An Integrated Geo-Physical Approach for Groundwater Investigation in Northwestern Part of Pakistan

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Abstract*: Climate change is causing severe hydrological perturbations commonly seen as erratic precipitation patterns in many regions. North-Western region of Pakistan is also facing severe rainfall decline which has rendered groundwater exploration crucial for the sustenance of agricultural and domestic activities. The integrated geophysical method described here employs Automatic Mapping Water Detector (AMWD) to locate aquifers with relative depths and Electric Resistivity (ER) Survey for investigating the groundwater salinity. AMWD generates output in the form of potential difference curves and profile map, which were interpreted combinedly to investigate the aquifers. ER survey, using Schlumberger configuration, was carried out at the demarcated location and the resistivity values were analyzed to establish a relation with groundwater quality. The AMWD and ER surveys were conducted at four locations. The first two, with known groundwater data, served to cross-check the results obtained from AMWD and ER surveys. Once the method validated, the remaining two locations (Sadiq and Baloch points) were explored with Baloch point showing auspicious prospects for freshwater availability but with underlying layers of saline water. Thus, the method not only aids in locating freshwater aquifers but also provides critical data for sustainable groundwater management in regions prone to both saline and freshwater conditions.

Keywords: Hydrogeology, Groundwater Investigation; Groundwater Quality; Geophysical Methods

1. INTRODUCTION

Water scarcity is escalating rapidly throughout the world including Pakistan where the current water crisis depicts an intensely grim situation (El Kharraz, El-Sadek, Ghaffour, & Mino, 2012; Jo-Ellen Parry, 2016; Mekonnen & Hoekstra, 2016). Climate change is causing higher temperatures every year in many regions of the world (Easterling et al., 2000; Perkins, Alexander, & Nairn, 2012; Sheffield & Wood, 2008) including Pakistan (Farooqi, Khan, & Mir, 2005) which will increase the country’s water demand in both agricultural as well as industrial sectors (Jo-Ellen Parry, 2016). In many regions of Pakistan, lack of rainfall has rendered the need for groundwater exploration extremely necessary to meet the agricultural and domestic needs of the indigenous communities but in order to ensure its sustainable consumption, groundwater management becomes crucial for the future of our freshwater resources.

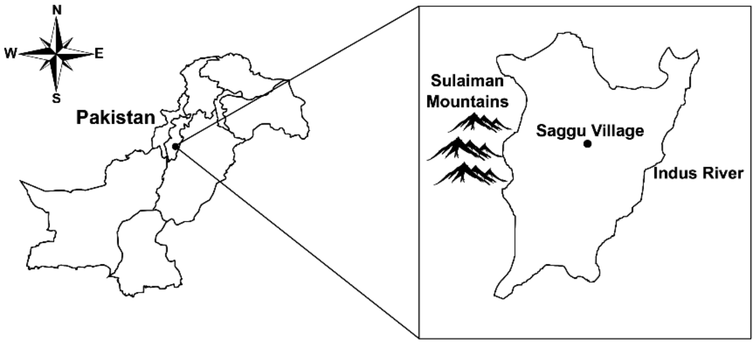

Figure 1. Map of district Dera Ismail Khan (DI Khan) and village Saggu

Study area i.e. village Saggu is located in the northwestern region of Pakistan in the district of Dera Ismail Khan (DI Khan) and is home to about 2000 indigenous people. Indus River flows on the Eastern side of the region and on the Western side there lies Sulaiman Mountains (Figure 1). Residents of Saggu and nearby villages are dependent on the local groundwater resources for domestic and agricultural needs. However, the groundwater presents a very complex situation in the region where both saline and freshwater aquifers are abundantly available at significantly varying depths. Thus, an integrated approach of geophysical techniques is highly imperative for the exploration as well as the sustainable management of freshwater aquifers in the region.

Many geophysical techniques have been used in the past for groundwater exploration. Electrical Resistivity Survey (Roy & Elliott, 1980; Stewart, 1982) though deemed to be the most useful technique for groundwater investigation but has its limitations. One of the most complicated tasks for the electric resistivity method is to probe the aquifers bearing freshwater because resistivity values vary over a wide range which rarely delineates a certain lithology (Goldman & Neubauer, 1994). Other techniques such as Seismic reflection method and Frequency domain electromagnetic (FDEM) have also been successfully used for groundwater exploration. But there are certain discrepancies among these methods with the former one requiring vigilant scrutiny to avoid possible pitfalls in data collection (Steeples & Miller, 1988) and the later comprising of complicated theory and interpretation (Goldman & Neubauer, 1994). Remote sensing and GIS techniques have also been widely used for demarcating potential groundwater locations (Jaiswal, Mukherjee, Krishnamurthy, & Saxena, 2003) but it has certain limitations since groundwater cannot be directly sensed through remote sensing and we have to infer the potential sites for freshwater aquifers from the identification of surface features (Das, Behera, Kar, Narendra, & Guha, 1997; Ravindran & Jeyaram, 1997).

2. METHODOLOGY

The integrated method described in this article combines electromagnetic geophysical technique with electric resistivity (ER) survey to successfully locate potential locations for freshwater aquifers. Natural Electric Field Geophysical Prospecting Instrument, referred to as the Automatic Mapping Water Detector (AMWD) in this article, was used for electromagnetic testing. AMWD works by measuring the electric field component of the earth’s magnetic field in different frequencies ("PQWT Operation Manual for S-Series," ; "PQWT Water Detector Case Share,") and can easily demarcate the potential points for groundwater aquifers. Once the points were marked, an electric resistivity survey was conducted at the indicated locations for the assessment of groundwater quality (Nejad, Mumipour, Kaboli, & Najib, 2011; Pervaiz Sikandar, Bakhsh, Arshad, & Rana, 2010).

A co-relation between the electrical resistivity and subsurface geological conditions with water quality, as shown in Table 1, was developed by Pakistan Council for Research in Water Resources (PCRWR, 2003) based on the geological information derived from the test bores, tube wells and other data of geological investigations in the district of DI Khan. This co-relation serves the purpose of reference in this article and ER values at all the survey sites are compared with Table 1 to investigate the groundwater quality.

Table 1. Co-relation between electrical resistivity and subsurface geological condition with water quality established by PCRWR

Zone Classification	**Resistivity Range (Ohm-m)**	**Co-relation with the geological formation and water quality**
Low resistivity zone	<20	This zone indicates the presence of fine material like clay/shale with rare sand and has, therefore, saline to less saline water-bearing potential.
Medium resistivity zone	20-35	This zone indicates the presence of intermediate sand with some clay. It may indicate alternate bedding of sand and clay/shale. The formation can yield groundwater if below the water table.
High resistivity zone	35-100	This zone is interpreted as the dominance of coarser material i.e. sand with good quality water.
Very high resistivity zone	>400	Very high resistivity may represent the presence of unsaturated zone above the water table and bedrock if below the water table.

Source – Pakistan Council for Research in Water Resources (PCRWR, 2003)

ER survey was conducted at the test sites and the standard electrode configuration of Schlumberger array was adopted during the procedure. Though various electrode configurations such as pole-pole, dipole-dipole and Wenner array have been employed in the past for ER surveys Schlumberger array was preferred because it is less arduous, enhances the accuracy in data collection (Khan & Waheedullah, 2013) and has better depth sensitivity (P Sikandar, Bakhsh, Ali, & Arshad, 2010). Thus because of its numerous advantages, the same electrode configuration of Schlumberger array was adopted for all the ER surveys discussed in this article.

Data gathered from the ER survey was interpreted using IX1D software (Interpex, 2008) developed by Interpex Limited and iterative technique was employed for the calculation of layer models. Parameters for models were made to adjust after every iteration and the deviation of the relevant curve was checked. This deviation is defined by root mean square error (RMSE) which is displayed after every iteration. Finally, the model with the smallest error is plotted presenting layer's interpreted resistivity and relative thickness and finally tabular interpretation of IX1D model is indicated with corresponding depth and layer thickness.

Geophysical investigation surveys (AMWD and ER surveys) for groundwater exploration were executed at a total of four locations in the vicinity of District Dera Ismail Khan. Two of these investigation sites already had installed bore wells which are referred to as Reference Bore Well 1 (RBW 1) and Reference Bore Well 2 (RBW 2) in this article and the remaining two consists of unexplored locations which are referred to as Sadiq Point and Baloch point in this article. Bore log data and water quality reports for the two reference bore wells served to substantiate the validity of results obtained from the stated integrated method.

The mentioned integrated technique requiring significantly less interpretive efforts and inexpensive characteristics is particularly serviceable in those regions where both saline and fresh groundwater reserves exist. However, groundwater management becomes momentous while exploiting freshwater in such regions otherwise salinization of freshwater resources can itself produce detrimental effects on freshwater reserves (Reilly & Goodman, 1985) in the region.

3. RESULTS AND FINDINGS

The proposed method for groundwater investigation described here encompasses two basic objectives i.e. *(a) Groundwater Location (b) Groundwater Quality*, thus each of the surveyed regions is expounded accordingly in this article and respective AMWD and ER results are presented with relevant interpretations.

3.1 Groundwater Location at RBW 1

Bore log data (Figure 2) of the first reference bore well was obtained from the Public Health Engineering Department (PHED). According to PHED's report water was encountered at a depth of 250 meters and screens were inserted accordingly as shown in Figure 2. The total depth of the tube well is 313 meters.

AMWD survey was conducted near the installed tube well and the generated results were compared with the available bore log data to examine their validity. AMWD apparatus generates outcome in the form of potential difference curves (Figure 3) and profile map (Figure 4) both when interpreted together leads to locating the groundwater reserves with relevant depths ("PQWT Water Detector Operation and Analysis,"). Potential difference curves drop significantly at the point with the high probability of groundwater ("PQWT Water Detector Operation and Analysis,") as shown in Figure 3 where potential difference curves depict a drop at point number 5. When Figure 3 is combined with the profile map generated by AMWD (Figure 4) then point number 5 shows light blue color starting from depth 260 meters and beyond which characterizes the probability of water ("PQWT Water Detector Operation and Analysis,").

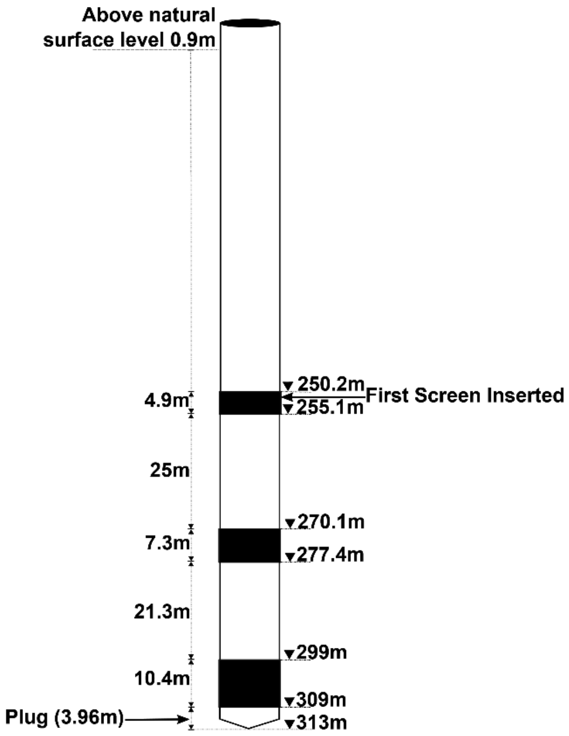

Figure 2. Bore log data for RBW 1 obtained from the PHED's report

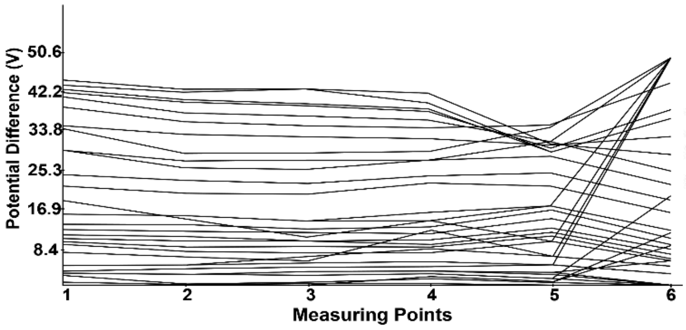

Figure 3. Potential Difference curves generated by AMWD at RBW 1

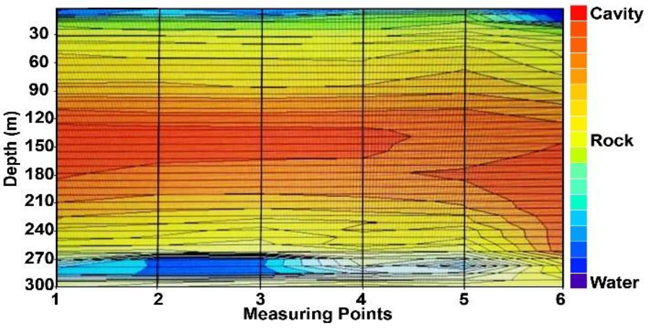

Figure 4. Profile map generated by AMWD at RBW 1

Now after comparing these results with the available bore log data (Figure 2), it can be concluded that the established interpretation of AMWD survey corresponds with the actual lithological conditions. Bore log data shows that water was first encountered at a depth of 250 meters and interpretation of AMWD results concludes that water reserves are available at a depth of 260 meters. Thus, with a reasonable margin of error, the validity of results generated by AMWD survey is substantiated.

3.2 Groundwater Quality at RBW 1

ER survey by employing the standard electrode configuration of Schlumberger array, was executed at the site of RBW 1 and the data obtained were interpreted using IX1D software. Both the IX1D model (Figure 5) and the relevant tabular interpretations (Table 2) were analyzed accordingly. It can be observed in Table 2 that starting from the depth of 241.6 meters up to the depth of 319.5 meters the resistivity values lie in the medium resistivity zone as mentioned in Table 1 which indicates saline water potential. Since the RBW 1 was already pumping out water thus, a water sample was collected and a water quality test was performed to check if the mentioned values in Table 1 actually correspond with groundwater quality.

Figure 6 shows the observed and permissible water quality parameters (WHO, 2011) obtained from the water quality test conducted at PCRWR's lab.

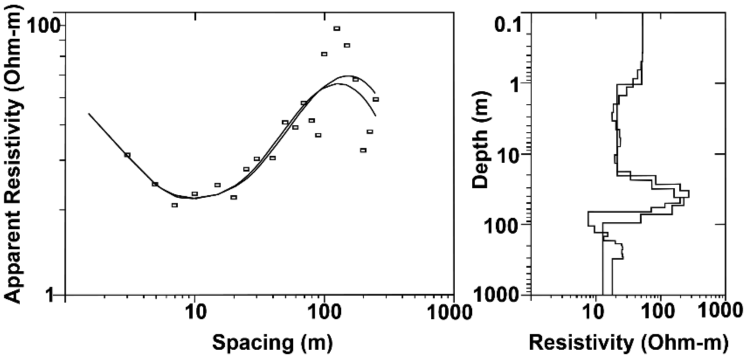

Figure 5. IX1D model for ER data obtained at RBW 1

Table 2: Tabular interpretation of IX1D model obtained for RBW 1

Resistivity (Ohm-m)	**Thickness (m)**	**Depth (m)**
83.7926	27.03346	27.03346
198.1582	8.54429	35.57775
267.7745	10.09663	45.67438
199.3390	9.99463	55.66901
114.5620	11.37972	67.04873
70.9210	41.04807	108.0968
7.54584	30.69571	138.79251
9.37251	20.96468	159.75719
15.31528	34.39072	194.14791
13.24250	22.38449	216.5324
19.77158	12.04436	228.57676
24.45006	**13.02701**	**241.60377**
25.15410	**6.02800**	**247.63177**
25.66573	**8.01326**	**255.64503**
25.93613	**23.10304**	**278.74807**
24.96881	**20.78836**	**299.53679**
25.58737	**19.92892**	**319.46571**

It can be observed from Figure 6 that the total dissolved solids (TDS) also referred as total salt concentration or salinity (Grattan, 2002) in the water sample collected from RBW 1 is 1820ppm while the permissible value for potable water should be no more than 1000ppm (WHO, 2011) thus the contamination exceeds far beyond the permissible value of TDS for drinking purposes. This validates the co-relation between ER and groundwater quality (Table 1) and confirms the application of the ER survey for exploring the groundwater quality.

3.3 Groundwater Location at RBW 2

Though above stated integrated approach for groundwater exploration has been successfully validated by the correspondence between available data (bore log data and water quality reports) for RBW 1 and geophysical surveys (AMWD survey and ER survey) conducted at the RBW 1 yet to further strengthen the plausibility of the mentioned method, the same procedure of geophysical surveys was conducted at another installed tube well in the vicinity of village which is hereby referred to as RBW 2. Groundwater location and groundwater

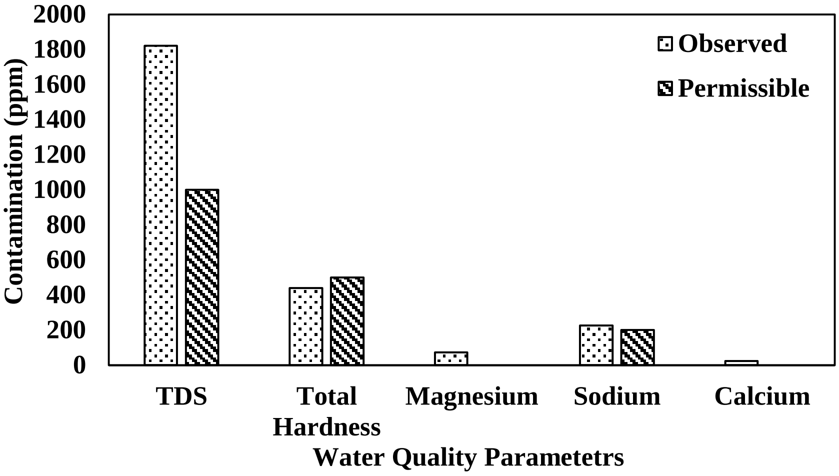

Figure 6. Observed and permissible water quality parameters obtained from water quality test for RBW 2

quality are discussed accordingly.

RBW 2, drilled in the year 2014, was located in a school in the village of Saggu. The tube well was installed by PHED driven down up to the depth of 90 meters. Bore log data of the tube well is shown in Figure 7 which depicts that water was first encountered at a depth of 72 meters. According to the residents of the village Saggu, this tube well has worse quality of water as compared to the RBW 1 thus a water sample was also tested in order to check its quality.

AMWD survey was conducted near the RBW 2 and the generated potential difference curves (Figure 8) with lithological profile map (Figure 9) were analyzed to compare the results with actual bore log data. Potential difference curves show a steep fall at point number 8 in Figure 8 which when combined with Figure 9 shows a light blue color at the same mentioned point number 8 in the lithological mapping. Since blue is interpreted as water ("PQWT Water Detector Operation and Analysis,") so Figure 9 indicates the presence of water starting from a depth of approximately 70 meters up to the depth of 140 meters. A comparison of the mentioned interpretation with bore log data further justifies the validity of the results produced by AMWD survey since bore log data also reflect the availability of groundwater starting from

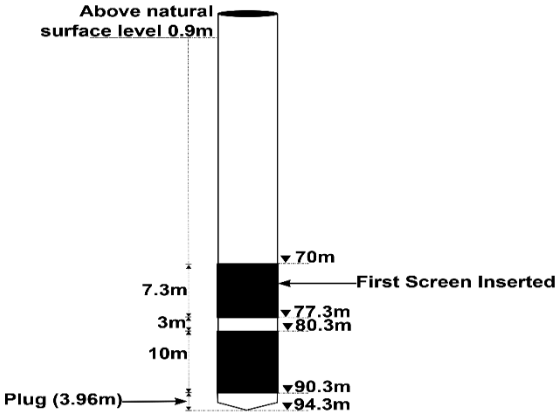

Figure 7. Bore log data for RBW 2 obtained from the PHED's report

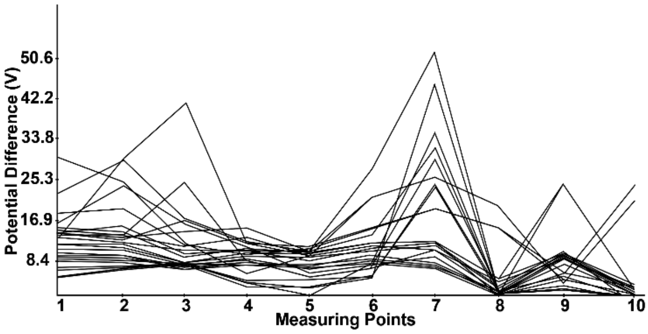

Figure 8. Potential Difference curves generated by AMWD at RBW 2

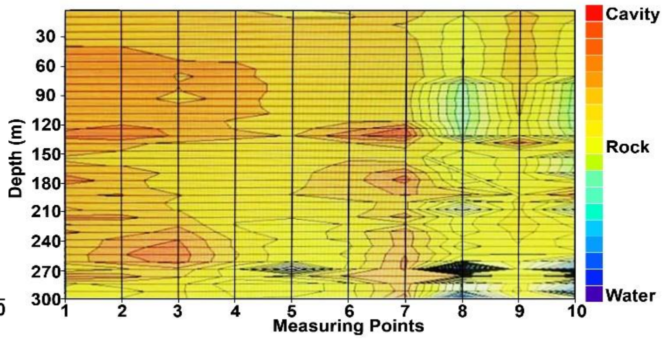

Figure 9. Profile map generated by AMWD at RBW 2

the depth of 70 meters. Thus, the AMWD survey successfully demarcated the groundwater location and both reference bore wells (1 and 2) confirm the acceptability of the results obtained from the survey.

3.4 *Groundwater Quality at RBW 2*

Electric resistivity survey was conducted near the RBW 2 and the garnered data was interpreted using IX1D software (Interpex, 2008) by employing an iterative approach to develop the layer models with relative thickness and layer resistivity (Figure 10).

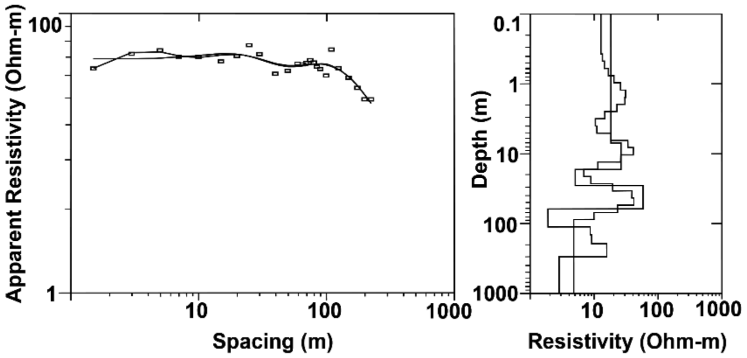

Figure10. IX1D model for ER data obtained at RBW 2

Table 3. Tabular interpretation of IX1D model obtained for RBW 2

Resistivity (Ohm-m)	**Thickness (m)**	**Depth (m)**
69.01679	7.04824	7.04284
88.14256	9.99898	17.04722
29.40617	11.66819	28.71541
15.4424	**33.63828**	**62.35370**
15.30086	**50.02170**	**112.3754**
42.05780	32.75863	145.1340
43.63005	50.22191	195.3559
63.11035	103.8713	299.2272

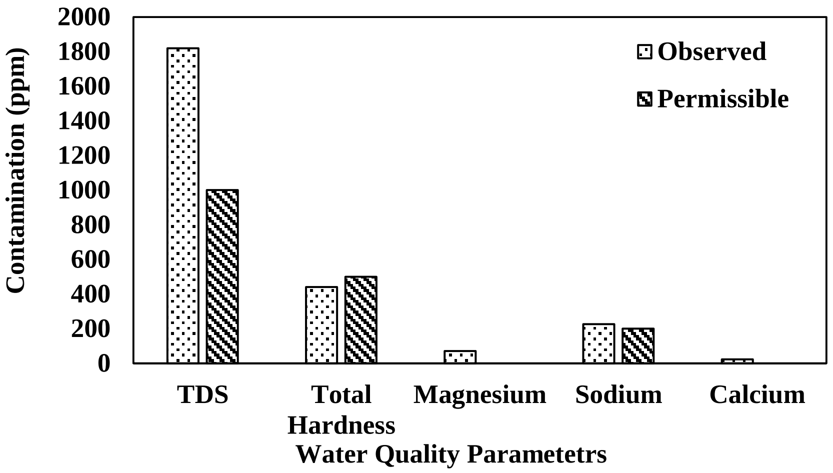

Figure 11. Observed and permissible water quality parameters obtained from water quality test for RBW 2

Table 3 represents the tabular interpretation of the mentioned IX1D model which is further compared with Table 1 (Co-relation between resistivity values and water quality) to scrutinize the groundwater quality. It can be observed that starting from the depth of 62 meters up to the depth of 112 meters resistivity value is less than 20 ohm-m thus characterizing the saline water potential which was further confirmed after performing chemical analysis of the water sample obtained from the RBW 2 (Figure 11). TDS shows a quite high value of 2734 ppm as perceptible from the water quality graph presented in Figure 11 which being a clear suggestion for groundwater salinity clarifies the water quality interpretation as deduced from the electric resistivity survey and Co-relation between resistivity values and water quality.

Thus, after verifying the mentioned integrated approach to detect groundwater location and groundwater quality, the method was utilized and geophysical tests were conducted at virgin locations in the vicinity of village Saggu to locate the fresh groundwater aquifers. Further in this article two of the unexplored points are discussed with relevant geophysical interpretations. Since these points were located in the lands owned by the local people, therefore, named as Sadiq Point and Baloch Point depending on the names of landowners of their respective locations for the ease to be discussed in this article.

3.5 Groundwater Location at Sadiq Point

After conducting the AMWD survey at Sadiq point, potential difference curves were plotted and the profile map was generated by the AMWD apparatus ("PQWT Operation Manual for S-Series,"). Subsequently, both the outcomes had to be interpreted to demarcate the location of point deemed to show the most probable location of the groundwater aquifer.

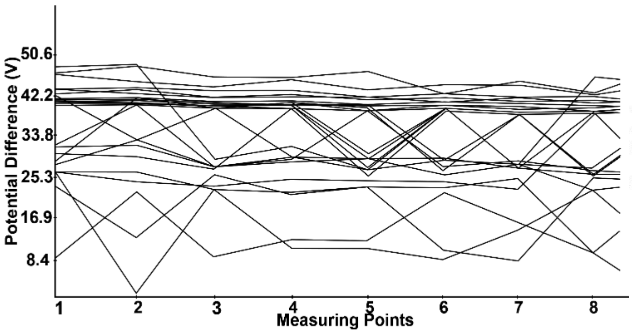

Figure 12. Potential Difference curves generated by AMWD at Sadiq point

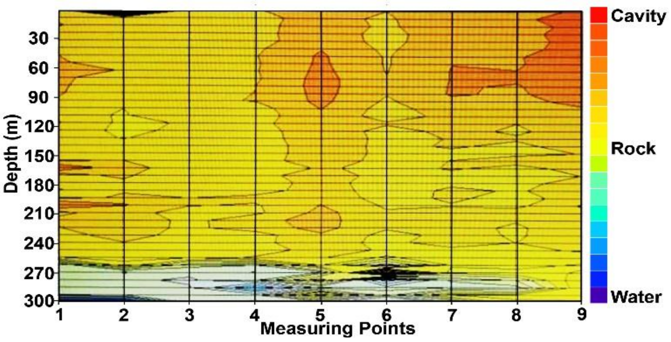

Figure 13. Profile Map generated by AMWD at Sadiq Point

But in the case of Sadiq point, perceiving at Figure 12 it can be clearly comprehended that no point shows a significant drop in potential difference curves which indicates that there exists a very narrow possibility of groundwater aquifers located in the vicinity of Sadiq point. Figure 13 shows the profile map generated by AMWD at Sadiq point which when combined with Figure 12 depicts that no such point exists which can correspond with potential drop curves in Figure 12 i.e. drop in potential difference curves and blue color in profile map must co-exist at the same point in both the figures generated by AMWD ("PQWT Water Detector Operation and Analysis,") that hereby is non-existent.

As Sadiq point did not indicate any promising prospects for the availability of groundwater thus, ER survey was not conducted at the mentioned point to investigate the groundwater quality.

3.6 Groundwater Location at Baloch Point

Baloch point was located at the edge of a non-perennial canal which has gone dry for the past ten years due to the lack of sufficient rainfall and this typical characteristic was the major reason to consider Baloch point for geophysical investigation. AMWD survey was executed and the potential difference curves were generated as shown in Figure 14.

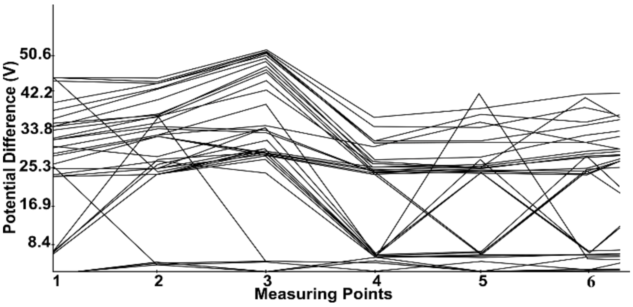

Figure 14. Potential Difference curves generated by AMWD at Baloch point

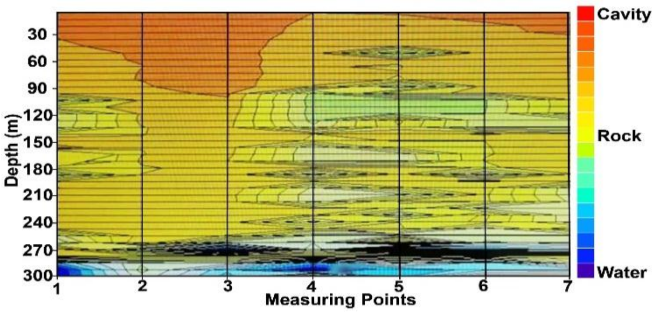

Figure 15. Profile Map generated by AMWD at Baloch Point

It can be perceived from Figure 14 that potential difference curves show a drop at point number 4 which as mentioned in the previous accounts is an indication for groundwater aquifers. Now when interpreted in combination with profile map generated at Baloch point (Figure 15), it can be observed that for the same point number 4 starting from a depth of 90 meters up to the depth of 150 meters, profile map shows a bluish yellow color which is the characteristic of coarser material capable of holding water. Further below 150 meters at point number 4, the profile map shows bluish yellow color in layers of varying depths which again characterizes the availability of water aquifers.

Since both of these Figures (14 & 15) correspond with each other thus Baloch point showed good prospects for the availability of groundwater aquifers. Henceforth to further cross-check and investigate the groundwater quality ER survey was conducted at the Baloch point.

3.7 Groundwater Quality at Baloch Point

ER survey was executed at the propitious location of Sadiq point and similar to the previous accounts iterative approach was employed to develop layer models with relative thickness and corresponding layer resistivity (Figure 16). Table 4 presents the tabular interpretation of the IX1D model plotted for Baloch point and in order to probe the groundwater quality, resistivity values in Table 4 are compared with Co-relation between resistivity values and water quality (Table 1).

Starting from the depth of 85 meters up to the depth of 159 meters resistivity values lie in the high resistivity zone (35-100 ohm-m) which indicates the freshwater potential of the groundwater aquifer. But after the depth of 159 meters the resistivity values suddenly fall into the low resistivity zone (< 20 ohm-m) which suggests that water available below 150 meters has saline potential as low resistivity values are the characteristics of water prone to salinity.

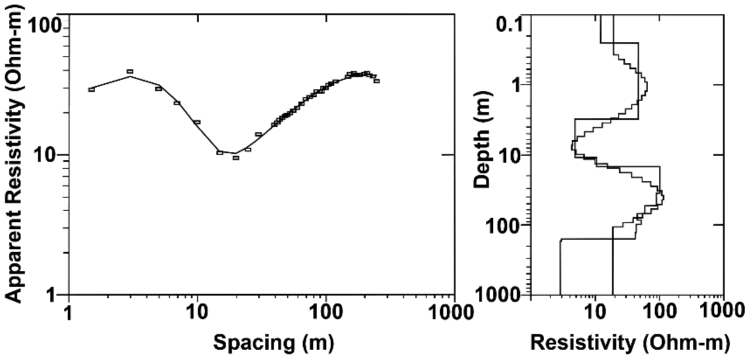

Figure 16. IX1D model for ER data obtained at Baloch Point

Table 4: Tabular interpretation of IX1D model obtained for Baloch Point

Resistivity (Ohm-m)	**Thickness (m)**	**Depth (m)**
12.11292	0.25266	0.25266
46.81805	2.86082	3.11348
4.80692	7.75906	10.87254
10.57481	3.81438	14.68692
100.8787	20.90377	35.59070
88.90398	17.93430	53.52500
59.47564	16.24100	69.76600
44.75794	**15.93699**	**85.70299**
52.08754	**12.81583**	**98.51881**
43.27145	**30.42761**	**128.9464**
42.13385	**30.43660**	**159.3830**
2.95632	2.95844	162.3414
2.95672	2.95848	165.2999
2.95651	2.95848	168.2584
2.95618	2.95850	171.2169

This implies that the stated integrated approach to groundwater exploration can provide efficacious prospects for groundwater resource management in areas that have abundant resources of both fresh and saline water aquifers. Since, in such areas, if abstraction is not properly managed then saline water intrudes in freshwater aquifers which itself leads to deterioration of freshwater reserves (Adeoti, Alile, & Uchegbulam, 2010; Barlow & Reichard, 2010; Nowroozi, Horrocks, & Henderson, 1999; Post & Abarca, 2010) and loss to agricultural activities (Harun-ur-Rashid & Islam, 2007) thus skimming wells (Saeed & Ashraf, 2005; Sufi, Latif, & Skogerboe, 1998) should be installed in these cases for sustainable extraction of fresh groundwater.

4. CONCLUSION

An integrated approach has been devised which links electromagnetic geophysical technique with electric resistivity (ER) survey to explore and investigate groundwater reserves. Profile maps and potential difference curves were interpreted combinedly to probe groundwater location while the ER survey aided in the inspection of groundwater quality. Intelligible correspondence of available bore log data and water quality reports with interpretations of AMWD and ER surveys at reference bore wells (1 and 2) cogently validated the soundness of the mentioned integrated technique for groundwater exploration. Once the viability established, the stated integrated approach was employed at two unexplored locations.

With changing climate, droughts are happening frequently leading to the communities depending more and more on groundwater resources. In the prevailing situation, sustainable extraction and groundwater management is possible only when the groundwater reserves are explored properly and reliable data is available. The mentioned integrated approach to groundwater exploration owing to its ease of simplicity and requiring less interpretative efforts can be particularly helpful in collecting critical data for groundwater management.

In areas where both saline and freshwater aquifers exist e.g. Coastal Areas, groundwater management is necessary because if not properly managed then there arises the serious risk of saline water intrusion in freshwater aquifers leading to a great loss to freshwater resources and agricultural activities in the region. The described integrated method for groundwater exploration can be very useful in such regions and can efficiently provide data about groundwater quality with relative depths.

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