Resistivity-Chemistry Integrated Approaches for Investigating Groundwater Salinity of Water Supply and Agricultural Activity at Island Coastal Area

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Abstract. Groundwater suitability for water supply and agriculture in an island coastal area may easily be influenced by seawater intrusion. The aim of this study was to investigate seawater intrusion to the suitability of the groundwater for water supply and oil palm cultivation on Carey Island in Malaysia. This is the first study that used integrated method of geo-electrical resistivity and hydrogeochemical methods to investigate seawater intrusion to the suitability of groundwater for water supply and oil palm cultivation at two different surface elevation and land cover. The relationship between earth resistivity, total dissolved solids and earth conductivity was derived with water type classifications and crop suitability classification according to salinity, used to identify water types and also oil palm tolerance to salinity. Results from the contour resistivity and conductivity maps showed that the area facing severe coastal erosion (east area) exhibited unsuitable groundwater condition for water supply and oil palm at the unconfined aquifer thickness of 7.8 m and 14.1 m, respectively. Comparing to the area that are still intact with mangrove (west area), at the same depth, groundwater condition exhibits suitable usage for both socioeconomic activities. Different characteristics of surface elevation and land cover are paramount factors influencing saltwater distribution at the west and east area. By the end of the twenty-first century there will no longer be suitable water for supply and oil palm plantation based on the local sea-level rise prediction and Ghyben–Herzberg assumption (sharp interface), focusing on the severe erosion area of the study site.

1. Introduction

Knowledge on the groundwater requirement for domestic water supply and agricultural activity is important to ensure a holistic management approach of groundwater aquifer. This scenario is more complex at the coastal areas due to saltwater contamination that restricted groundwater usage for water supply and agricultural activities. Degree of salinity in groundwater aquifer should be suitable for both requirements in order to ensure sustainability for both important socioeconomic activities at the coastal areas. Problems of saltwater contamination always related to the seawater intrusion phenomena due to its close proximity to the sea. However, previous studies [1, 2] had focused on the salinity problem in order to define the suitability of agriculture towards soil salinity. There were limited studies on the effect of seawater intrusion into groundwater aquifer that are related to groundwater supply and agriculture activities at the coastal areas. Furthermore, groundwater for water supply and agriculture usage in the coastal areas can be affected by sea level rise in the 21st century due to its climatic change.
The climatic change is expected to worsen the existing environmental problems along the coastal areas. Future sea-level rise near coastal aquifers may lead to a change in the present hydrogeological boundary. Saline groundwater is thicker than before and more shifts to the landward coastal areas in the future \cite{4, 5}. In the present study, the combined geo-electrical and geochemical methods were implemented, but emphasizing more on the present seawater intrusion status, water supply and oil palm cultivation at Carey Island, located in Langat Basin on the west coast of Peninsular Malaysia. The technique was aided by the information related to the elevation, land cover and oil palm plant physiology. The elevation and land cover discussed in the current work involves the physical changes in the coastal area that can influence seawater intrusion distribution at the coastal islands.

2. Study Area and Methodology

The study was conducted in the West Estate of Sime-Darby Estate Plantation of Carey Island Selangor, the exact location being the side that faced the Straits of Malacca (Figures 1). Total area for the oil palm plantation in the West Estate is 5,016.90 ha where 3,795.45 ha is producing crops and 1,221.35 ha is planted with oil palms that are not yet producing any crops \cite{6}.

The root system plays an important role for extracting nutrients and water for the growth of an oil palm. Salinity tolerance is the most important factor in determining the impact of soil and groundwater salinity to plant growth at coastal areas. Plant tolerance limit based on salinity was introduced to Peninsular Malaysia by \cite{7, 8, 9} as listed in Table 1.

Eight monitoring wells (Figure 1) were installed in the unconfined aquifer: four (MW6, MW11, MW12, MW13) in the northwest in the mangrove preserved area and four (MW5, MW7, MW10, and MW14) in the southeast in the heavily eroded area without mangrove. Additionally six other wells (MW1, MW2, MW3, MW4, MW8, and MW9) were installed in the semi-confined aquifer in the southwest of the semi-confined aquifer. The wells reached various depths (40, 50, and 80 m), respectively, with open screens installed in the 34–36, 47–49, and 67–69 m depths for groundwater quality sampling. Soil samples collected from each of the well boreholes by rotary-washing were visually examined and laboratory analysed. Soil classification followed the \cite{10}: fine sand (0.063–0.1 mm); medium sand (0.1–0.4 mm); and coarse sand (1–2 mm). Tests on the soil physical properties included particle-size distribution, Atterberg limit, moisture content, specific gravity, and linear shrinkage. Surface elevations were conducted to obtain topography information of the study area. The precision of total station equipment, model GPT-3100N Series Top Con were used for data acquisition of elevation for the fourteen (14) monitoring wells and also along a route survey. The reference datum is benchmarked to station BM No. 3082 obtained from Department of Survey and Mapping Malaysia (DSSM) (Figure 1).

Earth resistivity (ER) was measured following the traverse set up (Figure 1) using a resistivity meter (ABEM Terrameter SAS4000 with electrode selector ES10-64). Spread in two phases, the first phase data were collected in August 2009, November 2009, and February 2010 and the second phase data in December 2010. The former data were used to establish a Total Dissolved Solid (TDS) and Earth Resistivity (ER) relationship in the vertical profile of the study area; whereas the latter data were used to map out the subsurface resistivity in the horizontal profile. \cite{11} proposed the classification of groundwater salinity can be classified into three types namely; fresh, brackish and saline by using TDS values. Freshwater is classified with TDS values < 1000 mg/L, brackish water is classified as TDS values ranging from 1000 mg/L to 10000 mg/L and TDS values > 10000 mg/L are classified as saline groundwater. According to Interim National Water Quality Standards for Malaysia \cite{12}, TDS values of < 1000 mg/L requires no treatment for water supply. In this study groundwater specific conductance was assumed as the reciprocal of water resistivity (\(\rho_w = \frac{1}{\sigma_w}\)) while soil conductance as the inverse of earth resistivity (\(\sigma_s = \frac{1}{\rho_e}\)). The TDS-ER relationship derived from the empirical equation,
log $TDS = -0.1411 \rho_e + 4.4286$ [2] revealed that three types of groundwater salinity can be depicted in the resistivity images. The water types are fresh ($\rho_e > 10.0 \ \Omega \cdot m$), brackish ($3.0 \ \Omega \cdot m < \rho_e < 10.0 \ \Omega \cdot m$), and saline ($\rho_e < 3.0 \ \Omega \cdot m$). The correlation relationship between the subsurface resistivity and TDS data can be used to determine the distribution and location of the boundaries of freshwater, brackish and saline in the aquifer system. Resistivity distribution for groundwater salinity is represented by using different colour codes. The colour codes used are blue for freshwater (> 10 \ \Omega \cdot m), green for brackish water (3 to 10 \ \Omega \cdot m), and red for saline water (< 3 \ \Omega \cdot m). Conductivity distributions for the suitability of oil palm towards salinity are represented by using different colour codes. The colour codes used are blue for suitable (> 0.4 S/m), green for moderately suitable (0.4 S/m < C < 0.2 S/m), and red for not suitable (< 0.2 S/m). The soil salinity and oil palm tolerance suggested by [7,8,9] can be widely used under Malaysian condition whether for saturated or unsaturated water condition (Table 1). The oil palm will not be able to tolerate salinity when the EC limit exceeds 0.4 S/m, eventually will be leading the plant to its death [9].

Figure 1. Locations of monitoring wells, resistivity survey lines, drainages system and boundary between unconfined and semi-confined aquifers.
Table 1. Different degree of salinity, plant tolerance and oil palm tolerance for various electrical conductivity ranges.

| EC value (S/m) | Degree of salinity [7] | Plant tolerance [8] | Oil palm plant tolerance [9] |
|---------------|------------------------|---------------------|-----------------------------|
| > 0.4         | Severely saline        | very serious limitation | Not suitable                |
|               | Moderately saline      | serious limitation   | Moderately suitable         |
| 0.2 – 0.4     | Non-saline             | moderate limitation  | Suitable                    |

3. Results and Discussion

3.1 Resistivity images (Inverted 2D)

Figure 2 shown the results of resistivity profiles for the five traverse lines using the inversion model (RES2DINV) software. Note that all profiles started at the 2.5 m depth measured from the ground surface. The resistivity profiles selected in the five different locations, outlined below, were selected as to represent variations in the two distinctively different land cover settings overlying the unconfined aquifer. Note that L’ and L refer respectively to the south and north ends of the resistivity traverse line.

a) Profile L1-L1’ is located in the mid-aquifer with mangrove cover in the west and south.

b) Profile L2-L2’ is located in the west of the aquifer with mangrove cover.

c) Profile L3-L3’ is in the middle east of the aquifer with open mangrove area in the east and south.

d) Profile L4-L4’ is located close to heavily eroded coastal belt in the south.

e) Profile L5-L5’ is located close to the estuary where the agriculture hydraulic structures (tidal gate, bund and main canal) are found.

Three colour codes (blue, green, and red) were used to denote the different water types (respectively freshwater, brackish water, and saline water) as apparent in the resistivity image. Inserting the measured TDS values in Equation 2, the resistivity values were predicted, from which the water types were determined according to the set colour coding with the designated range of resistivity values. The results obtained are as follows: fresh water ($\rho_e > 10.0 \ \Omega \ m$); brackish water ($3.0 \ \Omega \ m < \rho_e < 10.0 \ \Omega \ m$), and saline water ($\rho_e < 3.0 \ \Omega \ m$).

Resistivity profile L1-L1’

This profile (Figure 2) is respectively 1.6 km and 2.5 km from the south and west of the study area. Freshwater thickness (blue coded) varied in depth from 28 m (minimum) to 40 m (maximum) with the overall resistivity within the freshwater lens ranging from 10 $\Omega \ m$ to 55 $\Omega \ m$. Below the freshwater was found brackish water (green coded) overlying saline water (red coded) separated by an undulating saline-brackish water interface.
Resistivity profile L2-L2’

This profile (Figure 2) crossed MW11 at mid-survey line, traversing from the mangrove into the oil palm cultivation area (Fig. 2). Freshwater lenses were scattered about throughout the cross-section in approximately 10 m thickness with resistivity between 10.0 $\Omega\,m$ and 24 $\Omega\,m$. Saline water (red coded) was dominantly found in the 19m depth (with resistivity below 3 $\Omega\,m$) overlain by brackish water (green coded). These water types exhibited almost horizontal interfaces between each other.

Resistivity profile L3-L3’

This profile (Figure 2) crossed over MW10 in the mid-profile (Figure 1). The nearest coastal area to the study area was about 2.2 km away in the south beneath the open mangrove with severely eroded land cover. Brackish water (green) was thin, overlying the saline water (red coded) which was predominantly found with low resistivity (below 3 $\Omega\,m$) below the 10 m depth. The freshwater lens appeared only 5 m thick.

Resistivity profile L4-L4’

This profile (Figure 2) located 15 m away from the coast crossed over MW7. In the distance about 3.2 km landward was found coastal mangrove, heavily deforested and eroded. Freshwater was less than 10m thick with resistivity exceeding 10.0$\Omega\,m$. The saline water was however more prominent in the subsurface with low resistivity (< 3$\Omega\,m$).

Resistivity profile L5-L5’

This profile (Figure 2), about 98 m away from the coast crossed over MW6. Close to it were found some of the estuarine hydraulic structures such as open canals and tidal gates. In the shallow subsurface was saline water 2.5 – 10 m deep with resistivity between 0.5$\Omega\,m$ and 3$\Omega\,m$. Brackish water was predominant below the saline water in the 400 m distance of the traverse line with resistivity between 3$\Omega\,m$ and 10$\Omega\,m$. This explains why the freshwater was saline in the estuarine canals.

In relative profile comparison, it is noted that all profiles had freshwater in varying thickness except for L5-L5’. Profiles L2-L2’; L3-L3’; and L4-L4’ appeared to have thinner freshwater compared to L1-L1’. Both L3-L3’ and L4-L4’, it is noted, were located in the eroded side (west) of the study area. Profile L1-L1’ has practical implication in that freshwater production wells could be constructed in the vicinity of the traverse line at depths exceeding 20 m as compared to the shallower wells for all other profiles.
Figure 2. True inverted resistivity profiles for L1-L1’, L2-L2’, L3-L3’, L4-L4’ and L5-L5’.
3.2 Resistivity and Conductivity image (Inverted 3D)

Resistivity and conductivity distributions was spatially analysed by interpolation using the Kriging technique available in Surfer 8. The true (inverted 2D) vertical profiles, shown in Figures 3 and 4 for selected depths. Although the 3D images have apparently limited resolution due to the limited number of profiles examined in comparison to the survey area (100 km²), the method has produced sufficiently better resistivity and conductivity distributions of the different water types and oil palm tolerance toward salinity respectively.

The three colour codes are used to describe resistivity distribution for water types: blue for freshwater (>10 Ω m); green for brackish water (3-10 Ω m); and red for saline water (<3 Ω m). The following discussion is only confined for demonstrative purposes for the 2.5-5.0m depth [Figure 3a) and b)] of the unconfined aquifer. In this water zone freshwater (horizontal) coverage is about 3km², half that for brackish-saline water (about 7.0 km²). The dominancy of water brackishness/salinity was due to seepage from the irrigation canals (profile L6-L6 near MW6, profile L7-L7’ and profile L8-L8’ shown in Figure 1). The freshwater contamination in the shallow aquifer was believed to be caused by seawater infiltrating from the irrigation canals. In the same depths (2.5-5.0 m) the saline water occurred mostly in the southwest (in the reserved mangrove) due to tides moving from the mangrove to the bunds separating it from the oil palm cultivation. In the past, the bunds in the mangrove have been frequently damaged, causing the saline water to overflow into the oil palm plantation, thus contributing to the groundwater salinity in the southwest area. An important finding in the study is the indication of freshwater availability in the midwest-study area as deep as 21.8 m into the aquifer beneath the mangrove as shown in Figure 4i). For depths exceeding 7.8 m, the saline water occurrence was mainly due to seawater intrusion.

In the east, close to profiles L1-L1’, L2-L2’ and L3-L3’, no freshwater appeared at depths exceeding 7.80 m [Figure 3c)] due to the saline-brackish water dominancy resulting from seawater intrusion that seemed more dominant than on the western side. In contrast, there was freshwater in the west close to the mid-study area (profiles L2-L2’ and L3-L3’) in the 21.8 m depth [Figure 4 i)] underlying the brackish-saline water. This observation has correlation with TDS in the monitoring wells on the eastern side in the 36m depth, having concentrations twice (20,000 mg/L) as high as on the western side (10,000 mg/L). Freshwater in the 30-40 m zone was less thick compared to the 10-20 m zone, concentrating in the mid-aquifer over 10 - 30% of the mapped area. The freshwater lens in these depths seemed to be isolated from the surrounding saline water especially in the east, west and south directions, indicating saline water dominancy in every direction.

Conductivity distributions for the suitability of oil palm towards salinity were represented by using different colour codes. The colour codes used are blue for suitable (> 0.4 S/m), green for moderately suitable (0.4 S/m < C < 0.2 S/m), and red for not suitable (< 0.2 S/m).

The 3-D conductivity slice images at the depths of 2.5 m and 5.0 m [Figures 3 d)-f) and 4 j)-l)] showed that more than 80% of the area with conductivity values of 0.2 S/m is suitable for oil palm plantation. These results contradict with water type’s distribution that showed almost 50% is suitable for water supply at the same depth [Figures 3a)-b)]. The image also showed that some areas are moderately suitable and not suitable for plantation, especially along the main agricultural canal drainages (mid-study area) and areas near the coast with un-bund mangroves (west area). On the east side area with severe coastal erosion, the area still exhibits suitable condition for oil palm cultivation. The severe erosion in the area was mitigated by the construction of man-made bund and well-developed roads that prevented the penetration of saline water into the plantation ground surface. Contradict to the west coastal mangrove side, saline water intrusion occurred during high tide when seawater flooded the area. Mangrove plants that grow close to this coastal area are more tolerant towards salinity due to saline water intrusion. Behind the mangrove reserved area, man-made bunds were constructed to prevent saline water intrusion into the plantation area.
As for the severely eroded area on the east side, the moderate conductivity condition (0.2–0.4 S/m) appeared at a depth of 7.8 m. This results showed a different condition in the same depths of water type resistivity distribution [Figure 3 c)] where all of the east side is covered by brackish and saline water (not suitable for water supply). On the west side, a similar depth is still suitable for oil palm cultivation [Figure 3 f)]. The conductivity value for the severely eroded area which is not suitable for oil palm plantation was at 14.10 m depth [Figure 4 k)]. In the west side, where mangrove forests still exist, the conductivity value suitable for plantation is at 21.80 m depth [Figure 4 l)].

**Figure 3.** Resistivity and conductivity distribution relative to elevation from 2.5 to 7.8 m depths.

**Figure 4.** Resistivity and conductivity distribution relative to elevation from 10.8 to 21.8 m depths.
4. Discussion and Conclusions

The 3-D resistivity and conductivity slice image revealed different groundwater suitable salinity distribution and depth for water supply and oil palm in Carey Island. The factors of different results of groundwater salinity for two different socioeconomic activities are due to the water levels standard towards salinity for both areas are different. Water level standard for water supply can be deduced as TDS < 1000 mg/L meanwhile for oil palm requirement the TDS <5300 mg/L. Note that the conductivity for oil palm suitability toward salinity can be converted into TDS by using Equation [2] and groundwater specific conductance was assumed as the reciprocal of water resistivity \( \rho_w = \frac{1}{\sigma_w} \).

Other factors that determined the tolerance of water supply and oil palm for groundwater salinity are different elevation height and land cover between the west and east area as well as groundwater salinity distribution finding. The east area has a low surface elevation and no mangroves covered the coastal area. Compared with the west area, surface characteristics in the east area naturally provide a more conducive environment for seawater intrusion into the groundwater system. The middle area between east and west has a high topography, which prevents the migration of salinity from the east to the west. The middle area also showed the dominance of brackish water as a result of the seepage of saline water from the main canal that is located in this area. As discussed by [13], the variations in the hydrogeology conditions, such as terrain effects, vegetation pattern and sea level rise, are among the factors that can contribute to groundwater salinity. In this study, the terrain effect and land cover were considered significant to seawater intrusion due to high variations (1.3-2.3 m) in the elevation and land cover of the study area. These might have a major influence on the wider saline-brackish water distribution in the south-east where the semi-confined aquifer was located which showed low elevation and no mangrove covered compared to the west area.

According to the Ghyben-Herzberg assumption, a 0.5 m increase in the sea level will reduce the thickness of freshwater storage by 20 m. The predicted sea level rise in the 21st century will increase seawater intrusion in the area. Based on the predicted slope from 2001 to 2010 by a sea level rise prediction study, which used the B1, A1B, and A2 scenarios from the Special Report on Emissions Scenarios, the mean sea level rise rate at Port Klang is 0.387 m [14]. Based on the Ghyben-Herzberg assumption and local scenario sea-level rise prediction, the east area will become unsuitable for water supply and oil palm plantation much sooner than the west area, which still has a mangrove forest.

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References

[1] Tajul Baharuddin M.F, Taib S and Hashim R 2009 Electrical imaging resistivity study at the coastal area of Sungai Besar, Journal of Applied Sciences, 9 (16), p2897-2906.

[2] Tajul Baharuddin MF, Taib S, Hashim R, Zainal Abidin MH, and Rashid MA 2013 Evaluating freshwater lens morphology affected by seawater intrusion using chemistry-resistivity integrated technique: a case study of two different land covers in Carey Island, Malaysia. Environ Earth Sci, 69,p 2779–2797
[3] IPCC (2001) Climate Change 2001: Impacts, Adaptations, and Vulnerability: contribution of working group II to the third assessment report of the Intergovernmental Panel on Climate Change. McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. and White, K. S. Cambridge University Press, Cambridge, UK and New York, NY, USA. http://www.grida.no/publications/other/ipcc_tar/

[4] IPCC 2007 Climate Change 2007: Impacts, Adaptations, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK. (can be download at: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg2_report_impacts_adaptation_and_vulnerability.htm).

[5] Været, L., Kelbe, B., Haldorsen, S. and Taylor, R.H. (2009). A modelling study of the effects of land management and climatic variations on groundwater inflow to Lake St Lucia, South Africa, Hydrogeology Journal, 17, 1949–1967.

[6] BeritaHarian (Daily News) 2011 BeritaSawit, January 2011. Can be downloaded at http://www.mpob.gov.my/index.php?option=com_content&view=article&id=1012%3Aberita-sawit-januari-2011&catid=187%3A2011&lang=en Official Portal for Malaysian Palm Oil Board (MPOB)

[7] Wong IFT 1986 Soil-crop Suitability Classification for Peninsular Malaysia (Revised). Soils and Analytical Services Bulletin no. 1. Department of Agriculture, Ministry of Agriculture Kuala Lumpur, Malaysia. 9

[8] Mohd. Hashim, G. 2003 Salt-affected soils of Malaysia. A report prepared for the Food and Agriculture Organisation of the United Nations (FAO).

[9] Abd.Ghani, E, Zakaria, Z.Z, Wahid, M.B. 2004 Guidelines for palm oil industries, Perusahaan Sawit di Malaysia, Millennium Edition.Malaysian Palm Oil Board, Ministry of Plantation Industries &Commodities, Malaysia.

[10] British Standard (BS) 1377 1990 Part 2: Method of Test for Soils for Civil Engineering Purposes. British Standard Institution, London, ISBN: 0580178676, 1-68.

[11] Fetter CW 2002 Applied Hydrogeology, 4th Ed, Prentice Hall Inc., New Jersey, 1-598. ISBN: 0131226878.

[12] Department of Environment Malaysia 2010 Interim National Water Quality Standards for Malaysia. Department of Environment, Malaysia.

[13] Schneider, J.C. and Kruse, S.E. 2006 Assessing selected natural and anthropogenic impacts on freshwater lens morphology on small barrier Islands: Dog Island and St. George Island, Florida, USA, Hydrogeology Journal, 14, 131-145, doi: 10.1007/s10040-005-0442-9, http://www.springerlink.com/content/v515467525r2n551/fulltext.pdf.

[14] California Hydrologic Research Laboratory 2010 Final report for the study of the impact of climate change on sea level rise at Peninsular Malaysia and Sabah and Sarawak, California Hydrologic Research Laboratory, USA. 96