INTEGRATION OF GEOINFORMATION WITH GEOLOGICAL AND GEOPHYSICAL APPROACHES FOR POTENTIAL GROUNDWATER EXPLORATION

MUHAMAD ASYRAF BIN ZAMARI

UNIVERSITI TEKNOLOGI MALAYSIA

INTEGRATION OF GEOINFORMATION WITH GEOLOGICAL AND GEOPHYSICAL APPROACHES FOR POTENTIAL GROUNDWATER EXPLORATION

MUHAMAD ASYRAF BIN ZAMARI

A thesis submitted in fulfilment of the requirements for the award of the degree of Master of Philosophy

Faculty of Built Environment and Survey
Universiti Teknologi Malaysia

MARCH 2022

DEDICATION

This research is dedicated to all those who help essentially:

Special to Ayah and Ibu and not to forget to Arwah Ibu

I REALLY MISS THEM

And

Also you,

Nur Shahkilah Binti Madom….

ACKNOWLEDGEMENT

First of all, I would like to thank my supervisor, Assoc Prof Sr Dr Tajul Ariffin Musa and Prof Dr Edy Tonnizam Mohamad, for their continued support and encouragement in completing the study. Without them, I might not have completed this thesis on time. In addition, I would also like to thank the lecturers and staff of Geoinformation, Dr Ivin Amri Musliman, Dr Wan Anom Wan Aris, Assoc Prof Dr Muhammad Zulkarnain Abdul Rahman, Assoc Prof Dr Zulkarnaini Mat Amin, Sr Dr. Tan Liat Choon and Mr Khairunizam Md Ribut for helping me in this research.

I would also like to thank my research team (GnG) and all my friends, Muhammad Farid, Muhamad Hanif Hamden, Nazrin Afiq Abdul Rahman, Muhammad Syazwan, Muhamad Hanifah, Siti Syukriah, Nur Jehan, Muhamad Fahmi, Amirul Hakim, Ikmal and Izzudin for always advising, motivating and helping me complete this study. Finally, I would like to thank my beloved family members and my future wife for their unceasing support and prayers.

ABSTRACT

Groundwater is one of the most important water source alternatives to meet daily needs especially for a clean drinking water supply. However, the major concern in groundwater exploration is to determine the precise location of the groundwater source zone. This study aimed to integrate the geoinformation approaches into the potential area of groundwater exploration area at Universiti Teknologi Malaysia (UTM), Johor. Aerial images were captured using a photogrammetry approach incorporated with precise Global Positioning System (GPS) ground control points to generate topographic map for the study area, which form as the primary data source. It was found that the positional accuracy of the horizontal and vertical components for this topographic information was 9.1 cm and 10.3 cm respectively, at 95% confidence level. Meanwhile, the secondary data source consists of geological and geophysical data. Existing geological maps were extracted, and the rock samples were collected through field geological investigations. After that, two types of geophysical data collection were implemented in the study area, namely resistivity and seismic refraction with four resistivity lines (R1-R4) and one seismic line (S1). Then, the subsurface geological information such as lithology and geological structure were combined together to evaluate the subsurface profile. The subsurface profile model indicated that the zone of low resistivity with a value <300 Ohm m was identified on the resistivity lines R2 and R3, and it was interpreted as a saturated zone that has potential as a source of groundwater. The geospatial database was developed with the used of Geographic Information System (GIS) software. A map of the potential groundwater zone was generated and two potential locations of groundwater resources, namely A1 and A2, have been identified based on the line of resistivity R2 with coordinate location is -52364.90 m E, 7748.82 m N and -52376.90 m E, 7806.70 m N, respectively. Finally, locations of these groundwater resources were marked on the ground by using the GPS real-time kinematic (RTK) method. The drilling process has discovered the groundwater source in gabbro rock aquifers with a final depth of 158 m and preliminary estimate of the groundwater rate was found more than 0.5 million of litres per day. Based on the success of the discovery of groundwater resources in the study area, it has been proven that integrating geoinformation approaches has a significant impact on groundwater exploration work.

ABSTRAK

Air bawah tanah merupakan salah satu alternatif sumber air terpenting bagi memenuhi keperluan harian terutamanya untuk bekalan air minuman yang bersih. Walau bagaimanapun, kebimbangan utama dalam penerokaan air bawah tanah adalah untuk menentukan lokasi tepat zon sumber air bawah tanah. Kajian ini bertujuan untuk mengintegrasikan pendekatan geoinformasi ke dalam kawasan potensi kawasan penerokaan air bawah tanah di Universiti Teknologi Malaysia (UTM), Johor. Imej udara telah dirakam menggunakan pendekatan fotogrametri yang digabungkan dengan titik kawalan Sistem Penentudududukan Global (GPS) yang berkejituan tinggi untuk menjana peta topografi bagi kawasan kajian yang menjadi sumber data utama. Didapati bahawa ketepatan kedudukan komponen mendatar dan menegak untuk maklumat topografi ini adalah masing-masing 9.1 cm dan 10.3 cm, pada tahap keyakinan 95%. Manakala sumber data sekunder pula terdiri daripada data geologi dan geofizik. Peta geologi sedia ada telah diekstrak, dan sampel batuan geologi telah dikumpulkan melalui penyiasatan geologi lapangan. Selepas itu, dua jenis pengumpulan data geofizik dilaksanakan di kawasan kajian iaitu kerintangan dan biasan seismik dengan empat garisan kerintangan (R1-R4) dan satu garisan seismik (S1). Kemudian, maklumat geologi bawah permukaan seperti litologi dan struktur geologi digabungkan bersama untuk menilai profil bawah permukaan. Model profil bawah permukaan menunjukkan bahawa zon kerintangan rendah dengan nilai <300 Ohm m telah dikenal pasti pada garisan kerintangan R2 dan R3 dan ia ditafsirkan sebagai zon tepu yang berpotensi sebagai sumber air bawah tanah. Pangkalan data geospasial dibangunkan dengan penggunaan perisian Sistem Maklumat Geografi (GIS). Peta zon potensi air bawah tanah telah dijana dan dua lokasi potensi sumber air bawah tanah iaitu A1 dan A2 telah dikenal pasti berdasarkan garis rintangan R2 dengan lokasi koordinat masing-masing adalah -52364.90 m E, 7748.82 m N dan -52376.90 m E, 7806.70 m N. Akhirnya, lokasi sumber air bawah tanah ini ditanda di atas tanah dengan menggunakan kaedah Kinematik Masa Hakiki (RTK) GPS. Proses penggerudian telah menemui sumber air bawah tanah di akuifer batuan gabbro dengan kedalaman akhir 158 m dan anggaran awal kadar air bawah tanah didapati lebih daripada 0.5 juta liter sehari. Berdasarkan kejayaan penemuan sumber air bawah tanah di kawasan kajian, telah terbukti bahawa pengintegrasian pendekatan geoinformasi memberi keberkesanan yang penting dalam kerja - kerja penerokaan air bawah tanah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DR	-	2D Resistivity
2D	-	2-Dimension
ASPRS		American Society of Photogrammetry and Remote Sensing
AHP	-	Analytic Hierarchy Process
AOI	-	Area of Interest
CP	-	Check Point
CORS	-	Continuously Operating Reference Station
JMG	-	Department of Minerals and Geosciences
DSMM	-	Department of Survey and Mapping
DEM	-	Digital Elevation Model
ERT	-	Electrical Resistivity Tomography
EBF	-	Evidential Belief Function
FR	-	Frequency Ratio
GDM 2000	-	Geocentric Datum of Malaysia 2000
GIS	-	Geographical Information System
GnG	-	Geomatic Innovation Research Group
GPS	-	Global Positioning System
GCP	-	Ground Control Point
GSD	-	Ground Sample Distance
JPEG	-	Joint Photographic Experts Group
MyRTKnet	-	Malaysia Real-Time Kinematic Gnss Network
MSL	-	Mean Sea Level
MP	-	Megapixel
MLD	-	Millions of Litre Per Day
NRE	-	Ministry of Natural Resources and Environment
MCA	-	Multicriteria Analysis
MCDA	-	Multicriteria Decision Analysis
NRC-net	-	National Reference CORS Network
NSSDA		National Standard for Spatial Data Accuracy
RTK	-	Real-Time Kinematic

RMSE	-	Root Mean Square Error
SR	-	Seismic Refraction
TBC	-	Trimble Business Center
USGS	-	United States Geology Survey
UTM	-	University Teknologi Malaysia
UAV	-	Unmanned Aerial Vehicle
V	-	Voltage
WLC	-	Weighted Linear Combination

LIST OF SYMBOLS

Ai	-	CP Coordinate Value from The GPS Measurement
Bi	-	CP Coordinate Value from The Aerial Photo Processing
n	-	The Total Number Of CP
°	-	Degree
’	-	Min
”	-	Sec
m	-	Meter
cm	-	Centimeter
ac	-	Acres
Ωm	-	Ohm-m
m/s	-	Meter Per Second
i	-	An Integer Ranging

CHAPTER 1

INTRODUCTION

1.1 Introduction

Groundwater is a vital component of water resources in nature and is being used in various usage such as agricultural, industrial and especially for drinking water supply. Since the demand for groundwater resources has increased with population growth, it is necessary to explore them more intensively. The groundwater resources depend greatly on the capability of water flows and the capacity to store the water underground. In addition, it is also strongly reliant on the rock and soil type, geological structures, regional environment and geomorphology factor. Therefore, proper management of surface water resources and groundwater resources are needed in groundwater exploration through systematic inventory, conservation and proper planning is essential for of any country's economic and social development.

The best approach to identify subsurface layer thickness and provide the discreet location of groundwater resources is provided by using a drilling test. However, this approach is too expensive and requires skilled manpower (Yang *et. al.*, 2018). Nowadays, the integration of geological and geophysical studies is commonly used in groundwater exploration. Usually, this approach is combined with geoinformation knowhow such as field survey and supported with existing topographic and thematic maps. Nevertheless, the advancement in geoinformation applications such as aerial photo mapping, precise global positioning system (GPS) surveying and geographical information system (GIS) data management could be utilized to augment the groundwater exploration (Savita *et. al.*, 2018; Pandey *et. al.*, 2014; Sinha *et. al.*, 2012; Rahman, 2008). Moreover, the applications of geoinformation approach such as GIS application can be cost effective and time efficient to assess and manage geospatial information of groundwater resources (Nampak *et. al.*, 2014; Manap *et. al.*, 2013).

Malaysia is a tropical country that experiences hot and humid summer throughout the year and receives an annual rainfall of 2500 mm to 3000 mm contributed to the country's water resource needs (Paterson et. al., 2015). In general, water resources in Malaysia can be divided into surface water resources and groundwater (shallow groundwater - deep rock aquifers). In addition, Malaysia has adequate surface water reserves based on the total number of rivers and lakes reservoirs available. In 2016, surface water consumption rate for Malaysia is 13330.6 million litres per day (MLD) and 95% from the clean water supply is channelled from the rivers and existing dams (JMG, 2019). However, some problems aroused concerning these surface water resources especially in meeting the demands of clean water supply for the daily usage. Factors contributing to these problems was the level of water pollution is at an alarming state and also climate change. These factors resulted in the clean water treatments cost to be unreasonably increased and consequently declining the water levels in water catchment areas.

Hence, there is an alternative to overcome this problem by fully utilized of groundwater resources. This resource has unlimited reserves and availability to continuously supply fresh water. Therefore, groundwater exploration in this country requires support and integration of the modern geoinformation approaches into the exploration works, which can produce high chances to identify groundwater resources potential zone

1.2 Problem Background

Water is the basic human need; however, many countries nowadays face a lack of adequate supply of freshwater to fulfill demand in several important sectors such as agriculture, industry and drinking water. According to a statement from the world water development report in 2015 (UNESCO, 2015), water demand will increase by 55 per cent by 2030. However, existing reserves of water resources can only supply 60 per cent of the world’s water needs. Moreover, Malaysia is also facing a problem meeting the demand for fresh water supply. This problem is due to nature environment and the human impact such as climate change and water pollution at the critical levels.

Consequently, there is an alternative of groundwater resources to fulfill the demand of water supply. This distinct groundwater or specifically rock aquifer usually has unlimited reserves of fresh water supply.

Groundwater exploration studies are increasingly being implemented in several developed countries, which include Malaysia. Furthermore, the major challenge of this exploration is to identify the precise location and depth of the potential that exists in the deep rock aquifer which could provide a more sustainable water resource. The drilling approach is one of the best methods often used to identify the source location of this aquifer. However, this method is difficult to operate, expensive and time-consuming (Ahmed & Mansor, 2018; Manap *et. al.*, 2014). Therefore, this exploration requires effective approaches and expertise to understand the criteria of subsurface geological systems (Tajuddin *et. al.*, 2018).

Several groundwater exploration studies are conducted with the integration of geological and geophysical approaches in Malaysia (Ilahi *et. al.*, 2021; Zakaria *et. al.*, 2020; Aziman *et. al.*, 2018; Nazaruddin *et. al.*, 2017; and Saad *et.al*., 2012). However, there is a lack of researchers who have applied and integrated comprehensive geoinformation approaches in the exploration the lack of exposure and application of incorporation geoinformation approach along with geological and geophysical approach in groundwater exploration. The geoinformation approach focuses on the use of remote sensing and GIS analysis in groundwater exploration (Mogaji & Lim, 2017; Manap *et. al.*, 2014; Nampak *et. al.*, 2014; and Manap *et. al.*, 2013).

In addition, there are deficiencies in the management system of the study data. the constraints of systematic and effective management of groundwater survey data are a factor in the difficulty of the implementing the groundwater survey (Abdulazeez, 2018). Moreover, this study of groundwater exploration still lacks in Johor, especially in the southern of Johor because the implementation of this exploration is focused on areas with problems in the lack of clean water supply such as in Kelantan and Perlis (Saifuddin et. al., 2021).

Therefore, the UTM Johor Bahru Campus area located in the southern Johor has been selected to study the potential of groundwater resources. In fact, geoinformation approaches are used and applied together with geological and geophysical approaches in order to identify and increase the chances of discovering groundwater resources in this study. There are three (3) geoinformation approaches applied in the study namely GPS measurement, photogrammetry measurement integrated with UAV technology and GIS approach. The study also focuses on the management of research data by using the GIS approach.Thus, these exploratory works can be enhanced by integrating modern approaches in geoinformation to develop potential groundwater zone renewal maps, geospatial data management reforms and precise spatial placement for groundwater exploration. Therefore, it is desirable to explore further the opportunities to apply the latest geoinformation approaches into groundwater exploration.

1.3 Research Aim

This study aims to integrate of geoinformation approaches into the potential of groundwater exploration.

1.4 Research Objectives

To achieve the aim of the study, the following objectives are specified:

I. To develop a geospatial database for groundwater exploration,

II. To analyse the potential of groundwater zones based on the geospatial database.

III. To locate the potential location of groundwater resources in the study area.

1.5 Research Scope

The scopes of this study are given as follows:

I. The area for this study is in the Universiti Teknologi Malaysia (UTM) Johor Bahru campus, Johor as shown in Figure 1.1. The study area covered the whole campus about 2,816 acres (ac).

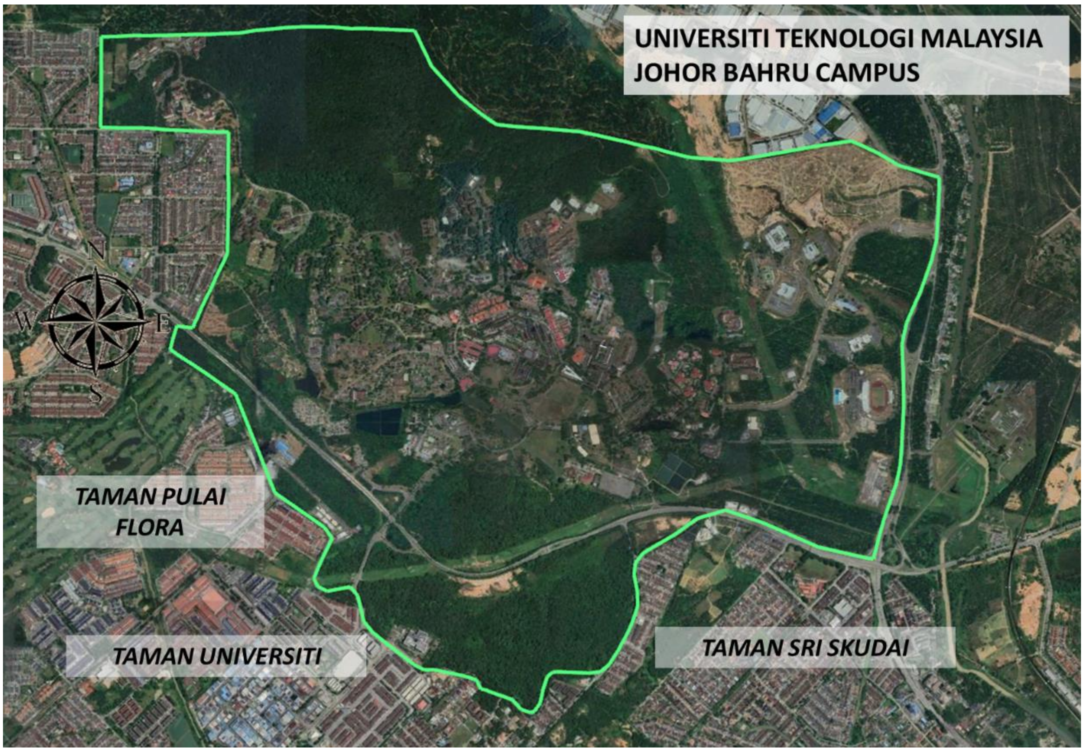

Figure 1.1 Location of the study area.

II. There are two types of data was used in this study, namely primary and secondary data. Primary data involving GPS observations data and digital aerial imagery. Meanwhile, secondary data involves geological and geophysical mapping information based on previous studies in the study area.

III. Integration of geological, geophysical and topographic information in developing of geospatial databases to produce potential maps of groundwater resource zones using GIS environment.

IV. The implementation of GPS data observations only focuses on the utilized of satellite constellations from GPS satellites only.

1.6 Significance of the Study

The significance of this study can be summarized as follows:

1. This study will help position potential exploration groundwater accurately and develop a database by integrating the geological and geophysical approach into geoinformation applications.
2. This study will help better understand subsurface profile condition in order to identify the location potential zone of groundwater in this study.
3. From this study, the potential zones of groundwater resources and suitable geospatial locations for potential exploration of groundwater shall be identified.

1.7 Thesis Structure

The thesis structures consist of five chapters. The descriptions for each chapter are as follows:

Chapter 1: Introduction

This chapter described the background, problem statement, objectives of study, scope and significance of the study.

Chapter 2: Literature Review

This chapter has been focused on several topics such as exploration of the status of utilization of groundwater and its exploration groundwater in Malaysia are also discussed. This chapter also reviewed the integration of geoinformation approach in groundwater resources exploration and the interpretation of groundwater potential zone by using subsurface and geoinformation approach.

Chapter 3: Research Methodology

Describes the research methodology for this research. This proposal is divided into five different phases as mentioned in sub-chapter 1.7. The methodology is set out to achieve the objectives of the research. Besides, it explained about the method of data acquisition and pre-processing.

Chapter 4: Result and Discussions

This chapter discussed on the analysis of the accuracy assessments which were carried out on the final coordinate for GPS measurement data and aerial photo mapping used to produce information of topographic in the study area. Subsequently, the final results of these measurements have been utilized for geospatial database development for groundwater exploration in UTM by adopting the GIS approach. This geospatial database was used to generate several thematic maps related to topographic information and subsurface information. Next, the thematic map was used to analyses the potential of groundwater resource zones within the study area. Based on the potential map, the location marking of the potential of groundwater resources is carried out by using the GPS RTK measurement method in the field before drilling of groundwater resources in the study area.

Chapter 5: Conclusion and Recommendations

This chapter summarizes the thesis and draws some conclusions. Several recommendations were suggested for further works in the future**.**

REFERENCES

Abdulazeez, A. (2018). A Spatial Assessment and Mapping of Groundwater Potentials in Parts of North-Western Kano State, Nigeria. *Techno Science Africana Journal*, 14 (1), 103-114. ISSN: 2006, 2273.

Adagunodo, T. A., Akinloye, M. K., Sunmonu, L. A., Aizebeokhai, A. P., Oyeyemi, K. D., & Abodunrin, F. O. (2018). Groundwater exploration in Aaba residential area of Akure, Nigeria. *Frontiers in Earth Science*, 6, 66.

Adiat, K. A. N., Nawawi, M. N. M., & Abdullah, K. (2012). Assessing the accuracy of GIS-based elementary multi criteria decision analysis as a spatial prediction tool–a case of predicting potential zones of sustainable groundwater resources. *Journal of Hydrology*, 440, 75-89.

Ahmed II, J. B., & Mansor, S. (2018). Overview of the application of geospatial technology to groundwater potential mapping in Nigeria. *Arabian Journal of Geosciences*, 11(17), 1-16.

Alnour, I. A., Wagiran, H., Ibrahim, N., Hamzah, S., Elias, M. S., Laili, Z., & Omar, M. (2013). Assessment of natural radioactivity levels in rocks and their relationships with the geological structure of Johor State, Malaysia. *Radiation Protection Dosimetry*, 158(2), 201-207.

American Society for Photogrammetry and Remote Sensing (ASPRS). (2015). ASPRS positional accuracy standards for digital geospatial data. *Photogramm. Eng. Remote Sens.*, 81(3), A1-A26.

Araffa, S. A., Mohamadin, M. I., Saleh Sabet, H., & Takey, M. S. (2019). Geophysical interpretation for groundwater exploration around Hurghada area, Egypt. *NRIAG Journal of Astronomy and Geophysics, 8(1), 171-179*

Asry, Z., Samsudin, A. R., Yaacob, W. Z., & Yaakub, J. (2012). Groundwater investigation using electrical resistivity imaging technique at Sg. Udang, Melaka, Malaysia. *Bulletin of the Geological Society of Malaysia*, 2(58), 55–58.

Aziman, M., Hazreek, Z. A. M., Azhar, A. T. S., Fahmy, K. A., Faizal, T. B. M., Sabariah, M., Ambak, K., & Ismail, M. A. M. (2018). Electrical resistivity technique for groundwater exploration in quaternary deposit. *Journal of Physics: Conference Series*, 995(1), 012110.

Azizan, F. A., Aznan, A. A., Ruslan, R., Nazari, M., & Jaafar, M. N. (2018). Groundwater assessment using geophysical survey at Insat, Perlis, Malaysia. *IOP Conference Series: Materials Science and Engineering*, 429(1).

Baharuddin, M. F. T. (2016). Remapping of water resources in Johor opens up opportunities for alternatives. https://www.nst.com.my/news/2016/05/142888/remapping-water-resources-johor-opens-opportunities-alternatives

Balasubramanian, A. (2007*)*. Methods of groundwater exploration*. Centre for Advanced Studies in Earth Science, University of Mysore.*

Barker, D. S. (1983). Igneous rocks. Prentice Hall.

Bradybrooke, J.C. (1988). The state of art of rock cuttability and rippability prediction. *Fifth Australia-New Zealand Conference on Geomechanics. Sydney*, 13-42.

Caterpillar Performance Handbook, Edition 31. (2001). Peoria,Illnois, USA: CAT publication, Caterpillar Inc.

Chao, W.A., Lin, C.H., Yang, C.M., Kang, K.H., Kuo, Y.T., Nugi, J., Chung, M.C., Lin, C.P. & Tai, T.L., (2020). Seismologically understanding the basal sliding depth and groundwater level for deep-seated landslide. *EGU General Assembly Conference Abstracts*, 8862.

Dabove, P. (2019). The usability of GNSS mass-market receivers for cadastral surveys considering RTK and NRTK techniques. *Geodesy and Geodynamics*, 10(4), 282-289.

Darwin, N., Ahmad, A., & Akib, W. A. A. W. M. (2014). The potential of low altitude aerial data for large scale mapping. *Jurnal Teknologi*, 70(5).

Department of Mineral and Geoscience Malaysia (JMG) (2019). Groundwater Overview in Malaysia. *National Groundwater Conference 2019*, 1–54.

Department of Surveying & Mapping Malaysia (DSMM) (2005). Garis panduan mengenai penggunaan perkhidmatan Malaysian RTK GPS Network (MyRTKnet). In *Pekeliling Ketua Pengarah Ukur Dan Pemetaan Bil. 9 Tahun 2005.*

Ghofur, M. N. A., Udin, W. S., Mansor, H. E., & Khan, M. M. A. (2020). Mapping of groundwater potential zones in a crystalline terrain using remote sensing, GIS techniques and field observations: a case study in parts of Tanah Merah, Kelantan, Malaysia. *IOP Conference Series: Earth and Environmental Science,* 549(1), 012026.

Griffiths D.H. & Barker R.D., 1993. Two-dimensional resistivity imaging and modelling in areas of complex geology. *Journal of Applied Geophysics*, 29, 211-226.

Hamzah, U., Yaacup, R., Samsudin, A. R., & Ayub, M. S. (2006). Electrical imaging of the groundwater aquifer at Banting, Selangor, Malaysia. *Environmental Geology,* 49(8), 1156.

Hatta A. K. (2010). Issues and challenges of groundwater data collection, organisation and usage.

Hatta, A. M., & Rashid, B. A. (1999). Groundwater resources in johor, malaysia: resource potential and information management. http://www.groundwater.org/get-informed/basics/whatis.html.

Hazreek, Z. A. M., Raqib, A. G. A., Aziman, M., Azhar, A. T. S., Khaidir, A. T. M., Fairus, Y. M., Rosli, S., Fakhrurrazi, I. M., & Izzaty, R. A. (2017). Preliminary Groundwater Assessment using Electrical Method at Quaternary Deposits Area. *IOP Conference Series: Materials Science and Engineering*, 226(1).

How Jin Aik, D., Ismail, M. H., & Muharam, F. M. (2020). Land use/land cover changes and the relationship with land surface temperature using Landsat and MODIS imageries in Cameron Highlands, Malaysia. Land, 9(10), 372.

Ilahi, W. F. F., Hassan, N. H. A., Ismail, M. R., Che'Ya, N. N., Berahim, Z., Omar, M. H., Zakaria, N. I., & Zawawi, M. A. M.(2021). Potential groundwater exploration in use of 2-D Electrical Resistivity Tomography (ERT) techniques at the department of agriculture kelantan research and developmental platform Padang Raja Kelantan. *Pertanika Journal of Science and Technology,* 29(2), 1219–1228.

Isnain, Z. & Akhir, J. M. (2017). Integrated GIS based approach in mapping groundwater potential zones in Kota Kinabalu, Sabah, Malaysia. *Indonesian Journal on Geoscience,* 4(2), 111–120.

Jakosky, J. J. (1950). Exploration geophysics, 2nd edition, *Newport Beach, Calif. : Trija Pub. Co., c1950.*

Jhariya, D. C., Kumar, T., Gobinath, M., Diwan, P., & Kishore, N. (2016). Assessment of groundwater potential zone using remote sensing, GIS and multi criteria decision analysis techniques. *Journal of the Geological Society of India*, 88(4), 481-492.

Juanah, M. S., Ibrahim, S., Sulaiman, W. N. A., & Latif, P. A. (2013). Groundwater resources assessment using integrated geophysical techniques in the southwestern region of Peninsular Malaysia. *Arabian Journal of Geosciences*, 6(11), 4129-4144.

Kandel, A. (1983). The Analytic Hierarchy Process-Planning, Priority Setting, Resource Allocation, Thomas L. Saaty (Ed.), McGraw-Hill, Basel (1980), p. 287.

Karim, M.H., (2006) Groundwater resources in Malaysia: issues and challenges. *Technical papers volume 3. Minerals and Geoscience Department Malaysia*

Keller, G.V., & Frischknecht, F.C. (1966). Electrical methods in geophysical prospecting. *Pergamon Press Inc., Oxford*.

Korumaz, S. A. G., & Yıldız, F. (2021). Positional accuracy assessment of digital orthophoto based on UAV images: an experience on an archaeological area. *Heritage*, 4(3), 1304-1327.

Kumar, P., Herath, S., Avtar, R., & Takeuchi, K. (2016). Mapping of groundwater potential zones in Killinochi area, Sri Lanka, using GIS and remote sensing techniques. *Sustainable Water Resources Management*, 2(4), 419-430.

Lee, S. C. H., Noh, K. A. M. and Zakariah, M. N. A. (2021). High-resolution electrical resistivity tomography and seismic refraction for groundwater exploration in fracture hard rocks: A case study in Kanthan, Perak, Malaysia. *Journal of Asian Earth Sciences*, 218,104880.

Li, Z., Taylor, J., Frewer, L., Zhao, C., Yang, G., Liu, Z., Gaulton, R., Wicks, D., Mortimer, H., Cheng, X., & Sun, Z. (2019). A comparative review on the state and advancement of Site-Specific Crop Management in the UK and China. *Frontiers of Agricultural Science and Engineering*.

Loke, M.H. & Barker, R.D. (1996). Practical techniques for 3-D resistivity surveys and data inversion. *Geophysics,* 44:499-523.

Madrucci, V., Taioli, F., & de Araújo, C. C. (2008). Groundwater favorability map using GIS multicriteria data analysis on crystalline terrain, Sao Paulo State, Brazil. *Journal of Hydrology,* 357(3-4), 153-173.

Madun, A., Madun, S. A. A., Sahdan, M. Z., Dan, M. F. M., & Talib, M. K. A. (2018). Electrical resistivity and induced polarization techniques for groundwater exploration. *International Journal of Integrated Engineering*, 10(8), 56–60.

Madun, S. A. A., Said, M. J. M., Madun, A., Zainalabidin, M. H., & Sahdan, M. Z. (2018). Groundwater exploration in granitic rock formation using electrical resistivity and induced polarization techniques. *Journal of Physics: Conference Series*, 1049 (1), 012076.

Manap, M. A., Nampak, H., Pradhan, B., Lee, S., Sulaiman, W. N. A., & Ramli, M. F. (2014). Application of probabilistic-based frequency ratio model in groundwater potential mapping using remote sensing data and GIS. *Arabian Journal of Geosciences*, 7(2), 711–724.

Manap, M. A., Sulaiman, W. N. A., Ramli, M. F., Pradhan, B., & Surip, N. (2013). A knowledge-driven GIS modeling technique for groundwater potential mapping at the Upper Langat Basin, Malaysia. *Arabian Journal of Geosciences*, 6(5), 1621-1637.

Manu, E., Agyekum, W. A., Duah, A. A., Tagoe, R., & Preko, K. (2019*)*. Application of vertical electrical sounding for groundwater exploration of Cape coast municipality in the central region of Ghana. *Arabian Journal of Geosciences, 12(6), 1-11*.

Mogaji, K. A. & Lim, H. S. (2017). Application of a GIS-/remote sensing-based approach for predicting groundwater potential zones using a multi-criteria data mining methodology. *Environmental Monitoring and Assessment*, 189(7).

Mohamaden, M. I., & Ehab, D. (2017). Application of electrical resistivity for groundwater exploration in Wadi Rahaba, Shalateen, Egypt. *NRIAG Journal of Astronomy and Geophysics*, 6(1), 201-209.

Mohana, P., & Muthusamy, S. (2021). Use of earth observation images and GIS techniques for groundwater exploration in hard rock terrain. *Journal of Geography and Cartography*, 4(1).

Moss R, Moss GE (1990). Handbook of ground water development. *Wiley-Interscience, New York*, 34–51.

Mukherjee P, Singh CK, Mukherjee S (2012). Delineation of groundwater potential zones in arid region of India a remote sensing and GIS approach. *Water resources management*, 26(9), 2643–2672.

Nampak, H., Pradhan, B. & Manap, M. A. (2014). Application of GIS based data driven evidential belief function model to predict groundwater potential zonation. *Journal of Hydrology*, 513, 283–300.

Narany, T. S., Aris, A. Z., Sefie, A., & Keesstra, S. (2017). Detecting and predicting the impact of land use changes on groundwater quality, a case study in Northern Kelantan, Malaysia. *Science of the Total Environment*, 599–600, 844–853.

Nazaruddin, D. A., Amiruzan, Z. S., Hussin, H., & Jafar, M. T. M. (2017). Integrated geological and multi-electrode resistivity surveys for groundwater investigation in Kampung Rahmat village and its vicinity, Jeli district, Kelantan, Malaysia. *Journal of Applied Geophysics*, 138, 23-32.

Oyeyemi, K. D., Aizebeokhai, A. P., & Olofinnade, O. M. (2018). Geoelectrical investigations for groundwater exploration in crystalline basement terrain, SW Nigeria: implications for groundwater resources sustainability. *International Journal of Civil Engineering and Technology*, 9(6), 765-772.

Pandey, N. K., Shukla, A. K., Shukla, S., & Pandey, M. (2014). Assessment of underground water potential zones using modern geomatics technologies in Jhansi district, Uttar Pradesh, India. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(8), 377.

Paterson, R. R. M., Kumar, L., Taylor, S., & Lima, N. (2015). Future climate effects on suitability for growth of oil palms in Malaysia and Indonesia. Scientific reports, 5, 14457.

Puengnate, M. S., & Pramsane, C. S, (2012). The evaluation of exterior orientation parameters from global positioning system and inertial measurement unit in the test field. *Asian Conference on Remote Sensing,1-8.*

Rahman, A. (2008). A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India. *Applied geography*, 28(1), 32-53.

Rolia, E., & Sutjiningsih, D. (2018). Application of geoelectric method for groundwater exploration from surface (A literature study). *AIP Conference Proceedings*, 1977(1), 020018.

Ruiz-Lendínez, J. J., Ariza-López, F. J., & Ureña-Cámara, M. A. (2019). Study of NSSDA variability by means of automatic positional accuracy assessment methods. *ISPRS International Journal of Geo-Information*, 8(12), 552.

Saad, R., Nawawi, M. N. M., & Mohamad, E. T. (2012). Groundwater detection in alluvium using 2-D electrical resistivity tomography (ERT). *Electronic Journal of Geotechnical Engineering*, 369–376.

Saifuddin, M. F. U., Ash'aari, Z. H., Aris, A. Z., & Mohd, F. (2021). A hybrid gis and knowledge-driven approach for water resources potential zonation. *International Journal of GEOMATE*, 21(83), 56–64.

Saimy, I. S., & Raji, F. (2015). Applications and sustainability in groundwater abstraction in Malaysia. *Jurnal Teknologi*, 73(5).

Sajjad, H., Iqbal, M., & Bhat, F. A. (2014). Integrating geospatial and geophysical information for deciphering groundwater potential zones in Dudhganga catchment, Kashmir Valley, India. *American Journal of Water Resources*, 2(1), 18-24.

Samsudin, A. R., Rafek, A. G., & Hamzah, U. (1996). Geophysical investigation for groundwater exploration at UKM's Kuala Pilah Matriculation Centre, Negeri Sembilan.

Sander, P., Chesley, M. M., & Minor, T. B. (1996). Groundwater assessment using remote sensing and GIS in a rural groundwater project in Ghana: lessons learned. *Hydrogeology Journal*, 4(3), 40-49.

Savita, R. S., Mittal, H. K., Satishkumar, U., Singh, P. K., Yadav, K. K., Jain, H. K., & Davande, S. (2018). Delineation of Groundwater Potential Zones using Remote Sensing and GIS Techniques in Kanakanala Reservoir Subwatershed, Karnataka, India. *Int J Curr Microbiol App Sci*, 7(1), 273-288.

Shirazi, S. M., Imran, H. M., Akib, S., Yusop, Z., & Harun, Z. B. (2013). Groundwater vulnerability assessment in the Melaka State of Malaysia using DRASTIC and GIS techniques. *Environmental earth sciences*, 70(5), 2293-2304.

Siemon, B., Christiansen, A. V., & Auken, E. (2009). A review of helicopter-borne electromagnetic methods for groundwater exploration. *Near Surface Geophysics*, 7(5-6), 629-646.

Sinha, D. D., Mohapatra, S. N., & Pani, P. (2012). Mapping and assessment of groundwater potential in bilrai watershed (Shivpuri District, MP)—A

Geomatics Approach. *Journal of the Indian Society of Remote Sensing*, 40(4), 649-668.

Suratman S (2004) IWRM: managing the groundwater component. Paper presented at Malaysia Water Forum, Kuala Lumpur, Malaysia.

Syukri, M. S., Samat, N., & Ismail, M. H. (2021). The Integration of GIS, AHP, and Remote Sensing Methods for Potential Areas Groundwater: Case Study for Pontian District, Johor, Malaysia. *Malaysian Journal of Geosciences (MJG)*, 5(1), 6–11.

Tan, S. T., Lee, C. T., Hashim, H., Ho, W. S., & Lim, J. S. (2014). Optimal process network for municipal solid waste management in Iskandar Malaysia. *Journal of Cleaner Production*, 71, 48-58.

Telford, W. M., & Sheriff, R. F.(1984). Applied Geophysics, *Cambridge University Press.*

Udin, W. S., & Ahmad, A. (2014). Assessment of photogrammetric mapping accuracy based on variation flying altitude using unmanned aerial vehicle. In *IOP conference series: earth and environmental science*, 18(1).

United Nations Educational, Scientific and Cultural Organization (UNESCO) (2015). Water for a sustainable world. *The United Nations World Water Development Report 2015.*

United Stated Geological Survey USGS (2017, January 23) Geologic mapping field methods. https://ncgmp.usgs.gov/geomaps/field_methods.html

Yang, F., Gao, P., Li, D., Ma, H., & Cheng, G. (2018). Application of comprehensive geophysical prospecting method in groundwater exploration. *IOP Conference Series: Earth and Environmental Science,* 108(3), 032022.

Zakaria, M. T., Muztaza, N. M., Olugbenga, A. T., Saad, R., & Rahman, M. N. A. (2018). Self-potential and 2-D resistivity application for groundwater exploration in fractured reservoirs. *Songklanakarin Journal of Science and Technology,* 42(2), 292–298.

Zamari, M. A., Musa, T. A., Mohamad, E. T., Musliman, I. A., & Aris, W. A. W. (2019). Geospatial approach for groundwater exploration at UTM Johor Bahru Campus. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(4/W16).

LIST OF PUBLICATIONS

Zamari, M. A., Musa, T. A., Mohamad, E. T., Musliman, I. A., & Aris, W. A. W. (2019). Geospatial approach for groundwater exploration at UTM Johor Bahru Campus. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(4/W16).

Zamari, M. A., Musa, T. A., & Mohamad, E. T., (2021). Geospatial approach for geological investigation at district of Mersing. *International Graduate Conference of Built Environment and Surveying*.