# ESTIMATION AND MODELLING OF OLAK LEMPIT PEATLANDS BASED ON GROUND PENETRATING RADAR AND LABORATORY INVESTIGATION

NURUL IZZATI ABD KARIM

UNIVERSITI TEKNOLOGI MALAYSIA

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NURUL IZZATI ABD KARIM

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Universiti Teknologi Malaysia

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# DEDICATION

*To my beloved :*

*husband,*

*mama,*

*abah*

*family*

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# ABSTRACT

Peat soil is an important ecosystem which acts as natural fertilizer that can increase the quality of soil and is considered as gold mine for the agriculturists and farmers. Hence, the knowledge of peat soil properties which is high in water content must be well understood. During dry periods, if water content is lower than the point of no return, the soil will shrink. Hence, by determining the accurate water content of peat soil during dry and wet seasons, the quality of peat soil can be enhanced. The aim of the thesis is to determine accurately the soil water content (SWC) estimation of peat soil using Ground Penetrating Radar (GPR) especially during wet and dry seasons. To achieve this aim, a site-specific petrophysical relationship model for SWC estimation was developed for wet and dry seasons. Samples of peat soils were collected during dry and wet seasons for laboratory measurements by utilising two processes namely dielectric permittivity determination and water content estimation. A 2-dimensional soil cylindrical capacitor was designed to measure the capacitance from the results of current and voltage produced by the samples. Then, dielectric permittivity of the soil was calculated using an equation. After the 24-hour oven-drying process at 105°C, the water content of the peat samples was measured. The results obtained from both measurements were used as a parameter for modelling the site-specific petrophysical relationship of wet and dry seasons. Third-order polynomial was found to be the best fitting model for dry season with the result of $R^2$ = 0.944 and standard error = 0.146 and wet season with $R^2$ = 0.981 and standard error = 0.063. Three existing models namely Roth model; Schaap model and Idi model were evaluated along with the third-order polynomial model and validated by gravimetric measurements for dry and wet seasons. Based on the result, the proposed model gives the most accurate measurement of water content with RMSE for dry and wet seasons at 0.15 and 0.17 respectively. The findings suggest the importance of site-specific petrophysical relationship to estimate water content using GPR and laboratory investigation for wet and dry seasons.

# ABSTRAK

Tanah gambut merupakan ekosistem penting yang bertindak sebagai baja semulajadi yang boleh meningkatkan kualiti tanah dan dianggap sebagai lombong emas bagi petani dan penternak. Oleh itu, pengetahuan tentang sifat tanah gambut yang tinggi kandungan airnya perlu difahami sepenuhnya. Semasa tempoh pengeringan, jika kandungan air lebih rendah ke titik tanpa pengembalian, tanah akan mengecut. Oleh itu, dengan menentukan kandungan air yang tepat dari tanah gambut semasa musim kering dan basah, kualiti tanah gambut boleh dipertingkatkan secara strategik. Tujuan kajian ini adalah untuk menentukan anggaran kandungan air (SWC) dengan tepat dalam tanah gambut menggunakan *Ground Penetrating Radar* (GPR) terutamanya semasa musim basah dan kering. Untuk mencapai matlamat ini, model perhubungan petrofisik spesifik tapak untuk perkiraan SWC telah dibangunkan untuk musim basah dan kering. Sampel tanah gambut dikumpulkan semasa musim kering dan basah untuk pengukuran makmal dengan menggunakan dua proses iaitu penentuan kepelbagaian dielektrik dan anggaran kandungan air. Kapasitor silinder direka bentuk untuk mengukur kapasitan hasil daripada keputusan arus dan voltan yang dihasilkan oleh sampel. Kemudian, kepelbagaian dielektrik tanah dikira menggunakan persamaan. Selepas proses pengeringan oven pada 105° C selama 24 jam, kandungan air sampel tanah gambut dianggarkan. Hasil yang diperoleh dari kedua-dua ukuran telah digunakan sebagai parameter untuk membentuk hubungan petrofisik spesifik tapak untuk musim basah dan kering. Polinomial ketiga yang didapati sebagai model yang terbaik untuk musim kering dengan $R^2 = 0.944$ dan kesilapan standard = 0.146 dan musim basah dengan $R^2 = 0.981$ dan kesilapan standard = 0.063. Tiga model sedia ada iaitu model Roth, model Schaap dan model Idi telah dinilai dengan model polinomial ketiga dan disahkan oleh pengukuran gravimetrik untuk musim kering dan basah. Daripada hasilnya, model yang dicadangkan memberikan pengukuran kandungan air yang paling tepat dengan RMSE untuk musim kering dan basah 0.15 dan 0.17. Penemuan daripada kajian menunjukkan bahawa pentingnya hubungan masing-masing pada petrofisik spesifik tapak untuk menganggarkan kandungan air menggunakan GPR dan penyelidikan makmal untuk musim basah dan kering.

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# LIST OF ABBREVIATIONS

a.c - Alternate Current
ANOVA - Analysis of Variance
ASTMD - American Society for Testing and Materials
CMP - Common Mid-Point
DC - Direct Current
DGW - Direct Groundwave
EM - Electromagnetic
EMI - Electromagnetic Induction Method
GPR - Ground Penetrating Radar
MHz - Mega Hertz
MOG - Multi-Offset Gather
pla - Polylactic acid
RMSE - Particle Swarm Optimization
SWC - Soil Water Content
TDR - Time-Domain Reflectometry
WARR - Wide Angle Reflection and Refraction
ZOP - Zero-Offset Profile

# LIST OF SYMBOLS

$\theta$ - Water content

$\varepsilon$ - Dielectric permittivity

$X_c$ - Capacitive reactance

$V_c$ - Voltage

$f$ - Signal frequency

$S_o$ - Slope

$\varepsilon_o$ - Dielectric permittivity of the space

$c$ - Velocity of the electromagnetic waves in free space

$C_o$ - Capacitance of free space capacitor

$C_{er}$ - Error in capacitance

$C_s$ - Capacitance of a capacitor

$M_d$ - Mass of dried sample

$v$ - Radar signal velocity

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Study

Soil water dynamics are a fundamental driver of the terrestrial hydrologic cycle, environmental processes, and ecosystem productivity. For example, soil water content conditions are important for quality of soil especially during drying periods. Transformations and subsequent losses to groundwater or atmosphere are mediated by moisture conditions in the soil. Success or failure of food, fibre, and energy production from agricultural crops depends on soil water storage between rainfall and/or irrigation events. Despite this importance, predicting soil water dynamics remains a major challenge in hydrology, environmental science, agriculture, and engineering.

Soil water (moisture) content is defined generally as the amount of water contained in the unsaturated soil zone (Tang, 2015). It is one of the parameter and important factors in quality control of the peat soil especially in agriculture and climate studies. Without water, plant cannot absorb the nutrient in the soil causes the quality of soil decreases. On the other hand, often less attention is paid to peat soil, risk and impact on them increase as water content is becoming the limited resource, unequally distributed in space and time widely exploited (Aguilera et al., 2016). Therefore, the knowledge of the water content of peat soil is needed. By modeling the water content using soil water conditions as peatlands health indicator may be useful as predicting tools. As noted by Jolly et al. (2008), simulation of processes in the unsaturated zone within around peatland is important in terms of ecological responses related to vegetation growth or nutrient release.

Peat soils performs a fundamental of ecological, economical function as water filter and buffers, by storing nutrient and carbon in their sediments (Reddy and

DeLaune 2008; Mitsch et al.,2008. It is made up of decomposed organic matter that have accumulated over thousand years (Adon et al., 2013). On the other hand, it is also called as an organic soil (Boelter, 1966) with lack of oxygen under waterlogged conditions. Peat soils is defined as materials that artificially drained for a long periods if saturated. In natural state, peat soil is very high water content. If the water content is lowered or decrease, the peat formation will stop and the peat start to decompose (Petersen and Madsen, 1978). During drying periods, soil water content (SWC) arises as the controlling factor for environmental and ecological disturbances such as the spread of invasive plants species, the combustibility of organic soil, nutrient distributions or soil physical disruption (Aguilera et al., 2016).

Peat soil is geographically spread around the world. Peat deposit covers large areas of Northern America, northern Europe, western Siberia, Indonesia and South East Asia (Kuhry 1994). Malaysia ranked at the 9th country with the highest total area of peat soil. The total area of peat soil in Malaysia is 26,000 km2 (2.6 million hectares) where Sarawak dominates the peat soil over 80%, while 13% in peninsular Malaysia and 5% from Sabah (Leete, 2006 and Ongkili, 2005). Knowledge of peat soil distribution is therefore great important in assessing the economic potentialities of natural resources. Therefore, the development of the appropriate method to help sustain this vital natural system plays important role for present and future decision making.

A potential method to acquire more adequate field-scale information is provided by non–invasive tools such as Ground Penetrating Radar (GPR) that can easily recordable for physical variables that correlates with physical properties of peat soil such as water content and dielectric permittivity (Altdorff et al., 2016) . The GPR is a geophysical tool which can be used to map the interface between a peat deposit and the mineral surface (Plado et al., 2011; Holden et al., 2002). Using GPR, an electromagnetic (EM) waves is reflected from the transmitting antenna to the receiving antenna. The waves are reflected at interface layers varying of the dielectric permittivity. The dielectric permittivity is then directly related to SWC (Steelman and Endres, 2011).

At the field-scale, soil moisture is important to precision agriculturalists; for instance, optimum crop yield and quality is achieved through appropriate irrigation management practices which rely on continuous high-resolution temporal and spatial moisture information (Robinson et al., 2008). Since a comprehensive understanding of soil moisture dynamics in the vadose zone is of utmost importance to the sustainable management of our water resources, and production and longevity of our crops, novel measurement strategies facilitating the attainment of soil moisture information will continue to play a fundamental role in future management practices of our water and food resources.

Ground penetrating radar (GPR), a high frequency electromagnetic method has been identified and tested in the recent past as an effective geophysical tool for field scale soil moisture and water table depth mapping over large areas (Galagedara, 2004). However, due to considerable spatial heterogeneity and temporal variability of soil water content, quantitative monitoring of soil water dynamics has remained a challenge, especially at intermediate scales, despite considerable efforts and advances in recent years (Robinson et al., 2008). To bridge that gap, electromagnetic geophysical measurement methods have been investigated throughout the last two decades to observe soil water dynamics up to the field scale. For example, high-frequency electromagnetic methods such as time domain reflectometry (TDR) and ground-penetrating radar (GPR) have received considerable attention, due to their high sensitivity to variations in the dielectric permittivity of the subsurface. Such variations are foremost connected to differences in soil water content due to the large permittivity difference between water and air lack of petrophysical relationship and performance

## 1.2 Problem Statement

The importance of accurate Soil Water Content (SWC) of characterization at peat soil has boosted the development of SWC methods. It can be categorized into direct method and in-direct method. Previous studies have reported most research in SWC estimation had emphasized the use of direct method such as gravimetric measurements as it can give better accuracy. However, the method is time consuming and destructive. Over the past years, the use of in-direct method has been introduced to estimate the water content of the soil. Even though the methods are efficient, but they are relatively highly in cost that limits their widespread use. Despite the problem occurs, the geophysical method, Ground Penetrating Radar (GPR) has drawn attention becoming the suitable and best method to estimate the water content in large area with better accuracy. This non-invasive tool can produces high resolution continuous profiling of an area and can yielding much information compare than conventional method for SWC estimation on peat soil.

There are a few methods or methodology for GPR to measure the SWC estimation at peat soil such as common-offset method, common-midpoint (CMP) method, groundwave method and borehole method. The above mentioned method for GPR is commonly used among the researchers to estimate the SWC of soil either mineral or organic soil. However, all the methods consists the main disadvantages and drawbacks itself, but, the choice of method for SWC estimation is chosen based on the application of measurements. For an example, CMP method is cumbersome and time consuming method. This is because, the method do not allow reconnaissance of water content of the soil variation. Besides, groundwave method also shows drawback in determination of soil water content. In this method, there are some uncertainties associated regarding of this method. The main important issue in this method is the ineffective measurements volume over which the ground averages. On the other hand, borehole also does not suitable to conduct the measurements of SWC in this study as the soil heterogeneity affects the sampling volume of borehole method of GPR. In other hand, common-offset method is a simple and straightforward to determine the velocity of the measurements, however, although it is simple, it also has it disadvantage. The main disadvantage is during the measurements, this method only gives the average value SWC to the depth of the reflector but the user has no control over the depth of the resolution of the measurements. Among all the GPR methods, common-offset method is the best method to conduct the measurements of SWC in this case study. Even though, the method itself shows disadvantage, but the main concern in this study is to determine the water content of peat soil. Hence, the depth of the measurements is chosen over the resolution of the measurements.

However, to estimate the water content of the peat soil using GPR, an appropriate of petrophysical relationships models is needed. Water content is the vital parameter that defines the physical and chemical properties of peat soil. Unlike other soils, peat soils are highly in water content makes it impossible for prediction. The relationship between dielectric permittivity and water is the strategic way for effective acquisition for the petro physical modelling of SWC. Even though there is a clear relationship between moisture content and apparent measured dielectric permittivity of peat as in the case of mineral soils, the signal tends to deviate from the globally acceptable model relations to peat soil that are found to be applicable to all mineral soils. Further research work on peat soil moisture content and dielectric permittivity relationship such as the work of Pumpanem and Ilvesniems (2005) and Persekian et al (2011) showed that both the nature and parametric of the model are site-specific due to the variation in climate and vegetation type of the peat-forming plant community.

The most important property of peat soil is retaining water (moisture) in soil while it is dry and yet preventing the excess of water from killing roots when it is wet. In natural state, peat soil is wet with very high water content. The biggest issue need to be encountered is when the water content lower to the point of no return where the soil will shrink. During dry periods, water content arises, as the controlling factor for environmental and ecological disturbances resulting in the ability to absorb peat water so that peat was difficult to cultivate for agriculture. Most tropical soils are considered to be infertile due to intensive weathering and leaching caused by the high temperatures and heavy rainfall that prevail in the peat soil areas. Hence, the SWC of the peat soil need to be taking care as it can enhancing the quality of the plantation on peat soil and increase the production of the plantation. By estimate the SWC properties during wet and dry season, are strategic move toward effective acquisition of useful data necessary for sustainable management initiative of the resources.

## 1.3 Aim and Objectives of the Study

The aim of this research is to estimate the soil water content of peat soil using Ground Penetrating Radar (GPR). Four specific objectives to achieve the aim of this research are defined:

1. To assess the performance of the GPR frequency for SWC profile of peat soil from collected GPR data with common-offset measurements.
2. To develop the site-specific of petrophysical relationships between the dielectric permittivity and water content for dry and wet conditions.
3. To validate the parameter site-specific of petrophysical relationship model between GPR data and gravimetric measurements data.
4. To evaluate of the site specific of petrophysical relationship between GPR data and laboratory measurements.

## 1.4 Significance of the Study

The analysis of this study can be referred by geophysicist as useful guidance for them to apply in geophysics on peat soil. Research on the physical properties of peat soil especially water content is behind the literature on utilization of peat. Early publications mentioned that the water content of peat soil is the important parameter especially for the agricultural sector. Driessen et al. (1975) expressed their opinions and their findings that the poor chemical and physical properties of lowland peat soils in South East Asia indicate very low suitability for any agricultural use. Hence, the detailed study in water content as one of the major physical properties of the peat soil can enhance for the decomposition of the peat soil. According to (Firdaus, Gandaseca, and Ahmed, 2011), the physical properties of the Kuala Langat peat soil area was describe in Table 1.1.

Table 1.1 Mean values of physical properties of peat soil

| Variable | Mean |
|---|---|
| Fibre content (%) | 30.497 |
| Gravimetric water content (%) | 39.623 |
| Volumetric water content (%) | 55.628 |
| Loss on Ignition (%) | 96.7 |
| Ash content (%) | 3.3 |
| Bulk density (gcm$^{-3}$) | 0.136 |
| Porosity (%) | 89.671 |
| Surface soil temperature ($^{O}$C) | 27.727 |
| Saturate hydraulic conductivity (cms$^{-1}$) | 0.035 |
| Soil bearing capacity (kNm$^{-2}$) | 32.667 |

Despite the relevance of the relationships between the dielectric permittivity and water content, is due to the lack of literature evidences about the peat soil at South East Asia country (Comas et al., 2015). Most of the knowledge of the peat soils and peatlands are from the Northern Europe and North America where large peat bogs have been reclaimed for centuries. Modelling approaches in South East Asia country have mostly focused on other soil and based on the temperature of peat soil so far. Malaysia has a climate change of mainly tropical hot and humidity throughout of the year round with plentiful of rainfall. Considering the climate change and vegetation of the Southeast Asia country, it is believed that modelling of this parameter will enhance the knowledge of the peat soil in Malaysia especially. Researchers themselves have high confident in these relationships because the results obtained from the conventional methods, however, there seems to be evidence that site and frequency dependent relationship may be required for those. Although numerous petrophysical relationships are available in the literature to convert bulk dielectric permittivity into volumetric water content, many of these relationships were developed using other dielectric sensors or under controlled laboratory conditions; consequently, their suitability for GPR measurements is not well known explain the existing numerical model problems of the existing numerical model. Since soil moisture directly controls fluxes of water and energy at the land surface, it is an important variable in most environmental (land surface) models (LSMs) such as those used for weather and climate prediction, ground water flow, rainfall-runoff, and crop growth. In order to simulate soil moisture, models need atmospheric forcing, initial conditions, and parameter values at every spatial grid point. For forecasting, near-real time soil moisture fields are required as initial condition. Three problems associated with soil moisture modelling have received considerable attention in the recent literature: the problem of parameter identification, spatial representativeness, and initialization.

A detailed serious review of SM literature review will reveal that there is no presently available method that can be considered to meet the ideal characteristics (Dobriyal, Qureshi, Badola, and Hussain, 2012). In fact, most methods have serious failings in several of these areas. It is believed that the capacitance measurements system described here can and will ultimately meet the requirements for an ideal system. Soils are complex three-phase media whose physical properties are difficult to model and therefore often described by macroscopic empirical equations. Water content has a major influence on these properties, and because of its importance for plant growth, a great deal of effort has been put into determining soil water content. Recent studies have demonstrated how the permittivity and water content relation depends on moisture history and displays hysteresis (the phenomenon in which the value of a physical property lags behind changes) between wetting and drying cycles (Lai et al., 2006). Such studies suggest that it will often be necessary to generate site-specific calibrations of petrophysical relationship for use in the interpretation of low-frequency GPR measurements.

Peat soil can be considered as a gold mine for farmers and agriculturist. This is because, it is highly water content, rich in organic content that acts as natural fertilizer that can increase the quality of the soil. Thus, the knowledge of properties of peat soil need to be fully understands, to improve the quality of the soil. Water content is one of the parameter that influenced the quality of soil. It serves as a solvent and carrier of food nutrients. The yield of crop is more often is determined by the amount of water available rather than deficiency of food nutrients. Peat soil in their natural condition is highly water content. Water content in the dry season is predicted to be slightly lower than the rainy season.

## 1.5 Scope and Limitation of the Research

This study was carried out in two phases which is field work measurements and laboratory measurements. To conduct the field work measurements, GPR IDS Detector Duo (i.e. 250 and 700 MHz) with dual frequencies was used. According to (Idi and Kamarudin, 2012), 250 MHz is the suitable range of lower frequency to estimate the water content and 700 MHz is the suitable range for higher frequency of water content estimation. The field work measurements were conducted at the peat soil (oil palm) area located at Olak Lempit Banting, Selangor. Pilot survey was done to determine the best antenna frequency that suit with the depth penetration of peat soil between 250 and 700 MHz frequencies. The water content of the soil was computed using the petrophysical relationships from the literature (i.e. Roth equation, Schaap equation and Idi equation).

To estimate the water content of the peat soil, an appropriate of petrophysical relationship is needed. Hence in this study, two sites-specific of petrophysical relationships were developed (i.e. wet and dry season) on peat soil. The parameter of the model consists of dielectric permittivity and water content. To determine the dielectric permittivity parameter, a 2-dimensional adjusting of soil cylindrical capacitor was designed and fabricated. A 2-D adjusting soil cylindrical capacitor was fabricated to be used for dielectric permittivity determination. The soil samples taken were also be used for water content estimation of peat soil. Oven-drying measurements were conducted for water content estimation at 105°C for 24 hours. The regression model (polynomial model) was chosen for modelling the site-specific of petrophysical relationship of SWC estimation.

The site-specific of petrophysical relationships for SWC estimation were validated using gravimetric measurements. The models for wet and dry season were validated. The validation process was calculated with GPR measurements and gravimetric measurements data. According to the (*Global*, 2010), the peat depth in this study area is categorized into moderate peat soil (100-150cm). Hence, the samples of soil were taken from 0.1cm to 1.0 cm and laboratory measurements were conducted. The accuracy of the models validated using root mean square (RMSE) measurements.

To evaluate the performance of the site-specific of petrophysical relationship for SWC estimation using GPR common-offset measurements, the models (wet and dry) were compared with the three established of site-specific of petrophysical relationship developed for organic soil such as Schaap equation, Roth equation and Idi equation. The models were tested using GPR measurements collected at peat soil area and will be validated with gravimetric measurements. To undergo the process of analysis of the data, software of Reflex2DQuick Scan will be used to analyse the results from the GPR image. It will be used for interpretation and visualization of the data. The soil water dynamics will consist of one parameter which is dielectric permittivity.

Experience with time domain reflectometry (TDR) has shown that *k-q* relationships should be calibrated for particular field conditions (Yu et al., 1997) by conducting laboratory or field measurements of both k and q on same volume of material. Because the sample volume of GPR is large, it is not always possible to make direct measurements of water content at a scale comparable to that at which k is determined. Therefore the k-q relationship typically cannot be directly calibrated for field-scale GPR data. As an alternative, laboratory-scale measurements may be used to determine a k-q relationship, which could then be applied to field-scale GPR measurements.

## 1.6 Thesis Organization

This research is divided into seven chapters. Chapter one presents the introduction of the research works of soil water content (SWC) estimation of peat soil. The problems were discussed in detail regarding the issues for estimation of water content. The solution were discussed and was believed can counter the problem regarding the upbringing issues. In this chapter, the research work by presenting the background of the study, problem statement, research objectives, significance of the study and scopes of the study.

Chapter II covers a further discussion for literature review. This includes review for the past researches related to the application of GPR in peat soil with particular emphasis on water content. The methods of SWC estimation were discussed and compared in detail based on several factors. The GPR methods/techniques were compared and discussed in detail to be chosen for the GPR survey measurements based on some factors.

Chapter III describes the research methodology of the study. The site area and data collection were discussed in this chapter. Data collection consists of field measurements (i.e. GPR Survey measurements and soil sampling) and laboratory measurements (i.e. capacitance-based method and oven drying). The techniques, calculations and procedures for the measurements were explained and discussed in this chapter. For field measurements includes a brief description of the study area, research design, and GPR system description, field procedure, and method for data collection, data processing strategy, interpretation procedure and method for data analysis. The laboratory measurements include the method for modeling the petrophysical relationship of SWC estimation which is for dielectric permittivity determination and soil water content estimation. The numerical modeling for petrophysical relationship of SWC estimation was used to estimate the water content of the peat soil when measure it with the GPR. As the GPR can only estimate the water content of the soil in-directly, this method needs the petrophysical relationship to compute the water content of the soil.

Chapter IV illustrates and discussed the results of the GPR measurements using different established petrophysical relationship. The results were compared with the gravimetric measurements. Through the results, there is needed for the site-specific for modeling of the petrophysical relationship for soil water content estimation at peat soil. The models were developed to estimate the water content of the soil for wet and dry season. The models then were calibrated and validated with gravimetric measurements. The closer agreements between GPR measurements and gravimetric measurements data is made to verify the results as the initial for evaluation and prediction for SWC estimation. In addition, in this chapter also depicts the evaluation of the modelled of site-specific of petrophysical relationship of soil water content estimation. Three established petrophysical relationship were used to estimate the water content along with the modelled of petrophysical relationships for wet and dry season. Using GPR measurements, the dielectric permittivity were compute using the petrophysical relationship to estimate the water content. The results were compared between the modelled of site-specific of petrophysical relationship and the established of the petrophysical relationship with the gravimetric measurements.

Finally, Chapter V concludes the SWC estimation of peat soil using the modelled of site-specific of petrophysical relationship. The recommendations were illustrates to be taken up for future studies on the modelling of the site-specific of petrophysical relationship for SWC estimation on peat soil.

## 1.7 Contributions of the Study

The use of capacitance-based method to determine dielectric permittivity of the soil shows great potential of parallel-plate capacitor as a calibration tool to develop the numerical model on SWC estimation especially at peat soil area. The needs of site-specific of petrophysical relationship is needed when estimates the SWC using GPR. The maintenance of the SWC is important for the peat soil because it can determine the environmental impact of the peat deposit where it can be used for the predicting the effect of seasonal and climatic changes to the environment.

The site-specific models developed for dry and wet season were revealed for the first time for this application. The models for GPR application in the SWC estimation at Olak Lempit peat soil were developed based on the derived empirical equation. Third order-polynomial models for dry and wet season are applicable to any peat soil of the same climate condition and vegetation type cover.

This work shows great potential for GPR application. This is contrast with the non-invasive methods and destructive techniques which is less accurate and labour intensive. The parameters itself is great important to agricultural and application of the soil. Method of common-offset measurements shows the great potential of geophysical tool on SWC estimation especially on peat soil area. The model can be applied for GPR technology to a peat soil field site to estimate temporal and spatial variations in water content under peat soil area.

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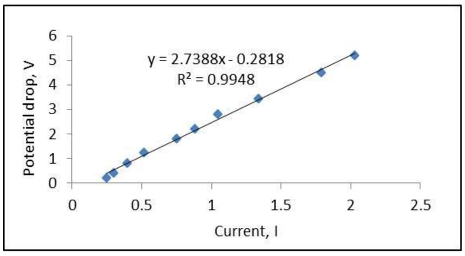
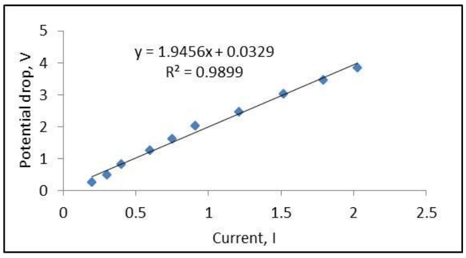
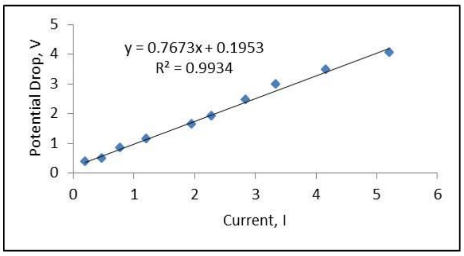
# APPENDICES

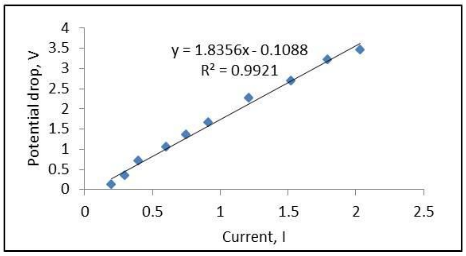
## Appendix A I-V Relationship

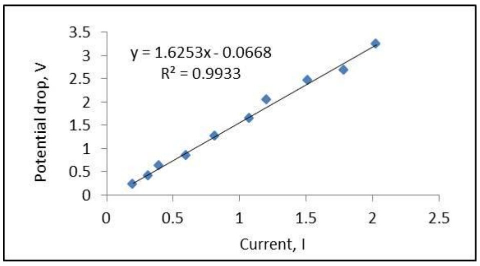
Point 10

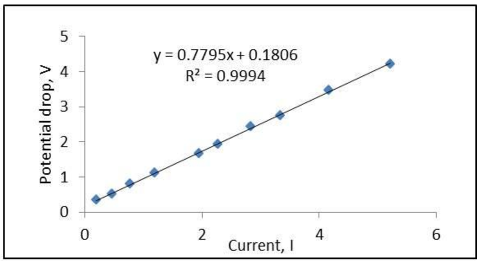


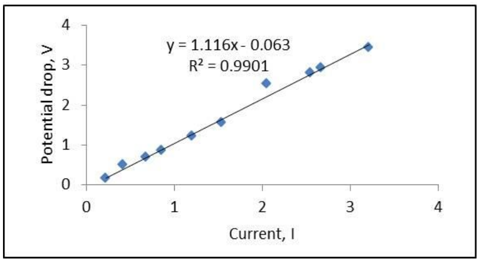


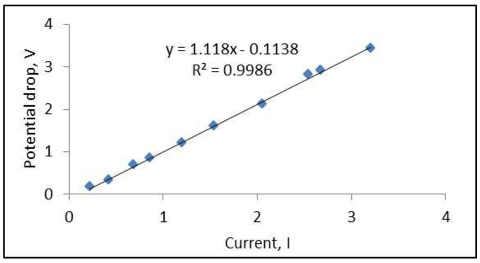


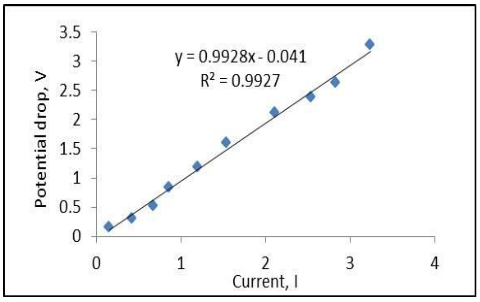


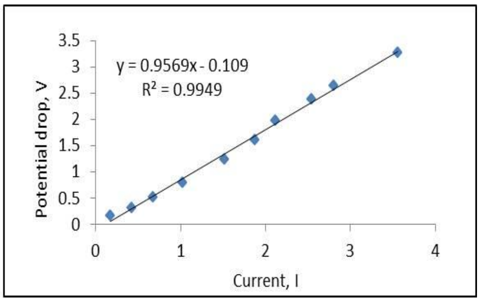




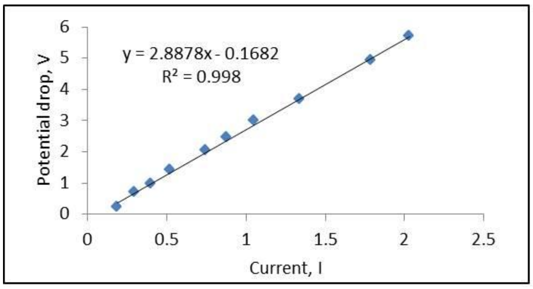


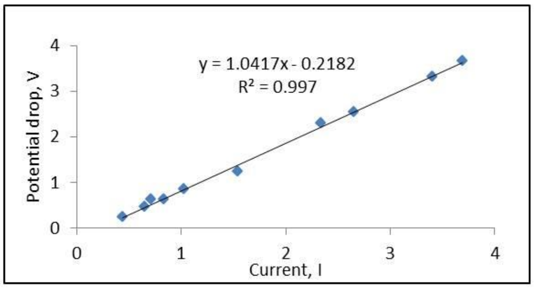


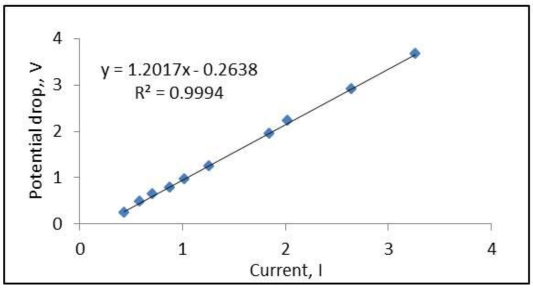


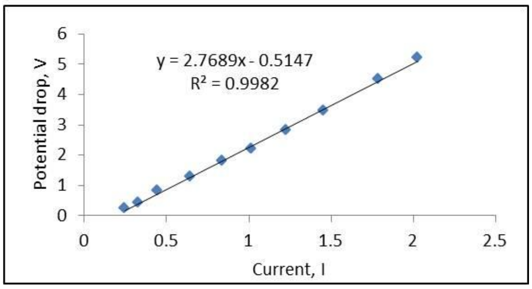


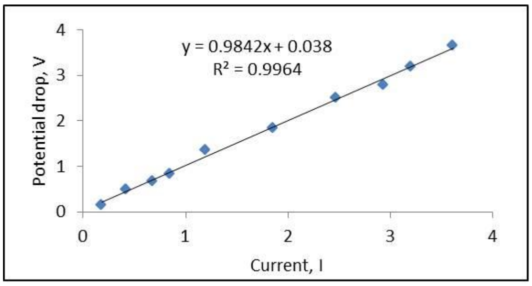
Point 15

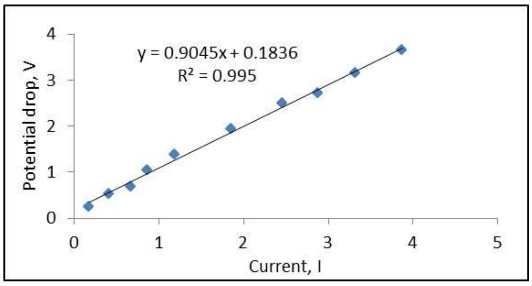


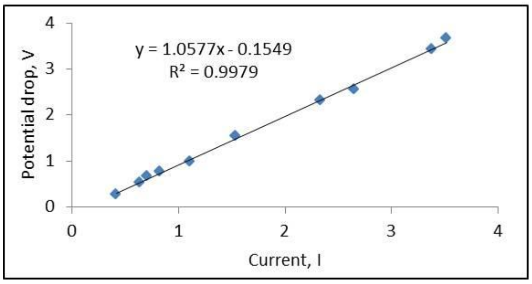


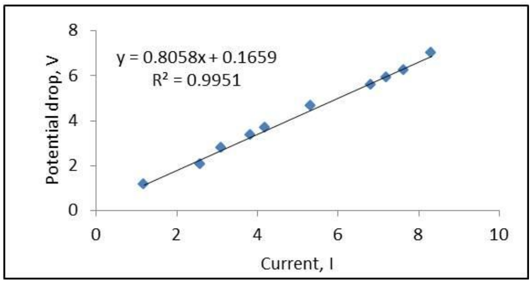


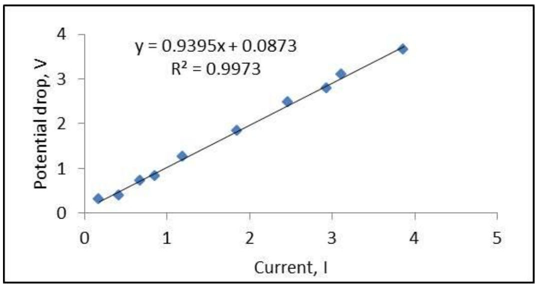


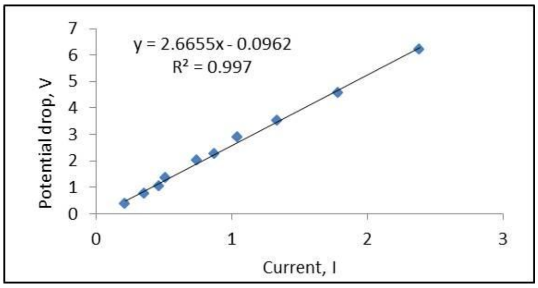












## Appendix B Water Content Measurements (Wet season)

Point 10

| Depth (m) | W1 | W2 | W3 | W2 - W3 | W3 -W1 | W |
|---|---|---|---|---|---|---|
| 0.1 | 18.88 | 35.98 | 27.6 | 8.38 | 8.72 | 0.961009 |
| 0.2 | 18.95 | 40.3 | 29.78 | 10.52 | 10.83 | 0.971376 |
| 0.3 | 18.91 | 47.62 | 33.32 | 14.3 | 14.41 | 0.992366 |
| 0.4 | 9.26 | 34.71 | 21.84 | 12.87 | 12.58 | 1.023052 |
| 0.5 | 19.03 | 44.18 | 31.1 | 13.08 | 12.07 | 1.083679 |
| 0.6 | 18.74 | 42.77 | 30 | 12.77 | 11.26 | 1.134103 |
| 0.7 | 18.9 | 37.86 | 27.62 | 10.24 | 8.72 | 1.174312 |
| 0.8 | 18.86 | 41.24 | 29.11 | 12.13 | 10.25 | 1.183415 |
| 0.9 | 18.89 | 36.95 | 27.07 | 9.88 | 8.18 | 1.207824 |
| 1 | 18.77 | 36.95 | 26.99 | 9.96 | 8.22 | 1.211679 |

Point 15

| Depth (m) | W1 | W2 | W3 | W2 - W3 | W3 -W1 | W |
|---|---|---|---|---|---|---|
| 0.1 | 18.85 | 36.96 | 27.03 | 9.93 | 8.18 | 1.213936 |
| 0.2 | 18.9 | 42.85 | 29.66 | 13.19 | 10.76 | 1.225836 |
| 0.3 | 9.52 | 30.74 | 19.02 | 11.72 | 9.5 | 1.233684 |
| 0.4 | 18.91 | 42.12 | 29.26 | 12.86 | 10.35 | 1.242512 |
| 0.5 | 18.8 | 38.92 | 27.73 | 11.19 | 8.93 | 1.25308 |
| 0.6 | 18.93 | 36.84 | 26.85 | 9.99 | 7.92 | 1.261364 |
| 0.7 | 18.95 | 35.07 | 26.01 | 9.06 | 7.06 | 1.283286 |
| 0.8 | 18.92 | 36.02 | 26.34 | 9.68 | 7.42 | 1.304582 |
| 0.9 | 18.96 | 33.24 | 25.09 | 8.15 | 6.13 | 1.329527 |
| 1 | 18.98 | 34.25 | 24.69 | 9.56 | 5.71 | 1.674256 |

Point 10

| Depth (m) | W1 | W2 | W3 | W2 - W3 | W3 -W1 | W |
|---|---|---|---|---|---|---|
| 0.1 | 18.86 | 57.6 | 37.12 | 20.48 | 18.26 | 1.12158 |
| 0.2 | 18.86 | 57.32 | 36.5 | 20.82 | 17.64 | 1.18027 |
| 0.3 | 29.72 | 76.92 | 51.12 | 25.8 | 21.4 | 1.20561 |
| 0.4 | 29.71 | 62.36 | 44.4 | 17.96 | 14.69 | 1.2226 |
| 0.5 | 29.49 | 64.1 | 44.88 | 19.22 | 15.39 | 1.24886 |
| 0.6 | 29.69 | 62.07 | 43.69 | 18.38 | 14 | 1.31286 |
| 0.7 | 29.68 | 75.85 | 48.97 | 26.88 | 19.29 | 1.39347 |
| 0.8 | 29.47 | 60.53 | 42.29 | 18.24 | 12.82 | 1.42278 |
| 0.9 | 29.66 | 60.83 | 42.19 | 18.64 | 12.53 | 1.48763 |
| 1 | 29.62 | 68.81 | 44.89 | 23.92 | 15.27 | 1.56647 |

Point 15

| Depth (m) | W1 | W2 | W3 | W2 - W3 | W3 -W1 | W |
|---|---|---|---|---|---|---|
| 0.1 | 29.66 | 71.97 | 45.65 | 26.32 | 15.99 | 1.64603 |
| 0.2 | 29.62 | 70.63 | 43.57 | 27.06 | 13.95 | 1.93978 |
| 0.3 | 29.65 | 59.76 | 39.01 | 20.75 | 9.36 | 2.21688 |
| 0.4 | 29.65 | 76.1 | 41.45 | 34.65 | 11.8 | 2.93644 |
| 0.5 | 29.67 | 61.04 | 37.3 | 23.74 | 7.63 | 3.1114 |
| 0.6 | 29.79 | 59.84 | 36.8 | 23.04 | 7.01 | 3.28673 |
| 0.7 | 29.41 | 67.04 | 37.21 | 29.83 | 7.8 | 3.82436 |
| 0.8 | 29.64 | 62.03 | 36.25 | 25.78 | 6.61 | 3.90015 |
| 0.9 | 29.72 | 74.53 | 38.31 | 36.22 | 8.59 | 4.21653 |
| 1 | 29.67 | 62.48 | 35.8 | 26.68 | 6.13 | 4.35237 |

## Appendix D The Site-Specific of Petrophysical Relationship Parameters (Dry season)

| Dielectric permittivity | Water content |
|---|---|
| 22.82 | 0.77 |
| 23.81 | 0.85 |
| 24.08 | 0.87 |
| 24.75 | 0.98 |
| 27.79 | 0.99 |
| 27.97 | 1.06 |
| 34.03 | 1.07 |
| 36.09 | 1.11 |
| 38.23 | 1.11 |
| 38.75 | 1.11 |
| 40.80 | 1.12 |
| 55.30 | 1.18 |
| 59.47 | 1.21 |
| 59.58 | 1.22 |
| 62.87 | 1.25 |
| 62.88 | 1.31 |
| 63.57 | 1.39 |
| 63.59 | 1.42 |
| 63.85 | 1.49 |
| 65.71 | 1.57 |
| 66.53 | 1.65 |
| 67.01 | 1.94 |
| 67.60 | 2.22 |
| 82.64 | 3.90 |
| 85.44 | 4.22 |
| 86.80 | 4.35 |

# Appendix E The Site-Specific of Petrophysical Relationship Parameters (Wet season)

| Dielectric permittivity | Water content |
|---|---|
| 2.91 | 0.60 |
| 3.24 | 0.64 |
| 3.35 | 0.68 |
| 4.17 | 0.67 |
| 4.55 | 0.73 |
| 4.96 | 0.82 |
| 5.12 | 0.84 |
| 5.13 | 0.84 |
| 5.17 | 0.94 |
| 5.45 | 0.95 |
| 6.30 | 0.96 |
| 6.65 | 0.97 |
| 6.61 | 0.99 |
| 7.99 | 1.02 |
| 8.39 | 1.08 |
| 9.44 | 1.13 |
| 9.53 | 1.17 |
| 9.72 | 1.18 |
| 12.41 | 1.21 |
| 15.51 | 1.21 |
| 16.80 | 1.21 |
| 16.90 | 1.23 |
| 19.70 | 1.23 |
| 25.03 | 1.24 |
| 26.85 | 1.25 |
| 42.33 | 1.26 |
| 44.99 | 1.28 |
| 47.80 | 1.30 |
| 50.74 | 1.33 |
| 56.60 | 1.67 |

## Appendix F Residual Value for Linear model (Dry season)

| Observation | Predicted water content | Residuals | Standard Residuals |
|---|---|---|---|
| 1.00 | 0.47 | 0.30 | 0.48 |
| 2.00 | 0.51 | 0.34 | 0.54 |
| 3.00 | 0.52 | 0.35 | 0.55 |
| 4.00 | 0.55 | 0.44 | 0.70 |
| 5.00 | 0.66 | 0.33 | 0.52 |
| 6.00 | 0.67 | 0.39 | 0.61 |
| 7.00 | 0.90 | 0.17 | 0.27 |
| 8.00 | 0.98 | 0.13 | 0.20 |
| 9.00 | 1.06 | 0.05 | 0.07 |
| 10.00 | 1.08 | 0.03 | 0.05 |
| 11.00 | 1.16 | -0.04 | -0.06 |
| 12.00 | 1.72 | -0.54 | -0.85 |
| 13.00 | 1.88 | -0.67 | -1.07 |
| 14.00 | 1.88 | -0.66 | -1.05 |
| 15.00 | 2.01 | -0.76 | -1.21 |
| 16.00 | 2.01 | -0.69 | -1.10 |
| 17.00 | 2.03 | -0.64 | -1.02 |
| 18.00 | 2.03 | -0.61 | -0.97 |
| 19.00 | 2.04 | -0.56 | -0.89 |
| 20.00 | 2.12 | -0.55 | -0.87 |
| 21.00 | 2.15 | -0.50 | -0.80 |
| 22.00 | 2.17 | -0.23 | -0.36 |
| 23.00 | 2.19 | 0.03 | 0.04 |
| 24.00 | 2.77 | 1.13 | 1.80 |
| 25.00 | 2.87 | 1.34 | 2.14 |
| 26.00 | 2.93 | 1.43 | 2.27 |

## Appendix G Probability Output for Linear model (Dry season)

| Percentile | water content |
|---|---|
| 1.92 | 0.77 |
| 5.77 | 0.85 |
| 9.62 | 0.87 |
| 13.46 | 0.98 |
| 17.31 | 0.99 |
| 21.15 | 1.06 |
| 25.00 | 1.07 |
| 28.85 | 1.11 |
| 32.69 | 1.11 |
| 36.54 | 1.11 |
| 40.38 | 1.12 |
| 44.23 | 1.18 |
| 48.08 | 1.21 |
| 51.92 | 1.22 |
| 55.77 | 1.25 |
| 59.62 | 1.31 |
| 63.46 | 1.39 |
| 67.31 | 1.42 |
| 71.15 | 1.49 |
| 75.00 | 1.57 |
| 78.85 | 1.65 |
| 82.69 | 1.94 |
| 86.54 | 2.22 |
| 90.38 | 3.90 |
| 94.23 | 4.22 |
| 98.08 | 4.35 |

# Appendix H   Residual Output for Second-Order Polynomial

| Observation | Predicted water content | Residuals | Standard Residuals |
|---|---|---|---|
| 1.00 | 1.18 | -0.41 | -1.60 |
| 2.00 | 1.13 | -0.28 | -1.10 |
| 3.00 | 1.11 | -0.25 | -0.98 |
| 4.00 | 1.08 | -0.10 | -0.39 |
| 5.00 | 0.95 | 0.04 | 0.16 |
| 6.00 | 0.94 | 0.11 | 0.44 |
| 7.00 | 0.77 | 0.30 | 1.17 |
| 8.00 | 0.74 | 0.37 | 1.44 |
| 9.00 | 0.72 | 0.39 | 1.53 |
| 10.00 | 0.72 | 0.39 | 1.54 |
| 11.00 | 0.72 | 0.40 | 1.58 |
| 12.00 | 1.10 | 0.08 | 0.31 |
| 13.00 | 1.34 | -0.13 | -0.52 |
| 14.00 | 1.34 | -0.12 | -0.48 |
| 15.00 | 1.57 | -0.32 | -1.27 |
| 16.00 | 1.57 | -0.26 | -1.01 |
| 17.00 | 1.62 | -0.23 | -0.90 |
| 18.00 | 1.62 | -0.20 | -0.79 |
| 19.00 | 1.64 | -0.16 | -0.61 |
| 20.00 | 1.79 | -0.23 | -0.89 |
| 21.00 | 1.86 | -0.21 | -0.85 |
| 22.00 | 1.90 | 0.04 | 0.15 |
| 23.00 | 1.95 | 0.26 | 1.04 |
| 24.00 | 3.65 | 0.25 | 0.98 |
| 25.00 | 4.05 | 0.17 | 0.66 |
| 26.00 | 4.25 | 0.10 | 0.40 |

## Appendix I Probability Output for Second-Order Polynomial (Dry season)

| Percentile | water content |
|---|---|
| 1.92 | 0.77 |
| 5.77 | 0.85 |
| 9.62 | 0.87 |
| 13.46 | 0.98 |
| 17.31 | 0.99 |
| 21.15 | 1.06 |
| 25.00 | 1.07 |
| 28.85 | 1.11 |
| 32.69 | 1.11 |
| 36.54 | 1.11 |
| 40.38 | 1.12 |
| 44.23 | 1.18 |
| 48.08 | 1.21 |
| 51.92 | 1.22 |
| 55.77 | 1.25 |
| 59.62 | 1.31 |
| 63.46 | 1.39 |
| 67.31 | 1.42 |
| 71.15 | 1.49 |
| 75.00 | 1.57 |
| 78.85 | 1.65 |
| 82.69 | 1.94 |
| 86.54 | 2.22 |
| 90.38 | 3.90 |
| 94.23 | 4.22 |
| 98.08 | 4.35 |

## Appendix J Residual Output for Third-Order Polynomial (Dry season)

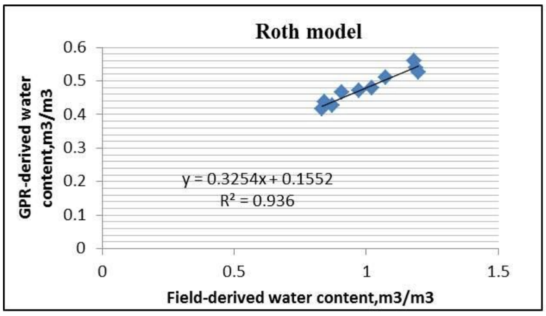
| Observation | Predicted water content | Residuals | Standard Residuals |
|---|---|---|---|
| 1.00 | 0.86 | -0.08 | -0.61 |
| 2.00 | 0.89 | -0.04 | -0.31 |
| 3.00 | 0.90 | -0.03 | -0.25 |
| 4.00 | 0.92 | 0.06 | 0.47 |
| 5.00 | 0.99 | 0.00 | 0.00 |
| 6.00 | 0.99 | 0.06 | 0.45 |
| 7.00 | 1.06 | 0.01 | 0.06 |
| 8.00 | 1.07 | 0.04 | 0.29 |
| 9.00 | 1.07 | 0.04 | 0.28 |
| 10.00 | 1.07 | 0.04 | 0.29 |
| 11.00 | 1.07 | 0.05 | 0.36 |
| 12.00 | 1.18 | 0.00 | -0.02 |
| 13.00 | 1.31 | -0.10 | -0.73 |
| 14.00 | 1.31 | -0.09 | -0.63 |
| 15.00 | 1.46 | -0.21 | -1.52 |
| 16.00 | 1.46 | -0.14 | -1.05 |
| 17.00 | 1.49 | -0.10 | -0.74 |
| 18.00 | 1.50 | -0.07 | -0.53 |
| 19.00 | 1.51 | -0.02 | -0.16 |
| 20.00 | 1.62 | -0.06 | -0.42 |
| 21.00 | 1.68 | -0.03 | -0.25 |
| 22.00 | 1.72 | 0.22 | 1.64 |
| 23.00 | 1.76 | 0.46 | 3.33 |
| 24.00 | 3.68 | 0.22 | 1.59 |
| 25.00 | 4.24 | -0.02 | -0.18 |
| 26.00 | 4.54 | -0.19 | -1.37 |

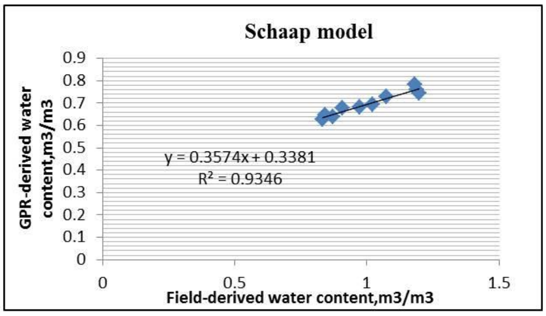
## Appendix K Probability Output for Third-Order Polynomial (Dry season)

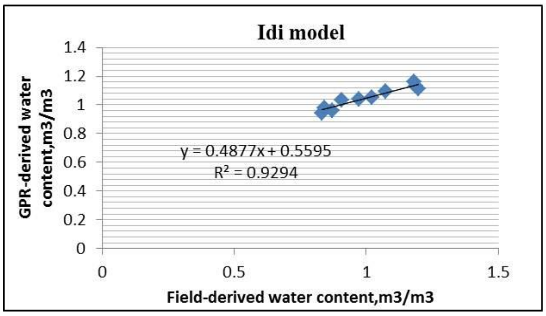
| Percentile | water content |
|---|---|
| 1.92 | 0.77 |
| 5.77 | 0.85 |
| 9.62 | 0.87 |
| 13.46 | 0.98 |
| 17.31 | 0.99 |
| 21.15 | 1.06 |
| 25.00 | 1.07 |
| 28.85 | 1.11 |
| 32.69 | 1.11 |
| 36.54 | 1.11 |
| 40.38 | 1.12 |
| 44.23 | 1.18 |
| 48.08 | 1.21 |
| 51.92 | 1.22 |
| 55.77 | 1.25 |
| 59.62 | 1.31 |
| 63.46 | 1.39 |
| 67.31 | 1.42 |
| 71.15 | 1.49 |
| 75.00 | 1.57 |
| 78.85 | 1.65 |
| 82.69 | 1.94 |
| 86.54 | 2.22 |
| 90.38 | 3.90 |
| 94.23 | 4.22 |
| 98.08 | 4.35 |

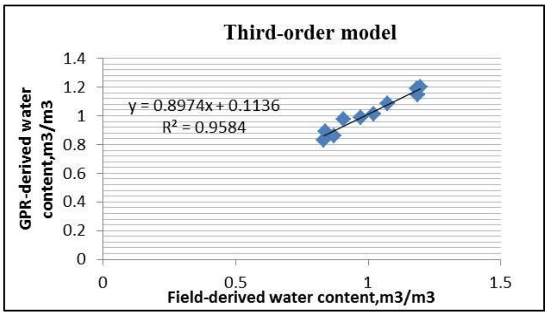
# Appendix L Correlation Between Field-derived Water Content and GPR Derived Water Content for the Petrophysical Relationship

## Dry Season

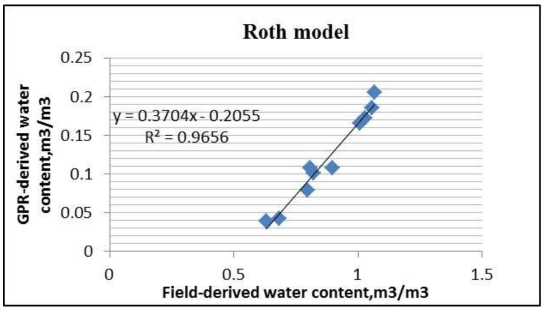


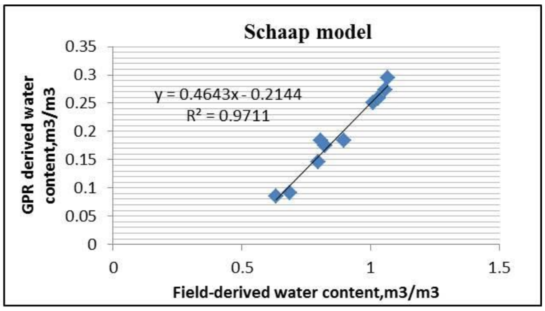


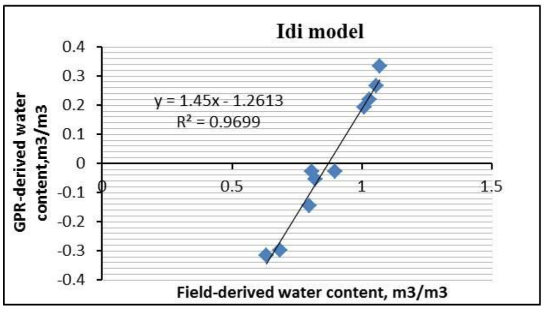


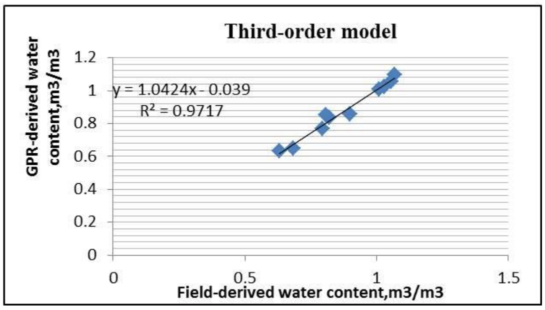


## Wet Season









# Appendix M Summary of the Water Content of GPR Corresponding with Water Content by Gravimetric Measurements (Oven-drying)

Roth Model

| Sampling depth (cm) | Dry | | Wet | |
|---|---|---|---|---|
| | Water content (GPR) | Water content (Oven-drying) | Water content (GPR) | Water content (Oven-drying) |
| 0-10 | 0.0386 | 0.6319 | 0.4172 | 0.8317 |
| 10-20 | 0.0427 | 0.6847 | 0.4267 | 0.8704 |
| 20-30 | 0.0783 | 0.7958 | 0.4364 | 0.8406 |
| 30-40 | 0.1076 | 0.8976 | 0.4669 | 0.9085 |
| 40-50 | 0.1007 | 0.8219 | 0.4707 | 0.9726 |
| 50-60 | 0.1073 | 0.8063 | 0.4801 | 1.02176 |
| 60-70 | 0.1656 | 1.008 | 0.5595 | 1.1824 |
| 70-80 | 0.2053 | 1.0678 | 0.5111 | 1.0725 |
| 80-90 | 0.1721 | 1.0296 | 0.5391 | 1.1874 |
| 90-100 | 0.1855 | 1.0556 | 0.5252 | 1.1958 |

Schaap Model

| Sampling depth (cm) | Dry | | Wet | |
|---|---|---|---|---|
| | Water content (GPR) | Water content (Oven-drying) | Water content (GPR) | Water content (Oven-drying) |
| 0-10 | 0.0849 | 0.6319 | 0.6273 | 0.8317 |
| 10-20 | 0.0918 | 0.6847 | 0.6371 | 0.8704 |
| 20-30 | 0.1454 | 0.7958 | 0.6472 | 0.8406 |
| 30-40 | 0.1836 | 0.8976 | 0.6795 | 0.9085 |
| 40-50 | 0.1748 | 0.8219 | 0.6836 | 0.9726 |
| 50-60 | 0.1833 | 0.8063 | 0.6938 | 1.02176 |
| 60-70 | 0.2513 | 1.008 | 0.7840 | 1.1824 |
| 70-80 | 0.2941 | 1.0678 | 0.7281 | 1.0725 |
| 80-90 | 0.2585 | 1.0296 | 0.7601 | 1.1874 |
| 90-100 | 0.2730 | 1.0556 | 0.7442 | 1.1958 |

Idi Model

| Sampling depth (cm) | Dry | | Wet | |
|---|---|---|---|---|
| | Water content (GPR) | Water content (Oven-drying) | Water content (GPR) | Water content (Oven-drying) |
| 0-10 | -0.3151 | 0.6319 | 0.9439 | 0.8317 |
| 10-20 | -0.2971 | 0.6847 | 0.9623 | 0.8704 |
| 20-30 | -0.1454 | 0.7958 | 0.9804 | 0.8406 |
| 30-40 | -0.0265 | 0.8976 | 1.0325 | 0.9085 |
| 40-50 | -0.0545 | 0.8219 | 1.0385 | 0.9726 |
| 50-60 | -0.0276 | 0.8063 | 1.0530 | 1.02176 |
| 60-70 | 0.1946 | 1.008 | 1.1579 | 1.1824 |
| 70-80 | 0.33391 | 1.0678 | 1.0965 | 1.0725 |
| 80-90 | 0.2183 | 1.0296 | 1.1323 | 1.1874 |
| 90-100 | 0.2658 | 1.0556 | 1.1148 | 1.1958 |

Third Order Model

| Sampling depth (cm) | Dry | | Wet | |
|---|---|---|---|---|
| | Water content (GPR) | Water content (Oven-drying) | Water content (GPR) | Water content (Oven-drying) |
| 0-10 | 0.6346 | 0.6319 | 0.8311 | 0.8317 |
| 10-20 | 0.6488 | 0.6847 | 0.8612 | 0.8704 |
| 20-30 | 0.7661 | 0.7958 | 0.8911 | 0.8406 |
| 30-40 | 0.8547 | 0.8976 | 0.9786 | 0.9085 |
| 40-50 | 0.8342 | 0.8219 | 0.9888 | 0.9726 |
| 50-60 | 0.8539 | 0.8063 | 1.0133 | 1.02176 |
| 60-70 | 1.0097 | 1.008 | 1.1880 | 1.1824 |
| 70-80 | 1.0988 | 1.0678 | 1.0877 | 1.0725 |
| 80-90 | 1.0254 | 1.0296 | 1.1477 | 1.1874 |
| 90-100 | 1.0562 | 1.0556 | 1.1977 | 1.1958 |

# Appendix N Estimation of Peat Soil Water Content Using GPR Radargrams (Dry season)

Profile 2

| Distance (m) | Velocity (m/ns) | Time (ns) | Depth (m) | Dielectric permittivity, ε | Water content, θ |
|---|---|---|---|---|---|
| 0.03 | 0.06 | 17.90 | 0.90 | 25.73 | 1.00 |
| 0.79 | 0.04 | 19.37 | 0.97 | 54.26 | 1.78 |
| 1.00 | 0.04 | 18.15 | 0.91 | 56.74 | 1.93 |
| 1.72 | 0.05 | 15.94 | 0.80 | 35.52 | 1.23 |
| 4.91 | 0.03 | 21.58 | 1.08 | 87.23 | 7.32 |
| 5.35 | 0.04 | 24.03 | 1.20 | 62.90 | 2.44 |
| 5.40 | 0.04 | 26.48 | 1.32 | 68.97 | 3.17 |
| 5.90 | 0.05 | 23.30 | 1.16 | 36.24 | 1.24 |
| 5.94 | 0.03 | 27.46 | 1.37 | 76.40 | 4.46 |
| 6.66 | 0.04 | 25.75 | 1.29 | 63.58 | 2.51 |
| 7.10 | 0.04 | 23.54 | 1.18 | 61.59 | 2.31 |
| 7.13 | 0.04 | 26.24 | 1.31 | 60.64 | 2.23 |
| 7.72 | 0.04 | 23.05 | 1.15 | 58.19 | 2.03 |

Profile 3

| Distance (m) | Velocity (m/ns) | Time (ns) | Depth (m) | Dielectric permittivity, ε | Water content, θ |
|---|---|---|---|---|---|
| 0.16 | 0.04 | 21.33 | 1.07 | 59.09 | 2.10 |
| 0.17 | 0.03 | 26.97 | 1.35 | 86.69 | 7.15 |
| 0.48 | 0.04 | 29.43 | 1.47 | 55.07 | 1.83 |
| 0.94 | 0.04 | 24.03 | 1.20 | 62.57 | 2.41 |
| 1.14 | 0.04 | 27.71 | 1.39 | 66.73 | 2.87 |
| 1.21 | 0.05 | 20.84 | 1.04 | 43.80 | 1.39 |
| 2.88 | 0.04 | 24.52 | 1.23 | 56.74 | 1.93 |
| 3.65 | 0.05 | 27.22 | 1.36 | 41.57 | 1.34 |
| 3.65 | 0.04 | 31.39 | 1.58 | 48.38 | 1.52 |
| 5.06 | 0.05 | 26.24 | 1.31 | 35.81 | 1.24 |
| 5.60 | 0.05 | 27.22 | 1.36 | 37.74 | 1.27 |
| 5.84 | 0.04 | 24.28 | 1.21 | 59.09 | 2.10 |
| 6.07 | 0.04 | 25.01 | 1.25 | 64.60 | 2.62 |

Profile 4

| Distance (m) | Velocity (m/ns) | Time (ns) | Depth (m) | Dielectric permittivity, ε | Water content, θ |
|---|---|---|---|---|---|
| 0.34 | 0.04 | 24.52 | 1.23 | 50.71 | 1.61 |
| 0.62 | 0.04 | 34.33 | 1.72 | 58.19 | 2.03 |
| 1.14 | 0.05 | 28.44 | 1.42 | 37.59 | 1.27 |
| 1.56 | 0.04 | 24.28 | 1.21 | 57.61 | 1.99 |
| 1.57 | 0.03 | 26.73 | 1.34 | 87.23 | 7.32 |
| 2.00 | 0.03 | 24.77 | 1.24 | 94.75 | 10.12 |
| 2.58 | 0.03 | 20.35 | 1.02 | 86.69 | 7.15 |
| 3.26 | 0.03 | 25.99 | 1.30 | 92.93 | 9.37 |
| 5.10 | 0.03 | 25.75 | 1.29 | 115.47 | 22.22 |
| 5.51 | 0.03 | 26.73 | 1.34 | 77.30 | 4.65 |
| 5.54 | 0.04 | 23.79 | 1.19 | 59.40 | 2.12 |
| 5.78 | 0.03 | 22.81 | 1.14 | 85.62 | 6.81 |
| 5.81 | 0.04 | 27.46 | 1.37 | 59.70 | 2.15 |
| 6.41 | 0.04 | 24.28 | 1.21 | 63.24 | 2.47 |

## Appendix O Estimation of Peat Soil Water Content Using GPR Radargrams (Wet Season)

Profile 2

| Distance (m) | Velocity (m/ns) | Time (ns) | Depth (m) | Dielectric permittivity, ε | Water content, θ |
|---|---|---|---|---|---|
| 0.18 | 0.04 | 23.05 | 1.15 | 61.92 | 1.81 |
| 0.41 | 0.05 | 20.11 | 1.01 | 40.52 | 0.33 |
| 0.49 | 0.04 | 19.62 | 0.98 | 62.57 | 1.91 |
| 1.32 | 0.04 | 20.60 | 1.03 | 45.18 | 0.41 |
| 1.96 | 0.04 | 18.15 | 0.91 | 60.32 | 1.57 |
| 2.85 | 0.04 | 18.15 | 0.91 | 51.44 | 0.69 |
| 3.77 | 0.04 | 18.64 | 0.93 | 68.21 | 2.98 |
| 4.96 | 0.04 | 18.15 | 0.91 | 64.26 | 2.19 |
| 5.45 | 0.04 | 20.11 | 1.01 | 45.39 | 0.42 |
| 6.19 | 0.04 | 16.92 | 0.85 | 53.47 | 0.84 |
| 6.55 | 0.03 | 20.35 | 1.02 | 86.69 | 9.41 |
| 6.60 | 0.03 | 25.99 | 1.30 | 97.90 | 16.09 |
| 6.93 | 0.04 | 16.67 | 0.83 | 59.09 | 1.41 |
| 7.96 | 0.05 | 19.13 | 0.96 | 39.84 | 0.32 |

Profile 4

| Distance (m) | Velocity (m/ns) | Time (ns) | Depth (m) | Dielectric permittivity, ε | Water content, θ |
|---|---|---|---|---|---|
| 0.26 | 0.03 | 35.31 | 1.77 | 90.58 | 11.46 |
| 0.32 | 0.04 | 26.48 | 1.32 | 52.19 | 0.74 |
| 0.62 | 0.04 | 37.36 | 1.89 | 72.54 | 4.05 |
| 1.39 | 0.04 | 28.44 | 1.42 | 59.40 | 1.45 |
| 1.17 | 0.04 | 32.61 | 1.63 | 65.30 | 2.38 |
| 1.88 | 0.05 | 26.24 | 1.31 | 44.19 | 0.38 |
| 2.32 | 0.04 | 25.01 | 1.25 | 53.21 | 0.82 |
| 2.43 | 0.04 | 23.05 | 1.15 | 54.26 | 0.90 |
| 2.43 | 0.03 | 28.20 | 1.41 | 92.33 | 12.48 |
| 3.05 | 0.04 | 26.24 | 1.31 | 57.03 | 1.17 |
| 3.91 | 0.03 | 25.99 | 1.30 | 97.90 | 16.09 |
| 4.29 | 0.03 | 25.26 | 1.26 | 99.20 | 17.03 |
| 4.65 | 0.04 | 23.79 | 1.19 | 56.46 | 1.11 |
| 4.85 | 0.03 | 26.97 | 1.35 | 102.58 | 19.63 |
| 5.51 | 0.04 | 23.79 | 1.19 | 72.13 | 3.94 |
| 5.79 | 0.03 | 23.05 | 1.15 | 90.58 | 11.46 |
| 5.95 | 0.03 | 25.50 | 1.28 | 105.41 | 22.01 |
| 6.99 | 0.04 | 22.56 | 1.13 | 59.09 | 1.41 |
| 7.44 | 0.03 | 24.28 | 1.21 | 98.55 | 16.56 |

Profile 5

| Distance (m) | Velocity (m/ns) | Time (ns) | Depth (m) | Dielectric permittivity, ε | Water content, θ |
|---|---|---|---|---|---|
| 0.33 | 0.03 | 28.69 | 1.43 | 97.26 | 15.64 |
| 1.14 | 0.04 | 24.77 | 1.24 | 55.34 | 1.00 |
| 1.92 | 0.04 | 22.81 | 1.14 | 57.61 | 1.23 |
| 1.95 | 0.04 | 28.69 | 1.43 | 54.53 | 0.93 |
| 2.29 | 0.04 | 24.03 | 1.20 | 63.24 | 2.02 |
| 2.78 | 0.03 | 24.03 | 1.20 | 82.04 | 7.31 |
| 2.28 | 0.03 | 29.43 | 1.47 | 123.29 | 41.54 |
| 3.27 | 0.03 | 23.05 | 1.15 | 92.33 | 12.48 |
| 4.28 | 0.03 | 24.03 | 1.20 | 110.66 | 26.89 |
| 5.12 | 0.04 | 23.54 | 1.18 | 60.01 | 1.53 |
| 5.14 | 0.03 | 28.94 | 1.45 | 127.99 | 48.10 |
| 6.13 | 0.03 | 23.79 | 1.19 | 97.90 | 16.09 |
| 6.48 | 0.03 | 22.56 | 1.13 | 101.89 | 19.08 |

# LIST OF PUBLICATIONS

## PUBLICATIONS OF INDEXED SCOPUS

(a) Izzati, N. et al., 2018b. Modeling of Petrophysical Relationship of Soil Water Content Estimation at Peat lands. *The International Journal of Integrated Engineering*, 7, pp.177–187.

(b) Izzati, N. et al., 2018c. Performance of Soil Water Content Using Ground Penetrat- ing Radar with Different Antenna Frequencies. *International Journal of Engineering and Technology*, 7, pp.815–820.

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(d) Karim, I.A., Kamaruddin, S.A. & Hasan, R.C., 2018. The Petrophysical Relationship between Dielectric Permittivity and Water Content of Peat Soil Moisture Measurements. *2018 2nd International Conference on Smart Sensors and Application (ICSSA)*, (July), p.2018.

## OTHER PUBLICATIONS

(a) Izzati, N. et al., 2016. Application of Ground Penetrating Radar on Soil Water Content Estimation : an Overview. *International Graduate Conference on Engineering, Science and Humanities*, (2016), pp.1–8.

(b) Izzati, N. et al., 2018a. Comparison of Petrophysical Relationship for Soil Water Content Estimation at Peat Soil using GPR Common-Offset Measurements. *World Academy of Science, Engineering and Technology*, 12, pp.1–12.