Journal of Environmental Protection, 2012, 3, 1039-1046
http://dx.doi.org/10.4236/jep.2012.39121 Published Online September 2012 (http://www.SciRP.org/journal/jep)

Geophysical Investigation of the Fresh-Saline Water Interface in the Coastal Area of Abergwyngregyn

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Received February 9th, 2012; revised May 1st, 2012; accepted July 2nd, 2012

ABSTRACT

The importance of the study of saline/fresh water incursion cannot be over-emphasized. Borehole sampling has been extensively used, but it is intrusive, quite expensive and time consuming. Electrical resistivity and electromagnetic techniques have proved successful in groundwater studies since geologic formation properties like porosity and permeability can be correlated with electrical conductivity signatures. Non-intrusive surface geophysical mapping comprising electrical resistivity and electromagnetic methods has been employed to investigate freshwater intrusion and delineate the fresh-saline water interface at the inter-tidal area of Abergwygregyn, North Wales, United Kingdom. Frequency Domain Electromagnetic Profiling and Constant Separation Traversing were used to produce 2-D images and contour plots enabling the identification of freshwater plumes onshore and in the central parts of the study area. Ground truth methods comprised chemical analyses and detailed, point specific information on the stratigraphy. The freshwater intruding from the coastal area appears to be pushing the saline-water further offshore due to the high piezometric head caused by the mountains and hills of Snowdonia adjacent to the study area. The fresh/saline water interface correlates quite well with previous studies carried out in the area. On the basis of the results of the resistivity and conductivity geophysical investigations the freshwater plumes and fresh/saline water interface in the study area were effectively identified and delineated.

Keywords: Fresh-Saline Water

1. Introduction

In order to delineate the problems caused by saline intrusions, caused by both natural and anthropogenic activities, different methods have been employed. The application of borehole surveying is intrusive, cumbersome, quite expensive, and involves a large time frame. This project investigated the effectiveness of the use of non-intrusive surface geophysical techniques to map and delineate the fresh/saline-water interface in the Abergwygregyn area of North Wales, United Kingdom. Abstraction of freshwater resources is a major cause of saline intrusion. Over-withdrawal leads to head loss causing saline-water to be drawn into a freshwater body. Many countries the world over rely on groundwater for a large proportion of their high quality water supply. Consequently the study of saline intrusion is crucial in order to avoid extracting saline-water for consumption and general usage. There is therefore a need to undertake a monitoring exercise in order to identify and assess saline intrusion.

Combining electrical resistivity and electromagnetic (EM) techniques partially compensates for their individual shortcomings. The electrical resistivity technique is one of the geophysical methods, which enables the determination of sub-surface resistivity by introducing artificially produced electric current into the ground through a set of two electrodes, and measuring the potential field generated by the current by the aid of another set of two electrodes. Electromagnetic induction profiling is a surface geophysical technique, which is used to measure terrain conductivity, that is, the bulk electrical conductivity (EC) of sub-surface materials. It employs a changing primary electromagnetic field created around a current-carrying transmitter coil to induce a current flow within the ground, which in turn creates a secondary electromagnetic field sensed by a receiver coil. The strength of the secondary field created is a measure of the ground conductivity.

The reliability of resistivity mapping in delineating coastal zones invaded by saline-water was shown in the work of Soomro [1] when he found that the salinity of groundwater could be directly detected by determining

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its electrical conductivity and hydro-chemistry. Rosalomanana [2] also described electrical and EM methods as being well suited for coastal aquifer studies because of the large contrast in resistivity between freshwater-bearing and saltwater-bearing formations. The high electrical conductivity of saline-water made the electromagnetic and electrical resistivity techniques particularly appropriate for this study.

2. Study Area: Geography and Geology

The project site was a beach area along the North Wales coastline adjacent to the A55, North Wales Coast Highway at Abergwygregyn, situated between Bangor and Llanfairfechan along the banks of the Menai Strait. **Figures 1** and **2** show the locations of North Wales and the study area, respectively. The site can be accessed through a nature reserve car park.

The area comprises essentially flat sandy and muddy deposits. Gravels and boulders bound the southern end, and this area marks the boundary between the marine environment and the farmland (**Plate 1**). As the sea is approached, the dominant tall grassland at the southern end gives way to shrub-like grasses (salt marsh), which begin to break up into disseminated parts, as the sea is approached. About 30 m from a fence that demarcates the higher elevated land from the inter-tidal area, the grassland gives way to the Traeth Lafan (the Lavan Sands) and as the sea is approached mudflats dominate. A continuously flowing thin layer of surface water characterizes the sands and the mudflats (**Plate 2**).

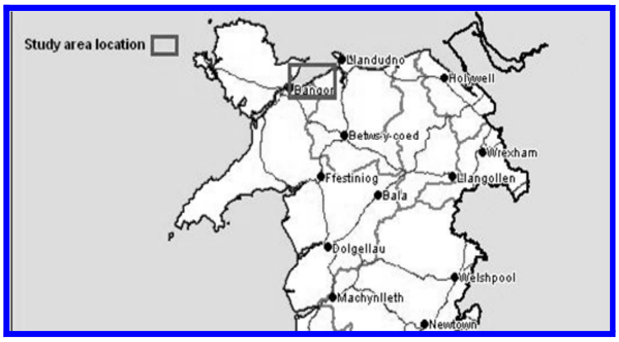

Figure 1. Map of north Wales showing the location of the study area.

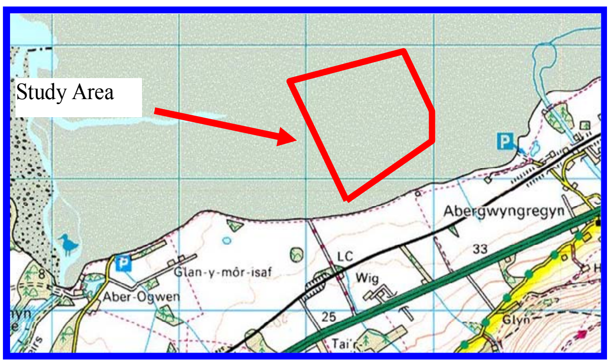

Figure 2. Location map of the study area.

3. Methodology

A geophysical survey consisting of 12, Frequency Domain Electromagnetic (FDEM) profiles and 5,2-D Resistivity Imaging (RI) profiles was conducted on the site. The position of the transect lines were determined using a hand-held GPS system. Soil and water samples were collected from specific points along some of the survey lines in order to carry out geochemical analyses to ground truth the geophysical data.

3.1. Frequency Domain Electromagnetic (FDEM) Survey

Electromagnetic mapping was carried out along premarked transects. Every 5-m along each transect, an apparent conductivity reading was taken using a Geonics EM-31 conductivity meter carried on the shoulder. Readings were continued along the transects for at least 400 m or until the conductivity values indicated that the sediments were fully saturated with seawater. A total of 12 survey lines were completed (**Figure 3**).

Plate 1. Study area showing southern bounded area with gravels, boulders and grasses.

Plate 2. Study area showing thin layer of water flowing on the sands and mudflats.

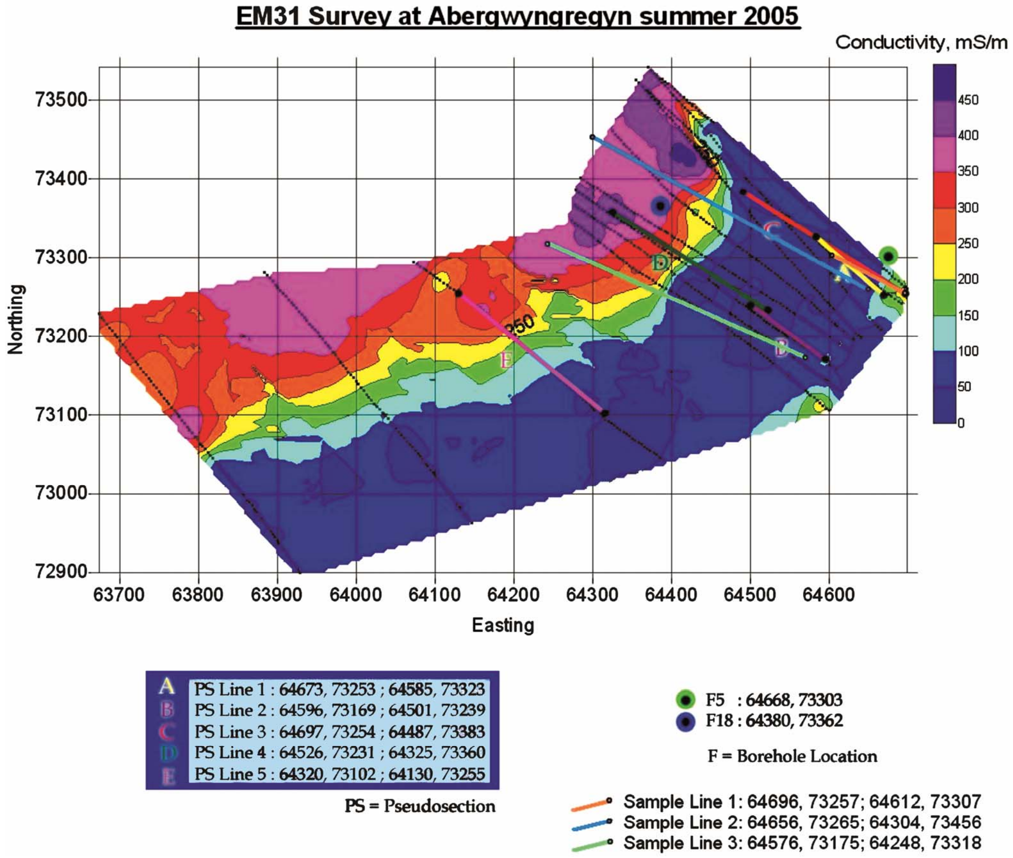

Figure 3. EM31 conductivity contour plot with pseudo-section lines; sample lines and borehole points superimposed.

3.2. 2-D Resistivity Imaging (RI)

Resistivity profiles were carried out almost perpendicular to the shore. They were positioned in a way that would allow easy correlation with the EM31 surveys (**Figure 3**). Twenty-five electrodes were deployed with 5 m spacing along survey lines 1 and 2, while fifty electrodes with 5 m spacing were deployed along survey lines 3, 4 and 5. Good contacts were achieved and measurements were completed automatically using a laptop computer interfaced to a Campus Geopulse resistivity meter. 2-D resistivity models were obtained by inverting the apparent resistivity pseudo-section data using Geotomo RES2-DINV software.

3.3. Geochemical Analysis

Soil water and soil samples were collected along RI and EM survey lines, from which the salinity and electrical conductivity (EC) were measured. Particular attention was paid to sites that showed anomalous conductivity values in the EM31 survey.

4. Results and Analysis

The 2-D resistivity imaging, the EM profiling and soil/water samples were all carried out perpendicular to the direction of the advancing sea. For each method, data acquisition was superimposed in order to generate results that would be correlative.

A contour map of the EM31 conductivity values was produced (**Figure 3**).

It can be observed that the conductivity varies indicating an uneven distribution of saline-water within the beach sediments. A slightly high value of conductivity (150 - 200 mS/m) occurs in the southeast corner, indicating a slightly more saline-water medium. In a previous study carried out to the east of this study area [3] a conductivity value of 200 - 300 mS/m was found adjacent to this area. This is probably due to the presence of salt marsh vegetation and soil retaining saline-water after being covered by spring tides. A freshwater plume, extending from points 64620 - 64660 E and 73120 - 73220 N can be seen. There is a central area with conductivity of about 300 mS/m but it is quite small in extent. Further offshore trending northwest is a saline-water region, which extends from the limits of the study site and heads down the beach with increasing conductivity as the main channel in the Menai Strait is approached. This area is predominantly mudflats.

Figure 3 also displays the positions of the 2-D electrical image lines (pseudo-sections) within the study site. The resistivity images have an advantage over the EM31 conductivity contour plot in that they are able to define both the lateral and vertical extent of the sediment layers, as can be observed in **Figures 4-8**.

4.1. PS1

PS1: extends for 120 m from the southern grassland out into the Lavan Sands. At the center is a region of high resistivity (approx 512 Ω-m). At the beginning of the line (at 7.5 m along the profile), there is a small region of

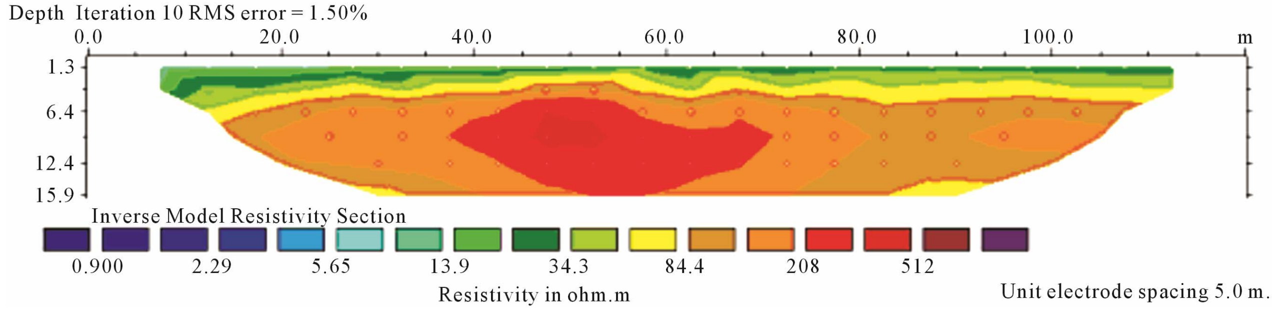

Figure 4. 2-D electrical image section of line PS1 (A).

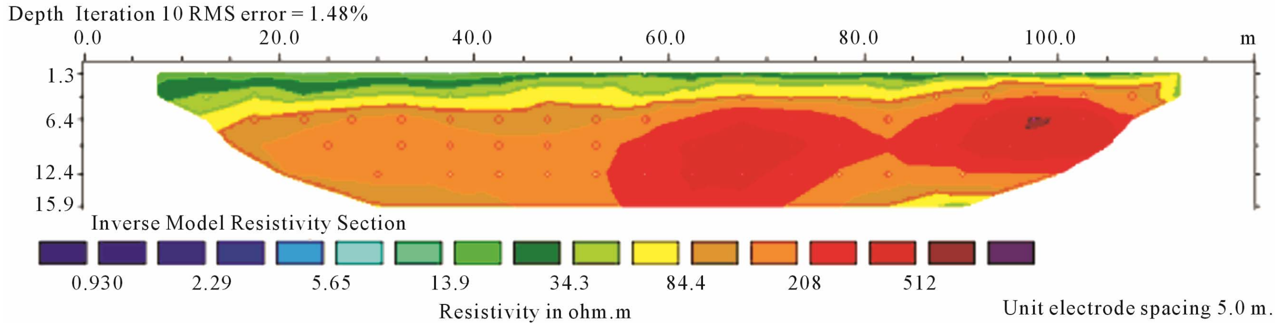

Figure 5. 2-D electrical image of line PS2 (B).

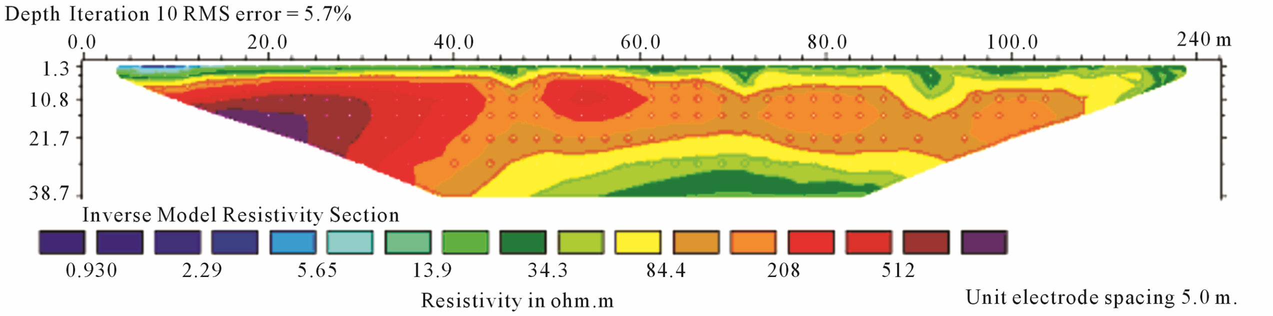

Figure 6. 2-D electrical image of line PS3 (C).

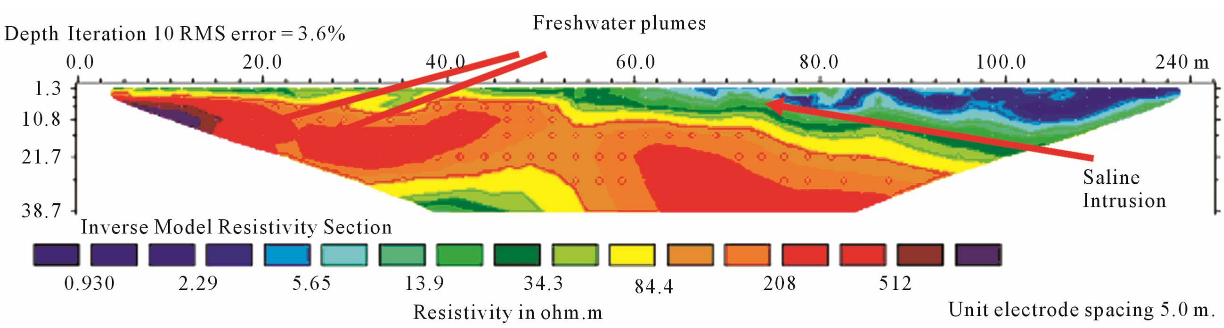

Figure 7. 2-D electrical image of line PS4 (D).

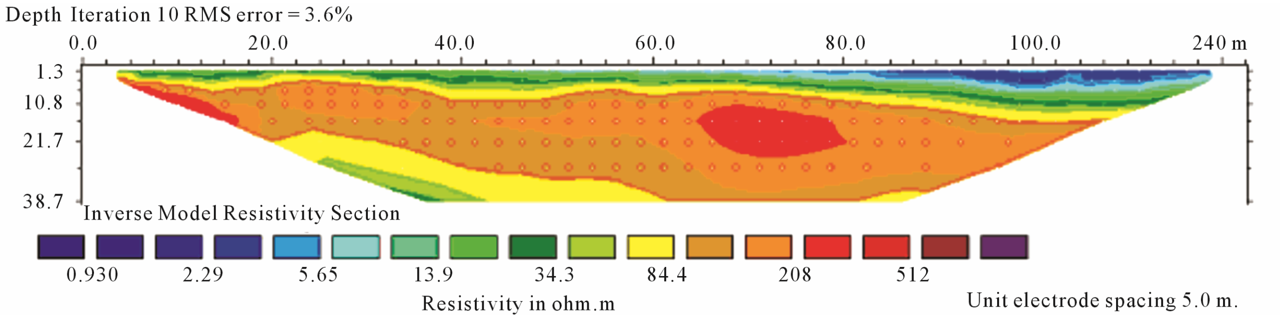

Figure 8. 2-D electrical image of line PS5 (E).

more saline-water sediment (resistivity of 5.65 Ω-m) on top of the 15 Ω-m freshwater sediment just at the southern end of the survey site.

4.2. PS2

PS2: extending the same distance as PS1, it is similar to PS Line 1 in that freshwater sediments generally occupy almost the entire model. Unlike PS Line 1, however, in the central part, between 55 and 107.5 m are two regions of high resistivity about 512 Ω-m.

4.3. PS3

PS3: extends for 245 m onto the Lavan Sands and mudflats. An overlying saline-water sediment can be seen at 20 m along the model with a resistivity 3 Ω-m. Below this is a region of very high resistivity. This point is at the beginning of the profile, at the southern end of the beach on the salt marsh. It is evident that the freshwater is extending both laterally and vertically, pushing out seawards.

4.4. PS4

PS4: also extends for 245 m across the Lavan Sands and the mudflats. A saline-water sediment body is identified on top of the freshwater plume at the northern end of the profile, which extends from 120 to 235 m. This is characterized by a resistivity value of 1 to 3 Ω-m. Note that there appears to be fresher water sediment above the saline-water sediment creating a saline intrusion towards the shore. The higher resistivity zone seems to be dipping seawards.

4.5. PS5

PS5: is the final 2-D survey with a total coverage of 245 m, from the grassland onto the Lavan Sands and the mudflats. There is a high resistivity zone (with a resistivity value of 512 Ω-m) occurring between 130 m and 160 m along the profile. Again this is seen to dip slightly seawards. A distinct freshwater/saline-water is delineated at a depth of 8 m where the saline-water sediment (resistivity of 1 to 3 Ω-m) is on top of freshwater sediment of intermediate resistivity (ranging from 6 to 84 Ω-m).

For the soil water analysis the salinity and EC were measured along the sample survey lines shown in **Figure 3**. The results are tabulated below (**Tables 1-3**). This data has also been contoured in **Figures 9** and **10**. Generally, the salinity and EC can be seen to decrease from offshore to inland, signifying a predominantly fresh-water region in the south.

Table 1. Table of data for soil water sample line 1.

Sample No	EC (mS/m)	Salinity (ppt)	GPS Reading
SWS 0 m	46.1	24	64,696, 73,257
SWS 20 m	28	14	64,678, 73,266
SWS 40 m	39.4	21	64,659, 73,273
SWS 60 m	21.3	10	64,647, 73,290
SWS 80 m	33.4	17	64,640, 73,298
SWS 100 m	22.6	11	64,612, 73,307

Table 2. Table of data for soil water sample line 2.

Sample No	EC (mS/m)	Salinity (ppt)	GPS Reading
SWS 20 m	53.4	28.5	64,656, 73,265
SWS 40 m	38.0	19	64,641, 73,277
SWS 60 m	43.1	22	64,624, 73,289
SWS 80 m	60.6	32	64,608, 73,298
SWS 100 m	56.1	29.5	64,592, 73,312
SWS 140 m	60.1	31	64,556, 73,330
SWS 180 m	52.1	27	64,520, 73,348
SWS 220 m	58.8	30	64,484, 73,366
SWS 260 m	56.0	30	64,448, 73,384
SWS 300 m	62.4	33	64,412, 73,402
SWS 340 m	64.5	34	64,376, 73,420
SWS 380 m	65.0	35	64,340, 73,438
SWS 400 m	54.6	27.5	64,304, 73,456

Table 3. Table of data for soil water sample line 3.

Sample No	EC (mS/m)	Salinity (ppt)	GPS Reading
SWS 20 m	51.6	26	64,576, 73,175
SWS 40 m	47.6	24	64,558, 73,183
SWS 60 m	47.0	24	64,539, 73,191
SWS 80 m	45.2	24	64,521, 73,199
SWS 100 m	55.1	30	64,503, 73,209
SWS 140 m	36.9	19	64,466, 73,222
SWS 180 m	62.7	33	64,426, 73,238
SWS 220 m	58.9	33	64,395, 73,253
SWS 260 m	64.0	33	64,361, 73,270
SWS 300 m	59.9	32	64,325, 73,285
SWS 340 m	58.4	31	64,292, 73,298
SWS 380 m	60.3	30	64,258, 73,307
SWS 400 m	59.6	31	64,248, 73,318 pool

5. Interpretation and Discussion

Both PS1 and PS2, carried out on the salt marsh, correlate well with the EM31 data. Both images indicate freshwater plumes extending and pushing the saline-water seawards. The position of PS Line 1 allowed the 2-D image to be correlated with the EM31 data around the southeast corner of the site. The occurrence of saline-water can be observed near the surface at the southern end of the model at 7.5 m, extending to a depth of 3 m. This agrees with the high conductivity values shown in this region by the EM31 data. PS3 illustrates the saline-water region better than PS1. The borehole data F5 [4], displayed in **Table 4**, indicates that grey shelly sands and gravels predominate in this region at a depth of 2 m making it possible for the freshwater to permeate through the sediment and outcrop at the surface. The high resistivity zones in both PS lines 1 and 2 are probably due to the layer of grey firm boulder clay at the depth of about 10 m. PS3 shows a similar pattern to PS1 and PS2; however, since it utilized a 50-electrode array, the section is more extensive and reaches further into the near shore saline-water sediments associated with the salt marsh. PS3, however, is not long enough to reach the offshore saline-water sediment. This indicates the extent of the freshwater influence.

Both PS4 and PS5 cover the Lavan Sands and the mudflats and extend out into the region of saline-water sediment offshore. Basically, PS4 is a continuation of PS2 where the beginning of PS line 4 marks the midpoint of PS line 2. At about 100 - 200 m along the PS line 2, 2-D image lower resistivity (40 Ω-m) freshwater overlays a higher resistivity zone at a depth of 5 m, and this is shown to continue in the PS line 4 2-D image. Borehole F18 [4] (**Table 4**) identified the presence of boulder clay and glacial sands starting from a depth of 9.91 m. The offshore low resistivity zone corresponds to the high EM31 conductivity values shown in **Figure 3**. At 160 m along the 2-D image of PS line 4, a higher resistivity freshwater occurs at 2 m depth on top of the dominating

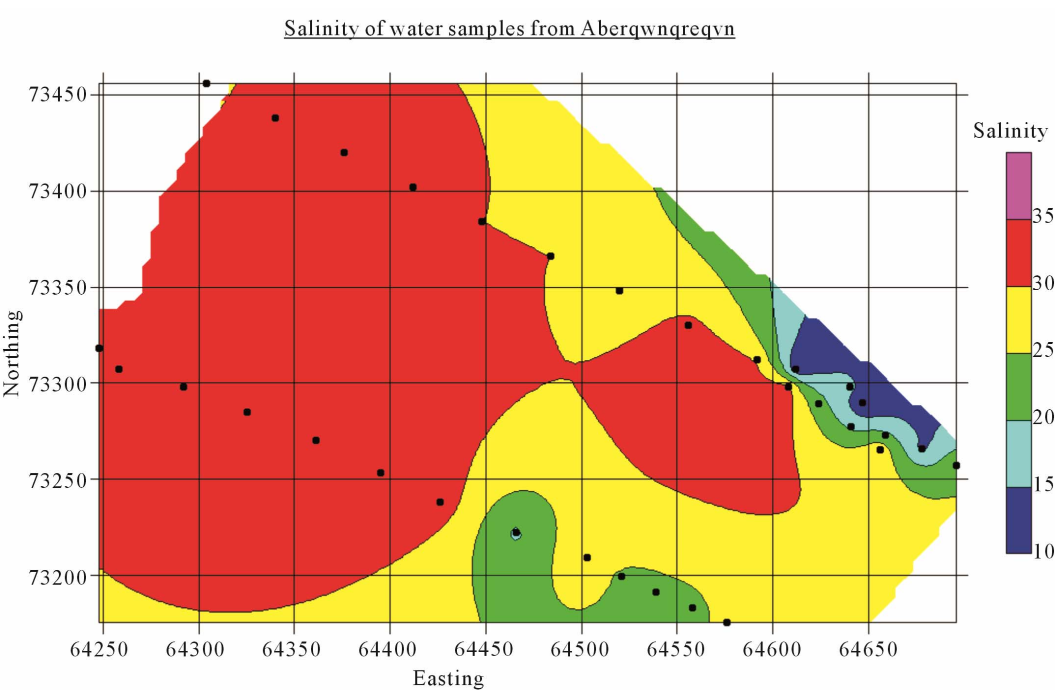

Figure 9. Contour plot of soil water salinity.

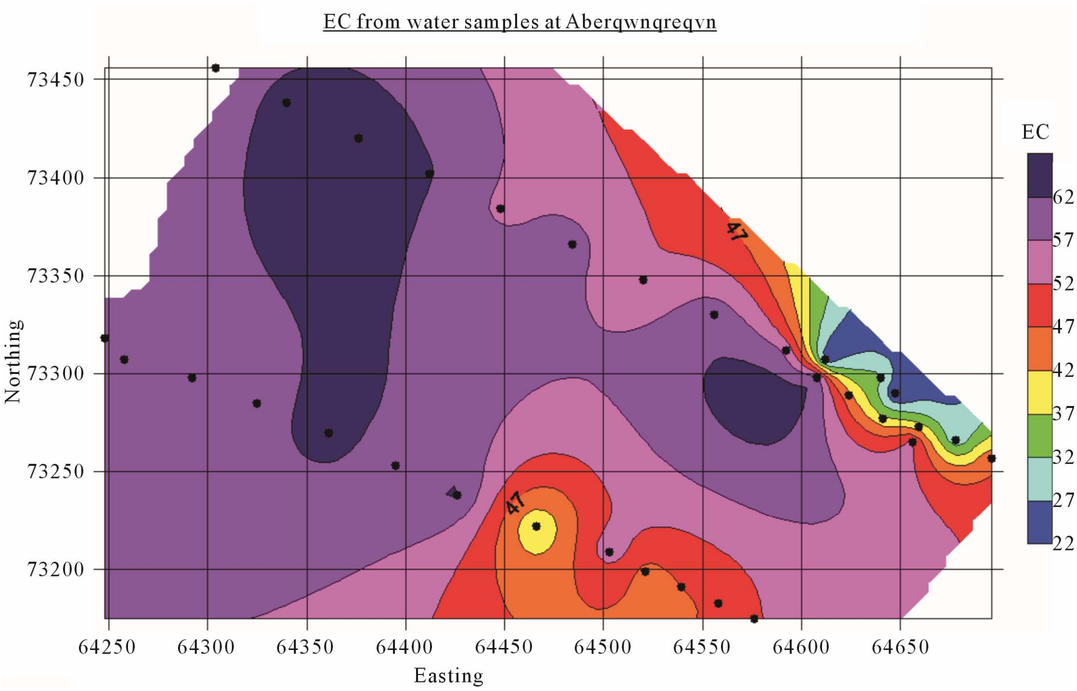

Figure 10. Contour plot of soil water EC.

Table 4. Borehole points and recovered sediments in the Menai strait modified from PEMS (1971).

Borehole No	GPS Reading	Sediment Type	Depth (m)
	ABERGWYGREGYN		
		Mud	0
			2
F5	64666,73303	Grey shelly sand and gravel	
			9.45
		Grey firm boulder clay	
			0
		Sand and silt	
			9.91
		Boulder clay	
F18	64380,73362		10.91
		Sandy boulder clay/glacial sand	
			14.02
		Boulder clay	
			19.51

saline-water, producing a shallow saline intrusion. The underlying high resistivity zone appears to be dipping seawards in both 2-D images which is probably the result of the increasing thickness of sands, silts and gravels overlying dipping boulder clay.

The soil and water samples correlate adequately with the EM31 and the PS data. Sample line 1 (**Table 1**) shows high values of electrical conductivity (EC) and salinity at 64696E, 73257N.

This point corresponds to the southeast corner of the site and has already been identified by EM31 lines and 2-D images PS1 (A) and PS3 (C) as a region of saline-water sediment or salt marsh. Sample line 2 started at the mid-point of PS line 3, an area corresponding to freshwater saturated sediment (**Figures 3** and **6**). Sample line 3 correlates very well with the 2-D images of PS lines 2 (B) and 4 (D). Initially, there were high values of 51.6 mS/m EC and 26 ppt salinity (**Table 3**). Further to the north a decrease in both values indicates the presence of the freshwater plume displayed by PS line 4 (D) in **Figure 7**.

Generally, the salinity and EC decrease from offshore to onshore, signifying a predominantly freshwater region in the south. **Figures 9** and **10** show reasonably good agreement with each other, and the pattern shown clearly correlates with the EM31 and resistivity images which show that saline-water is dominant offshore, having been pushed from the coast northwards by the intruding freshwater. The freshwater, intruding from the coastal area and pushing the saline-water further offshore, is due to the high piezometric head caused by the elevated water table in the mountains and hills of Snowdonia adjacent to the study site, from which fresh pore water percolates through the sub-surface sediments and moves down into the lower coastal area.

6. Conclusion

The analysis of soil water samples has been able to establish the effectiveness of the surface geophysical techniques for identifying freshwater and saline-water intrusions in coastal sediments. The EM31 data and 2-D resistivity images have been shown to be complimentary when mapping and delineating the fresh/saline water interface and the path of freshwater incursion into the Abergwygregyn inter-tidal area.

7. Acknowledgements

This research formed part of an MSc degree undertaken at the School of Ocean Sciences, University of Wales, Bangor and the authors are grateful for the facilities provided by the University.

REFERENCES

[1] S. A. Soomro, "Detection of Saline Intrusions in Coastal and Estuarine Sediments," Ph.D. Thesis, University of Wales, Bangor, 1993.

[2] E. Rasolomanana, "Mapping Coastal Aquifers by Joint Inversion of DC and TEM Soundings-Three Case Histories," *Groundwater*, Vol. 39, No. 1, 2001, pp. 87-97. doi:10.1111/j.1745-6584.2001.tb00354.x

[3] M. Hattersley, "Mapping Fresh-Salt Water Interface on the Lavan Sands, Abergwyngregyn," Master's Thesis, University of Wales, Bangor, 2004.

[4] PEMS, "Menai Strait and Lavan Sands Feasibility Study," Contract Report 171, For the Menai Strait Pipeline, Project Engineering and Management Services Ltd., London, 1971.

