Journal of Nepal Geological Society, 2020, vol. 60, pp. 181-194
https://doi.org/10.3126/jngs.v60i0.31262

Geo-electrical resistivity survey for fresh groundwater investigation in Mirsharai Economic Zone, Chittagong in the south-eastern coastal areas of Bangladesh

***A.S.M. Woobaidullah, Md. Ariful Islam, Md. Zakir Hossain, Md. Shahidul Islam**

Geology Department, Dhaka University, Dhaka 1000, Bangladesh
**Corresponding author's email: woobaid.du@gmail.com*

ABSTRACT

Salinity in the groundwater is one of the major concerning issues in the coastal region of Bangladesh. Mirsharai Economic Zone, Mirsharai Upazila in the south-eastern coastal region of Chittagong District of Bangladesh, requires substantial amount of fresh groundwater supply for industrial and household use.

The purpose of this study is to delineate the aquifer system of the study area and to determine the extension of potential fresh water aquifer for groundwater development through geophysical electrical resistivity sounding survey. Vertical Electrical Sounding in conjunction with borehole data provides information about the saline-fresh water interface, depth distribution, thickness of the fresh-water aquifers and local lithology. Lithological cross section shows that the sedimentary deposition and aquifer-aquitard distribution of this region are irregular even within a short spatial distance. The surface layer of top soil of clay or silty clay composition identified as aquitard shows resistivity in the ranges from 1.24 Ωm to 11 Ωm. This aquitard is underlain by a sand layer acting as shallow aquifer of varying thickness shows resistivity ranging mostly from 1.9 Ωm to 11Ωm reflecting the pore space water as saline to brackish. A second aquitard is underlain by the shallow aquifer of varying thickness. A deep fresh water aquifer, overlain by the second aquitard, shows resistivity in the range of 16 Ωm to73 Ωm indicating the pore space water as fresh. But the aquifer is interrupted by clay/silty clay layers at the deeper part in the middle portion. This study provides depth to the fresh water aquifer as well as probable suitable regions for groundwater development.

Keywords: Resistivity; Aquifer; Aquitard; Vertical electrical sounding; Borehole log

Received: 6 May, 2020 **Received in revised form:** 5 July, 2020 **Accepted:** 6 July, 2020

INTRODUCTION

Adequate supply of fresh water is a major concern for most of the nation worldwide, particularly along the coastal regions due to saline sea water intrusion. Saline water intrusion into the aquifers of coastal areas worldwide creates a great problem to ensure clean water supply for all sorts of usage. Bangladesh like other countries needs essential background information about the geology and present hydrogeological setting of coastal area for developing optimal management strategies (Woobaidullah et al., 1996; Islam, 2019; Zahid et al., 2016).

Over the past few decades geophysical methods have gained popularity due to their ability to map hydrogeologic properties. The emerging use of geophysical methods for hydrogeological imaging has yielded a new field of research, hydro-geophysics. Electrical resistivity method is one of the most widely used, easiest, highly reliable and cheapest method for surveying large areas (Serres,1969; Buggand Lloyd, 1976; Oteri et al., 1983; Elwaheidi et al., 1992; Acworth, 2001; Kouzana et al., 2009; Woobaidullah and Zohir Uddin, 2011; Rahman et al.,2013; Gautam et al., 2014; Rahman and Bhattacharya, 2014; Woobaidullah et al., 2014, 2019). Mirsharai economic zone of Chittagong District, a coastal and tidal floodplain area, contains shallow aquifers contaminated with saline water. Both surface and shallow aquifer water in the study area, especially in the dry months, are not drinkable due to less rainfall and intrusion of saline water (BEZA, 2014; Zahid et al., 2016; Islam, 2019;). For rapid and intensive industrialization of the area it is now inevitable to search for an option of deep fresh water aquifers.

The coastal areas of Bangladesh, stretching from Khulna at the west to the Cox's Bazar in the east, have been studied previously by academic scholars, agencies and organizations for exploration of the local geology and groundwater (Hasan et al., 1997; Imam et al., 2013; BEZA, 2014; Woobaidullah et al., 1994, 1996, 1998, 1999, 2006, 2008; Zahid et al., 2016). Very few works have been carried out in the Mirsharai economic zone specifically for deciphering subsurface geological and hydrogeological conditions (BEZA, 2014; Farah Didul Nabi et. el., 2019).

As the sub-surface geology of Mirsharai area is complex few available boreholes in the area often fail to identify sustainable fresh water supplies. The main objective of the research was to delineate the safe aquifers in Mirsharai economic zone, specifically to explore sustainable fresh water aquifers for large scale abstraction, the required depth and spatial and vertical changes in water quality based on surface geophysical resistivity survey in conjunction with available borehole log information.

STUDY AREA

Geomorphology and Drainage

Mirsharai Upazila (Chittagong District) is located between 22˚39' and 22˚59' north latitudes and between 91˚27' and 91˚39' east longitudes and has an area of 482.88 km^2 (BBS) and is bounded by Tripura State of India, Chhagalnaiya and Feni Sadar Upazilas to the north, Sitakunda and Sandwip Upazilas on the south, Fatikchhari Upazila on the east, Sonagazi and Companyganj (Noakhali) Upazilas on the west (Fig. 1). The entire study area Mirsharai economic zone contains plain land topography. It is situated on the northernmost part of the Sitakunda anticline.

The main drainage in the area occurs through river Feni and Sandwip channel with some small canals like Ichhakhali, Mahamaya, Domkhali, Hinguli, Koila-Govania and Mayani Khal. Tidal effects along the coast are generally up to 2 m above mean sea level on the floodplain are generally masked by the depth of river flooding. This region occupies the northern edge of the young Meghna Estuarine Floodplain. It comprises smooth, almost level floodplain ridges and shallow basins (http://en.banglapedia.org).

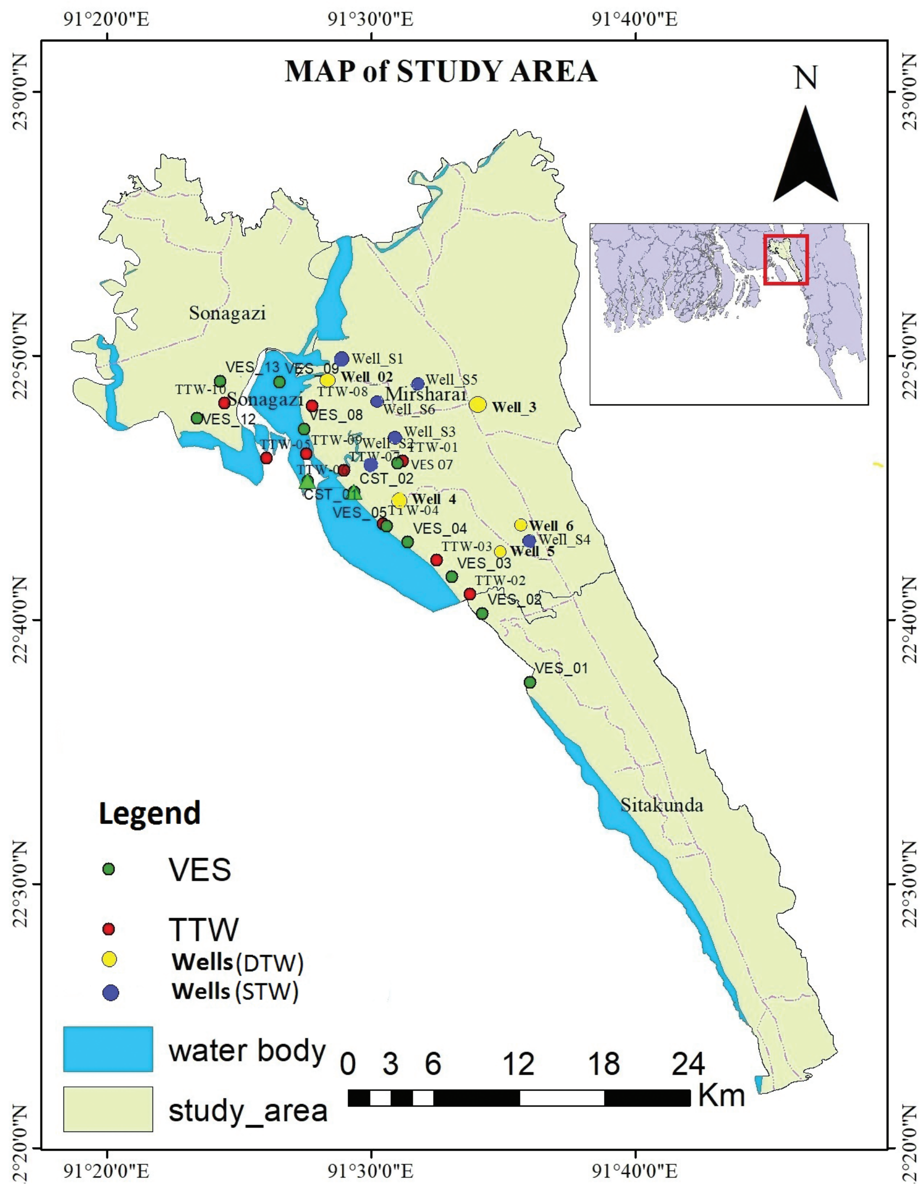

Fig. 1: Map of study area showing its location within Bangladesh.

Geological Settings

Surface geology of the study area has two distinct patterns. The tertiary sediments are exposed in the eastern hilly part following the regional trend of the area. A stratigraphy for the Chittagong and adjacent area has been proposed by Karim, 1990 (Table 1).

Table 1: Stratigraphy of Chittagong and surrounding area (Karim, 1990).

Age	Formation	Description
Holocene	Alluvium	Fluvio-tidal complex
	Unconformity	
Pliocene	Dihing	Poorly sorted, Pebbly sandstone and mottled clay
	Unconformity	
Mio-Pliocene	Dupitila	Massive medium to coarse grained sandstone, Sandy clay and siltstone
	Unconformity	
Miocene	Girujan Clay	(Mottled Clay (Not exposed in this area
Miocene	Tipam Sandstone	Interbedded sandstone, interlaminated silty sandstone with occasionally thinly laminated siltstone and shale
Miocene	Bokabil	Silty clayey shale with interbedded sandstone

The plain land is covered with Holocene Alluvium sediments and the western part has tidal influence. The study area belongs to the plain land of Holocene Alluvium sediments. The Holocene Alluvium sediments are mainly composed of alternations of sand, silty clay and clay. Available borehole log data of the area suggest that the thickness of these sediments covers more than 300 m of depth.

Water Resources and Hydrology

Surface water is dominated by standing water such as ponds, lakes and watercourses such as streams, rivers, and wetlands. The major rivers in the area are Feni and Muhuri. The Muhuri River originates in the Lushai Hills of Tripura and flows west into Bangladesh covering an area of 40,080 hectares. The Muhuri has a width of about 150 to 200 meters but influence of tidal action increases as it approaches the sea. Irrigation is mostly done from canal water and also by adding tube-well water. Water is generally muddy and saline in nature. The depth of the water table varies from a few meters to 20 meters (Islam, 2019). A shallow saline water aquifer of about 20-50m thickness exists near the surface. Main aquifer is deep seated whose nature and extent are not known. Moderate soil salinity is also observed in many patches of the area (BEZA, 2014; Khan, 1991).

METHODOLOGY

Electrical resistivity techniques are based on the response of the earth to the flow of electrical current. In these methods, an electrical current is passed into the ground through a pair of current electrodes and two potential electrodes records the resultant potential difference between them, giving a way to measure the electrical impedance of the subsurface material. The current electrodes are generally placed outside of the potential electrodes (Kearey and Brooks, 1984). The apparent resistivity is then a function of the measured impedance (ratio of potential to current) and the geometry of the electrode array. Depending upon the survey geometry, the apparent resistivity data are plotted as 1-D soundings, 1-D profiles, or in 2-D cross-sections in order to look for anomalous regions (Griffiths and Ring, 1981).

The presence of ground water controls much of the conductivity variation in the subsurface. Measurement of resistivity (inverse of conductivity) is, in general, a measure of water saturation and connectivity of pore space. Ground water decreases resistivity and electric current follows the path of least resistance (Keller and Frischknecht.1996). Increasing saturation, salinity of the ground water, porosity of rock and number of fractures (water-filled) tend to decrease measured resistivity. Depth of burial, age and compaction of soils or rock units effectively increase resistivity. Saturation of hydrocarbon in voids/fractures in rocks increases subsurface resistivity (David and Ofrey, 1983; Schwartz and MCClymont, 1977; Telford et al., 1976).

Resistivity measurements are associated with varying depths depending on the separation of the current and potential electrodes in the survey, and can be interpreted in terms of a lithologicand/or geo-hydrologic model of the subsurface. Computer modeling can help interpret geoelectric data in terms of more accurate earth models (Telford et al., 1976;

David and Ofrey, 1983; Kearey et al., 1991; Burger, 1992). Based on the position of current or potential electrodes and variation in distance between them, a variety of electrode configurations are possible of which some are mentioned below: 1) Wenner configuration 2) Schlumberger configuration 3) Dipole-dipole configuration.

The electrical resistivity survey involves electrical sounding using Schlumberger configuration with McOHM (Model-2115) resistivity meter. Schlumberger proposed this configuration in 1916. The Schlumberger configuration, widely used in measuring the earth resistivity, is designed to approximately measure the potential gradient. In this array four electrodes are placed symmetrically from the center, where the outer two electrodes are current electrodes (Fig. 2). The current electrodes (A and B) are spaced much further apart than the potential electrodes (M and N). The distance between the potential electrodes is 1/5 to 1/10th of the current electrodes(Keller and Frischknecht, 1996).

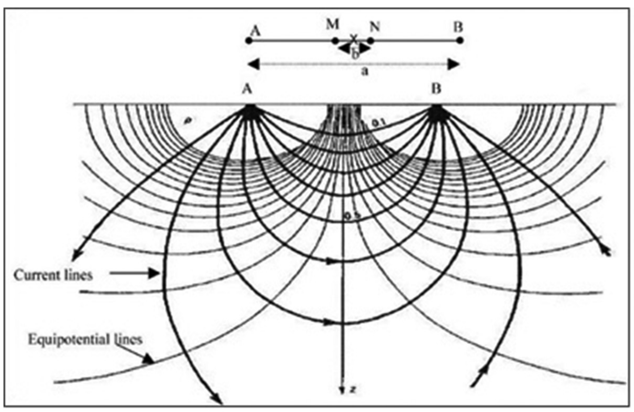

Fig. 2: Schlumberger array and distribution of electric field underneath.

In depth probing the potential electrodes remain fixed while the current electrodes spacing is expanded symmetrically about the center of the spread. For large values of current electrode separation, it may be necessary to increase the potential electrode separation in order to maintain a measurable potential within the accuracy limit of the instrument. In case of lateral exploration, the electrode spacing remains fixed and the whole array is moved along the line in suitable steps. For Schlumberger configuration the apparent resistivity (ρ_a) is determined by the following equation (Telford et al., 1976):

$$\rho a = 2\pi \, (L^2 - l^2)/2l \times \Delta V/I$$

Where, L = half of the current electrode separation; l = half of the potential electrode separation and ΔV = measured potential difference.

Field Procedure of Vertical Electrical Soundings (VES)

At the early stage of ground water exploration, geo electrical resistivity survey is very effectiveto understand the subsurface lithological variation, determine aquifer geometry, and possible thickness and extension of the aquifers and aquitards. With this objective 10 Vertical Electrical Resistivity Soundings (VES) of Schlumberger Configuration with maximum 600 m spread (AB/2 = 300 m) is planned to execute in the study area.

The resistivity measuring equipment "Resistivity Meter McOHM (Model-2115)" for the survey is kept at the center of the array. The layout is done along a straight line from the center. The half of the current electrode separation (AB/2) is selected as 1 m, 2 m, 4 m, 6 m, 8 m, 10 m, 12 m, 15 m, 20 m, 25 m, 30 m, 40 m, 60 m, 80 m, 100 m, 120 m, 150 m, 200 m, 250 m and 300 m on each side of the center.

The potential electrode spacing is selected depending on the measured potential difference. The potential electrode spacing was 0.5 m, 1 m, 2 m, 5 m, 10 m and 20 m on each side of the center. If large variations are observed in the subsequent values of apparent resistivity measurements were repeated to find the steadiness in the measurements. Locations of VES points are provided in Table 2 and Fig. 1.

Table 2: Locations of VES Points.

VES ID	Latitude	Longitude
VES_01	22.627401	91.59985
VES_02	22.670772	91.569969
VES_03	22.694125	91.550758
VES_04	22.715783	91.523005
VES_05	22.725838	91.509602
VES_07	22.765715	91.516459
VES_08	22.787334	91.457285
VES_09	22.816759	91.442064
VES_12	22.793902	91.38983
VES_13	22.81751	91.404679

INTERPRETATION

The software used for the interpretation is Interpex 1-D sounding Inversion (IX1D). At First apparent resistivity (ρ) of field data is plotted on an excel sheet along with current electrode separation (AB/2) and potential electrode separation (MN/2). IX1D software can read the excel files and create a smooth sounding curve for corresponding VES point. Manual curve matching results using two layer master and auxiliary curves (Orellana and Mooney, 1972) are fed into computer

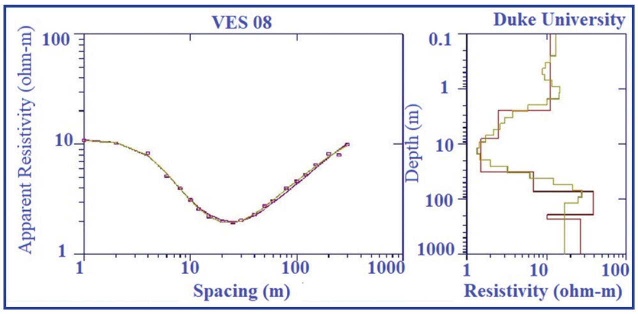

Fig. 3: Sounding Curve of VES-08 (left) and its interpreted geo-electric model (right).

as input model which is then manipulated by the software within the given range to produce a smooth curve of good match with the field sounding curve.

Comparison between borehole data and VES data

For the comparison between borehole log and vertical electrical sounding (VES), it is essential that the location of the borehole is on or very close to the VES location point.The software generated matched model parameters consisting of several layers with distinct average resistivity and thickness are compared with borehole data for matching and defining resistivity of individual borehole obtained lithology (Figs. 3 and 4).

After comparing between existing borehole TTW-08 lithology and adjacent VES-08 interpretation parameter the resistivity against different lithologic types have been defined (Table 3).

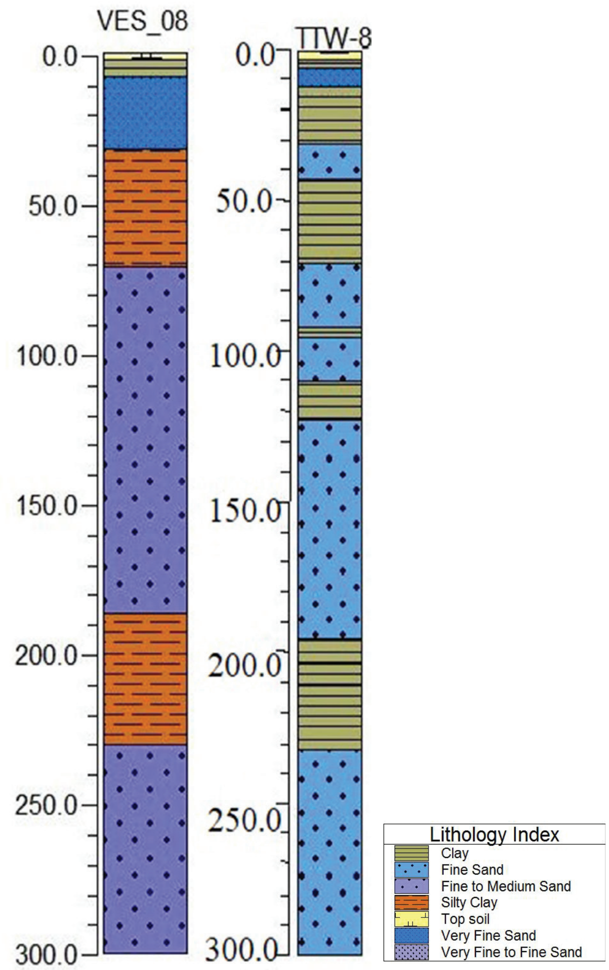

Fig. 4: Lithological comparison between existing borehole TTW-08 and adjacent VES-08.

Table 3: Comparison between Borehole TTW-08 and adjacent VES-08.

Layer No.	From Borehole		From VES model		
	Lithology	Depth range (m)	Depth range (m)	Apparent Resistivity (Ωm)	Lithology
1	Top soil	0-3	0-2.42	11.21	Top soil
2	Clay	3.0-6	2.42-7.94	2.48	Clay
	Very Fine Sand	6.0-12	7.94-31.74	1.51	Clay/Very Fine Sand (Saline)
	Clay	12.0-30	31.74-71.10	6.77	Clay
3	Very Fine Sand	30-43	71.10- 187.09	38.91	Fine Sand (Fresh)
	Clay	43-70			
	Fine Sand	70-91			
4	Clay	91-94	187.09 – 230.40	10.18	Silty Clay
	Fine Sand	94-110			
	Clay	110-122			
	Fine Sand	122-195			
5	Clay	195-231	230.40 -300	26.69	Medium to Fine Sand (Fresh)
	Fine Sand	231-300			

After comparing other VES 1D model data with closest borehole lithology an overall relation between lithology and resistivity is established and summarized in table 4. Very fine sand or fine sand containing saline water shows resistivity value of clay range and it becomes very difficult to identify the lithology based on resistivity value. Comparing borehole log data with resistivity values it is found that sand with saline to brackish water shows resistivity in the range of 0.9-11 ohm-m which is very similar to the resistivity range for silty to sandy clay with saline water (Table 4).

Interpreted Result of Vertical Electrical Sounding Data

VES interpretation results suggest non-uniformity in the distribution of resistivity in vertical as well as in lateral directions. From the interpretation of VES curves (Fig. 5) several geo-electric models of different thickness and resistivity are identified (Table 5).

Table 4: Resistivity range of different rock types established by correlating surface resistivity results to borehole log data

Resistivity (Ω m)	Corresponding Lithology
1.94-21.64	Top Soil
1.24-11	Clay/silt clay/sand with saline water
12-17	Very fine Sand with fresh water
18-23	Fine Sand with fresh water
24-73	Mediumto Fine Sand with fresh water

Table 5: Interpreted results of vertical electrical soundings

Layer Nos.	Resistivity (Ω m)	Thickness (m)	Depth to base (m)	Lithology Type
VES 01				
01	2.52	3.60	3.60	Top soil
02	1.67	5.80	9.39	Clay/Very Fine Sand (Saline)
03	2.64	136.56	145.95	Clay
04	17.39	Undefined		Very Fine Sand (Fresh)
VES 02				
01	3.78	0.54	0.54	Top soil
02	1.91	6.74	7.28	Very Fine Sand (Saline)
03	5.48	5.83	13.12	Clay
04	1.39	16.21	29.33	Clay/Very Fine Sand (Saline)
05	3.46	136.03	165.35	Clay
06	17.53	Undefined		Very Fine Sand (Fresh)
VES 03				
01	19.13	1.77	1.77	Top Soil
02	10.25	5.02	6.79	SiltyClay (dry)
03	2.14	13.05	19.84	clay
04	14.20	41.84	61.68	Very fine Sand(Fresh)
05	4.16	60.31	121.99	Clay/Very Fine Sand (Saline)
06	1.49	Undefined		Clay
VES 04				
01	21.64	0.60	0.60	Top soil
02	15.66	5.70	6.30	Silty Clay
03	5.63	6.12	12.42	Clay
04	22.14	28.32	40.74	Very Fine Sand (Fresh)
05	6.75	105.89	146.63	Clay
06	17.84	43.23	189.86	Very Fine Sand (Fresh)
07	2.17	Undefined		Clay

Table 5 continued

Layer Nos.	Resistivity (Ω m)	Thickness (m)	Depth to base (m)	Lithology Type
		VES 05		
01	4.87	4.17	4.17	Top soil
02	3.81	3.81	7.98	Clay
03	12.01	16.16	24.14	Silty Clay
04	17.35	76.30	100.44	Very Fine Sand (Fresh)
05	73.12	Undefined		Medium to Fine Sand (Fresh)
		VES 07		
01	10.98	1.91	1.91	Top soil
02	8.03	12.52	14.44	Clay
03	1.41	23.27	37.71	Clay/Fine sand (Saline)
04	3.93	42.83	80.53	Clay
05	16.67	65.83	146.36	Very Fine Sand (Fresh)
06	23.46	Undefined		Very Fine to Fine sand (Fresh)
		VES 08		
01	11.206	2.4196	2.4196	Top soil
02	2.4795	5.5190	7.9385	Clay
03	1.5087	23.8	31.739	Clay/Very Fine Sand (Saline)
04	6.7677	39.365	71.103	Clay
05	38.909	115.99	187.09	Medium to Fine Sand (Fresh)
06	10.183	43.306	230.4	Silty Clay
07	26.691	Undefined		Fine to Medium Sand (Fresh)
		VES 09		
01	3.46	2.23	2.23	Top soil
02	6.21	10.08	12.31	SiltyClay
03	1.50	13.18	25.49	Very Fine sand (Saline)/ Silty Clay
04	16.22	39.73	65.22	Very Fine Sand (Fresh)
05	35.53	Undefined		Medium to Fine sand (Fresh)
		VES 12		
01	4.41	0.59	0.59	Top soil
02	15.59	1.29	1.88	Silty clay
03	2.67	3.39	5.27	Clay
04	21.45	32.06	37.33	Fine sand (Fresh)
05	3.36	6.94	44.27	Clay
06	1.31	23.38	67.65	Clay/Fine sand (Saline)
07	10.42	22.57	90.22	Silty Clay
08	34.01	Undefined		Medium to Fine sand (Fresh)
		VES 13		
01	1.95	3.82	3.82	Top soil
02	15.71	6.53	10.36	Very Fine Sand (Fresh)
03	3.43	29.92	40.28	Clay
04	4.85	14.51	54.79	Clay
05	16.69	23.09	77.88	Very Fine Sand (Fresh)
06	72.04	Undefined		Medium to Fine Sand (Fresh)

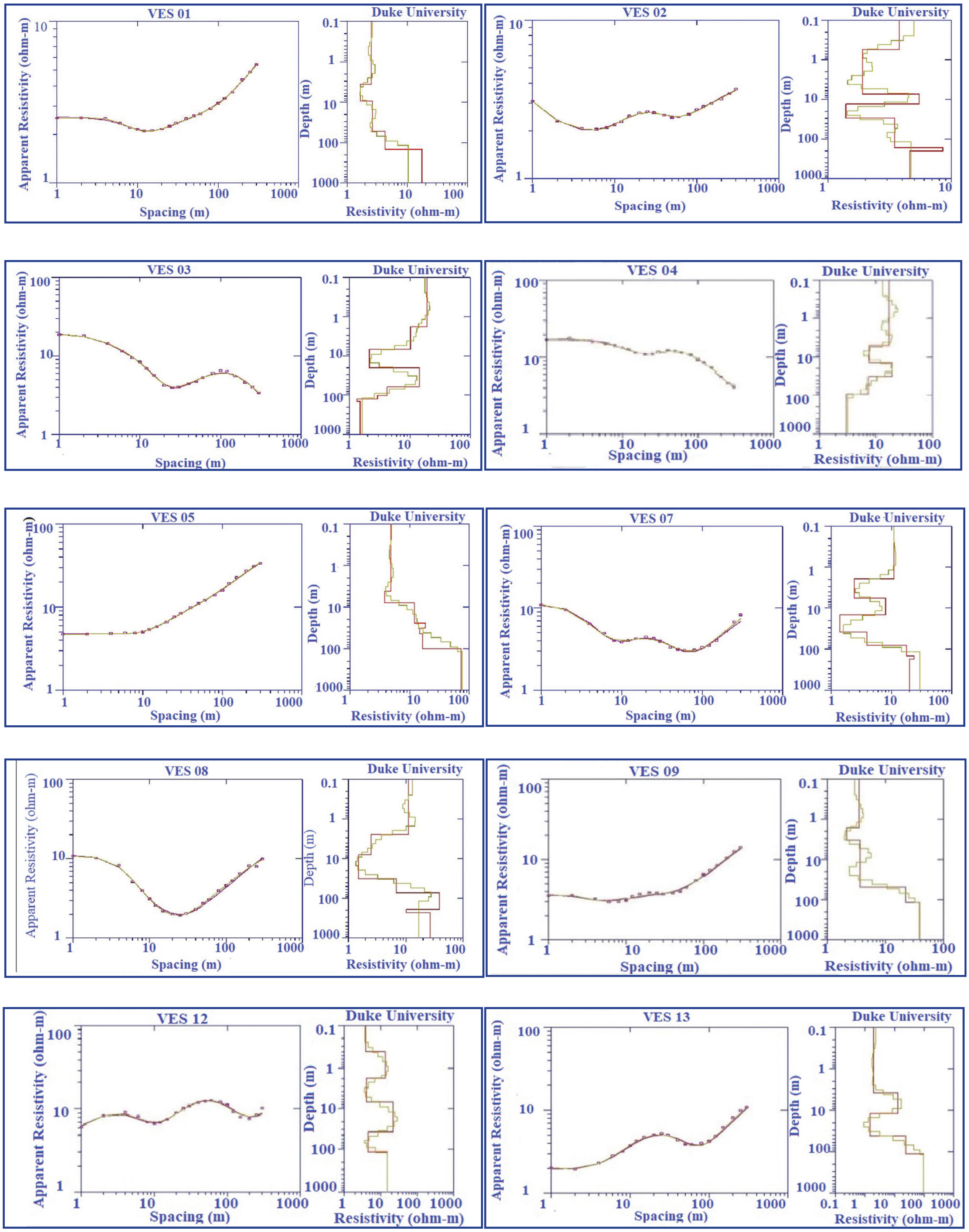

Fig. 5: Sounding Curves of VES-01, VES- 02, VES- 03, VES- 04, VES- 05, VES- 07, VES- 08, VES- 09, VES- 12 and VES-13 (left) and their interpreted geo-electric models (right).

Lithology of individual layers has been approximated from existing borehole data. Alternating sand and clay layers exist below the top soil across the study area. The top soil of the area is characterized by resistivity variation from 1.94-21.64 Ω m and the thickness varies from 0.5 m to 4.2 m. The large range of resistivity variation is related to nature and wetness of the top soil. Dry and hard compacted silty soil shows higher resistivity while clayey moist soil shows lower resistivity.

A continuous clay or silty clay layer, identified as aquitard, is present below the top soil and the resistivity value ranges from 1.24 Ω m to 11 Ω m. This aquitard is underlain by a sand layer acting as shallow aquifer showing resistivity varying from 1.4 Ω m -21.45 Ω m reflecting the pore space water as of variable quality. The depth of the shallow aquifer ranges from 6m to 24 m. In general, the shallow aquifer is saline to brackish except some isolated fresh water pockets where resistivity is within 14 Ω m to 22 Ω m. Brackish to saline water saturated sand shows low resistivity in the range of clay and it is difficult to differentiate them without the help of borehole log or water quality data.

The shallow aquiferis followed by a laterally extended second aquitard of variable thickness. Second aquitard of varying thickness is underlain by the deep fresh water aquifer. The deep fresh water aquifer occurs at a depth of about 145 m in the southeast while it is about 75 m in the northwest of the study area. In the central part of the area deep aquifer is intercepted by clay/silty clay layers at multiple levels of depth and along VES-03, TTW 3, VES-04, TTW-8 and TTW 10 thick isolated clay/silty clay layers are identified at the bottom part of the deep aquifer. The deep aquifer shows resistivity in the range of 16 Ω m to 73 Ω m indicating the pore space water as fresh. Wide range of resistivity may be related to sand sizes, the compactness of the sand grains, degree of mineralization of pore space water, etc.

Interpretation of geohydrologic cross-sections of the study area

Borehole log data contributes the most important information about the aquifer system of an area but boreholes are not distributed all around the study area. VES data may fill the gaps between boreholes and based on available borehole log and VES data, geohydrologic cross-sections have been constructed to delineate the aquifer system for better understanding about hydrogeological condition of the area. Three profiles in different directions for construction of geohydrologic cross sections along lines A – A’, B – B’ and C – C’ and the fence diagram are shown in Fig. 6.

Aquifer framework of the study area has been delineated based on the interpreted VES parameters and borehole log data of the five monitoring wells. At each location of borehole and VES, lithological data have been grouped into layers of aquifers and aquitards based on lithological characteristics and similarities.

Geohydrologic cross section along line A-A` in southeast to northwest direction shows the presence of two aquifers (Fig. 7). Top soil of silty clay composition of minor thickness overlies the clay/ silty clay layer of variable thickness and acts as the top aquitard. The thickness of the aquitard decreases from southeast to northwest. In the southernmost area thickness is around 145 m whereas in the northwest it is about 10 m thick.

A shallow aquifer (absent in the southeastern most part), seen in the cross section just beneath the top aquitard (Fig. 7), contains mostly saline to brackish water with some isolated fresh water pockets and is underlain by a laterally continuous second aquitard. The thickness of the second aquitard decreases from southeast (145 m) to northwest (30 m).

Second aquitard of varying thickness is underlain by the deep fresh water aquifer. The deep fresh water aquifer occurs at a depth of about 145 m in the southeast while it is about 75 m in the northwest. But in the middle part of the section along VES-03, TTW 3, VES-04 and TTW-8 the deep aquifer is cut at the bottom by thick isolated clay/silty clay layers.

Geohydrologic cross section along profile B-B` (Fig. 8) passing through VES_07, VES_08 and VES_09 of the study area shows the presence of a shallow aquifer of about 10m thickness covered by the top aquitard at the two ends of the profile. Below the shallow aquifer a laterally persistentsecond aquitard occurs with maximum thickness of about 150 m at the southeast and at the center and at the northwest thickness reduces to around 40 m.

A very thick deep aquifer is found to exist below the second aquitard throughout the section with an isolated silty clay layer at the middle part of the cross section at VES 8 at a depth of about 190m with a thickness of around 45m. The shallow aquifer within the depth of 10m to 25 m is saline to brackish with some isolated fresh water while the deepaquifer is fresh.

Geohydrologic cross section along C-C` (Fig. 9) from southwest to northeast of the study area shows the presence of a shallow saline to brackish water aquifer indicated by low resistivity is covered by the top aquitard of around 5m thickness at the northeastern part. This shallow aquifer is thicker in the central to southwestern part (55m-60m) and in the northeastern part thickness reduces to 30m.

Shallow aquifer is interrupted by a thin (~5 m) isolated clay layer at a depth of around 35 m at the southwestern end of the profile. A second aquitard overlain by the shallow aquiferof about 35m thickness at depth of around 60m at southwest and around 40m at the northeast is laterally extending along the section. Below the second aquitard a very thick deep aquifer

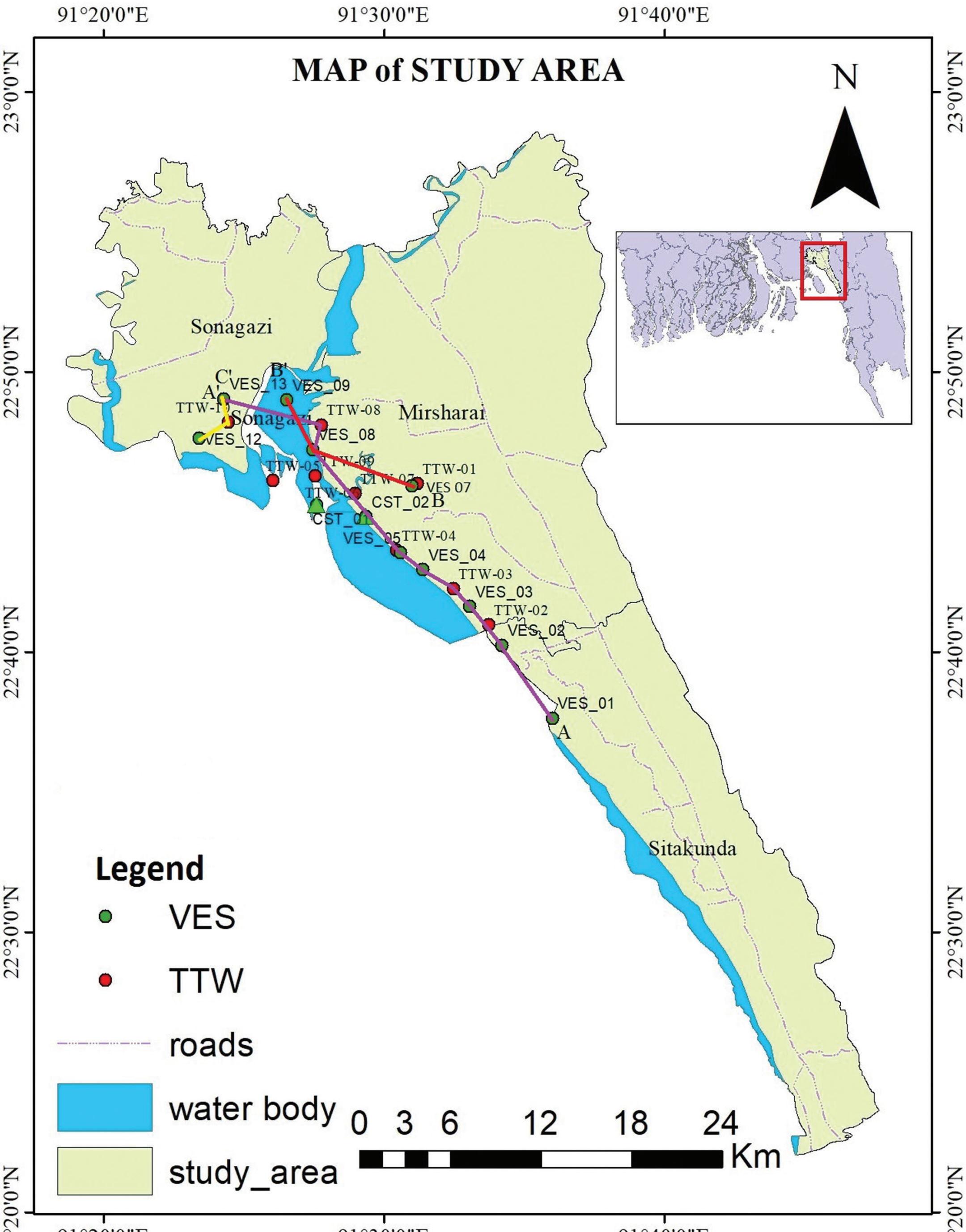

Fig. 6: Selected profiles for geohydrological cross sections.

is present throughout the section with an isolated silty clay layer at the middle part of the section at a depth of around 230 m along borehole TTW 10 (Fig. 9).

A fence diagram in southeast-northwest and southwest-northeast views is drawn to observe the aerial variation of the aquifer system vertically and laterally within the area (Fig. 10).

From the fence diagram (Fig. 10) it is evident that the shallow and deep aquifers are separated by a laterally continuous aquitard of variable thickness and in the southeastern part of the area the shallow aquifer is absent and the aquitard is getting much thick at VES 1. The shallow aquifer exists throughout the area except in southeast corner with variable thickness. Deep aquifer is thick but interrupted at multiple levels of depth by isolated clay/silty clay layers seen in southeast-northwest view extending from VES 2 to VES 12 and it also is found at VES 8 in southwest-northeast view. Isolated thick clay/silty clay layers are identified at the bottom of the deep aquifer at VES 3, TTW 3 and VES 4 and at TTW7. At VES 8 in southwest-northeast view a clay/silty clay lens is demarcated within the deep aquifer.

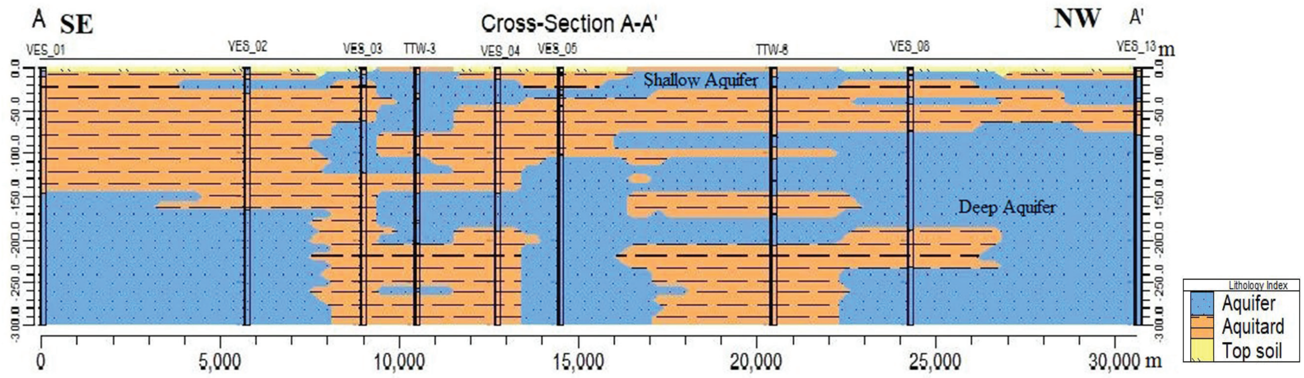

Fig. 7: Geohydrologic cross-section along line A-A` of the study area.

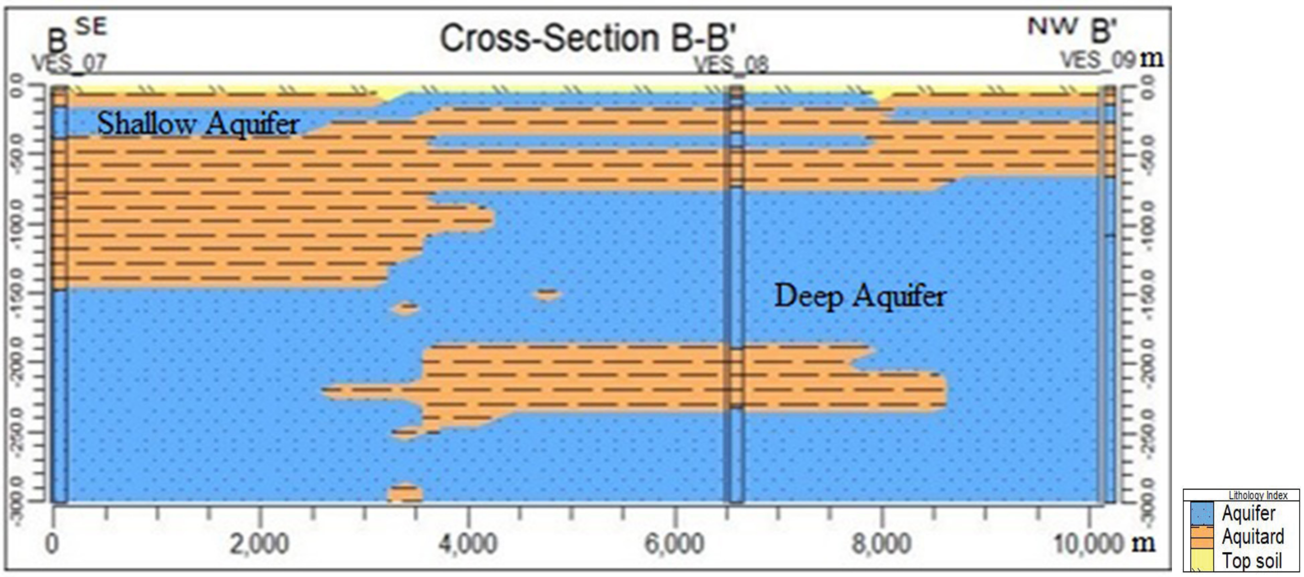

Fig. 8: Geohydrologic cross-section along line B-B` of the study area.

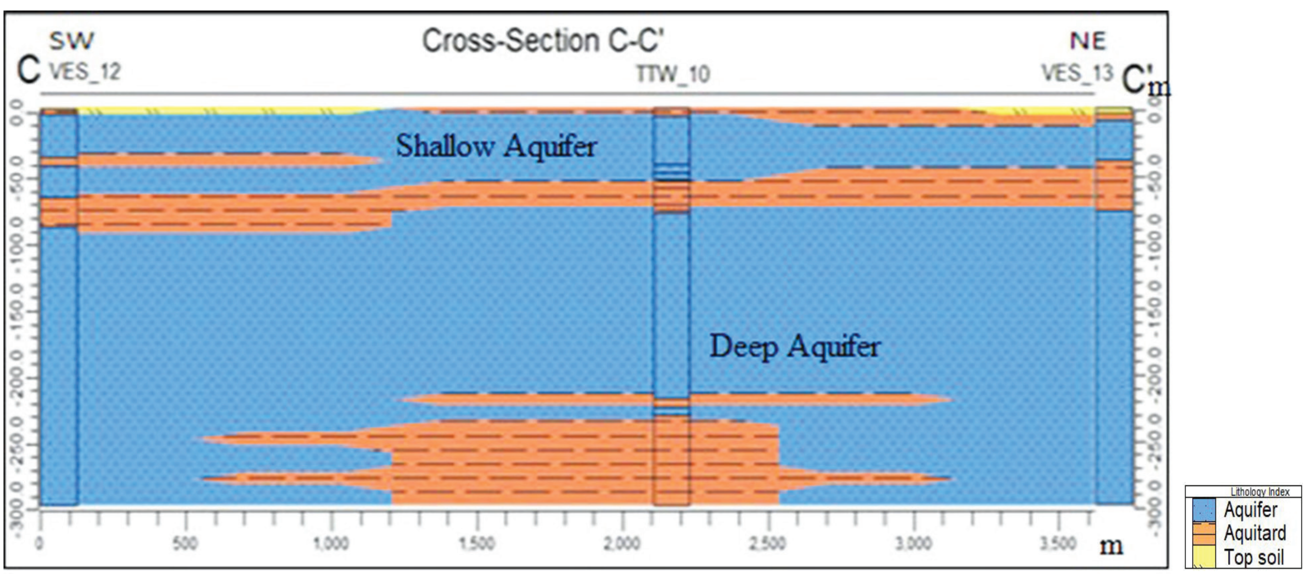

Fig. 9: Geohydrologic cross-section along line C-C` of the study area.

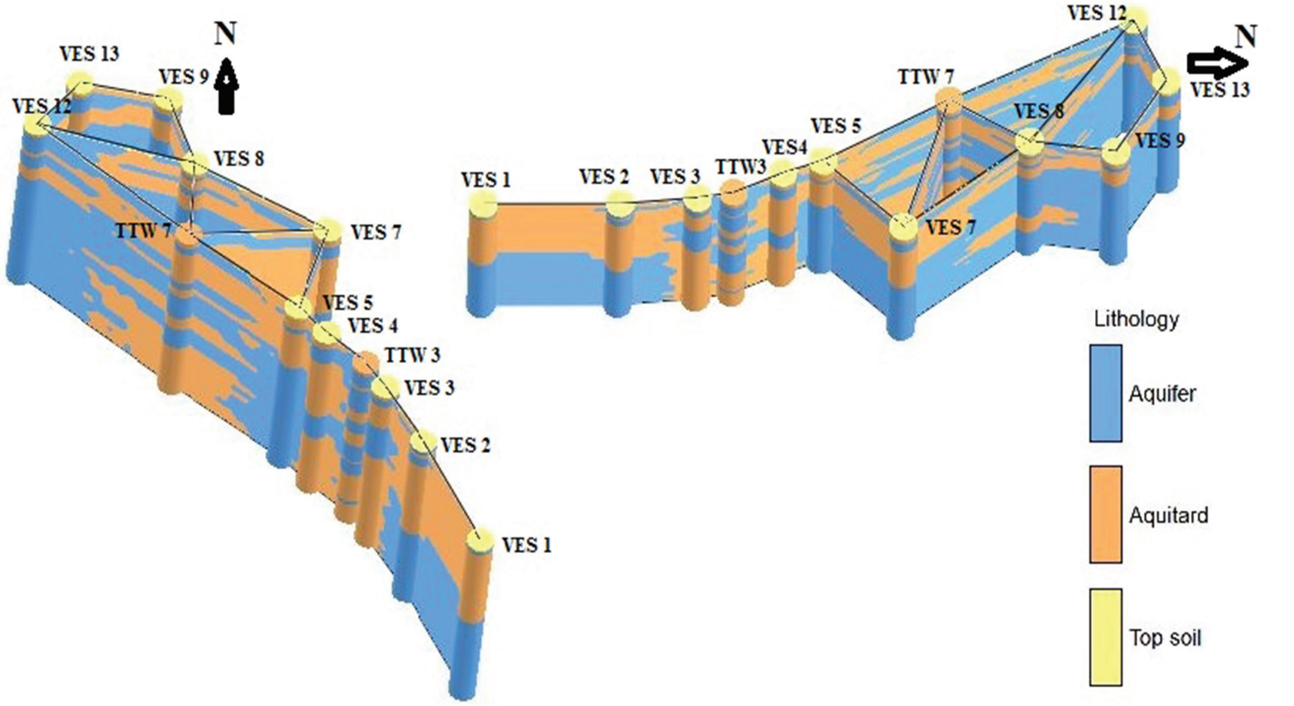

Fig. 10: Fence diagram showing the distribution of aquifers in southeast-northwest and southwest-northeast views of the area.

CONCLUSIONS

Vertical electrical resistivity sounding survey and existing borehole log data of the study area are analyzed for the assessment of subsurface geological and hydrogeological conditions and water quality of the coastal area of Mirsharai economic zone of Mirsharai Upazilla. Model parameters obtained through interpretation of the field sounding curves and the existing borehole log data characterize the subsurface geology and hydrogeology of the area and based on the findings the following conclusions are made:

The top geo-electric unit composing of clay or silty clay of resistivity ranging from 1.24 Ω m to about 11 Ω m resistivity range acts as an aquitard.

The next geoelectric unit within 6 m to 24m of depth shows resistivity in the range of 1.9 Ω m to 12 Ω m (with scattered higher values) indicating the layer as clay or silty clay. Litholog suggests the unit as very fine to fine sand and acts as the shallow aquifer but the low resistivity value indicates the water quality of the aquifer as saline to brackish(with isolated fresh water pockets showing higher resistivity). In this case direct information about the texture or the water quality of the formation is required and borehole log or water quality data help to overcome the ambiguity.

This shallow aquifer is underlain by a laterally continuous aquitard of variable thickness and depth and it separates the shallow saline/brackish water aquifer from the deep fresh water aquifer. The deep aquifer occurs at a depth ranging from 65 m to 230 m below the surface and shows high resistivity in the range of 16 Ω m to 73 Ω m confirming the water quality as fresh. This study provides information about the depth to the fresh water aquifer as well as probable suitable regions for future groundwater development.

AUTHOR'S CONTRIBUTIONS

The research was planned and designed by A.S.M. Woobaidullah. Field Electrical Resistivity Sounding Survey was carried by Md. A. Islam, Md. Z. Hossain, Md. S. Islam under the direct supervision of A.S.M. Woobaidullah. Data processing and maps and geohydrologic cross sections were performed by Md. A. Islam, Md. Z. Hossain, Md.S. Islam. Figures were finally drafted by Md. Z. Hossain. Manuscript was drafted by Md. A. Islam and was modified and corrected by A.S.M. Woobaidullah and finally all authors read, discussed and approved the manuscript.

REFERENCES

Acworth, R.I., 2001, *Electrical methods in groundwater studies*. UNSW Groundwater Center, 132p.

Bangladesh Economic Zones Authority (BEZA), 2014, *Feasibility Study for Mirshorai Economic zone. Bangladesh Economic Zones Authority*, Unpublished Report.

Bugg, S.F., Lloyd, J.W., 1976, A study of freshwater lens configuration in the Cayman Islands using resistivity methods. Quarterly Journal of Engineering Geology and Hydrogeology, v. 9(4), pp. 291-302.

Burger, H.R., 1992, *Exploration geophysics of the shallow subsurface*: Prentice-Hall, Inc.

David L. M., Ofrey D., 1983, An Indirect Method of Estimating, Groundwater Level in Basement Complex Regolith Resources,v. 1(2), pp. 161–164.

Elwaheidi, Mahmoud, Merlanti, F., Mauro Pavan, 1992, Geoelectrical Resistivity Survey of the Central Part of Azraq Basin (Jordan) for identifying Saltwater/ Freshwater Interface, Journal of Applied Geophysics 29 (August), pp. 125–133.

Farah Didul Nabi, Md. Imam Sohel Hossain, and A.S.M. woobaidullah, 2018, Groundwater investigation in Bangladesh economic zone, Chittagong by applying geophysical resistivity survey, DU Jour. Earth & Env. Sc., v. 6 & 7, pp. 19-24.

Gautam, G., Saumen, M., and Vinit, C., 2014, Analysis of Electrical Resistivity Data in Resolving the Saline and Fresh Water Aquifers in West Coast Maharashtra, Journ. Geol. Society of India, v. 84, pp.555-568.

Griffiths D.H., and Ring R.F.,1981, Theory of Electrical resistivity Surveying Practical and Applications in Resistivity Surveying APP GRY for Geologists and engineering Pergamon Press, 2nd Edition, pp. 70 – 111.

Hasan, M.A., Woobaidullah, A.S.M., Ahmed, K.M., and Rahman, M.M., 1997, Geochemistry and origin of saline ground water in Manda Thana, Naogaon District, NW Bangladesh, Indian Jour. of Earth Sciences, v. 24, Nos. 3-4, pp. 26-32.

Imam, H. M., Hossain D., and Woobaidullah, A.S.M., 2013, Geo-electrical Resistivity survey for the evaluation of hydrogeological condition of Bagerhat sadar and adjacent areas, Bangladesh, Journ. Geol. Society of India, v. 82, pp. 290-294.

Islam, M. M., 2019, Assessing sustainability of aquifers for providing potable water in the proposed economic zone in Mirsharai Upazila, Chattogram, Bangladesh.

Karim, M. A., 1990, *Engineering geology of Chittagong City, Bangladesh.* Geological Survey of Bangladesh (GSB) Report, Unpublished.

Kearey, P., Brooks, M., and Hill, Y., 1991, *An introduction to geophysical exploration.* Blackwell Scientific Publications, London, 272p.

Kearey, P. and Brooks, M., 1984, *An introduction to geophysical exploration.* Blackwell Scientific Publications, London, 296 p.

Keller, G. V. and Frischknecht, F. C., 1966, *Electrical methods in Geophysical Prospecting,* Pergamon, London.

Khan, F. H., 1991, *Geology of Bangladesh*, The University press limited, Dhaka-1000, Bangladesh, 207p.

Kouzana, L., Abdallah, B. M., and Mennoubi, F., 2009, Seawater Intrusion and Associated Processes: Case of the Korba Aquifer (Cap-Bon, Tunisia), Comptes Rendus Geoscience - C R GEOSCI 341 (January), pp. 21–35.

Orellana, E. and Mooney H. M., 1972, *Two and Three layer master curve and auxillary point diagrams for VES*, Interciencia. Madrid, Spain, 43p.

Oteri, A. Ulaya-Egbe, 1983,Delineation of Saline Intrusion in the Dungeness Shingle Aquifer Using Surface Geophysics, Quarterly Jour. of Engineering Geology and Hydrogeology, v. 16 (1), pp. 43–51.

Rahman, M. M. and Bhattacharya, A. K, 2014, Saline Water Intrusion in Coastal Aquifers: A Case Study from Bangladesh. IOSR Jour. of Engineering (IOSRJEN), pp. 07-13.

Rahman M.M., Woobaidullah, A.S.M., Ahmed, K. M., Hasan, M. Hossain, M., Bhattacharya, P., Siddique, A., Bromssen, M., and Jacks, G., 2013, Evaluation of hydrogeological conditions through vertical electrical soundings survey in regions with high arsenic groundwater at Matlab, Southeastern Bangladesh, Dhaka Univ. Journ. Earth & Env. Sciences, v. 2(2), pp. 1-8.

Rahman, M. M. Woobaidullah, A.S.M., Ahmed, K. M., Hasan, M. Hossain, M., Bhattacharya, P., Siddique, A., Bromssen, M., Jacks, G., 2013, Assessment of hydrogeological conditions for safe drinking water to underprivileged community in regions with high arsenic groundwater at Matlab, Bangladesh, The Int. Jour. of Social Sciences, v. 13(1), pp 67-75.

Schwartz F. W., and MCclymont, G. L., 1977. Application of Surface Resistivity Method Science, v. 2(1), pp. 31-34.

Serres, Y.F., 1969, Resistivity prospecting in a United Nation Groundwater study of Western Argentina. Geophysical prospecting, v. 17, pp. 449-467.

Telford, W.M., Geldart, L.P., Sheriff, R.E., 1990, Applied geophysics. Cambridge University Press, 2nd ed., pp. 552-566.

Woobaidullah, A.S.M., Shahnewaz, S.M., Munirul Islam, M., Kamrul Islam, M., and Zakir Hossain, M., 2019, Electrical resistivity survey in the investigation of hydrogeological condition of Sylhet-Sunamganj Haor area, Bangladesh, Jour. of Nepal Geol. Soc., 2019, v. 58 (Sp. Issue), pp. 21–28.

Woobaidullah, A.S.M., Rahman, M. M., and Zohir Uddin, M., 2014, Evaluation of hydrogeological condition through vertical electrical soundings survey at Manikganj Pourashava, Manikganj, Central part of Bangladesh, Bangladesh J.Sci. Res. 27(2), pp. 109 – 120.

Woobaidullah, A. S. M., and ZohirUddin, M., 2011, Geoelectric resistivity sounding for deciphering hydrogeology and locating deep tubewell installation sites in Pouroshava area of Bagerhat, Bangladesh, Jour. Nepal Geol. Soc., Vol. 42, pp. 99-108.

Woobaidullah, A. S. M., Chowdhury, S.H., Ahmed, K. M., Rahman, M.W., Arafin, S.K., Al-Ejaz, O., 2008, Geo-electric Resistivity Survey in the Evaluation of Hydrogeological Condition in Haziganj Upazila, Chandpur District, Bangladesh, Jour. Geol. Soc. India, v. 72(6), pp. 753-763.

Woobaidullah, A. S. M., Ahmed, K. M., Karmaker, U., Biswas, D., and Arafin, S.K., 2006, Geoelectric Survey in the Evaluation of Hydrogeological condition in the Coastal Area of Kalapara Upazila, Patuakhali District, Bangladesh. Dhaka Univ. Jour. Sci., v. 54 (1), pp. 115-119.

Woobaidullah, A.S.M., Rahman, M., Tofazzal H., and Khaleque, M.A., 1999, Results of geoelectric survey in deciphering the aquifer in and around Dhaka city, Dhaka Univ. J. Science, v. 47(1),pp. 93-101.

Woobaidullah, A.S.M., Ahmed, K.M., and Hasan, M.A., 1998, Saline ground water movement in Manda Thana of Noagaon District, NW Bangladesh, Jour. Geol. Soc. India, v. 51(1), pp. 49-56.

Woobaidullah, A.S.M., Rahman, M., and Arndt, R., 1996, Electrical survey for groundwater exploration in the coastal belt of Satkhira, north-west Bangladesh, Jour. Geologiche Bundes Anstalt, Austria, pp. 127-137.

Woobaidullah, A.S.M., Hasan, M.A., Reza, H., and Noor, A., 1994, An analysis of resistivity sounding data for groundwater exploration in Dumdumia-Nayapara, Teknaf, Dhaka Univ. Jour. of Science, v. 42 (2), pp. 229-234.

Zahid, A., Rahman, A., Hassan, M. R., and Ali, M. H., 2016, Determining sources of groundwater salinity in the multi-layered aquifer system of the Bengal Delta, Bangladesh. BRAC University Journal, XI (2), pp. 37–51.