CHARACTERISATION AND EVALUATION OF ROCK AQUIFER IN JURONG FORMATION

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DEDICATION

This thesis is dedicated to Almighty God, my parents, family and friends who believed in me to complete this PHD. Also, to all teachers who have helped me since my school time. Thank you to you all:

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ABSTRACT

Geologically complex of Jurong Formation underlies part of Southern Johor Bahru which comprises of well cemented and consolidated volcanic-sedimentary rocks. Unlike alluvial aquifers, groundwater extraction from hard rocks is challenging due to their complex and highly heterogeneous nature. This study aims to characterise and evaluate rock aquifer in Jurong Formation. Methodology adopted in this study includes review of previous boreholes data and analysis of geomorphology and lineaments. During field work, 5 outcrops located near studied area were mapped. The geological profile of study area changes from fresh pyroclastic volcanic rocks to semi-consolidated older alluvium in west-east direction. Sandstone (sedimentary roof pendant) are overlain by members of Jurong Formation (Bukit Resam Clastic Member overlying Gunung Pulai Volcanic Member) at study area. The average strike/dip angle of beddings is $067^o/42^o$. Twelve resistivity and five seismic lines were also surveyed for subsurface evaluation. Resistivity value of <1000 Ohm.m is suggested to be fractured zone. Whereas, depth of bedrock with seismic velocity of >3200 m/s ranges from 20 m to 30 m and deeper (40 m) towards southern region. Upon understanding the subsurface geology, 3 exploratory wells, namely W1-W3 were drilled. A downhole camera survey was carried out to investigate the characteristics of the fracture system. Fracture density in W2 (175/150 m) is higher than W1 (79/165 m). Gently dipped ($<20^o$), single set of joints with tight to open aperture (<0.1 – 4 cm) are dominant in both wells. Major orientation of discontinuities is north-east (0^o-90^o) to south-west (180^o-270^o) which is subparallel to bedding plane and lineament orientations. The pumping test indicated that W1 and W2 act as double porosity and unconfined aquifer with yields of 37.85 m^3/hr and 60 m^3/hr respectively. The groundwater in the study area is fresh and non-saline with hardness of soft to hard. The groundwater transitioned from CaCl (W4) to $CaNaHCO_3$ (W1) as well as from $CaHCO_3$ (W2) to CaNa (W3). Based on the hydrogeological characterization, it is found that the fractures with major opening (>4 cm) and litho-contact found in fresh zone domain at 69-165 m depth dominantly control the groundwater occurrence and productivity at the study area. In addition, the nature of fractures such as density and aperture influence the groundwater productivity. Meanwhile, the primary porosity of rocks is found not to control groundwater productivity except at completely weathered to residual soil zones. Yet, the productivity at weathered layer is insignificant in the study area. The fractured zones at depth <102 m are less productive with airlift yield of <11 m^3/hr, characterised by fracture with major opening (>4 cm) less than 2 nos/5 m with transmissivity and hydraulic conductivity of 1.65-2.55 m^2/d and 0.01-0.02 m/d respectively. At depth of 110-125 m, joints are characterised by fracture with major opening (>4 cm) less than 4 nos/5 m with airlift yield, transmissivity and hydraulic conductivity of 15 m^3/hr, 3-3.3 m^2/d and 0.02 m/d respectively. Meanwhile, the most productive fractured zones located at depth of 142-165 m are characterised by 2-4 sets of joints with major opening aperture (>4 cm), gentle dip angle (20^o) and density of 3-12 nos/ 5 m along with multiple open fractures (>0.1 cm). Significant increase in airlift yield up to 55 m^3/hr indicates capacitive function of the zones with hydraulic conductivity and transmissivity of 0.01-0.12 m/d and 3-17.1 m^2/d respectively. Based on the results, a conceptual model on fractured system is proposed for fresh zone domain which controls the rock aquifer productivity.

ABSTRAK

Formasi Jurong yang kompleks secara geologi yang mendasari sebahagian Johor Bahru Selatan terdiri daripada batuan gunung berapi dan sedimen. Tidak seperti akuifer, pengekstrakan air bawah tanah dari batuan keras adalah mencabar kerana kompleks dan sangat heterogen. Kajian ini bertujuan untuk mencirikan dan menilai akuifer batuan dalam Formasi Jurong. Kaedah kajian ini termasuk tinjauan data lubang gerek dan analisis geomorfologi dan lineamen. Semasa kerja lapangan, 5 singkapan berhampiran kawasan kajian dipetakan. Profil geologi kawasan kajian berubah daripada batu segar gunung berapi piroklas kepada aluvium tua pada arah barat-timur. Batu pasir (pending bumbung sedimen) dilapisi oleh anggota Formasi Jurong (Kumpulan Klastik Bukit Resam mengatasi Anggota Gunung Berapi Gunung Pulai) di sini. Jurus/sudut miring lapisan batuan adalah 067^{o}/42^{o}. 12 garisan keberintangan dan 5 garisan juga seismik dikaji untuk penilaian bawah permukaan. Keberintangan <1000 Ohm.m dicadangkan sebagai zon batuan retak. Kedalaman batuan dasar dengan nilai seismik >3200 m/s adalah antara 20 m hingga 30 m dan lebih dalam (40 m) ke arah bahagian selatan. Setelah memahami geologi bawah permukaan, 3 telaga eksplorasi, iaitu W1-W3 digerudi. Tinjauan kamera dalam lubang gerek dilakukan untuk menyiasat ciri sistem retakan. Didapati bahawa kepadatan retakan pada W2 (175/150 m) lebih banyak daripada W1 (79/165 m). Satu set kekar dengan sudut miring (<20^{o}) dan apertur terbuka (<0.1-4 cm) adalah dominan dalam kedua-dua telaga. Haluan utama rekaan adalah utara-timur (0^{o}-90^{o}) ke selatan-barat (180^{o}-270^{o}) selari dengan haluan satah lapisan dan lineamen. Sampel batuan telah diuji untuk keporosan dan petrografi. Di samping itu, ujian pengepaman dilakukan untuk menentukan ciri hidraulik. Berdasarkan ujian ini, W1 dan W2 didapati bertindak sebagai keporosan berganda dan akuifer tidak terkurung dengan menghasilkan 37.85 m^3/jam dan 60 m^3/jam. Air bawah tanah di kawasan kajian adalah segar dan tidak masin dengan kekerasan lembut hingga keras. Air bawah tanah beralir dari CaCl (W4) ke $CaNaHCO_3$ (W1) dan juga dari $CaHCO_3$ (W2) ke CaNa (W3). Berdasarkan pencirian hidrogeologi, retakan dengan bukaan utama (>4 cm) dan sentuhan lito di domain zon segar pada kedalaman 69-165 m didapati mengawal kejadian dan produktiviti air bawah tanah di kawasan ini. Tambahan pula, ciri retakan seperti ketumpatan dan bukaan mempengaruhi produktiviti air bawah tanah. Sementara itu, keporosan batuan didapati tidak mengawal produktiviti air bawah tanah kecuali pada lapisan terluluhawa. Namun, produktiviti ini tidak ketara. Zon retakan pada kedalaman <102 m adalah kurang produktif dengan hasil <11 m^3/jam, dicirikan sebagai retakan dengan bukaan utama (>4 cm) kurang dari 2 nos/5 m dengan kememancaran dan keberkonduksian hidraulik sebanyak 1.65-2.55 m^2/d dan 0.01-0.02 m/d. Pada kedalaman 110-125 m, kekar dicirikan sebagai retakan dengan bukaan utama (>4 cm) kurang dari 4 nos/5 m dan hasil, kememancaran dan keberkonduksian hidraulik sebanyak 15 m^3/jam, 3-3.3 m^2/d dan 0.02 m/d. Sementara itu, zon retakan yang paling produktif terletak pada kedalaman 142-165 m dicirikan sebagai 2-4 set kekar dengan bukaan utama (>4 cm), sudut miring 20^{o} dan ketumpatan 3-12 nos/5 m bersama dengan banyak retakan terbuka (>0.1 cm). Peningkatan hasil yang ketara sehingga 55 m^3/jam menunjukkan fungsi kapasiti zon dengan keberkonduksian hidraulik dan kememancaran sebanyak 0.01-0.12 m/d dan 3-17.1 m^2/d. Berdasarkan analisis, model berkonsepkan sistem retakan yang mengawal akuifer batuan pada zon segar dicadangkan.

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Na^+	-	Sodium ion (mg/L)
K^+	-	Potassium ion (mg/L)
Mg^{2+}	-	Magnesium ion (mg/L)
Ca^{2+}	-	Calcium ion (mg/L)
Cl^-	-	Chloride ion (mg/L)
SO_4^{2-}	-	Sulphate ion (mg/L)
HCO_3^-	-	Bicarbonate ion (mg/L)
CO_3^{2-}	-	Carbonic acid (mg/L)
R	-	Recharge (m^3/year)
P	-	Mean annual rainfall (mm/year)
EA	-	Actual evapotranspiration (mm/year)
W	-	Change in soil water storage (mm/year)
RO	-	Run-off (mm/year)
CA	-	Catchment area (m^2)
S_w	-	Drawdown IN WELL (m)
B	-	Linear well loss coefficient
C	-	Non-linear well loss coefficient
Q	-	Discharge rate (m^3/d or ft^3/s)
T	-	Transmissivity (m^2/d)
E_w	-	Efficiency of well (%)
R_p	-	Percentage of recovery (%)
RD_0	-	Residual drawdown at 0 minute
RD_{480}	-	Residual drawdown at 480 minutes
C_e	-	Effective discharge coefficient, 0.578 for 90 ^{o}
Ɵ	-	Angle of V-notch (^{o})
h_1	-	Head on the weir (ft)
k_h	-	Head correction factor, 0.003 for 90 ^{o} (ft)
T_i	-	Transmissivity of each fractured zone (m^2/d);
Q_i	-	Flowrate at each fractured zone (m^3/hr)
Q_t	-	Total flowrate/ airlift yield in a well (m^3/hr)

K_i	-	Hydraulic conductivity of each fractured zone (m/d)
b_i	-	Depth of each fractured zone (m)
K	-	Hydraulic conductivity of well from pumping test (m/d)
M_{sub}	-	saturated-submerged mass (g)
$M_{beaker+sample}$	-	Mass of beaker with sample (g)
M_{beaker}	-	Mass of beaker (g)
M_A	-	Mass of the container with lid (g)
M_B	-	Mass of the container with lid and sample (g)
M_C	-	Mass of container with lid and air-dried sample (g)
M_{sat}	-	Saturated-surface dry mass (g)
M_s	-	Grain weight (g)
V	-	Bulk volume (cm^3)
ρ_w	-	Density of water (1 g/cm^3)
V_v	-	Pore volume (cm^3)
n	-	Porosity (%)
PE	-	Polyethylene
IBE	-	Ionic balance error (%)
TH	-	Total hardness (mg/L)
ICP-OES	-	Inductively Coupled Plasma Optical Emission Spectroscopy
AAS	-	Atomic Absorption Spectrometry
S	-	Storativity
GIS	-	Geographical Information System
BH1	-	Borehole
W1	-	Well
R1	-	Resistivity survey line
S1	-	Seismic refraction survey line
hr	-	hour
m	-	meter
d	-	day
mm	-	millimeter
min	-	minute
km	-	kilometer

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The rate of clean water demand upsurges with increase in world population (Connor, 2015). Urbanization, irrigated agriculture and industrialization are some of the factors that contribute to the increase in water demand (Lee *et al*., 2012). Although the importance of groundwater as alternative or conjunctive water resource is being emphasized in various studies, the resource is not considered in developments of many cities (Bricker *et al*., 2017). This issue occurs due to a few misconceptions such as groundwater is a finite resource, uncertain, polluted, pricey to develop and maintain, hard to extract and give unfavourable impact to the environment (Yunus and Hatta, 2009). However, in recent times, explorations of groundwater as an alternate and conjunctive water source are going on worldwide including Malaysia (Roslan, 2017). Still, only several states namely Kelantan, Selangor, Sabah and Sarawak are actively exploiting groundwater for domestic and industrial purpose in Malaysia (Yunus and Hatta, 2009). The alluvial aquifer is greatly exploited compared to hard rock aquifers in worldwide including Malaysia.

Hark rock is defined as rock which is difficult to drill (Singhal, 2008) which includes plutonic, metamorphic and several well-cemented sedimentary rocks (Alle *et al*., 2018; Schlumberger, n.d.). These rocks have low porosity and permeability while being highly heterogeneous in nature (Lachassagne, 2008) which result in low groundwater productivity. Yet, weathering and fracturing can improve hydrodynamic properties of the hard rock aquifers through secondary porosity and permeability (Soro *et al*., 2017). According to Chandra *et al*. (2010) and Roslan (2017), a few reasons including declination of water level up to deep fractures due to overexploitation of groundwater and increasing demand cause this aquifer to be explored more actively.

Finally, the unique, complex and highly heterogeneous properties of fractured hard rocks cause high failure rate of groundwater exploration which ranges from 10 % to 50 % even with comprehensive studies (Holland, 2011; Alle *et al*., 2018). Therefore, characterization of the aquifers is required for the sustainability of continued supply and safe portable water through an in-depth understanding of factors controlling the groundwater yield and quality, especially in rock aquifers. This study explores the possibility of acquiring rock aquifer in Jurong Formation which consists of consolidated and interbedded sandstone, shale and subordinate conglomerate overlying the volcanic rocks at Southern Johor Bahru.

1.2 Problem Statement

Many studies (Lee *et al*., 2012; Rajaveni *et al*., 2017; Yin *et al*., 2018) related to groundwater exploration raised concern on the productivity and quality of groundwater that could be extracted. The researchers agree that those variables depend greatly on the depths and site-specific geologic condition of the wells drilled. This is supported by Holland (2011) stating that the properties of rock aquifers are definitely not forthright and results are volatile due to its native heterogeneity. In addition, the occurrence and flow of groundwater and its controlling factors are inadequately grasped by many which caused the resource not to be developed to its utmost capacity (Abija and Nwankwoala, 2017). The alluvial and carbonate rocks had always been the favoured in groundwater explorations as they have comparably high productivity and shallow in depth (Limaye, 2009). The hard rock aquifer has been avoided due to its low productivity and permeability as well as the high cost of drilling (Singhal, 2008). There is only a limited knowledge is available on hydrogeology of various type of rock aquifers (Singhal, 2008; Holland, 2011). In Malaysia itself, the alluvial aquifer is more utilized and studied (Chong and Tan, 1986; Yunus and Hatta, 2009) compared to hard rock aquifers although its distribution is comparable smaller as in Figure 1.1.

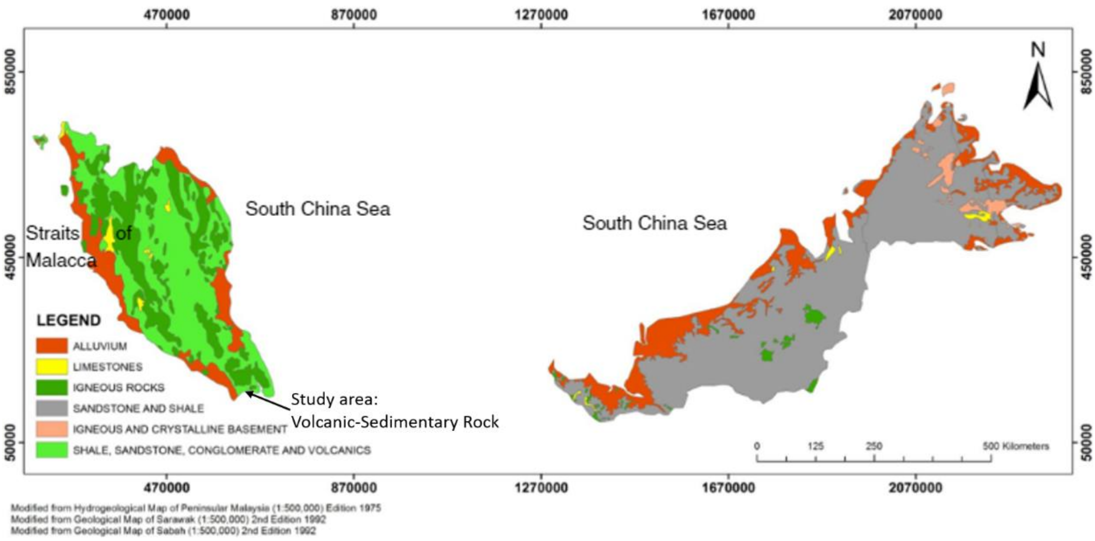

Figure 1.1 Modified hydrogeological map of Malaysia (Kura *et al.*, 2013)

Southern Johor Bahru and western part of Singapore are underlain by Jurong Formation. It is characterised by consolidated and interbedded sandstone, shale and subordinate conglomerate as well as volcanic rocks with age of Lower to Upper Triassic (209-242 million years). According to Burton (1973), Jurong Formation consists of two members namely, Bukit Resam Clastic Member and Gunung Pulai Volcanic Member. The Bukit Resam Clastic Member is composed primarily of shale and immature sandstone with minor siltstone, conglomerate and volcanic layers while Gunung Pulai Volcanic Member is comprised dominantly of tuffs such as welded tuffs of rhyodacitic composition and containing hornblende and minor lava.

Due to the historic nature of the rock masses of Jurong Formation, this study attempts to investigate the character of the rock aquifer at the studied area. The productivity and quality are much dependent on the capability of surrounding medium to transmit the water into the well. The mineralogy of the earth material plays significant role in determining the water quality. The difficulty in understanding properties of rock aquifers aggravates further in rock aquifers as they demonstrate a vast range of characteristics. For instance, their behaviour could range from permeable to highly permeable or from porous to fractured rock for volcanic rock (Cabrera and Custodio, 2004). In addition, the characteristics of rocks differ spatially even over short span indicating strong heterogeneity. Thus, it requires development of understanding of rock aquifer characteristics formed in Jurong Formation.

1.3 Aim and Objectives

Groundwater is generally classified as confined and unconfined aquifer system. The confined aquifer system could exist in the soil or the rock medium and its characterisation depends greatly on the site-specific geological condition. The aim of this study is to characterise and evaluate rock aquifer in Jurong Formation at Southern Johor Bahtu. The objectives of this study are listed as the following:-

(a) To investigate the regional and local geological and hydrogeological characteristics of the studied site

(b) To evaluate the hydraulic and hydrogeochemical properties of rock aquifer in the studied site

(c) To analyse the physical characteristics of the fracture system of rock aquifer in the drilled wells

(d) To establish the characteristics of rock aquifer system found at the studied area

1.4 Scope of the Study

To carry out the study in a compelling manner, the following scopes of this study are discussed as following. A comprehensive review on the geology of Southern Johor Bahru is carried out based on previous literature and reports. As Singapore has similar geology, it is also reviewed to obtain an overall regional understanding. The understanding of local geology is developed through mapping of outcrops, downhole camera as well as data of boreholes and wells. The rock samples are collected for the petrographic survey which provided further details on the minerals and geologic events in the past. The structural analysis of the study area is carried out through interpretation of lineaments, mapped bedding and discontinuities as well as fractures observed during downhole camera survey. The geophysical surveys such as resistivity and seismic refraction surveys are carried out complementary to available geological knowledge of the study area to understand deeper subsurface geology. The hydrogeology, hydraulic and hydrogeochemistry are studied to determine the factors controlling groundwater quantity and quality in the study region. Finally, the rock aquifer system at the studied area is characterised.

1.5 Significance of the Study

The characteristics of deep rock aquifers are not well developed due to the high cost and difficulty of drilling. The site specific and variable nature of rock type further aggravates the limited understanding of rock aquifer. This study investigates the regional and local geology as well as hydrogeological characteristics of the studied site. The understanding of characteristics of well-cemented and consolidated hard rock aquifers of Jurong Formation is one of the significant contributions in this study. In addition, this study contributes the understanding of properties of fracture system present in the rock masses which significantly controls the groundwater availability in this geologic setting. This study also evaluates the quality and hydrogeochemistry of extracted groundwater. The findings of this study would become a base for future groundwater exploration projects for locations with similar geological characteristics.

1.6 Organisation of the Thesis

This thesis is organised into five parts. Chapter 1 briefly introduces the research background and significance. It discusses the problem statement of current study and establishes the aim and objectives of the research.

The literature from previous studies is critically reviewed in Chapter 2. The review includes groundwater exploitation in Malaysia, groundwater exploration techniques in hard rocks, conceptual models of hard rock aquifers, control of geological factors on borehole productivity, hydraulic assessment and water quality as well as hydrogeochemistry of hard rock aquifers.

Chapter 3 presents the methodology of desk study, field works and laboratory works. The desk study includes collection of site investigation boreholes data, assessment of geomorphology and climate as well as lineament mapping. The field works include field mapping, geophysical survey, collection of rock samples, well development, downhole camera survey, pumping tests and groundwater sampling as well as in-situ quality testing. Meanwhile, laboratory works include porosity test, petrographic survey and water quality test.

Chapter 4 discusses the regional and local geology which primarily focus on fracture system in the region. Then, hydraulic properties of aquifer such as hydraulic conductivity, transmissivity and storativity are determined. Later, hydrogeological characteristics such as lithology, weathering grade, porosity and fracture system are correlated with hydraulic properties of fractures. Also, groundwater quality and hydrogeochemistry are determined. Besides, rock aquifer system of Jurong Formation at Southern Johor Bahru is discussed.

Finally, Chapter 5 summarizes and concludes all the findings based on objectives of the study as mentioned earlier in this chapter. Also, it provides recommendations for future works.

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