Geophysical Assessment of Seawater Intrusion into Coastal Aquifers of Bela Plain, Pakistan

Muhammad Hasan 1,2,3,*, Yanjun Shang 1,2,3,*, Weijun Jin 1,2,3, Peng Shao 1,2,3, Xuetao Yi 1,2,3 and Gulraiz Akhter 4,5

1 Key Laboratory of Shale Gas and Geoenineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China; wjjin@mail.iggcas.ac.cn (W.J.); shaopeng17@mails.ucas.edu.cn (P.S.); yixuetao19@mails.ucas.ac.cn (X.Y.)
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 Innovation Academy for Earth Science, Chinese Academy of Sciences, Beijing 100029, China
4 Department of Earth Sciences, Quaid-i-Azam University, Islamabad 45320, Pakistan; agulraiz@qau.edu.pk
5 China-Pakistan Joint Research Centre on Earth Sciences, Islamabad 44000, Pakistan
* Correspondence: hasan.mjinnww@gmail.com (M.H.); jun94@mail.iggcas.ac.cn (Y.S.); Tel.: +86-130-513-617-10 (M.H.); +86-139-100-993-15 (Y.S.)

Received: 22 October 2020; Accepted: 1 December 2020; Published: 4 December 2020

Abstract: Seawater intrusion is a major challenge in many coastal areas all around the world, mainly caused by over-exploitation of freshwater resources, climate change, and sea-level rise. Consequently, seawater intrusion reaches several kilometers inland, thus making the freshwater resources polluted and unsuitable for human use. Conventionally, the fresh-saline water interface is delineated by the number of laboratory tests obtained from boreholes. However, such tests suffer from efficiency in terms of data coverage, time, and cost. Hence, this work introduces Dar-Zarrouk (D-Z) parameters, namely transverse resistance ($T_r$), longitudinal conductance ($S_c$), and longitudinal resistivity ($\rho_L$) computed from non-invasive vertical electrical sounding (VES). Two-dimensional (2D) imaging of D-Z parameters provides a clear distinction of fresh-saline aquifers. Such techniques remove ambiguities in the resistivity interpretation caused by overlapping of fresh and saline aquifers during the process of suppression and equivalence. This study was carried out by 45 VES along five profiles in the coastal area of Bela Plain, Pakistan. D-Z parameters delineate fresh, brackish, and saline aquifers with a wide range of values such as freshwater with $T_r > 2000 \ \Omega \cdot m^2$, $S_c < 3 \ \text{mho}$, and $\rho_L > 20 \ \Omega \cdot m$; saline water with $T_r < 1000 \ \Omega \cdot m^2$, $S_c > 25 \ \text{mho}$, and $\rho_L < 5 \ \Omega \cdot m$; and brackish water with $T_r$ between 1000–2000 $\Omega \cdot m^2$, $S_c$ from 3 to 25 mho, and $\rho_L$ between 5–20 $\Omega \cdot m$. The D-Z results were validated by the physicochemical analysis using 13 water samples and local hydrogeological setting. The obtained results propose that D-Z parameters can be used as a powerful tool to demarcate the fresh-saline aquifer interface with more confidence than other traditional techniques. This geophysical approach can reduce the expensive number of borehole tests, and hence contributes to the future planning and development of freshwater resources in the coastal areas.

Keywords: coastal aquifers; fresh-saline interface; seawater intrusion; Dar-Zarrouk parameters; electrical resistivity; Bela Plain

1. Introduction

In Pakistan, groundwater is an essential resource for sustaining the population and economy [1]. Recently, groundwater utilization in the coastal areas has increased to meet water demand for industrial, agricultural, domestic, and tourist uses [2]. Consequently, improper management, excessive development, and over-exploitation of freshwater have deteriorated both the quantity and quality of groundwater.
reserves [3]. The main concern is seawater intrusion, which has resulted in groundwater contamination and well reduction [4, 5]. Seawater intrusion is a natural occurrence caused by the density difference between seawater and freshwater. Seawater intrusion occurs when, due to the over-extraction of groundwater resources, outflow exceeds the aquifer recharge which is dynamically connected to the sea [6, 7]. Generally, problems arise, when the seawater enters the aquifer system due to excessive pumping beyond the natural recharge rate, or when the potentiometric surface lowered by the extreme pumping at local individual wells causes the upcoming of the natural boundary between saline water and freshwater [8, 9]. In addition, coastal aquifers are sensitive to the sea level rise due to global warming, and the melting snowcaps add to the level of seawater encroachment and ease the accessibility of freshwater reserves [10]. Therefore, demarcation of the fresh-saline groundwater boundary is very important for extraction and management of freshwater reserves in the coastal areas.

Delineation of the saltwater intrusion has become a global issue within the last century. In the last two decades, many studies around the world were conducted to assess the fresh/saline aquifers [1, 2, 10–14]. Classically, seawater intrusion is monitored using the physicochemical analysis of groundwater samples and piezometry through the measurements of water-level fluctuations [15, 16]. For successful monitoring of saltwater encroachment, observation wells are required to be dispersed over the entire investigated area. However, the economic reason mainly causes the sparse density of test wells, and thus the distributed wells do not characterize the total area sufficiently [17]. With the intent to ease the lack of information and improve the monitoring of the aquifer system, an efficient technique is necessary. The surface geophysical methods such as vertical electrical sounding (VES) are known as one of the most proficient techniques to assess groundwater resources quantitatively and qualitatively [18–21]. Electrical resistivity is extensively used to delineate seawater intrusion into coastal aquifers. A clear difference in resistivity values of freshwater and saltwater is useful to assess the fresh-saline water interface in the coastal areas [22, 23]. Low resistivity values show saltwater, whereas high values suggest freshwater. Subsurface resistivity depends on many factors such as water content, saturation degree, porosity, rock type, soil type, salinity, and mineralization of groundwater, etc. [12]. Conversely, some geophysical similarities cause uncertainty in the resolution. Sometimes, the interpretation shows an intermixing of resistivity values for fresh and saline groundwater [24]. Dar-Zarrouk (D-Z) parameters can remove the overlapping of fresh/saline aquifers, and provide a more certain, practical, and reliable solution to the interpretation [11,25]. Applications of the D-Z parameters, namely transverse resistance, longitudinal conductance, and longitudinal resistivity computed from VES measurements mark a clear boundary between saline and fresh groundwater. Many studies have used D-Z parameters for delineation of the fresh-saline aquifer interface [1, 11,12,17,25]. However, these studies provide only a 1D (one-dimensional) delineation of fresh-saline aquifer. Mostly, ERT is used to delineate the 2D demarcation of fresh-saline groundwater, however, ERT cannot cover a large area. In order to get a clear insight into the fresh-saline aquifer, the 2D delineation of the aquifer system is essential. This work provides a new innovative approach for the 2D demarcation of fresh-saline aquifer using the D-Z parameters. Based on local geological settings and groundwater conditions, D-Z parameters were acquired for each distinct layer of fresh or saline water with various arrangements of resistivity and thickness. These parameters delineated saline and fresh aquifers with a wide range of specific values depending on local hydrogeological conditions and wells information. Freshwater was delineated by high values of transverse resistance and longitudinal resistivity but low values of longitudinal conductance, whereas saltwater was assessed with high values of longitudinal conductance but low values of the two other parameters.

During the last two decades, the coastal aquifers of Bela Plain have become polluted due to the over-extraction of groundwater resources mainly for agriculture demand. Groundwater, with seawater intrusion of more than 50 km from the Sonmiani Bay of Arabian Sea towards the inlands of the study area, has become unsuitable for drinking and agriculture purposes. The number of boreholes near the coast is discarded due to seawater intrusion. The main aim of the present investigation is to emphasize the application of D-Z parameters derived from VES data for 2D mapping of seawater intrusion into
coastal areas of Bela Plain, Pakistan, and to display how this non-invasive geophysical technique can be used to reduce the number of expensive well samples of hydrogeochemical information. In addition, the monitoring boreholes data of physicochemical parameters were integrated with a geophysical interpretation to improve and validate the results of the D-Z parameters for the assessment of saline and fresh aquifers.

2. Study Area and Hydrology

Bela Plain is located in Lasbela District covering an area of 3100 km$^2$. The study area is situated south of the Baluchistan Province between latitude 25–26.55° N and longitude 66–67° E. Bela Plain is surrounded by hills of sedimentary rocks from three sides in the east, west, and north and Sonmiani Bay (Arabian Sea) in the south (Figure 1). The study area is located in the arid region having an average annual precipitation of 80–130 mm, high evaporation, and low recharge to groundwater. Agriculture is the main source of earning for people in the study area, which mainly relies on tubewells, streamflow, and rainfall. The investigated area has intermittent streams mostly, and the only perennial one is the Porali River in the southeast. The alluvial cover of unconsolidated deposits was formed during the quaternary age, and the erosion processes shaped the topographic relief of the study area.

The stream runoff and rainfall are the main sources of water in foothills and piedmont areas of Bela Plain. In northern areas, groundwater is mainly recharged by streamflows of Porali River through permeable beds. Whereas, rainafill is mainly the source of groundwater recharge for the rest of the areas in Bela Plain. In northern Mor and Par Ranges, Porali River at the Sinchi Bent guaging station, is the major source of water with an irrigation land of 4039 km$^2$. The surface water hydrology, WASID (water and soil investigation division) is responsible for measuring the discharge rate of rivers and streams in the study area [26]. The mean annual flow is 120 million m$^3$, which is mostly used in agriculture [27]. About 14–18 km downstream from the Sinchi Bent guaging station, Kud River joins the Porali River. At Mai Gondrani, the mean annual flow is 102 million m$^3$ [27]. Windar Nai with a drainage area of 1733 km$^2$ is a non-perennial stream, which directly flows into the Arabian Sea in the south. Khantra Nai is another main non-perennial stream in the study area.

Gravel, sand, clay, and silt are the main lithologies in the investigated area as revealed by the drilling tests. However, gravel forms the most extensive and permeable aquifer, which lies in the unconsolidated deposits under the alluvial fans and piedmonts places. Generally, the study area has the unconfined aquifer system. However, the semi-permeable beds of silt and clay are dominant in the south and southwest parts where they make the confined aquifer sytem with saltwater. The water table varies between 0-15 m in the investigated area. The shape of the water table depth is of concave type in the southwest and middle of the investigated area along Porali River and Khantra Nai.

The groundwater recharge rate is mainly controlled by the seasonal conditions of discharge from the surfacewater into the groundwater. The general flow direction of surface water in Bela Plain is from the northeast to the southwest towards the Arabian Sea. This investigation was conducted by the Water And Power Development Authority, Pakistan (WAPDA) under a project in order to assess seawater intrusion into the coastal area of Bela Plain for the development and management of freshwater resources. All the 45 VES were performed in the same time period/season (April/May, 2017) as the groundwater samples were collected from the 13 wells. The location of VES and wells inuding the hydrogeological setting of the investigated area is given in Figure 1a. Figure 1b shows a schematic diagram of seawater intrusion into the coastal aquifer.
Figure 1. (a) Location of vertical electrical sounding (VES)/wells measurements including the hydrogeological setting of the investigated area (modified after [27]); (b) a schematic diagram of seawater intrusion into the coastal aquifer (modified after [18]).
3. Materials and Methods

3.1. VES Survey

Seawater intrusion into coastal aquifers is delineated by many techniques. It is never easy to directly interpret the measurements of apparent electrical conductivity quantitatively, since it depends on several properties, such as clay containing high concentrations of cations and dissolved electrolytes, temperature, porosity, etc. [28]. In addition, a high electrical conductivity shows saltwater, whereas its low values suggest freshwater [11]. This difference between the electrical conductivity of freshwater and saltwater is highly significant, and therefore, the VES method is more suitable to assess the fresh-saline groundwater interface in the coastal regions [29]. Geophysical methods such as vertical electrical sounding (VES) are widely used in environmental and hydrogeological studies given their ability to incorporate with other methods, such as hydrochemical and geological methods, through a comprehensive interpretation. A useful correlation is found between hydraulic and electrical properties of the saturated geological formations, which make the geoelectrical methods even more effective in such studies [30–33]. An integrated approach of the VES and geochemical method in combination with hydrogeological data has been used to evaluate the characteristics of groundwater and delineate the expansion of seawater intrusion into the coastal aquifer.

In this research, a VES survey was performed to compute the subsurface resistivity. Electrical resistivity depends on the characteristics of subsurface materials, such as rock texture, nature of mineralization, and electrical conductivity [34]. It varies from formation to formation. Coarse grains show high values of resistivity, whereas an increase in the clay content or salinity gives low values. In the VES survey, an electric current is injected into the subsurface through two electrodes known as current electrodes, and two other electrodes namely potential electrodes are used to measure the electrical potential. The measured voltage is converted into the resistance value using the resistivity meter. The anomalies are observed by plotting the resistance values on a log-log paper in the field. With each resistivity measurement, spacing between the current electrodes is increased to acquire the large depth of investigation. The signal to noise ratio is enhanced by increasing spacing between the inner potential electrodes. In this survey, 45 VES measurements (Figure 1a) were acquired by a resistivity meter (Syscal R1 Plusmodel, Iris) using the Schlumberger array. The VES data points were divided into five profiles, i.e., A, B, C, D, and E as shown in Figure 1a. The spacing of current electrodes (AB) and potential electrodes (MN) was adjusted at all depths according to a relationship, i.e., 2(AB/2) > 5 MN [35]. The minimum and maximum half-current
electrodes spacing (AB/2) was used as 1 and 200 m, respectively, whereas the potential electrodes spacing (MN) varied between 0.25-20 m. The resistivity measured directly from the VES data is apparent resistivity. This resistivity needs to be inverted, as it does not represent the true values of subsurface layers [36]. The apparent resistivity data were inverted by the IPI2WIN software version 3.1.2c, developed by Moscow State University [37]. The software program compared the theoretical curve with the inverted (true) resistivity and the calibrated field curve (Figure 2a). The shape of the modeled VES curves shows variations in different layers with different resistivities [35]. The VES models divide the subsurface formation into distinct layers with a specific value of thickness and resistivity. The correct interpretation of VES models is performed using the local information acquired from boreholes data and hydrogeological setting.

3.2. Dar-Zarrouk Parameters

Occasionally, the VES interpretation causes ambiguity in the resolution and resistivity values, which shows the overlapping of demarcation of saline and fresh groundwater [24]. D-Z parameters remove any such uncertainty in the resistivity interpretation, and provides a clear interface between the freshwater and saltwater. They present a more practical, definite, and reliable solution to the interpretation [11,25]. D-Z parameters mark a clear interface between saline and fresh groundwater with a wide range of their values without overlapping of values or aquifers. D-Z parameters, namely transverse resistance (\(T_r\)), longitudinal resistivity (\(\rho_L\)), and longitudinal conductance (\(S_c\)) were first introduced by Maillet in 1947. These parameters offer sufficient resolutions to subsurface resistivity for the delineation of seawater intrusion [11]. They efficiently mark a distinct boundary between saline and fresh groundwater with a specific range of their values [12]. These parameters are estimated through different arrangements of thickness and resistivity acquired from the VES models (Figure 2b), and thus they give a better understanding of the subsurface discrete layers for the evaluation of a boundary between saline and fresh groundwater [11,38,39]. Any geoelectrical layer in a VES model is defined by two fundamental properties, namely resistivity (\(\rho\)) and thickness (\(h\)) [40]. Various arrangements of resistivity (\(\rho\)) and thickness (\(h\)) for each lithologic unit of VES model describe the D-Z parameters [11,41]. Transverse resistance was estimated by the following arrangement of \(h\) and \(\rho\) [11,41]:

\[ T_r = (h)(\rho) \]  

(1)

where \(h\) and \(\rho\) are the aquifer thickness and resistivity of each layer in the VES model. \(T_r\) is the transverse resistance measured in units of \(\Omega\text{m}^2\). Longitudinal conductance was calculated by the following formula [11,41]:

\[ S_c = \left(\frac{h}{\rho}\right) \]  

(2)

where \(S_c\) is the longitudinal conductance of each saturated layer, and it is measured in Siemens (mho). The longitudinal resistivity is acquired using the following equation [11,41]:

\[ \rho_L = \left(\frac{h}{S_c}\right) \]  

(3)

where \(\rho_L\) is the longitudinal resistivity of each layer, and is estimated in \(\Omega\text{m}\). Equations (1)–(3) were used to estimate the D-Z parameters of each distinct layer of the VES model (Figure 2b). D-Z parameters were estimated for all 45 VES models to get the 2D mapping of discrete saline and fresh groundwater in Bela Plain. Specific values ranges of \(T_r\), \(S_c\), and \(\rho_L\) for saline, brackish, and fresh aquifers were obtained based on the hydrogeological setting and wells information of the investigated site. To obtain specific values ranges of the D-Z parameters, the lithological logs data of the 13 wells were integrated with the D-Z parameters of the selected 13 VES nearby the wells. An example of such integration between the selected VES 9 and the lithological well log 3 is shown in Figure 2a. However, these values ranges of D-Z parameters are not unique and may vary from area to area based on the local hydrogeological setting.
determine the concentrations of calcium, bicarbonate, sodium, as determined at 25 °C, whereas chloride, sulphate, potassium, chloride, and magnesium [44]. Bicarbonates and chlorides ions were obtained by the volumetric method. The UV–visible spectrophotometer was applied for the analysis of sulphates. The atomic absorption spectrometry was performed to analyze the main cations. The concentration of cations and anions was measured in milligrams per liter (mg/L). The concentration of the electrical conductivity in microsiemens per centimeter (μS/cm) was determined at 25 °C. The consistency of the groundwater quality parameters was confirmed using the ionic balance of water, and the acceptable reliability was found between +5% and −5%.

4. Results

4.1. Interpretation of Resistivity Data

Resistivity measured in the field is not a true representative of subsurface geologic units, and therefore, apparent resistivity is inverted to true resistivity through an inversion procedure of the software [1]. Resistivity varies even with a minor change in lithology. The resistivity of sand is lower than the resistivity of gravel, similarly, the resistivity of silt/clay is lower than that of sand. Moreover, freshwater shows a high resistivity, while saline water indicates a low resistivity. Mostly,

Figure 2. (a) A four-layered VES model generated by the IPI2WIN software, and the comparison (calibration) between the lithological well log 3 and the interpreted VES 9; (b) subsurface layered model of longitudinal conductance (Sc) and transverse resistance (Tr) [42].

3.3. Geochemical Method

The physicochemical analysis was conducted for 13 groundwater samples obtained from the pumping wells with an average depth range of 60–110 m. The laboratory analysis of groundwater samples was conducted using the ion chromatography technique by the Pakistan Council of Research in Water Resource (PCRWR). The physicochemical study was performed by the recommended limits of the World Health Organization [43] for main anions such as chloride (Cl⁻), sulphates (SO₄²⁻), nitrate (NO₃⁻), and bicarbonates (HCO₃⁻), as well as main cations including magnesium (Mg²⁺), sodium (Na⁺), potassium (K⁺), calcium (Ca²⁺), and other geochemical parameters such as electrical conductivity (EC), pH, and total dissolved solids (TDS) [44]. The standard procedures method was used to determine the concentrations of calcium, bicarbonate, sodium, sulphate, potassium, chloride, and magnesium [44]. Bicarbonates and chlorides ions were obtained by the volumetric method. The UV–visible spectrophotometer was applied for the analysis of sulphates. The atomic absorption spectrometry was performed to analyze the main cations. The concentration of cations and anions was measured in milligrams per liter (mg/L). The concentration of the electrical conductivity in microsiemens per centimeter (μS/cm) was determined at 25 °C. The consistency of the groundwater quality parameters was confirmed using the ionic balance of water, and the acceptable reliability was found between +5% and −5%.
gravel/sand reveal freshwater, whereas clay delineates saltwater [12]. However, with a homogeneous and anisotropic subsurface, uncertainties can be expected in VES methods for the characterization of subsurface lithologies [36]. Therefore, the VES models and local hydrogeological information obtained from wells are correlated to constrain the subsurface into discrete lithologic layers. In this study, the non-predictive bias evaluation of the subsurface was obtained by correlating 45 VES models with lithological logs of 13 boreholes (Table 1). A comparison between the interpreted VES 9 and lithological well log 3 is shown in Figure 2a. Similarly, the calibration (comparison) between the 45 VES models and 13 lithological well logs was performed to obtain a resistivity values range for each layer containing fresh-saline or brackish aquifer with specific lithology. This calibration delineated the subsurface into several lithological units, such as dry strata/topsoil cover (above water table) having resistivity >35 Ωm, clay (below water table) with saline water having resistivity <7 Ωm, clay-sand (below water table) with brackish water and resistivity between 4–24 Ωm, sand (below water table) having a freshwater and resistivity range of 18–42 Ωm, gravel-sand (below water table) with freshwater and resistivity from 34 to 60 Ωm, and gravel (below water table) having freshwater and resistivity >50 Ωm (Table 1).

Table 1. Overlapping in resistivity values and lithologies obtained after calibration between the local boreholes information and subsurface resistivity in Bela Plain.

| Subsurface Resistivity (Ωm) | Lithology Type                  | Overlapping Resistivity | Overlapping Lithology | Aquifer          |
|----------------------------|---------------------------------|-------------------------|-----------------------|------------------|
| >35 (above water table)    | Topsoil cover (dry strata)      | -                       | -                     | -                |
| <7 (below water table)     | Clay (saline water)             | 4–7                     | Clay and Clay-sand    | Saline-brackish  |
| 4–24 (below water table)   | Clay-sand (brackish water)      | 18–24                   | Clay-sand and sand    | Brackish-fresh   |
| 18–42 (below water table)  | Sand (freshwater)               | 34–42                   | Sand and gravel-sand  | -                |
| 34–60 (below water table)  | Gravel-sand (freshwater)        | 50–60                   | Gravel-sand and gravel| -                |
| >50 (below water table)    | Gravel (freshwater)             | -                       | -                     | -                |

The calibration shows that the interpreted layers have very narrow resistivity ranges with an overlapping nature. The clay of saline water having resistivity <7 Ωm intermixes with the clay-sand of brackish water with resistivity between 4–24, and thus causes an overlapping of saline-brackish aquifer with resistivity between 4–7 Ωm. Similarly, the clay-sand of brackish water having a resistivity range of 4–24 Ωm interferes with the sand of freshwater with resistivity from 18 to 42 Ωm, and hence creates an overlapping of brackish-fresh aquifer with a resistivity range of 18–24 Ωm. In addition, Table 1 shows the intermixing of sand with gravel-sand for resistivity overlapping of 34–42 Ωm, and gravel with gravel-sand for resistivity overlapping of 50–60 Ωm. Therefore, such overlapping causes an ambiguity in resolution for the separation between saline and fresh groundwater. This implies that the VES technique cannot interpret the subsurface with a high resolution, especially when the lithological units have some similarities, such as clay-sand and clay or sand and clay-sand. However, D-Z parameters estimated from the VES models can remove any such ambiguity, and thus provide a more confident resolution to the interpretation of fresh-saline aquifers. These parameters have a wide range of values to mark a clear interface between freshwater and saline water.

4.2. Transverse Resistance

An important parameter of the D-Z parameters, namely transverse unit resistance ($T_r$), was estimated for each layer of the 45 VES models along profiles A-E through the arrangement (Equation (1)) of aquifer thickness and resistivity of the layer. Transverse unit resistance was used
to demarcate fresh, brackish, and saline water with a wide range of $T_r$ values based on the wells information and hydrogeological setting of the investigated area. High values of $T_r$ suggest that freshwater has sand or gravel as the main lithology, while its low values indicate saline water has clay as the main lithology. In this study, transverse unit resistance delineated saline water with $T_r < 1000 \ \text{Ω} \text{m}^2$ containing clay, brackish water with $T_r$ between 1000–2000 $\text{Ω} \text{m}^2$ having clay-sand, and freshwater with $T_r > 2000 \ \text{Ω} \text{m}^2$ having sand, gravel-sand, and gravel (Table 2). The values range of $T_r$ for fresh, brackish, and saline water shows no intermixing, which suggests that the aquifers delineated by $T_r$ have no intermixing of saline-brackish or brackish-fresh aquifers.

**Table 2.** Study of Dar-Zarrouk (D-Z) parameters for the demarcation of saline, brackish, and fresh aquifers in Bela Plain.

| D-Z Parameters              | Range       | Type of Aquifer | Overlapping |
|-----------------------------|-------------|-----------------|-------------|
| Transverse unit resistance ($T_r$) | $>2000 \ \text{Ω} \text{m}^2$ | Fresh          | None        |
|                            | 1000–2000 $\text{Ω} \text{m}^2$ | Brackish       | None        |
|                            | $<1000 \ \text{Ω} \text{m}^2$ | Saline         | None        |
| Longitudinal unit conductance ($S_C$) | $<3 \ \text{mho}$ | Fresh          | None        |
|                            | 3–24 mho    | Brackish        | None        |
|                            | $>24 \ \text{mho}$ | Saline         | None        |
| Longitudinal resistivity ($\rho_L$) | $>20 \ \text{Ω}$ | Fresh          | None        |
|                            | 5–20 $\ \text{Ω}$ | Brackish       | None        |
|                            | $<5 \ \text{Ω}$ | Saline         | None        |

The distribution of transverse unit resistance values over 45 VES in Figure 3a suggests that $T_r$ increases from the sea (in the south) towards the inland (in the north). Based on the interpretation of $T_r$, Figure 3b provides the demarcation of saline, brackish, and fresh aquifers at different depths (50, 100, 150, and 200 m). At a 50 m depth, $T_r$ varies between 50–4100 $\text{Ω} \text{m}^2$ with a $T_r$ range of 50–574 $\text{Ω} \text{m}^2$ for saline water, 1280–1705 $\text{Ω} \text{m}^2$ for brackish water, and 2520–4100 $\text{Ω} \text{m}^2$ for freshwater. At a 100 m depth, the $T_r$ values range is 10.9–36,400 $\text{Ω} \text{m}^2$ with $T_r$ between 10.9–574 $\text{Ω} \text{m}^2$ for saline aquifer, 1280–1705 $\text{Ω} \text{m}^2$ for brackish aquifer, and 3000–36,400 $\text{Ω} \text{m}^2$ for fresh aquifer. At 150 and 200 m depths, $T_r$ changes from 10.9 to 36,400 $\text{Ω} \text{m}^2$ having $T_r$ of 10.9–92.8 $\text{Ω} \text{m}^2$ for saline aquifer, 1280–1705 $\text{Ω} \text{m}^2$ for brackish aquifer, and 2730–36,400 $\text{Ω} \text{m}^2$ for fresh aquifer. Generally, $T_r$ (from 2520 to 36,400 $\text{Ω} \text{m}^2$) for freshwater increases with depth, whereas $T_r$ (from 574 to 10.9 $\text{Ω} \text{m}^2$) for saltwater decreases with depth, which suggests seawater intrusion with an increasing depth (Figure 3b).
The 2D transverse unit resistance was obtained and interpreted for saline, brackish, and fresh groundwater along five profiles (A–E) (Figure 4a,b). Transverse unit resistance values vary along profile A to E with $T_r$ between 11.3–28080, 8.8–6750, 11.3–9951, 11.3–9951, and 10.5–9951 $\Omega\text{m}^2$, respectively (Figure 4a). Along profile A, the saline aquifer was delineated with $T_r$ between 11.3–384 $\Omega\text{m}^2$ for VES 11–13, brackish aquifer was revealed by $T_r$ from 1386 to 1650 $\Omega\text{m}^2$ for VES 8–10, and fresh aquifer was interpreted with a $T_r$ range of 2700–28080 $\Omega\text{m}^2$ for VES 20–26 (Figure 4b). Seawater intrusion for profile A was observed about 45 km towards the inland along VES 8–13. Along profile B, freshwater was revealed by a $T_r$ range of 2788–6750 $\Omega\text{m}^2$ for VES 14–16, brackish water was interpreted with $T_r$ of 1376 $\Omega\text{m}^2$ for VES 16 and 17, and saline water was assessed with $T_r$ between 8.8–384 $\Omega\text{m}^2$ for VES 11 and 17–22 (Figure 4b). Seawater intrusion of about 75 km was found along this profile for VES 11 and 16–22. Along profile C, saline water was evaluated with $T_r$ between 11.5–180 $\Omega\text{m}^2$ for VES 20 and 26–29, brackish water was interpreted by $T_r$ of 1440 $\Omega\text{m}^2$ for VES 26, and freshwater was delineated with $T_r$ between 3330–9951 $\Omega\text{m}^2$ for VES 23–25 (Figure 4b). Seawater intrusion of 50 km was delineated along profile C with VES 20 and 26–29. Along profile D, freshwater was revealed by a $T_r$ range of 2275–9951 $\Omega\text{m}^2$ for VES 23 and 30–33, brackish water was interpreted with $T_r$ between 1512–1705 $\Omega\text{m}^2$ for VES 31–34, and saline water was delineated with $T_r$ between 11.3–390 $\Omega\text{m}^2$ for VES 13, 34, and 35 (Figure 4b). This profile reveals seawater intrusion of about 27 km along VES 13 and 31–35. Along profile E, saline aquifer was revealed by $T_r$ between 10.5–560 $\Omega\text{m}^2$ for VES 40–45, brackish aquifer was interpreted with $T_r$ 1650–1700 $\Omega\text{m}^2$ for VES 38–42, and fresh aquifer was delineated with $T_r$ 2520–9951 $\Omega\text{m}^2$ for VES 23 and 36–39 (Figure 4b). Seawater intrusion of about 65 km
was revealed along profile E with VES 38–45. Figure 5a shows the integrated 2D maps of transverse unit resistance, and Figure 5b provides the demarcation of saline, brackish, and fresh groundwater for the integrated 2D $T_r$ maps. Generally, seawater intrusion of about 27–75 km is delineated from the Arabian Sea in the southwest towards the inland of Bela Plain in the northeast (Figure 5b).

Figure 4. (a) Two-dimensional (2D) mapping of transverse unit resistance along profiles A–E in Bela Plain; (b) 2D interpreted maps of (a) for the delineation of saline, brackish, and freshwater based on the correlation between (b) and local hydrogeological information.
Figure 5. (a) Integrating 2D maps of transverse unit resistance along profiles A-E in Bela Plain; (b) interpreting (a) for the delineation of saline, brackish, and freshwater based on the correlation between (b) and local hydrogeological information.

4.3. Longitudinal Conductance

Longitudinal unit conductance ($S_c$) was estimated using a combination (Equation (2)) of aquifer thickness and resistivity obtained from 45 VES models along profiles A-E. Based on the wells information and hydrogeological setting of the study area, a specific values range of longitudinal unit conductance was obtained to delineate fresh, brackish, and saline aquifers with a clear interface. Low values of $S_c$ reveal freshwater with gravel-sand, whereas high values delineate saline water mainly with clay. Saline aquifer was delineated with $S_c > 24$ mho having clay, fresh aquifer was demarcated by $S_c < 3$ mho with sand, gravel-sand, and gravel, and brackish aquifer was interpreted with $S_c$ between 3–24 mho containing clay-sand (Table 2). Figure 6a shows mapping of the longitudinal unit conductance, whereas the demarcation of saline, brackish, and fresh groundwater at different depths (i.e., 50, 100, 150, and 200 m) is given in Figure 6b. At a 50 m depth, longitudinal unit conductance varies from 0.7 to 80 mho with $S_c$ between 34.1–80 mho delineating saline aquifer, 14–21.5 mho demarcating brackish aquifer, and 0.7–2.4 mho revealing fresh aquifer. At a 100 m depth, $S_c$ ranges from 0.15 to 1460 mho having $S_c$ between 34.1–1460 mho for saline aquifer, 13.6–21.5 mho for brackish aquifer, and 0.15–2.4 mho for fresh aquifer. At a 150 m depth, $S_c$ varies between 0.23–1460 mho with a $S_c$ range of 80–1460 mho revealing saline aquifer, 4.1–21.5 mho delineating brackish aquifer, and 0.23–2.2 mho interpreting fresh aquifer. At a 200 m depth, $S_c$ ranges from 0.07 to 1460 mho with $S_c$ between 42–1460 mho for saline aquifer, 4.1–20 mho for brackish aquifer, and 0.07–2.2 mho for fresh aquifer. Longitudinal unit conductance values for saline water increase with depth from 34.1 to 1460 mho and decrease for freshwater with depth from 2.4 to 0.07 mho, and thus suggest an increase in seawater intrusion with depth (Figure 6b).
Longitudinal unit conductance ($S_c$) was obtained to delineate fresh, brackish, and saline aquifers with different ranges from 0.15 to 1460 mho having $S_c$ values between 0.1–2.4 mho for fresh aquifer, 0.1–2.43 mho for brackish aquifer, and 0.7–2.2 mho for saline aquifer. Longitudinal unit conductance values for saline water increased with depth from 2.4 to 0.07 mho, and thus suggest an increase in seawater intrusion with depth (Figure 6b).

The 2D mapping of longitudinal unit conductance and the interpreted zones of fresh, brackish, and saline water along profiles A–E are shown in Figure 7a,b. The fresh-saline aquifers interpreted by $S_c$ are given in Figure 7b. Along profile A, saline aquifer was demarcated by $S_c$ from 37.5 to 1130 mho for VES 10–13, brackish aquifer was delineated with $S_c$ between 4.28–16.5 mho for VES 4–11, and fresh aquifer was revealed with $S_c$ ranging from 0.15 to 2.28 mho for VES 1–10. Seawater intrusion of about 80 km was delineated along profile A for VES 4–13. Along profile B, fresh aquifer was assessed by $S_c$ ranging from 0.07 to 2.4 mho for VES 14–16, brackish aquifer was revealed with $S_c$ of 21.5 mho for VES 15–17, and saline aquifer was demarcated with $S_c$ between 37.5–1090 mho for VES 11 and 16–22. This profile delineated seawater intrusion of about 90 km along VES 11 and 15–22. Along profile C, saline water was interpreted by $S_c$ from 45 to 1150 mho for VES 20 and 24–29, brackish water was delineated with $S_c$ of 17.8 mho for VES 24–26, and freshwater was evaluated with $S_c$ between 0.1–2.43 mho for VES 23–25. Seawater intrusion of 60 km was revealed along profile C with VES 20 and 24–29. Along profile D, freshwater was identified with $S_c$ between 0.9–2.4 mho for VES 23 and 30–34, brackish water was interpreted by a $S_c$ range of 4.67–14.1 mho for VES 30–34, and saline water was demarcated with $S_c$ from 35.76 to 1130 mho for VES 13, 34, and 35. This profile reveals seawater intrusion of about 35 km along VES 13 and 30–35. Along profile E, saline aquifer was delineated with a $S_c$ range of 35–128 mho for VES 40–45, brackish aquifer was interpreted by $S_c$ from 5 to 17 mho for VES 37–42, and fresh aquifer was

![Figure 6. (a) Distribution of longitudinal unit conductance in Bela Plain at depths of 50, 100, 150, and 200 m; (b) delineation of saline, brackish, and freshwater for (a) based on the correlation between (b) and local hydrogeological information.](image-url)
assessed by $S_c$ ranging from 0.1 to 2.43 mho for VES 23 and 36–39. Seawater intrusion of about 75 km was delineated along this profile with VES 37–45. Figure 8a provides the integration of 2D $S_c$ maps. The fresh, brackish, and saline aquifers delineated by the integrated 2D $S_c$ maps over the entire study area are given in Figure 8b. The integration of 2D $S_c$ maps delineates seawater intrusion of about 35–90 km from the seaside in the southwest towards the investigated area in the northeast (Figure 8b).

Figure 7. (a) 2D mapping of longitudinal unit conductance along profiles A–E in Bela Plain; (b) 2D interpreted maps of (a) for the delineation of saline, brackish, and freshwater based on the correlation between (b) and local hydrogeological information.
Figure 8. (a) Integrating 2D maps of longitudinal unit conductance along profiles A–E in Bela Plain; (b) interpreting (a) for the delineation of saline, brackish, and freshwater based on the correlation between (b) and local hydrogeological information.

4.4. Longitudinal Resistivity

Longitudinal resistivity ($\rho_L$) was estimated for 45 VES models along profile A–E from a relation (Equation (3)) obtained by the arrangement of aquifer thickness and longitudinal conductance. Longitudinal resistivity revealed saline, brackish, and fresh aquifers with a wide range of values based on local hydrogeological setting and wells information. Generally, a high $\rho_L$ suggests freshwater mainly with gravel-sand, while a low $\rho_L$ reveals saline water with clay as the dominant lithology. In this investigation, longitudinal resistivity delineated the saline aquifer with $\rho_L < 5 \Omega m$ having clay, the brackish aquifer with $\rho_L$ from 5 to 20 $\Omega m$ containing clay-sand, and freshwater with $\rho_L > 20 \Omega m$ having sand, gravel-sand, and gravel (Table 2). Mapping of the longitudinal resistivity over 45 VES is given in Figure 9a. The demarcation of fresh, brackish, and saline aquifers at different depths (50, 100, 150, and 200 m) is shown in Figure 9b. At a 50 m depth, $\rho_L$ values vary between 1–60 $\Omega m$ with $\rho_L$ range of 1–4.1 $\Omega m$ for saline aquifer, 8–11 $\Omega m$ for brackish aquifer, and 34–60 $\Omega m$ for fresh aquifer. At a 100 m depth, $\rho_L$ ranges between 0.1–432 $\Omega m$ with $\rho_L$ between 0.1–4.1 $\Omega m$ for saline aquifer, 8–11 $\Omega m$ for brackish aquifer, and 37–4320 $\Omega m$ for fresh aquifer. At 150 and 200 m depths, $\rho_L$ varies between 0.1–350 $\Omega m$ having $\rho_L$ of 0.1–0.9 $\Omega m$ for saline aquifer, 8–18 $\Omega m$ for brackish aquifer, and 35–350 $\Omega m$ for fresh aquifer. Figure 9 suggests that longitudinal resistivity increases (from 34 to 432 $\Omega m$) with depth within the fresh aquifer and decreases (from 4.1 to 0.1 $\Omega m$) with depth within the saline aquifer, which shows seawater intrusion from the seaside with the increasing depth (Figure 9b).
Along profile A, saline aquifer was assessed with $\rho_L$ between 0.1–432, 0.1–256, 0.1–321, 0.1–321, and 0.5–321 $\Omega$m, respectively (Figure 10a). The fresh, brackish, and saline aquifers revealed by the longitudinal resistivity are given in Figure 10b. Along profile A, saline aquifer was assessed with $\rho_L$ ranging from 0.1 to 3.2 $\Omega$m for VES 11–13, brackish aquifer was revealed with $\rho_L$ from 10 to 18 $\Omega$m for VES 8–11, and fresh aquifer was interpreted by $\rho_L$ between 35–432 $\Omega$m for VES 1–10. Seawater intrusion along profile A was delineated about 45 km inside the study area along VES 8–13. Along profile B, fresh aquifer was delineated by $\rho_L$ between 34–256 $\Omega$m for VES 14–16, brackish aquifer was demarcated with $\rho_L$ 8 $\Omega$m for VES 17, and saline aquifer was assessed with $\rho_L$ from 0.1 to 3.2 $\Omega$m for VES 11 and 17–22. Seawater intrusion of about 75 km was revealed along profile B for VES 11 and 17–22. Along profile C, saline aquifer was evaluated by $\rho_L$ between 0.1–2 $\Omega$m for VES 20 and 26–29, brackish aquifer was evaluated with $\rho_L$ 9 $\Omega$m for VES 26, and fresh aquifer was delineated by $\rho_L$ 37–321 $\Omega$m for VES 23–25. Seawater intrusion of 50 km was delineated along this profile with VES 20 and 26–29. Along profile D, freshwater was revealed with $\rho_L$ ranging from 37 to 321 $\Omega$m for VES 23 and 30–34, brackish aquifer was assessed with $\rho_L$ between 11–18 $\Omega$m for VES 31 and 33–35, and saline aquifer was delineated by $\rho_L$ between 0.1–3.3 $\Omega$m for VES 13 and 35. Profile D reveals seawater intrusion of about 25 km along VES 13, 31, and 33–35. Along profile E, saline aquifer was demarcated by $\rho_L$ between 0.5–4 $\Omega$m for VES 41–45, brackish aquifer was delineated with $\rho_L$ 10–17 $\Omega$m for VES 38–42, and fresh aquifer was revealed with $\rho_L$ 37–321 $\Omega$m for VES 23 and 36–40. This profile reveals seawater intrusion of about 55 km with VES
Figure 11a provides the integration of 2D longitudinal resistivity maps, whereas the separation of saline, brackish, and fresh groundwater zones in the integrated 2D $\rho_L$ maps is given in Figure 11b. The longitudinal resistivity delineated seawater intrusion of about 25–75 km from the Arabian Sea in the southwest towards the study area in the northeast (Figure 11b).

Saline, brackish, and fresh groundwater revealed by transverse unit resistance, longitudinal resistivity, and longitudinal unit conductance shows good matching. D-Z parameters delineate seawater intrusion of about 25–90 km from the sea towards the inland. Hence, D-Z parameters demarcate three different aquifers of fresh, brackish, and saline water without an overlapping character. The study of D-Z parameters suggest that the overlapping of saline, brackish, and fresh aquifers caused by intermixing of similar lithologies (clay-sand and clay or sand and clay-sand, etc.) in VES models can be successfully removed by the use of D-Z parameters in any aquifer system. Hence, D-Z parameters provide more confident solutions for the delineation of fresh-saline aquifers.
The suggested guideline of the World Health Organization (WHO) was used to assess the groundwater quality [42,43]. Here, we assessed the saline, brackish, and fresh groundwater by the suggested range of WHO for main cations, anions, and pH, as well as TDS and EC (Table 3). The parameters which exceeded the suggested limit of WHO were interpreted as brackish-saline aquifers and those which did not exceed the permissible range were evaluated as freshwater.

The interpretation of the physicochemical study reveals that four samples (1, 2, 5, and 8) lie in the fresh aquifer zone, five samples (3, 6, 9, 10, and 12) delineate the brackish aquifer, and the remaining four groundwater samples (4, 7, 11, and 13) reveal the saline aquifer (Figure 12). Fresh groundwater samples (Figure 12) lie in the zone of the fresh aquifer delineated by D-Z parameters (Figures 3–11). Similarly, locations of five brackish-groundwater samples match with the brackish aquifer revealed by D-Z parameters (Figures 3–11). Moreover, saline groundwater samples are located in the zone of the saline aquifer as demarcated by D-Z parameters (Figures 3–11). The results suggest a strong correlation for saline, brackish, and fresh groundwater revealed by physicochemical and D-Z parameters. Hence, saline, brackish, and fresh groundwater zones revealed by D-Z parameters of the VES method are

![Figure 11](image-url)
validated by the physicochemical analysis, which suggests that this approach can be successfully used as an alternate to the expensive laboratory tests analysis in order to assess seawater intrusion into fresh aquifers for coverage of large areas.

Table 3. Study of physicochemical analysis for the demarcation of saline, brackish, and fresh groundwater using the suggested limits of WHO.

| Physicochemical Parameters | Units | Minimum | Maximum | Mean | Median | SD | WHO Range for Aquifers |
|---------------------------|-------|---------|---------|------|--------|----|------------------------|
| Cations                   |       |         |         |      |        |    | Fresh                |
| Na⁺                       | (mg/L)| 28      | 3654    | 1056.3 | 283    | 1406.9 | <200                   |
| K⁺                        | (mg/L)| 15      | 235     | 89.3  | 61     | 76.4  | 55–70                  |
| Ca²⁺                      | (mg/L)| 30      | 650     | 294.1 | 245    | 211.9 | <200                   |
| Mg²⁺                      | (mg/L)| 21      | 495     | 206   | 120    | 184.2 | <100                   |
| Anions                    |       |         |         |      |        |    | Brackish               |
| Cl⁻                       | (mg/L)| 110     | 8122    | 2401 | 760    | 3078.8 | <250                   |
| SO₄²⁻                     | (mg/L)| 114     | 1144    | 443.9 | 365    | 329.6 | <200                   |
| HCO₃⁻                     | (mg/L)| 95      | 756     | 479.9 | 520    | 194.2 | <500                   |
| NO₃⁻                      | (mg/L)| 1       | 14      | 8.1   | 8      | 3.9  | 7–10                   |
| Other Parameters          |       |         |         |      |        |    | Freshwater             |
| EC                        | (μS/cm)| 40      | 19232   | 5882.3| 2232   | 7124.7 | <1500                  |
| TDS                       | (mg/L)| 311     | 13271   | 4058 | 1540   | 4915.5 | <1000                  |
| pH                        | -      | 7.1     | 9.5     | 8.4  | 8.6    | 0.8  | 8.5–9                  |

Figure 12. Graphical analysis of physicochemical parameters for the demarcation of saline, brackish, and fresh groundwater in Bela Plain.

5. Discussion

This research was conducted for the demarcation of saline, brackish, and fresh groundwater in a coastal area (Bela Plain) of Pakistan. Due to the over-exploitation of freshwater resources, especially for agriculture purposes, the study area is facing a problem of seawater intrusion, and thus, it is a big challenge for the proper management of freshwater resources in Bela Plain. Seawater intrusion is a universal problem, especially in the coastal areas. Conventionally, seawater intrusion into coastal aquifers is delineated by laboratory tests using the groundwater samples. However, such tests are expensive, and still cannot assess large areas. Geophysical methods especially VES techniques have been widely used for an evaluation of contaminated aquifers. The use of such methods is inexpensive, non-invasive, and user friendly. However, in some cases, the subsurface lithologies show similarities such as clay-sand and clay or sand and clay-sand, which cause the intermixing of resistivity values. Such intermixing in resistivity values of subsurface layers produce an overlapping of lithologies, and hence cause an overlapping of fresh-saline aquifers associated with these lithologies. In this work, we have used Dar-Zarrouk parameters to solve this problem. D-Z parameters namely longitudinal resistivity (ρL), longitudinal conductance (Sₗ), and transverse unit resistance (Tᵣ) estimated from resistivity models delineate the fresh-saline aquifer interface without causing any intermixing of saline, brackish, and fresh groundwater. Several studies have used such parameters for the delineation of fresh-saline aquifers, however, none of these studies provides 2D mapping of the fresh-saline interface.
In addition, the 2D ERT cannot cover large areas. Therefore, this work is the first ever investigation, which provides 2D delineation of fresh-saline aquifers using the D-Z parameters computed from VES. The results of $T_r$, $S_c$, and $\rho_L$ in Figures 3–11 are highly agreeable to each other, especially the fresh-saline aquifers delineated by $T_r$ and $\rho_L$ show good matching. However, there are still some minor discrepancies. For instance, the $S_c$ results do not show perfect matching with those of the other two D-Z parameters. The brackish-fresh interface of $S_c$ is delineated further inland (north/northeast) as compared to that of $T_r$ and $\rho_L$ while the saline-brackish interface of $T_r$ and $\rho_L$ is demarcated more towards the sea (south/southwest) as compared to that of $S_c$. This inconsistency is due to the nature of these parameters. High values of $T_r$ and $\rho_L$ with a wide range (i.e., 2000–29000 $\Omega$ m$^2$ and 20–440 $\Omega$ m, respectively) delineate freshwater, while low values of these parameters with a small range (i.e., <2000 $\Omega$ m$^2$ and <20 $\Omega$ m, respectively) reveal brackish-saline water. Conversely, low values of $S_c$ with a low range (i.e., <3 mho) delineate freshwater, whereas its high values with a wide range (i.e., 3–1200 mho) demarcate the brackish-saline aquifer. The comparison of saline-brackish and brackish-fresh interface revealed by the three D-Z parameters and the resultant interface of these parameters including the topography of the investigated area is shown in Figure 13. The resultant fresh, brackish, and saline aquifers of the D-Z parameters (Figure 13) are in good agreement with those of the hydrogeological map of the investigated area (Figure 1a).

**Figure 13.** Delineation of fresh, brackish, and saline aquifers using the resultant of D-Z parameters on the topographic map of the investigated area.
This innovative geophysical approach is applicable in any aquifer system under any hydrogeological setting. This investigation clearly marks the fresh-saline boundary (i.e., intermixing of fresh and saline aquifers), and proposes that the inland areas in the north and northeast of the nearby brackish-fresh boundary are the most sensitive areas, which can be easily intruded by seawater in the future. A 2D/3D ERT survey is suggested to be conducted in the sensitive areas near the brackish-freshwater interface for future management of freshwater resources in Bela Plain.

6. Conclusions

In this study, the calibration between the formation resistivity computed from 45 VES models and lithological logs constructed from 13 boreholes constrained subsurface units into six layers, such as clay having resistivity <7 Ωm with saline aquifer, clay-sand having a resistivity range of 4–24 Ωm with brackish aquifer, sand having resistivity between 18–42 Ωm with fresh aquifer, gravel-sand with resistivity between 34–60 Ωm containing fresh aquifer, and gravel with resistivity greater than 50 Ωm having fresh aquifer. This calibration shows the intermixing of resistivity values for subsurface layers, which cause an overlapping of fresh-brackish and brackish-saline groundwater zones. Based on the local wells information and hydrogeological conditions, D-Z parameters delineate saline, brackish, and fresh groundwater with a wide range of values. The saline aquifer was delineated by \( T_r < 1000 \Omega m^2 \), \( \rho_L < 5 \Omega m \), and \( S_c > 24 \text{ mho} \), brackish groundwater was revealed for \( T_r \) between 1000–2000 \( \Omega m^2 \), \( \rho_L \) range of 5–20 \( \Omega m \), and \( S_c \) between 3–24 \( \text{ mho} \), and fresh aquifer was demarcated by \( T_r > 2000 \Omega m^2 \), \( \rho_L > 20 \Omega m \), and \( S_c < 3 \text{ mho} \). These parameters delineate seawater intrusion of about 25–90 km from the Sonmiani Bay towards Bela Plain. Saline, brackish, and fresh groundwater demarcated by 2D mapping of D-Z parameters was confirmed by the physicochemical analysis of 13 groundwater samples and the hydrogeological map of the investigated area. The results confirm that the qualitative analysis of D-Z parameters is consistent with the regional geology of the study area. Hence, D-Z parameters can delineate seawater intrusion into fresh aquifer through clear demarcation of 2D/3D mapping of fresh-saline aquifers, and thus reduce the number of expensive laboratory tests. This economical approach is effective in both homogeneous and heterogeneous aquifers.

Author Contributions: Conceptualization, M.H.; methodology, M.H. and Y.S.; software, M.H.; validation, M.H., Y.S., and W.J.; formal analysis, M.H. and Y.S.; investigation, M.H., Y.S., W.J., P.S., X.Y., and G.A.; resources, M.H. and Y.S.; data curation, M.H., Y.S., W.J., and P.S.; writing—original draft preparation, M.H., Y.S., and X.Y.; writing—review and editing, M.H. and Y.S.; visualization, M.H.; supervision, M.H. and Y.S.; project administration, M.H., Y.S., and W.J.; funding acquisition, M.H. and Y.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Chinese Academy of Sciences for a Post-Doctoral fellowship (no. 2020PD01), National Basic Research Program of China (no. 2014CB046901), Chinese National Scientific Foundation Committee (NSFC) (no. 41772320), National Science and Technology Basic Resources Investigation Project (no. 2018FY100503), and the second Tibetan Plateau Scientific Expedition and Research Program (STEP) (no. 2019QZKK0904).

Acknowledgments: The authors wish to acknowledge the support received from IGG’s International Fellowship Initiative (IIFI) for Post-doctorate; Key Laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China; the Pakistan Council of Research in Water Resources, Islamabad Pakistan (PCRWR); and the Water And Power Development Authority, Pakistan (WAPDA).

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Hasan, M.; Shang, Y.; Akhter, G.; Jin, W. Application of VES and ERT for delineation of fresh-saline interface in alluvial aquifers of Lower Bari Doab, Pakistan. J. Appl. Geophys. 2019, 164, 200–213. [CrossRef]
2. El Baba, M.; Kayastha, P.; Huysmans, M.; De Smedt, F. Evaluation of the Groundwater Quality Using the Water Quality Index and Geostatistical Analysis in the Dier al-Balah Governorate, Gaza Strip, Palestine. Water 2020, 12, 262. [CrossRef]
3. Carol, E.; Kruse, E.; Mas-Pla, J. Hydrochemical and isotopical evidence of ground water salinization processes on the coastal plain of Samborombőn Bay, Argentina. J. Hydrol. 2009, 365, 335–345. [CrossRef]
4. Najib, S.; Fadili, A.; Mehdi, K.; Riss, J.; Makan, A. Contribution of hydrochemical and geoelectrical approaches to investigate salinization process and seawater intrusion in the coastal aquifers of Chaouia. *Morocco. J. Contam. Hydrol.* 2017, 198, 24–36. [CrossRef]

5. Adepeulu, A.A.; Ako, B.D.; Ajayi, T.R.; Afolabi, O.; Omotoso, E.J. Delineation of saltwater intrusion into the freshwater aquifer of Lekki Peninsula, Lagos, Nigeria. *Environ. Geol.* 2009, 56, 927–933. [CrossRef]

6. Shammas, M.I.; Jacks, G. Seawater intrusion in the Salalah plain aquifer, Oman. *Environ. Geol.* 2007, 53, 575–587. [CrossRef]

7. Cimino, A.; Cosentino, C.; Oieni, A.; Tranchina, L. A geophysical and geochemical approach for seawater intrusion assessment in the Acquedolci coastal aquifer (Northern Sicily). *Environ. Geol.* 2008, 55, 1473–1482. [CrossRef]

8. Alfarrah, N.; Walraevens, K. Groundwater overexploitation and seawater intrusion in coastal areas of arid and semi-arid regions. *Water* 2018, 10, 143. [CrossRef]

9. Vann, S.; Puttiwongtrak, A.; Suteerasak, T.; Koedsin, W. Delineation of Seawater Intrusion Using Geo-Electrical Survey in a Coastal Aquifer of Kamala Beach, Phuket, Thailand. *Water* 2020, 12, 506. [CrossRef]

10. Barlow, P.M.; Reichard, E.G. Saltwater intrusion in coastal regions of North America. *Hydrogeol. J.* 2010, 18, 247–260. [CrossRef]

11. Hasan, M.; Shang, Y.; Akhter, G.; Khan, M. Geophysical Investigation of Fresh-Saline Water Interface: A Case Study from South Punjab, Pakistan. *Groundwater* 2017, 55, 841–856. [CrossRef] [PubMed]

12. Hasan, M.; Shang, Y.; Akhter, G.; Jin, W. Delineation of Saline-Water Intrusion Using Surface Geoelectrical Method in Jahanian Area, Pakistan. *Water* 2018, 10, 1548. [CrossRef]

13. Costall, A.; Harris, B.; Pigois, J.P. Electrical Resistivity Imaging and the Saline Water Interface in High-Quality Coastal Aquifers. *Surv. Geophys.* 2018, 39, 753–816. [CrossRef]

14. Goebel, M.; Pidlisecky, A.; Knight, R. Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast. *J. Hydrol.* 2017, 551, 746–755. [CrossRef]

15. Khublaryan, M.G.; Frolov, A.P.; Yushmanov, I.O. Seawater intrusion into coastal aquifers. *Water Resour.* 2008, 35, 274–286. [CrossRef]

16. Kouzana, L.; Benassi, R.; Ben Mammou, A.; Sfar Felfoul, M. Geophysical and hydrochemical study of the seawater intrusion in Mediterranean semi-arid zones. Case of the Korba coastal aquifer (Cap-Bon, Tunisia). *J. Afr. Earth Sci.* 2010, 58, 242–254. [CrossRef]

17. Hasan, M.; Shang, Y.; Akhter, G.; Jin, W.J. Geophysical Assessment of Groundwater Potential: A Case Study from Mian Channu Area, Pakistan. *Groundwater* 2017, 56, 783–796. [CrossRef]

18. Hasan, M.; Shang, Y.; Metwaly, M.; Jin, W.J.; Khan, M.; Gao, Q. Assessment of Groundwater Resources in Coastal Areas of Pakistan for Sustainable Water Quality Management using Joint Geophysical and Geochemical Approach: A Case Study. *Sustainability* 2020, 12, 9730. [CrossRef]

19. Al Farajat, M. Characterization of a coastal aquifer basin using gravity and resistivity methods: A case study from Aqaba in Jordan. *Acta Geophys.* 2009, 57, 454–475. [CrossRef]

20. Abdalla, O.A.E.; Ali, M.; Al-Higgi, K.; Al-Zidi, H.; El-Hussain, I.; Al-Hinai, S. Rate of seawater intrusion estimated by geophysical methods in an arid area: Al Khabourah, Oman. *Hydrogeol. J.* 2010, 18, 1437–1445. [CrossRef]

21. Akpan, A.E.; Ugbaja, A.N.; George, N.J. Integrated geophysical, geochemical and hydrogeological investigation of shallow groundwater resources in parts of the Ikom-Mamfe Embayment and the adjoining areas in Cross River State, Nigeria. *Environ. Earth Sci.* 2013, 70, 1435–1456. [CrossRef]

22. Niculescu, B.M.; Andrei, G. Using Vertical Electrical Soundings to Characterize Seawater Intrusions in the Southern Area of Romanian Black Sea Coastline. *Acta Geophys.* 2019, 67, 1845–1863. [CrossRef]

23. Gurunadha Rao, V.V.S.; Tamma Rao, G.; Surinaidu, L.; Rajesh, R.; Mahesh, J. Geophysical and geochemical approach for seawater intrusion assessment in the Godavari Delta basin, A.P., India. *Water Air Soil Pollut.* 2011, 217, 503–514. [CrossRef] [PubMed]

24. George, N.J.; Obianwu, V.I.; Obot, I.B. Estimation of groundwater reserve in unconfined frequently exploited depth of aquifer using a combined surficial geophysical and laboratory techniques in The Niger Delta, South–South, Nigeria. Pelagia Research Library (USA) AASRFC. *Adv. Appl. Sci. Res.* 2011, 2, 163–177.

25. Singh, U.K.; Das, R.K.; Hodlur, G.K. Significance of Dar-Zarrouk parameters in the exploration of quality affected coastal aquifer systems. *Environ. Geol.* 2004, 45, 696–702. [CrossRef]
26. Water and Power Development Authority, Pakistan (WAPDA). Annual report of river and climatological data of Pakistan, river discharge, sediment and quality data. In Prepared by Surface Water Hydrology Project, WASID; WAPDA: Lahore, Pakistan, 1973.
27. Water and Power Development Authority, Pakistan (WAPDA). Annual Reports 1988–89; WAPDA: Lahore, Pakistan, 1989; pp. 21–98.
28. McNeill, J.D. Electromagnetic Terrain Conductivity Measurements at Low Induction Numbers; Technical Note TN-6; Geonics, Ltd.: Misissauga, ON, Canada, 1980.
29. Sherif, M.; El Mahmoudi, A.; Garamoon, H.; Kacimov, A.; Akram, S.; Ebraheem, A.; Shetty, A. Geoelectrical and hydrogeochemical studies for delineating seawater intrusion in the outlet of Wadi Ham, UAE. Environ. Geol. 2006, 49, 536–551. [CrossRef]
30. Khalil, M.I.; Didar-Ul Islam, S.M.; Uddin, M.J.; Majumder, R.K. Coastal Groundwater Aquifer Characterization from Geoelectrical Measurements—A Case Study at Kalapara, Patuakhali, Bangladesh. J. Appl. Geol. 2020, 5, 1–12. [CrossRef]
31. Himia, M.; Tapias, J.; Benabdelouahab, S.; Salhi, A.; Rivero, L.; Elgettafi, M.; Mandour, A.E.; Stitou, J.; Casas, A. Geophysical characterization of saltwater intrusion in a coastal aquifer: The case of Martil-Alila plain (North Morocco). J. Afr. Earth Sci. 2017, 126, 136–147. [CrossRef]
32. Eissa, M.S.; Mahmoud, H.H.; Orfan, S.S. Geophysical and geochemical studies to delineate seawater intrusion in Bagoush Area, Northwestern coast, Egypt. Afr. Earth Sci. 2016, 121, 365–381. [CrossRef]
33. Zarroca, M.; Bach, J.; Linares, R.; Pellicer, X.M. Electrical methods (VES and ERT) for identifying, mapping and monitoring different saline domains in a coastal plain region (Alt Empord_a, Northern Spain). J. Hydrol. 2011, 409, 407–422. [CrossRef]
34. Gao, Q.; Shang, Y.; Hasan, M.; Jin, W.; Yang, P. Evaluation of a Weathered Rock Aquifer Using ERT Method in South Guangdong, China. Water 2018, 10, 293. [CrossRef]
35. Telford, W.M.; Geldart, L.P.; Sheriff, R.E. Applied Geophysics; Cambridge University Press: Cambridge, UK, 1990; p. 770.
36. Loke, M.H.; Acworth, I.; Dahlin, T. A comparison of smooth and blocky inversion method in 2D electrical tomography surveys. Explor. Geophys. 2003, 34, 182–187. [CrossRef]
37. Ipi2Winv.2.1Usersguide. In Computer Software User Guide Catalog; Moscow State University, Geological Faculty, Department of Geophysics and GEOSCAN-M Ltd.: Moscow, Russia, 2001; p. 25.
38. Batayneh, A.T. The estimation and significance of Dar-Zarrouk parameters in the exploration of quality affecting the Gulf of Aqaba coastal aquifer systems. J. Coast. Conserv. 2013, 17, 623. [CrossRef]
39. Hasan, M.; Shang, Y.; Akhter, G.; Jin, W.J. Delineation of contaminated aquifers using integrated geophysical methods in Northeast Punjab, Pakistan. Environ. Monit. Assess. 2019, 192, 12. [CrossRef]
40. Ehirim, C.N.; Nwankwo, C.N. Evaluation of aquifer characteristics and groundwater quality using geoelectric method in Choba, Port Harcourt. Arch. Appl. Sci. Res. 2010, 2, 396–403.
41. Henriet, J.P. Direct application of the Dar-Zarrouk parameters in ground water surveys. Geophys. Prospect. 1976, 24, 344–353. [CrossRef]
42. Kelly, W.E.; Reiter, P.F. Influence of anisotropy on relation between electrical and hydraulic properties. J. Hydrol. 1984, 74, 311–321. [CrossRef]
43. WHO (World Health Organization). Guidelines for Drinking-Water Quality. Recommendations Incorporating 1ST and 2nd Addenda, 3rd ed.; World Health Organization: Geneva, Switzerland, 2008; Volume 1.
44. APHA (American Public Health Association). Standard Methods for the Examination of Water and Wastewater; American Public Health Association: Washington, DC, USA, 2000.

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.