Application of Electrical Resistivity Survey and GIS for Hydrogeological Analysis and Salinity Zoning-A Case Study of District, Okara, Pakistan

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This is to certify that the

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THESIS ACCEPTANCE CERTIFICATE

It is certified that final copy of MS Thesis written by Mr. Muhammad Hamza, Registration No. 00000275532, MS Water Resources Engineering and Management (WRE&M) of batch 2018 has been vetted by undersigned, found complete in all respects as per NUST MS Policy, is free of plagiarism, errors, and mistakes, and is accepted as partial fulfillment for award of MS degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature:______________________________

Name of Supervisor: Dr. Shakil Ahmad

Date: _________________________________

Signature (HOD): ______________________

Date: _________________________________

Signature: _____________________________

Date: _________________________________

DEDICATION

I dedicate this research work to my parents for their love, support and encouragement.

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Almighty ALLAH never squanders any effort. Every piece of work is rewarded based on the nature of devotion. The author expresses gratitude to Almighty, the compassionate, for endowing him with the abilities to complete this research project. I would also like to express my heartfelt gratitude and indebtedness to my supervisor, Dr. Shakil Ahmad, NICE, NUST, for his highly experienced technical advice, dynamic supervision, and valuable guidance.

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Notation	Representation
K	Hydraulic Conductivity
K	Permeability
Q	Rate of Flow
A	Cross-sectional Area
EC_{iw}	Electrical Conductivity of Irrigation Water
EC	Electrical Conductivity
µ	Dynamic Viscosity
Σ	Density of Fluid
g	Gravitational Velocity
Mha	Million Hectares
Ppm	Parts Per Million
Mgd	Million Gallon Per Day
DC	Direct Current
T	Transmissivity
δz	Saturated Thickness of Aquifer
R_a	Apparent Resistivity
R	True Resistivity
V	Voltage
I	Current
G	Geometric Factor

LIST OF ABBREVIATIONS

Abbreviation	Description
IBIS	Indus Basin Irrigation System
SCARP	Salinity Control and Reclamation Project
CDA	Capital Development Authority
CIPB	Central Indus Platform Basin
RS	Remote Sensing
ERS	Electrical Resistivity Survey
VES	Vertical Electrical Sounding
GWPI	Groundwater Potential Index
SAR	Sodium Adsorption Ratio
RSC	Residual Sodium Carbonate
PCRWR	Pakistan Council of Research in Water Resources
LBDC	Lower Bari Doab Canal
IDW	Inverse Distance Weighting
GPS	Global Positioning System
RMS	Root Mean Square

ABSTRACT

Numerous groundwater management concerns have arisen as a result of excessive groundwater use. The yearly pumpage has already exceeded the annual safe yields in certain regions, which has caused the water table to drop. Due to continuing, intensive groundwater pumping in Punjab, Pakistan, the quality of the groundwater is declining. Vertical Electrical Soundings (VES) were used to conduct geoelectrical resistivity survey investigations at District Okara, Punjab, Pakistan. The tool used for the collection of data was ABEM Terrameter SAS 4000, Sweden. To evaluate the spatial inconsistency of soil and groundwater quality Schlumberger array was used. Overall field data was collected from 28 different locations of the study area. The computer software "Interpex IX1D" was used for the interpretation of field apparent resistivity to true resistivity values and corresponding thickness of sub surface layers. Geographic Information System (GIS) was used for the mapping of groundwater quality at 50 m intervals by employing Inverse Distance Weightage (IDW) interpolation technique. The results shows that the uppermost layer of 0 – 50m comprised of maximum potential of fresh and useable quality water. In addition, as we increase the investigation depth and move away from the river i.e. center of district Okara, the resistivity values shows a decreasing trend reflecting the saline groundwater.

Chapter 1

INTRODUCTION

1.1. Background

Enhanced crop production per unit of surface and groundwater sources utilized for watered areas is required as the world population increases rapidly. Irrigated agriculture's protection of the environment, demands the conservation of land and water while preserving and increasing crop output. Pakistan is an agro-based economy with harsh to semi-arid climates with rainfall that provides just 13 percent of the total water needed for cultivation (S. J. T. P. D. R. Ahmad, 2007). This situation prompted the development of irrigation systems in the river Indus, which has proved to financially beneficial as compared to rain-fed farming. Nevertheless, due to irregular rainfall patterns, significant range in seasonal rainfall and extent, increased cropping intensity, and climate change the country's ground water resources are constrained. As a result, across the south Asian subcontinent, groundwater is becoming vital to augment agricultural water needs (Hussain & Lee, 2013). One of the most important exploration administration parameters is underground water evaluation (Cheema, Immerzeel, & Bastiaanssen, 2014). In Pakistan, however, there really is no method or system for regulating aquifers. Regulation does not safeguard groundwater levels extraction entitlements. Even without authorization of any government department or national treasury, any agricultural or businessman with land and funds generally can establish the tube well (Irfan, Qadir, Ali, Jamil, & Ahmad, 2019). Moreover, the growers have little knowledge about the best site in terms of groundwater resources and health. Unforeseen groundwater pumping creates a slew of governance and economic issues.

The population growth of Pakistan rapidly increases from 87 million to 134 million between 1982 and 1999 (Asian Development Bank 2002), and is now above 144 million. Crop yields grew at a comparable rate during the same era, owing to improved freshwater resources with the building of the Tarbela and Mangla dams, as well as fast rise in the usage of individual bore wells in the River Indus. However, silt deposition is reducing the live storage space of biggest storage dams. (WCD, 2000)

In locations where fresh water is not accessible; this rise in crop productivity is mostly owing to the utilization of groundwater or effective irrigation technologies. By the end of 1979, moisture absorption and salinity had impacted approximately 42% of the IBIS (WAPDA, 1979). During the 1960s, the Salinity Control and Reclamation Projects (SCARP) were started, and by the mid-1990s, roughly 38 SCARPs had been constructed. These practices were quite effective in the freshwater zone, however result in secondary soil salinity in the subsurface zone (WCD, 2000).

Currently, the country has about 531,000 tube wells. Groundwater consumption peaked at 62 billion m^3 in 1996-97 and then began to decline. Around six billion m^3 of water was pumped yearly in 1999-2000 (GOP, 2000). The irrigation environment has altered because of increased usage of groundwater. The benefits to the growers are obvious, as freshwater permits watering at times and in quantities that the farmers desire. The use of groundwater appears to be economical, especially in locations where canal water is scarce. Groundwater resources are reduced as a result of tube-wells pumping, which is beneficial in locations where crops are waterlogged or salinized owing to passage of water of shallow aquifers (IWASRI, 1991).

Engagement in agriculture management control is insufficient; in contrast to administration, farmers have a crucial part to play in groundwater quality and quantity judgement. The duty for groundwater planning and improvement has steadily passed from the state to the commercial sector in Pakistan. Farmers are now developing and managing groundwater using private (personal) and communal (Farmers' Organizations) (S. Ahmad, Ahmad, Yasin, Akbar, & Khan, 2000). The type of surface flow, terrain, and pumping with amendment methods influence groundwater quality. The Indus basin's aquifer accounts for about a third of the entire water accessible for agriculture, while the quality of groundwater in the remaining 60% is mediocre to salty (S. Ahmad, Majeed, & Sciences, 2001; Bank, 1997)..

Because of leakage from the IBIS rivers and streams, this natural salty aquifer is now overlain by available freshwater. Fresh surface and groundwater seepage from rivers and streams in the Indus basin has enhanced the quality of groundwater system to depths of 90 - 120 meters. As a result, a deep fresh water zone exists between the pre-irrigation ground water and the current water tables. The quality of groundwater is the most important consideration for effective crop production on a long-term basis without compromising soil health (S. J. T. P. D. R. Ahmad, 2007).

1.2. Objectives

Over sixty percent of Pakistan's agricultural sector's water needs are satisfied by groundwater, making it an essential component in the country's agricultural growth. In Indus basin, groundwater salinity behavior has changed as a result of the excessive construction of tube wells, and groundwater is now decreasing in numerous river basins and practically all metropolitan areas. Same is the situation with district Okara where groundwater is depleting alongwith degradation of its quality. So this imposes to study and pay attention towards the better management of the aquifer.

The objectives of this study are as follows;

1) Application of Electrical Resistivity Survey to estimate subsurface lithology and groundwater salinity.

2) Spatial mapping of groundwater salinity using ArcGIS.

1.3. Rationale

Pakistan is a land-rich but water-scarce state with periodic water surpluses during the rainy season, raising and optimizing water efficiency is necessity to fulfil the rapidly growing population future agricultural and food needs. In Pakistan, irrigated agriculture is predominantly conducted in the Indus Basin, that's been used for agricultural since olden history and is one of the world's biggest continuous drainage network. The command area is 16.20 million hectares (Mha), and the yearly mean groundwater delivery through this network is roughly 180109 m^3. The climate of Pakistan varies from arid to semi-arid. Rivers, lakes and precipitation are insufficient to supply the basin's agricultural water needs. Groundwater will be used to make up for this shortfall. Saltwater intrusion as a result of significant freshwater removal is severely limiting the use of aquifers for agricultural, urban, and commercial purposes.(N Ahmad, 1993)

Pakistan's total yearly hydrological output is expected to be 68 billion m^3. The yearly pumpage of freshwater has risen from 04 km^3 in 1961 to over 60 km^3 in 1999-2000. Fresh groundwater suitable for cultivation can be found in 79 percent of Punjab and 28 percent of Sindh (Afzal et al., 2000; Alurralde, Gandarillas, & Skogerboe, 1998). When rivers and streams are insufficient in a number of irrigated regions in Pakistan, Province of Punjab, cultivation with low-quality aquifer is widespread this has resulted in aquifer degradation and ground solidity (Kijne, 1996).

Despite considerable drainage investments in Pakistan over the last 2 decades, water stress continues to afflict large areas of the country (Bank, 1994). Enormous private tube wells in areas with fresh water availability results in over aquifer extraction and groundwater contamination (Zuberi, Sufi, Salinity Research Institute , & Power Development Authority 1992).

Ground water quality assessment is critical since it is strongly linked to public health and numerous medical illnesses (Li et al., 2019). It is also necessary for commercial, agronomic, and household needs. Because of the widespread use of freshwater, the reservoirs are being impacted, and over one billion of people are without safe water. Furthermore, improper waste element removal, industrial residues in groundwater, food spoilage, and unnecessary pesticide use in farmland substantially pollute aquifers (Sanchez-Martos, Jimenez-Espinosa, & Pulido-Bosch, 2001). Because 2 billion individuals utilize aquifers for consumption (Ahmada, Chanda, & Rafiqueb, 2017), groundwater management is critical for states as well as other organizations, as its purity is linked to economic growth. Hand pumps, tube wells, and injection pumps are used to provide water supply in Pakistan (Azizullah, Khattak, Richter, & Häder, 2011). And since, little thought has been devoted for improving the quality of groundwater as a result, water derived from such resources is generally contaminated (Von Ehrenstein et al., 2006).

Throughout Pakistan, water supply is often imbalanced, and water-borne diseases including cholera, cirrhosis, diarrhea, and gastrointestinal illness are frequent. The hygienic status of water in urban areas is also poor (M. Ahmad, Chand, Rafique, & Treatment, 2016). Highly contaminated and poisoned drinking water is responsible for around 40% of fatalities and 30% of illnesses in Pakistan. Meanwhile, every fifth Pakistani gets infected, resulting in roughly 0.1 million fatalities per year (Haydar, Arshad, Aziz, & Sciences, 2009).

Geographic Information Systems (GIS) and Electrical Resistivity Survey (ERS) have become more essential approaches in geosciences in recent years for enhancing the illustrative ways of data collecting and map production. Visual understanding views employing GIS and ERS methods have solved the problem of data insufficiency.

(Gebremichael et al., 2018). In dry places, multi-GIS data layers can be combined with geological research to determine water availability (Yousif & Sracek, 2016). In addition, the effects of land and urban development on groundwater resources have been extensively studied utilizing ERS and GIS methodologies (Panaskar et al., 2016). Boring has historically been the preferred method for subterranean site examinations because it provides great precision and clarity at any depth. Test boring, on the other hand, is costly and difficult, and it only provides know the right way. Surface meteorological approaches, from the other hand, provide continuous simulations that highlight critical examples when extrapolated into linear, two dimensional, and 3-dimensional perspectives. The original physical models for geotechnical, hydrogeological, and geo-environmental studies are clearly electrical approaches (Attwa, 2012). For hydro-geophysical investigations, the direct current (DC) resistivity approach in the form of 1-dimensional and two-dimensional surveys is frequently utilized.

Using a geometrical pattern, the DC resistance probing (1D) predicts the layer contacts automatically. 1-Dimensional DC sensing is still used for underground water investigation, particularly in dry and semi-arid regions. Electrical Resistivity Survey (ERS) has been successfully used to image near-surface inhomogeneities that reflect subterranean features in a non-destructive way (AL-Menshed & Thabit, 2018). As a result, using both 1D and 2D inversion processes, combined 1D and 2D DC resistivity surveys can give important information regarding underlying layer patterns and groundwater potential outcomes.

1.4. Study Area

Okara is a district in the Sahiwal division of Punjab, Pakistan. It is bordered on the East by the district of Kasur, on the West by Sahiwal and Pakpattan, on the North by

Faisalabad and Sheikhupura, on the South by Bahawalnagar. On the district's Southern edge, there is also the Indian border. Okara is divided into three Tehsils namely Okara, Depalpur and Renala Khurd and covers a total area of 3541 square kilometers. The Okara District is renowned for its productive grounds, serene climate and verdant fields of crops like Wheat, Maize, Potatoes, Rice and Sugarcane. Okara is a densely cropped district where majority of the people earn their livelihood from agriculture sector. Over the time due to massive urbanization and over exploitation of groundwater with no or minimum recharge opportunities water level is constantly declining. Therefore, provision of good quality water for drinking and irrigation purposes is a challenge. For this purpose, water specimens were taken from different places and resistivity surveys were conducted in Lower Bari Doab Canal (LBDC), Pakistan, by the Pakistan Council of Research in Water Resources (PCRWR) in Lahore for the physio chemical investigations and demarcation of fresh and saline groundwater.

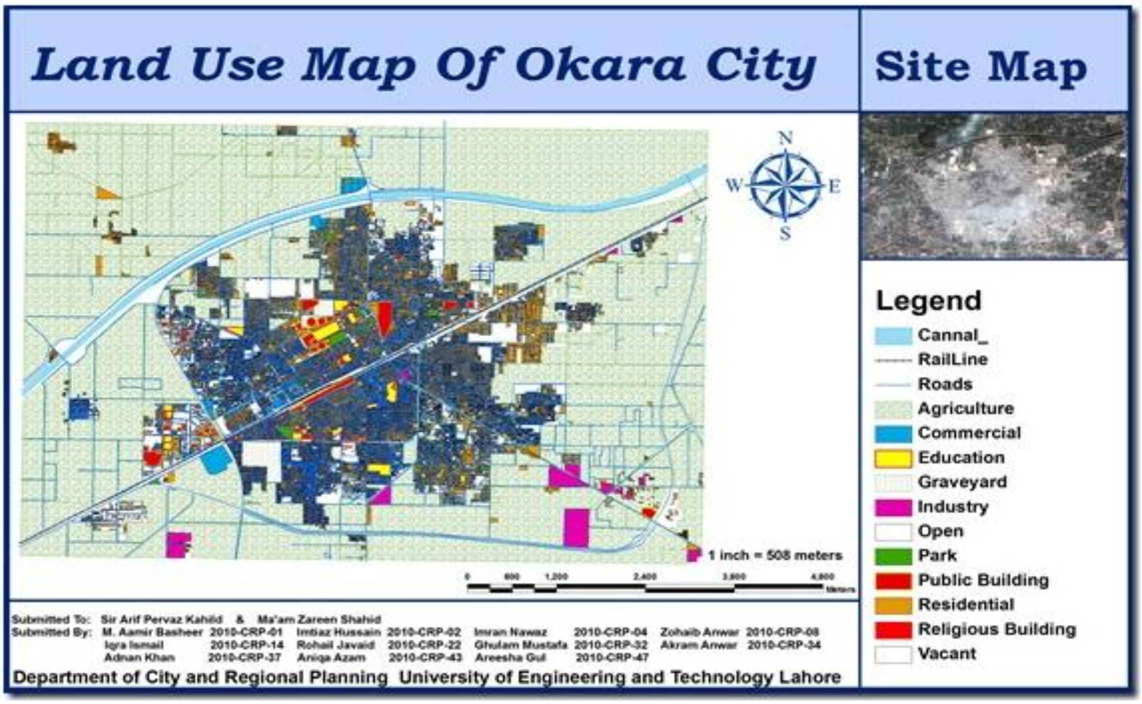


Figure.1.1 Land Use Map of Okara City

(Department of City and Regional Plannig, 2010)

It is located at 73°26'45' E longitude and 30°48'29" N latitude. It is a part of Central Indus Platform Basin of Pakistan. It was designated as a city (district) in 1982. The Ravi River connects the district of Okara with Lahore, which is 110 kilometers distant, and Faisalabad, which is 100 kilometers away. It has a population of 3,039,139 people, according to the 2017 survey. Okara bivouac is a lovely Pakistani canton. Okara has a semi - arid weather with an average precipitation of 296 mm and a temperature of 24.5°C.

1.5. Stratigraphic Sequence

This area's geologic history spans the Infra-Cambrian through Miocene-Pliocene periods. Because of the significant syn - rift at the foot of the Miocene, Miocene sediments directly overlie Cretaceous layers. The Infra-Cambrian is represented by clastics and carbonates, whereas the Cambrian is represented by clastics and dolomites, which are overlain by Permian clastics, glacial tillites, and limestone. Sandstones, shales, and carbonates describe the Triassic and Jurassic periods, whereas shales and sandstone characterize the Mesozoic and Miocene periods.

Chapter 2

LITERATURE REVIEW

2.1. Geology

Punjab Block is located in the Punjab, Pakistan districts of Pakpattan, Sahiwal, Okara, and Bahawalnagar. It is located in Pakistan's Central Indus Basin geologically. Prospectively Zone II applies to this block. The block is situated in the Centre Indus Platform Basin's eastern Basin (CIPB). The sedimentary rocks are not visible from the ground. It is a large monocline sloping slightly towards the Suleiman depression tectonically. The area is inclined eastward due to Pre-Cretaceous non-organic movements during the Paleozoic period. Because the area is far from the collision zone, it is the least affected by compression. As seen on seismic lines, the principal structures on the Punjab platform are paleo geographic highs caused by salt-pushed anticline folds. To date, a huge number of wells have been drilled on the platform. The stratigraphic sequence created by these wells showed some of Pakistan's most notable stratigraphic pinchouts (Haider et al., 2018).

According to subsurface evidence, the Precambrian basement rocks are formed of granites, unfossiliferous meta sediments, and metavolcanic. The Salt Range Formation (Infra-Cambrian) is the oldest rock discovered in the Punjab Platform through drilling. Pre-Himalayan orogenic motions caused lengthy uplifts/sea regression, resulting in unconformities. As a result, many salt-cored anticline formations are projected in the monocline's southern part (Asim et al., 2014) (Haider et al., 2018). Only sporadic crags of Precambrian period shield rocks can be found in the Shahkot, Kirana, Sargodha, and Sangla Hill areas (Aadil, Sohail, & Discovery Article-10364, 2011; Solangi et al., 2014).

The entire petroleum system may be found in Jurassic and Infra-Cambrian rocks. The presence of a viable petroleum system in the region is indicated by the presence of producing fields to the north-west of this block (MA Khan, Ahmed, Raza, & Kemal, 1986).

The Sembar development is the confirmed source rock in the Basin of Central Indus (Early Cretaceous). The Sembar formation has abundant source rocks for gas production that have reached the appropriate maturity (Quadri & Shuaib, 1986). The Datta and Shinawari Formations (Jurassic) exhibit high to very good potential as source rocks in the Platform region. Bilara is a putative source rock in the Central Indus Basin (Gee & Gee, 1989). The Bilara and Jodhpur Formations (Infra-Cambrian) might be possible reservoir rocks in the Central Indus Basin, as both formations have significant potential in the Punjab Platform area and are producing in neighboring Indian fields (Kazmi & Abbasi, 2008; MA Khan et al., 1986).

The only seals found in this region are shale. Within the shales that cover the reservoirs, sand beds can be found. The thin shale strata act as effective sealants in this location. Truncation traps and faults may be useful as supplementary system seals (Bender & Raza, 1995; Kazmi & Abbasi, 2008).

In this location, both structural and stratigraphical traps can be found. Along normal fault blocks and negative flower formations, stratigraphical traps constitute a substantial trapping mechanism. Horst and Graben's structures are generated as a result of the extensional regime. It's impossible to rule out the potential of stratigraphic traps in the form of sand lenses. (Quadri & Shuaib, 1986) found that transgressive shales from the Ghazij Formation and the Upper and Lower Goru Formations provide an efficient trapping mechanism for hydrocarbons trapped in the Lower Goru sand reservoirs (Tsutsumi et al., 2017).

2.2. STRATIGRAPHIC SUCCESSION

The stratigraphic categorization defined lateral stratigraphic connections and gave ordered lithostratigraphic and chronologic arrangements of the surface and subsurface strata. The stratigraphic and lithostratigraphic properties, as guides to the water, the placements of recognized formations play a vital role. Since the aquifer-forming rocks are mostly lithostratigraphic. Its location is strati graphically regulated, yet it is reliant. This is in reference to the projected groundwater position is shown, as well as the potential interactions with the environment hydrogeological pattern on the surface. The field work is being done to keep the rock units included on the geological map up to date Okara's map. The geology of the Okara area is then delineated, which includes: 1) determining the surface and shallow subsurface stratigraphic successions; following their horizontal and vertical extension in the Okara area; and defining the stratigraphic relationships between adjacent lithologic sections. 2) Rock samples and macrofossil specimens are collected. Rock types and rock units are identified using the samples gathered. The geologic ages were then determined using fossil indications and utilized to chronologically organize the sequence.3) identification of the physical qualities of the gathered samples, including diverse sedimentary natures, uneven hardness, and compaction of different rocks to withstand erosion and weathering processes, as well as rainfall and flood plow-up.

2.3. Geographic Information System (GIS)

In hydrologic assessments of drainage basins, Geographic information system (GIS) and Remote sensing (RS) techniques are commonly utilized. These hydrologic assessments cover a wide variety of connected activities, each with its own relevance based on the drainage basin's physical context and the surrounding locations. The shortage of water supplies and the occurrence of flash floods are two of the most serious hydrological issues in the dry country. As a result, the majority of hydrological assessments in these ecosystems are based on these concerns. Traditionally, the drilling is often the first choice for subsurface site investigations especially it gives high accuracy and resolution at any required depths. Nevertheless, the borehole drillings are time consuming and expensive and they give only point information. On the other hand, the surface geophysical methods give continuous models revealing the extreme points with extrapolation into 1D, 2D and 3D dimensions. For geological, hydrogeological and geo environmental investigations, the pioneering geophysical methods are undoubtedly electrical ones.(Attwa, Gemail, & Eleraki, 2016).

Morphology is the scientific term for the appraisal and quantitative analysis of the arrangement of the earth's crust, as well as the dimension and shape of its formations (Clarke, 1996). RS and GIS can be used to measure the linear, aerial, and relief features of basins for this investigation. The interaction of climate, geomorphology, geology and structural antecedents of the catchment is expressed through the morphometric study of the drainage basin and channel network. Many researchers have noticed the link between various drainage characteristics and the aforementioned components (Chorley, 2019; Reddy, Maji, Gajbhiye, & Geoinformation, 2004) (Lanka, Hubert, & Wesche, 1987).

GIS techniques are increasingly often used to provide a flexible environment and an important tool for manipulating and analyzing spatial data. However, recent advances in GIS have provided fresh insights into the precise analysis of hydrogeological factors (M Khan & Zaidi, 2015; A. Z. Zaidi, Khan, & Reviews, 2018).

2.4. Empirical Studies Based on Electrical Resistivity Survey

Incorporating the spatial location of the data into the analysis is frequently necessary for better understanding of hydrogeological data. Hydrogeological data and their spatial locations can be stored in a relational database using a geographic information system. In complement to this, it has the capacity to provide an objective assessment of geographical data under a variety of different logical situations. As a direct consequence of this, geographic information systems (GIS) are being applied rather regularly for more precise spatial forecasting of groundwater quality possibilities throughout a large region. Recent research has highlighted a variety of GIS uses for ground water exploration, and there are samples of these implications in published works.

Groundwater investigations and mapping in upper Indus plain is done by (A. Khan, Iqbal, Ashraf, & Sheikh, 2016). The geophysical investigations were supported by information derived from exploratory wells. Water as well as soil samples were collected at regular depth interval of 3m. The relation between earth resistivity and groundwater quality for BARI doab was developed with R^2=0.6657.

(Jamal & Singh, 2018) investigate groundwater bearing fracture zone by means of very small occurrence electromagnetic radiations and electrical resistivity method in study area of Rajasthan, India. To encounter the request of water of area, seven VLF-EM and three VES surveys were conducted. VLF-EM was primarily used to select appropriate zone then VES technique was applied to locate the position of well at specific depth. Based on this study two boreholes constructed in study area to meet the drinking and irrigation requirements.

(Muchingami, Hlatywayo, Nel, Chuma, & Chemistry of the Earth, 2012) examine a study of an urban Bulawayo aquifer situated at Zimbabwe. The resistivity values beneath 50 ohm-m showed that the central part of aquifer has greater groundwater potential and higher readings >500 ohm-m suggest that western part has a low potential. VES results demonstrates that there are three different layers, at 7.4m, 34m and 41m depth with apparent resistivity of 30, 94 and 2620 ohm-m respectively. More the value of apparent resistivity less the amount of water present in the aquifer.

(Orellana & Mooney, 1966) conducted an electrical resistivity survey in High Barind area to check the subsurface aquifer by using Vertical electrical sounding practices. Results displays that there are three to four sheets having resistivity values 10-260 ohm-m. From 4 - 41m, the layers consist sandy and silty clay. Morais *et al*., (2008) said that electrical resistivity technique is one of the most reliable method which determines the direction of water flow in soil pores and eventually the aquifer recharge. The experiment was performed at two different geological formations in Southern Brazil and measures the permeability. The results associate with the in-situ practical values of hydraulic conductivity of aquifer.

(Arshad, Cheema, Ahmed, & Biology, 2007) conducted an electrical resistivity survey a 9-different location along the bank of Jhang branch canal to study the groundwater characteristics of aquifer and came up with the results that soil present along the canal is alluvial and mostly consist of clay and sand. At the depth of 30-140m freshwater zone was found and suggest that groundwater below 140m depth is best fit for irrigation than the upper layer of water.

(Samouëlian et al., 2005) said that soil properties differ with temporal and spatial changes. Variations in resistivity is directly relates with the soil characteristics. They suggest that based on difference in aquifer properties like heterogeneous or anisotropic, Electrical resistivity survey should be conducted according to it i-e 1D, 2D or 3D survey. ERM is non-destructive mapping techniques with temporal monitoring of aquifer provides various scales application and data acquisition ability having larger resistivity measurement. The limitation of ERM is that it can be disturbed by some factors like contact of soil and electrode, calibration and non-uniqueness of the solution in inversion schemes

(Olubusola, Daniel, & Oladimeji, 2018) carried out a study which provides information regarding hydrogeological parameters. Schlumberger array of Electrical resistivity meter was used at 68 different locations. The result of Vertical electrical sounding shows four subsurface layers i.e. top, weathered, fractured and fresh water layers respectively. Groundwater yield index is obtained by multiplying anisotropy coefficient (λ) and Transverse resistance (T). For validation of this study pumping data was used

2.5. Himalayan Foothill Region

(Israil, Al-Hadithi, & Singhal, 2006) preformed a study In the piedmont zone of the Himalayan slopes area of Uttaranchal, India, a Geographical Information System (GWAS) has been utilized to integrate the findings of 70 vertical electrical soundings and hydrogeological information. The area's geomorphology and slope maps have been prepared using thematic maps created using Indian remote sensing (IRS) LWASS-III data. The limits of electrical resistivity values that correspond to the different positions have been determined using a calibration process that compares the boring information also with electric resistivity values. Data from boreholes, electrical resistivity measurements, groundwater level tracking, and satellite imagery have all been combined into the GWAS investigations in order to identify the hydrogeological segmentation of the study region. The many aspects affecting the groundwater potential were given appropriate weights The entire score for a certain place was converted into the region's potential for groundwater. According to the research results, the moderately steep landscape in the north part of the study region has a poor groundwater possibility, while the southern part of the area has a very good groundwater possibility for satiating the water requirements for agricultural and residence purposes. The elevated relief in the north part of the study region also contributes to the steepness of the landscape. The resulting definition of groundwater potential zones is generally consistent with the yield statistics of the tube wells that are already accessible.

In order to determine the specific aquifer topography, Vertical Electrical Soundings (VES) were documented at a total of 70 multiple places that use the Schlumberger setup. The highest electrode distance was approximately 900 meters, and the transmissions were managed to make at station intervals of approximately 2 kilometers or less. The change in resistivity that takes place near to the surface and deeper than 100 meters may be used to differentiate between shallower and deep groundwater networks. This distinction is possible because shallow groundwater systems are located at a shallower base than deeper aquifer systems. In order to examine the directional nature of the resistivity fluctuation, data are also collected in a direction that is perpendicular to the initial direction at the same location. To assess actual resistivity and depth, a computerized automated interpretation method was used to the data on apparent resistivity that were collected at each point. The existence of the water table is shown by the resistivity reading of 26 ohm-m taken at a depth of 15 meters below ground level. This particular spot has a depth of 13 meters all the way to the surface of the ocean. As a result, a resistivity value of 26 ohm-m is used so that the shallow aquifer may be accurately represented. The deeper aquifer has a resistivity of 74 ohm-m and is located at a depth of more than 67 meters below ground level. As a consequence of this, the aquifer system may be characterized by utilizing the data on the resistivity. These associations between internal resistance and lithology were used at multiple locations in the research area to define the electrical resistance ranges for a variety of lithologies. These resistivity ranges include the both saturated and unsaturated areas, terra cotta units, and the electrical resistance of shallow and profound groundwater. Clay units were also included.

2.6. MIDNAPORE DISTRICT, WEST BENGAL, INDIA

(Shahid & Nath, 2002) A Geographic Information System (GIS) has recently been developed as the core element of an incorporated explanatory methodology to evaluate ground water resources for the recognition of well places in Ghana. This technique was initially investigated for the assessment of geomorphic information recorded from SPOT photography for ground water prospective modelling. An Indian GIS-based model was developed for the purpose of determining groundwater levels potential areas in the Marudaiyar basin in Tamil Nadu. This model was developed by merging a variety of thematic layers that were obtained using remote sensing data. The results of the field validation of this approach shown that the GIS is successful in estimating the potential ground water storage.

According to (Sander, 1997; Teeuw, 1995), ground water resource evaluation has also been done using GIS. In the current study, vertical electrical sounding (VES) results and geological thematic maps created from remote sensing data are combined with GIS to create spatial modelling of the hydrogeological condition of a soft rock terrain in the Midnapur District, West Bengal, India. At 139 sites throughout the research region, vertical electrical sounding is done in order to create geophysical thematic maps. GIS is used to store the spatial location of the VES point and the relevant aquifer data, such as the resistivity and thickness of the aquifer. The relevant thematic map is then created by contouring the parameters. Aquifer resistivity thematic map components are rated according to their potential for predicting groundwater condition by superimposing them on a geology map of the area since the resistivity of the aquifer material depends on the geology of the area. The features on the thematic map of aquifer thickness, on the other hand, are graded according to the thickness values. The geographical model of the research area's hydrogeological prospects is created by integrating the two theme maps.

2.7. DIFFERENT MAPPING TECHNIQUES

It is commonly known that geology has a significant impact on how ground water is distributed and occurs. Geological studies conducted by (Šumanovac & Weisser, 2001) and others in a variety of terrains demonstrated the value of IRS-1A and IRS-1B data for geological mapping. Geological mapping is carried out in the current work employing upgraded IRS-1B, LISS-II images. The image is first corrected by utilising the UTM map projection method to put it onto a plane. For the computation of the transform matrix, a first order polynomial and Everest1830 spheroid are taken into account. Using the image processing programme ERDAS, the rectified image is then improved using linear stretching and principal component analysis for better exposition of hydrogeological features. By enabling a live-link facility between the image processing program ERDAS and the GIS package Arc/Info, features are mapped using GIS (Guerin & Benderitter, 1995).

The team successfully used a variety of geophysical techniques to solve the issue of water exploration beneath karst structures. To find karst pipes in limestone, Vogelsang used electromagnetic prospecting using the Sling ram method in 1987. MT-VLF and DC resistivity approaches were used by (Guerin & Benderitter, 1995). The advantages of using electrical techniques for dual-gradient mapping, two-dimensional electrical resistivity imaging, and seismic refraction. In karst water investigations, a method and HRS-high resolution seismic reflection approach are provided and analyzed on a typical karst instance in Croatia. These techniques were chosen because, when used together, they can produce an accurate geological model of the exploration area. Hard rock cracks and faults can be found using electromagnetic methods, however these techniques are often used to vertical and subvertical features.(Quadri & Shuaib, 1986)

Without the use of electrical and seismic techniques, it is difficult to conceive exploring for water in a karst region, but karst regions are extremely challenging conditions for any geophysical research due to very high surface non similarities. Two-dimensional resistivity imaging, high-resolution reflection techniques, dual gradient mapping measurements at two depth levels, and refraction techniques have all been used on a typical karst instance in Croatia. Weak reflections can be followed throughout the whole profile, but they are only visible in the seismic reflection section that is overlaid with the 2-D resistivity imaging profile. Faulted and fractured zones can be identified at the surface as well as at larger depths by integrating refraction and reflection data, which will allow for a detailed delineation of their extensions. In order to understand the relevance of the primary reflection horizon, two-dimensional inverse seismic modelling has been done. The combination of all the data has allowed for the establishment of a precise geological model. In karst water explorations of shallow targets, two-dimensional resistivity surveying can be employed extremely effectively, but for deeper targets, seismic methods can be very helpful due to the electrical resistivity methods' poor resolution.

Chapter 3

MATERIALS AND METHODS

3.1. Study Area

The study is conducted in the district of Okara, province Punjab, Pakistan. The study area i.e. Okara is divided into three tehsils namely Okara, Depalpur and Renala Khurd. Area wise Depalpur is the biggest tehsil. Field data was collected from 28 different locations within the study area. A total 11 VES readings were taken from different places with in tehsil Okara, 9 from tehsil Renala Khurd and 8 from tehsil Depalpur. There is a constraint in the data that limited VES data is available for Depalpur.

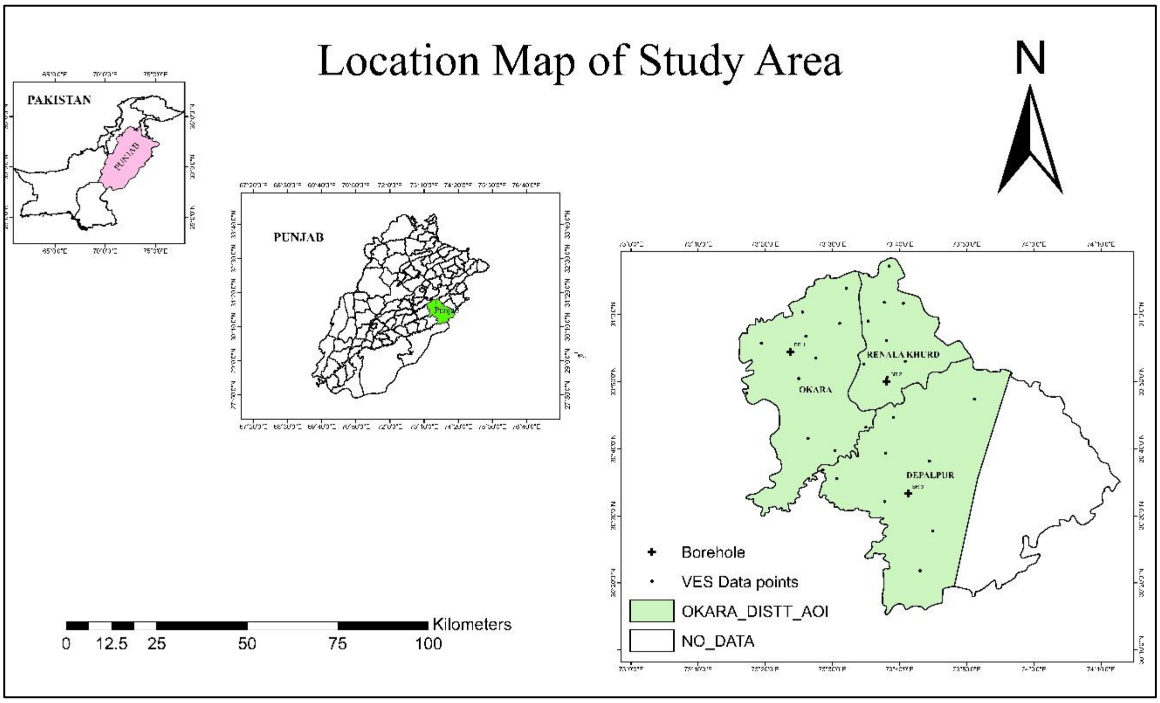


Figure.3.1 Location Map of Study Area

3.2. Sources of Salinity

Salts in shallow groundwater produced by weathering salts deposited in overlying corrosive sediments are transported from highlands to nearby lowlands and valleys. The water evaporates here, leaving salts on the surface (Nazir Ahmad & Chaudhry, 1988; Boers, Zuberi, & Ahmad, 1995). Deep groundwater flows can also contribute to salinity when water from recharge zones reaches formations having crystalline nature and is then transported to areas with low groundwater discharge. Due to articulation, convection and capillary flow brackish water rise .(Srisuk & Toth, 1994). Anthropogenic activities also affect the transport of salt in different ways. In the Indus Basin, deforestation, reservoir construction, numerous canals and waterways lead to soil salinization. The environmental impact of developing irrigation capacity from these structures is also negative. In the low-lying areas of the central delta, overflow from transportation systems and over-irrigation of fields lead to higher groundwater levels, especially in areas with natural drainage. This stagnant water creates problems with salinity.(Bhutta & Wolters, 1996)

3.3. Standards for Groundwater

The quality of groundwater in the Indus Basin is much different from that of canal water (Ibrahim & Hussain, 1988). Groundwater quality is generally poor, and it deteriorates as groundwater depth increases (Ghafoor et al., 1997; Gupta, Singh, & Sethi, 1994). The composition and concentration of all natural water's soluble salts determine its suitability for irrigation. Quality is typically measured using three criteria:

• Salinity (EC): The effect of liquified salts on crop development related with osmotic properties.

• Sodicity (SAR): The deteriorating effect of extra sodium on soil edifice.

• Toxicity: The effects of specific solutes on plant tissue cause a nutritional imbalance in plants, expressed in terms of ion concentration.

During the early stages of SCARP planning, total salinity, or the total dissolved-salt content of water, was the only parameter considered (A. Hameed, Randawa, & Gowan, 1966) (A. Hameed, M. S. Randhawa and K. D. Gowans, 1966; P, 2005; H. S. Zaidi, G. M. Rana and K. D. Gowans, 1966)**.** Water having EC_{iw} ranged from 0 – 3 dS/m can be used without any prior treatment for irrigation while water with an EC_{iw} of more than 3.0 dS/m shouldn't be used directly without treatment.

Table 3.1 Water Quality Parameters

Water Quality	EC (dS/m)	SAR	RSC (mmol/L)	Remarks
Usable	<1.5	<10	<2.5	To be used unmixed with canal water.
Marginal	1.5 – 2.5	10 – 18	2.5 – 5.0	To be used after mixing 1: 1 with canal water.
Hazardous	>3.0	>18	>5.0	To be used after higher dilution with canal water or application of chemicals.

Source: (WAPDA, 1979)

Groundwater is contained in it with varying amounts of dissolved salts, which are ionic conductive, allowing electricity to flow through the earth. Therefore, measuring ground resistance can identify groundwater salinity. Taking into account the groundwater quality limits above, a correlation between aquifer resistance and groundwater salinity was developed, and resistance limits for individual aquifers were plotted for suitable, moderately fitted, and unsuitable groundwaters. As a result, surface water quality can be assessed through surface geophysical VES surveys without the need to drill holes for groundwater samples.

3.4. Hydrogeological Factors

Groundwater has a number of parameters on which geophysical measurements of the surface depends. Majorly it depends on void spaces, thickness and conductance of aquifer. Aquifers are geological formations consisting of large quantities of water and permeable material, from which wells or springs obtain a certain amount of water. Water reserves can be unconfined or confined. In an unconfined aquifer, the groundwater table is under atmospheric pressure. In confined aquifer water pressure exceeds atmospheric pressure and usually lies in between impermeable sub surface layers. Surface resistance measurements can determine the presence or absence of water based on the following characteristics (Bernard, 2003):.

- A hard rock with no pores or cracks and dry sand with no water are both very resistant.
- The resistivity of a coarse-grained sand or weathered rock containing water depends on the amount of soluble salts and the void spaces in the rock.
- A water-bound layer having clay has greater conductivity or a smaller resistivity value.

Most of the time, groundwater resistance values are considered for groundwater detection. In hard rock (resistant) environments, low-resistance anomalies are the target, while in clay or saline environments, high-resistance anomalies are equivalent to fresh water (Awni, 2007; Park, Doh, & Yun, 2007).

3.5. Electrical Conductivity

The ability of a material that allows current to flow through it when a voltage is applied. Usually it is expressed in terms of deci-siemens per meter (dS/m). It is about quantity of salt dissolved in water or stored in it. (Bernard, 2003).

3.6. Methods of Electrical Resistivity Surveying

The principle of surface resistivity measurement is ground potential distribution around the current-carrying electrode and depends on the resistivity distribution of the surrounding surface. Generally, a current (direct or alternative) is applied between two electrodes that are grounded and measure the potential difference between two additional electrodes. In 1920 Schlumberger introduced DC resistance method and is useful in various field including hydrogeology. Schlumberger plotted the potential field produced by set of electrodes fixed on the ground and observe the equivalence of the general simple geometry shown by mapping to an electric field operating on the same ground in the presence of inhomogeneities. He later discovered that the resistance value of the ground material varied widely, and was reproducible and could be mapped by placing the electrodes in the background and vertically on the ground, an electric field is established and the potential droplets of different electrode geometries are measured (Van Nostrand & Cook, 1966).

The most commonly used technique in groundwater exploration is electrical resistivity. It has the added benefit of predicting water quality as well as subsurface geological formations. The technique is based on Ohm's Law and involves applying current to the ground at two points while measuring potential difference at other two points. To map subsurface geological formations and delineate the freshwater aquifer this calculated resistivity is used.

The resistivity of any formation is primarily determined by two factors: the formation's porosity and the presence of salts in water held in the pores. Dry rocks conduct electricity poorly. Moisture content in a formation is directly proportional to porosity, resistivity may indirectly reflect porosity under certain conditions.

There is a significant resistivity difference between sweet and saline water. This distinction serves as the foundation for using the electrical resistivity survey technique to delineate freshwater aquifers. Because saline water conducts electric current more quickly, its resistivity falls sharply when compared to the geological formation containing sweet water; whereas sweet water conducts electric current in a smaller amount due to its higher resistivity value. The quality of water in the area can thus be easily inferred from the gradient of the resistivity field curve.

When the medium is not homogeneous, the observed values of earth resistivity are not the resistivity of any particular formation in general, and thus we get apparent resistivity (Ra) instead of true resistivity (R)

However, the lack of uniformity can be detected by identifying variations in apparent resistivity and thus determining the structures causing these variations using various data processing and interpretation techniques.

Electrical resistivity surveys can be used;

i. To determining the type of water bearing formation, such as sand, sandstone, or gravel/admixture, etc., that can yield appreciable groundwater.

ii. To distinguish between saline and fresh water aquifers if the aquifer's lithology is uniform.

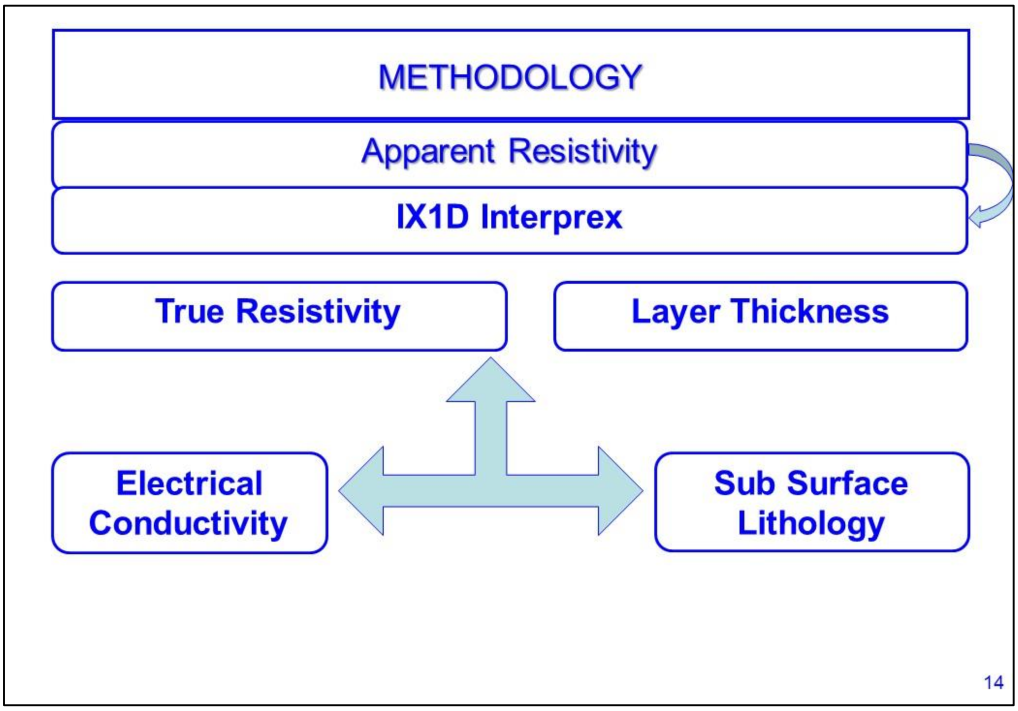


Figure 3.2 Methodology Flow Chart

3.7. Electrical Resistivity Survey

In earth-electrical (VES) resistivity measurements, two electrodes are placed on the Earth's surface at a distance from each other and create an electric field between them, which propagates the electric field around them. The focus point of the conductor arrangement remains fixed, but the electrode spacing is increased, allowing data to be obtained from deeper underground.

They are far away from each other rather than relatively close. Ground resistance can be measured by measuring the potential difference between the two electrodes within this electric field. Increasing the spacing between the current electrodes allows the electrical field to penetrate deeper (Figure. 3.3). Vertical electric sounding is the practice of taking repeated measurements over a single centre while moving the current electrodes outward in steps (VES). As shown in Figure 3.4, the tool used to evaluate electrical resistivity in the investigation zone was a DC Terrameter SAS 4000 (ABEM, Sweden). The instrument is owned by the Pakistan Council of Research in Water

Resources, Govt. of Pakistan. The field investigations were conducted by this department.

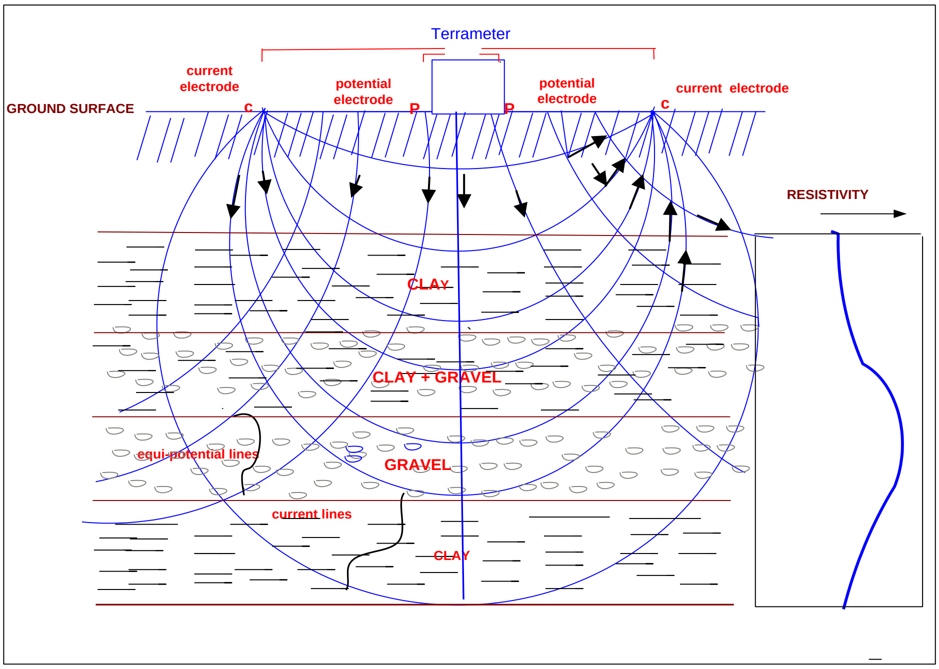


Figure.3.3 Setting of Potential and Current Electrodes

Figure.3.4 Terrameter SAS 4000 (ABEM Sweden) in use at Study Area

3.8. Resistivity Measurements

A commuted direct current is induced into the ground via two electrodes during resistivity surveys (A & B). The potential drop between a second pair of electrodes is measured (M & N). The four electrodes can be arranged in a variety of patterns. The apparent resistivity values are then calculated using the current and potential measurements. Schlumberger array was used in the field. This is the most common configuration for conducting electrical resistivity surveys around the world. Four electrodes are placed in the order AM NB with AB ≥ 5 MN. The overall arrangement of the current and potential conductors, as well as the arrangement of potential and current lines, is shown in Figure 3.3.

Terameter SAS 4000 was used to collect field data in the area. This instrument operates according to Ohm's laws, i.e.

$$\boldsymbol{R \propto V/I} \qquad \textit{Equation.1}$$

Also,

$$\boldsymbol{R = K \times V/I} \qquad \textit{Equation.2}$$

Where;

R = Resistivity; Ohm-meter

V = Voltage (potential drop) mili-volt

I = Current; mili-ampere

K = Constant of proportionality

$$K = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN} \qquad \text{Equation.3}$$

π= Constant i.e. 3.14159

AB = Distance between current electrodes: metre

MN = Distance between potential electrodes: metre

3.9. Electrode Configuration

The Schlumberger array for geo-electrical resistivity measurements is additional to the research area and yields well findings. The technique has several advantages over other electrode arrangement methods, such as the Wenner method. (Bhimasankaram & Gaur, 1977; Ward, 1990; Zohdy, Eaton, & Mabey, 1974). As a result, the Schlumberger electrode arrangement was employed in the investigation since it is less time-consuming and offers superior depth sensitivity and horizontal layer resolution. The electrodes in the Schlumberger array are arranged in a straight line and central point is fixed. The current was measured across the two outer electrodes A and B, and the electrodes M and N gave potential drop (Figure 3.6). MN/2 is always kept small in comparison to AB/2. The source to the target that is recorded on average across M and N is comparable to the potential gradient that is recorded at the module's center (Lashkaripour & Nakhaei, 2005). In the Schlumberger configuration, the distance between current electrodes increases as the investigation depth increases as illustrated in Figure 3.6.

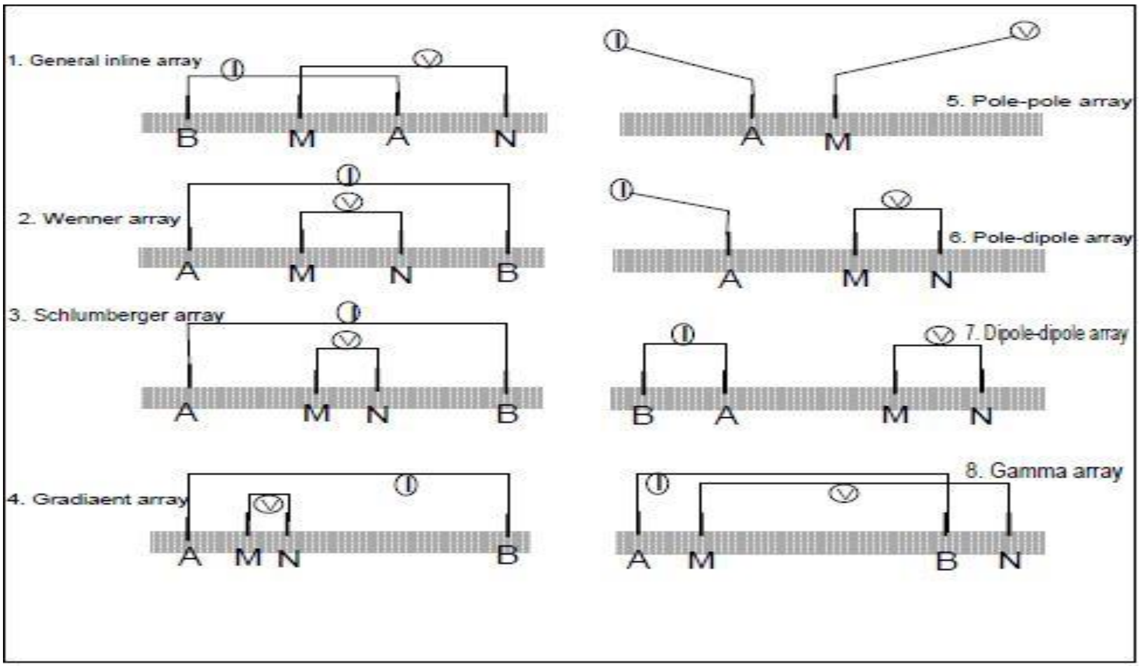


Figure.3.5 Different Electrode Configurations

In the Schlumberger electrode configuration, the geometric factor can be calculated by dividing the half current electrode spacings AB/2 by the half potential electrode spacings MN/2, as shown in Figure 3.6

The geometric factor (G) is calculated as follows (Srinivasa, 2004);

$$G = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN} \qquad \textit{Equation.4}$$

Moreover, the apparent resistivity (ρa) was calculated as

$$\rho_a = G \times R \qquad \textit{Equation.5}$$

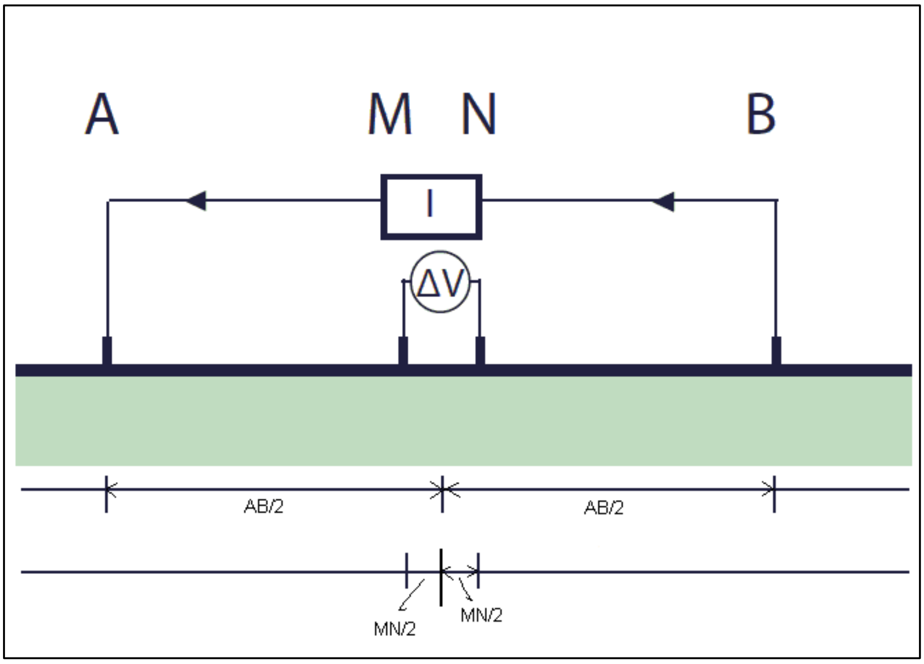


Figure.3.6 Schulumberger Configuration of Electrodes

3.10. Investigation Techniques

Vertical electrical resistivity soundings (VES) surveys were conducted in the study area. For this purpose Schlumberger array setup was created. In which current is passed through two current electrodes separated by a distance (AB/2). This distance ranged from the minimum of 2m to a maximum of 300m. The distance between current electrode (AB/2) was kept at 2, 4, 6, 8, 10, 15, 20, 25, 25, 30, 35, 40, 45, 50, 50, 60, 70, 80, 90, 100, 100, 120, 140, 160, 180, 210, 240, 270 and 300 m. When the current electrodes are at 25m, 50m, 100m, the spacing between potential electrodes is increased and two reading were taken for the same current electrode spacing. One reading at the previous potential spacing and other at the new potential electrode spacing. The distance between potential electrodes (MN/2) was maintained at 0.5m, 5m, 10m and 20m because the resistivity metre signals weaken with each step of AB spacing. As a result, the MN spacing was increased, and two values for the same AB/2 were measured, one for the short MN spacing and one for the long MN spacing. The earth resistivity at different locations was measured in the fields using a resistivity metre at various electrode spacing in Okara District. The apparent resistivity of the material beneath the electrodes was thus obtained. Annexure I contains the field data noting sheet.

3.11. Equipment used in this Study

The Pakistan Council of Research in Water Resources, which is part of the Pakistani government, was the owner of the Terrameter SAS 4000 (ABEM, Sweden) that was used in this research to measure geo-electrical resistance (Figure 3.4). Direct current enables greater depths of enquiry than alternating current does because it ignores a number of problems due to ground capacitance and inductance in addition to the rate reliance of resistivity. This makes it possible for direct current to be used in more applications. However, in actual practice, current flow is used very seldom due to the following two reasons:

(2) Earth's natural currents and impulsive possibilities, which are essentially uni - directional or gradually time differing, induce potentials in the electrodes.

(1) Direct current electrodes start generating polarized ionization fields in the electrolytes around them, and these fields generate additional electromotive forces that cause the current and potentials in the ground to differ from those in the electrodes.

3.12. Investigation Depth

The Terrameter SAS 4000 was set to automatic in terms of time, amount of transmitted current, and voltage, so that it could automatically adjust on each electrode spacing of the Schlumberger congiguration. Because of the heterogeneity and anisotropy of the earth in reality, there is no definite rule or formula between electrode spacings and current dissemination depth (Bernard, 2003). Depending on the type of layering, generally a 1 km distance between current electrodes results in 100 – 300m an operative current dissemination depth. A conductive basement, for example, will have a shorter AB line than a resistive basement. Though, in the first case, the signal is typically inferior than in the second. For district Okara, sub surface investigations were made upto 300m depth.

3.13. VES Survey Data Interpretation using IX1D Software

Software that uses the 1-D inversion approach was used to examine the apparent resistivity values that were determined from the observed data using Equation 3.8. (IX1D, Interpex, USA). By adjusting the obtained field data to the smallest root mean square (RMS) error between the model's simulated and real data, the programme creates a resistivity model. Use iteration until the fit error is small and constant between the field data and the generated model curve. The real resistivity (or just resistivity) values of the subsurface layers, their thickness, and depth are created after the field data (apparent resistivity) is interpreted by curve fitting the input data using the IX1D computer programme, as illustrated in Figure 3.7. one of the VES illustrations. Salinity, water content, clay content, and lithology all have an impact on sediment resistivity (Bernard, 2003; Choudhury & Saha, 2004). The resistivities of salt water, saturated soil, and sand overlap, which can cause issues with VES interpretation when mapping subsurface salinity. In order to better understand VES results, lithological and hydrological data from the same site must be correlated.

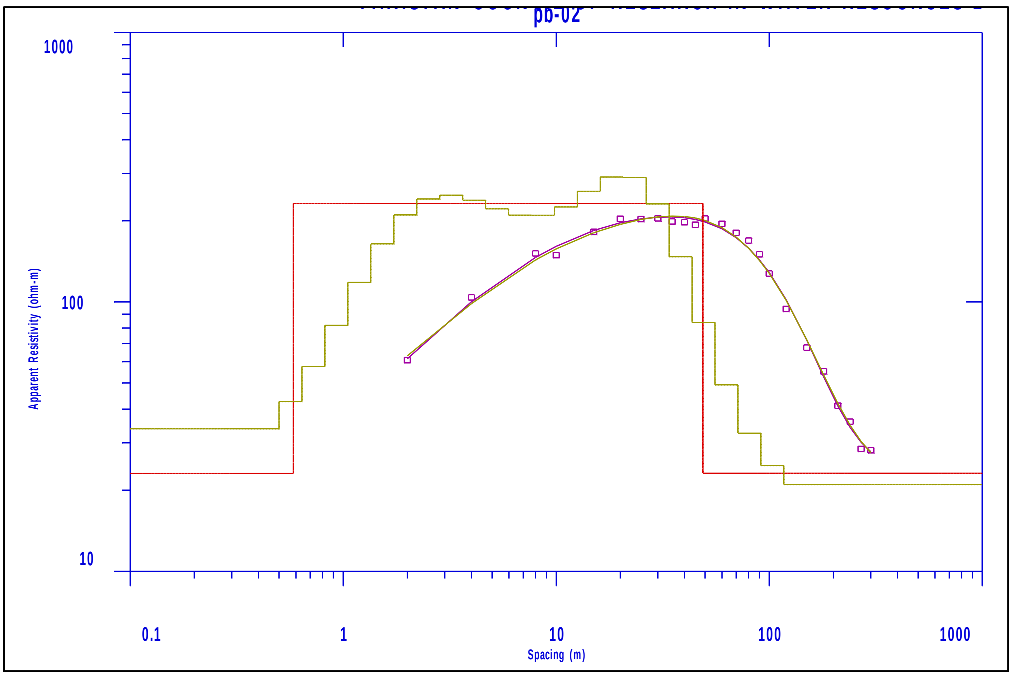


Figure.3.7 Computer Software IX1D (Interprex, USA)

3.14. VES Results and Borehole Data Correlation

The electrical resistivity technique is the most potent technique used in hydro - geological investigations, notably for evaluating the quality of groundwater. This technique not only reveals the lithological units of the subsurface, but it also identifies the existence of water in any horizon and calculates the amount of salt that is present in groundwater. The electrical resistivity of various geological substances may range greatly from one another, and this is mostly because of differences in water level and the types of soluble salts present in the water. Tests of resistivity may thus be used to detect areas with various electrical characteristics, which can subsequently be allocated to distinct geological strata. These zones can then be attributed to different layers of the earth. The inverse of conductivity or specific conductance is resistance, which is also known as specific resistance.

As a result of the fact that the most prevalent materials that make grounds and stones have an extremely high resistivity under dry circumstances, the resistivity of rock and soil is generally a function of the quality and quantity of water that is contained inside pore spaces and cracks. Another key factor is the extent to which the holes are related to one another. As a consequence of this, the electrical resistivity of a certain kind of soil or rock may vary substantially, as can be shown in Table 3.2. However, fluctuations within a narrow geographical region may be more restricted, and differences in resistivity in a particular soil or rock kind will represent fluctuations in the physical qualities of the soil or rock. For instance, low resistivities for sands and lithology suggest that the cavities in the rock are filled with moisture. High resistivities, on the other hand, suggest firmly cemented sedimentary rock or dry rock that is located above the groundwater level. Sand, pebbles, and sedimentary could all have extremely low resistivities if the pore spaces inside them are filled with salty water to the point of saturation. Aside from specific mining minerals, new crystalline rock has a high resistance; nevertheless, aging sometimes creates clay-rich saprolite that is extremely conductive. The information on resistivity need to be validated against geological documentation such as define the following, trial pits, or digging. This is necessary due to the fact that one kind of geological substance might have a variety of properties even within itself. This, though, is true for each and every geophysics technique.

Every geoelectrical resistivity investigation that hopes to be successful must first and foremost focus on the confirmation of underlying truth. The outputs of the VES need to be carefully interpreted and integrated with the other geology and hydrogeologic data from the site in order for the system to be successful. In order to carry out a comprehensive analysis of the groundwater resources present in the research region, data collected from boreholes as well as a VES survey were used. As a direct consequence of this, the lithological data derived from the well logs was used in the process of calibrating the VES field lines. Both the VES and experimental boring data were used in the process of determining the aquifer properties as well as the water quality assessment (WAPDA, 1979).

Table.3.2 Electrical Resistivity of Rock

Rocks and Sediments	Resistivities
Limestone (marble)	>1012
Quartz	>1010
Granite	5000--104
Sand Stones	35—4000
Moraine	8—4000
Lime Stone	120—400
Clays	1—12
Alluvium Sands	10—800
Surface Water	15—100

(Nath, Sankar Kumar, Patra, & Shahid, 2000)

3.15. Conversion of Resistivity into Electrical Conductivity

There is a relationship developed between electrical conductivity and the earth resistivity by PCRWR, Islamabad for LBDC. This regression is basically used to convert the resistivity values into electrical conductivity at the corresponding depth. In general, the regression shows that resistivity values less than 10 Ohm-m indicate brackish groundwater with clay and silt subsurface lithology. The resistivity zone 11-24 Ohm-m denotes marginal-saline subsurface geology with clayey sand or silty sand. Similarly, resistivity values ranging from 25 to 34 ohm-m indicate that groundwater is fresh but of poor quality, or that the subsurface geology is sandy clay with some silt. The resistivity greater than 34 Ohm-m, on the other hand, refers to high-quality fresh groundwater with a sandy subsurface geological formation (A. Khan, Ashraf, Ghumman, & Iqbal, 2018).

The earth's resistivity is affected by the type of rock, void spaces, fluid content, and salt concentration in the fluid. Table 3.3 summarizes the interdependence of electrical resistivity, rock formation, and water type. The table shows that low resistivity is caused by either fine-grained rock or saline water in coarse-grained rock. Freshwater in sandy formation has a high resistivity value. (A. Khan et al., 2018)

Table.3.3 Interpretation of Resistivity Data, Correlation between Water Quality, Lithology and Resistivity

S. No	Resistivity (Ohm-m)	Water Quality if sandy sediments prevails	Geology if Groundwater is fresh
1	> 35	Fresh	Admixtures, sand, sandstone/limestone
2	25-39	Fresh, low quality	Sand with some clay mixture
3	11-24	Marginal water to brackish water	Clayey sand, silty sand
4	<10	Saline water	Clay, Silt

(A. Khan et al., 2018)

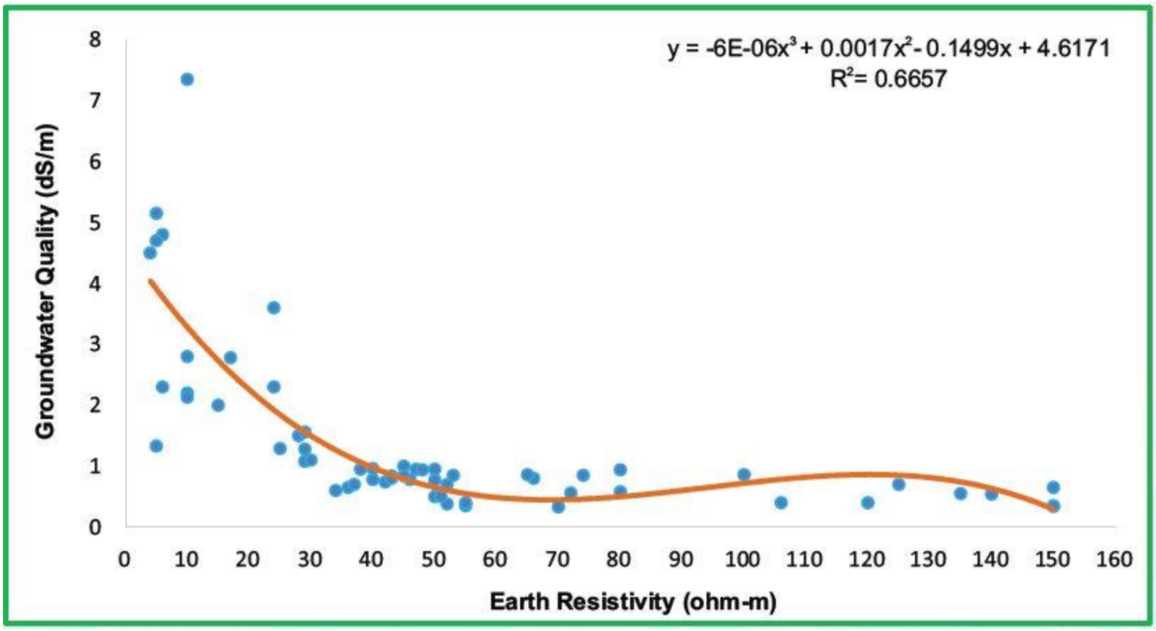


Figure 3.8 Regression Developed Between Earth Resistivity and Groundwater Quality in Upper Indus Plain, Pakistan

(A. Khan et al., 2018)

3.16. Groundwater Quality Mapping

The Geographic Information System (GIS) was used to present surveyed data and map resistivity at various depths. The resistivity maps were prepared and analyzed using ArcGIS 9.1. After relating the spatial and resistivity data, the Inverse Distance Weightage (IDW) method was used to map the field data. This technique is applied to interpolate dataset for those areas where physical approach is not feasible or data set of those areas are not available. The GIS maps were created for a variety of depths: 0-50m. 50-100m, 100-150m, 150-300m. The developed map are shown in figures 4-2 to 4-5. The groundwater quality was classified as freshwater (<1.5 dS/m), marginal quality water (1.5-2.5 dS/m), saline water (2.6 dS/m), from 0 to 300 m depth at 50 m intervals.

Chapter 4

RESULTS AND DISCUSSIONS

4.1. VES Results

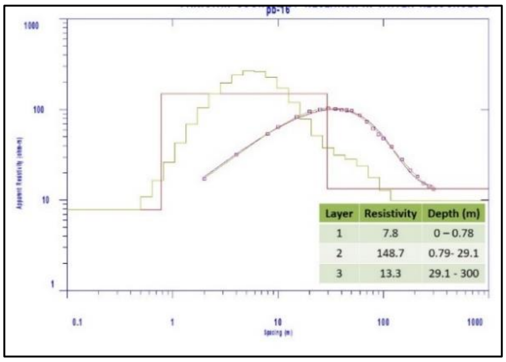
Instead of directly measuring resistivity, the resistivity metre (ABEM Terrameter SAS-4000) offers resistance readings. As the current electrode separation grew, the VES assessment data gathered at consecutive potential electrode (MN/2) and current electrode (AB/2) spacing generally indicated a declining trend. The apparent resistivity values given in Annexure-1 do not accurately reflect the genuine resistivity values of the ground. As a consequence of this, the data from the VES survey included in Annexure-2 were examined by means of some piece of software called Interpex, IX1D, in order to acquire the real resistivity values of the subsurface layers along with their respective thicknesses. This interpretation led to the production of graphical data, a layered model, and a smooth model respectively. The translated graphic resistivity modelling in terms of depth and subsurface layer resistivities are presented in Figure 4.1, 4.2, 4.3, and 4.4. These figures also provide the fitted model and the root mean square (RMS) error for each of the sites. The high regional variability of underground water and the nonuniformity of underlying aquifer characteristics were the defining characteristics of the apparent resistivity curves. The following resistivity zones are categorized according to their interpreted real resistivity:

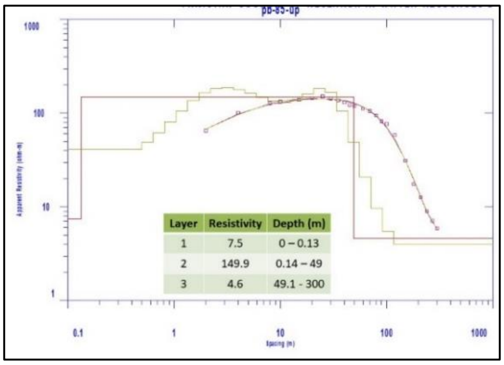
4.2. Resistivity Zones

The interpreted sub surface hydrogeological conditions were categories based on correlation developed between water quality, lithology and resistivity by (A. Khan et al., 2018) for UIP (Upper Indus Plain). The groundwater quality in subsurface layers ranged from 0 to > 4 dS/m for different resistivity values based on groundwater sample analysis (Figure 3.8). As a result, three resistivity zones were established, with resistivities of the hydrogeological layers to the corresponding EC values of groundwater less than 1.5 dS/m, 1.5 to 2.5 dS/m, and greater than 2.5 dS/m, corresponding to fit, marginally fit, and unfit for irrigation purposes, respectively (Table 3.3). The interpreted resistivities associated with relevant hydrogeological conditions in district Okara have been classified as follows:

4.3. Very Low Resistivity Zone

It was determined that the resistivity values of the underlying material ranged from 0 to 10 ohm-m, and this was how the extremely low resistivity zone was identified (Figure 4.1). These zones demonstrated the presence of either impermeable zones composed of hard silt clay with fresh water or sand with salty moisture content. Whenever these extraordinarily low resistivity readings were found in the upper strata of the soil profile in the district Okara, it was revealed that the soil was loamy to clay in texture, and it had a high proportion of water that was preserved. The existence of brackish groundwater with an electrical conductivity (EC) of higher than 3.0 dS/m in the sand media in the reduced ranks is seen in Table 4.2.





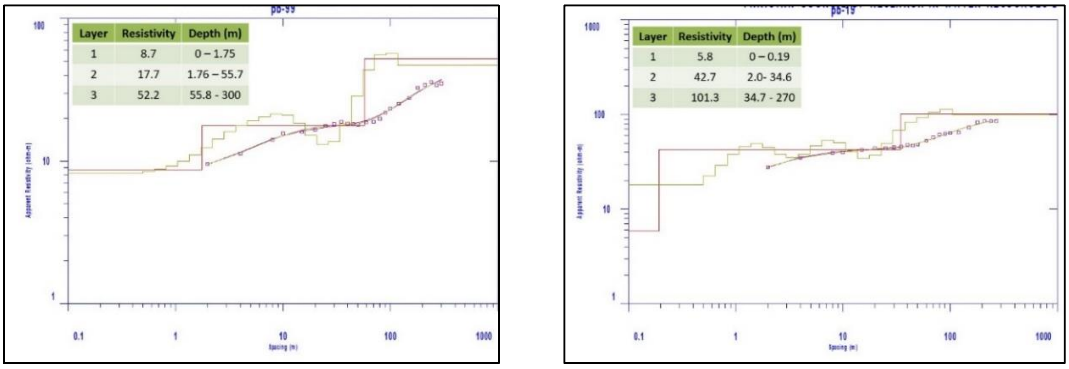
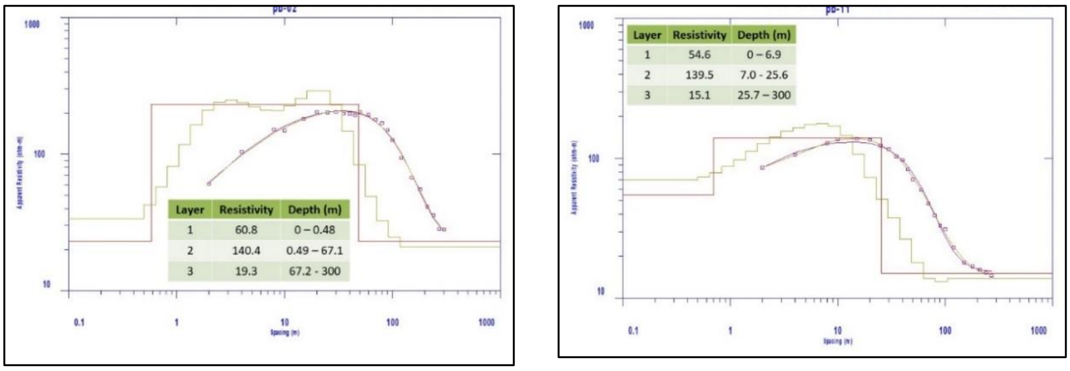


Figure.4.1 Interpreted VES Data (very low resistivity)

4.4. Low Resistivity Zone

Low resistivity zones were demarcated as interpreted resistivity values ranging from 11 to 24 ohm-m. These zones were mostly made up of geological formations like sand and a trace of clay (Figure 4.2). This indicates the presence of saline water with an EC of 2.5 to 3 dS/m and alluvial formations such as silt, sandy clay, clay, and fine sand. As shown in Table 4.2, 3rd layer of both sites of tehsil Okara (VES 1 and 3) were classified in this zone. The upper layers of the soil revealed that it was mostly loam with conserved moisture.



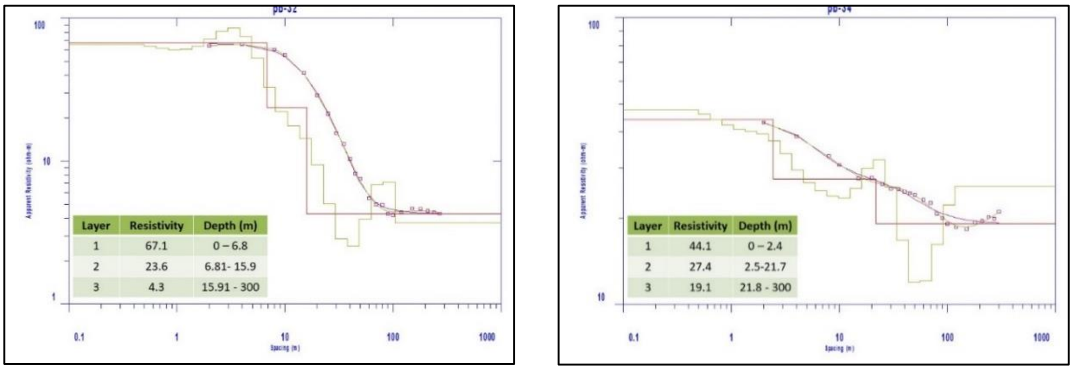
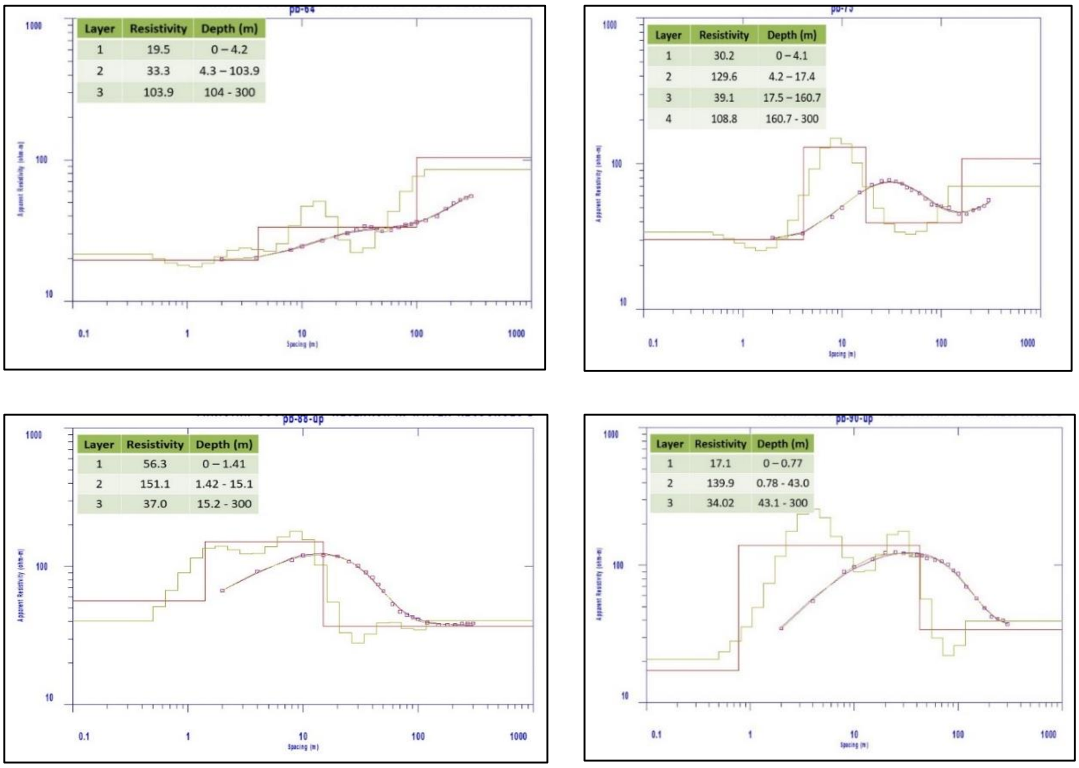


Figure.4.2 Interpreted VES Data (low resistivity)

4.5. Medium Resistivity Zone

Resistivity values ranging from 25 to 39 ohm-m were used to define the boundaries of zones with a medium resistivity. This suggested the existence of marginally salty water with soft clay sand, silt, or alternating layers of sand and clay, and an electrical conductivity (EC) range of between 1.5 and 2.5 dS/m. When this spectrum is shown in the top layer of the surface soil (Figure 4.3), it is an indication that the soil is clay loam, with extremely fine grit, and that it has an acceptable level of moisture (Table 4.2).



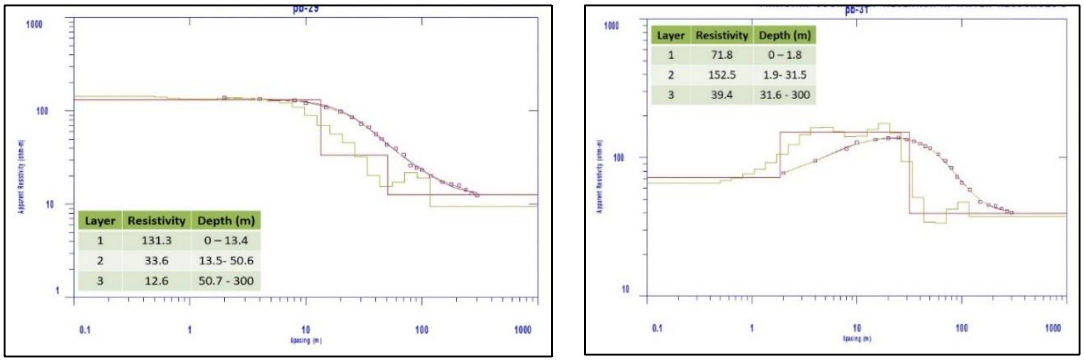
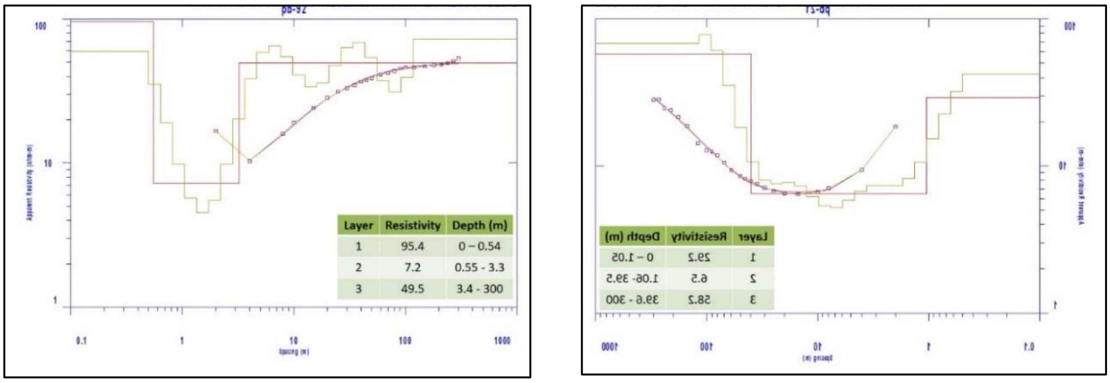
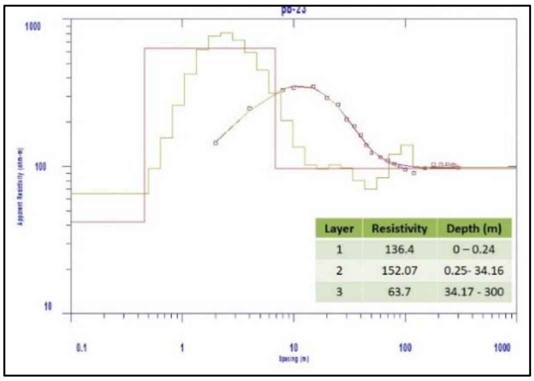


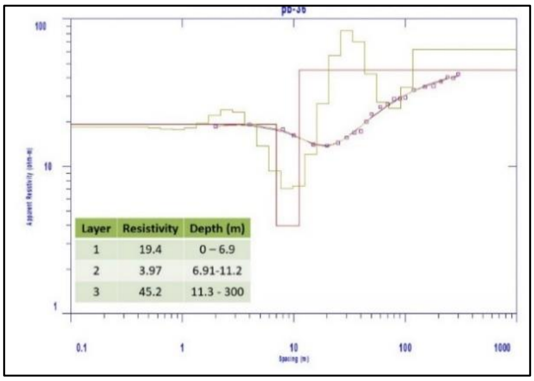
Figure.4.3 Interpreted VES Data (medium resistivity)

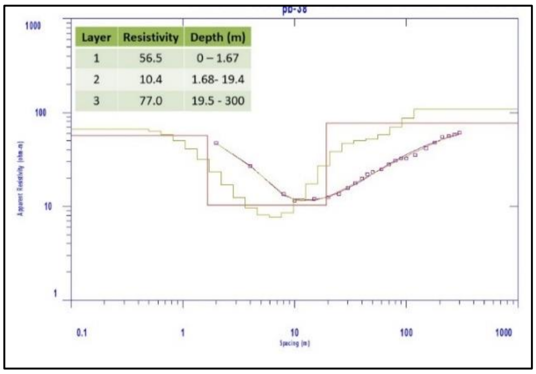
4.6. High Resistivity Zone

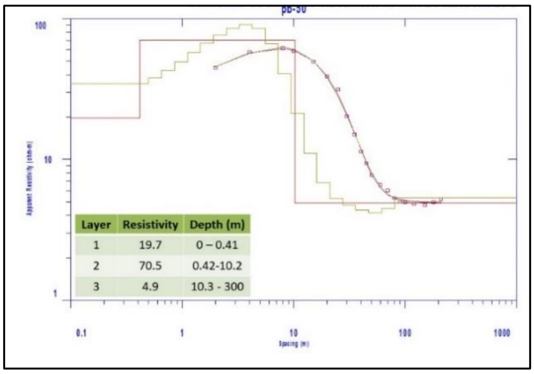
High resistivity zones were defined as resistivity values exceeding 35 ohm-m. This indicated the presence of freshwater with sandy formation and minor patches of silt. As shown in Table 4.2, resistivity values in this range provided good quality water in the medium to coarse sand formation with alternate layers of thin clay. Groundwater has an electrical conductivity of 0.5 to 1.5 dS/m (Figure 3.8). The extremely high resistivity values (Figure 4.4) indicates the presence of clean medium to coarse-grained sand and excellent groundwater quality. With these extremely high resistivity values, the presence of dry sandy loam to sandy soil was discovered in the upper layers above the groundwater table.

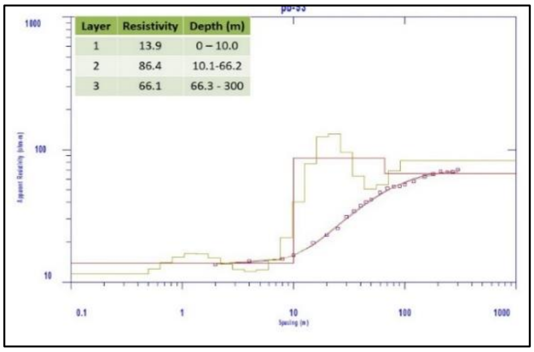


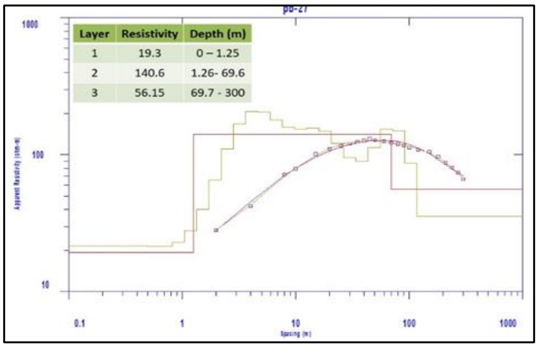

Layer Resistivity Depth (m)
1 136.4 0 – 0.24
2 152.07 0.25- 34.16
3 63.7 34.17 - 300

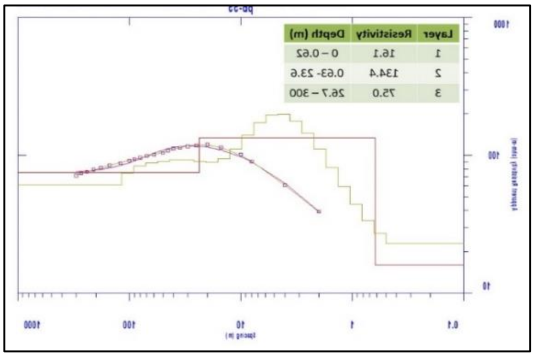

Layer Resistivity Depth (m)
1 19.4 0 – 6.9
2 3.97 6.91-11.2
3 45.2 11.3 - 300

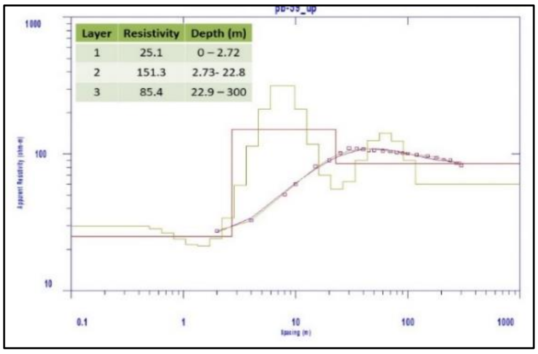

Layer Resistivity Depth (m)
1 56.5 0 – 1.67
2 10.4 1.68- 19.4
3 77.0 19.5 - 300


Layer Resistivity Depth (m)
1 19.7 0 – 0.41
2 70.5 0.42-10.2
3 4.9 10.3 - 300


Layer Resistivity Depth (m)
1 13.9 0 – 10.0
2 86.4 10.1-66.2
3 66.1 66.3 - 300


Layer Resistivity Depth (m)
1 19.3 0 – 1.25
2 140.6 1.26- 69.6
3 56.15 69.7 - 300


Layer Resistivity Depth (m)
1 16.1 0 – 0.62
2 134.4 0.63- 23.6
3 75.0 26.7 – 300


Layer Resistivity Depth (m)
1 25.1 0 – 2.72
2 151.3 2.73- 22.8
3 85.4 22.9 – 300

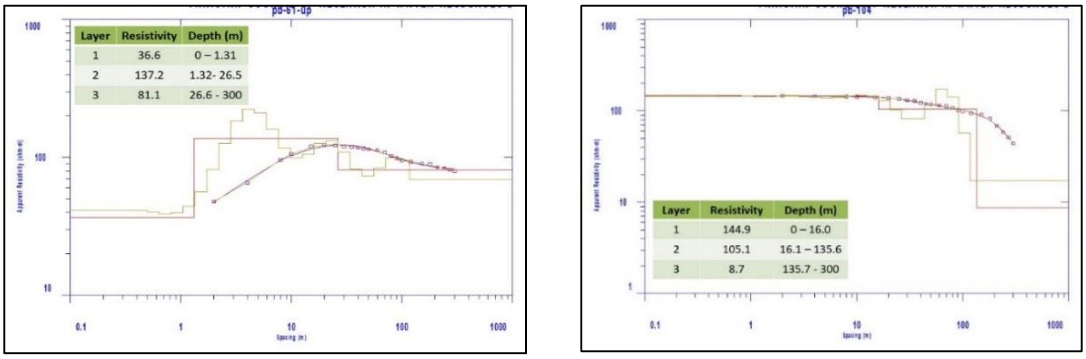
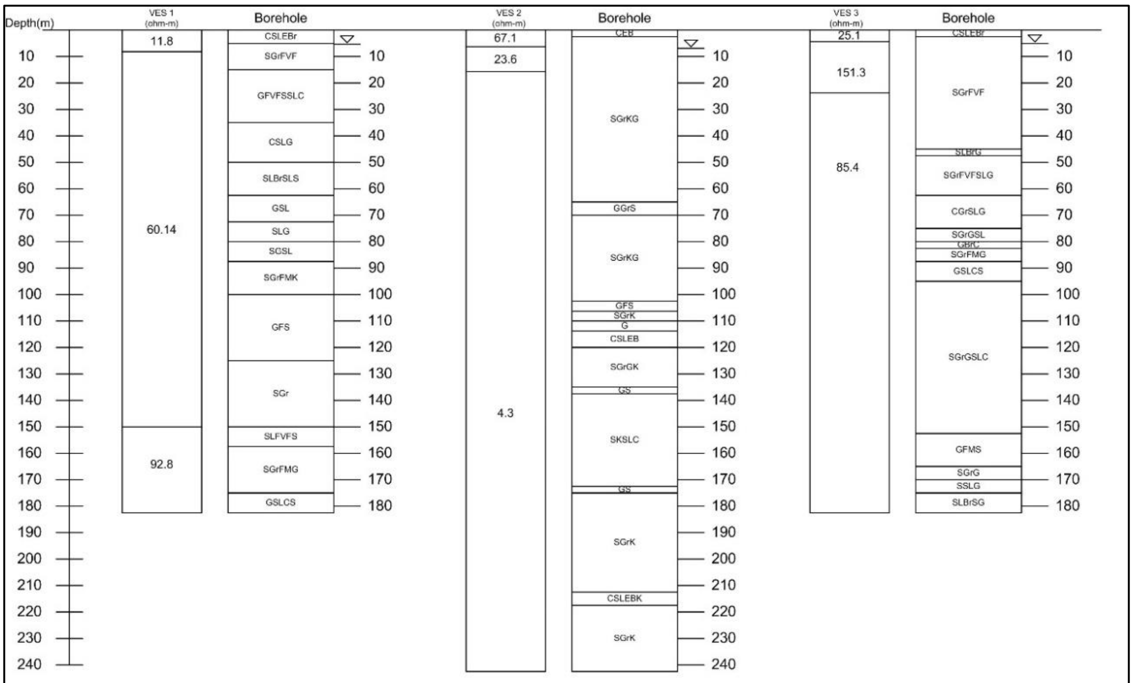


Figure.4.4 Interpreted VES Data (high resistivity)

4.7. Correlation between VES results and bore hole data

Any geophysical survey must be calibrated with hydrogeological and geological ground truth data in order to be successful. These bathymetric data were compared with samples (soil and ground) obtained from local boreholes in order to comprehend the link between the geoelectric parameters (strata, thickness, and resistivity) and the hydrogeological properties of the formation in the research region. water) is significant to the outcomes. same location. The hydrogeological profile and the Schlumberger electrical bathymetry data were found to be in good agreement when analyzed using the Sights computer programme 1X1D InterPex. (Figure 4.5).



CSLEB	Clay, Silt, Earthy Brown	GWFS	Gravels with Fine Sand
SGRFVF	Sand, Grey, Fine to very Fine	CSLGRWFS	Clay, Silt, gravels with Fine Sand
CSLEBG	Clay, Silt, Earthy Brown with Gravels	CGRSOSLS	Clay,Grey, Soft with Silt and Sand
CSLEBK	Clay, Silt, Earthy Brown with Kankers	SFMGR	Sand, Fine to Medium, Grey
SGRFMSLC	Sand, Grey, Fine to medium, Silt, Clay	GSLC	Gravels with Silty Clay
CGRWG	Clay, Grey with Gravels	CBrSLS	Clay, Brown with Silt and Sand
SGRF	Sand Grey Fine	CSLBrG	Clay, Silty brown with Gravel
CSLEBKG	Clay, Silt, Earthy Brown with Kankers and Gravels	GSLCS	Gravels with Silty Clay and Sand

Figure.4.5 Correlation between VES results and Bore hole data

4.8. Groundwater Quality Mapping

In the Indus Plain Aquifer, the quality of groundwater is naturally saline as it is originally of marine source and as compared to shallow depths, its salinity is higher at greater depths (Ashraf, Zeeshan, & Drainage, 2012). A fresh water layer has formed over time because of recharge from rivers, irrigation systems, and precipitation. This freshwater layer is thick along rivers and thins out in the center of doabs. The quality of groundwater varies, both lateral and vertically, depending on geological characteristics and recharge sources.

The spatial patterns in groundwater quality were investigated by creating maps at 50-meter intervals in district Okara up to a depth of 300 meter. Moreover, Tehsil wise combined results of study area from 0 to 300 m reflects that the maximum potential of freshwater is found in tehsil Okara (Table 4.1). Overall 68% of the total area in tehsil

Okara is underlain by freshwater, 16% by marginally saline water and 16% by saline to highly saline water. The area under usable (fresh, marginal) quality water i.e. fit for irrigation purposes is about 84%. However, saline water (16% of the total area) is not suitable for irrigation purposes directly. Tehsil Depalpur also comprises 84% of the total area under useable quality groundwater but the area underlain by freshwater is about 61%, which is 7% less than tehsil Okara. However, area pertaining to brackish water remains the same for both tehsils i.e. 16% (Table 4.1). In tehsil Renala Khurd, percentage of area underlain by freshwater i.e. 40% is lowest and that of by saline/highly saline water (32%) is highest amongst all the tehsils. The potential of useable quality water is about 68%. (Table 4.1) This is generally because of the fact that Renala Khurd lies in the center of district and far away from river Ravi and Sutlej resulting in less groundwater recharge and more abstraction.

Table.4.1 Detail of area coverage under different groundwater quality zone Tehsil wise

Sr.No	Tehsil	Groundwater Quality dS/m	Area Coverage (km2)				Percentage of Total Area (km2)	
			0-50m	50-100m	100-150m	150-300m	(0-300 m)	
1	Okara	0-1.5	1101	924	678	680	68	84
		1.6-2.5	128	206	284	160	16	
		>2.5	8	107	275	397	16	16
2	Depalpur	0-1.5	1325	983	967	838	61	84
		1.6-2.5	334	378	395	430	23	
		>2.5	17	315	314	408	16	16
3	Renala Khurd	0-1.5	231	210	275	277	40	68
		1.6-2.5	204	185	156	155	28	
		>2.5	187	227	191	190	32	32

4.9. Groundwater Quality from 0 - 50 m

In district Okara, the upper 50 m sub surface layer has s good potential for freshwater. As shown in Figure 4.6, 75 % of total area comprise of freshwater. Also, the area underlain by marginal saline water is 18 %. However, this top layer shows only 7 % of area under brackish or highly saline groundwater. The total area under usable quality groundwater is about 80 % which keep on decreasing with increasing sub surface depth and as we move away from river. The main source of recharge of this top layer in district Okara is River Ravi and River Sutlej. As shown in Figure 4.6, the area along the river contains mainly freshwater. Therefore, most of the area of tehsil Okara and Depalpur is under freshwater zone as compared to Tehsil Renala Khurd, which is in the center of District and has less recharge from river. Moreover, this top layer contains a patch of marginally saline water in tehsil Depalpur along river Sutlej. Which reflects that due to high use of fertilizers, pesticides, etc. the groundwater quality is deteriorating and thus results in polluting the aquifer.

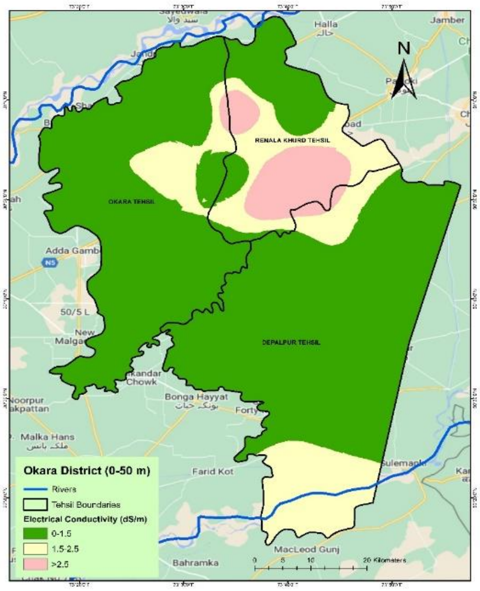


Figure.4.6 Groundwater Quality Mapping 0 - 50 m in District Okara

4.10. Groundwater Quality from 50 – 100 m

From 50-100 m as shown in Figure 4.7, the area underlain by fresh water is reduced to about 59%. Contrary to this, the area under marginally saline water is increased to 21 %. In addition, the brackish groundwater is increased and comprised of about 20 % of the total area. The increase in hydro salinity is observed as the investigated depth is increased in the area. Typically, the area in the center of District Okara having maximum distance from the river Ravi and Sutlej is mostly affected and under stress.

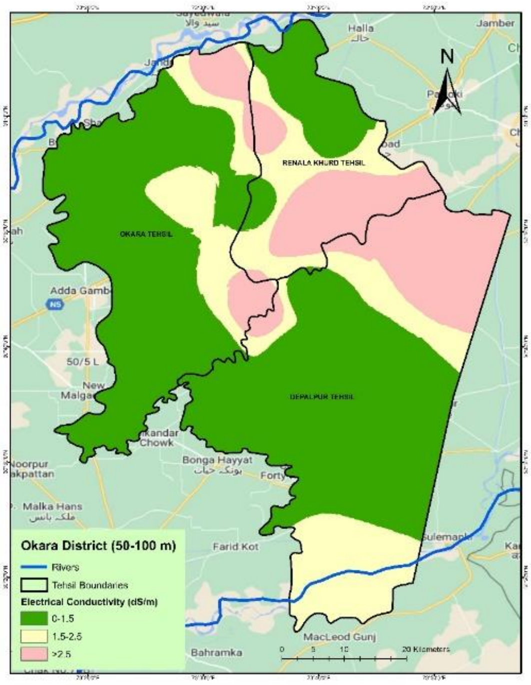


Figure.4.7 Groundwater Quality from 50 - 100 m in District Okara

4.11. Groundwater Quality from 100 – 150 m

As shown in Figure 4.8, the sub surface layer from 100 – 150 m comprise of 54 % of fresh groundwater. Marginally saline water is now increased to about 24 %. However, the saline water in the area under study has increased to about 22 %, which shows that as we keep on increasing the depth of investigation, salinity values estimated through the regression reflect poor quality water. Although the total useable groundwater is about 78 % but availability of fresh groundwater is reducing with depth. This indicates that as we move into greater depth the recharge from rainfall is less which results in more salinity values.

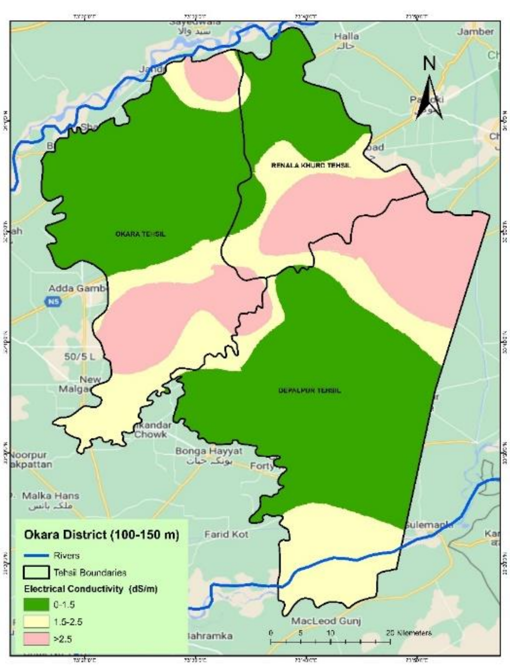


Figure.4.8 Groundwater Quality from 100 - 150 m in District Okara

4.12. Groundwater Quality from 150 – 300 m

The ground water quality below 150 m upto 300 m is mapped and is shown in the Figure 4.9, due to minimum variation in the sub surface lithology, this layer comprised of about 50 % fresh water, 21 % marginally saline water and 29 % saline water. This layer has the least amount of useable quality water due to over abstraction and less recharge. This layer reflect that due to less recharge from rainfall, it holds less freshwater. Moreover, as the map shows, due to the geographical location of tehsil Renala Khurd, it is the most affected area as the recharge from the river Ravi and Sutlej is minimum in this area.

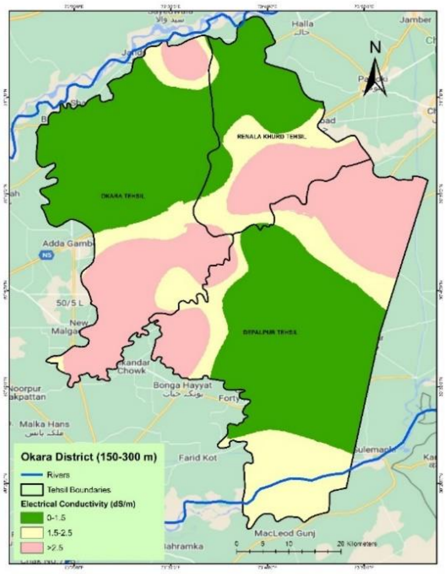


Figure.4.9 Groundwater Quality from 150 - 300 m in District Okara

Table.4.2 Interpreted Lithology with resistivity and thickness of VES data at all sites

Site (VES)	Layers	Depth (m)	Resistivity (ohm-m)	Interpretation
1.	1	0 – 0.48	60.8	Clay with weathered surface material
	2	0.49 – 67.1	140.4	Layers of clay mixed with sand containing fresh water
	3	67.2 – 300	19.3	Alternate layers of clay with coarse sand containing brackish water
2.	1	0 – 8.5	11.8	Clay and fine sand with conserved moisture
	2	8.6- 149.9	60.14	Layers of coarse grained sand with alternate thin layers of clay containing freshwater
	3	150 – 300	92.9	Alternate layers of sand and clay containing good water quality
3.	1	0 – 6.9	54.6	Silty clay with conserved moisture
	2	7.0 - 25.6	139.5	Layers of coarse grained sand with alternate thin layers of clay containing fresh water
	3	25.7 – 300	15.1	Alternate layers of sand & clay containing marginal to saline water
4.	1	0 – 0.78	7.8	Admixture of clay and silt
	2	0.79- 29.1	148.7	Alternate layers of clay and coarse grained sand containing fresh groundwater
	3	29.1 – 300	13.3	Layers of clay and sand containing saline water
5.	1	0 – 4.2	19.5	Clay with weathered surface material
	2	4.3 – 103.9	33.3	Clay with fine sand containing good quality of water
	3	104 – 300	103.9	Alternate layers of clay and coarse grained sand containing freshwater
6.	1	0 – 4.1	30.2	Clay with surficial material
	2	4.2 – 17.4	129.6	Coarse sand with clay containing freshwater
	3	17.5 – 160.7	39.1	Alternate layers of clay and fine sand containing marginal quality of water
	4	160.7 - 300	108.8	Coarse grained sand and clay with good water quality
7.	1	0 – 0.13	7.5	Silty clay with conserved moisture (weathered material)
	2	0.14 – 49	149.9	Coarse grained sand with thin layers of clay containing good quality water
	3	49.1 – 300	4.6	Clay with fine sand containing brackish water
8.	1	0 – 1.41	56.3	Hard clay with weathered surficial material having conserved moisture
	2	1.42 - 15.1	151.1	Coarse grained sand with thin layers of clay comprised of good quality water

	3	15.2 – 300	37.0	Fine sand with clay having marginal to saline water
9.	1	0 – 0.77	17.1	Silty clay with moisture conserved
	2	0.78 - 43.0	139.9	Coarse grained sand with alternate thin layers of clay containing freshwater
	3	43.1 – 300	34.02	Fine sand with clay containing marginal to saline water
10.	1	0 – 0.54	95.4	Clay with conserved moisture contect (surficial material)
	2	0.55 - 3.3	7.2	Silt with clay
	3	3.4 – 300	49.5	Alternate layers of clay and coarse sand containing marginal quality of water
11.	1	0 – 1.75	8.7	Clay with conserved moisture
	2	1.76 – 55.7	17.7	Alternate layers of clay and coarse sand or admixture of both, containing saline water
	3	55.8 – 300	52.2	Alternate layers of clay and coarse sand comprised of freshwater
12.	1	0 – 0.19	5.8	Clay with conserved moisture
	2	0.2 - 34.6	42.7	Layers of clay and sand containing marginal quality water
	3	34.7 – 270	101.3	Coarse sand with thin layer of clay containing good quality of water
13.	1	0 – 1.05	29.2	Clay with conserved moisture (surficial material)
	2	1.06- 39.5	6.5	Clay with thin layer of fine sand having brackish water
	3	39.6 – 300	58.2	Alternate layer of coarse sand and clay with freshwater
14.	1	0 – 0.24	136.4	Dry clay with weathered material
	2	0.25- 34.16	152.07	Fine sand with thin layers of clay containing freshwater
	3	34.17 – 300	63.7	Coarse sand with clay having good quality of water
15.	1	0 – 6.8	67.1	Clay with conserved moisture and weathered material
	2	6.81- 15.9	23.6	Clay with fine grained sand containing marginal to saline water
	3	15.91 – 300	4.3	Clay with thin layers of fine sand containing brackish water
16.	1	0 – 2.4	44.1	Clay with weathered surficial material and conserved moisture
	2	2.5-21.7	27.4	Fine sand with alternate thin layers of fine sand having marginally saline water
	3	21.8 – 300	19.1	Fine sand with alternate thin layers of fine sand having saline water
17.	1	0 – 6.9	19.4	Clay with conserved moisture
	2	6.91-11.2	3.97	Clay with saline water
	3	11.3 – 300	45.2	Alternate layers of Clay and fine sand having good quality of water
18.	1	0 – 1.67	56.5	Clay with weathered material and conserved moisture
	2	1.68- 19.4	10.4	Silty clay with fine sand having saline water
	3	19.5 – 300	77.0	Alternate layers of coarse sand and clay containing freshwater
19.	1	0 – 0.41	19.7	Clay with conserved moisture
	2	0.42-10.2	70.5	Clay with coarse sand having good quality water
	3	10.3 – 300	4.9	Clay with fine sand having saline water
20.	1	0 – 10.0	13.9	Clay and thin layers of fine sand with conserved moisture
	2	10.1-66.2	86.4	Coarse sand with thin clay layers having fresh water
	3	66.3 – 300	66.1	Coarse sand with clay having good quality of water
21.	1	0 – 1.25	19.3	Clay with conserved moisture
	2	1.26- 69.6	140.6	Coarse sand with thin clay layer containing freshwater
	3	69.7 – 300	56.15	Coarse sand with alternate clay layers having good quality water
22.	1	0 – 13.4	131.3	Dry clay with weathered material
	2	13.5- 50.6	33.6	Clay with thin layers of fine sand having marginal quality of water
	3	50.7 – 300	12.6	Alternate layers of clay and fine sand containing saline water
23.	1	0 – 1.8	71.8	Clay with conserved moisture (surficial material)
	2	1.9- 31.5	152.5	Alternate layers of clay and coarse sand comprise of good water quality
	3	31.6 – 300	39.4	Layers of fine sand with clay containing marginal quality water
24.	1	0 – 2.1	7.7	Clay with conserved moisture

	2	2.2- 33.4	17.1	Alternate layers of clay and fine sand having saline water
	3	33.5 – 300	24.4	Layers of sand and clay with low quality water
25.	1	0 – 0.62	16.1	Clay with weathered material (conserved moisture)
	2	0.63- 23.6	134.4	Alternate layers of clay with coarse sand having good quality water
	3	26.7 – 300	75.0	Clay with alternate layers of sand having good quality of water
26.	1	0 – 2.72	25.1	Clay with surficial material
	2	2.73- 22.8	151.3	Coarse sand with thin layers of clay containing fresh water
	3	22.9 – 300	85.4	Coarse sand with alternate layers of clay containing good quality of water
27.	1	0 – 1.31	36.6	Clay with conserved moisture (surficial material)
	2	1.32- 26.5	137.2	Coarse sand and thin layers of sand containing fresh water
	3	26.6 – 300	81.1	Alternate layers of sand and clay containing good quality water
28.	1	0 – 16.0	144.9	Dry clay with conserved moisture (surficial moisture)
	2	16.1 – 135.6	105.1	Coarse sand with alternate layers of thin clay having freshwater
	3	135.7 – 300	8.7	Clay with alternate layers of fine sand having saline water

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSION

The electrical resistivity approach is indeed the most effective one used in hydrogeological investigations, particularly for assessing various elements of groundwater quality. This approach not only offers data on subsurface lithologies but also indicates the existence of water with an estimate of groundwater salinity. Vertical Electrical Sounding (VES) survey was conducted in the study area and the field data was interpreted using “IX1D Interpex”. On the basis of these interpreted true resistivity values, electrical conductivity defining the quality of groundwater is estimated. The findings of the VES interpreted data and groundwater quality maps showed that the analyzed sites often had saline water at the bottom of an unconfined aquifer. These fresh water layers can be targeted using the VES approach in order to dig a well up to the bottom of these layers and prevent additional drilling. The extent of these layers also helped us choose a well location on the farmers landholding where the fresh groundwater layer was thicker. It is observed that the resistivity values decrease as the investigation depth increases thus reflecting the poor water bearing strata with saline to brackish quality water. Sites comprised of good potential for water are found to be along the river and as we move away or towards the center of study area there is low potential for good quality water.

Based on interpreted geoelectrical data following conclusions were drawn for district Okara. In tehsil Okara, 11 VES survey were conducted at different locations. The interpreted resistivities shows different values at all locations of tehsil Okara because of the presence of varying sub surface lithology and groundwater quality. The interpreted true resistivity values ranged from 4.6 ohm-m to 151.1 ohm-m represent 3 layered sub surface model. At VES 5 of Tehsil Okara, the maximum thickness of the subsurface layer containing fresh groundwater with a resistivity of 103.9 ohm-m was discovered from 104 m up to a depth of 300 m. In tehsil Renala Khurd, field data was collected from 9 different locations. The resistivity values displayed variations ranging from 3.97 ohm-m to 152.2 ohm-m. It is found that tehsil Renala Khurd has the least potential for good quality groundwater as the resistivity values are low. This is mainly due to less recharge from river as it is located away from River Ravi and Sutlej. Tehsil Depalpur is situated along the the bank of river Sutlej. The true resistivity values in this area fluctuated from 7.7 ohm-m to 151.3 ohm-m and reflects the maximum potential for good quality water. The maximum thickness of layer comprised of good quality water stretched from 23 m up to 300m having 85.4 ohm-m resistivity.

5.2. RECOMMENDATIONS

I. I. The locations used to collect the data were chosen at random throughout the landscape. Therefore, it is proposed that in future research, the sites should be picked on grids of either 1x1 km2 or 2x2 km2 or any other according to the available capabilities. This must be done in order to ensure accurate results.

II. Extreme weather conditions like flooding, prolonged dry spells, and other weather-related problems might impair the findings of a one-time examination. If any extreme hydrologically significant event occurs, it is advised to update the current data.

III. Before undertaking drilling operation for tube wells, it is strongly recommended that the VES survey must be carried out.

IV. IV. The VES study has the ability to offer data that are acceptable in terms of their accuracy and which may be utilized to get an understanding of the subsurface in geothermal exploration. The findings of the VES need to be checked and linked with the actual conditions below the ground (borehole data).

V. The study area have better quality of groundwater in their shallow aquifer layers than in the deep layers. Therefore, these fresh groundwater zones could be used for safe extraction.

VI. Techniques for creating artificial groundwater recharge should be promoted in the area.

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ANNEXURES

ANNEXURE-1

VES Data Recording Sheet					
Location					
GPS Information			**Survey Details**		**Probe ID:**
Latitude	**Longitude**	**Elevation**	**Grid Size**	**Type**	**Operating Officer**
					Name:
Electrode Spacing		**Terrameter SAS (1000 or 4000)**		**Calculated Apparent Resistivity RA = (Ω) @ = RXK**	**Designation:**
AB/2 (Meter)	**MN/2 (Meter)**	**Terrameter Readings R = (Ω)**	**Geomatrical Factor = K**		**Signature** **Date**
2	0.5		12	0	
4	0.5		49	0	
8	0.5		200	0	
10	0.5		313	0	
15	0.5		705	0	
20	0.5		1255	0	
25	0.5		1962	0	
25	5		188	0	
30	5		275	0	
35	5		377	0	
40	5		495	0	
45	5		628	0	
50	5		777	0	
50	10		377	0	
60	10		550	0	
70	10		754	0	

80	10		989	0	
90	10		1256	0	
100	10		1554	0	
100	20		754	0	
120	20		1100	0	
150	20		1735	0	
180	20		2512	0	
210	20		3430	0	
240	20		4490	0	
270	20		5691	0	
300	20		7034	0	

ANNEXURE-2

OKARA VES DATA												
AB/2	MN/2	Pb 02	Pb 09	Pb 11	Pb 16	Pb 64	Pb 75	Pb 85	pb 88	pb 90	Pb 92	Pb 99
2	0.5	107.8	11.99	86.08	17.32	19.76	30.98	65.16	67	34.76	16.68	9.5
4	0.5	119.97	11.76	106.16	31.56	20.39	33.18	101.08	92.69	54.97	10.29	11.29
8	0.5	131.4	12.9	128.6	54	23	43	128.2	111.2	89.8	16	14.1
10	0.5	133.17	14.4	136.86	63.84	24.41	49.77	132.97	119.95	97.29	19.09	15.65
15	0.5	135.89	17.62	138.23	82.88	26.79	63.45	139.52	120.56	110.96	24.08	16.03
20	0.5	141.39	20.1	135.79	94.97	28.61	71.54	144.83	118.74	123.55	28.38	16.58
25	0.5	146.04	23.07	123.1	100.3	30.27	76.14	151.52	108.64	124.8	31.35	17.62
30	5	144.32	27.5	116.15	102.7	31.9	77.28	143.75	101.18	122.75	33	18.22
35	5	138.91	29.41	103.35	101.13	33.93	75.4	137.67	90.56	120.32	34.68	18.85
40	5	137.52	30.69	97.6	99.07	33.66	72.76	130.64	83.09	119.13	36.63	18.32
45	5	133.17	32.66	83.52	98.04	32.66	68.45	123	74.24	117.76	37.68	18.21
50	5	128.9	36.45	70.65	97.64	31.3	66.04	119.53	66.37	112.02	38.83	17.87
60	10	124.9	40.25	59.35	86.95	31.8	62.7	111.7	53.35	109.45	41.05	18.7
70	10	120.41	42.73	47.68	72.9	33.18	57.3	105.89	46.99	107.07	42.21	18.85
80	10	112.9	44.51	39.16	61.76	34.62	52.42	95.31	44.56	101.11	43.56	19.78
90	10	107.26	45.22	33.14	52.99	35.17	51.73	82.04	42.68	91.93	45.19	21.84
100	10	101.43	46.17	31.21	47.9	36.19	50.98	76.9	41.44	86.84	45.99	23.37
120	20	90.1	49	23	39.1	37.4	49.8	58.4	39.3	69.7	46	25.3
150	20	67.67	52.05	17.98	28.07	39.9	45.11	31.23	37.7	57.28	46.85	27.76
180	20	55.26	55.26	16.86	21.34	45.22	45.22	17.58	37.68	48.9	47.73	32.66
210	20	41.16	59.74	16.05	18.17	49.45	48.02	12.72	37.73	42.32	48.02	34.3
240	20	35.92	61.86	15.23	15.37	51.88	49.39	8.98	38.61	40.82	49.39	35.92
270	20	28.45	62.6	14.51	14.22	54.06	51.22	7.12	38.7	39.67	51.22	34.15
300	20	28.14	63.31		13.24	55.57	56.27	5.92	38.69	37.37	53.46	35.17