CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusions

Groundwater contamination is a serious issue because it depletes fresh groundwater resources. Groundwater resources in coastal areas are exposed to seawater intrusion because coastal areas are near the sea. Seawater intrusion can induce groundwater salinity, which affects groundwater resources and socioeconomic activities, such as agriculture, along coastal areas. This situation becomes more severe in island coastal areas as the primary water resources are mainly from freshwater lenses.

The geo-electrical-and-geochemical integrated technique is used in this study to assess groundwater salinity towards suitability to agriculture activities in island coastal areas.

A correlation between subsurface resistivity and TDS was established to identify an empirical relationship for groundwater salinity and oil palm suitability toward salinity degree at coastal island areas in Malaysia. This technique has been used to determine groundwater salinity condition in groundwater aquifer. However, this technique has not been previously used to determine the impact of groundwater salinity on the suitability of agriculture activities, especially in oil palm cultivations. Moreover, this technique was combined with surface and subsurface hydrogeology study to assess current groundwater salinity conditions. This integrated technique was applied in a coastal area in Carey Island, Selangor, Malaysia.

Chapter 2 provided an overview of Carey Island in terms of geological condition, subsurface hydrogeology, socioeconomic activities, and land cover from literature reviews. This chapter also overviewed the physiography and salinity tolerance of oil palm plants. Carey Island is located in the Langat Basin catchment area and is separated by Langat River at the east and the north sides. On the west and the south, the island coastal area is exposed to seawater (Straits of Malacca). Geological and geomorphological studies of Carey Island are important in providing its hydrogeological background.

Past literature presented information on hydrogeological conditions of Carey Island and its connection to the mainland. Part of the island is close to the mainland (separated by Langat River) until two-thirds of the area to the west, which showed a similar subsurface profile. Both areas showed a semi-confined aquifer with nearly the same depth for each in Gula and Simpang Formation. Thus, geological subsurface strata in certain parts of the study area may be connected to the mainland, especially at the east area of Carey Island. Based on past studies, fresh groundwater in the mainland of Langat Basin occurs as regional groundwater flow. Interface boundary exhibits an inclined saline–fresh water boundary. Based on hydrogeological conditions in the area, groundwater flow occurred mostly on a regional scale in mainland Langat Basin, whereas groundwater in Carey Island is more localized to freshwater lenses. In addition, a major part of the island is in close proximity to the Straits of Malacca, which exposes the area to seawater intrusion and can deteriorate the freshwater quality of the groundwater aquifer. Previous studies determined the existence of freshwater lenses in Carey Island from a limited number of monitoring wells and geochemistry tests. This approach did not provide the overall distribution and extent of freshwater lens morphology.

With regard to socioeconomic activity, the oil palm plantation area in Carey Island is about 1% of the total oil palm plantation in West Peninsular Malaysia. Carey Island is Malaysia’s biggest and only island that relies on cultivation of oil palm trees as a major source of income. Apart from oil palm plantation, another land cover activity in Carey Island is mangrove reserve forest. The mangrove forest is mainly distributed along the coastal area except for the southern area, which underwent extensive deforestation.

Before the early 1900s, the majority of Carey Island (especially in the coastal areas) was a mangrove swamp. Carey Island is located in the thickest belt of the coastal swamp, most of which is sand, mud, and mangrove. Oil palm plants have limited tolerance for saline conditions. Based on studies for oil palm tolerance toward salinity by using electrical conductivity (EC) values, the EC limit exceeds 0.4 S/m and can be categorized as unsuitable for oil palm cultivation.

Chapter 4 provided information on surface and subsurface characteristics of Carey Island from the current study. Surface characteristic study comprises surface elevation, land cover, and drainage distribution. Different surface characteristics were observed between the east and west area. The west area showed higher surface elevation, denser mangrove reserves in the coastal areas, and less dense drainage distribution compared with the east area. The east area has a low-lying valley area that runs parallel to wells MW7, MW5 and MW10. The southeast coastal area experienced severe erosion, and tree stumps can be observed as far as 300 m from the shoreline. The study of subsurface characteristics includes subsurface hydrogeological strata, groundwater tables, TDS, and groundwater chemistry of the east and west sides of the study area. A subsurface hydrogeological study showed that semi-confined aquifer covers two-thirds of Carey Island, and subsurface hydrogeological information reveals two types of aquifers in this area. In this study, the first unconfined aquifer was encountered at the western part of the study area with the semi-confined aquifer in the east area. This study revealed that the aquifer system in Carey Island consists not only of a semi-confined aquifer system as indicated by previous studies, but also of an unconfined aquifer system. Interestingly, the unconfined aquifer (sandy material) was located at the end of Carey Island, which is close to seawater.

The groundwater tables increased in the wet season but decreased in the dry season, which indicates that the unconfined layer responded more quickly to seasonal conditions. The groundwater tables in the west area were about four time's greater (0.6 to 0.8 m mean sea level) than those in the east area (0.15 to 0.2 m mean sea level) during both wet and dry seasons. A study of the correlation between groundwater tables and TDS showed contrasting results in the east and the west areas. Low groundwater tables revealed high TDS in the east area, with TDS values exceeding 20,000 mg/L, whereas TDS values in the west area reached 10,000 mg/L only. Thus, the TDS of groundwater in the east area was twice as high as that in the west. The contrast in the surface elevation, land cover and drainages distribution of the east and west area in Carey Island contributed to the difference in the effect of seawater intrusion in the area. The data obtained from the TDS monitoring represented 34 to 36m depths (single point) of the unconfined aquifer system. To obtain a better view of the seawater intrusion condition in this area, two dimensional (2-D) resistivity images for water types' profiles can be used with correlation between TDS of groundwater and subsurface resistivity.

Groundwater chemistry showed that Na and Cl content constituted more than 70% of the whole ion content in the groundwater, which indicates that the salinity of the groundwater system was due to seawater intrusion. Conductivity measurement of groundwater obtained a value that exceeded 5 mS/cm, which indicates that groundwater in this area, was affected by seawater. The obtained geochemistry data represent the condition of the groundwater samples at a single point in the subsurface profile. To assess dynamic changes of the groundwater salinity, TLERT method was used, and the results were discussed in Chapter 5.

Chapter 5 discussed the subsurface resistivity results and the correlation between subsurface resistivity and groundwater salinity degree for the study area. While conducting the resistivity survey, ground contact condition was improved by performing a few steps, as discussed in Chapter 3 (Methodology), such as hammering down the electrodes deeper than 0.3 m to improve ground contact, maintaining sufficient moisture for ground contact by using a formulated solution (bentonite polymer solution mixed with salt solution), and by using a more powerful battery (current injection >60 Ah). Improved ground contact can improved the apparent resistivity data obtained during resistivity measurements.

The correlation between subsurface resistivity results and TDS was derived to obtain the empirical relationship of the groundwater salinity degree in the study area. The correlation was limited to the unconfined aquifer only. Semi-confined aquifer (clay) showed a non-linear correlation between subsurface resistivity results and pore water, as mentioned by past studies. The correlation results were used to derive the empirical equation for the groundwater salinity degrees (fresh, brackish, and saline) of a sandy unconfined aquifer system in Carey Island. The resistivity measurements and groundwater sampling from deep monitoring wells were conducted at a three-month interval when twenty-three data from subsurface resistivity and TDS were collected to establish the empirical relationship. Through statistical analysis, the data were evaluated by using skewness, kurtosis, and Pearson correlation coefficient (r) to evaluate the distribution and correlation of the data used for deriving the empirical relationship. The statistical analysis showed that the distribution of the data followed the normal distribution where the skewness and kurtosis value was nearly in the range of −1 to +1. Pearson correlation coefficient (r) for all the data showed a strong linear relationship, which illustrated the value approach −0.9 to +0.9 and can be used to derive a linear regression to determine the relationship between the data, especially subsurface resistivity versus water resistivity and subsurface resistivity versus TDS data. The plotted graph of the subsurface resistivity versus water resistivity and subsurface resistivity versus TDS showed R^2 value of 0.959 and 0.932, respectively, which indicates a strong linear relationship.

In this study, an empirical relationship between TDS and subsurface resistivity was obtained (see Equation 5.2), by which three TDS-based groundwater salinity degree was identified following the classification: saline water (TDS> 10,000 mg/L), brackish water (1,000<TDS<10,000 mg/L), and freshwater (TDS<1,000 mg/L). The relationship derived from the empirical equation revealed that three groundwater salinity degree can be depicted in the resistivity images. The groundwater salinity degree are fresh (ρ_e> 10.0 Ω.m), brackish (3.0 Ω.m <ρ_e< 10.0 Ω.m), and saline (ρ_e< 3.0 Ω.m). Results showed more than 80% of the resistivity images showed low resistivity (<3 Ω.m), except for MW6 and MW12. The value for saline water (ρ_e< 3.0 Ω.m) obtained in this study area was similar to that in previous studies. A subsurface material with a resistivity of less than 5 Ω.m was used for saline water identification in the western coast of Peninsular Malaysia. Meanwhile, in the eastern coast of Peninsular Malaysia, the saline alluvial layer had a resistivity of less than 2 Ω.m. Unfortunately, previous studies did not include the correlation between subsurface resistivity and groundwater quality. Successful integration between subsurface resistivity and groundwater quality confirmed the existence of freshwater lens in Carey Island. Previous studies relied only on groundwater quality monitoring and did not provide an overall image of the existing freshwater lens. 2-D resistivity profile images clearly showed freshwater floating on top of brackish and saline water with different thicknesses depending on the surface characteristics.

The TLERT measurement results showed differences in the percentage of resistivity changes with positive and negative values. Dynamic changes in the salinity of groundwater aquifer occur daily according to tide conditions. In addition to the results of geochemistry analysis, the TLERT results reaffirmed that seawater intrusion was the source of salinity in groundwater aquifer of Carey Island. The confirmation of the source of salinity is important as seawater intrusion is closely related to rising sea levels. Based on the assumption of Ghyben-Hezberg, groundwater salinity caused by seawater intrusion together with sea level rise, which is the effect of climate change, will cause the disappearance of freshwater lens.

2-D resistivity images did not provide a horizontal view of the overall groundwater salinity degree distribution. To assess the effect of groundwater salinity degree distribution at two different land covers, topography, and drainage distribution, 3-D resistivity slice images were plotted, which provided a better view of the distribution and location of the boundaries of groundwater salinity that covered the whole study area.

Chapter 6 provided 2-D and 3-D views of the groundwater salinity degree distribution. The 2-D and 3-D views showed the dominance of water brackishness and salinity from the agriculture drainages. Freshwater contamination in the shallow aquifer was caused by saline water that infiltrates from the agriculture drainage at depths of up to 5 m. The mid-west area, except for the mangrove reserve area, showed the presence of freshwater up to a depth of 30 m. The mid-east area showed the presence of freshwater at a depth of only 10 m. This phenomenon contradicts the findings of a previous study that more freshwater lenses are located in the center of the island and decrease toward the coastal area. The phenomenon in Carey Island, in which different freshwater lens thicknesses occurred laterally, are different from the normal condition of an island, as discussed by previous studies. This phenomenon occurred because of the different surface characteristics of the east and west areas. The east area has a low surface elevation. No mangroves covered the coastal area, and it has more drainage than the west 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.

The study also presented the current limitations and suitability of oil palm toward salinity. This issue is critical especially at the unconfined aquifer that faces the severely eroded coastal area. 3-D conductivity slice images showed that the mid-east area has conductivity values that are more unsuitable for oil palm plantation at shallower depths compared with the mid-west area. The mid-east and mid-west areas showed conductivity values those are unsuitable for oil palm plantation at 14 and 31 m, respectively. The 3-D conductivity slice image revealed different groundwater salinity levels for oil palm in Carey Island. The factors that determine the tolerance of oil palm for groundwater salinity are different surface characteristics between the west and east area as well as groundwater salinity distribution finding.

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. Based on the Ghyben-Herzberg assumption and local scenario sea-level rise prediction, the east area will become unsuitable for oil palm plantation much sooner than the west area, which still has a mangrove forest.

A classification of TDS values for groundwater salinity suitability to oil palms was derived from the correlation of groundwater system in an unconfined area at Carey Island. Groundwater salinity suitability to oil palms classification that uses TDS value showed that TDS < 5,300 mg/L is suitable, 5,300 mg/L <TDS< 12,000 mg/L is moderately suitable, and TDS>12,000 mg/L is unsuitable. The TDS value > 12,000 mg/L showed the unsuitable condition for oil palm as this condition can kill the plant.

For the unsuitable condition, the TDS value is slightly higher than the groundwater salinity classification value of saline water (TDS > 10,000 mg/L). The suitable TDS value for oil palm (TDS < 5,300 mg/L) is half the value of the TDS for brackish water (1,000 mg/L to 10,000 mg/L) because oil palm has a higher tolerance for salinity. For the unconfined system, the conductivity slice images showed that the current condition is moderately suitable for oil palm plantation. This classification can be used in the future to assess groundwater quality for oil palm suitability based on TDS value.

The integrated technique successfully determined the impact of seawater intrusion on groundwater aquifer. The technique was also applied to assess the impact of groundwater salinity distribution toward agricultural activities of different surface and subsurface characteristics. Furthermore, the integrated technique identified the existence of freshwater lens occurrence in the study area. It also successfully identified seawater intrusion as the source of groundwater salinity as well as established a classification of TDS values for groundwater salinity suitability to oil palms in an unconfined aquifer in Carey Island. The identification of surface characteristics and subsurface hydrogeology further enhanced the ability of the integrated technique to determine the groundwater salinity of the study area. The integrated technique applied in this study can be used to determine the impact of groundwater salinity on other socioeconomic activities of coastal areas.

7.2 Recommendations for future work

This study investigated a new issue and a serious problem that will become of considerable concern for many countries with coastal areas. It presents a first step in preparing for the current status of groundwater resources and agriculture vulnerability before seawater intrusion worsens as a result of sea level rise. In view of this situation, the following possible future research directions are propose as a continuation of this work:

a) The current results can be extended to 3-D groundwater numerical modelling simulations for prediction of seawater intrusion due to surface characteristics and future sea level rise.
b) To study seawater intrusion in semi-confined aquifer area, future studies can focus on clayey soil material.
c) The research correlation can be extended to subsurface resistivity and pore water in clayey soil material (semi-confined aquifer).
d) More work needs to be carried out on the site, such as an experimental study of saltwater intrusion coastal aquifers and comparison with numerical results.
e) The current and suggested methods can be applied in studies on seawater intrusion in other areas.
f) More tests need to be carried out on the geochemistry aspects and related with TLERT measurements.
g) Geochemistry analysis can be extended to include the usage of Piper and Stiff's diagram to evaluate groundwater composition and chemistry changes in more detail.