UNIVERSITI PUTRA MALAYSIA

HYDROGEOCHEMISTRY OF THE LOWER KELANTAN BASIN, MALAYSIA

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FPAS 2018 13

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the degree of Master of Science

May 2018

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

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Chairman: Ahmad Zaharin Aris, PhD
Faculty: Environmental Studies

Groundwater plays a crucial role in supporting the physical and economic development of any region, especially in areas that are experiencing shortage of surface water resources. Due to industrialization, population growth and intensive agriculture, the dependence on groundwater resources has increased dramatically from time to time resulting in quantity and quality deterioration, consequently, affecting human health and plant growth. A comprehensive hydrogeochemical study is essential in understanding the evolution of groundwater in a multi-layered aquifer system. The aims of this study were to construct a conceptual model, identify the factors controlling the chemistry of the groundwater, assess the hydrogeochemical facies of the groundwater, and evaluate the suitability of the groundwater for drinking and agricultural purposes. 101 groundwater samples were collected and analyzed for physico-chemical parameters such as the pH, the electrical conductivity (EC), the total dissolved solid (TDS), Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, NO_3^-, Fe^{2+} and Mn^{2+}. Based on lithological data correlation of exploration wells, three aquifer layers were delineated; a shallow, an intermediate and a deep. PCA demonstrated that Factor 1 (VF1) for the shallow aquifer represents 41.23% of the total variance. The variables Na^+, Cl^-, the TDS, the EC, Mg^{2+}, and SO_4^{2-} showed strong positive factor loadings and indicate the influence of remnant saltwater in the aquifer system. Factor 2 (VF2) which accounts for 13.23% of the total variance exhibited a strong positive loading for HCO_3^- and suggests an origin from the weathering of carbonate. Factor 3 (VF3) was associated with 9.33% of the total variance and had strong positive loadings for Fe^{2+} and Mn^{2+}, while NO_3^- showed a strong positive loading in Factor 4 (VF4) representing 7.23% of the variance. The Fe^{2+} and Mn^{2+} in Factor 3 (VF3) are attributed to weathering of iron and manganese bearing minerals, whereas NO_3^- is assigned to anthropogenic sources like sewage and fertilizer usage. The four principal components (VF1, VF2, VF3 and VF4) account for 71.11% of the total variance for the shallow aquifer. FA for the intermediate aquifer resulted in three significant factors accounting for 75.92% of the total variance. Factor 1 (VF1) demonstrated strong positive loadings for the TDS, the EC, Cl^-, Na^+, Mg^{2+}, K^+ and Ca^{2+} representing 53.73% of total variance, and attributed dissolution of minerals from seawater remnant. Factor 2 (VF2) which explained 14.55 % of the variance showed a strong positive loading for pH and a strong negative loading for Fe^{2+}. This indicated the pH was affected due to enhanced dissolution and Fe^{2+} was assigned to weathering of iron bearing minerals. The variable of SO_4^{2-} showed a strong negative loading in Factor 3 (VF3) that explained 7.64% of the total variance, and it is attributed to oxidation and dissolution of sulfate-rich marine deposits. For the deep aquifer, Factor 1 (VF1) showed strong positive loadings for Cl^-, the EC, the TDS, Na^+, Fe^{2+}, K^+, Mg^{2+} and Ca^{2+}, and a strong negative loading for pH, accounting for 55.08% of the total variance. Factor 2 (VF2) accounted for 12.13% of the total variance, with strong positive loadings for carbonate that are explained by calcium carbonate weathering processes. Factor 3 (VF3) showed strong positive loadings for pH, Na^+, K^+ and Fe^{2+} and represented 8.39% of the total variance. This was attributed to the dissolution and weathering of rock forming minerals. Factor 4 (VF4) representing 7.38% of the total variance showed a strong negative loadings for SO_4^{2-} reflecting oxidation and dissolution of sulfate-rich marine deposits. The abundance of the major cations followed the order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, while that of anions was $HCO_3^- > Cl^- > SO_4^{2-} > CO_3^{2-}$. The prominent groundwater facies in the shallow aquifer are Ca-HCO_3 and Na-HCO_3 and indicate the presence of fresh water and mix-water types. The Na-HCO_3 and Na-Cl are the main water types in the intermediate aquifer and exhibit the presence of mix-water and saltwater types. The Na-HCO_3 is the dominant water type in the deep aquifer and is probably due to the consumption of H^+ in the chemical weathering of feldspars to clay minerals. The Gibbs diagram stipulates that the groundwater in the aquifers are mostly affected by rock dominance, regardless of aquifer depth. Based on US Salinity Laboratory (USSL) diagram, the shallow groundwater samples fall in the C1-C3 and S1, and is suitable for irrigation of most crops. Samples from the intermediate aquifer plot in the C1-C4 and S1-S4 and are not suitable for irrigation of crops. The samples from deep aquifer fall in the C1-C3 and S1 and some samples are unsuitable for irrigation of crops. Some groundwater samples taken from the intermediate and the deep aquifers that fall into S4 zone are categorized as very high salinity hazard samples. The groundwater samples obtained from areas located more than 8 km from coast for all aquifers are suitable for crop irrigation. A high SAR value in the groundwater leads to the formation of an alkaline soil which reduces soil permeability due to hardening and compaction when dry. The physical structure of the soil crumbles and renders it unsuitable for plant growth. The study reveals that the groundwater quality from the shallow and the deep aquifers are better for domestic and agricultural purposes relative to groundwater from the intermediate aquifer for aquifer located less than 8 km from coast. These results provide a baseline data and offers insights on the status of groundwater quality in the Lower Kelantan Basin. The study also determined the factors controlling the quality of groundwater in each aquifer. Groundwater quality in the Lower Kelantan Basin is governed by anthropogenic activities and natural factors.

Keywords: Lower Kelantan Basin, conceptual model, multivariate statistical analyses, hydrogeochemical facies, saturation index, groundwater quality assessment

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

HIDROGEOKIMIA DI KAWASAN LEMBANGAN KELANTAN HILIR, MALAYSIA

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Mei 2018

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Air tanah memainkan peranan penting dalam menyokong pembangunan fizikal dan ekonomi di sesuatu kawasan terutamanya di kawasan yang mengalami kekurangan sumber air permukaan. Akibat daripada aktiviti perindustrian, pertumbuhan penduduk dan pertanian secara intensif, kebergantungan kepada sumber air tanah telah meningkat secara mendadak dari semasa ke semasa yang menyebabkan kemerosotan kuantiti dan kualiti yang seterusnya akan menjejaskan kesihatan manusia dan tumbesaran tanaman. Kajian hidrogeokimia secara menyeluruh adalah penting dalam memahami evolusi air tanah dalam sistem akuifer pelbagai lapisan. Tujuan kajian ini adalah untuk membina model konseptual, mengenalpasti faktor yang mengawal geokimia air tanah, menilai hidrogeokimia air tanah dan kesesuaiannya untuk kegunaan minuman dan pertanian. Sebanyak 101 sampel air tanah telah diambil dan dianalisis bagi parameter fiziko-kimia seperti pH, kekonduksian elektrik (EC), jumlah pepejal terlarut (TDS), Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, NO_3^-, Fe^{2+} dan Mn^{2+}. Berdasarkan korelasi data litologi telaga eksplorasi, sebanyak tiga lapisan akuifer utama dikenalpasti; akuifer cetek, pertengahan dan dalam. Analisis komponen prinsip (PCA) menunjukkan Faktor 1 (VF1) bagi akuifer cetek mewakili 41.23% daripada jumlah varian. Pembolehubah Na^+, Cl^-, TDS, EC, Mg^{2+} dan SO_4^{2-} mempunyai beban positif tinggi yang menunjukkan pengaruh tinggalan air masin dalam sistem akuifer. Faktor 2 (VF2), menyumbang 13.23% daripada jumlah varian dan mempunyai beban positif yang tinggi bagi HCO_3^- di mana ia terhasil daripada proses perlarutan karbonat. Faktor 3 (VF3) mewakili 9.33% daripada jumlah varian yang mempunyai beban positif bagi Fe^{2+} dan Mn^{2+}, manakala NO_3^- mempunyai beban positif yang tinggi bagi Faktor 4 (VF4) iaitu mewakili 7.23% varian. Fe^{2+} dan Mn^{2+} bagi Faktor 3 (VF3) adalah disebabkan oleh luluhawa mineral besi dan mangan manakala NO_3^- berpunca daripada aktiviti manusia seperti sisa kumbahan dan penggunaan baja. Empat komponen prinsip (VF1, VF2, VF3 dan VF4) mencakupi 71.11% daripada jumlah varian bagi akuifer cetek. FA bagi akuifer pertengahan menjana tiga faktor penting yang menyumbang 75.92% daripada jumlah varian. Faktor 1 (VF1) mempunyai beban positif yang tinggi bagi TDS, EC, Cl^-, Na^+, Mg^{2+},

K^+ dan Ca^{2+} mewakili 53.73% daripada jumlah varian yang disebabkan oleh perlarutan mineral kesan tinggalan air laut kuno. Faktor 2 (VF2) mewakili 14.55% daripada jumlah varian dan mempunyai beban positif yang tinggi bagi pH dan berkadar songsang dengan Fe^{2+}. Ini menunjukkan penurunan nilai pH akan meningkatkan perlarutan Fe^{2+} hasil proses luluhawa mineral besi. Pembolehubah SO_4^{2-} menunjukkan beban negatif yang tinggi bagi Faktor 3 (VF3) yang mewakili 7.64% daripada jumlah varian dan ia dikaitkan dengan proses pengoksidaan dan perlarutan enapan marin yang kaya sulfat. Bagi akuifer dalam, Faktor 1 (VF1) menunjukkan beban positif yang tinggi bagi Cl^-, EC, TDS, Na^+, Fe^{2+}, K^+, Mg^{2+} dan Ca^{2+}, dan beban negatif tinggi bagi pH dengan menyumbang 55.08%. Faktor 2 (VF2) menyumbang 12.13% daripada jumlah varian dengan bebanan positif yang tinggi bagi karbonat yang menjelaskan proses luluhawa kalsium karbonat. Faktor 3 (VF3) menunjukkan beban positif tinggi bagi pH, Na^+, K^+ dan Fe^{2+} yang mewakili 8.39% daripada jumlah varian. Ini mungkin disebabkan oleh perlarutan dan luluhawa mineral batuan. Faktor 4 (VF4) yang mewakili 7.38% daripada jumlah varian menunjukkan beban negatif tinggi bagi SO_4^{2-} yang juga menggambarkan proses pengoksidaan dan perlarutan enapan marin kaya sulfat. Kelimpahan kation utama mengikut susunan ialah $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, sementara anion adalah $HCO_3^- > Cl^- > SO_4^{2-} > CO_3^{2-}$. Fasies air tanah yang utama bagi akuifer cetek adalah Ca-HCO_3 dan Na-HCO_3 yang menunjukkan kehadiran air tawar dan campuran air tawar-masin. Na-HCO_3 dan Na-Cl adalah jenis air utama dalam akuifer pertengahan yang menunjukkan percampuran air tawar-masin. Na-HCO_3 adalah jenis air yang dominan bagi akuifer dalam yang mungkin disebabkan oleh penggunaan H^+ dalam luluhawa kimia feldspar kepada mineral lempung. Gambarajah Gibbs menunjukkan air tanah dipengaruhi oleh dominasi batuan tanpa mengira kedalaman akuifer. Berdasarkan kepada gambarajah US Salinity Laboratory (USSL) pula, semua sampel air tanah bagi akuifer cetek berada dalam zon C1-C3 dan S1 yang sesuai digunakan bagi kebanyakan jenis tanaman untuk tujuan pengairan. Sampel bagi akuifer pertengahan pula, sebahagian besar sampel berada dalam zon C1-C4 dan S1-S4 di mana ia tidak sesuai untuk pengairan tanaman. Manakala sebahagian sampel air tanah daripada akuifer dalam berada dalam zon C1-C3 dan S1 tidak sesuai untuk pengairan tanaman. Beberapa sampel air tanah yang diperolehi dari akuifer pertengahan dan dalam berada dalam zon S4 dan dikategorikan sebagai bahaya kemasinan yang sangat tinggi. Semua sampel air tanah yang diambil dari semua akuifer dan berada di kawasan lebih 8 km dari garis pantai adalah sesuai untuk pengairan tanaman. Nilai nisbah serapan sodium (SAR) yang tinggi di dalam air tanah akan memberi kesan kepada pembentukan tanah beralkali yang mengurangkan kebolehtelapan tanah kerana pengerasan dan pemadatan apabila kering. Struktur fizikal tanah akan rosak menjadikannya tidak sesuai untuk pertumbuhan tanaman. Kajian ini menunjukkan kualiti air tanah dari akuifer cetek dan dalam adalah sesuai untuk tujuan domestik dan pertanian berbanding dengan akuifer pertengahan terutama yang terletak kurang 8 km dari garis pantai. Hasil kajian ini menyediakan data asas dan memberi gambaran yang lebih jelas mengenai status semasa kualiti air tanah di Lembangan Kelantan Hilir. Ia juga dapat menentukan faktor utama yang mengawal kualiti air bagi setiap akuifer. Ini dapat disimpulkan bahawa kualiti air tanah di Lembangan Kelantan Hilir dikawal oleh aktiviti antropogenik dan juga faktor semula jadi.

Kata kunci: Lembangan Kelantan Hilir, model konseptual, analisis statistik multivariat, fasies hidrogeokimia, indeks ketepuan, penilaian kualiti air tanah

ACKNOWLEDGEMENTS

In the name of Allah, the most beneficent, the most eternally merciful. Alhamdulillah, I am grateful and thankful to the Almighty Allah S.W.T for giving me strength, courage, patience and determination in preparing and completing this research successfully. I would like to express my deepest gratitude to my supervisor, Prof. Dr. Ahmad Zaharin Aris for his patience, continuous supervision, assistance, motivation, invaluable advices, guidance and suggestions. I would also like to thank the other my committee members, Associate Prof. Dr. Mohammad Firuz Ramli and Dr. Saim Suratman for giving valuable suggestions and continuous encouragement during the preparation of this thesis. I would like to express my honest thanks to Dr. Tahoora Sheikhy Narany and Dr. Hafizan Juahir for their valuable guide, advices and helps.

In addition, I wish to thank all the government agencies especially Tuan Haji Mohamad Yusof bin Che Sulaiman from Minerals and Geosciences Department (MGD) of Kelantan, Air Kelantan Sdn Bhd (AKSB), Chemistry Department of Malaysia, Ministry of Agriculture (MOA), Malaysia Meteorological Department (MMD), Drainage and Irrigation Department (DID) and Department of Environment (DOE) that have been assisting me in groundwater sampling and analyses activities. They also provided secondary groundwater quality, land use, hydrological and environmental data as well as groundwater analyses throughout the study. I would also like to acknowledge the Ministry of Natural Resources and Environment (NRE) for financing this research. My deepest appreciation to the Public Services Commission of Malaysia for the financial support.

I would like to thank all the research officers and assistants from National Hydraulic Research Institute of Malaysia (NAHRIM) for their continuous support, reminders, encouragement, advice, ideas, assistances and for lending their hands especially Mr. Ismail Tawnie, Mr. Mohd Khairul Nizar Shamsuddin, Mr. Azrul Normi Idris, Mr. Syaiful Bahren Saadudin, Mr. Arshad Osman, Mr. Mohammad Huzaifah Wahap and Mr. Mohd Ali Sarudin who have helped and accompanied in groundwater sampling and *in-situ* analyses.

Last but not least, I wish to thank Mr. Ridzuan Isa and all my friends at the Faculty of Environmental Studies, particularly Ms. Wee Sze Yee, Tuan Mohd Fauzan, Dr. Noorain, Dr. Shahcristiani, Ms. Farhana, Ms. Hanisah, Ms. Afifah, Ms. Nasyitah, Dr. Looi Ley Juen and Ms. Lim Ai Phing. My appreciation is extended to my beloved parents, Haji Sefie Ibrahim and Hajjah Halimah Awang for their constant support, encouragement and prayers. Lastly, the warmest thank to my dearest wife, Mrs Haslinda Hasanuddin for her sincere support, advice and inspiration. There are no words that I can give, other than how thankful I am for all the assistance in making this research a reality. I believe only Allah can repay the kindness that each one have given me in order for my dreams to come true. Honestly, these experiences have been nothing but the best in my life. Thank you to all that have directly or indirectly contributed to the completion of this research.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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a.s.l.	Above sea level
AKSB	Air Kelantan Sdn Bhd
ANOVA	Analysis of Variance
BGR	Bundesanstalt Für Geowissenschaften Und Rohstoffe
DA	Discriminant Analysis
DEM	Digital Elevation Data
DID	Department of Irrigation and Drainage of Malaysia
EIA	Environmental Impact Assessment
GDP	Gross Domestic Product
GIS	Geographic Information System
GSD	Geological Survey Department
HCW	Horizontal Collector Well
IADA	Integrated Agricultural Development Area
KADA	Kemubu Agricultural Development Authority
Kbg	Kubang
Kg	Kampung
Km	Kilometers
KR	Kelly's Ratio
LOD	Limit of Detection
m	Meter
MAR	Magnesium Adsorption Ratio
MGD	Minerals and Geoscience Department
MLD	Million Litres per Day
MLR	Multiple Linear Regression
MMD	Malaysia Meteorological Department
MOH	Ministry of Health Malaysia
NAHRIM	National Hydraulic Research Institute of Malaysia
NEPU	National Economic Planning Unit
NWRS	National Water Resources Study
PCA	Principal Component Analysis
PI	Permeability Index
PWD	Public Works Deparment
RSC	Residual Sodium Carbonate
SAR	Sodium Adsorption Ratio
SI	Saturation Index
Tg	Tanjung
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
USSL	United States Salinity Laboratory
VF	Varimax Factors
WHO	World Health Organisation

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Groundwater is a vital source of fresh water in many countries such as India, China, USA, Pakistan, Iran, Bangladesh, Mexico and Saudi Arabia (Van der Gun, 2012). Nearly one-third of the global population relies on it to meet domestic, industrial and agricultural demands (UNEP, 2013). Over the past few decades, the great competition for economic expansion resulted in rapid population growth, urbanization, industrialization and intensive agricultural activities. These changes orchestrated significant demands on land use and food production, increasing the demand for groundwater as a freshwater resource (Singh et al., 2015). Such demand inevitably leads to the exploitation of invaluable resources in ways that deteriorate water quality.

The quality of groundwater is controlled by reactions associated with natural processes and anthropogenic influences (Zuane, 1990). The negative effects of poor water quality on human health and the environment have increasingly been prominent in the eyes of the public. The preservation of groundwater quality is important because around 80% of water-borne diseases in developing countries are related to poor water quality (Olajire and Imeokparia, 2001). An understanding of groundwater chemistry, the hydrogeological evolution and the factors controlling the groundwater quality is crucial to determine its suitability for domestic, industrial and agricultural uses (Mokhtar et al., 2009; Department of Water, 2010; Alaya et al., 2014; Fijani et al., 2017).

The state of Kelantan ranks first in the consumption of groundwater in Malaysia (Manap et al., 2013). The total groundwater abstraction for public water supply in 2012 was 160.08 million liters per day (MLD), amounting to approximately 41% of the total abstraction for public water supply in Kelantan (AKSB, 2012). About 80% of the inhabitants in the region depend on groundwater, from either dug or tube wells. The Lower Kelantan Basin is a densely populated region, with high development activities due to its fertile soils, a low relief, a shallow water table and the widespread occurrence of aquifers with sufficient and accessible water. Groundwater quality is generally better than that of surface water, making it suitable to meet the increasing global water demand (Lan et al., 2015). It also requires minimal treatment, the development for water supply is low and it is scarcely affected by prolonged drought associated with climate change.

1.2 Problem Statement

Population growth, urban expansion and agricultural activities stress the water resources and pose threats to groundwater quality. In recent decades, the competition for water increased significantly due to the needs of the rising population. Since water supply is vital in any region, an understanding of groundwater resources is essential for the planning of future developments (Kudoda and Abdalla, 2015).

It is estimated that one billion people rely on groundwater for daily needs in Asia (Sivasankar and Gomathi, 2009). In Malaysia, groundwater utilization is expected to increase by 63% between 2000 and 2050 (Manap et al., 2013). The average public water supply coverage in Malaysia for 2014 was 94.7%, with 96.9% and 90.7% reported for urban and rural areas, respectively. The public water supply coverage by state is Johor (99.8%), Kedah (98.2%), Labuan (100%), Malacca (100%), Negeri Sembilan (99.9%), Penang (99.9%), Pahang (98.0%), Perak (99.6%), Perlis (99.5%), Sabah (82.0%), Sarawak (93.5%), Selangor (99.8%) and Terengganu (96.0%). However, 59.9% of the population in Kelantan depends on treated water from the public water supply (ASM, 2015).

The dependence of the inhabitants on groundwater is significant due to the unsatisfactory quality of the public water supply. Low water pressure, poor water quality such as odor, and frequent disruption of supply are some of the problems. These problems are attributed to the lack of funds to upgrade the water supply infrastructure and augment the water supply coverage (Association of Water and Energy Research of Malaysia, 2011).

Most inhabitants in the Lower Kelantan Basin obtain water from an unconfined shallow aquifer with a depth of less than 6 m, because it is cost effective and provides adequate supply throughout the year. Several studies indicate that the intermediate aquifer with depths of 20-40 m is brackish to saline and not suitable for drinking and agriculture (Abdul Rashid, 1989; Ang and Ismail, 1995; Azmi, 2004).

Since more than 95% of groundwater wellfields are in the study area, large-scale abstraction to meet high demand can cause lowering of the regional water level and induce deeper and spread-out cones of depression. Lowering of regional water level poses a further threat to the groundwater quality because it favors seawater intrusion (Aris et al., 2010). The understanding of a groundwater system is complicated by aquifer heterogeneity, groundwater flow and chemical evolution (Han et al., 2009).

Groundwater quality is a preoccupation (WHO, 2011; Vasanthavigar et al., 2012a; Bouderbala, 2015; Nag and Das, 2017) because poor water quality severely affects human health and crop growth. Accurate groundwater quality data is indispensable since the study area is exposed to contamination from the surface activities like sewerage, waste disposal, agricultural and industrial. Previous studies in the area

(Sofner, 1989; Suratman, 1997) were localized and restricted to parts of the urban and the wellfield areas, and focused on elevated concentrations of iron (Fe^{2+}), electrical conductivity (EC), chloride (Cl^-), manganese (Mn^{2+}) and nitrate (NO_3^-).

The Lower Kelantan Basin is located downstream of the Kelantan River and the river was considered as sufficient for freshwater because it is part of the largest river basin originating upstream of the mountainous region of the Titiwangsa Range. The encroachment of seawater into the Kelantan River which is observed up to 13 km from the estuary, subsequently restricted the utilization of the surface water resource (Chong, 1974).

The Department of Irrigation (DID, 2000) estimated that the total groundwater discharge from shallow and deep aquifers was approximately 488 MLD with allowable abstraction of 148 MLD. Since the total groundwater abstraction in 2012 of over 160 MLD (AKSB, 2012) exceeded the recharge capacity, monitoring on groundwater pumping activities is needed to prevent saltwater intrusion into freshwater aquifers. The study area is vulnerable to saltwater intrusion because it is a flat and low-lying coastal plain with limited drainage infrastructure (Tran et al., 2012). Despite the existence of several studies on groundwater in the Lower Kelantan Basin, few exist on aquifer continuity, the extent of remnant saline water hydrogeochemistry, factors controlling the groundwater quality, and groundwater suitability.

1.3 Objectives of the Study

The objectives of this study were:

i. To construct a conceptual model of the groundwater aquifer system.
ii. To identify the factors contributing to the variations in groundwater chemistry.
iii. To assess the hydrogeochemical characteristics in different aquifers (shallow, intermediate and deep aquifers).
iv. To evaluate the groundwater suitability and potential usage of different aquifers for drinking and agricultural purposes.

1.4 Scope of the Study

This study covers the following:

i. Generating data (primary data) from groundwater sampling of existing tube wells.
ii. Five new tube wells were constructed to obtain soils for description, creation of geological cross sections, and construction of a conceptual hydrogeological model. The constructed tube wells were also used for *in-situ* measurements as well as groundwater sampling.

iii. Groundwater sampling was conducted primarily to evaluate the physico-chemical parameters of the water that were not covered in earlier studies and to complement secondary data.
iv. This study involved acquiring and reviewing available secondary data including groundwater quality, geophysical, lithologic, land use, digital elevation model (DEM), rainfall and hydrology data.
v. The study integrated the primary and secondary data, performed further treatment and analyses using a multivariate statistical approach to examine the relationship between the variables and the factors controlling the quality of groundwater in each aquifer.

1.5 Significance of the Study

Water supply coverage represents the proportion of residents with access to a safe drinking water supply. The water operator capability should be extended to service all residents. For instance, the water supply coverage in Kelantan was 59.9% in 2014, whereas other states had already attained more than 90% coverage (ASM, 2015). This distinct difference was due to either the enhanced availability of groundwater or the direct abstraction of water from rivers, which made a portion of the population less dependent on public water supply services. However, an insufficient water supply, low water pressure, frequent water disruptions, and poor water quality could also contribute to low water supply coverage.

Since groundwater is important for drinking, industrial and agricultural purposes, the assessment of its suitability for different purposes is vital. This study will help in characterizing the groundwater quality and evolution of the aquifer systems, as well as develop conceptual hydrogeological models. The findings will establish a water quality baseline data and elucidate the suitability for drinking and agricultural purposes of different aquifers.

This study will also assess the factors controlling the groundwater quality in different aquifers. It will enable the delineation of the extent of saltwater remnants and groundwater contamination sources (anthropogenic and natural). Furthermore, this study will facilitate the estimating of the scale or corrosive potential of groundwater sources. This study aims to estimate a suitable drilling depth to aid assessments of groundwater potential for the quantitative valuation of water resources, therefore reducing the financial burden of soil investigations.

This study can also easily evaluate the spatial distribution of groundwater of various qualities in different aquifers for domestic, industrial, and agricultural use in the study area. This information helps stakeholders to take appropriate actions because of the problems corrosive water causes when it reacts with pipes and plumbing fixtures.

1.6 Research Framework of the Study

The research framework developed for the hydrogeochemistry study of the Lower Kelantan Basin is depicted in Figure 1.1.

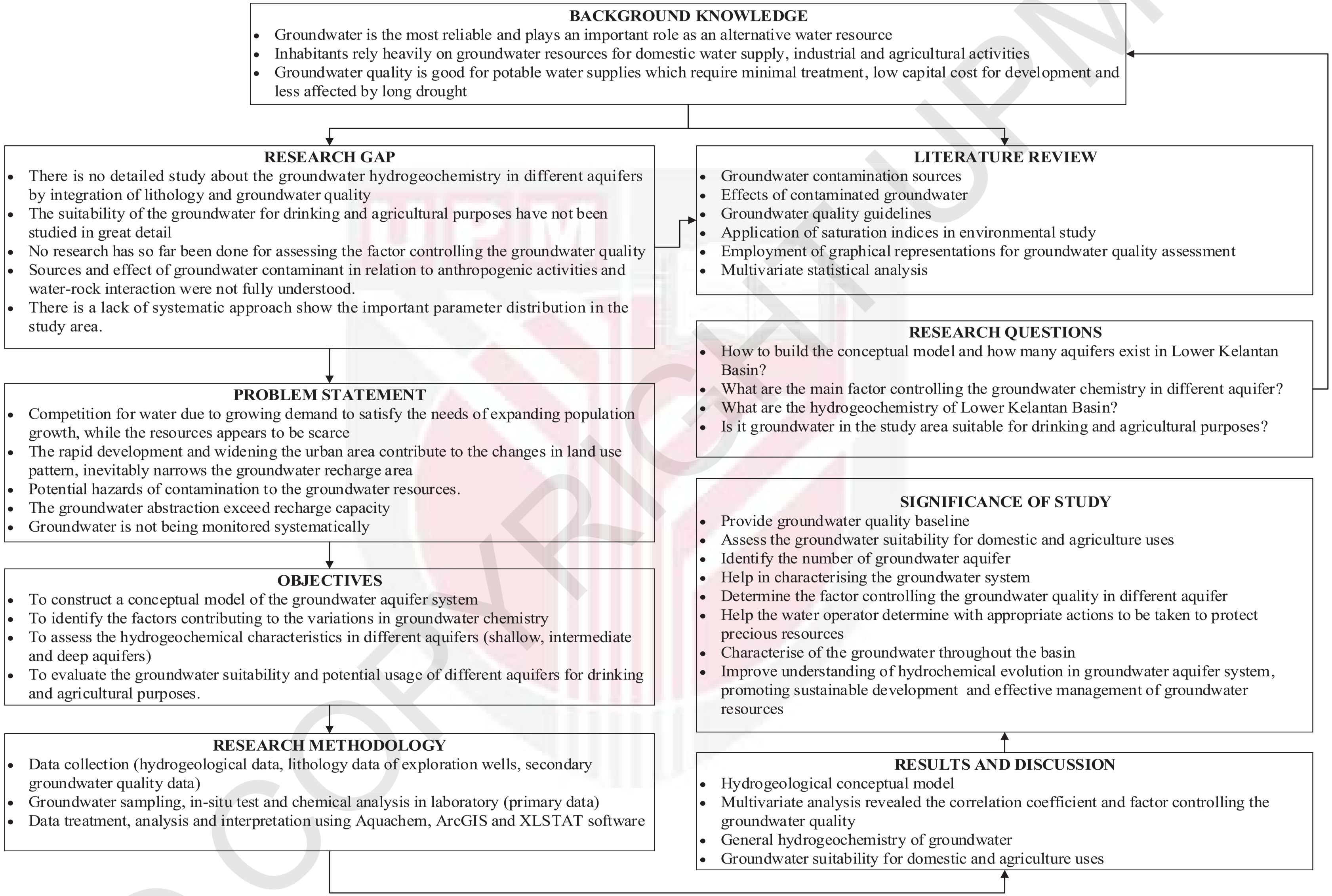

Figure 1.1: Research framework for the hydrogeochemistry study of the Lower Kelantan Basin.

1.7 Thesis Outline

The body of this thesis consists of five chapters with information on the hydrogeochemistry, the suitability of the groundwater for drinking and agricultural purposes, and the factors affecting the quality of the groundwater. The chapters, from the introduction to the conclusion are as follows:

i. Chapter 1 is an introduction with a study background, objectives, a problem statement and significance of the study.
ii. Chapter 2 provides a comprehensive review of literature related to pollution of groundwater, the sources and effects on human health and plant growth based on comparisons with standards or guidelines, and the application of graphical representations and multivariate statistical analysis on the groundwater quality data.
iii. Chapter 3 comprises the materials and methods including groundwater sampling, *in-situ* and laboratory analysis, and data interpretation.
iv. Chapter 4 elaborates on the factors controlling variations in groundwater quality using multivariate statistical analysis, hydrogeochemistry, groundwater evaluation and its suitability for drinking and agricultural uses.
v. Chapter 5 summarizes and concludes on the findings and recommendations made on appropriate measures for managing groundwater resources in a sustainable manner.

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