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Coastal Groundwater Aquifer Characterization from Geoelectrical Measurements—A Case Study at Kalapara, Patuakhali, Bangladesh

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ABSTRACT. Vertical electrical sounding has been carried out in the coastal area in the southern part of Bangladesh to locate the groundwater aquifers containing fresh water. Field apparent resistivity data of vertical electrical sounding is processed using the Interpex1X1Dv3 computer program. Geoelectric layers identified in the context of resistivity and thickness from the vertical electrical sounding data. From the initial parameters layered model was achieved using the inversion technique. Correlation of the obtained layer model with a nearby lithologic log concludes the groundwater aquifer system of the area. From the electrical properties of the subsurface layers, water-bearing layers were detected and characterized. Very fine sand geoelectric layer with a thickness varying from 20 to 143 meters is an upper aquifer and has 0.66–14.02 Ωm apparent resistivity value. Fine sand geoelectric layer with 0.21-5.99 Ωm apparent resistivity value is lower aquifer with maximum thickness ~250 meters. The resistivity value of the upper aquifer reveals that it contains saline to brackish-fresh water, while the resistivity value of the lower aquifer indicates that it contains saline water. The water quality of the upper zone varies geographically from the southern to the northern part in the investigated area. The water quality of the upper aquifer is fresh in the northern part of the study, while the lower aquifer contains saline water there.

Keywords: Aquifer · Coastal land · Geoelectrical sounding · Groundwater · Vertical electrical sounding (VES).

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1 INTRODUCTION

People living in the coastal areas of Bangladesh are mostly poor. They get water either from a pond or from tubewells. The availability of fresh potable water and irrigation water is an acute problem in the coastal area of Bangladesh (Islam *et al.*, 2013). Surface water in the coastal area is almost saline, all the year round; groundwater would be an alternative source for irrigation and drinking as well. Groundwater in the coastal area also facing salinity problems (Sakamoto, 2017). This salinity problem is being accelerated with time by human-made events like tourism, urbanization, infrastructure development. Water salinity has taken into account as a major constraint for farming lands in the coastal areas of this country (Huq *et al.*, 1999; Basar, 2012). It will hamper the development of the socio-economic conditions of the country, and it is essential to find the potential source of water for households, industries, and irrigation.

Moreover, salinity increased by about 26 % within a few decades in the coastal region of Bangladesh (Mahmuduzzaman *et al.*, 2014). Water demand is meet up without planning and regulated method. Consequently, seawater has intruded in coastal areas of Bangladesh,

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which is common, and natural phenomena degrading the groundwater quality from fresh to saline (Mahtab and Zahid, 2018; DMB, 2010). This intrusion of seawater into the alluvial aquifer potentially polluting groundwater in coastal zones to use it for household, cultivation, and industrial purpose (MoA, 1999; Abd-Elhamid and Javadi, 2011; Sherene and Ravikumar, 2018). More than 30 % of the cultivable land of Bangladesh is in the coastal belt, where cultivation depends on irrigation (Huq and Rabbani, 2011; Alam *et al.*, 2017). The geophysical investigation, particularly the electrical resistivity method, is distinctive in the groundwater exploration program in assessing the groundwater quality. Electrical conductivity/resistivity is the unique property of groundwater quality attributing the salinity of groundwater (Ebraheem *et al.*, 1997; Stamatis and Voudouris, 2003). Many parameters control the resistivity of subsurface materials. Among them, the conductivity of the pore fluid plays a vital role in defining the hydrogeological condition of an area together with other geological and mineralogical parameters. Many researchers (Lee *et al.*, 2002; Bataynch, 2006; Wilson *et al.*, 2006; Morrow *et al.*, 2010; Mario *et al.*, 2011) worked with the salinity determination of the groundwater applying the geo-electrical methods in order to find out the freshwater aquifers. The geo-electrical method utilizes the resistivity difference of the constituent materials of the subsurface water layers of the investigation area to determine the electrical properties of the layers (USEPA, 2016).

Moreover, resistivity methods, together with the borehole drilling, posses the best possible elucidation of groundwater aquifer and its quality (Zohdy *et al.*, 1974). In this study, an attempt has been made to delineate the fresh/ saline water zone in the study area using the electrical resistivity method and to evaluate the seawater intrusion effect over the groundwater. This study has been carried out in Kalapara, Patuakhali of Bangladesh.

2 MATERIALS AND METHODS

2.1 Study area and methodology

The study area of Kalapara Upazila within the Patuakhali district is a coastal plain strip of Bay of Bengal, which lies in the southern part of Bangladesh (Figure 1). Kalapara is one of the important Upazila in the southern part of Bangladesh having, 491.89 sq.km areas. One of the most attractive sea beaches, Kuakata, is located in Kalapara, and it has visited by many tourists every day. About 237,831 people use groundwater for domestic and irrigation purposes (BBS, 2011). Agriculture and fishing are the main professions of most people. Land erosion and accretion is an acute problem in the area due to strong tidal currents. Moreover, other natural phenomena like cyclones, storm surges, tidal floods, and saline water intrusion affect the area.

The major rivers are the Andharmanik, Nilganj, and Dhankhali. Electrical resistivity is a very useful tool when studying coastal aquifers due to the large difference in resistivity between freshwater and saltwater, with the former having a higher resistivity and the latter having a lower resistivity. The basic setup for a resistivity survey involves using a resistivity meter and four electrodes. Vertical Electrical Sounding (VES) is one of the more commonly used and cost-effective resistivity survey methods. In the VES method, four electrodes are grounded where two electrodes are current electrodes for current injection, and the other two are potential electrodes. Current is moved through the subsurface from one current electrode to the other, and the potential as the current moves has recorded. From this information, resistivity values of various layers had acquired, and layer thickness can be identified. Plotted the apparent resistivity values as a log function versus the log of the spacing between the electrodes, these plotted curves identify the thickness of layers. In this study, 10 VES has performed at different locations of the study area using the SARIS (Canada) resistivity meter to cover the study area. Schlumberger's four-electrode configuration method is applied where maximum current electrode separation (AB/2) and potential electrode separation (MN/2) were 350 and 20 meters, respectively. The layered resistivity model in 1X1Dv3; Version 3.50 (Interpex 2011) software applied in the interpretation of the subsurface layers based on the investigation result. Individual layer thickness and its resistivity value obtained from the model. Available

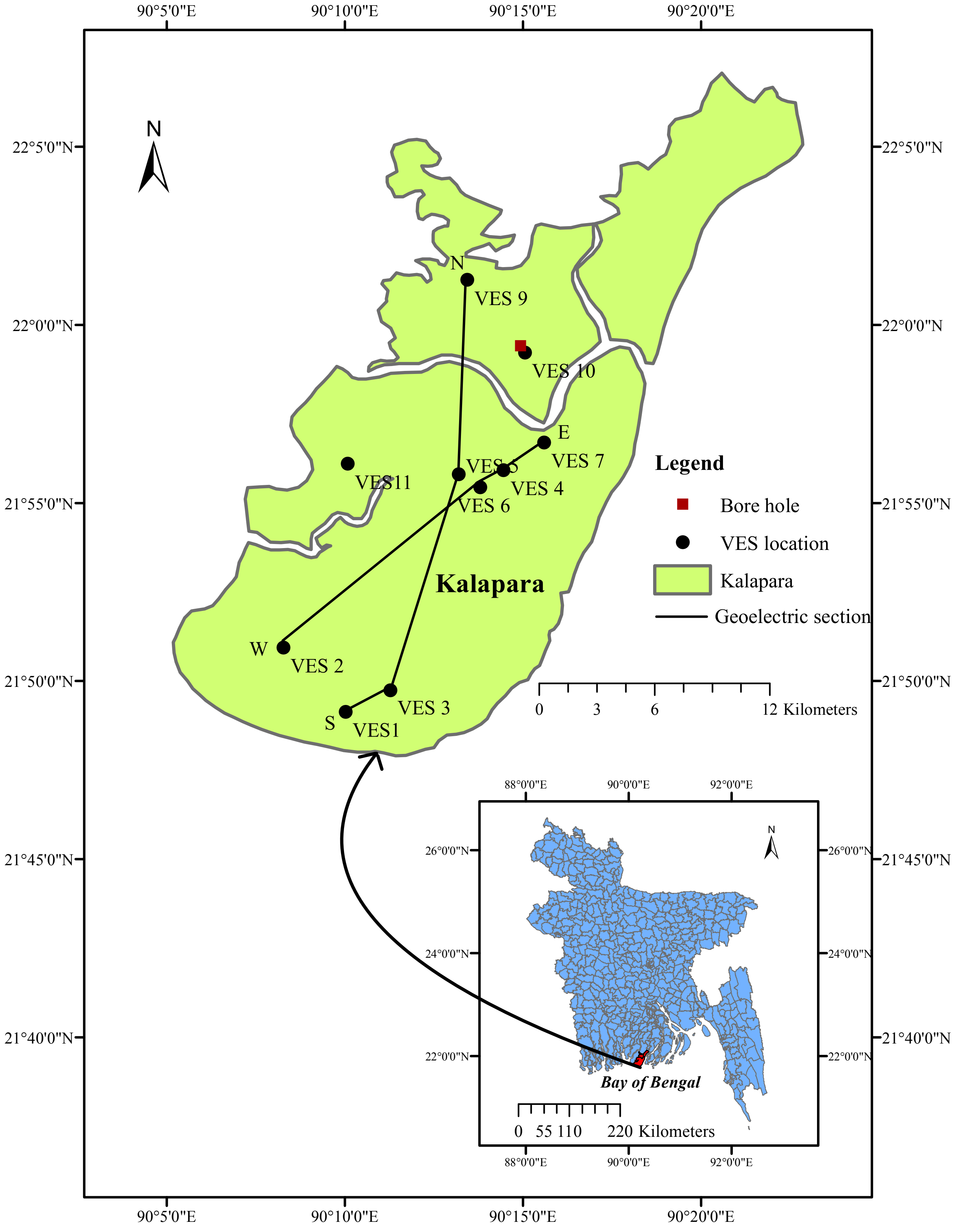

FIGURE 1. Geographic location of the vertical electrical sounding at the KalaparaUpazila in Bangladesh.

well log data of drilled hole close to the VES location has used in correlation and calibration of the VES model. The available lithological log of the drilled well is also utilized to limit the extent of major layers and aquifers.

2.2 Geology of the study area

Bangladesh constitutes the major parts of the Bengal Basin, which is bounded in the west by the Indian Shield of Precambrian rocks, in the east by the Arakan Yoma Mega anticlinorium, in the north by the Shillong massif. To the south it is open to the Bay of Bengal (Roy and Chatterjee, 2015) The study area falls in the Barisal Gravity High tectonic element (Alam *et al.*, 2003) which is a part of the Bengal Basin and lies on the Late Holocene-Recent alluvium of the Ganges deltaic plain in the north and Ganges estuarine plain in the south. The geology of the coastal area is part of the overall Quaternary geology of the Bengal Basin. Geomorphological the study area is in the tidally active deltaic floodplain with deltaic surface lithology (Isalm, 2016; Dola *et al.*, 2108). The shallow aquifers of the Bengal delta have a shallow groundwater table which has a close relation with the precipitation amount (Shamsudduha *et al.*, 2009). Over pumping and abstraction of groundwater have a negative impact on aquifers even though they are fully recharged (BGS and DPHE 2001). Shallow groundwater quality is usually brackish, but some freshwater bodies found as isolated pockets. Lithology and stratigraphy of this formation to a certain depth obtained from the drilling for tubewells reveal that fine sand, silt, clays, and silty clays are constituents of the formation (DPHE, 2006). The lower deltaic plain of the Ganges delta covered with Holocene deltaic deposits composed of clay, silt, sand, and their admixtures (Islam, 2014). The deposits have been identifying based on geomorphic expression and associated lithological characteristics. The deposits have characterized by a fining upward sequence and have been summarized in Table 1.

A study on hydrogeochemical characteristics of groundwater in the study area reveals that the groundwater is slightly alkaline and brackish in nature (Islam *et al.*, 2016). Islam *et al.* (2016) also reported that the trends of dominant cations and anions are $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > Br^-$ respectively and $Na–Cl–HCO_3$ is the dominant groundwater type.

3 RESULTS AND DISCUSSION

3.1 Geoelectric and lithologic characteristics

Apparent resistivity data obtained from the survey were analyzed using the IX1DV3 computer program of Interpex (2011). Sounding curves obtained from a plot of apparent resistivities versus spacing (AB/2) for Schlumberger sounding array on log scale were processed and modeled using the program. The best-fitted curves were obtained using forward modeling and the automated inversion processes. The VES curves represent models of the subsurface layers from which individual bed thickness and apparent resistivity value are obtained. Each model gives information on constituent material of subsurface layers and pore water quality. This interpretation does not require manual construction of VES curves for layer resistivity and thickness. Sounding curves (Figures 2, 3 and 4) obtained from the plot of field data are interpreted to get the layer parameters, particularly thickness and apparent resistivity of individual layers as described in Table 2. The individual layer boundary is marked in the y-axis of the model representing depth.

Figures 2 and 3 suggest that the subsurface has made up of four layers with apparent resistivity values ranging between 0.42 Ωm and 8.28 Ωm. From the resistivity value of these layers, It has inferred that the top layer is silt and underlain by silty clay, very fine sand, and fine sand layers. The upper two layers might not host groundwater while the third and fourth layer contains groundwater. 0.42 to 2.95 Ωm resistivity values of the third and fourth layer attribute these layers as brackish water containing aquifers. Figure 4 shows a five-layer VES curve where resistivity varies from 1.41 to 14.02 Ωm attributing silt, silty clay, clay, fine sand layers.

The fourth layer of fine sand with 14.02 Ωm resistivity value denotes this layer as freshwater aquifer while underneath the fine sand layer with 3.48 Ωm resistivity is a brackish water aquifer. Correlation of lithology obtained from VES10 with lithology log of a borehole

TABLE 1. Surficial deposits of the study area (Islam, 2014).

Age	Geomorphic domain	Geomorphic unit	Geologic unit	Lithology
Holocene	Lower deltaic plain	Channel	Channel deposit	Clayey silt, silt, and sandy silt; light grey to light live-grey, parallel laminated to cross-laminated.
		Natural levee	Natural levee deposit	Clayey silt; light olive-grey, laminated.
		Lower tidal mudflat	Lower tidal mudflat deposit	Silty clay (mud); light-olive grey.
		Upper tidal mudflat	Upper tidal mudflat deposit	Silty clay; light-olive grey, flat massive.
		Mangrove swamp	Mangrove swamp deposit	Clayey silt (mud); light-olive grey to dark grey.
		Chenier	Chenier deposit	Sand; light-yellowish brown, cross-bedded.
		Beach	Beach deposit	Sand; light grey, Parallel laminated, very fine to fine-grained.

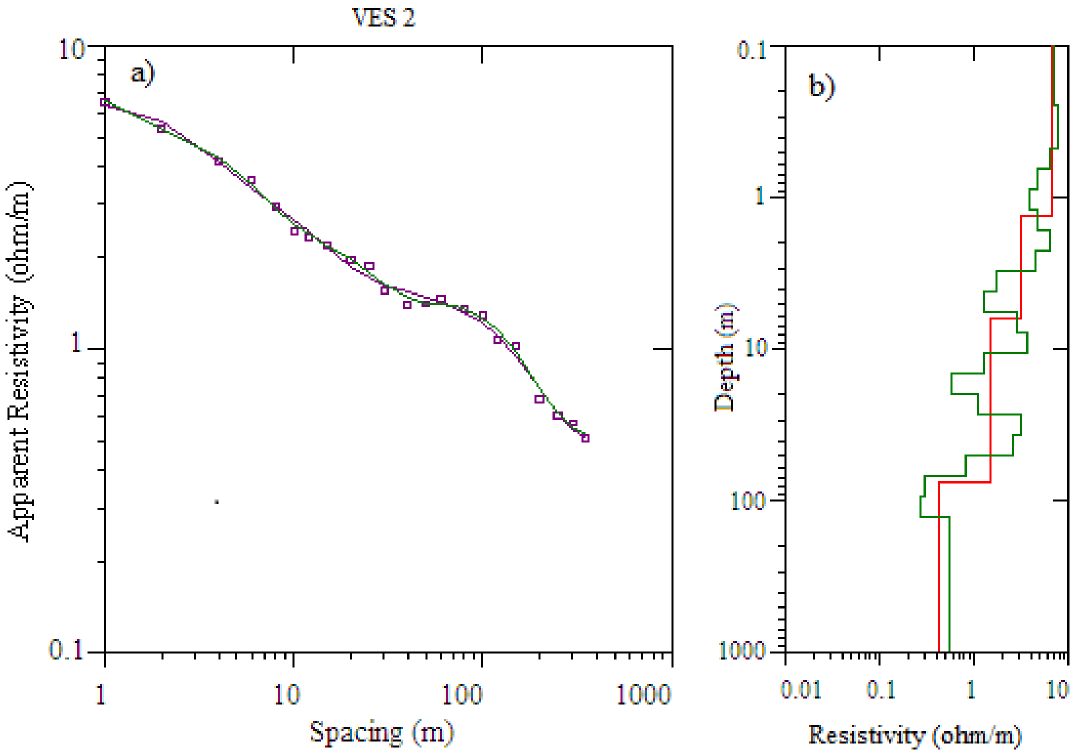

FIGURE 2. a) Apparent resistivity curve of VES 2. b) Inverse models of VES 2 (smooth and layered).

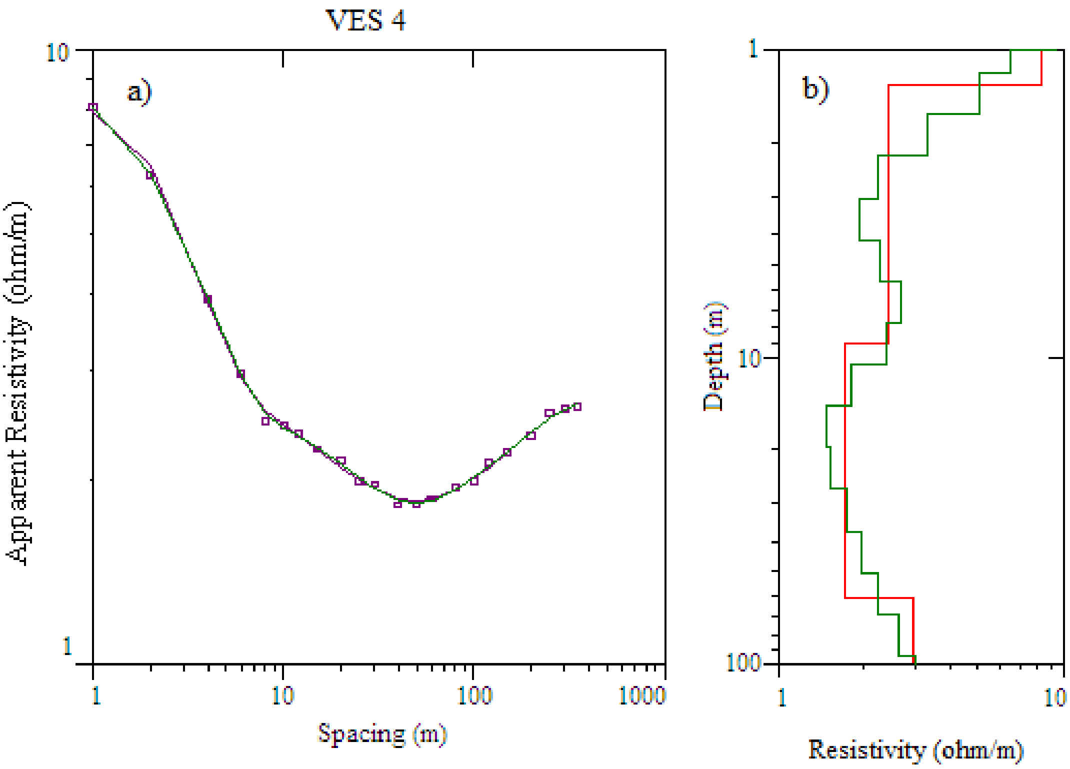

FIGURE 3. a) Apparent resistivity curve of VES 4. b) Inverse models of VES 4 (smooth and layered).

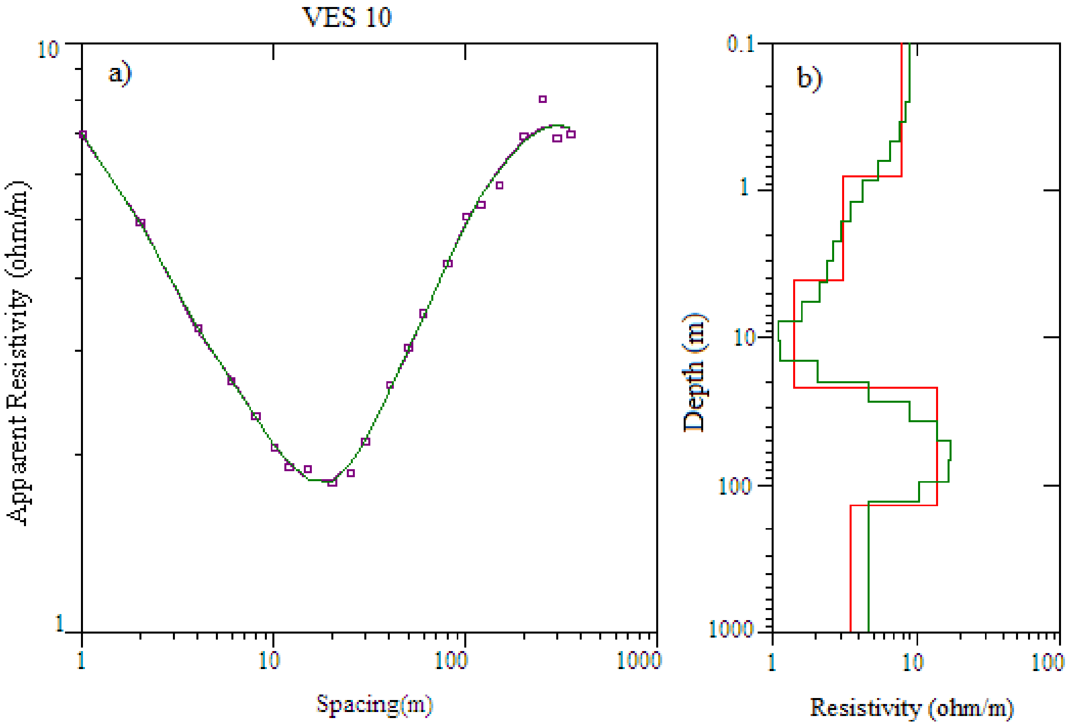

FIGURE 4. a) Apparent resistivity curve of VES 10. b) Inverse models of VES 10 (smooth and layered).

TABLE 2. Subsurface layer parameters from VES.

VES ID	Thickness (m)	Resistivity (Ωm)	VES ID	Thickness (m)	Resistivity (Ωm)
VES1	0.48468	2.4384	VES6	0.3873	30.768
	2.0118	1.2287		1.76	5.2573
	20.724	0.65245		18.897	2.2656
	72.736	1.6066		77.19	5.6727
	-	0.20247		-	0.51475
VES2	1.3408	6.5421	VES7	0.72957	21.066
	4.9957	3.0841		3.376	9.6994
	68.684	1.4855		3.8104	3.1252
	-	0.427		133.63	3.4188
				-	5.987
VES3	1.2124	3.1779	VES9	0.36336	10.3
	4.5497	1.8398		6.8946	6.0056
	98.2	0.79528		143.5	3.0416
	-	0.37494		-	5.6214
VES4	1.303	8.2805	VES10	0.80265	7.8852
	7.7761	2.4246		3.2926	3.0272
	52.034	1.7172		17.624	1.4145
	-	2.9556		116.43	14.02
				-	3.4857
VES5	1.0257	10.85	VES11	0.51641	15.09
	5.2438	3.1017		2.4262	3.8252
	72.667	1.8393		68.705	1.8322
	51.68	12.739		72.053	8.0222
	-	1.3334		-	0.64269

(PTW/P/K1 by DPHE-DANIDA) drilled near the VES location reveals a good correlation. Thin clay and silty clay bed in the sand sequence of the borehole log could not be identifying as a geoelectric layer due to its tiny thickness. Silt and silty clay layers with 5 meters thickness are reflected in the geoelectric model having 2–10 Ωm resistivity (Figure 5). Fifteen meters thick clay layer underneath is also delineated from its 1.42 Ωm resistivity value. The next 150 meters thick, very fine sand with a silty clay layer of a borehole is correlate with sand geoelectrical layer, and 14 Ωm resistivity value of this layer attributes it as a freshwater container while in VES 1, 6 and 7 this layer has 1.60–5.68 Ωm resistivity value. The Decline of the resistivity value of the layer with location is related to pore water quality degradation near the coast. Underneath the fine sand layer, the fifth layer consists of fine sand with silty clay, and clay lenses have 3.48 Ωm resistivity value in the geoelectric section attributing saline pore water container. Correlation of the borehole log with geoelectric layers potentially delineates the individual beds and determines the pore water quality. The 2D geoelectric cross-section along line N–S and W–E (Figures 6 and 7), which are composites of 1D models, represent the stratigraphy of the area. The length of the N–S profile is about 24 km, and the W–E profile is about 16 km, and both constructed with 4 VES points. From N–S (Figure 6) geoelectric section, it is revealed that the upper layer (upper aquifer) has a limited thickness and is composed of very fine sand with 0.06–15 Ωm resistivity. Silty clay geoelectric layer with resistivity value 3–6 Ωm has a maximum thickness in the central part. The topsoil is thin in the central part and has more than 20 Ωm resistivity. Fine sand is about 250 meters thick and dominant in the whole area, with 0.02–6 Ωm resistivity attributing to the saline water aquifer.

On the other hand, the geoelectric section along W–E direction (Figure 7) shows that the upper very fine sand layer is thicker in the western and eastern parts. The thin topsoil layer is common in the central and eastern side with >20 Ωm apparent resistivity. Clay geoelectric

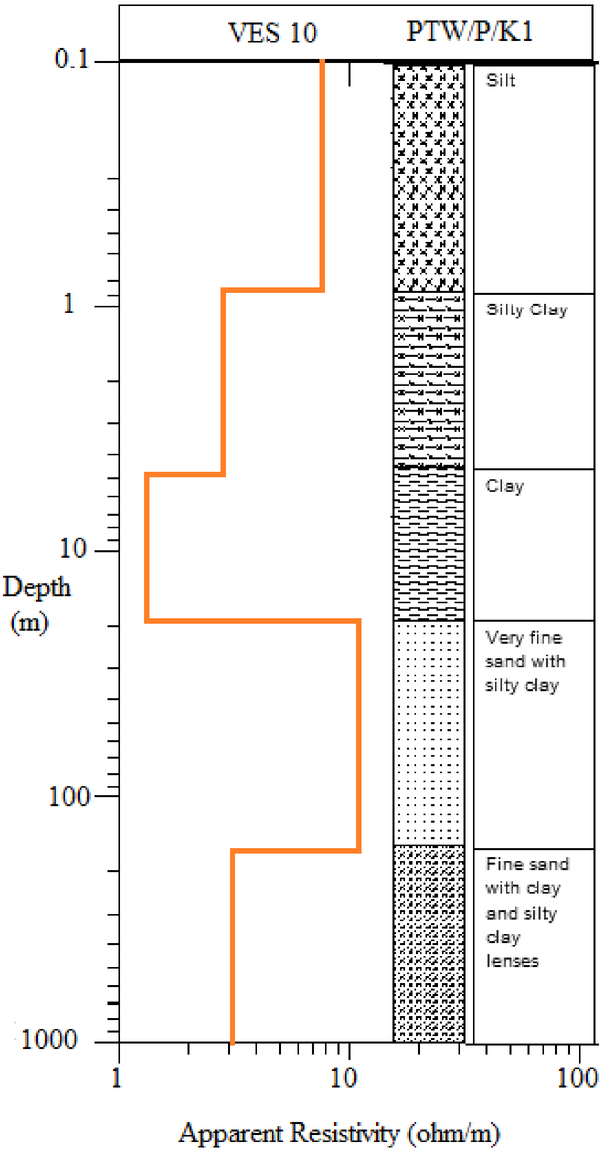

FIGURE 5. VES model curve and borehole section near the sounding site is correlated.

layer is found thick on the eastern side, and have <3 Ωm apparent resistivity. Silty clay geoelectric layer is thick in the center of the section, and it has 3–6 Ωm apparent resistivity. Fine sand is also thicker and dominant in the whole area with resistivity 0.02–6 Ωm and containing saline water.

3.2 Aquifer delineation

The resistivity of the subsurface layer varies spatially and vertically in the investigated area. From resistivity data of the layers and its correlation with the borehole lithology data delineated two water-bearing sand bodies in the study area. The electrical resistivity value of a very fine sand layer characterizes it as saline to brackish-fresh water upper aquifer, which is found between 23 to 150 meters from the surface with 20–143 m thickness. This zone is thicker in the south and the north parts, while in the central part of the area, it has a limited extent.

The second aquifer is composed of fine sand, which lies between 61 to 350 m depth with more than 100 meters thickness. This layer has 0.21 to 5.99 Ωm resistivity values attributing it as a saline water aquifer. 11.12–14.02 Ωm apparent resistivity of the upper aquifer in the northern part of the area (VES 5, 10, 11) attributes freshwater containing aquifer, which is far away from the coast while, 0.79–1.60 Ωm value (VES 1, 2, 3) of this aquifer near to coast attributes saline water (Figure 8). Islam *et al.* (2016) reported that the highest level of salinity in the study area is in the southern part, and it decreases gradually inland towards the north. Groundwater quality of the upper aquifer varies geographically as a consequence of seawater intrusion effect while 0.20–5.92 Ωm resistivity value of the lower aquifer throughout the study area indicate seawater intrusion effect in the deeper part also. Woobaidullah *et al.* (2006) also reported the variation of upper zone resistivity values, which was attributed as an isolated freshwater aquifer. The eastern part of the study area (VES 4, 6, 7, and 9) also contains saline water, which might be the influence of the 'Rabnabad' channel (river) containing saline water. Brackish to saline water quality of the two aquifers in the southern part and lower aquifer in the northern part leads to a comprehensive concept of seawater intrusion in the study area.

4 CONCLUSION

Geoelectrical survey data, together with lithological data of the study area, give scope to find out the groundwater containing layers together with quality assessment of the contained pore water. Two water-bearing sand layers at different depth throughout the study area were observed and they are very fine sand upper aquifer and fine sand lower aquifer. Resistivity values of the very fine sand layer were from 0.66 to 14.02 Ωm with a maximum thickness of 143 m, which is identified as an up-

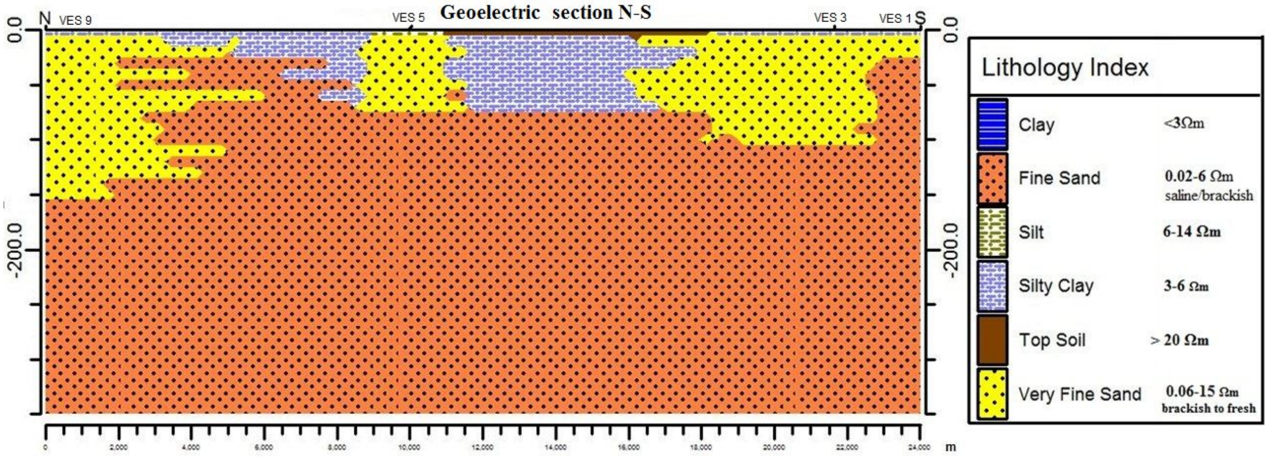

FIGURE 6. Geoelectric section along N–S direction.

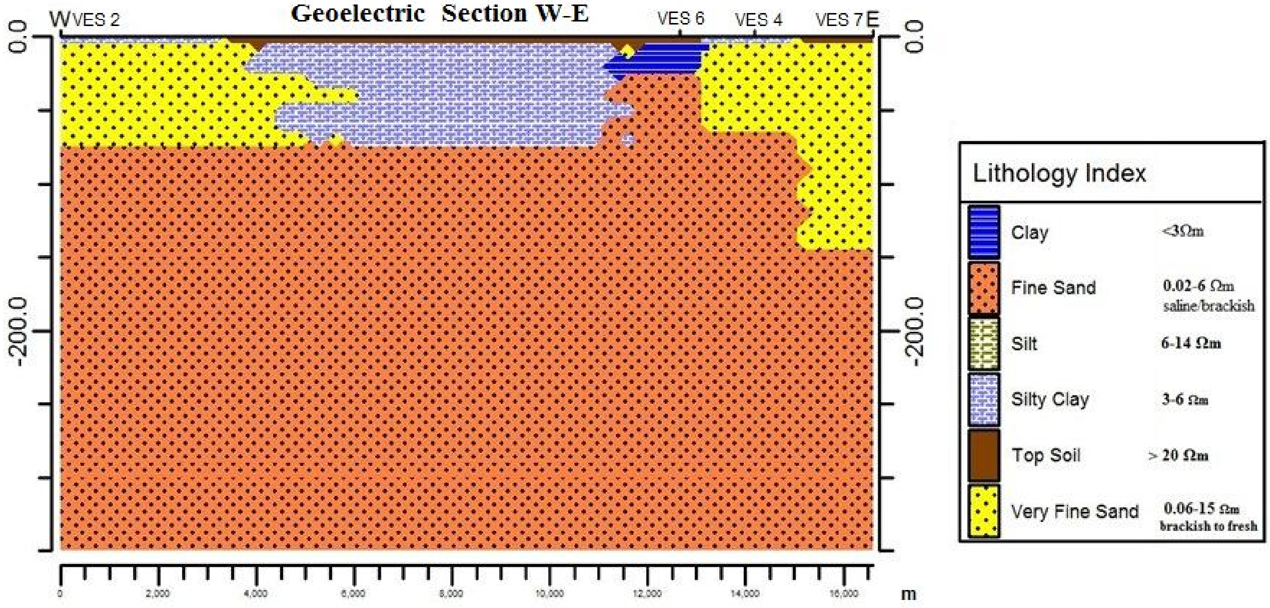

FIGURE 7. Geoelectric section along W–E direction.

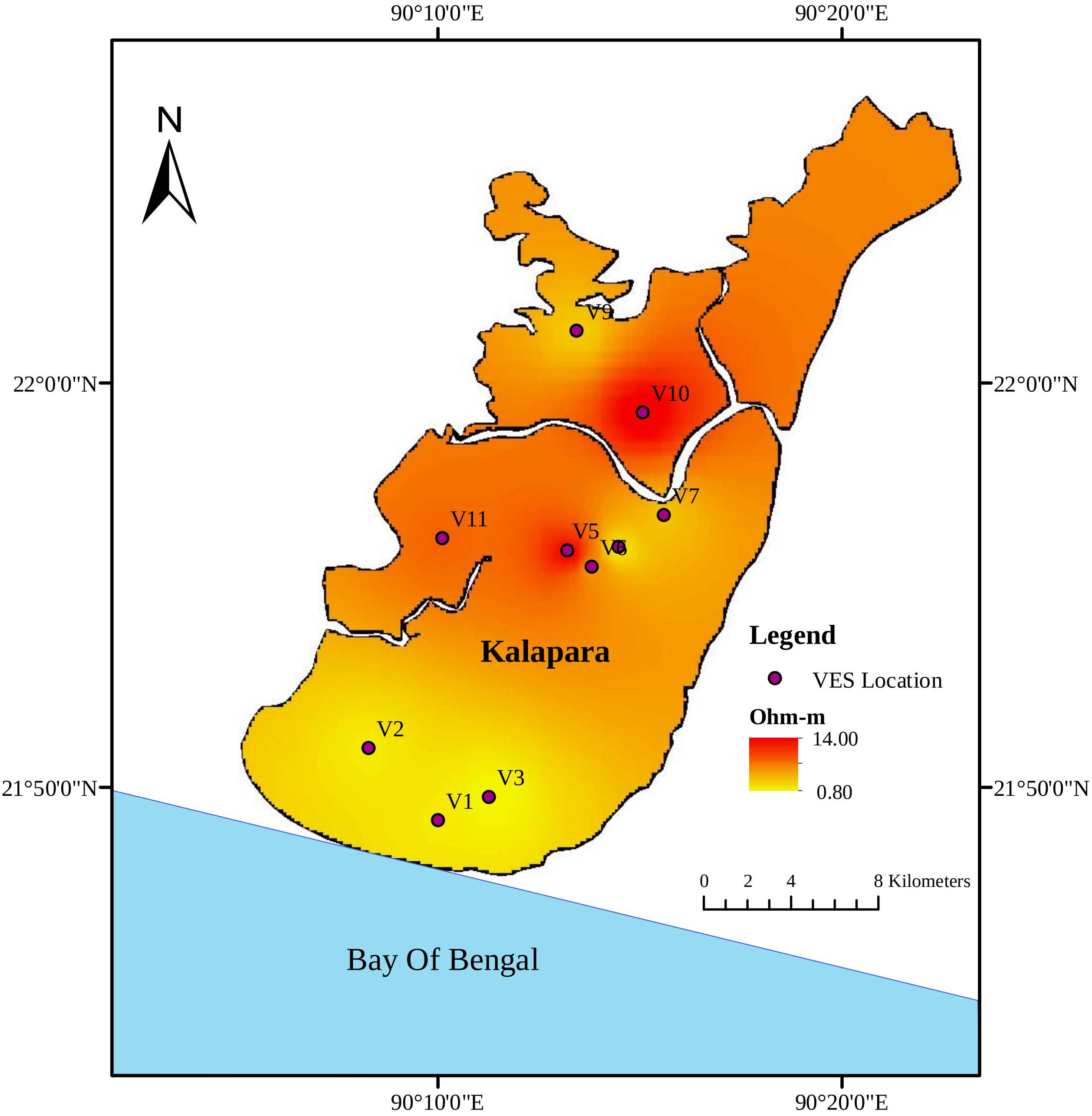

FIGURE 8. Spatial distribution of apparent resistivity (ohm-m) of upper zone aquifer.

per aquifer. The lower aquifer has resistivity values of 0.21 to 5.99 Ωm, which extends below 350 meters. Correlation of the geoelectrical layers with the lithological layers obtained from the borehole also delineates the two water-bearing sand layers. Geographic variation of water quality of the upper aquifer is observed, which could be related to the seawater intrusion effect. Groundwater quality in the northern part of the study area found fresh in the upper aquifer, while in the lower aquifer, it is reported as saline water. The upper aquifer is highly vulnerable towards the southern part as it is very close to the sea. The lower aquifer is saline throughout the study area. The studied coastal area is at an acute threat because of water salinity. The Geoelectrical sounding method applied in this study found useful in delineation of the deteriorating low-quality groundwater zone in coastal areas. Prior to future development activities in the coastal area, this geoelectrical method needs to be applied for the potential groundwater resource determination.

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ABBREVIATIONS

BBS	Bangladesh Bureau of Statistics
BGS	British Geological Survey
DPHE	Department of Public Health Engineering
DMB	Disaster Management Bureau
ID	Identification
K1	Kalapara 1
MoA	Ministry of Agriculture
P	Patuakhali
PTW	Production Tubewell
USEPA	United Nations Environment Protection Agency
VES	Vertical Electrical Sounding
V1	Vertical Electrical Sounding 1
MN	Potential Electrode Separation
AB	Current Electrode Separation

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