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Geophysical Mapping of Saltwater Intrusion using ERT and TEM Methods at Pantai UMT, Terengganu, Malaysia

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Saltwater intrusion is a common problem in a coastal setting and can contaminate the groundwater source. The depth of saltwater intrusion can also be heterogeneous in relative to the distance from the shoreline, which is highly dynamic in the coastal setting due to the rising sea level. Typically, saltwater intrusion is identified by drilling wells and carrying out water sampling, although this method can be time-consuming and unreliable for a large area. In this study, geophysical surveys (i.e., ERT and TEM) were carried out at Pantai UMT to determine the depth of saltwater intrusion. Two resistivity survey lines (L1, L2) were set up parallel and perpendicular to the shoreline by using ABEM Terrameter LS2. Three electromagnetic data (P1, P2, P3) also were collected using ABEM WalkTEM 2. The findings show the seawater is correlated with significantly low resistivity values (ca. < 1 Ωm), saltwater-freshwater is correlated with medium resistivity values (ca. < 10 Ωm) and sandy beach is correlated with high resistivity values (ca. > 10 Ωm). This study indicates that both ERT and TEM methods can identify shallow saltwater intrusion (ca. 2 – 10 m depth), but TEM method can detect a deeper saltwater intrusion at 90 – 120 m depth. This study also reveals that the rising sea level can reduce the saltwater intrusion depth and contaminate the groundwater in a coastal setting.

Keywords: saltwater intrusion; sea level rise; resistivity; electromagnetic

I. INTRODUCTION

Saltwater intrusion into freshwater aquifers poses a significant environmental challenge in coastal regions worldwide. Saltwater intrusion often occurs when over-exploitation, over-population and climate change have caused the saltwater to be pushed landwards and pollute the freshwater aquifers (Mansourian *et al.*, 2022). As seawater infiltrates, it increases the salinity of groundwater, making it unsuitable for drinking, agricultural irrigation, and other essential uses. The coastal areas usually represent a dynamic zone where fresh groundwater in coastal aquifers mixes with saline ocean waters (Goebel *et al.*, 2017). The freshwater-saltwater interface is controlled by the differences in density and pressure on both sides of the interface. Fluid movement is influenced by the subsurface hydrologic properties within the coastal area (Goebel *et al.*, 2017). The density difference between freshwater and saltwater can cause a saltwater wedge, which causes saltwater to progress inland when freshwater flow in groundwater is reduced due to pumping for groundwater extraction (Kinzelbach *et al.*, 2003).

Terengganu has the longest coastline in Peninsular Malaysia, which the rising sea level can lead to saltwater intrusion in coastal areas. Saltwater intrusion can be identified based on water sampling at a certain location to provide information on groundwater quality, which indicates high saltwater intrusion in the Kuala Terengganu coast (Hairoma, 2016). The geophysical survey (i.e., resistivity) and monitoring wells were carried out along the Kuala

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Terengganu coast, which indicates about 8 – 10 m depth of freshwater-saltwater interface (Tawnie *et al.*, 2013). However, well samplings are expensive, labour-intensive, time-consuming, and limited to a small spatial area. Thus, there is an increasing need for more efficient methods to identify saltwater intrusion over a large area before carrying out groundwater drilling. This study aims to integrate two geophysical methods (i.e., resistivity and electromagnetic) for identifying saltwater intrusion efficiently.

The electrical resistivity tomography (ERT) method is a geophysical method used to outline the subsurface layers of the study area, including the aquifer locations and, to a certain extent, the quality of groundwater (Harikrishna *et al.*, 2017). It helps to visualise the subsurface resistivity distribution in two-dimensional or three-dimensional models (Werner *et al.*, 2013). In recent years, resistivity survey methods have been useful for the application of saltwater intrusion detection in various places. According to Goebel *et al.* (2017), electrical resistivity tomography (ERT) survey methods have been used in the detection of saltwater intrusion along the coast of the Monterey Bay in central California.

In addition, the transient electromagnetic (TEM) method has been used with significant success when it comes to mapping groundwater salinity variations in coastal areas (Werner *et al.*, 2013). TEM methods have been more preferred than detailed ERT methods due to their lower cost and lower labour (Paine, 2003). The inverted resistivity data combined with borehole logging data can be used to underline areas of groundwater salt concentration in an aquifer, which highlights the critical role of fault pathways in groundwater mineralisation issues faced by coastal aquifers (Zhu *et al.*, 2024). The Time Domain Electromagnetic (TDEM) method also has been widely used in mapping and assessment of groundwater resources and saltwater intrusion along coastal alluvial plains to locate the depth of freshwater aquifers (El-Kaliouby, 2020). Thus, these geophysical techniques have emerged as a promising alternative for identifying saltwater intrusion.

This study aims to determine the saltwater intrusion in a coastal setting of Pantai Universiti Malaysia Terengganu (UMT), Terengganu (Figure 1). Pantai UMT is located at Kuala Nerus, Terengganu, in the east coast of Peninsular Malaysia. The climate is characterised by high humidity and significant rainfall throughout the year. The area experiences two main monsoon wind regimes, the southwest and northeast monsoons. The southwest monsoon winds blow south-westerly across the South China Sea from May to September, whereas the northeast monsoon winds blow north-easterly from November to March. Generally, the temperature varies in the range of 25°C to 32°C. Pantai UMT consists of Quaternary deposits, which is described as unconsolidated to semi-consolidated deposits of gravel, sand, clay, and silt (JMG, 2014). The area is also characterised by coastal landforms such as sandy beaches, costal dunes and estuarine.

II. MATERIALS AND METHOD

The geophysical surveys were conducted at Pantai UMT to investigate the saltwater intrusion in a coastal setting (Figure 1). The geophysical surveys consist of ERT and TEM surveys. The ERT survey was conducted by setting up two survey lines of L1 and L2 (Figure 1, Table 1) and by using ABEM Terrameter LS2 instrument. The survey line L1 is parallel to the shoreline (Figure 2), whereas the survey line L2 is perpendicular to the shoreline (Figure 3). The TEM survey was conducted by collecting data at point P1, P2, and P3 using ABEM WalkTEM2 instrument (Figure 1).

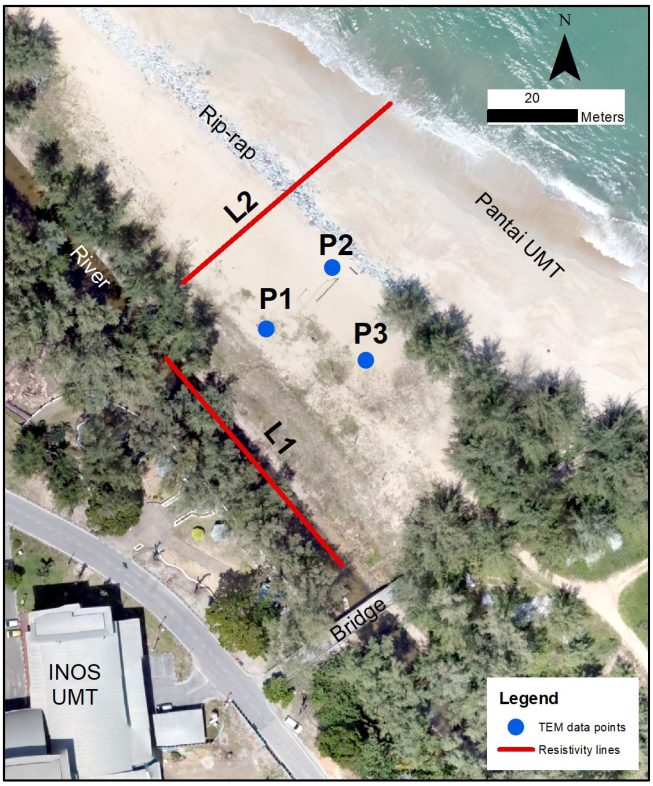

Figure 1. Study area at Pantai UMT.

Figure 2. Setting up resistivity survey for line L1, parallel to the shoreline.

Figure 3. Setting up resistivity survey line L2, perpendicular to the shoreline.

Table 1. Resistivity survey parameters

Parameters	Survey line L1	Survey line L2
Survey length (m)	64	64
Electrode spacing (m)	2	2
Vertical exaggeration	0.59	0.59
RMS error (%)	10.2	14
Depth penetration (m)	8	12

A. ERT Survey using ABEM Terrameter LS2

The ERT survey was carried out using ABEM Terrameter LS2 (Figure 4). The selected array configuration is the gradient array (combination of Schlumberger and dipole-dipole), which can produce high-density data and a detailed model of subsurface resistivity variation in both lateral and vertical (Lee *et al.*, 2021). The gradient array also has lower sensitivity to noise compared to other arrays and rapid data collection, which is for greater depth penetration (Lee *et al.*, 2021). The stainless-steel electrodes were inserted into the ground at 2-meter intervals. Each electrode was hammered into the soil to establish good electrical contact with the ground, which is critical for accurate measurements. Multicore cables were then connected to the electrodes and cables were arranged neatly to avoid tangling or crossing, which could interfere with signal quality. The Terrameter injected a controlled electrical current into the ground through two selected electrodes, referred to as current electrodes. The resulting voltage difference was measured between another pair of electrodes, called potential electrodes. The system then calculated the apparent resistivity values using Ohm's Law, which relates current, voltage, and resistivity.

Multiple measurements were taken at each configuration, and the process was repeated automatically for all possible electrode combinations along the survey line. The Terrameter's built-in switching system allowed seamless activation of different electrode pairs without manual intervention, improving efficiency and consistency. After completing the field measurements, the resistivity data were transferred from the ABEM Terrameter LS2 to a computer for further processing and analysis. Field notes documenting the survey setup, electrode positions, and environmental conditions, such as soil type and weather, were recorded to provide additional context for data interpretation.

Figure 4. ABEM Terrameter LS2

The collected apparent resistivity data was processed using Res2DInv software. This software uses applied mathematical inversion techniques to convert the raw apparent resistivity data into a model of true subsurface resistivity. The resistivity model was then analysed to identify subsurface features. Low resistivity zones were interpreted as conductive materials, such as clay or water-bearing layers, while high resistivity zones indicated materials like rock or dry sand (Loke, 1999).

B. TEM Survey using ABEM WalkTEM2

ABEM WalkTEM 2 is an electromagnetic survey used to measure subsurface resistivity variations. ABEM WalkTEM 2 equipment consists of transmitter, receiver, and cables (Figure 5). The transmitter loop measuring 20 m x 20 m was laid flat on the ground. The loop forms a closed circuit and is securely connected to the transmitter unit of the ABEM WalkTEM 2. This loop generates the primary electromagnetic field during the survey. The receiver coil measures the secondary electromagnetic field generated by the subsurface currents and was placed at the centre of the transmitter loop (central-loop configuration) or near the loop (in-loop configuration). The positioning of the receiver coil was determined based on the desired depth of investigation. The receiver was then connected to the WalkTEM 2 system to record electromagnetic signals.

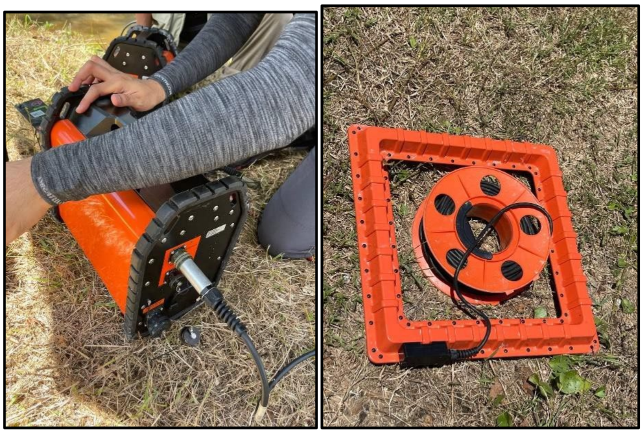

Figure 5. ABEM WalkTEM instrument.

The data acquisition process began when the transmitter generating a strong current pulse through the loop and creating a primary electromagnetic field that penetrated the subsurface. Once the current pulse was turned off, eddy currents were induced in the ground and generated a secondary electromagnetic field. The receiver coil measured the decay of this secondary electromagnetic field over time and recorded the data in the form of decay curves. These curves represent the relationship between time and the strength of the secondary field, which varies based on the resistivity of the subsurface materials. For each station, multiple measurements were taken to minimise noise and improve accuracy. After completing the measurements at one location, the equipment was relocated to the next station within the grid, and the process was repeated until the entire survey area was covered.

The recorded decay curves were analysed using Aarhus Workbench. The software converted the decay curves into resistivity models, which visually represent subsurface resistivity variations. The processed data was interpreted to identify high and low resistivity zones. High resistivity zone indicates dry sand or rock, whereas low resistivity zone indicates conductive material such as clay, saline water, or mineralised zones. These interpretations were used to understand the subsurface geological structures, hydrological conditions, or potential resource distributions.

III. RESULTS AND DISCUSSION

A. ERT Survey

The resistivity profiles show two distinct layers of low and high resistivity values. Line L1 is located in the river (i.e., drain) parallel to the shoreline. Line L1 profile shows low resistivity values that vary from 0.3 to 2.1 Ωm in shallow depth (ca. 2 m depth) (Figure 6). The deeper depth (ca. > 2 m depth) is dominated by high resistivity values that vary from 7.7 to 28.1 Ωm (Figure 6). In the shallower depth, the resistivity values also vary laterally, which is high resistivity values (2.11 to 4.03 Ωm) towards the inland (SE direction) and lower resistivity values (0.3 to 1.1 Ωm) towards the shoreline (NW direction) (Figure 6, Table 2).

The saltwater intrusion is identified as a low resistivity value (< 1 Ωm) flowing towards the sea (NW direction) and freshwater is identified as a higher resistivity value (> 1 Ωm) towards the inland (SE direction) (Figure 6). Lateral variation of resistivity values in the shallow depth indicates freshwater – saltwater mixing in the river. This freshwater – saltwater mixing is also consistent with broad variation of salinity values (13.35 to 32.39 ppt) of the river during the dry period

(Sathiamurthy *et al.*, 2021). A higher resistivity value (>7 Ωm) at deeper depths may indicate sand/mud lithology.

Line 2 is located perpendicular to the shoreline towards the NW direction (Figure 2). The resistivity profile of Line 2 shows medium to very high resistivity values (ca. 5 – 4,000 Ωm) dominate in the landward (SW direction) and in the shallow depth (ca. 2 – 4 m depth) (Figure 7). Very low resistivity values (ca. 0.4 – 1.5 Ωm) dominate the shoreward (NE direction) starting from the shoreline and continue in the deeper depth (> 4 m depth) (Figure 7, Table 2).

Very low resistivity value (< 1 Ωm) is correlated with the seawater. Medium to very high resistivity values are correlated with sandy beach, where very high resistivity (> 1,000 Ωm) possibly correlates with dry sand and medium resistivity (5 – 400 Ωm) correlates with wetter sand. The saltwater intrusion can infiltrate landwards within 2 – 8 m depth at the irregular boundary between the sandy beach and saltwater. The depth of saltwater intrusion also occurs at irregular depth (ca. 2 – 10 m), which the saltwater can penetrate through the rip-rap.

In addition, these two survey lines (L1, L2) show different depth penetrations although both survey lines use similar electrode spacing (Table 1). These depth differences occur due to different environmental settings and medium, where line L1 was set up inside the river and line L1 was set up on the coast. The resistivity is more conductive in water/saltwater medium compared to sand medium (Loke, 1999). The current flows easily and spreads out horizontally in water medium, but with reduced vertical penetration (Pierce *et al.*, 2012). Thus, survey line L1 has a shallower penetration (8 m depth) compared to survey line L2 (10 m depth). However, survey line L2 has a high RMS error percentage compared to line L1 (Table 1) due to high resistivity variation and crosses various medium (i.e., saltwater/coastline, rip-rap, and dry and loose sandy beach. The extreme contrast in the near surface condition (e.g., rip-rap) introduces heterogeneous medium and causes current path distortion, which leads to difficulty in achieving best-fitting algorithm for inversion and finally results in high RMS error.

Table 2. Comparison between two geophysical methods for saltwater detection.

Geophysical methods	**ERT**		**TEM**		
Survey line/point	L1	L2	P1	P2	P3
Setting	Inside the river	Coast – sea	Coast (ca. 30 m from the shoreline)		
Sensitivity to salinity (Ωm)	0.3 – 1.1	0.4 – 1.5	1 and 0.1	0.3 and 1.1	0.8 and 0.1
Saltwater intrusion depth (m)	0 – 2	2 – 10	6 – 8 and 100	6 and 120	6 and 116

B. TEM Survey

A 1D WalkTEM data shows resistivity (Ωm) values change with depth at a point location. The profile is typically plotted with resistivity on the horizontal axis and depth on the vertical axis. The 1D WalkTEM data was taken at three different locations (P1, 2 and 3) within the survey area (Figure 1). The line indicates how the resistivity values change from the surface (at the top) to just beyond the reliable depth of investigation.

1D WalkTEM data show low resistivity (<1 Ωm) consistently occurs at two different depths, which is shallow depth (ca. 6 – 8 m) and deeper depth (90 – 120 m), whereas high resistivity value (> 1 Ωm) occurs at ca. 10 – 90 m depth (Figure 8). In details, Point P1 shows low resistivity values at 6 – 8 m depth (resistivity value of 1 Ωm), depth 90 m (resistivity value of 0.1 Ωm) and depth 100 m (0.001 Ωm) (Figure 8, Table 2). Point P2 shows low resistivity value at 6 m depth (resistivity value of 0.3 Ωm) and 120 m depth (resistivity value of 1.1 Ωm) (Figure 8, Table 2). Point P3 shows low resistivity at 6 m depth (resistivity value of 0.8 Ωm) and 116 m depth (resistivity value of 0.1 Ωm) (Figure 8, Table 2).

The low resistivity value (0.001 to 1 Ωm) is correlated with saltwater intrusion, and the high resistivity value is correlated with sand lithology (> 1 Ωm). Low resistivity value in 1D WalkTEM data can indicate saltwater intrusion, which occurs at shallow depths (ca. 6 – 8 m) and deeper depths (ca. 90 – 120 m).

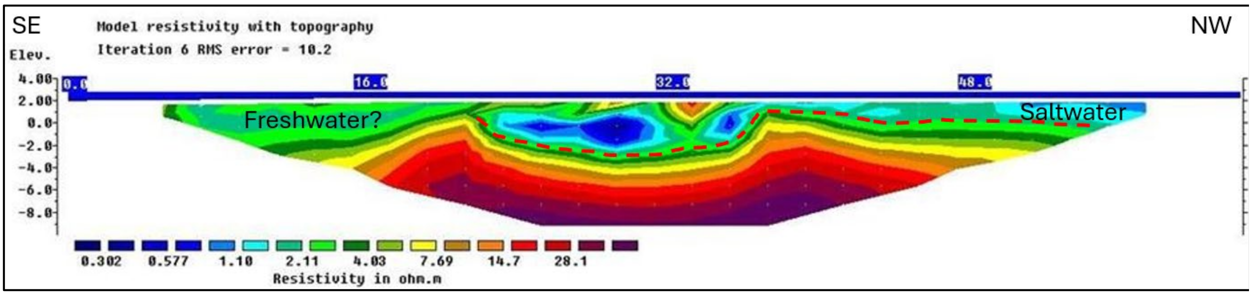

Figure 6. Resistivity profile of line L1, which is located parallel to the shoreline.

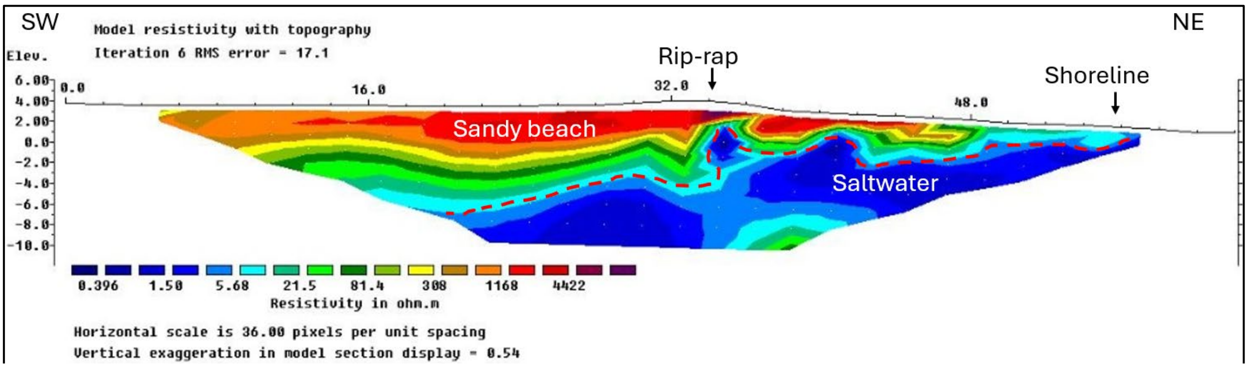

Figure 7. Resistivity profile of Line L1, which is perpendicular to the shoreline.

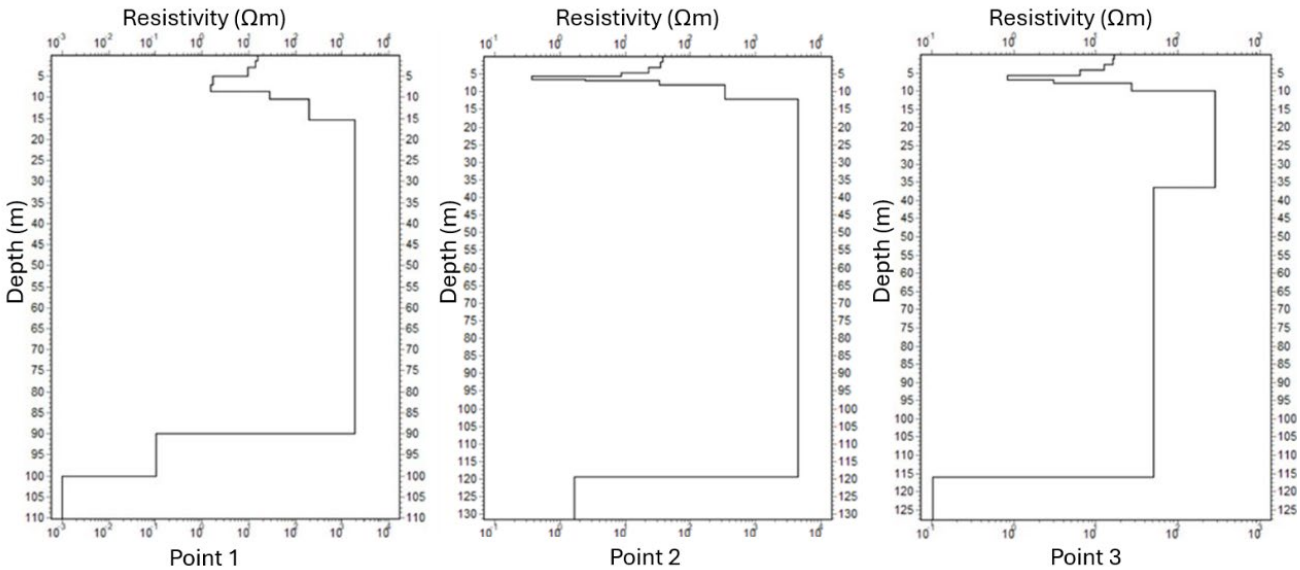

Figure 8. Three points of WalkTEM data.

C. Detecting Saltwater Intrusion using Geophysical Techniques

ERT and TEM techniques are essential for detecting saltwater intrusion, particularly in coastal areas. Saltwater intrusion can be identified based on by resistivity values. In this study, very low resistivity (< 1 Ωm) indicates high salinity, medium resistivity (1 – 10 Ωm) indicates wetter sand and very high resistivity (> 1,000 Ωm) indicates dry sand (Table 2). Thus, saltwater intrusion is identified based on very low resistivity value (< 1 Ωm), as successfully detected by these two geophysical techniques. Saltwater intrusion has a very low resistivity (ca. 0.2 – 1 Ωm) due to its high ion concentration (Werner et al., 2011). High resistivity values can represent dry or unsaturated sediment like sand and a gradual transition between resistivity zones may indicate mixing between freshwater and saline water (Werner *et al.*, 2013).

The depth of saltwater intrusion has high variation relative to distance from the shoreline. The resistivity profile parallel to the shoreline (line L1) indicates that the depth of saltwater intrusion within 2 m deep. The resistivity profile perpendicular to the shoreline (line L2) indicates that the depth of the saltwater intrusion varies from 2 – 10 m deep towards the inland. The depth of saltwater intrusion in Terengganu coast is consistent with another study at Pantai Batu Buruk (Tawnie *et al.*, 2013).

The depth of saltwater intrusion from the TEM survey also identifies a much deeper saltwater intrusion. TEM technique penetrates deeper than ERT technique, which TEM can detect a much deeper saltwater intrusion at 90 – 120 m deep (Table 2). Both techniques can detect the shallow saltwater intrusion, which is varies within 2 – 10 m depth (Table 2). However, TEM technique is limited to a certain point, whereas ERT is more efficient for a larger area.

This study also indicates that saltwater intrusion depth is highly varied with the coastline distance. The saltwater intrusion depth increases towards inland. The rising sea level can change the coastline position, reduce the saltwater depth and finally contaminate the groundwater source especially in a coastal area. Thus, further work is needed on identifying the water quality of the identified saltwater intrusion and to verify the geophysical interpretation.

IV. CONCLUSION

In conclusion, the geophysical surveys conducted using the ABEM Terrameter LS 2 and ABEM WalkTEM 2 at Pantai UMT have yielded significant insights into the impact of the rising sea level and saltwater intrusion in a coastal setting. The resistivity measurements indicate a clear boundary between sandy beach and saltwater intrusion. The analysis of the resistivity and electromagnetic methods illustrates low resistivity values (<1 Ωm) correlate to seawater and high resistivity values (> 1 Ωm) correlate to sandy beach.

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