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Locating of Salt and Fresh Water Interface in Coastal Zones Using 2D Resistivity Imageries

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Abstract. Demarcation of fresh- and saline-water interface is important in water supply engineering in coastal regions. A resistivity imager system was employed to investigate the saline water intrusion to freshwater table at selected coastal locations in Sri Lanka. This is the first such attempt in Sri Lanka using the above technique. Systematic geo-resistivity investigations were carried out at randomly selected sites at Mundel and Rekawa coastal areas. Measured and calculated values generally show good agreement, especially in Mundel area, where the current penetration is good. The results indicate a possibility of using resistivity imager system to demarcate the saline and fresh water interfaces and intermixing zones, especially in the wet zone.

Introduction

Demand for water is increasing by the day with the growth of population and increased activities. Though water is plentiful along the coastal belt, finding potable (fresh) water in this region is a challenge due to sea water intrusion to fresh water table. Therefore, pre-determination of the boundary between fresh and saline waters is important to provide fresh water for the people who are living along the coastal stretch.

Groundwater quality of the coastal aquifers may be diminished by intrusion of saltwater into freshwater aquifers. Salinity changes the physical properties of groundwater. An increase in salinity increases the density and viscosity of the groundwater. Density differences cause the salt water to intrude into coastal aquifers, forming a salt water wedge underneath the freshwater that moves towards the sea [1].

According to Verruijt [2], the salt water is stationary under the steady state conditions, while the freshwater is mobile. He also noted that the mixing zone between freshwater and salt water tends to be rather thin and the brackish water is being flushed away to the sea. Haitjema [3], estimated the position of interface using the *Badon-Ghyben Herzberg* principal which states that the depth (d) of the interface below sea level is,

$$d = [G_f/(G_s-G_f)]h. \tag{1}$$

Where G_f and G_s are the specific gravity of freshwater and salt water respectively, and h is the elevation of the freshwater table above sea level.

Resistivity imager system (2D imaging or tomography) surveys to map areas with moderately complex geology have been in use for the last two decades [4]. The use of resistivity imager system is a modern technique which is utilised in groundwater explorations. Ground resistivity variations due to vertical and horizontal stratification can be measured with a resistivity meter. Increasing salinity in groundwater may decrease ground resistivity by increasing the concentration of ions. This is the phenomenon that helps to demarcate fresh and saline water interface in the study area.

Resistivity method in geophysical investigation was first employed by *Schlumberger brothers* in 1920's in their experiments. During that time, the resistivity method was used for quantitative interpretations and conventional Schlumberger depth soundings were conducted [5]. Resistivity sounding is a useful and effective geophysical method to detect vertical and lateral resistivity variations beneath the earth surface [6]. Although basic theory assumes that the subsurface resistivity is evenly distributed along strike direction, this is not the case in some situations. However, modern computer software is capable of handling subsurface conditions that are laterally variable. The resistivity distribution is related to the structural and stratigraphic information, which can be correlated to the geological and hydro-geological environments of the corresponding area.

Multi-electrode geo-electric resistivity imager system is a faster and newer technique, compared to the traditional four-electrode method for investigation of vertical and horizontal variations of geo-resistivity. It has been the practice to conduct vertical electrical sounding (VES) at a number of locations on a profile or grid and collate the inverted 1-D resistivity depth information to produce a 2-D or 3-D surface map. However, this procedure is based on the assumption that the subsurface is composed of horizontal stratification with no lateral variations in resistivity. Lateral resistivity variations, especially if and when they occur at closely spaced regions, may introduce serious misinterpretation of the actual subsurface.

Objectives of the Study. In Sri Lanka, only a little work has been done using resistivity imaging on thermal springs, archaeological sites and in groundwater exploration investigations [7] and this was the first attempt to apply resistivity imaging system for demarcation of freshwater/ seawater interface.

Main objectives of this research were to identify the salt-freshwater interface and its effect on the groundwater (freshwater) exploration and exploitation in coastal regions of Sri Lanka.

Behaviour of the Groundwater Table in Coastal Regions

Fig. 1 shows a model illustrating subsurface behaviour of groundwater table and possible intrusion of saline water into groundwater. The model that describes the relationship of the interface between salt and fresh water is called *Ghyben-Herzberg relation* [8]. According to this relationship, interface is shifted towards the seaward direction during the rainy season with the thrust effect of fresh water on land. However, the effect is reversed during the dry season and the interface is shifted landwards. Study of the behavior of salt- and fresh-water interface will assist to gather useful information pertaining to the transition zone of interface during wet and dry seasons. This information may be utilized to construct deep wells that will stay productive throughout the year under changing weather conditions.

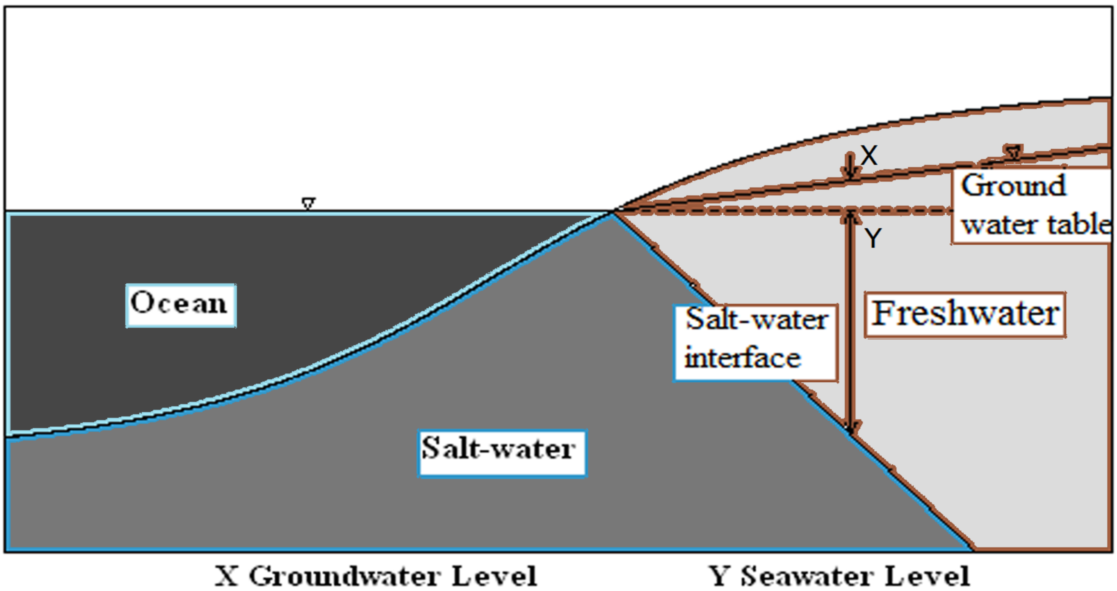

Fig. 1. Salt-water interface in unconfined coastal aquifer according to the Ghyben-Herzberg relation (after Solinst Canada Ltd, 1997).

Geological and Structural Background of the Study Area

The basement of Sri Lanka mainly consists of three major lithological complexes (Fig 2). About nine tenth of the country is underlain by Precambrian (Proterozoic) crystalline crust [9, 10]. The rest is chiefly made up of Miocene limestones in the north and north-western coastal region. Quaternary deposits lie along the north-western and eastern regions [9]. In addition to the major lithological complexes, small scale sedimentary units belong to Jurassic period could be identified in the Andigama, Pallama and Tabbowa basins. Also, two granitic intrusions lie in the Tonigala (pink granite) and Ambagaspitiya (white granites) areas.

Structural map of the country shows that majority of the structures are trending north east (NE) to south west (SW) directions throughout the country, while at the southern tip it gradually changes from north west to south east direction [9].

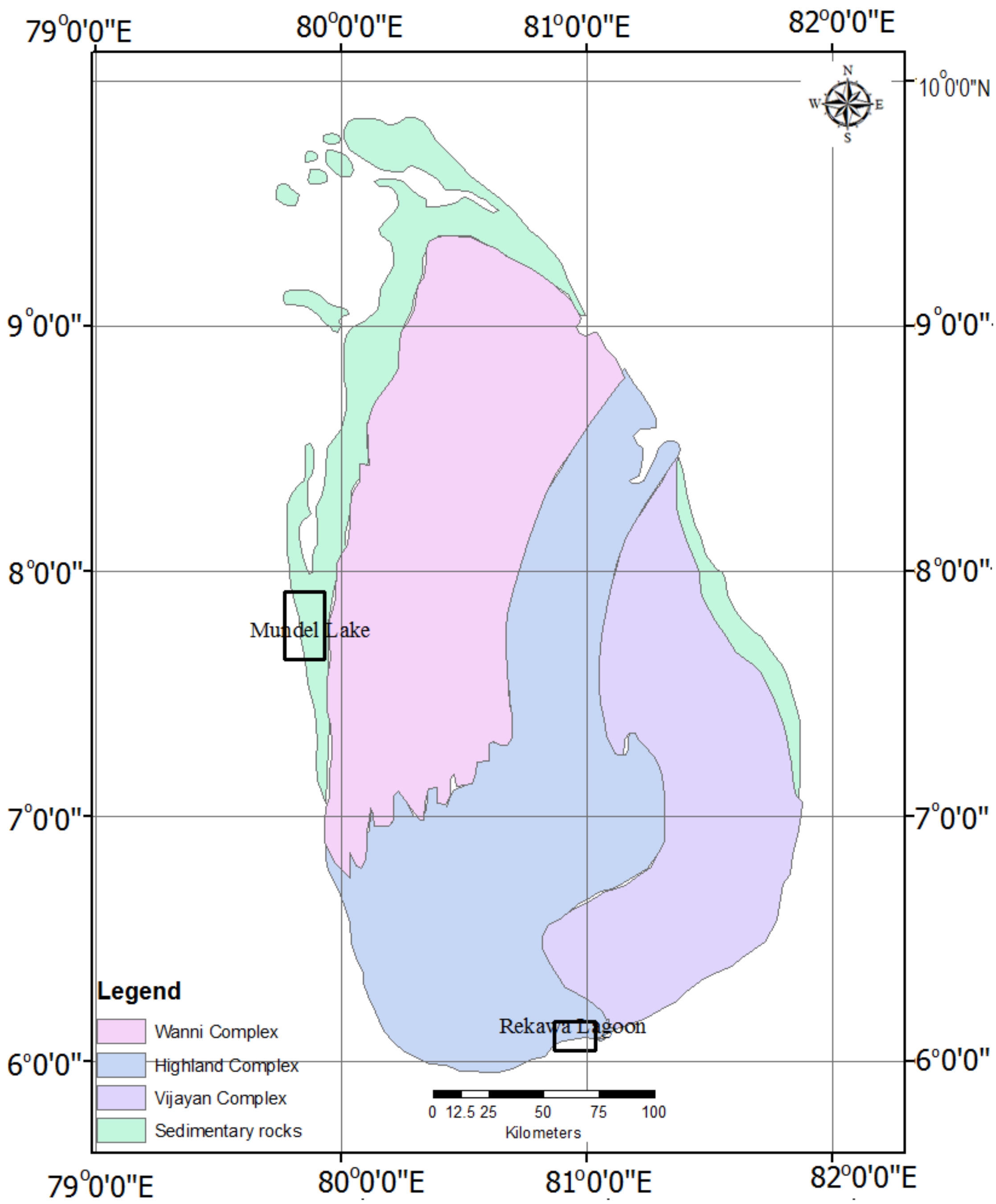

Fig. 2. Geological map of Sri Lanka with study areas marked (boxes).

Location of Study

Two study sites were selected to conduct this survey. One site is located in north western part of Sri Lanka on Miocene limestone bed which is covered by *Recent* sediments around Mundel Lake. Other site, Rekawa, is in southern coastal stretch underlying mainly of crystalline basin rocks of Highland Complex [9]. The rocks in this region are granulite facies metamorphic rocks, commonly meta-quartzite, marble, scapolite-wollostonite gneiss, granulitic gneiss, garnet sillimanite graphite gneiss, cordiarite bearing gneiss and garnet quartz feldspar granulites. These rocks are interlayered with granitoids [11].

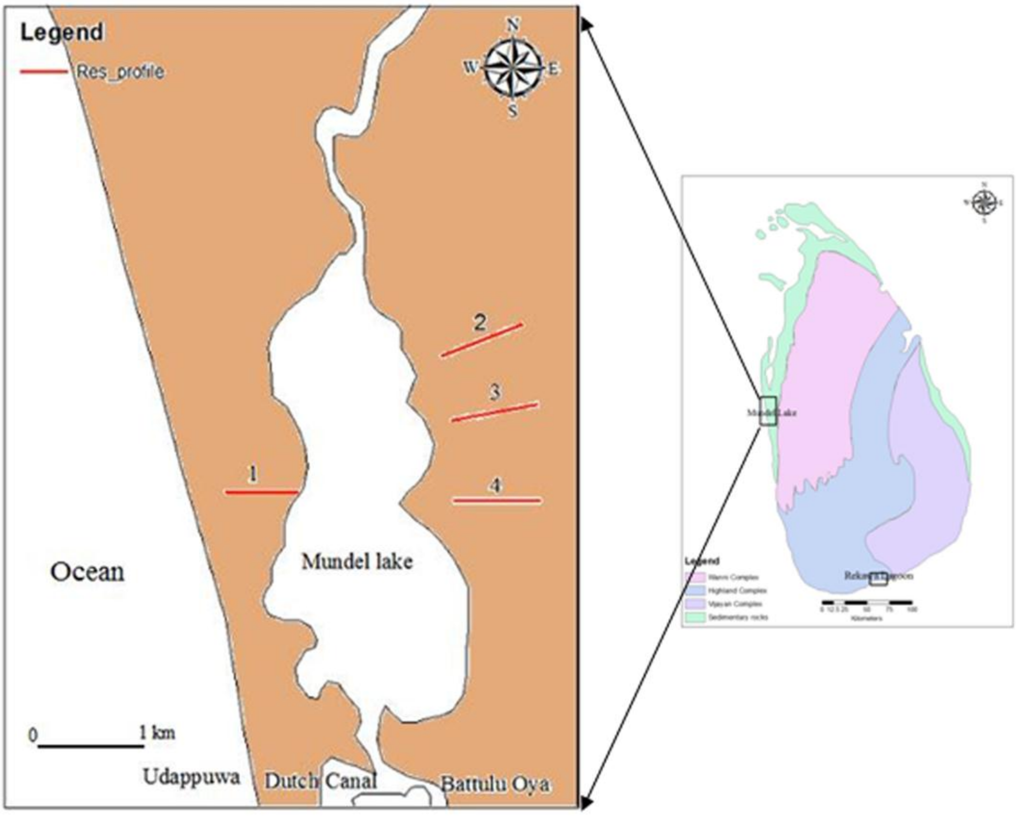

Fig. 3 Resistivity imager study sites at Mundel Lake area

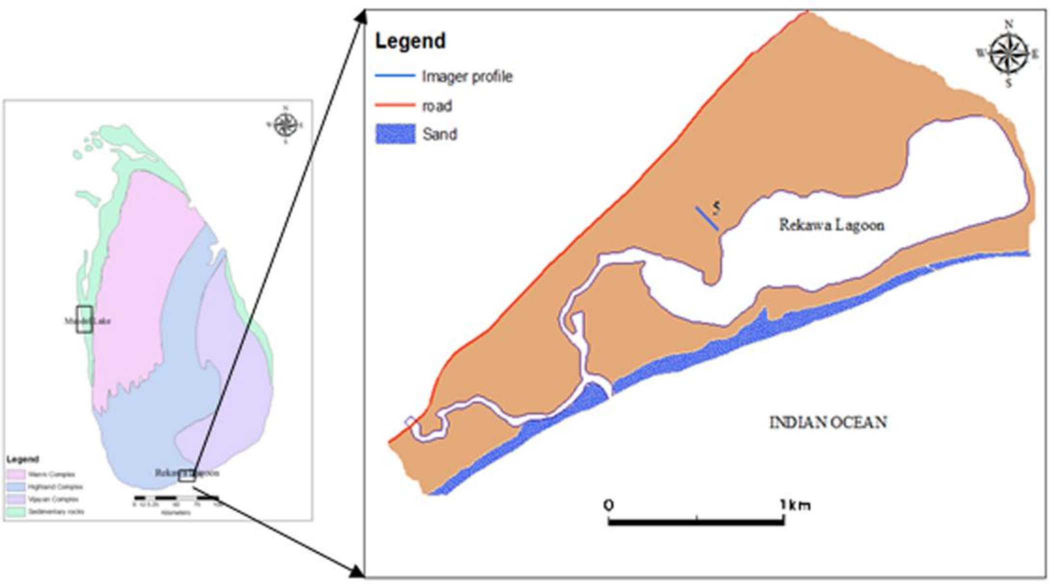

Fig. 4 Resistivity imager traverse 5 at Rekawa lagoon

Total of five resistivity traverses were investigated during this survey. Four traverses were surveyed in Mundel Lake (Fig 3) area and the other one was done in Rekawa area (Fig 4), perpendicular to the coast line. Survey sites were randomly selected, assuming that the resistivity would not be changed in the direction perpendicular to the survey lines. In many situations, particularly for surveys over elongated geological entities, this is a reasonable assumption [12]. Total length of an average line was 120 metres but extensions were made using offset method when necessary. Average total ground penetration of current was about 20 metres. However, the penetration depth depends on the ground status such as moisture and ion content in soil [7].

Methodology

As shown in Fig. 5 multi electrode resistivity imager system was employed to acquire resistivity data in the study area using *Wenner* electrode configuration. In this survey, 25 electrodes were connected together by multi-core cable that are connected to a lap top computer through a resistivity meter. In the first step, 22 measurements were obtained. Each consecutive step was carried out with 3 less measurements from the previous step. Thus, a total of 90 readings were recorded in seven steps. These readings were later converted to 2-D resistivity model profile using computer software called *RES2DIN*. Necessary corrections such as the topographic corrections were also applied.

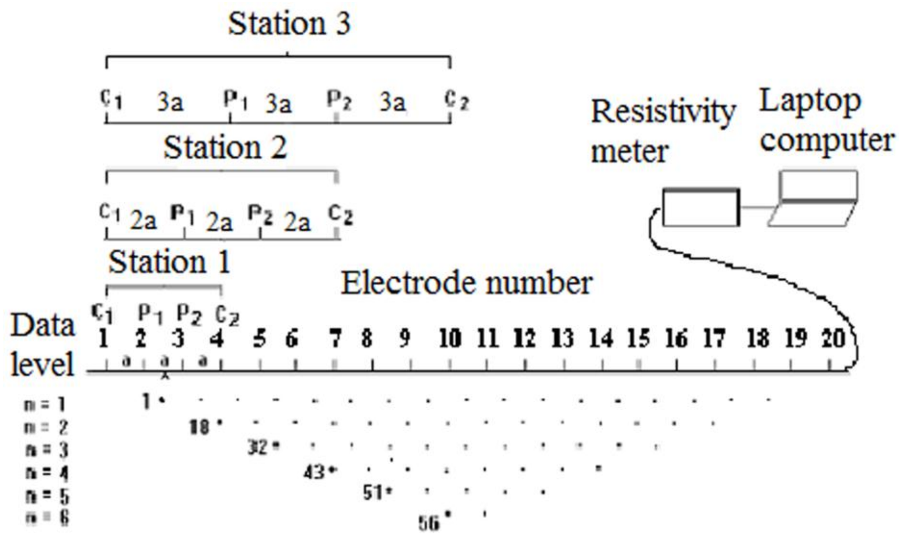

Fig. 5. Electrode configuration of the resistivity imager system.

The locations of the resistivity imaging were detected using a NAV5000 hand held Global Positioning System (GPS). The coordinates of starting and end points of the traverses were recorded for resistivity imaging system.

Results and discussion

This resistivity study was conducted in the coastal region of Sri Lanka with the intention of demarcating seawater fresh water interface of the area. Figures 6 to 9 show the results of the resistivity survey from the area 1 (Mundel lagoon). Fig. 6 shows the resistivity variations starting from 0.120 Ωm to around 11 Ωm. It also illustrates the penetration depth up to 19 m. Minimum resistivity could be observed in the top layer. However, it is not possible to locate the salt and freshwater interface in this figure.

Fig. 7 represents a profile parallel to the previous one. Resistivity values vary between 0.48 Ωm and 5.86 Ωm in this profile. The penetration depth of this profile is less than that of the earlier one. Resistivity values gradually increase with the depth indicating decreasing salinity towards the bottom.

Mundel

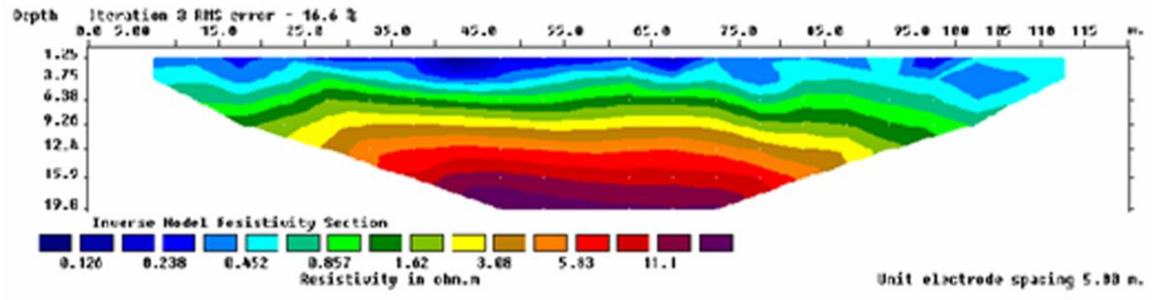

Fig. 6 Resistivity traverse 1, around Mundel Lake.

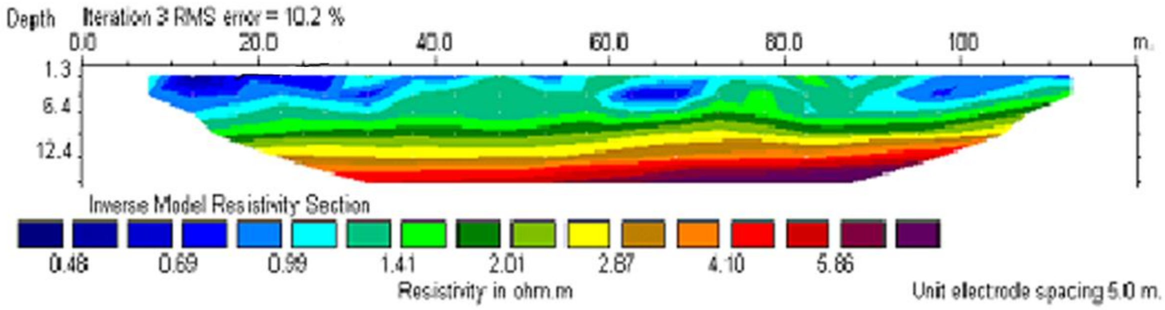

Fig. 7 Resistivity traverse 2, around Mundel Lake.

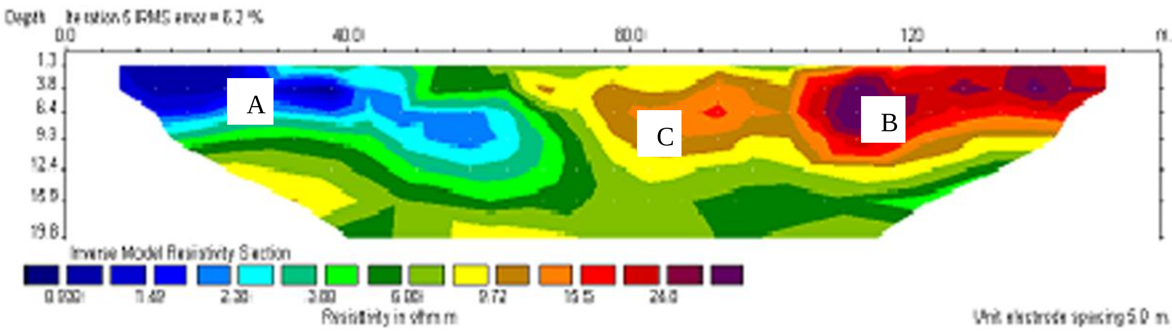

Fig. 8 Resistivity traverse 3, around Mundel Lake.

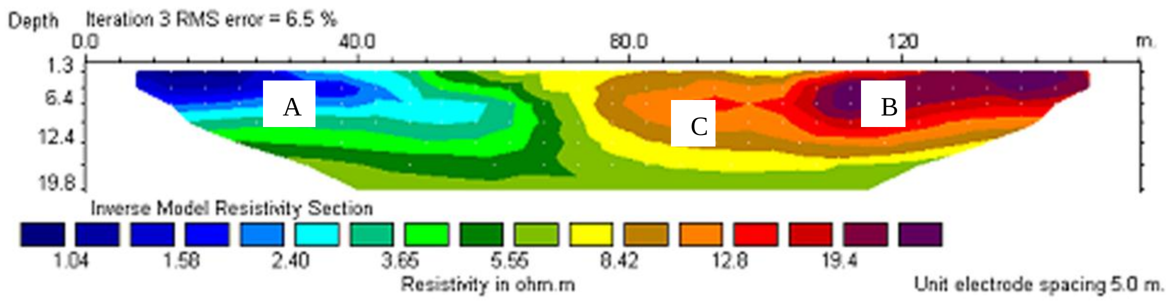

Fig. 9 Resistivity traverse 4, around Mundel Lake.

Figures 8 and 9 show the resistivity measurements from traverses 3 and 4. These profiles were surveyed parallel to each other. Both diagrams clearly illustrate abrupt resistivity changes along the profile. The saline water (A), intermixing zone (C) and fresh water zone (B) are clearly indicated in the figures. In both diagrams interface is marked as C.

Fig. 10 shows the resistivity survey profile obtained from Rekawa area. It is expected that saline water may exist below the depth of 6m, underneath the freshwater table.

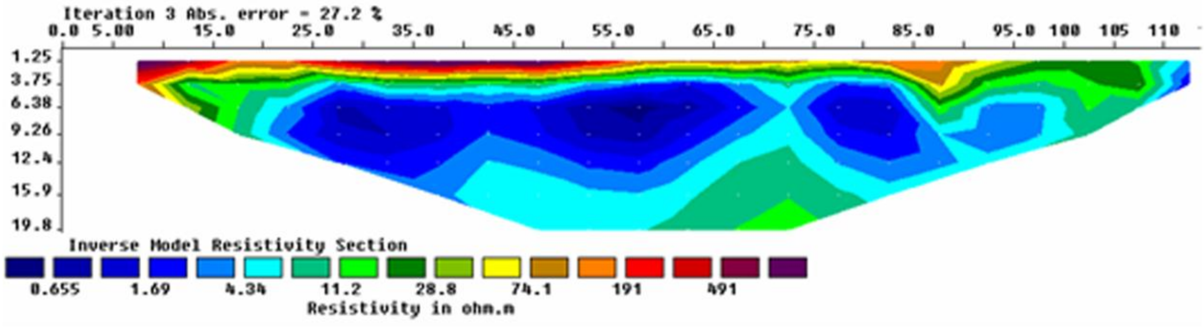

Fig. 10 Resistivity traverse around Rekawa lagoon area

Depth values to interface between fresh and saline water were calculated using *Badon-Ghyben Herzberg* principal. The calculated values were compared with the measured values, as shown in the Table 1.

Table 1. Calculated and measured depths to interface using *Badon-Ghyben Herzberg* principal

Resistivity traverse	**h [m]**	**Measured depth [m]**[1]	**Theoretically calculated depth [m]**	**Percentage Difference**	**Remarks**
Traverse 1	-	ND	ND	-	The interface was not detected within the imager profile
Traverse 2	-	ND	ND	-	
Traverse 3	0.075	2.60	2.78	6.1 %	The interface point selected for the calculations is located 40 m away from the first electrode and 55 m away from Mundel Lake.
Traverse 4	0.105	3.80	3.88	2.1 %	The interface point selected for the calculations is located 30m away from the first electrode and 65 meter away from Mundel Lake.
Traverse 5 (Rekawa)	0.1	3.75	3.70	1.4 %	The interface point selected for the calculations is located about 50 m away from the Rekawa lagoon.

[1] measured values were rounded up to the nearest 5 cm.

Where an interface could be detected (Traverses 3 to 5), measured and theoretically calculated values show a close agreement with maximum error not exceeding 6.1%. This value is well within the acceptable range, when the limitations and error margins of the measurements are considered.

Fresh/ saline water interface could be identified about 400 m away from the Mundel lake (lagoon) using resistivity imager profile obtained. In order to avoid contamination, drinking water wells should be positioned beyond this limit.

Current penetration was poor in Rekawa area due to the dry climatic condition of the region and, as a result. it was difficult to demarcate the fresh/ saline water interface using resistivity imager profile in Rekawa lagoon area. However, it could be noted that the saline water level lies about 6 m below the top soil layer in the study area at Rekawa lagoon. Further studies are needed to investigate seasonal shifting and tidal impact on fresh and saline water interface.

Summary

The results indicate that the measured depth to the interface using imager profiles and the calculated depth using "*Badon-Ghyben Herzberg*" principal are closely matching in the traverses 3, 4 and 5. The depth to interface will assist to estimate the thickness of fresh water wedge. The estimated thickness of the freshwater layer may be effectively utilised to establish coastal freshwater wells.

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