CHARACTERIZATION AND ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF GROUNDWATER SYSTEM AS AN AUXILIARY RESOURCE FOR PADDY IRRIGATION IN LABU KUBONG, TELUK INTAN, PERAK

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by

NASEEM AKHTAR

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LIST OF SYMBOLS

Al	Aluminium
As	Arsenic
B	Aquifer Loss
b	Aquifer Thickness
Be	Beryllium
C	Well Loss
Ca	Calcium
Cd	Cadmium
Cl	Chloride
CO_2	Carbon di Oxide
CO_3	Carbonate
Cr	Chromium
Cu	Copper
d	Day
D	Domain
Ew	Well Efficiency
Fe	Iron
Fe^{3+}	Ferric
Fe^{2+}	Ferrous
Fl	Fluoride
h	Depth
hr	Hour
HCO_3	Bicarbonate
H_0	Hydraulic Head

K	Potassium
k	Permeability
K	Hydraulic Conductivity
Kg	Kilogram
KW	Kilowatt
Km	Kilometer
L	Well Screen Length
L	Leakage Factor
m	Meter
m^2	Square meter
m^3	Cubic meter
m^5	Power five
Mg	Magnesium
Mn	Manganese
mg/L	Milligram Per Liter
mm	Millimeter
msec	Meter. Second
Na	Sodium
Na%	Sodium Percentage
NO_3	Nitrates
NTU	Nephelometric Turbidity
O	Oxygen
pH	Potential of Hydrogen
Pb	Lead
Q	Discharge rate
r	Well Radius
R	Well radius casing with gravel packing!

s	Drawdown
S	Storativity
Sc	Specific Capacity
S_{cor}	Corrected Drawdown
SiO_2	Silica
St	Total drawdown
Stei	Surface Time Equivalent
S_y	Specific Yield
S/N	Signal-to-Noise
TH	Total Hardness
T	Transmissivity
TCU	True Colour Unit
t_o	Basic Time Lag
t	Elapsed Times
V/I	Voltage/Current
Zn	Zinz
Ωm	Ohm.meter
µm	Micrometre
µS/cm	Micro-Siemens Per Centimeter
Δs	Difference in the Drawdown
W(u)	Walton well function
Ø	Diameter
°C	Degree Celsius
%	Percent
∞	Infinity
2D	Two Dimensional

LIST OF ABBREVIATIONS

AAS	Atomic Absorption Spectrometers
AC	Alternative Currency
APHA	American Public Health Association
ASM	Academy of Sciences Malaysia
ASTEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AMD	Available Water Minus Demand
AWARE	Available Water Remaining
BH	Borehole
COD	Chemical Oxygen Demand
CFs	Characterization factors
CTA	Consumption-to-Availability
DTA	Demand-to-Availability
DOE	Department of Environment
DID	Department of Irrigation and Drainage
DC	Direct Current
DEM	Drainage Elevation Map
EC	Electrical Conductivity
EDX	Energy Dispersive X-ray
ERI	Electrical Resistivity Imaging
ERT	Electrical Resistivity Tomography
EWR	Environmental Water Requirements
FAO	Food and Agriculture Organization
FTIR	Fourier Transmission Infrared
GIS	Geographical Information System
GSM	Geological Survey of Malaysia
GPS	Global Positioning System
HWC	Human Water Consumption
IADA	Integrated Agricultural Development Area
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
ISO	International Organization for Standardization

ISSS	International Soil Science Society
IP	Induced Polarization
IADA	Integrated Agricultural Development Area
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
ISO	International Organization for Standardization
ISSS	International Soil Science Society
IC	Ion Chromatography
JMG	Jabatan Mineral Dan Geosains
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LDM	Lazer Diffraction Method
MICP	Mercury Injection Capillary Pressure
MPD	Milliliter Per Day
MGD	Mineral and Geoscience Department
MOA	Ministry of Agriculture
MADA	Muda Agricultural Development Authority
NEAC	National Economic Action Council
NGDWQ	National Standard for Drinking Water Quality
NWQS	National Water Quality Standard
NWRS	National Workforce Reporting Service
OW	Observation Well
PSD	Particle Size Distribution
PCA	Principal Component Analysis
PWD	Public Works Department
RMC	Right Main Canal
RMS	Root-Medium-Squared
SEM	Scanning Electron Microscope
SAS	Signal Averaging System
SDWR	Sime Darby Water Resource
SAR	Sodium Adsorption Ratio
SDGs	Sustainable Development Goals
SGDA	Sustainable Groundwater Management Act
TDIP	Time-Domain-Induced Polarization

TDS	Total Dissolved Solid
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USM	Universiti Sains Malaysia
UTHM	Universiti Tun Hussien Onn Malaysia
UTM	University of Technology Malaysia
USSL	US Salinity Laboratory
VES	Vertical Electrical Sounding
WA	Water Availability
WF	Water Footprint
WFA	Water Footprint Assessment
WSF	Water Scarcity Footprint
WSI	Water Stress Indicator
WULCA	Water Use in Life Cycle Assessment
WTA	Withdrawal-to-Availability
WHO	World Health Organization
XRD	X-ray Diffraction

LIST OF APPENDICES

PENCIRIAN DAN PENILAIAN KELESTARIAN PERSEKITARAN SISTEM AIR TANAH SEBAGAI SUMBER BANTUAN PENGAIRAN PADI DI LABU KUBONG, TELUK INTAN, PERAK

ABSTRAK

Cabaran yang dihadapi Malaysia, seperti pengurusan air yang terbatas, perubahan iklim, kemarau, serta pencemaran air yang semakin meruncing telah menekan sumber air bagi tujuan pengairan, teutamanya di kawasan plot padi terpencil. Kajian ini membincangkan peranan penting air tanah sebagai sumber sokongan bagi pengairan padi dalam menangani trend penyusutan saiz kawasan "jelapang padi " di Labu Kubong. Potensi hasil air tanah adalah penting bukan sahaja bagi tujuan pembangunan sumber air tanah semata mata, malah ia amat penting dalam menentukan impak persekitaran kesan daripada pembangunan infrastruktur serta penggunaan air tanah untuk tujuan pengairan. Justeru, dalam memahami potensi air tanah secara mampan, kajian ini telah dijalankan merangkumi objektif-objektif seperti berikut: (i) Menganalisis profil geofizik kawasan bawah permukaan, (ii) Pencirian profil tanah pada lubang gerudi, (iii) Penentuan transmissiviti, kekonduksian hidraulik dan storativiti akuifer, serta (iv). Penilaian potensi impak pembangunan dan penggunaan sumber air tanah bagi tujuan pengairan. Hasil kajian telah menunjukkan bahawa ciri akuifer ini terdiri daripada jujukan pasir-kelodak dengan peratusan purata komposisi 94% (pasir) dan 6% (kelodak), menunjukan persekitaran aluvium dengan batuan pada Formasi Gula sebagai dasar. Transmisitiviti (T), kekonduksian hidraulik (K), dan storativiti (S) telah dinilai melalui siri ujian pengepaman bermula pada tahun 2020 dan 2021. Nilai T (purata 7.84 m^2/hari) menunjukan bahawa kapasiti aquifer adalah sesuai sebagai sumber air tanah tambahan. Nilai K adalah di antara 0.432 hingga 0.576

m/hari, menunjukan ciri aquifer yang terdiri daripada kelodak pasir dalam julat halus dan berubah kepada kasar pada kedalaman profil yang semakin bertambah. Penjelasan ini adalah konsisten dengan analisis pencirian tanah yang telah dilakukan. Selain itu, analisis unsur bumi melalui pembelauan laser dan mikroskop elektron pengimbasan juga adalah konsisten dengan analisis pencirian tanah, menjelaskan tentang ciri lapisan Teluk Intan pada Formasi Gula. Nilai S adalah 0.00345 pada tahun 2020 dan 0.0763 pada tahun 2021, menunjukan kemungkinan akuifer jenis terkurung atau jenis separa terkurung berdasarkan kaedah anggaran Cooper dan Jacob. Secara keseluruhannya, potensi hasil telaga yang diperoleh adalah pada kadar 194 m^3/hari iaitu mencukupi bagi keperluan pengairan padi pada keluasan 1.5 ha yang memerlukan jumlah air sebanyak 107 m^3/hari. Impak persekitaran berdasarkan pengiraan *Water Scarcity Footprint (WSF)* bagi sistem air tanah ini adalah 0.4 m^3*. eq deprived*. iaitu kurang daripada nilai purata dunia yang dinormalisasi iaitu 1 m^3*. eq deprived,* menjelaskan keterjejasan sumber air yang minimum bagi aktiviti pengairan padi menggunakan sistem air tanah ini. Hal ini adalah kerana Labu Kubong merupakan kawasan yang kaya sumber air secara tabii kerana faktor geografinya yang bersifat tropika. Walaupun nilai WSF adalah memuaskan (< 1 m^3*. eq deprived*), namun, faktor impak penggunaan sumber tenaga untuk pembangunan infrastruktur sistem air tanah merupakan penyumbang terbesar kepada nilai WSF.

CHARACTERIZATION AND ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF GROUNDWATER SYSTEM AS AN AUXILIARY RESOURCE FOR PADDY IRRIGATION IN LABU KUBONG, TELUK INTAN, PERAK

ABSTRACT

The challenges facing Malaysia, such as inadequate water management, climate change, drought, and water pollution, are becoming more severe, leading to water stress in isolated paddy plot areas. The study highlights the role of groundwater as an auxiliary resource for paddy irrigation to counteract the alarming trend of the shrinking "rice bowl" area in Labu Kubong. Knowledge of the potential well yield of groundwater resources is critical not only for groundwater resource management purposes but also to determine the significant impact of associated water consumed in groundwater infrastructure and development. Therefore, this study's objectives are: (i) To analyse the geophysical profile of the subsurface area, (ii) To characterize the vertical profiling of soil textures and elemental compositions in the borehole, (iii) To evaluate the transmissivity, hydraulic conductivity and storativity of the aquifer, and (iv) To assess the impact potentials of water consumed associated with the groundwater system. Results showed that the aquifer consists of a sand-silt sequence with an average percentage of 94% and 6%, respectively indicating an alluvial environment with hard rock underlying the Gula Formation. The transmissivity (T), hydraulic conductivity (K), and storativity (S) were evaluated from the series of pumping tests in years 2020 and 2021. The results of T (average 7.84 m^2/day) are classified as intermediate, suitable as an auxiliary groundwater resource. The K was quantified between 0.432 to 0.576 m/day, indicating sand-silt formation from fine to

coarse as the depth of soil profile increase, consistent with soil characteristics results. Moreover, elemental analysis using laser diffraction and scanning electron microscope also agreed with soil characteristic findings, indicating Teluk Intan members of Gula formation. The observed S is 0.00345 in 2020 and 0.0763 in 2021, one order of magnitude larger than previous S in 2020, suggesting confined aquifer to semiconfined aquifer type based on Cooper and Jacob's estimation. Overall, potential well yield was obtained at 194 m^3/day of which sufficient to meet the irrigation requirement of 1.5 ha paddy plot (107 m^3/day). Water Scarcity Footprint (WSF) of the groundwater system is 0.4 m^3. eq. deprived, which indicates minimal water deprivation compared to the normalized world average. This is due to Labu Kubong is an abundant water region by nature (tropics). However, despite the satisfactory of WSF value, the energy infrastructure appeared as significant concern associated with WSF.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Water resource for agriculture application is vital, in this case, particularly for paddy irrigation (Azwan et al., 2010; Liu et al., 2021). Generally, the required amount of water for paddy crop is determined by the soil condition, the quantity and type of nutrients, the water quality and the climate conditions of the area (Amin et al., 2011; Yadav et al., 2014; Wang et al., 2021). For the record, the amount of water required to produce 1 kg of rice is estimated between 800 to 5000 liters with an average 2500 liters per kg of rice (Bouman, 2003; Surendran et al., 2021).

Conflicts between high demand for water from industrial and residential use have resulted in water stress for irrigation purposes including paddy irrigation (Haque et al., 2006; Akinbile et al., 2011; Nan et al., 2021). Today, groundwater has appeared as important water supply to satisfy the ongoing demand from industrial, domestic, and agricultural sectors. In fact, it is also become an alternative resource for paddy irrigation (Amin et al., 2011; Nan et al., 2021). Note, about 30% of the world's available groundwater resource is currently used for the paddy industry (Bouman, 2007). The availability of groundwater is characterized by the geology of subsurface, soil characteristics, groundwater quantity-quality, hydraulic properties and other hydrogeological factors in the area (i.e., groundwater recharge from rainfall or surface water) (Akhtar & Rai, 2019; Ahmed et al., 2020; Rahman et al., 2020).

In this study, the Labu Kubong paddy plot area was selected as study site due to its isolated location where the plot received insufficient amount of water from the main irrigation source, the Sungai Batang Padang. Given the fact that the groundwater resource in Labu Kubong is characterized by alluvial aquifer which has been recognized as the most suitable source for exploitation (Mohamed et al., 2009), hence the groundwater development in the area as supplementary resource to support the irrigation seems viable. However, the knowledge on potential well yield of the groundwater resource is important for a sustainable groundwater management, therefore, warrants further investigation on the subsurface formation, soil characteristics and hydraulic properties of the aquifer in the area.

1.2 Background of study

The demand on water resource has increased for human consumption, especially for paddy irrigation (Jais, 2017). According to statistics compiled by the Food and Agriculture Organization (FAO) between the years 1961 and 2018, the paddy planted region and the amount of paddy produced both expanded from 115 million hectares and 215 million tonnes to 167 million hectares and 782 million tonnes, respectively (FAO, 2019). Paddy is produced in 118 nations worldwide. Out of 167 million hectares globally, about 146 million hectares of paddy are planted in Asia (Surendran et al., 2021). As a result, Asia is responsible for 705 million tonnes or Asia is responsible for about 90% of the world's paddy production (Fahad et al., 2018). In certain Asian countries including Malaysia, rice is the most important crop, whereas, the production of 2.4 million tons of paddy crops and cultivable land (0.7 million hectares) is currently ranked 25th in the world since the 1980s (Akinbile et al., 2011).

Paddy is cultivated on a large scale in several regions of Malaysia, however, the growing season for paddy varies from one place to another depending on the local climatic conditions and geographical scenarios. For rice production, the Ministry of Agriculture (MOA) and Agro-Based Industries has established the Integrated Agricultural Development Area (IADA) agency (MOA, 2010). In addition, the MOA has targeted three primary IADA goals based on the requirement for rice production, including developing rice cultivation yield to 6.5 metric tonnes per hectare by 2010, upgrading rice agriculture applications, and improving farmer productivity and income (MOA, 2010, 2011). Several areas like Kerian Sungai Manik, Seberang Perak, Barat Laut Selangor, and Pulau Pinang have reported that it was very challenging to achieve the IADA target of 6.5 metric tonnes per hectare. This was due to insufficient water supply and unsatisfactory monitoring and management system of water supply (MOA, 2010; Berahim et al., 2021).

Many authors have also asserted that the water requirements of the agricultural sector in Malaysia have not met the IADA's expectations due to factors such as insufficient freshwater and severe droughts (Abdullah, 2006; Haque et al., 2006; Akinbile et al., 2011; Fauzie, 2013). As an example, the Muda Irrigation Scheme in Kedah and Perlis, which is the largest granary area in Malaysia, encountered six episodes of drought between 1977 and 1992 (Mon & Chang, 2008). These events has led to critical water levels drop in Pedu and Muda dams (Ahmad & Low, 2003). In addition, about 184 hectares of paddy plantation in Melaka were not able to receive water due to drying canal (Fairuz, et al., 2018). Mon and Chang (2008) have predicted that the severity and frequency of drought can be increased in future. Climate change is inevitable and is responsible for changing monsoon patterns, low productivity, and water scarcity (David, 2004; Saira et al., 2023; Tilleard et al., 2023).

Nonetheless, Malaysia is blessed with abundance water resource, but it is not well distributed. For the record, Peninsular Malaysia, Sarawak and Sabah have received abundance rainfall with the average amount of 2400 mm, 3800 mm and 2300 mm, respectively (Keizrul, 2006; Che-Ani et al., 2009; Ahmad et al., 2017; Sanusi et al., 2021; Ng et al., 2022). However, some area like Kedah and Perlis were reported to receive lower than the normal days precipitation in 2006, resulting in delays and near cancellations off-season planting from February to May (K. Abdullah, 2006; Tan et al., 2021; Vaghefi et al., 2013).

In addition, surface water pollution also did contribute to water availability for irrigation (Haliza, 2007; Shuhaimi-Othman et al., 2007; Juahir et al., 2011; Ishadi et al., 2014; Razak et al., 2015; Huang et al., 2016; Haque et al., 2016; Haque & Roslan, 2017; Hou et al., 2017; Salam et al., 2019). As a result, the freshwater demand has increased, leading to water stress of which has caused inadequate water supplies for Malaysian farmers, consequently affecting the rice yield and ultimately reducing the farmers' incomes (Abdullah, 2006; Haque et al., 2006; Mon & Chang, 2008).

In comparison to the surface water issues, groundwater can provide better reliable supplies for the irrigation sector while reducing the risk of drought impact. In fact, the National Economic Action Council (NEAC) has recognized that groundwater as being one of the alternative water resources in Malaysia (Saimy & Raji, 2015; Teh & Koh, 2020). In certain places of Malaysia, such as Terengganu, Pahang, Kelantan, Manukan, Kapas Island, Sabah, Perlis, and Sarawak, the groundwater has been utilized as a primary supply of freshwater for human consumption (Ebrahim et al., 2020).

In Malaysia, challenges such as inadequate water management, climate change, drought and water pollution are escalating, leading to water stress especially in isolated paddy plot areas. Like our case, the study site in Labu Kubong is an isolated paddy plot area, where received unsatisfactory amount of water from the surface water supply (the main water resource for irrigation). In fact, one of the agendas in Rancangan Tempatan Daerah Hilir Perak 2035 is to maintain the Integrated Agriculture Development Authority (IADA) Sungai-Manik Labu Kubong Area as the "rice bowl" or known as "Jelapang Padi" (Maliki, 2008; Sayuti et al., 2018). It was reported that the area shrunk from 7,852.17 ha (2010) to 6,318 ha in year 2018 and therefore, any possibilities to mitigate the shrinking trend of the paddy are crucial (PLANMalaysia@Perak, 2021).

Essentially, the groundwater can play a role as an alternative water resource to mitigate the shrinking trend of land for paddy cultivation. In fact, National Economic Action Council has outlined that groundwater can be an alternative resource to adapt with climate change i.e., severe drought, essential to paddy plot area that experience water stress issue (due to isolated location). This problem, if not addressed sustainably, may lead to land conversion from paddy to oil palm cultivation, hence contribute to the current alarming shrinking trend of the "rice bowl" of Sungai Manik-Labu Kubong.

In this regard, groundwater resource can be explored as an auxiliary source to satisfy the irrigation requirement in the affected paddy plot area. Groundwater is seen as a resource that has less influence by drought and readily accessible as auxiliary resource for paddy irrigation. However, the knowledge on potential well yield of the groundwater resource is important to understand the capacity of groundwater system, hence warrants further investigation on the subsurface formation, soil characteristics and hydraulic properties of the aquifer in the area.

On the other hand, a hydrogeological study conducted in geological formations contexts throughout Peninsular Malaysia revealed the occurrence of groundwater zones ranging from medium to low potential water-bearing zones (Jais, 2017). Based on the hydrogeological setting of our research area, the Labu Kubong is characterized by Gula Formation with the expectation of withdrawal capacity from 50 to 100 m^3/hr per well (Marto & Yusoff, 2018). Such promising abstraction rates is possible but depends on the availability of groundwater in the aquifer system determined by number of factors i.e., subsurface lithology, soil properties and hydraulics properties of the aquifer, and other hydrological factors i.e., recharge and discharged.

In addition, the impact of groundwater development through the infrastructure setting for the groundwater abstraction also needs further evaluation considering the water scarcity footprint (WSF) of the system i.e., not only the impact of water consumed for the irrigation but also the impact of water consumed during groundwater infrastructure development (Schomberg et al., 2021).

The concept of WSF was initially introduced during an international expert meeting on virtual water trade in Delft, Netherlands, by Hoekstra in 2003. WSF represents the total freshwater needed to produce the goods or services consumed by individuals, communities, or businesses in a particular region, sourced from the local aquifer system or river basin (Hoekstra et al., 2012; Hoekstra, 2016). Since 2009, the life cycle assessment (LCA) community has shown interest in the WSF concept due to its significance in evaluating the environmental impact of products and services (Pfister et al., 2017). The WSF concept aligns well with addressing environmental concerns related to water resource allocation, specifically tailored to meet the goals of LCA (Hoekstra, 2016; Simmons et al., 2022; WULCA, 2022).

Several concepts related to the WSI models which is based on the ratio of water withdrawal-to-availability (WTA) and its ratio can be used as a characterization factor (CF) to evaluate the water deprivation of a watershed (Pfister et al., 2009). Following this, WSI has evolved based on the water consumption-to-availability (CTA) ratio with the assumption that water extracted from the environment and delivered to the same watershed does not often contribute to the local water crisis (Boulay et al., 2011; Hoekstra et al., 2012; Berger et al., 2014). Furthermore, the findings of professional discussions within Water Use (WU) in LCA (WULCA) initially recognized the requirement to transform from WTA and CTA to a demand-to-availability (DTA) ratio, given that both human consumption and ecosystem water demand are included in demand (Boulay et al., 2014; Boulay et al., 2015).

Three proposals have outlined by Boulay et al (2015) which are DTA_A, DTA_x, and 1/AMD based on DTA. Although DTA_x, includes two parameters on indicate absolute availability (DTA_x) and relative availability (DTA), as well as last one represents availability minus demand (1/AMD). In this context, they represented 1/AMD that indicates the inverse of the difference between availability per area and demand per area (Boulay et al., 2015). It estimates the potential for water deprivation, provides the impact score of water usage and calculates a WSI. After a long time, Boulay et al., (2018) developed the Available Water Remaining (AWARE) method for evaluating the impacts from water consumption and indicate absolute amount of available freshwater remaining in terms of global-equivalent cubic meters. In other words, AWARE method represent the available water remaining per unit of surface in a given watershed relative to the world average after human and aquatic ecosystem demands have been met (Boulay et al., 2018).

Thus, if the aquifer is abundance with water, this can be reflected in high potential well yield, allowing more consumption to satisfy the irrigation requirement at optimal groundwater infrastructure capacity. Nevertheless, it can turns the other way round if potential well yield is low, limit the groundwater abstraction to perform at optimal groundwater infrastructure capacity (Saimy & Raji, 2015; Alam, 2016; UNESCO, 2022).

Sustainable development and management of the groundwater system is imperative and served as a foundation to achieve SDG 6: '*To ensure availability and sustainable management of water and sanitation for all*' (Alves & Cunha, 2021;

Obaideen et al., 2022). This research is framed with consideration on the sustainability perspective in physical groundwater investigation comprising geophysical survey, soil texture and composition, hydraulic properties, and water scarcity footprint.

Geophysical investigation provides information of subsurface lithology through Electrical Resistivity Tomography (ERT) or Electrical Resistivity Imaging (ERI) or Induced Polarization (IP) surveys (Ahmed et al., 2019; Blanchy et al., 2020)., leading to better identification of groundwater potential zones (Kearey et al., 2002; Attwa et al., 2011; Muchingami et al., 2012; Anomohanran, 2015; Riwayat et al., 2018; Rolia & Sutjiningsih, 2018; Kumar et al., 2021).

Findings from the geophysical survey will be validated by the soil texture and composition analyses. The soil samples were analysed for its size distribution using Malvern Master Sizer instrument (Wang-Li et al., 2013). followed by elemental analysis of soil composition to support the subsurface characteristics interpreted from the geophysical survey. A Scanning Electron Microscope (SEM) equipped with the Energy Dispersive X-ray (EDX) is used to investigate numerous microscopic traces, makes it easy to define the soil morphology and the mineralogical composition of soils (Abd El-Aal et al; 2020; Philip & Singh, 2020).

As well the additional work on getting a snapshot of groundwater hydrogeochemistry information was performed using Piper diagram (Piper, 1944), Gibbs diagram (Gibbs, 1970), Sodium Percentage (Na%), Sodium Adsorption Ratio (SAR), and the US Salinity Laboratory (USSL) diagram (Richards, 1954; Wilcox, 1955b). This is to give a preliminary idea about the suitability of groundwater use for paddy irrigation.

Once the knowledge of subsurface characteristic is developed, later, further investigation was performed on hydraulic properties of the aquifer such as the transmissivity (T), a parameter that describes the ability of groundwater to transmit water from aquifer system through its entire saturated thickness (horizontally), storativity (S) (analogous to the amount of groundwater storage within an aquifer), and hydraulic conductivity (K) (rate of water flow in the aquifer) (Fauzie et al., 2014; Naderi, 2019). Here, a series of pumping test was performed to estimate the T, K and S (Krásný, 1993; Kruseman & Ridder, 1994; Todd & Mays, 2005; Trabucchi et al., 2018; Moharir et al., 2020; Hsu & Chou, 2019). The knowledge of T, K and S has been lead to further estimation of potential well yield (m^3/day) (Jacob, 1947; Boonstra & Kselik, 2001; Fitts, 2002; Summa, 2010; Brassington, 2017; Gallardo, 2019; Kaleris & Ziogas, 2020; Shekhar et al., 2020). Details methodology has been explained in Chapter 3.

The potential well yield is the key determinant factor on determining the environmental impact of groundwater development study using life cycle assessment approach. At this stage, the Water Scarcity Footprint (WSF) of groundwater system can be evaluated to address potential impact associated with the quantity aspect of water consumption (Schomberg et al., 2021). WSF is the outcome of Available Water Remaining (AWARE), a consensus-based method development to assess water use in Life Cycle Assessment. The WSF is based on the ISO 14046 framework (Boulay et al., 2018) to assess the potential impact, with the purpose to provide a management framework towards sustainable best practices in groundwater management taking the sustainability perspective of the impact of water consumed for irrigation and the impact of water consumed for the infrastructure development (Boulay et al., 2014, 2015, 2018).

The systematic study of groundwater system starting from gaining the geophysical data, vertical soil profiling, hydraulic properties and water stress insights provides framework of sustainable groundwater resource management for an optimal, objective, and effective consumption. In addition, this research demonstrated that selecting groundwater as an auxiliary resource for paddy irrigation required a holistic approach that considers not only the impact of water consumed for irrigation but also the impact of water consumed associated with infrastructure development.

1.3 Problem statements

In Malaysia, irrigation is almost consistently dependent on adequate water supplies, mainly from rivers and rainfall. However, there are certain dry months (Feb-May during the off-season) in some parts of Malaysia that experience insufficient water supply or an unsatisfactory monitoring and management system of water supply, which can result in an "agriculture drought". For example, Kerian Sungai Manik, Seberang Perak, Barat Laut Selangor, and Pulau Pinang have not met the IADA target of 6.5 metric tonnes per hectare according to irrigation schemes (MOA, 2010; Berahim et al., 2021). Furthermore, challenges such as inadequate water management and climate change may worsen the water stress issue in paddy cultivation. Therefore, considering the problems:

1) The study site has been selected due to its isolated location where the paddy plot received insufficient amount of water from the main irrigation source.
2) Quaternary alluvial formations have the best potential for groundwater resources, with estimated yields ranging from 50 to 100 m^3/hr (Mohamed et al., 2009(Jais, 2017). While abundant in a regional context, the aquifer with alluvial settings can only be exploited to a certain extent of development depending on the soil composition, hydraulic properties.

3) Soil composition and hydraulics properties are limiting factor that critical to balance between the demand for irrigation and at the same time adhere to sustainability obligations. Here, the potential well yield (m^3/hr) is the key knowledge to balance both irrigation demand and sustainability obligations.

Such sustainable perspective not just highlights the sustainability of groundwater exploitation dimension, but also pinpoints the associated significance impact of water consumed for the groundwater infrastructure. Thus, this work has been carried out in the context of the knowledge on the potential well yield and the water scarcity footprint (WSF) for sustainable groundwater development as auxiliary resource for paddy irrigation in the Labu Kubong area. Taking the sustainability perspective into consideration, hence, the estimation of groundwater resource availability requires the investigation steps comprising delineation of the geological subsurface settings, vertical profiling of soil composition in the borehole, aquifer hydraulic properties (TKS) and the water scarcity footprint (WSF).

1.4 Objectives of the research

The groundwater is seen as a resource that has less influence by drought and readily accessible as auxiliary resource for paddy irrigation. Nonetheless, the sustainability of the groundwater as an effective resource to meet the irrigation requirement need further investigation on the subsurface formation, soil characteristics, hydraulic properties, and water scarcity footprint of groundwater system. Thus, this study has aimed to investigate the role of groundwater system as auxiliary resource for paddy irrigation considering the impact of available water remaining in the aquifer at post irrigation as follows:

(i) To analyse the geophysical profile of the subsurface area.

(ii) To characterize the vertical profiling of soil textures and elemental compositions in the borehole.

(iii) To evaluate the transmissivity, hydraulic conductivity and storativity of the aquifer.

(iv) To assess the impact potentials of water consumed for the groundwater system.

1.5 Scope of the study

This work is a site-specific groundwater system study to characterize and evaluate the sustainability of the groundwater system as an auxiliary resource for paddy irrigation taking the existing tube well in the paddy plot of Labu Kubong area as a study site (1.5 ha). The subsurface profile was analysed and characterized, followed by a series of pumping tests in 2020 and 2021 to evaluate the hydraulic properties T, K, and S of the aquifer. As well, the water stress indicator of the groundwater system was assessed using the single method water footprint model (AWARE).

1.6 Novelty and significance of the study

This research is beyond the optimal and safe pumping rate studies. It focuses on the concept of potential well yield of groundwater resource to determine the associated impact of water consumed for both irrigation and groundwater infrastructure development based on systematic investigation starting from subsurface characterization, soil profiling analysis, periodic pumping test, and the water scarcity footprint evaluation.

1.7 Organization of the thesis

This thesis comprises five chapters and the content has been arranged as follows, as shown in Figure 1.1.

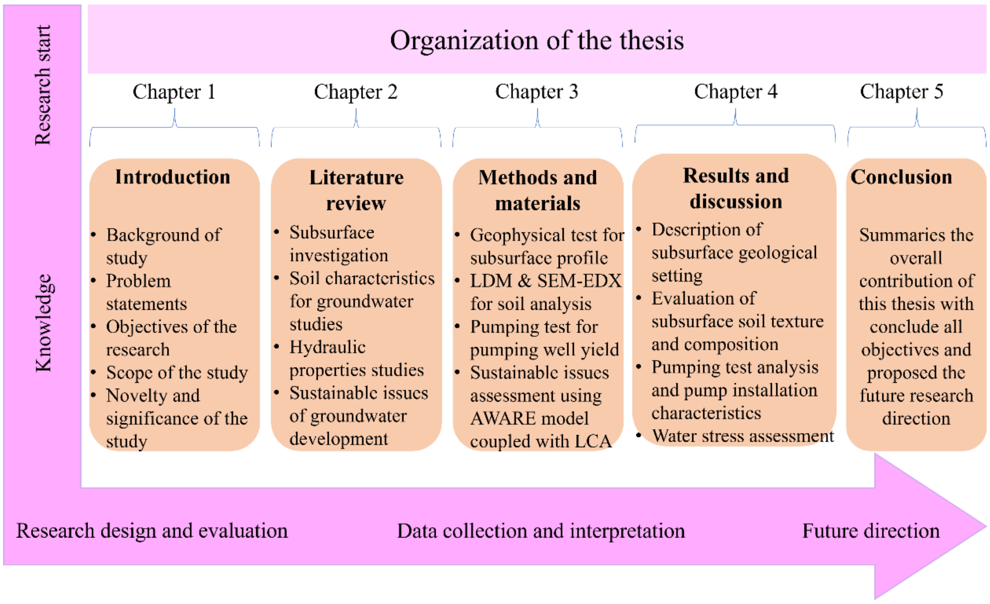

Figure 1.1 Framework for the organization of this thesis

Chapter 1 highlights the importance of groundwater resource as an auxiliary resource for paddy irrigation. The Labu Kubong paddy plot area was selected as study site due to its isolated location where the plot received insufficient amount of water from the main irrigation source. Potential well yield is important parameter in determining the sustainability of groundwater system encompasses the sustainability perspectives of water consumed for groundwater infrastructure and the amount of water consumed for irrigation. Such perspectives not just highlight the sustainability of groundwater exploitation for irrigation assessment but also to pinpoint the significance impact of water consumed for the groundwater infrastructure. Taking the sustainability perspective into consideration, hence, the estimation of groundwater resource availability requires further investigation comprises the subsurface formation via the geophysical survey, vertical profiling of soil composition in the borehole, hydraulic properties of the aquifer (transmissivity, hydraulic conductivity and storativity) and the water scarcity footprint (WSF) of the groundwater system as auxiliary resource for irrigation.

Chapter 2 discusses the previous studies on groundwater consumption in Malaysia. It encompasses the discussion on subsurface investigation for groundwater development using the (1) geophysical survey, (2) typical soil composition profiling, (3) hydraulic properties of aquifers and (4) life cycle assessment LCA studies of groundwater system.

Chapter 3 explains materials and methods of the study. It describes the location, climatic conditions, hydrogeology of the study site. The methodology is explained systematically starting from geophysical surveys, soil texture and composition analysis, elemental analysis, pumping tests, and water scarcity footprint evaluation using AWARE method.

Chapter 4 reports results and discussion. This chapter describes detail findings obtained from geophysical data analysis, vertical soil texture and composition characteristics, hydraulic properties i.e., transmissivity, hydraulic conductivity & storativity of the aquifer and water scarcity footprint of the groundwater system. The results provide better insights on the type of aquifer and its productivity which allow the quantification of potential well yield of the groundwater system. Subsequently, the potential well yield is the key parameter in determining the water scarcity footprint using the AWARE method.

Chapter 5 underlines conclusion and recommendations. This chapter highlights the key points from the findings and insights as the basis for conclusion. On the recommendations, further investigation should be focused on the water consumed for the infrastructure, so it would provide better understanding on the impact of water consumed by groundwater system for irrigation purposes in future. i.e., the concern on water-energy-food nexus. This chapter also explains the limitations of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review is prepared according to the research objectives comprising subsurface investigation, soil characteristics, groundwater quality, hydraulic properties, and the sustainability assessment work related to groundwater system for paddy irrigation in Peninsular Malaysia (Figure 2.1).

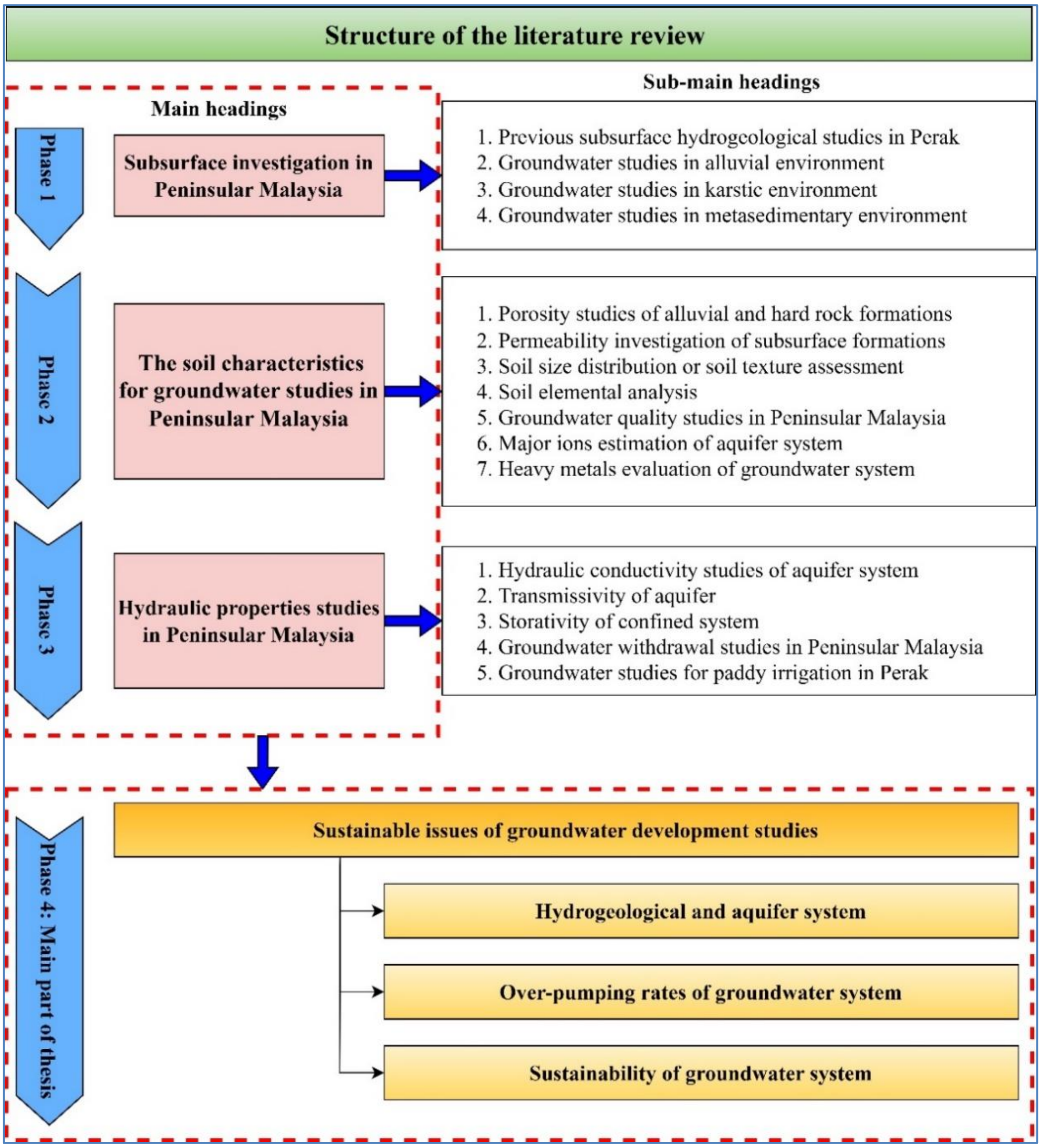

Figure 2.1 Flow chart of the literature review for this thesis

The groundwater resources contribution to the water supply, especially for paddy irrigation is increasing globally. These resources are determined by the regional water cycle and hydrogeological factors. When rainfall occurs, water moves downslope into overland and accumulates in the river and streams, some evaporated to the atmosphere via evapotranspiration, some discharged to the ocean, and some recharged (infiltration) as groundwater. Infiltration process into the pores or cracks of the soil and rocks and stored underground (Figure 2.2).

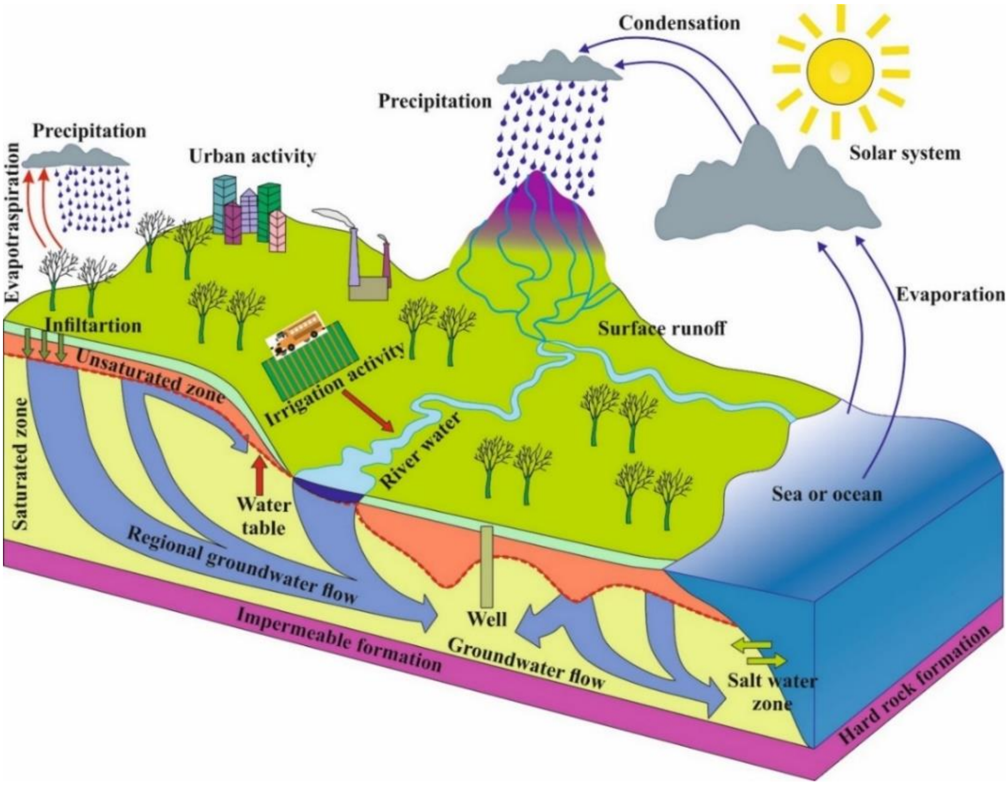

Figure 2.2 Hydrologic cycle showed the cyclic transfer of water between subsurface, surface and atmosphere

Groundwater is located beneath the ground surface in the aquifer system, which consists of either an alluvial aquifer that occurs in unconsolidated and consolidated formations or a fractured aquifer that is found in hard rock (Lachassagne et al., 2021), as shown in Figure 2.3.

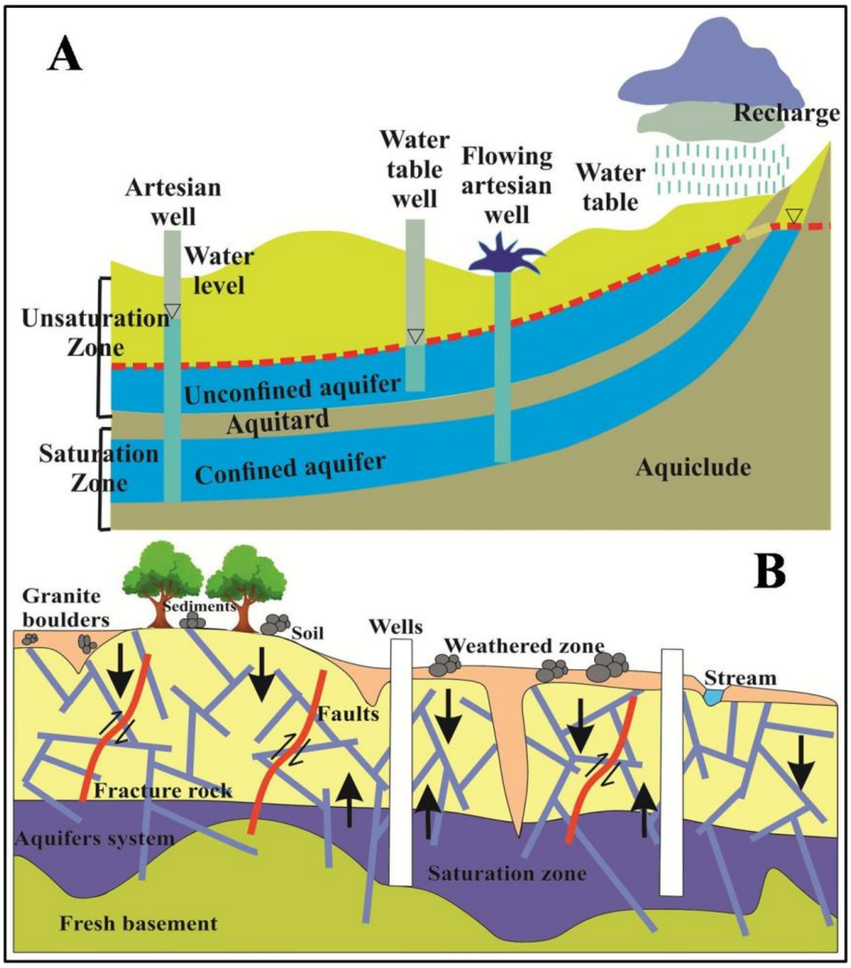

Figure 2.3 It indicates the distribution of groundwater shows (A) the alluvium formations and (B) hard rock formations (Source: Akhtar et al., 2020)

Groundwater has been referred as potential resources in Malaysia. Water demand increased dramatically in areas with rapid urbanization and industrialization, as well as for paddy irrigation especially during the prolonged droughts or dry seasons. Note, some paddy plots have received limited amount of water from the main irrigation system, increase the water stress of the areas (Chong & Tan, 1986; Shirazi et al., 2015). Detailed hydrogeological investigations in connection with environmental protection and groundwater development are becoming progressively necessary because of the water stress for human consumption in Malaysia (Abdulkareem et al., 2018; Garba et al., 2021). According to the National Workforce Reporting Service (NWRS), Peninsular Malaysia receives an annual amount of rainfall of approximately 330.98 billion m^3/year.

The amount of rainfall has reached the catchment through direct and indirect routes. Therefore, the water budget based on the rainfall amount were determined as 141.11 billion m^3/year that flow as surface runoff while about 170.26 billion m^3/year have lost as evapotranspiration. Here, the remaining 19.56 billion m^3/year of water are recharged and stored in groundwater aquifer (Heng, 2004; Jais, 2017; Yong et al., 2021), as shown in Figure 2.4.

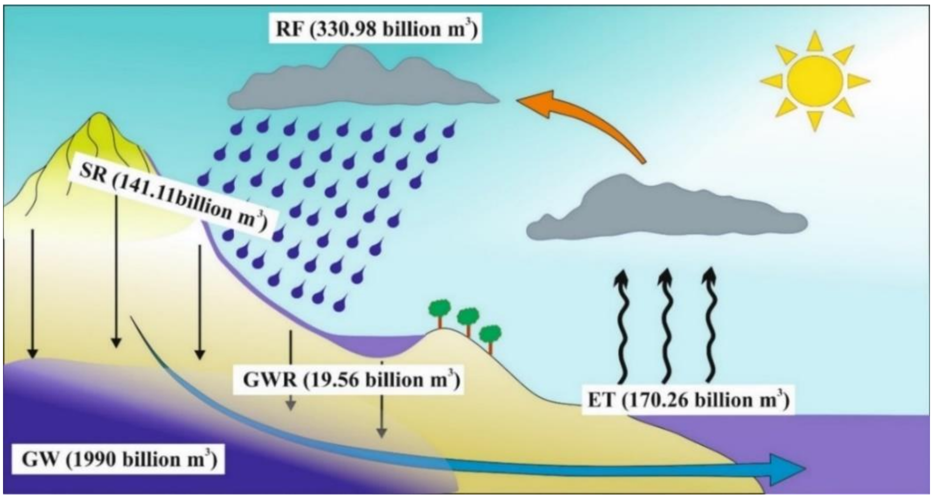

Figure 2.4 Hydrogeological balance for Peninsular Malaysia (SR is the surface runoff, RF is the rainfall, GWR is the groundwater recharge, GW is the groundwater and ET is the evapotranspiration)

In Malaysia, surface water is the primary resource of water supply, accounting for 97% of the total consumption. Only 3% remains for groundwater (Hussin et al., 2020). Here, groundwater is seen as potential alternative resource for human consumptions in Malaysia. Previous research also reported a brief study on the groundwater investigation in Malaysia where the resources have been used for various purposes such as domestic (60%), industrial (35%) and irrigation (5%). Particularly, in Peninsular Malaysia (Figure 2.5), the groundwater system is used for household (85%), industries (10%) and agriculture (5%) (Mohammed & Ghazali, 2009; Saimy & Raji, 2015).

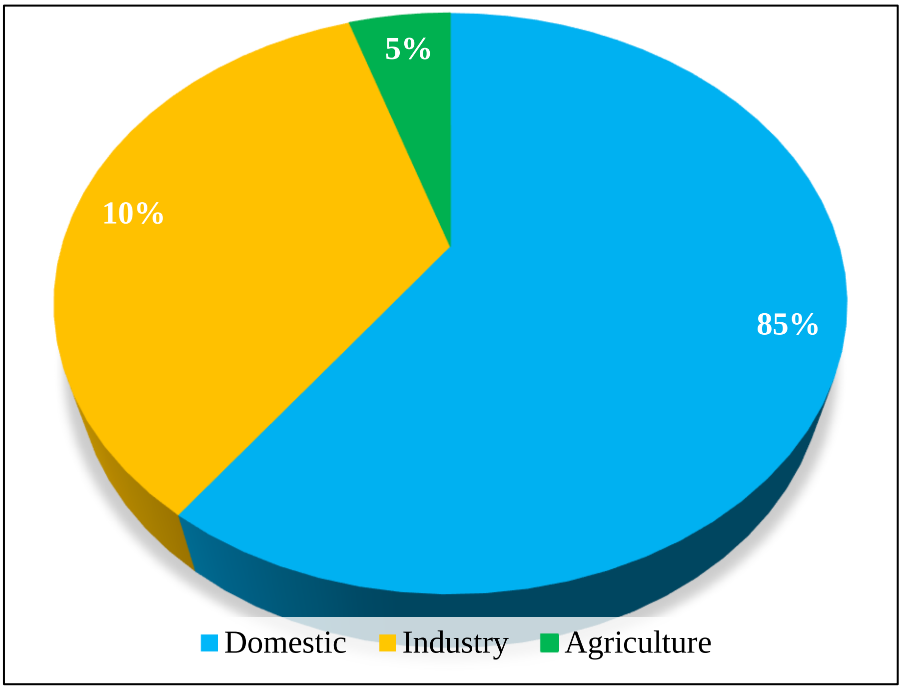

Figure 2.5 Groundwater utilization for domestic, industry and agriculture in Peninsular Malaysia

The demand for water (surface and groundwater) was expected to grow by 63% between 2000 and 2050 in Peninsular Malaysia (Jais, 2017). The groundwater demand in Peninsular Malaysia has increased since decades due to numerous factors such as surface water depletion caused by drought, increase water pollution and other issues (Heng, 2004). The groundwater demand for domestic, industrial and agriculture sectors in Peninsular Malaysia was expected to grow by 44% considering the increase amount from 13950 million m^3/year to 17675 million m^3/year 2010 to 2020, respectively (Anang et al., 2019). Note, the demand for irrigation was estimated to rise by 98% based on data reported from 2010 to 2050 while the domestic demand increased by 46% within the same period. Overall, the water demand (2000-2050) in Peninsular Malaysia is critical at three major sectors i.e., domestic, industrial, and agricultural in Peninsular Malaysia (Figure 2.6).

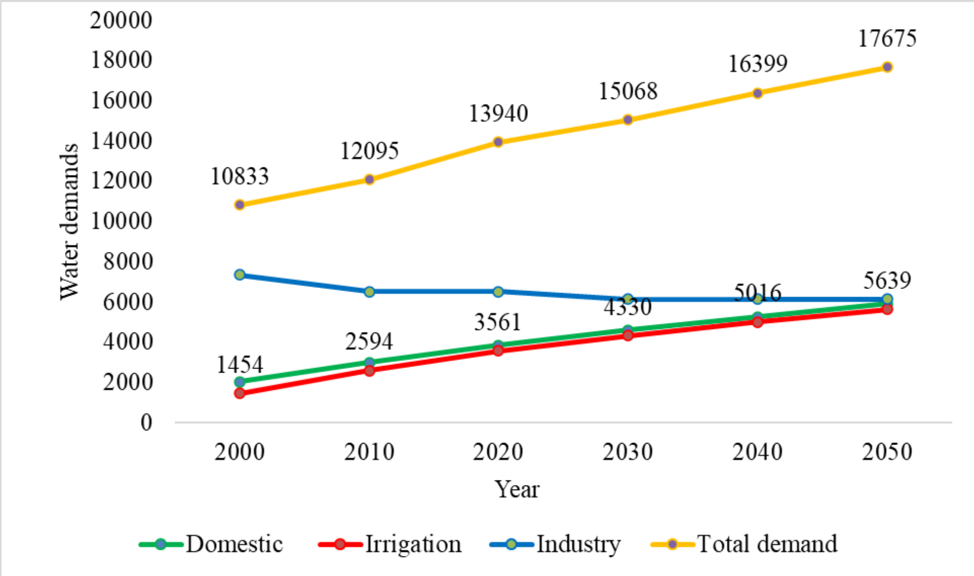

Figure 2.6 Water demand for domestic, industrial and irrigation in Peninsular Malaysia (NWRS, 2011)

Prolonged seasonal droughts and serious contamination of streams/rivers have caused a critical limitation on surface water resources. Here, it is crucial to develop a sustainable groundwater system management to support future groundwater development that would contribute significantly to our understanding on the groundwater resource exploitation, especially in Malaysia (Rajuli, 2014). The development of systematic knowledge on the hydrogeology, availability of groundwater, the purpose of usage, the demand for human consumption and sustainability matters are vital for the groundwater development initiatives.

2.2 Subsurface investigation in Peninsular Malaysia

The geological history of Peninsular Malaysia has been discussed in this section. Subsurface geological formations has been divided into four tectonic regions (Western Stable Shelf, Main Range Belt, Central Graben and Eastern Belt) (Burton, 1973; Gobbett & Hutchison, 1973). Tija and Zaiton (Tjia & Harun, 1985) have categorized the geology of Malaysia Peninsular based on lineaments that developed from tectonic activities/events such as North-West Domain, East, Central and West Domains.

The subsurface geology of Peninsular Malaysia is distinguished based on four longitudinal north-south belts such as the Eastern Belt, Benong-Raub Suture Zone, the Central Belt, and the Western Belt. In addition, these belts have been associated with the differences in stratigraphy, magmatism, structure, geological evolution, and geophysical signatures (Harbury et al., 1990; Metcalfe, 2013; Makoundi et al., 2014). Details geological setting of Peninsular Malaysia and its division was explained in Figure 2.7. Tectonically, geological events begun with seawater geosynclines sedimentation and separated into two splits through geoanticlinal ridges such as eastern eugeosyncline (deeper water deposits) and western miogeosyncline (shallower water deposits) (Roslan, 2017).

Herewith, the study area located at western area of Peninsular Malaysia is discussed. The Western Stable Shelf or Western Belt is comprised of lower and upper Palaeozoic miogeosyncline sedimentary formations. These formations are found as the gently folded and oldest formations of the Peninsula Malaysia The common geology is found in Peninsular Malaysia including shale, mudstone, sandstone, conglomerate, limestone, siltstone (sedimentary rocks), schist, Phyllite, slate, hornfels (metamorphic rocks) and usually granite (igneous rocks) (Burton, 1973; Harbury et al., 1990; Metcalfe, 2013).

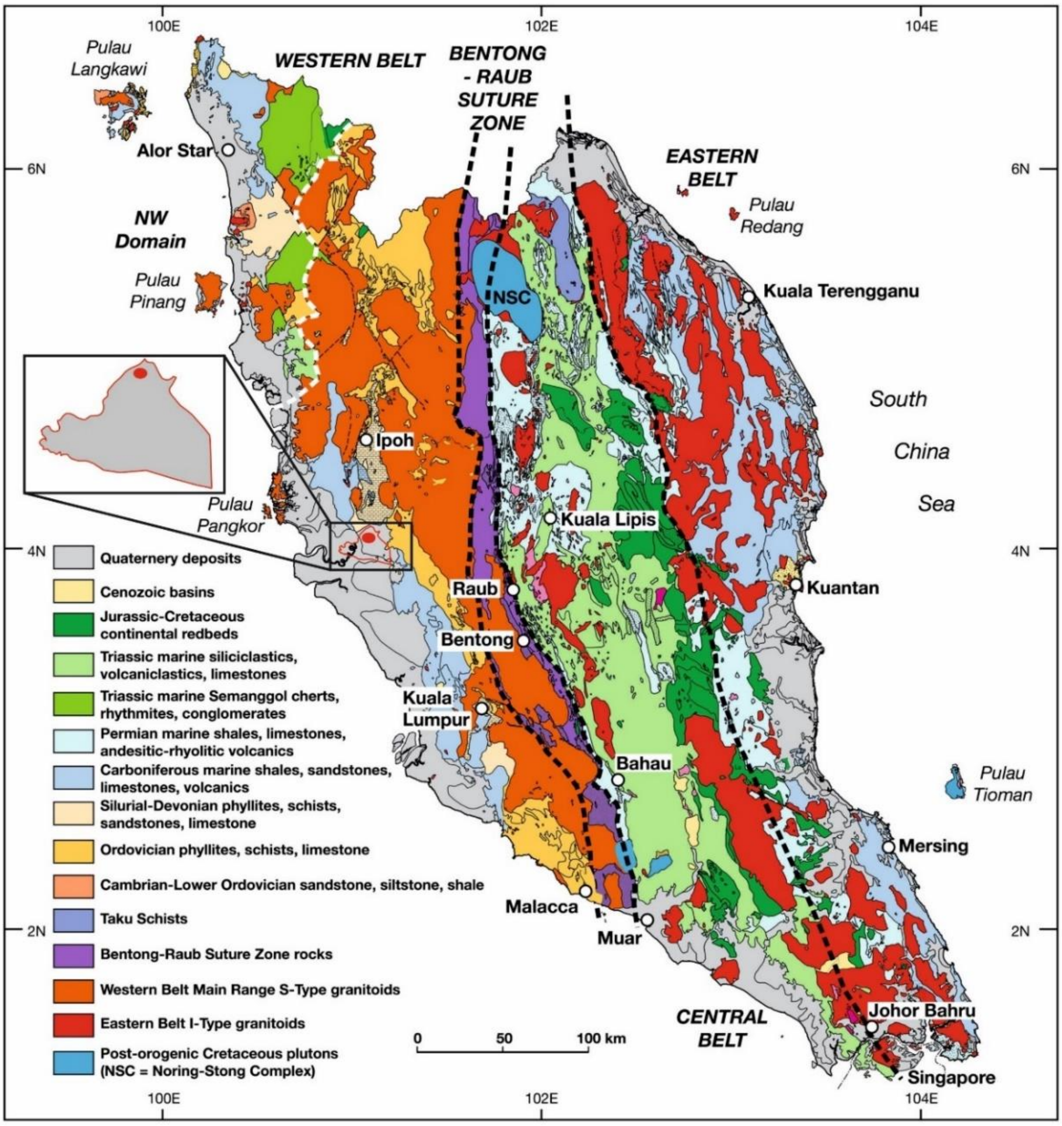

Figure 2.7 General geological map of in Peninsular Malaysia and its division (Western Belt, Benong-Raub Suture, Central Belt and Eastern Belt) (modified from Metcalfe 2013).

In this thesis, the geology of Perak has been focused subject. Perak is located in the Western belt and consists of continental sequences such as Quaternary deposits, sandstone, siltstone, shale, metamorphic rocks, and unconsolidated formations, as well as ranged from Cambrian to Quaternary period (Pour & Hashim, 2015; Sun et al., 2019). All these formations are explained in Figure 2.8.

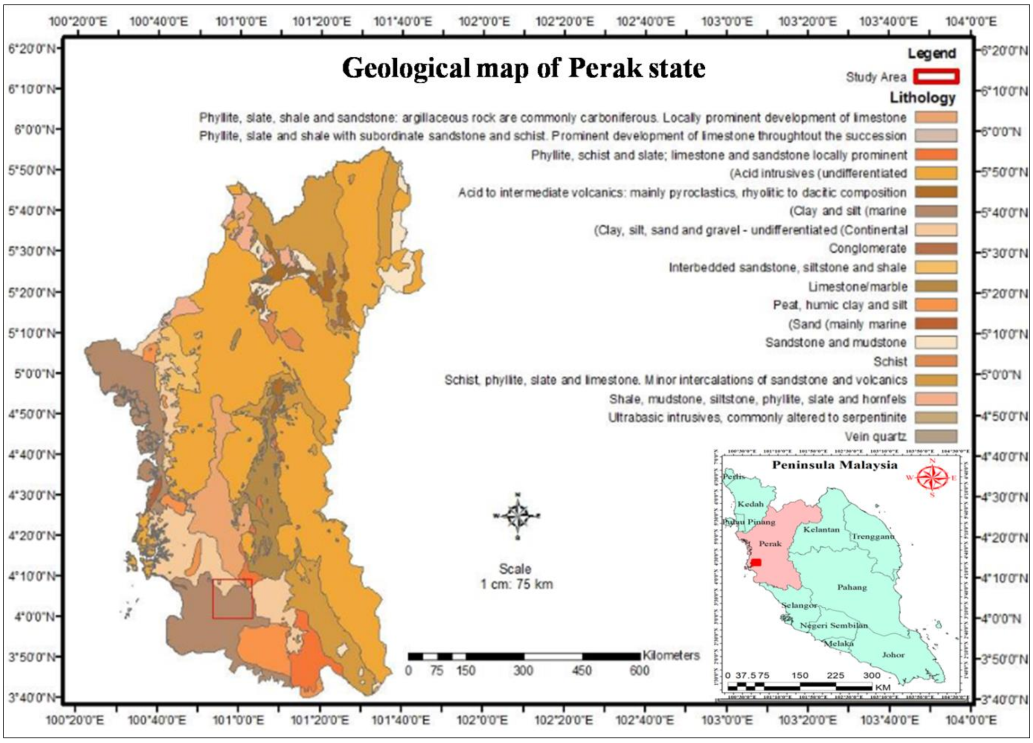

Figure 2.8 Geological map of Perak state in Peninsular Malaysia (source: Fauzi 2013)

The geological settings as discussed above are key determinant factor of groundwater flow and supply. There are three main division of Malaysia i.e., Peninsular Malaysia, Sarawak, and Sabah. The Geological Survey of Malaysia is the organization that involved actively to explore groundwater resource in Peninsular Malaysia since it was established in 1900s (Chong & Tan, 1986; Pour & Hashim, 2015; Sun et al., 2019). Historically, the Public Works Department (PWD) has investigated the first producing well in Kota Bahru, Kelantan in 1935s, followed by the groundwater exploration in Sabah (1940s) (Mohammed & Huat, 2004; Isnain & Akhir, 2012; Musa et al., 2012). Later, the groundwater extraction was also explored in Sarawak (1954) (Mohammed & Huat, 2004; Heng, 2004; Mohamed & Rushton, 2006). The groundwater exploration initiative has taking place through the Geological Survey of Malaysia (GSM) in collaboration with other related agencies i.e., Drainage and Irrigation Department of Malaysia. The most important contribution of GSM in hydrogeology research is the