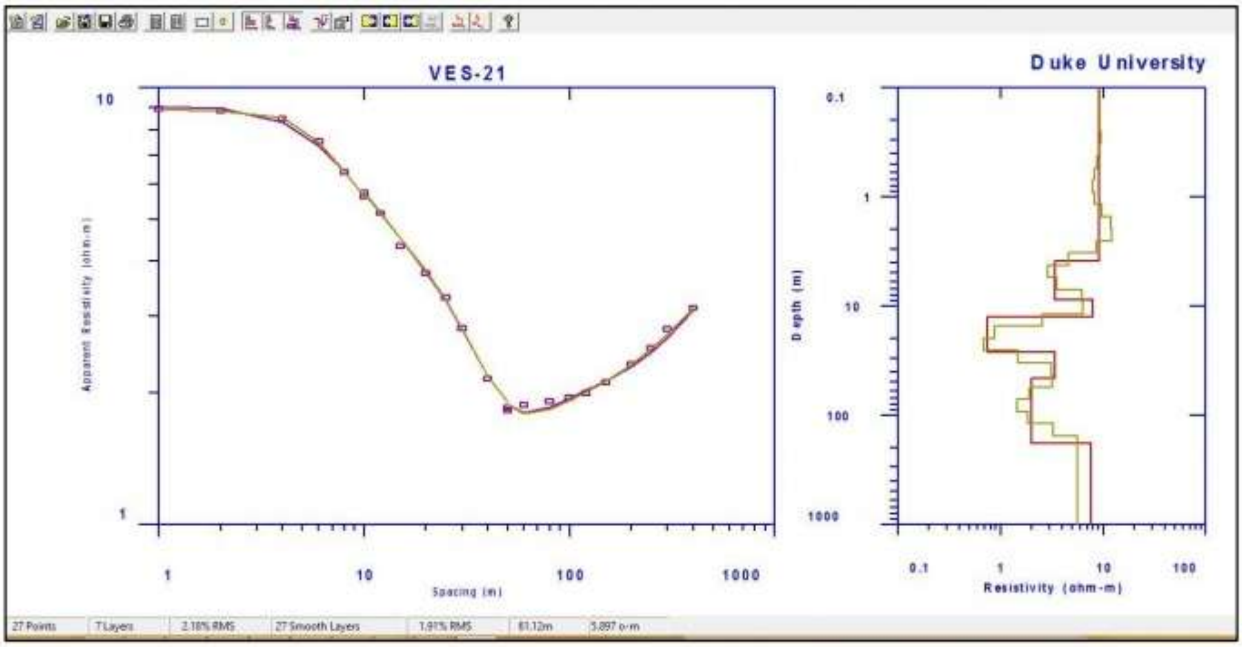

VES-16
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
5 Layers
3.58% RMS
27 Smooth Layers
2.90% RMS
12.12m
5.649 o-m


VES-17
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
4.17% RMS
27 Smooth Layers
3.45% RMS
62.32m
5.841 o-m

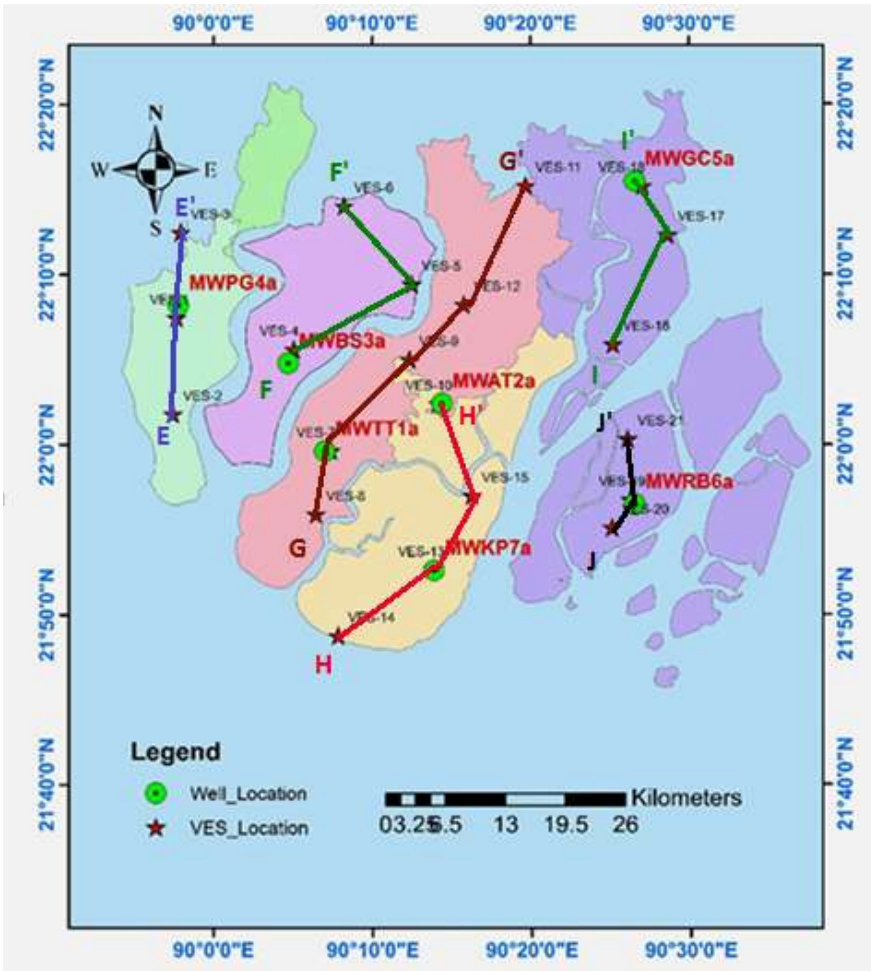

VES-18
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
2.13% RMS
27 Smooth Layers
2.08% RMS
66.22m
36.813 o-m

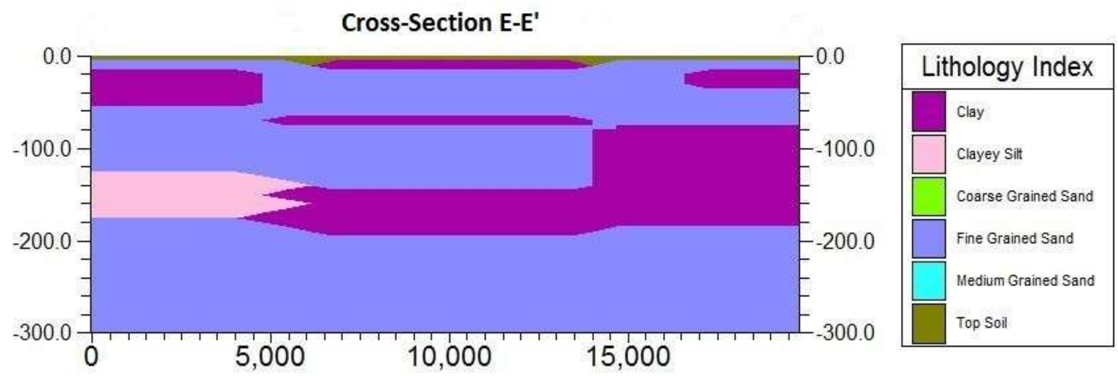

Point_19
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
6 Layers
2.47% RMS
27 Smooth Layers
1.99% RMS
14.69m
42.060 o-m

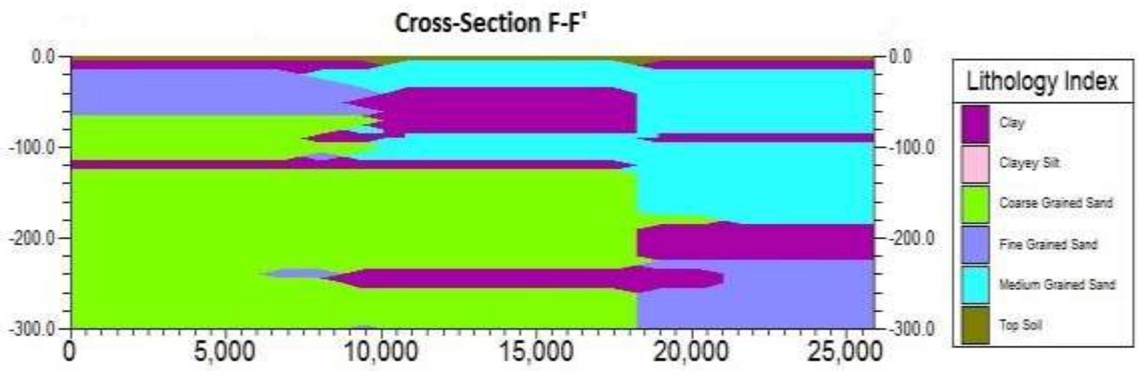

VES-20
Duke University
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)
27 Points
7 Layers
3.09% RMS
27 Smooth Layers
3.24% RMS
46.05m
5.841 o-m

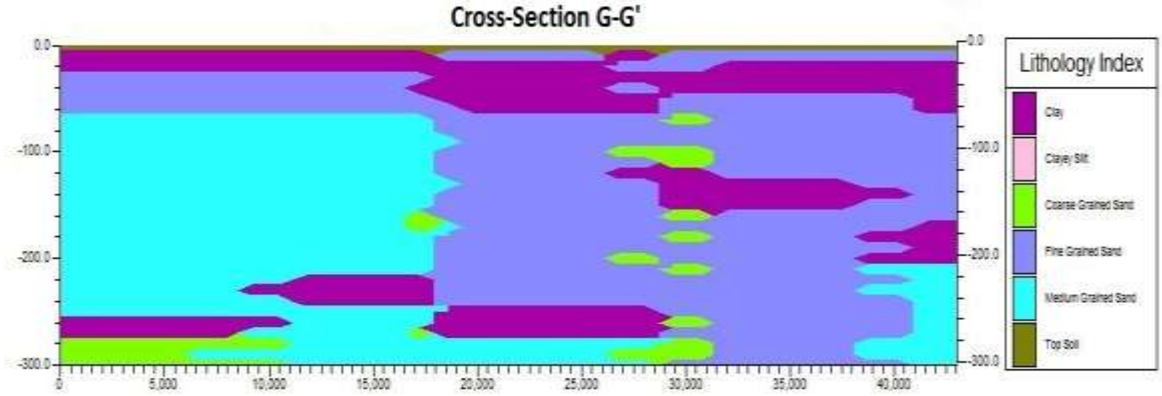


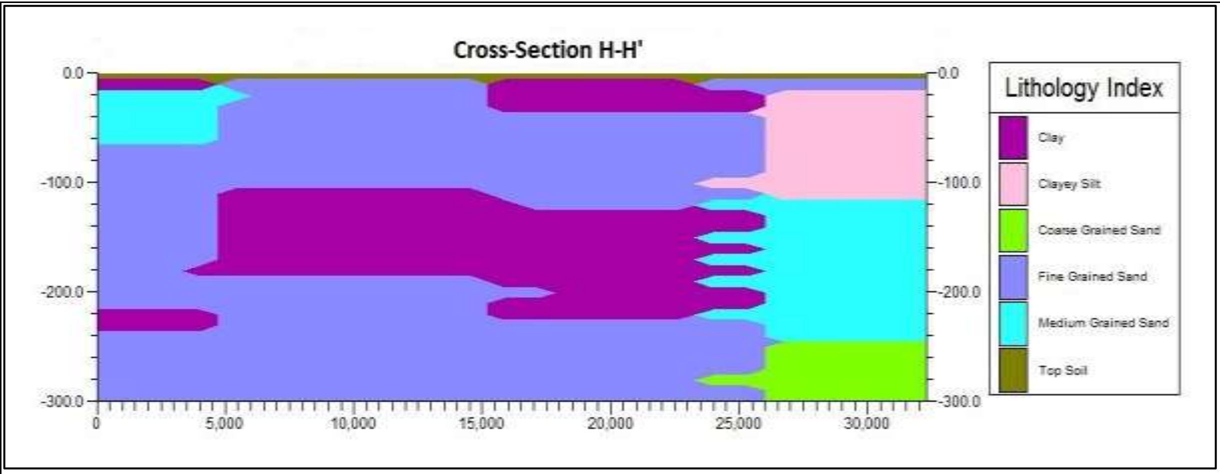
Lithological cross-sections E-E', F-F', G-G', H-H', I-I' and J-J' on the basis of VES data

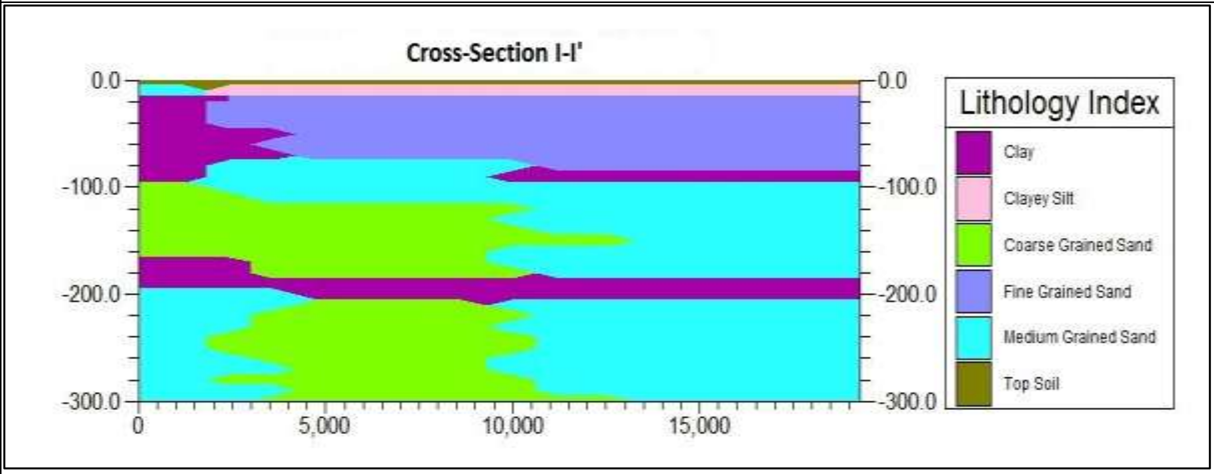


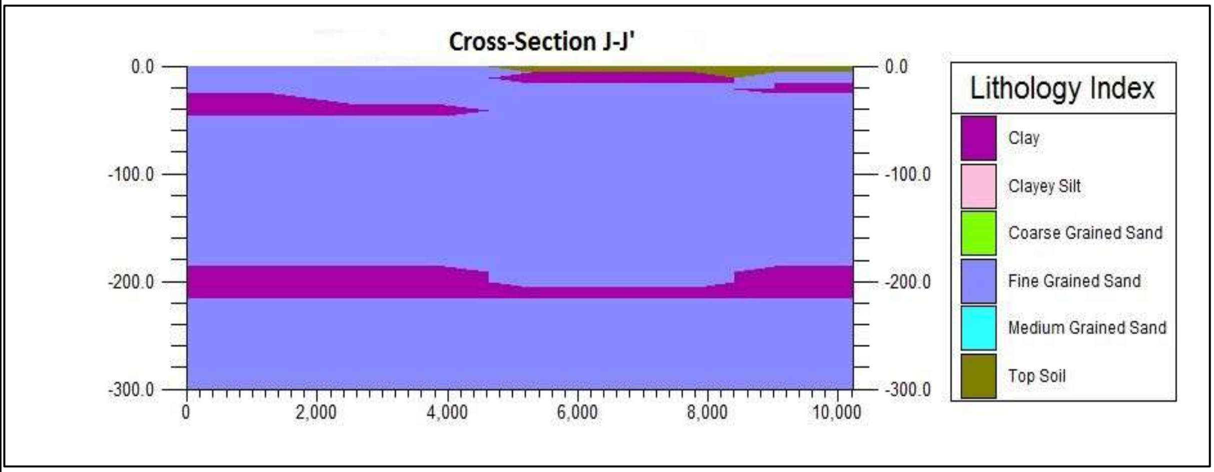

Cross-Section E-E'
0.0
-100.0
-200.0
-300.0
0
5,000
10,000
15,000
Lithology Index
Clay
Clayey Silt
Coarse Grained Sand
Fine Grained Sand
Medium Grained Sand
Top Soil


Cross-Section F-F'
0.0
-100.0
-200.0
-300.0
0
5,000
10,000
15,000
20,000
25,000
Lithology Index
Clay
Clayey Silt
Coarse Grained Sand
Fine Grained Sand
Medium Grained Sand
Top Soil


Cross-Section G-G'
0.0
-100.0
-200.0
-300.0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
Lithology Index
Clay
Clayey Silt
Coarse Grained Sand
Fine Grained Sand
Medium Grained Sand
Top Soil


Cross-Section H-H'
Lithology Index
Clay
Clayey Silt
Coarse Grained Sand
Fine Grained Sand
Medium Grained Sand
Top Soil
0.0
-100.0
-200.0
-300.0
0
5,000
10,000
15,000
20,000
25,000
30,000

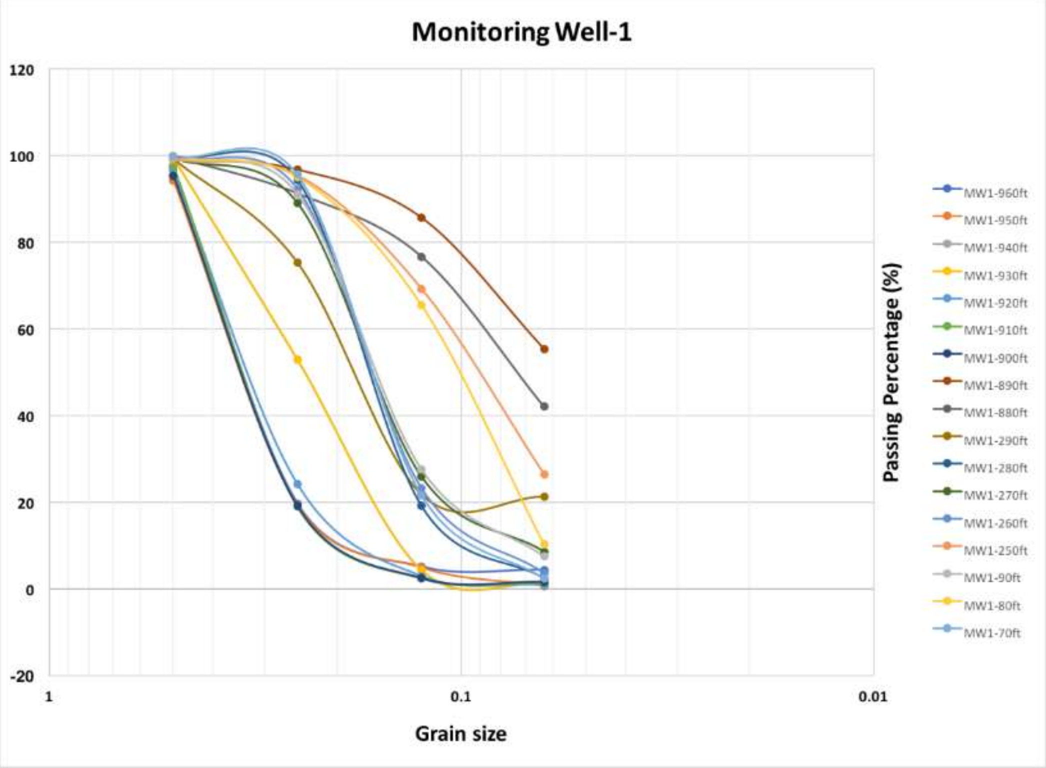

Cross-Section I-I'
Lithology Index
Clay
Clayey Silt
Coarse Grained Sand
Fine Grained Sand
Medium Grained Sand
Top Soil
0.0
-100.0
-200.0
-300.0
0
5,000
10,000
15,000


Cross-Section J-J'
Lithology Index
Clay
Clayey Silt
Coarse Grained Sand
Fine Grained Sand
Medium Grained Sand
Top Soil
0.0
-100.0
-200.0
-300.0
0
2,000
4,000
6,000
8,000
10,000

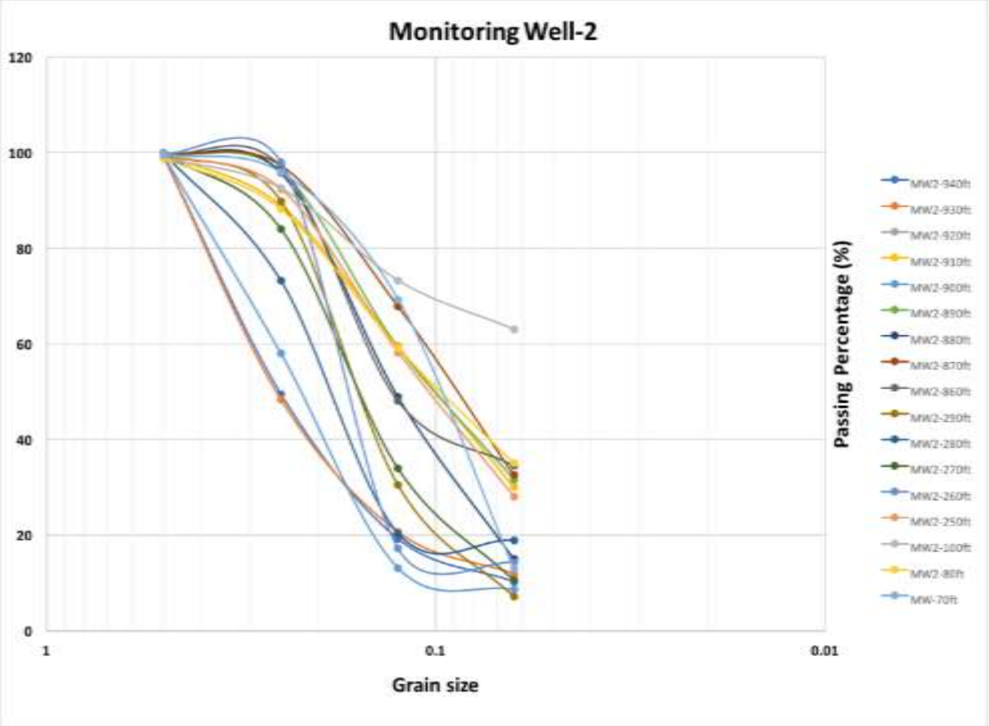
14 APPENDIX-D: Hydraulic Conductivity Data

Determination of Hydraulic conductivity using Grain Size distribution:

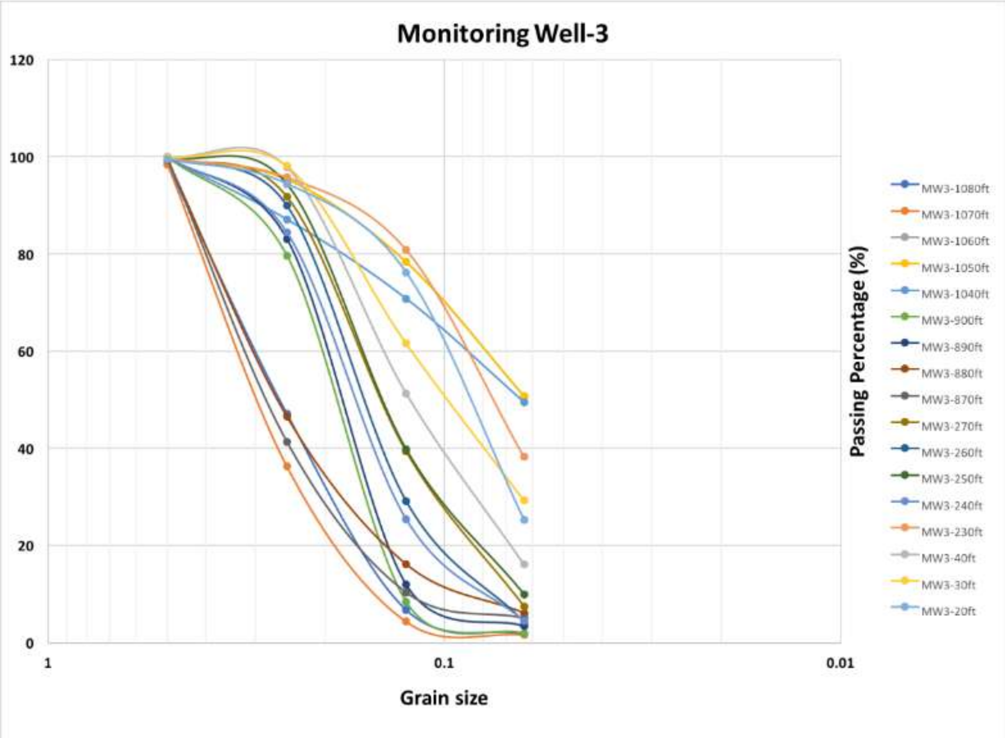
MW-1:



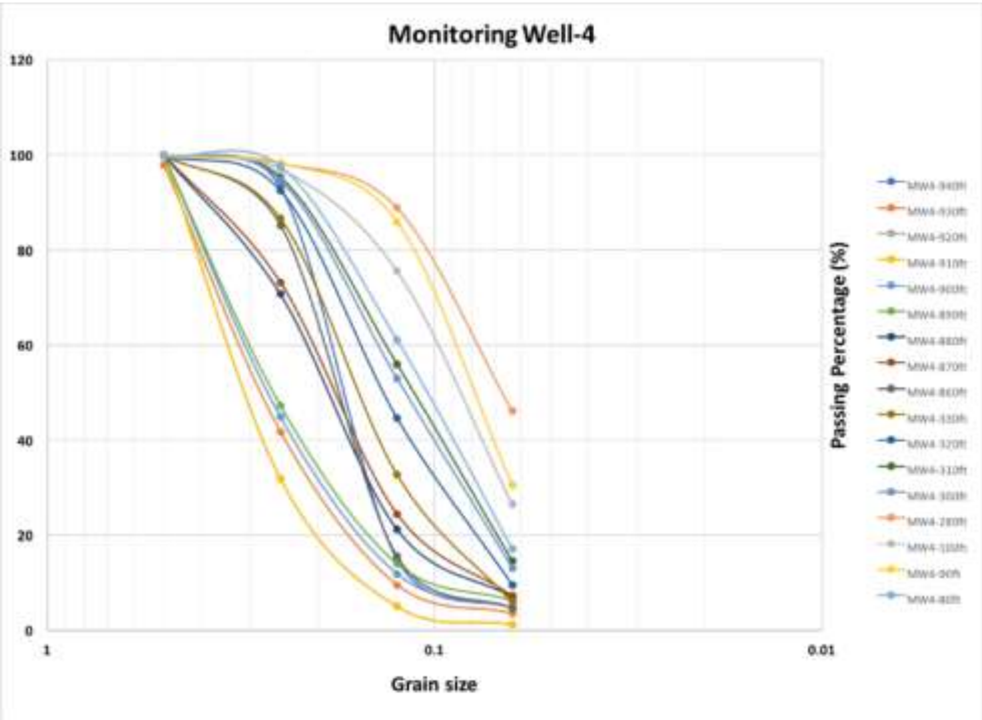
MW-2:



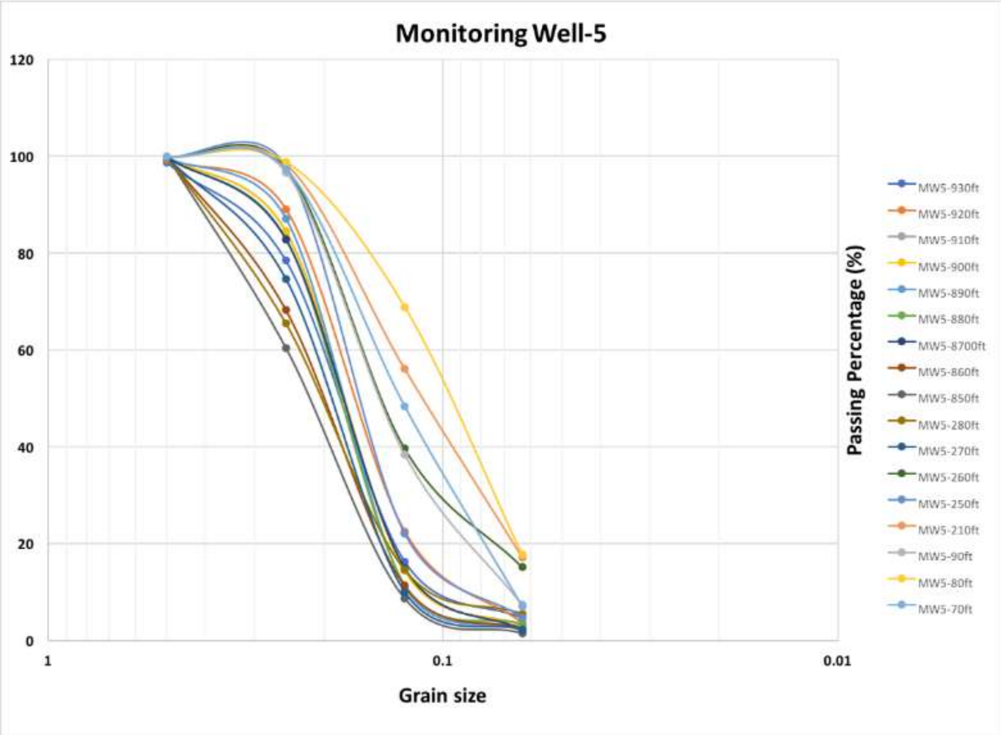
MW-3:


Monitoring Well-3
120
100
80
60
40
20
0
1
0.1
0.01
Grain size
Passing Percentage (%)
MW3-1080ft
MW3-1070ft
MW3-1060ft
MW3-1050ft
MW3-1040ft
MW3-900ft
MW3-890ft
MW3-880ft
MW3-870ft
MW3-270ft
MW3-260ft
MW3-250ft
MW3-240ft
MW3-230ft
MW3-40ft
MW3-30ft
MW3-20ft

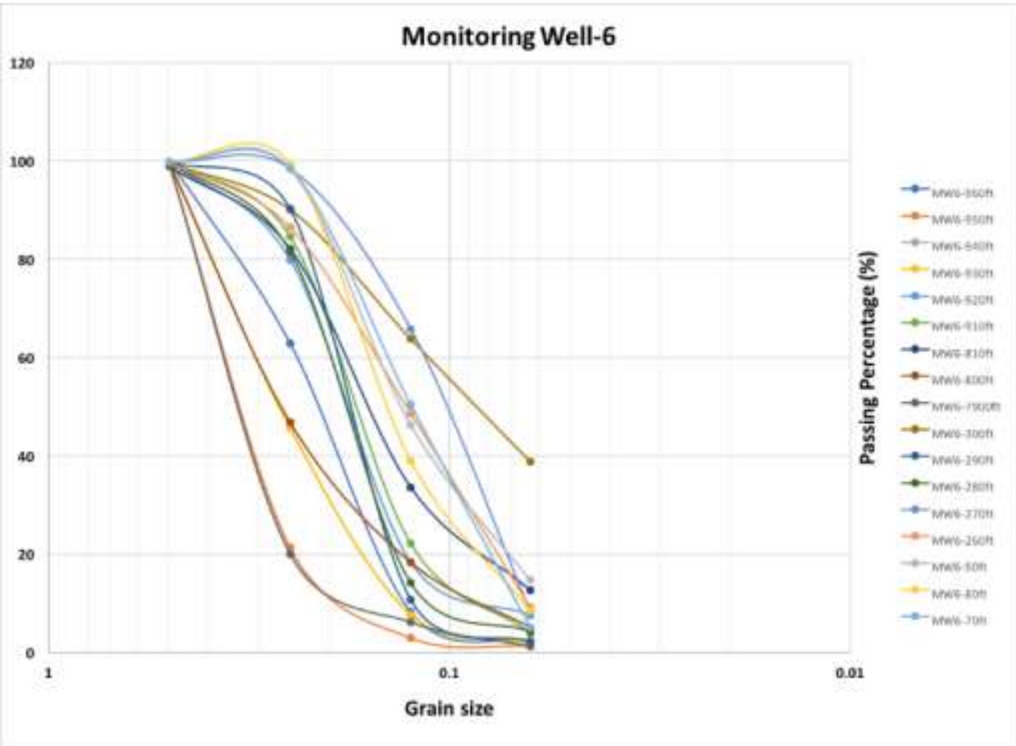
MW-4:


Monitoring Well-4
120
100
80
60
40
20
0
1
0.1
0.01
Grain size
Passing Percentage (%)

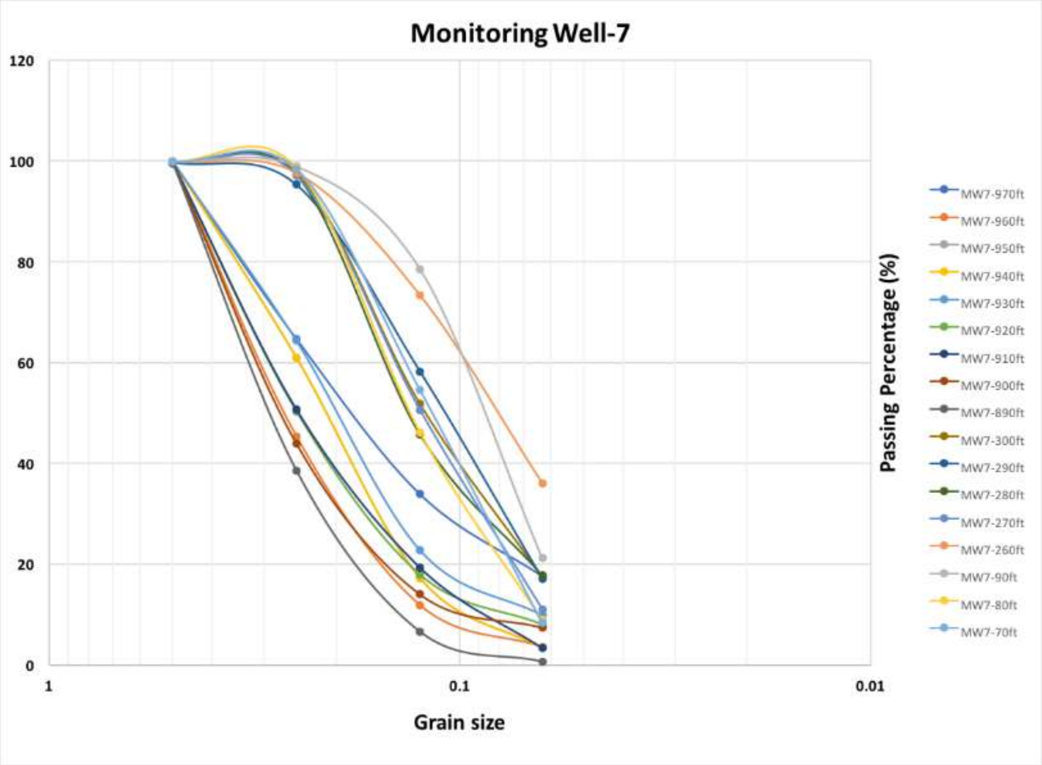
MW-5:


Monitoring Well-5
120
100
80
60
40
20
0
1
0.1
0.01
Grain size
Passing Percentage (%)
MW5-930ft
MW5-920ft
MW5-910ft
MW5-900ft
MW5-890ft
MW5-880ft
MW5-8700ft
MW5-860ft
MW5-850ft
MW5-280ft
MW5-270ft
MW5-260ft
MW5-250ft
MW5-210ft
MW5-90ft
MW5-80ft
MW5-70ft

MW-6:


Monitoring Well-6
120
100
80
60
40
20
0
1
0.1
0.01
Grain size
Passing Percentage (%)

MW-7:



Summary Table of measured Hydraulic conductivity by grain size analysis:

Monitoring Well	***Location***	***Sample Depth (ft)***	***Mean K***
MW-01	East Chakamaiya	70	2.032693215
MW-01	East Chakamaiya	80	0.279615708
MW-01	East Chakamaiya	100	0.086353037
MW-01	East Chakamaiya	250	0.436750158
MW-01	East Chakamaiya	260	1.671927276
MW-01	East Chakamaiya	270	3.079139084
MW-01	East Chakamaiya	280	0.957259537
MW-01	East Chakamaiya	290	4.32415595
MW-01	East Chakamaiya	860	0.289027812
MW-01	East Chakamaiya	870	0.324339819
MW-01	East Chakamaiya	880	1.529817997
MW-01	East Chakamaiya	890	0.34306006
MW-01	East Chakamaiya	900	5.837401345
MW-01	East Chakamaiya	910	0.379145975
MW-01	East Chakamaiya	920	26.5764631
MW-01	East Chakamaiya	930	2.429387925

MW-01	East Chakamaiya	940	3.308121644
MW-02	Nimtoli, Barguna	20	0.535397403
MW-02	Nimtoli, Barguna	30	0.402312807
MW-02	Nimtoli, Barguna	40	1.330649931
MW-02	Nimtoli, Barguna	230	0.234533941
MW-02	Nimtoli, Barguna	240	5.446835934
MW-02	Nimtoli, Barguna	250	3.441692951
MW-02	Nimtoli, Barguna	260	5.170439498
MW-02	Nimtoli, Barguna	270	3.998355734
MW-02	Nimtoli, Barguna	870	12.70990461
MW-02	Nimtoli, Barguna	880	6.576299521
MW-02	Nimtoli, Barguna	890	10.63972432
MW-02	Nimtoli, Barguna	900	14.1028255
MW-02	Nimtoli, Barguna	1040	0.139989156
MW-02	Nimtoli, Barguna	1050	0.13321652
MW-02	Nimtoli, Barguna	1060	7.026452671
MW-02	Nimtoli, Barguna	1070	18.72301396
MW-02	Nimtoli, Barguna	1080	15.74582057
MW-03	Galachipa	70	3.927497451
MW-03	Galachipa	80	1.088344284
MW-03	Galachipa	90	4.02593161
MW-03	Galachipa	210	1.16517491
MW-03	Galachipa	250	5.808049716
MW-03	Galachipa	260	1.50544355
MW-03	Galachipa	270	13.47442232
MW-03	Galachipa	280	7.547848053
MW-03	Galachipa	850	14.2169394
MW-03	Galachipa	860	11.72382368
MW-03	Galachipa	870	8.811852953
MW-03	Galachipa	880	11.1685467
MW-03	Galachipa	890	11.72968039
MW-03	Galachipa	900	8.834851969
MW-03	Galachipa	910	8.958470008
MW-03	Galachipa	920	6.115542486
MW-03	Galachipa	930	7.25006777
MW-04	Baliatoli, Kalapara	70	3.678248341
MW-04	Baliatoli, Kalapara	80	3.633869833

MW-04	Baliatoli, Kalapara	90	0.764200893
MW-04	Baliatoli, Kalapara	260	0.263883524
MW-04	Baliatoli, Kalapara	270	2.818742051
MW-04	Baliatoli, Kalapara	280	1.084943872
MW-04	Baliatoli, Kalapara	290	1.16856235
MW-04	Baliatoli, Kalapara	300	1.120834509
MW-04	Baliatoli, Kalapara	890	16.51336762
MW-04	Baliatoli, Kalapara	900	6.644816726
MW-04	Baliatoli, Kalapara	910	6.825814969
MW-04	Baliatoli, Kalapara	920	4.929982278
MW-04	Baliatoli, Kalapara	930	3.506621294
MW-04	Baliatoli, Kalapara	940	7.429781529
MW-04	Baliatoli, Kalapara	950	6.296903752
MW-04	Baliatoli, Kalapara	960	10.68736952
MW-04	Baliatoli, Kalapara	970	1.101894716
MW-05	Pathorghata	80	1.169189109
MW-05	Pathorghata	90	0.368072294
MW-05	Pathorghata	100	0.489110444
MW-05	Pathorghata	280	0.161197606
MW-05	Pathorghata	300	1.993167941
MW-05	Pathorghata	310	1.609573706
MW-05	Pathorghata	320	3.526483773
MW-05	Pathorghata	330	4.540825254
MW-05	Pathorghata	860	7.528422301
MW-05	Pathorghata	870	4.591716194
MW-05	Pathorghata	880	5.011110719
MW-05	Pathorghata	890	7.485022829
MW-05	Pathorghata	900	10.20878236
MW-05	Pathorghata	910	18.97477684
MW-05	Pathorghata	920	21.51418374
MW-05	Pathorghata	930	13.91280992
MW-05	Pathorghata	940	7.857408793
MW-06	Rangabali	70	4.201788493
MW-06	Rangabali	80	3.753349922
MW-06	Rangabali	90	1.59242093
MW-06	Rangabali	260	3.562916118
MW-06	Rangabali	270	3.602602847

MW-06	Rangabali	280	8.461436473
MW-06	Rangabali	290	12.33651744
MW-06	Rangabali	300	0.227783115
MW-06	Rangabali	790	22.02424587
MW-06	Rangabali	800	6.379203375
MW-06	Rangabali	810	2.125584999
MW-06	Rangabali	910	6.027183947
MW-06	Rangabali	920	5.136713178
MW-06	Rangabali	930	15.17615239
MW-06	Rangabali	940	16.64527403
MW-06	Rangabali	950	25.84292021
MW-06	Rangabali	960	14.36437309
MW-07	Zakirtabog,Taltoli	70	6.594112565
MW-07	Zakirtabog,Taltoli	80	3.251585826
MW-07	Zakirtabog,Taltoli	90	4.297831203
MW-07	Zakirtabog,Taltoli	250	0.487079487
MW-07	Zakirtabog,Taltoli	260	5.953029825
MW-07	Zakirtabog,Taltoli	270	3.992370084
MW-07	Zakirtabog,Taltoli	280	7.135565154
MW-07	Zakirtabog,Taltoli	290	0.759169723
MW-07	Zakirtabog,Taltoli	880	0.193909564
MW-07	Zakirtabog,Taltoli	890	0.111804705
MW-07	Zakirtabog,Taltoli	900	28.18023443
MW-07	Zakirtabog,Taltoli	910	28.64947179
MW-07	Zakirtabog,Taltoli	920	23.93438454
MW-07	Zakirtabog,Taltoli	930	16.77978002
MW-07	Zakirtabog,Taltoli	940	19.32750675
MW-07	Zakirtabog,Taltoli	950	24.57723428
MW-07	Zakirtabog,Taltoli	960	23.95054098

Measured hydraulic conductivity by slug test data analysis:

ID	Location	Latitude	Longitude	Hydraulic Conductivity (K)
A1	Amtoli	22.21404	90.289715	1.760418788
A6	Amtoli	22.18351	90.2753383	3.862259349
AAm01	Amtoli	22.10107692	90.2060335	2.274371234
AAm02	Amtoli	22.0775422	90.2328002	4.18296967
AAm05	Amtoli	22.0693319	90.2581322	3.272935691
AAm13	Amtoli	22.142769	90.2353558	4.18296967
AC09	Amtoli	22.1552396	90.2920053	4.505093484

AC10	Amtoli	22.1657521	90.244016	2.606374667
AC11	Amtoli	22.135511	90.2612772	3.184405853
AH07	Amtoli	22.0830467	90.3126511	4.18296967
AH08	Amtoli	22.1192764	90.3056818	2.898670725
AH12	Amtoli	22.1075708	90.2647482	3.953680185
BA01	Barguna sadar	22.1712082	90.213317	4.866676547
BB04	Barguna sadar	22.1438363	90.2060559	7.003322315
BB07	Barguna sadar	22.2012727	90.0622155	4.263249332
BB08	Barguna sadar	22.0805309	90.0851057	4.740091377
BG05	Barguna sadar	22.2124133	90.119065	3.558879552
BK02	Barguna sadar	22.171067	90.1594183	5.707687317
BK03	Barguna sadar	22.174142	90.1670697	5.038001819
BN09	Barguna sadar	22.0561154	90.0665385	3.106320519
BN12	Barguna sadar	22.0324464	90.0108894	2.405056139
BN13	Barguna sadar	22.0735166	90.059702	4.61535213
BP03	Barguna sadar	22.2148719	90.178901	3.163221751
BP04	Barguna sadar	22.2164783	90.142847	4.020181783
BS02	Barguna sadar	22.1619873	90.150074	3.622911959
BS04	Barguna sadar	22.1435492	90.1064924	6.323916249
BS06	Barguna sadar	22.1177164	90.1064924	7.298407019
G1	Galachipa	22.1315717	90.407825	1.201256034
G10	Galachipa	22.300383	90.484735	1.918845718
G12	Galachipa	22.20449	90.39119	1.62990077
G14	Galachipa	22.231205	90.39263	1.774000393
G14	Galachipa	22.23354	90.350025	1.919339794
G3	Galachipa	22.16666	90.42311	0.84675507
G4	Galachipa	22.1439083	90.4654367	1.364574581
G5	Galachipa	22.1960083	90.4849933	1.269926299
G6	Galachipa	22.2240917	90.4534433	1.463978712
G8	Galachipa	22.2992217	90.4067717	1.539350727
G9	Galachipa	22.2777283	90.4554467	0.848105769
GBB02	Rangabali	21.95802	90.35923	5.025503352
GBB03	Rangabali	21.984329	90.36765	6.421679532
GBB04	Rangabali	21.98899	90.38172	4.397808738
K03	Kalapara	21.9135733	90.251595	0.578149721
K06	Kalapara	21.903456	90.1866878	1.122351242
K08	Kalapara	21.8196244	90.1743647	0.56804915
K1	Kalapara	21.949955	90.2577767	0.650317877
K10	Kalapara	21.82991	90.16014	0.461544631
K11	Kalapara	21.82525	90.1186617	1.134954751
K12	Kalapara	21.8518567	90.1192433	0.910827066
K13	Kalapara	21.878585	90.123805	0.51450954
K14	Kalapara	21.879611	90.1546505	0.383920905
K15	Kalapara	21.91020483	90.1464217	0.632111721
K16	Kalapara	21.9496633	90.168905	0.311459456
K18	Kalapara	22.0048731	90.2664258	1.32395053
K19	Kalapara	21.983333	90.283435	0.383043569
K20	Kalapara	22.050006	90.283599	0.81789769
K20	Kalapara	21.9360133	90.2785183	0.904298235
K5	Kalapara	21.930205	90.2272317	0.719540188
K7	Kalapara	21.8600447	90.192643	0.714506576
KC01	Kalapara	22.0460927	90.2100902	0.975416179

KT_04	Kalapara	21.9984654	90.2153672	1.32395053
KT03	Kalapara	21.9930987	90.2292606	0.639662741
MW2	MW2	22.03933	90.23633	5.18920524
MW3	MW3	22.093639	90.082639	6.16177765
MW4	MW4	22.136667	89.962917	8.45557507
MW7	MW7	21.877250	90.230889	3.84837682
MWTT1a	Taltoli	21.994556	90.116667	2.38118157
PK01	Patharghata	22.1599573	90.052287	1.218705031
PK02	Patharghata	22.177698	90.0150082	0.850892868
RC03	Rangabali	21.9787136	90.4317237	4.00418678
RC04	Rangabali	21.9847495	90.4597191	6.118058812
RR05	Rangabali	21.9594762	90.41400087	6.016469846
RR06	Rangabali	21.9321278	90.4216525	7.293753328
RR07	Rangabali	21.939201	90.4468423	3.638413423
RR08	Rangabali	21.95541982	90.4585517	6.675964503
TB06	Taltoli	21.969073	90.0921944	3.140783855
TB07	Taltoli	21.9223003	90.0962822	2.791540696
TC05	Taltoli	21.9874458	90.0905627	2.46338511
TC14	Taltoli	22.0357536	90.0996851	3.184405853
TC15	Taltoli	22.0125723	90.0918295	3.184405853
TN08	Taltoli	21.8995334	90.1065715	2.906178985
TP12	Taltoli	22.077112	90.1347031	3.754974367
TP13	Taltoli	22.0480384	90.1472335	4.124872869
Tsa01	Taltoli	22.0371575	90.1751313	2.85841141

15 APPENDIX-E: Groundwater Quality

Field Parameter of Water Sample.

Sample ID	Latitude	Longitude	pH	ORP (mV)	EC(uS/cm)	TDS(ppt)	Arsenic ppb	Temperature (•C)	Depth of Tubewell (Feet)
K08	21.8196244	90.1743647	7.84	153	2090	1.05	0	29.6	950
K11	21.82525	90.1186617	8.13	222	2030	1.02	0	27.8	850
K10	21.82991	90.16014	7.89	142	3390	2.25	10	28.9	36
K12	21.8518567	90.1192433	7.83	159	1820	0.92	0	28.9	880
K7	21.8600447	90.192643	7.9	145	1860	0.94	0	29.6	950
K4	21.8685417	90.2331967	7.89	163	1640	0.83	0	28.9	1000
K13	21.878585	90.123805	7.77	195	1730	0.9	0	30.1	1000
K14	21.879611	90.1546505	8.19	158	1560	0.79	0	28.7	1000
TN08	21.8995334	90.1065715	7.95	253	1900	0.97	0	29.1	800
K6	21.903456	90.1866878	7.89	143	1280	0.65	0	28.3	850
K15	21.91020483	90.1464217	7.93	141	1500	0.75	0	29.7	1200
K3	21.9135733	90.251595	7.79	153	1590	0.8	0	29.6	700
TB07	21.9223003	90.0962822	7.96	-30	1910	0.96	0	29.7	800
K5	21.930205	90.2272317	7.85	138	1300	0.65	0	28.7	950
RR06	21.9321278	90.4216525	7.81	125	1450	0.73	0	28.8	900
K2	21.9360133	90.2785183	8	138	1350	0.68	0	28.3	1160
RR07	21.939201	90.4468423	8.23	153	1200	0.58	0	28.7	900
K16	21.9496633	90.168905	8.04	177	1340	0.89	0	28.4	950
K1	21.949955	90.2577767	8.16	132	1250	0.63	0	27.5	900
RR08	21.95541982	90.4585517	8.22	97	1200	0.62	0	28.2	905
TB09(BN09)	21.959281	90.0619385	7.86	-31	2020	1.01	0	28.3	961
RR05	21.9594762	90.41400087	7.76	153	1300	0.63	0	28.4	900
TB06	21.969073	90.0921944	7.92	175	1830	0.92	0	29.2	950
RC03	21.9787136	90.4317237	8.04	112	1150	0.58	0	28.3	950
K17	21.9815233	90.2170833	7.8	174	1130	0.57	0	29.9	950
K19	21.983333	90.283435	7.91	180	1140	0.58	0	28.5	1000
RC04	21.9847495	90.4597191	7.73	157	1150	0.57	0	28.1	900
TC05	21.9874458	90.0905627	8.15	-110	1800	0.9	0	28.2	Unknown
PB09	21.9918824	89.9645988	7.22	-153	1610	0.81	0	29	28
KT03	21.9930987	90.2292606	7.84	132	1130	0.57	0	28.3	1200
TC04	21.9945982	90.116808	7.36	118	5060	2.54	0	28.5	310
KT04	21.9984654	90.2153672	8.19	120	1260	0.68	0	28.2	950
TC10	22.0001358	90.1224829	8.02	128	1640	0.84	0	28.4	980
TK03	22.0010086	90.1463081	8.02	107	1550	0.78	0	28.2	950
K18	22.0048731	90.2664258	8.06	166	1070	0.54	0	28.1	850
PP10	22.0125562	89.9597348	7.46	-128	5730	2.88	0	28.9	30
TC15	22.0125723	90.0918295	7.95	147	1700	0.85	0	28.4	900
Tk02	22.0184833	90.1563055	7.87	142	1590	0.8	0	28.8	950
RC02	22.022401	90.4428307	7.66	161	1070	0.58	0	29.2	900
AAm03	22.025151	90.2428672	7.1	-115	1280	0.68	0	28.3	900
RC01	22.0268104	90.415793	7.94	178	990	0.54	0	29.8	Unknown
BB10	22.0269006	90.0433877	7.5	-91	1021	5.2	0	28.5	
KC02	22.0272875	90.2207048	7.46	-93	2400	1.15	0	27.7	950

Sample ID	Latitude	Longitude	pH	ORP (mV)	EC(uS/cm)	TDS(ppt)	Arsenic ppb	Temperature (•C)	Depth of Tubewell (Feet)
BN12	22.0324464	90.0108894	7.7	135	640	3.15	0	32.5	Unknown
TC14	22.0357536	90.0996851	8.08	-163	1570	0.79	0	28.5	960
TSa01	22.0371575	90.1751313	7.94	163	1350	0.68	0	28.1	950
PP08	22.0420571	89.9705573	7.29	-87	2480	1.25	0	28.3	Unknown
AAm04	22.045881	90.2502748	7.81	219	1060	0.53	0	30.3	Unknown
KC01	22.0460927	90.2100902	8.08	161	1190	0.59	0	28.2	1150
TP13	22.0480384	90.1472335	8.12	183	2010	1	0	27.9	Unknown
K20	22.050006	90.283599	8.05	148	1040	0.52	0	29.4	1000
BB09	22.0561154	90.0665385	8.15	107	1500	0.75	0	27.9	950
AA01	22.0683414	90.212209	7.94	-189	1160	0.58	0	28.1	950
AAm05	22.0693319	90.2581322	7.91	-166	1090	0.54	0	32.2	800
Pkl11	22.0697378	89.984001	7.75	-95	5360	2.78	0	28.4	950
PC07	22.0709368	89.9401063	7.88	-58	3410	1.79	0	27.1	36
BN13	22.0735166	90.059702	8.01	-88	2560	1.28	0	28.2	950
TP12	22.077112	90.1347031	8	135	1480	0.74	0	27.7	955
AH06	22.0773081	90.2851621	7.98	163	1020	0.5	0	30.1	900
AAm02	22.0775422	90.2328002	7.76	-222	1090	0.55	0	27.8	900
BB08	22.0805309	90.0851057	8.11	-58	1570	0.79	0	29.2	940
TP11	22.0805713	90.155434	7.92	107	1370	0.69	0	28	950
AH07	22.0830467	90.3126511	7.95	168	950	0.46	0	29.1	950
G2	22.0850437	90.4317471	7.97	202	960	0.48	0	28.7	1000
BB07	22.0963714	90.1076879	8.03	-135	1440	0.72	0	28.4	Unknown
Pkl12	22.0969163	90.0073617	8.16	51	2010	1.01	0	29.6	930
AAm01	22.10107692	90.2060335	7.96	135	1120	0.56	0	28.1	900
BS11	22.105321	90.0839332	7.98	111	1520	0.76	0	28.3	950
AH12	22.1075708	90.2647482	7.97	151	980	0.49	0	30.1	900
BS06	22.1177164	90.1064924	7.98	104	1360	0.68	0	27.2	1200
PC06	22.1189449	89.92655588	7.42	-116	4360	2.19	0	28.9	39
AH08	22.1192764	90.3056818	8.05	223	900	0.42	0	27.2	1000
G1	22.1315717	90.407825	8	-162	800	0.4	0	27.5	1000
PK15	22.1325424	90.014056	7.62	-117	6770	3.42	0	29.9	1152
AC11	22.135511	90.2612772	7.97	46	990	0.46	0	28.2	980
PN04	22.1414791	89.947774	7.69	-73	9530	4.78	0	28	1150
AAm13	22.142769	90.2353558	8.01	118	950	0.48	0	29.2	950
PN13	22.1430126	89.9675285	7.55	-117	7180	3.6	0	28.8	650
BS04	22.1435492	90.1064924	7.83	98	1180	0.59	0	27.2	850
BB04	22.1438363	90.2060559	8.03	37	990	0.5	0	27.9	950
G4	22.1439083	90.4654367	8.04	132	690	0.35	0	28.7	1050
PKt05	22.1499696	89.92226	7.5	128	7020	3.52	10	26	35
PK14	22.1511817	90.0062257	8.17	89	1110	0.56	0	29.3	950
AC09	22.1552396	90.2920053	8.08	174	930	0.47	0	27.7	900
BS01	22.1595263	90.1178344	8.15	40	1470	0.74	0	29.4	1150
PK01	22.1599573	90.052287	7.9		1120	2.38	0	26.7	950
BS02	22.1619873	90.150074	8.04	42	1020	0.51	0	27.6	1135

Sample ID	Latitude	Longitude	pH	ORP (mV)	EC(uS/ cm)	TDS(ppt)	Arsenic ppb	Temperature (•C)	Depth of Tubewell (Feet)
AC10	22.1657521	90.244016	7.98	202	920	0.46	0	28.1	950
G3	22.16666	90.42311	8.11	169	760	0.46	0	28.2	900
G11	22.1701382	90.3776567	8.13	167	790	0.4	0	29.5	1000
BK02	22.171067	90.1594183	7.91	136	950	0.45	0	27.6	1000
BA01	22.1712082	90.213317	7.85	153	860	0.44	0	28.9	950
BK03	22.174142	90.1670697	7.89	89	960	0.49	0	27.4	950
PK02	22.177698	90.0150082	7.8		1430	5.47	0	27	960
A7	22.1794317	90.3246083	8.32	176	840	0.42	0	28.4	1000
A6	22.18351	90.2753383	8.38	166	900	0.45	0	31	1000
BG06	22.1878384	90.0933955	8.06	-86	1040	0.52	0	29.2	900
A8	22.19081	90.3549417	8.09	153	800	0.4	0	28.5	950
G5	22.1960083	90.4849933	8.16	108	710	0.35	0	28.3	Unknown
PR03	22.1994289	89.9658537	7.51		4710	3.55	0	27.3	460
BB07	22.2012727	90.0622155	8.08	147	1060	0.54	0	28.6	900
G12	22.20449	90.39119	7.8	129	810	0.41	0	29.1	Unknown
BG05	22.2124133	90.119065	7.31	-58	2610	1.35	0	29.5	650
A1	22.21404	90.289715	8.29	148	940	0.47	0	28.3	900
BK 03	22.2148719	90.1786901	7.88	122	960	0.48	0	27	1050
BK03	22.2148719	90.178901	7.95	90	1020	0.51	0	27.6	1250
BP04	22.2164783	90.142847	7.89	89	960	0.49	0	27.4	950
G6	22.2240917	90.4534433	8.13	109	630	0.32	0	28.4	800
A5	22.2301017	90.3087967	7.89	138	890	0.44	0	28.9	1200
G13	22.231205	90.39263	8.06	193	670	0.34	0	29.6	1050
G14	22.23354	90.350025	7.97	143	780	0.39	0	28.9	1000
A2	22.2342644	90.2756822	8.29	148	940	0.47	0	28.3	900
A3	22.2538333	90.244845	7.53	143	840	0.43	0	28.9	900
G7	22.255683	90.4466033	8.54	142	680	0.32	0	28.2	860
G9	22.2777283	90.4554467	7.97	179	650	0.32	0	28.4	950
G8	22.2992217	90.4067717	8.06	139	680	0.34	0	29.1	850
G10	22.300383	90.484735	7.98	210	850	0.43	0	28.4	850
MW - 4(100	22.15004	89.95103	7.3	-184	20000	10	0	29	100
MW - 4(300	22.15004	89.95103	7.18	-151	20000	10	10	28.5	300
MW - 4(1000	22.15004	89.95103	7.46	-177	11920	5.96	0	28.9	1000
MW- 3(100	22.09279	90.08228	7.13	-154	9560	4.77	0	29.2	100
MW- 3(300	22.09279	90.08228	6.7	-138	20000	10	0	28.6	300
MW- 3(1100	22.09279	90.08228	8.2	-82	1220	0.61	0	29.9	1100
MW-1 (100 ft)	21.99934	90.11379	6.8	-109	2000	10	100	28.6	100

Sample ID	Latitude	Longitude	pH	ORP (mV)	EC(uS/ cm)	TDS(ppt)	Arsenic ppb	Temperature (•C)	Depth of Tubewell (Feet)
MW-1 (300 ft)	21.99934	90.11379	7.27	-114	5000	2.5	0	28.3	300
MW-1 (1000	21.99934	90.11379	7.91	-85	1640	0.82	0	28.2	1000
MW-2(100	22.04826	90.22414	7.68	14	1660	0.83	0	30.6	100
MW-2(300	22.04826	90.22414	8.01	14	1260	0.63	0	29.7	300
MW-2(1000	22.04826	90.22414	8	-38	1110	0.55	0	28.2	1000
MW-7(100	21.87086	90.23818	7.32	-121	20000	10	100	28.4	100
MW-7(300	21.87086	90.23818	6.75	-104	15270	7.64	25	28.5	300
MW-7(1000	21.87086	90.23818	8.28	-106	1660	0.84	0	28.9	1000
GBB-1	21.95802	90.35923	7.93		1210		0	26.9	950
GBB-2	21.91802	90.35923	7.9		1100		0	26.8	850
GBB-3	21.984329	90.36765	8.08		1160		0	27.6	Unknown
GBB-4	21.98899	90.38172	8.43		1130		0	27.1	1200
MW - 5(100	22.25891	90.44889	7.43	-183	12200	6.1	50	28.4	100
MW - 5(300	22.25891	90.44889	0	0	0	0	0	0	300
MW - 5(1000	22.25891	90.44889	7.88	-93	630	0.32	0	29.4	1000
MW-6(100	21.94847	90.45147	0	0	0	0	0	0	100
MW-6(300	21.94847	90.45147	0	0	0	0	0	0	300
MW-6(1000	21.94847	90.45147	0	0	0	0	0	0	1000
SC01	21.88467	90.49692	7.97	61	1230	0.62	0	29.8	980
p1	21.90430556	90.51288889	7.75		1090		0	28.1	920
Ck-4	22.09502	90.517158	7.94		1310		0	28.3	880
Ck-1	22.0136	90.51951	7.85		900		0	28	900
p2	21.89961111	90.52403889	8.1		1050		0	28.4	Unknown
p6	21.89897	90.52633	8.1		950		0	28.2	835
Ck-2	22.03945	90.52643	8.01		930		0	27.6	840
Ck-3	22.06173	90.53293	7.87		920		0	28.1	920
p3	21.8991	90.5389	7.82		1230		0	27.6	875
p4	21.89584	90.55445	7.96		960		0	28.6	915
p5	21.8949	90.838823	8.2		940		0	28.7	985

Ion Concentrations in Groundwater Samples in Pre-monsoon

Object ID	Ca^{2+} (mg/l)	Mg^{2+}(mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-}(mg/l)
G7	**4.719**	**2.32**	**152.03**	**2.098**	**525.25**	**5.9452**
G8	**4.481**	**2.518**	**151.496**	**2.24**	**490.88**	**6.2343**
A3	**3.248**	**3.132**	**190.24**	**3.092**	**640.5**	**14.6022**
AAm05	**5.118**	**5.419**	**229.678**	**4.21**	**793**	**20.6264**
G11	**5.833**	**3.194**	**185.124**	**3.1**	**594.75**	**7.504**
Ck-2	**5.754**	**3.832**	**204.356**	**3.508**	**632**	**7.7182**
Ck-4	**7.183**	**5.263**	**188.296**	**4.448**	**640.5**	**19.8124**
MW-2D	**6.036**	**4.736**	**260.1**	**4.516**	**524**	**36.0304**
A5	**2.606**	**3.311**	**201.388**	**3.334**	**670.65**	**9.9648**
MW -5D	**7.941**	**4.893**	**131.072**	**5.109**	**465.125**	**17.199**
AH12	**4.017**	**3.45**	**208.952**	**3.182**	**678.63**	**19.04**
AAm13	**3.588**	**3.732**	**205.022**	**3.292**	**650.75**	**14.1934**
A6	**3.039**	**3.668**	**202.35**	**3.484**	**650.5**	**12.2412**
BA01	**2.813**	**3.193**	**231.72**	**2.968**	**732**	**17.2812**
BS04	**2.143**	**2.885**	**218.968**	**3.112**	**709.13**	**19.2476**
RC02	**7.44**	**6.226**	**213.19**	**4.806**	**650.63**	**45.5676**
MW-3D	**3.666**	**2.518**	**290.292**	**3.13**	**557.5**	**92.2222**
BK 03	**2.626**	**2.816**	**220.99**	**2.736**	**715.88**	**15.2204**
p1	**4.321**	**3.32**	**241.868**	**3.736**	**701.5**	**56.445**
p4	**9.651**	**5.891**	**203.636**	**6.19**	**671**	**31.4764**
K20	**0**	**3.945**	**233.49**	**3.85**	**754.88**	**13.2296**
MW-1D	**8.359**	**6.153**	**211.235**	**2.79**	**415.25**	**191.8835**
SC01	**7.639**	**5.418**	**256.342**	**5.102**	**739.625**	**79.2442**
AA01	**2.786**	**3.741**	**256.604**	**3.54**	**793**	**32.4256**

RC03	**3.257**	**2.976**	**264.11**	**4.156**	**805.5**	**32.4548**
GBB-4	**3.924**	**2.957**	**263.738**	**3.708**	**831.125**	**26.3202**
GBB-2	**5.779**	**4.737**	**244.802**	**5.054**	**770.13**	**38.4088**
RR08	**3.154**	**2.559**	**272.9**	**3.39**	**846.38**	**28.9304**
TSa01	**5.882**	**4.193**	**293.99**	**4.292**	**831.13**	**77.5318**
K1	**6.601**	**3.215**	**317.088**	**4.58**	**861.63**	**42.744**
K16	**1.769**	**2.885**	**328.408**	**3.912**	**876.88**	**73.6768**
RR06	**11.443**	**10.676**	**300.596**	**6.18**	**724.38**	**222.695**
MW-7D	**4.472**	**4.804**	**379.785**	**4.325**	**595.625**	**152.2535**
BB04	**34.75**	**42.08**	**284.686**	**3.788**	**785.38**	**118.445**
TC14	**3.997**	**3.369**	**337.742**	**4.53**	**854**	**150.6156**
BS11	**6.134**	**5.661**	**315.862**	**4.224**	**823.5**	**130.112**
TC10	**4.522**	**3.286**	**349.675**	**4.235**	**861.63**	**155.077**
K4	**3.262**	**4.363**	**370.83**	**3.935**	**922.63**	**157.7905**
BB07	**3.756**	**3.584**	**316.634**	**5.08**	**815.875**	**141.4026**
TP13	**6.577**	**3.742**	**415.035**	**3.995**	**761.63**	**343.7445**
TB09(BN09)	**7.392**	**5.25**	**415.98**	**4.495**	**861.63**	**284.5585**
TB07	**4.817**	**4.176**	**405.12**	**4.315**	**915**	**195.1555**
KC02	**4.856**	**49.37**	**386.32**	**12.72**	**724.38**	**519.2445**
K08	**11.193**	**13.144**	**432.275**	**6.37**	**854**	**332.4265**
BN13	**6.013**	**5.705**	**527.24**	**5.77**	**846.375**	**501.8075**
Pkl11	**12.81**	**26.69**	**1157.86**	**10.99**	**709.125**	**1818.651**
PK15	**41.13**	**38.72**	**1262.89**	**10.96**	**518.5**	**2222.143**
PN04	**69.98**	**81.75**	**1884.9**	**28.32**	**541.375**	**3325.592**
MW -4D	**126.9**	**122.56**	**2181.16**	**22.18**	**449.875**	**3058.172**
MW-6D	**248.62**	**148.16**	**2380.88**	**46.36**	**533.75**	**4359.966**
MW -5I	**30.59**	**50.18**	**267.235**	**27.76**	**160.125**	**550.9665**

MW-2I	**15.43**	**28.97**	**250.786**	**9.658**	**115**	**490.9662**
PR03	**67.25**	**76.38**	**829.92**	**10.71**	**564.25**	**1511.466**
TC04	**120.04**	**107.94**	**662.59**	**27.66**	**280.38**	**1783.263**
MW-1I	**130.08**	**123.27**	**688.56**	**27.205**	**251.625**	**1889.084**
MW-7I	**336.58**	**164.34**	**2211.76**	**27.64**	**110.75**	**5547.288**
MW-3I	**334.75**	**95.91**	**3694.4**	**18.36**	**550.625**	**3333.94**
MW-6I	**390.7**	**489.1**	**4206.2**	**48.16**	**236.375**	**10169.52**
MW -4I	**68.26**	**590.95**	**5587.25**	**146.5**	**441.375**	**11892.5**
MW-6S	**3.903**	**2.894**	**270.546**	**3.296**	**565.125**	**37.5774**
K10	**5.77**	**46.74**	**608.385**	**27.02**	**650.13**	**909.763**
PC07	**15.68**	**58.25**	**570.175**	**29.785**	**635.38**	**983.732**
MW-2S	**15.72**	**31.06**	**239.146**	**10.786**	**90.5**	**524.2208**
PB09	**85.05**	**88.84**	**92.92**	**26.4**	**663.38**	**156.3896**
PKt05	**27.54**	**76.09**	**1319.42**	**41.99**	**1212.375**	**1994.181**
MW-3S	**140.61**	**190.55**	**1570.57**	**54.78**	**305**	**2371.646**
MW -5S	**11.294**	**223.64**	**2181.78**	**66.92**	**579.5**	**3727.5**
MW-7S	**116**	**170.04**	**4232.75**	**112.75**	**85.375**	**9030.325**
MW -4S	**143.65**	**504.9**	**5391.15**	**154.25**	**327.875**	**8491.43**
MW-1S	**361.06**	**897.4**	**6593.55**	**201.45**	**290.13**	**15252.07**

Ion Concentrations of Groundwater Samples in Post-monsoon

Object ID	Latitude	Longitude	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)
RB-01	21.94847	90.45147	5.546	3.23	291.528	2.688	838.75	32.311	0.2234
AA-02	22.04826	90.22414	6.378	4.936	273.96	3.454	770.125	32.421	0.7952
PG-03	22.15004	89.95103	155.6	127.36	2264.9	16.66	510.875	4720.136	0
BR-04	22.09279	90.08228	6.706	2.71	287.482	2.102	770.125	72.1576	0.152
GC-05	22.25891	90.44889	13.122	5.816	163.618	1.665	495.625	6.6125	0.4212
KP-06	21.87086	90.23818	5.212	4.982	393.83	2.45	876.875	156.6015	0.2215

Measured Electrical conductivity (EC) value (pre-monsoon):

Object ID	Latitude	Longitude	EC_µs_cm	Depth_ft	Category
G7	22.255683	90.446603	680	860	Deep Well
G8	22.299222	90.406772	680	850	Deep Well
A3	22.253833	90.244845	840	900	Deep Well
AAm05	22.069332	90.258132	1090	1152	Deep Well
G11	22.170138	90.377657	790	1000	Deep Well
MW-2D	22.04826	90.22414	1110	1000	Deep Well
A5	22.230102	90.308797	890	1200	Deep Well
MW -5D	22.25891	90.44889	630	1000	Deep Well
AH12	22.107571	90.264748	900	900	Deep Well
AAm13	22.142769	90.235356	980	950	Deep Well
A6	22.18351	90.275338	950	1000	Deep Well
BA01	22.171208	90.213317	960	950	Deep Well
BS04	22.143549	90.106492	860	850	Deep Well
RC02	22.022401	90.442831	1070	900	Deep Well

MW-3D	22.09279	90.08228	1220	1100	Deep Well
BK 03	22.214872	90.17869	990	1050	Deep Well
K20	22.050006	90.283599	1040	950	Deep Well
MW-1D	21.99934	90.11379	1640	1000	Deep Well
SC01	21.88467	90.49692	1230	980	Deep Well
AA01	22.068341	90.212209	1160	800	Deep Well
RC03	21.978714	90.431724	1150	950	Deep Well
GBB-2	21.91802	90.35923	1100	850	Deep Well
RR08	21.95542	90.458552	1200	905	Deep Well
TSa01	22.037158	90.175131	1350	950	Deep Well
K1	21.949955	90.257777	1250	900	Deep Well
K16	21.949663	90.168905	1340	950	Deep Well
MW-7D	21.87086	90.23818	1660	1000	Deep Well
BB04	22.143836	90.206056	1180	1200	Deep Well
TC14	22.035754	90.099685	1570	960	Deep Well
BS11	22.105321	90.083933	1520	950	Deep Well
TC10	22.000136	90.122483	1640	980	Deep Well
K4	21.868542	90.233197	1640	1000	Deep Well
BB07	22.201273	90.062216	1060	950	Deep Well
TP13	22.0480284	90.1472335	1370	1000	Deep Well
TB09(BN09)	21.959281	90.061939	2020	961	Deep Well
TB07	21.9223	90.096282	1910	961	Deep Well
KC02	22.027288	90.220705	2400	950	Deep Well
K08	21.819624	90.174365	2090	950	Deep Well
BN13	22.073517	90.059702	2560	950	Deep Well
Pkl11	22.069738	89.984001	5360	950	Deep Well
PK15	22.132542	90.014056	6770	1150	Deep Well
PN04	22.141479	89.947774	9530	1150	Deep Well
MW -4D	22.15004	89.95103	11920	1000	Deep Well
MW-2I	22.04826	90.22414	1260	300	Intermediate Well
PR03	22.199429	89.965854	4710	360	Intermediate Well
TC04	21.994598	90.116808	5060	310	Intermediate Well
MW-1I	21.99934	90.11379	5000	300	Intermediate Well
MW-7I	21.87086	90.23818	15270	300	Intermediate Well
MW-3I	22.09279	90.08228	10580	300	Intermediate Well
MW -4I	22.15004	89.95103	31620	300	Intermediate Well
K10	21.82991	90.16014	3390	36	Shallow Well

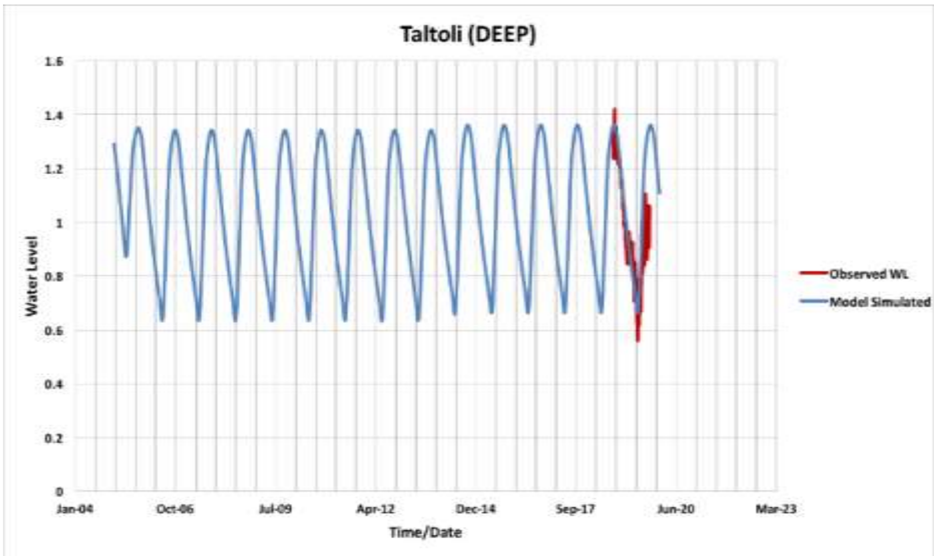
PC07	22.070937	89.940106	3410	36	Shallow Well
MW-2S	22.04826	90.22414	1660	100	Shallow Well
PB09	21.991882	89.964599	1610	28	Shallow Well
PKt05	22.14997	89.92226	7020	35	Shallow Well
MW-3S	22.09279	90.08228	9560	100	Shallow Well
MW -5S	22.25891	90.44889	12200	100	Shallow Well
MW-7S	21.87086	90.23818	23700	100	Shallow Well
MW -4S	22.15004	89.95103	29540	100	Shallow Well
MW-1S	21.99934	90.11379	36400	100	Shallow Well

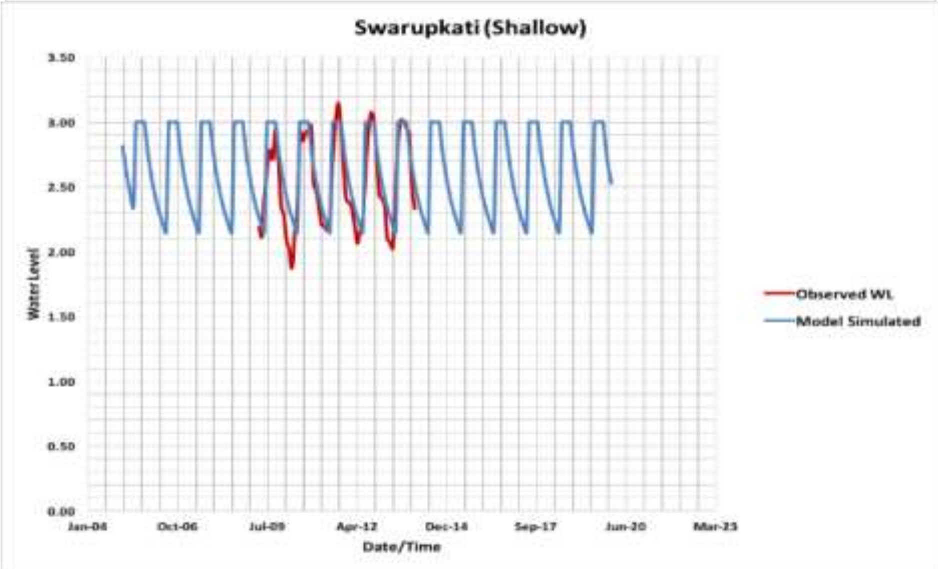
Appendix-6: Measured Electrical conductivity (EC) value (post-monsoon):

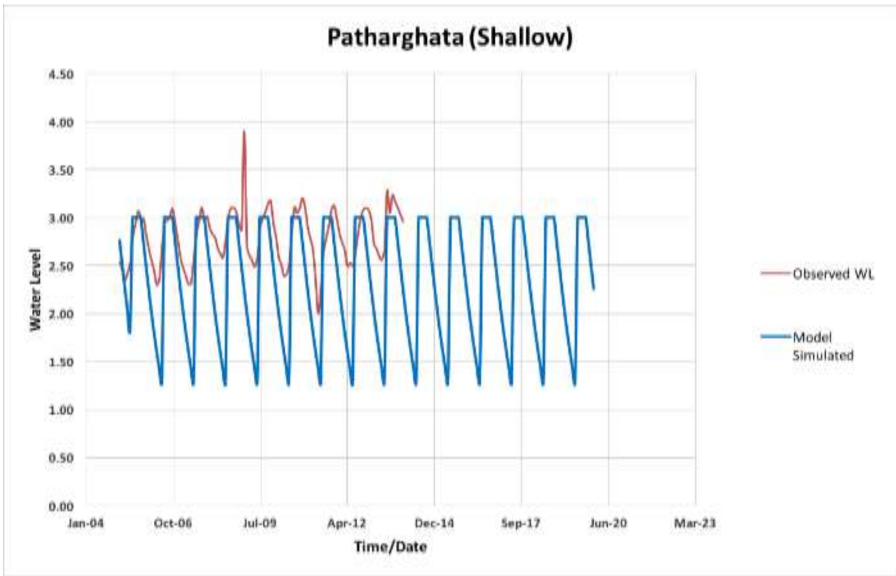
Object ID	Location	Latitude	Longitude	EC (µS/cm)
RB-01	Rangabali	21.94847	90.45147	1194
AA-02	Amtoli	22.04826	90.22414	1120
PG-03	Patharghata	22.15004	89.95103	10940
BR-04	Barguna Sadar	22.09279	90.08228	1242
GC-05	Galachipa	22.25891	90.44889	674
KP-06	Kalapara	21.87086	90.23818	1639

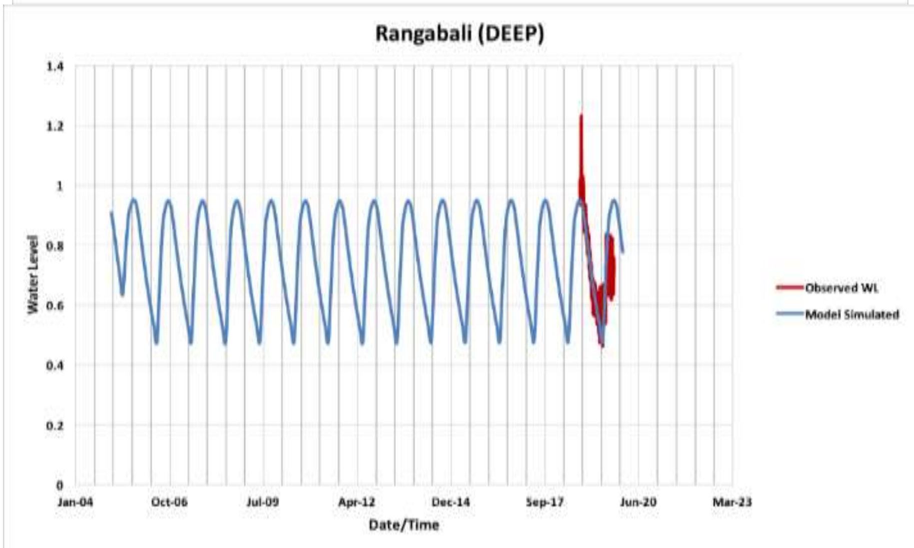
16 APPENDIX-F: Groundwater Model Data

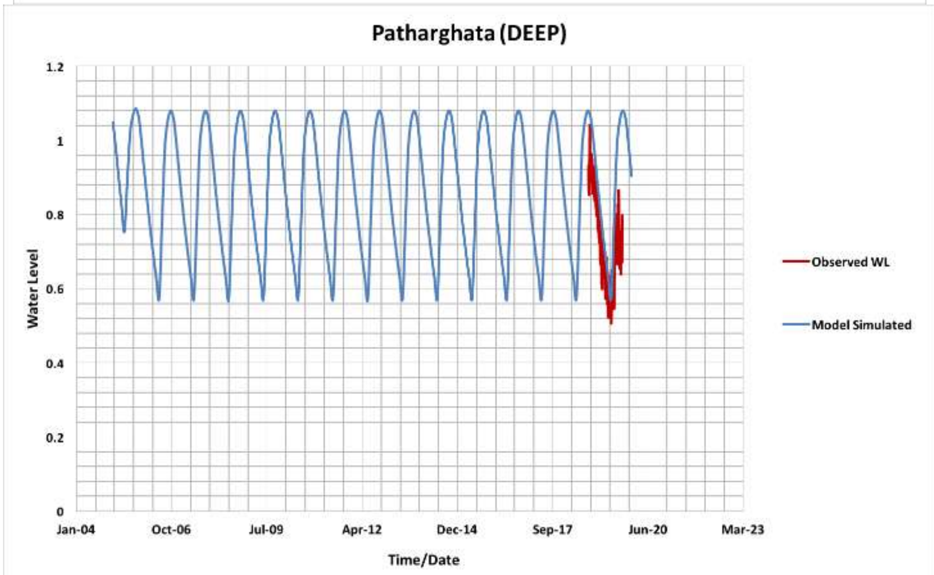
Model Calibration plots:

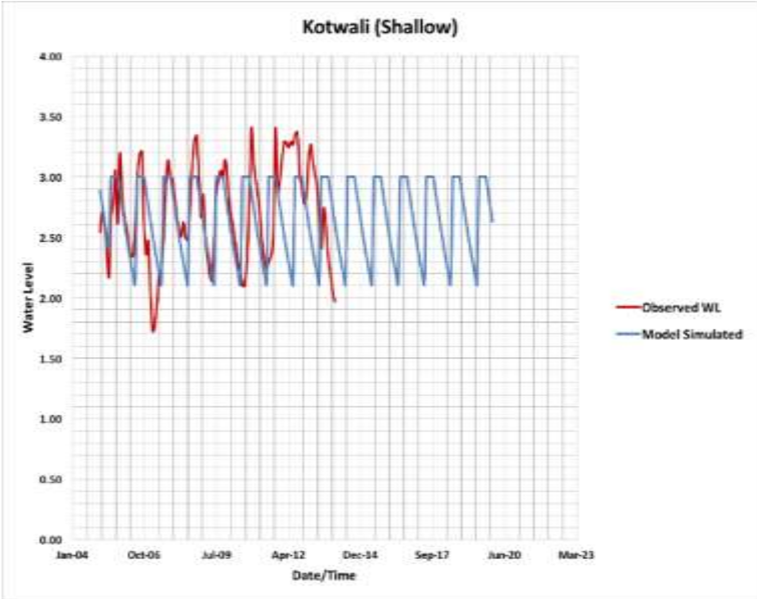


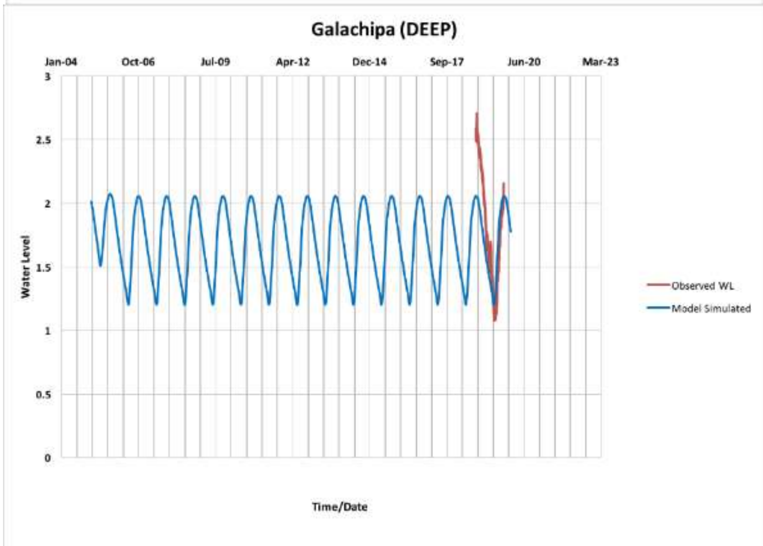


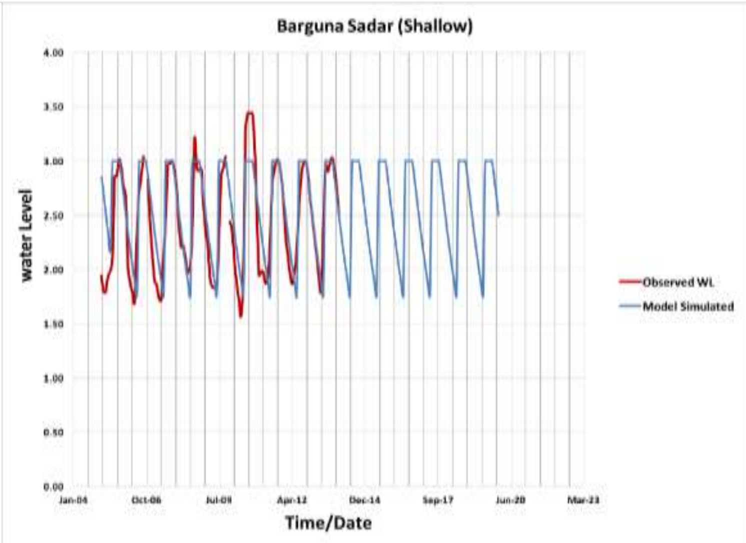

Patharghata (Shallow)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Water Level
Jan-04
Oct-06
Jul-09
Apr-12
Dec-14
Sep-17
Jun-20
Mar-23
Time/Date
Observed WL
Model Simulated

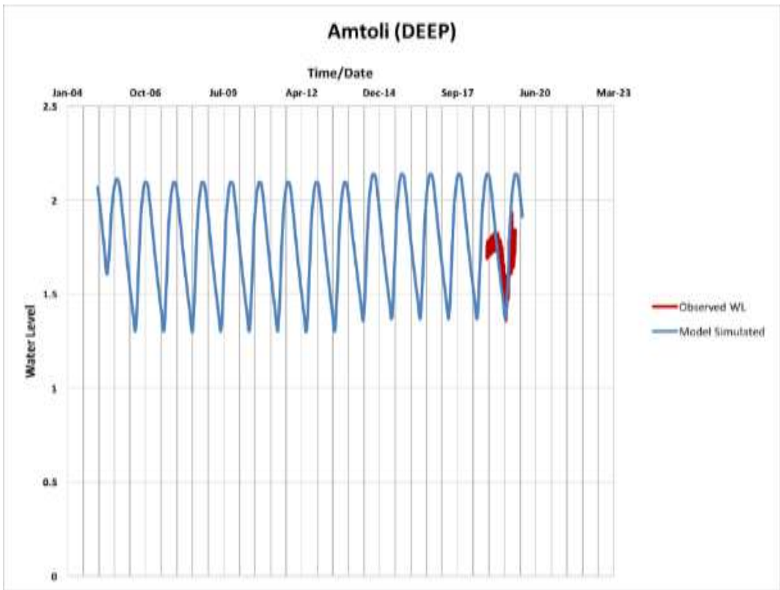

Rangabali (DEEP)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Water Level
Jan-04
Oct-06
Jul-09
Apr-12
Dec-14
Sep-17
Jun-20
Mar-23
Date/Time
Observed WL
Model Simulated

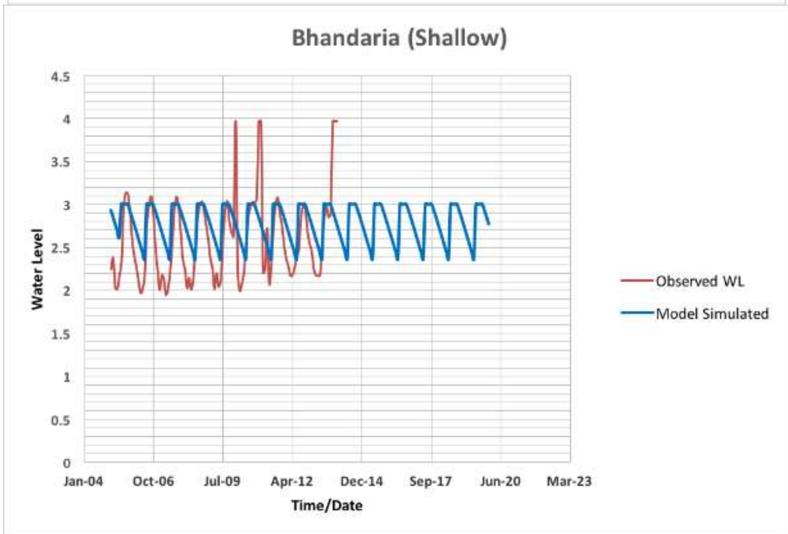

Patharghata (DEEP)
1.2
1
0.8
0.6
0.4
0.2
0
Water Level
Jan-04
Oct-06
Jul-09
Apr-12
Dec-14
Sep-17
Jun-20
Mar-23
Time/Date
Observed WL
Model Simulated

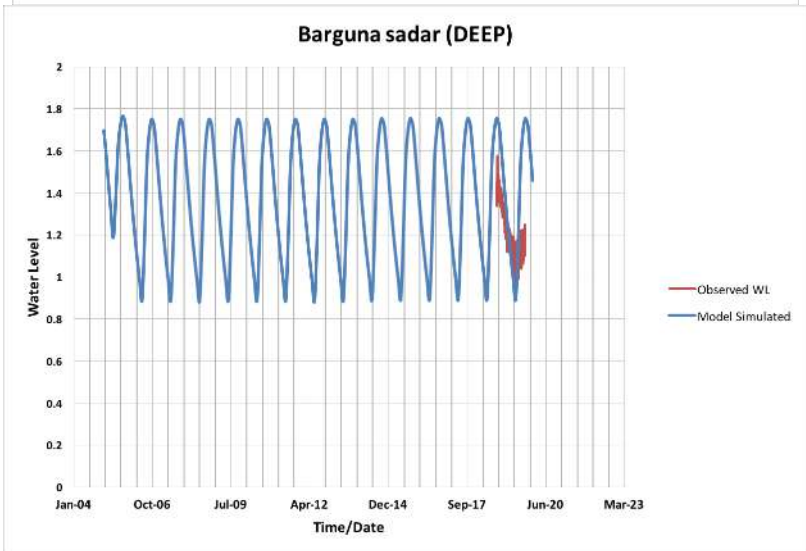

Kotwali (Shallow)
Water Level
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Jan-04
Oct-06
Jul-09
Apr-12
Dec-14
Sep-17
Jun-20
Mar-23
Date/Time
Observed WL
Model Simulated

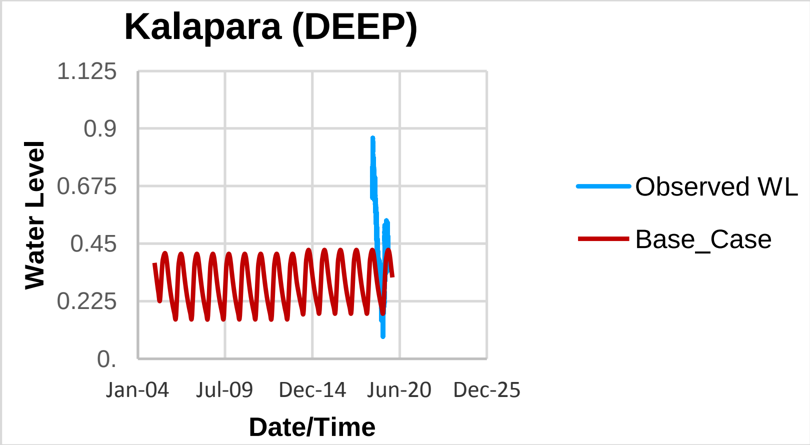

Galachipa (DEEP)
Jan-04
Oct-06
Jul-09
Apr-12
Dec-14
Sep-17
Jun-20
Mar-23
Water Level
3
2.5
2
1.5
1
0.5
0
Time/Date
Observed WL
Model Simulated


Barguna Sadar (Shallow)
water Level
Time/Date
Observed WL
Model Simulated


Amtoli (DEEP)
Time/Date
Jan-04
Oct-06
Jul-09
Apr-12
Dec-14
Sep-17
Jun-20
Mar-23
2.5
2
1.5
1
0.5
0
Water Level
Observed WL
Model Simulated


Bhandaria (Shallow)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Water Level
Jan-04
Oct-06
Jul-09
Apr-12
Dec-14
Sep-17
Jun-20
Mar-23
Time/Date
Observed WL
Model Simulated


Barguna sadar (DEEP)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Water Level
Jan-04
Oct-06
Jul-09
Apr-12
Dec-14
Sep-17
Jun-20
Mar-23
Time/Date
Observed WL
Model Simulated


Kalapara (DEEP)
Water Level
1.125
0.9
0.675
0.45
0.225
0.
Jan-04
Jul-09
Dec-14
Jun-20
Dec-25
Date/Time
Observed WL
Base_Case