UNIVERSITI PUTRA MALAYSIA

TERMITE MOUNDS MORPHOMETRY IN PREDICTING GROUNDWATER POTENTIALITY USING GEOSPATIAL TECHNOLOGY

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Chairman : Professor Shattri Mansor, PhD
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Termite mounds are conspicuous long lasting landscape features in many tropical to sub-tropical regions of the world. They provide several ecological and economic benefits to mankind amongst which is the classical believe of them to be good indicators of groundwater. This hypothesis is however, yet to be scientifically substantiated. The aim of this study therefore, is to develop a groundwater potential model in Geographical Information System (GIS) and evaluate the prospect of termite mounds in predicting suitable zones for groundwater development. To achieve this, a ground-based survey, remotely sensed data and GIS techniques were employed. From field survey, termite mounds were mapped and their structural characteristics recorded along 68 road transects covering 156 km^2 of the study area. The effects of five (5) environmental factors (elevation, land use/land cover, geology, drainage and static water level) on the distribution of termite mounds as well as their structure, mortality rate and species diversity formed a knowledge-base for multi-criteria evaluation of suitable sites for termite nesting. Thereafter, twelve (12) groundwater conditioning factors (GCFs) (geology, drainage density, lineament density, lineament intersection density, land use/land cover, topographic wetness index (TWI), normalized difference vegetation index (NDVI), slope, elevation, plan curvature, static water level and groundwater level fluctuation) were passed through a feature selection filter (Correlation-based feature selection using the best first algorithm) to select the optimum groundwater control factors (GCFs) for groundwater prediction in the study area. To assess the productivity potentials of aquifers beneath termite mounds, forty (40) electrical resistivity soundings using the Vertical Electrical Sounding (VES) method were conducted and an additional twenty eight (28) VES conducted in areas adjacent to termite mounds for comparison of potentials. The result produced two (2) models; termite mounds site suitability model (TMSM) and groundwater potential prediction model (GPPM) with validation accuracy using the area under ROC of 74.2% and 86.5% respectively. For termite mounds site suitability, the result revealed that moderate to low elevation, rock cover types that are more susceptible to weathering, cultivated areas and shallow water table are factor classes that influence the distribution of termite mounds. Frequency Ratio (FR) and Spearman's rank correlation applied to find relationships between termite mounds and the optimum GCFs revealed a consistent agreement that tall termite mounds (≥1.8m) and cathedral designed termite mounds are useful in locating groundwater prospective zones. The mean weights derived from electrical resistivity soundings also revealed that tall termite mounds (>2m), cathedral designed mounds and in addition, mounds built by the genus *Nasutitermes* showed greater aquifer productivity potential than other types of termite mounds. This study provides an exposition to the scientific rational for using termite mounds as bio-indicators of groundwater and the specific mounds types to adopt as guide.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MORFOMETRI TAMBUNAN ANAI-ANAI DALAM PERAMALAN POTENSIALITI AIR TANAH MENGGUNAKAN TEKNOLOGI GEORUANG

Oleh

AHMED JAMILU BALA

Februari 2020

Pengerusi : Profesor Shattri Mansor, PhD
Fakulti : Kejuruteraan

Tambunan anai-anai merupakan ciri landskap kekal yang menonjol dalam kebanyakan kawasan tropikal hingga ke subtropikal dunia. Tambunan tersebut memberikan manfaat ekonomik dan ekologikal kepada manusia, antaranya ialah kepercayaan klasikal yang menyatakan anai-anai merupakan indikator air bawah tanah yang baik. Hipotesis ini, walau bagaimanapun, belum dapat secara saintifik disahkan. Oleh itu, tujuan kajian ini adalah untuk membangunkan sebuah model berpotensi air bawah tanah dalam Sistem Maklumat Geografik (GIS) dan menilai prospek tambunan anai-anai dalam peramalan zon yang sesuai untuk pembangunan air bawah tanah. Bagi memperoleh objektif tersebut, tinjauan berasaskan tanah, data penderian janh dan teknik GIS telah digunakan. Dari tinjauan lapangan, tambunan anai-anai telah dicartakan dan karakteristik struktural mereka direkodkan di sepanjang 68 transek jalan meliputi 156 km^2 kawasan kajian. Kesan lima (5) faktor persekitaran (ketinggian, penggunaan tanah/liputan tanah, geologi, saliran dan tahap air statik) ke atas penyebaran tambunan anai-anai di samping struktur mereka, kadar mortaliti dan spesis diversiti membentuk suatu asas maklumat bagi penilaian multikriteria tapak yang sesuai bagi sarang anai-anai. Kemudian, dua belas (12) faktor penyesuaian air bawah tanah (GCFs) (geologi, densiti saliran, densiti lineamen, densiti persilangan lineamen, penggunaan tanah/liputan tanah, indeks kelembapan topografik (TWI), indeks vegetasi perbezaan terpulih (NDVI), Cerun, ketinggian, kelengkungan pelan, tahap air statik dan buaian tahap air bawah tanah) telah diresapi melalui sebuah turas pemilihan ciri (pemilihan ciri berasaskan korelasi menggunakan algoritma pertama paling baik) bagi memilih faktor kawalan air tanah optimum (GCFs) bagi peramalan air bawah tanah dalam kawasan kajian. Bagi menaksir potensi produktiviti akuifer di bawah tambunan anai-anai, empat puluh (40) bunyi resistiviti elektrikal menggunakan kaedah Bunyi Elektrikal Vertikal (VES) telah dijalankan dan sebanyak dua puluh lapan tambahan (28) VES telah dijalankan di kawasan bersebelahan dengan tambunan anai-anai bagi perbandingan berpotensi. Dapatan menghasilkan dua (2) model; model kesesuaian tapak tambunan anai-anai (TMSM) dan model peramalan berpotensi air tanah (GPPM) dengan ketepatan validasi menggunakan kawasan di bawah ROC, masing-masing 74.2% dan 86.5%. Bagi kesesuaian tapak tambunan anai-anai, dapatan menunjukkan bahawa ketinggian sederhana hingga ketinggian rendah, jenis liputan batu yang lebih terkesan pada luluhawa, kawasan tanaman dan jadual air cetek merupakan kelas faktor yang mempengaruhi penyebaran tambunan anai-anai. Nisbah Kekerapan (FR) dan korelasi rank Spearman yang diaplikasikan untuk mendapatkan hubungan antara tambunan anai-anai dan optimum GCF memperlihatkan keserasian yang konsisten bahawa tambunan anai-anai yang tinggi (≥1.8m) dan tambunan anai-anai berbentuk katedral adalah berguna dalam mengesan zon prospektif air tanah. Berat min yang diperoleh dari bunyi resistiviti elektrikal juga memperlihatkan bahawa tambunan anai-anai yang tinggi (>2m), tambunan berbentuk katedral dan di samping itu, tambunan yang dibina oleh *Nasutitermes* genus menunjukkan potensi produktiviti akuifer yang lebih berbanding dengan jenis tambunan anai-anai yang lain. Kajian ini memberikan suatu eksposisi kepada rasional saintifik bagi menggunakan tambunaan anai-anai sebagai indikator bio bagi air tanah dan jenis tambunan yang spesifik bagi diterima pakai sebagai panduan.

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

1-D	One-dimension
2-D	Two-dimension
AHP	Analytical Hierarchy Process
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
AUC	Area under Curve
CAO	Carnegie Airborne Observatory
CI	Consistency Index
CR	Consistency Ratio
CFS	Correlation-based Feature Selection
DEM	Digital Elevation Model
FR	Frequency Ratio
GCFSs	Groundwater Conditioning Factors
GIS	Geographic Information System
GPPM	Groundwater Potential Prediction Model
IDW	Inverse Distance Weight
KNP	Kruger National Park
LiDAR	Light Detection and Ranging
MCDA	Multi-criteria Decision Analysis
NDVI	Normalized Difference Vegetation Index
RF	Random Forest
RMSE	Root Mean Square Error

ROC	Receiver Operating Characteristics
SWL	Static Water Level
TM	Termite Mounds
TMSEM	Termite Mounds Suitability Evaluation Model
TWI	Topographic Wetness Index
USGS	United States Geological Survey
VES	Vertical Electrical Sounding
WLC	Weighted Linear Combination

CHAPTER 1

INTRODUCTION

1.1 Introduction

Termites are social insects of enormous ecological, economic and medicinal importance (Moe et al., 2009; Fufa et al., 2013; Figueiredo et al., 2015). Sharing ancestry with wood eating cockroaches, they are the first social insects to evolve a caste system (Inward et al., 2007a; Sekhar & Vidhyavathi, 2018). Thought to evolve during the Jurassic to Triassic period (Poinar, 2009), they are found mainly in the tropical to sub-tropical regions of the world with their abundance in the order of Africa > South America > Southeast Asia > Australia (Davies et al. 2003). Also, in terms of diversity, they are highest in Africa with more than 1000 species of the about 3000 species known worldwide (Huis, 2017). The nests of termites are broadly divided into subterranean, epigeal and arboreal (Noirot & Darlington, 2000). Some species of termites build epigeal nests which are high rising and conspicuous landscape features called termite mounds or termitaria.

Termite mounds are long lasting structures that are built from surrounding clays that can remain for centuries long (Davies et al., 2014a). Built in a wide variety of shapes and sizes, the mounds serve several purposes for the inhabitants amongst which include the protection against predators and sunlight, provision of high humidity and maintaining stable temperature through a network of ventilation system permeated within the mound, and as reservoir for food preservation (Jouquet et al., 2016b).

The soil on termite mounds and the annular zones surrounding the mounds in many cases, differ from that of the surroundings (where they are sourced) in terms of physical, chemical and biological compositions. This is as a result of reworking of the soil by termites to modify the porosity, water infiltration capacity and pH level among others (Choosai et al., 2009; Léonard & Rajot, 2001). Consequently, termites are referred to as ecosystem engineers (Dangerfield et al., 1998). Although termites cause considerable damage to man-made wooden structures, agronomic and forest resources globally estimated to cost around $40 billion (Rust & Su, 2012), they, through ecosystem engineering improve soil productivity to benefit mankind in several ways. Pharmaceutically, mound soils are consumed for regulating stomach pH while the termites themselves are used as alternative treatments for asthma, hoarseness and pregnancy complications (Figueiredo et al., 2015). Mound soils facilitate the growth of woody plants and contribute to the maintenance of savannah biodiversity just as they are appropriate sampling media for the exploration of concealed metallic mineralization such as gold, silver, copper, zinc, uranium etc. (Arhin et al., 2015).

Termite mounds form islands of enhanced nutrient content and soil water availability to support the growth and development of lush vegetation around them throughout seasons (Davies et al., 2016; Turner, 2006). This phenomenon has boosted the resilience of dry ecosystems against water shortages (Bonachela et al., 2015). Taking advantage of this, termite mound locations have been locally exploited for locating groundwater sources in many parts of Africa where scarcity of potable water is causing untold hardship including poverty and civil unrest (Ferriz & Bizuneh, 2002; Safriel et al., 2005).

To speedily address the water shortage crisis, emphasis must shift from surface water development which is expensive, cumbersome to operate and maintain to a less expensive, quick to develop, operate and maintain groundwater systems. Groundwater offers the advantages of shorter development time once favourable spots are located. It has limited vulnerability to pollution, drought reliability, is safer to consume with no or little treatment and exists in many geological formations (Talabi & Tijani, 2011; Jha et al., 2007). Despite these advantages, groundwater development requires exploratory stages that can be quite technical, laborious, time consuming and expensive to undertake (Jaiswal et al., 2003; Manap et al., 2012). The major challenge has been where to explore and drill as there is no guarantee of success should a well be sited haphazardly (Edet et al., 1998; Fenta et al., 2015; Suneetha et al., 2017).

The challenge of where to find groundwater is likely to be solved by termite mounds. Through the modification of soils by termites to enhance the physical and hydrological properties of mound areas, surface water runoff preferentially flows and become intercepted at termite mound sites (Bargués-Tobella et al., 2014; Léonard & Rajot, 2001) to recharge shallow aquifers. Furthermore, the mounds in other instances are built directly above structurally weakened bedrocks that serve as conduits for the movement of permanent groundwater that are either outcropped or buried by layers of sediments (West, 1965; Watson, 1972; Mege & Rango, 2009). Therefore, locating termite mounds might prove that the difficult part of groundwater prospecting has been done at no cost and marginal labour.

1.2 Problem Statement

Nigeria was listed among the few countries that never met the Millennium Development Goals (MDGs) target 7c aimed at reducing by half the number of population without access to improved sources of water (Durokifa & Abdul-Wasi, 2016; NBS 2015) neither is there adequate measures put in place the achieve the Sustainable Development Goals (SDGs) target 6.4. The percentage of the country's population with access to improved drinking water sources (piped borne water, borehole, protected spring or rain water) is put at 67% as against the 77% required target at the end of 2015 (NBS, 2015). Going by this statistics, there are currently more than 54 million people without access to clean drinking water, which is a major cause of deadly diseases such as cholera, diarrhoea and typhoid fever. Because of the above reason, the country was ranked third in infant mortality rate in the world

(WHO, 2017).

The challenges confronting water supply in Keffi, Nasarawa State of Nigeria (study area), is a reflection of the country's situation. Over the years, governments and policy makers in the water resources sector have focused attention on developing surface water resources to the detriment of groundwater resources.

- This development has resulted in erratic supply of treated water due to lack of sustainability in terms of power generation required to run the treatment plants and the procurement of chemicals for the actual water treatment.
- The upsurge in population of Keffi during the past decade, being an educational hub, is without commiserate expansion and upgrading of public water facilities to service newly developed and upcoming developing areas.
- Since there is a shortfall in public water supply, many residents have to resort to developing private water facilities such as hand-dug wells and boreholes. However, due to the complex nature of the geology, many borehole failures have been recorded.
- Currently, there is absence of hydro-geological base maps to guide the exploration, exploitation and management of groundwater not only for the study area but many parts of Nigeria (Akujieze et al., 2003; Fashae et al., 2013).
- Although termite mounds are used as guide when exploring for groundwater, it is not known what type of mounds are actually instructive to the occurrence of the groundwater due to the diversity in their sizes, shapes, environments of occurrence and the termite species building them.
- Exploring for groundwater around termite mounds is unconventional; therefore, there is lack of reference materials in the hydro-geological literatures.
- With the aforementioned challenges, identifying the types of termite mounds suitable for locating groundwater facilities with promising yields is essential to scaling up the access to cheap and clean drinking water thereby improving the health, income and social inclusion of the populace.

1.3 Motivation behind the research

There are abundance of literatures on termites and termite mounds which mostly addressed subjects related to pedogenetic processes such as soil porosity, water infiltration and run-off, (Ackerman et al., 2007; Adhikary et al., 2016; Jouquet et al., 2015; Léonard & Rajot, 2001). Others are, soil pH rise (Denovan et al., 2001), increase in soil CO_2 (Jamali et al., 2013), organic matter transformation by termite gut microbiota (Brauman, 2000) and vegetation types around termite mounds (Davies et al., 2016; Davies et al., 2014b) with all these having profound implications in agriculture. On the other hand, there is general lack of studies detailing the relationship between groundwater hydrology and termite colony settlements. As far as geosciences is concerned, research attention is mostly on mineral exploration such as the accumulation of Ag, U, Cu, Cd, Ni, Co, Mn, Pb and Zn on termite mounds (Kebede et al. 2004; Alvarez et al., 2015; Arhin et al., 2015).

However, a number of literatures have sparsely indicated some field evidences that saliently relate termite mounds with groundwater. Such evidences include termite mounds distributed along aquiferous dykes (Mège & Rango, 2010), increased density of riparian tree species around termite mounds (Davies et al., 2016) and robustness of trees around termite mounds in dry lands or dry seasons (Turner, 2006). Despite the significant field evidences, deliberate effort to study the connection of termite mounds with groundwater has yet to catch the attention of researchers in the field of groundwater hydrology. With this in mind, there is therefore, the need to better understand the driving factors of termite distributions and have a scientific basis for relating them with groundwater by studying how groundwater conditioning factors influence their distribution and structure. Only then can we ascertain what and how termite mounds serve as bio-indicators of groundwater.

1.4 Research Objectives

The aim of this research is to develop a groundwater potential model in Geographic Information System (GIS) and evaluate the prospect of termite mounds in predicting suitable zones for groundwater development.

The following are the specific objectives of the study;

1. To quantify termite mound density, identify species types, explore factors that influence termite distribution and develop a suitability model for mounds construction.
2. To develop groundwater potential model and examine the spatial relationships between various categories of termite mounds and groundwater conditioning parameters.
3. To estimate the aquifer productivity potentials beneath termite mounds and compare the potentials with that of adjacent areas.

1.5 Research questions

This study comprehensively addresses the following research questions:

1. What species of mound building termites characterise the study area?
2. What environmental factors exert control on termite mounds distribution?
3. How do termite mounds relate with groundwater conditioning parameters?
4. Are all termite mound types indicative of groundwater or are there any specific types to that regard?
5. What is the extent spatial distribution of groundwater in the study area?

6. Does aquifer productivity potential varies across termite mound types?

1.6 Scope, Limitation and General Methodology

1.6.1 Scope of research

This research covers Keffi Local Government Area and a part of Karshi Development Area of Nigeria comprising of an approximate area of 156 km^2. While there are many approaches developed for modelling and predicting natural resources such as the statistical based methods (e.g. frequency ratio, logistic regression, weights of evidence) and machine learning models (e.g. artificial networks and regression trees), this research adopted knowledge-based Analytical Hierarchy Process (AHP) for modelling termite mounds site suitability and Random Forest for groundwater potential prediction. In the case of termite mounds suitability modelling, AHP was selected because the influence of environmental factors driving the distribution and structure of termites and termite mounds are poorly understood and are site specific. The AHP, through knowledge-driven analysis has the capability to analyse the environmental factors in pair-wise comparisons to estimate weights for each factor in a consistent manner. On the other hand, the Random Forest was selected for groundwater potential prediction because it has proved to be very powerful and successful in modelling natural resources especially groundwater potentiality with high prediction accuracy due to its unique technique of sampling with replacement (bagging) and prediction error evaluation (OOB). The study also adopted ground based survey for mapping termite mounds distribution along road transects and because of the limitation in depth of penetration and challenges of multi-instrumentation of resistivity imaging technique, the study utilize the Vertical Electrical Sounding (VES) method in conducting geophysical survey. A flow representation of the research scope is presented in figure 1.1.

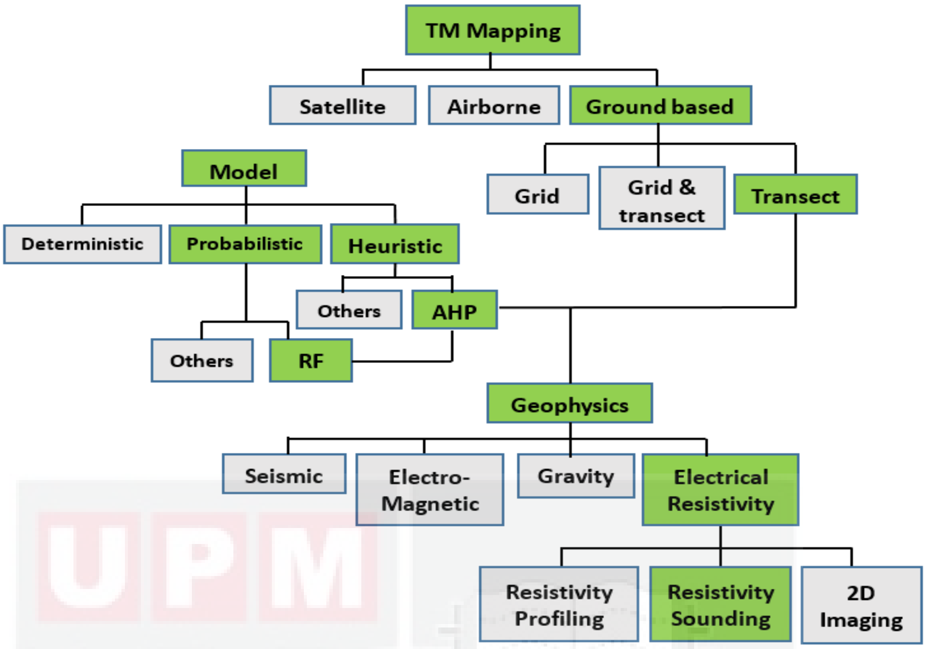

Figure 1.1 : Scope of study showing specific methods employed in the study in green colouration.

1.6.2 Limitation of the research

Moderate spatial resolution satellite imageries (Landsat OLI/TIRS and ASTER) used for this study. Primary geo-electrical properties interpreted from VES soundings only provided information on apparent resistivity and thicknesses of the subsurface layers and not aquifer characteristics such as hydraulic conductivity, specific yield and transmissivity.

1.6.3 General methodology

The study was carried out in three different phases that include; (1) mapping of termite mounds along road transect to record their coordinate locations, conduct morphometric measurements and sample termites for species identification (2) use of remote sensing and GIS techniques to produce thematic layers of conditioning factors that affect the distribution of termite mounds and groundwater (3) field measurements which include measuring static water levels in wells and conducting geophysical sounding surveys. From the first and second phases, the termite mounds site suitability model (TMSM) and groundwater potential prediction model (GPPM) were produced. Furthermore, GIS and statistical techniques were used to analyse relationships between termite mounds and groundwater conditioning factors (GCFs). From the third phase, primary geo-electrical parameters were produced from VES to assess aquifer potentials and make comparisons. The general methodology flow chart is presented in figure 1.2.

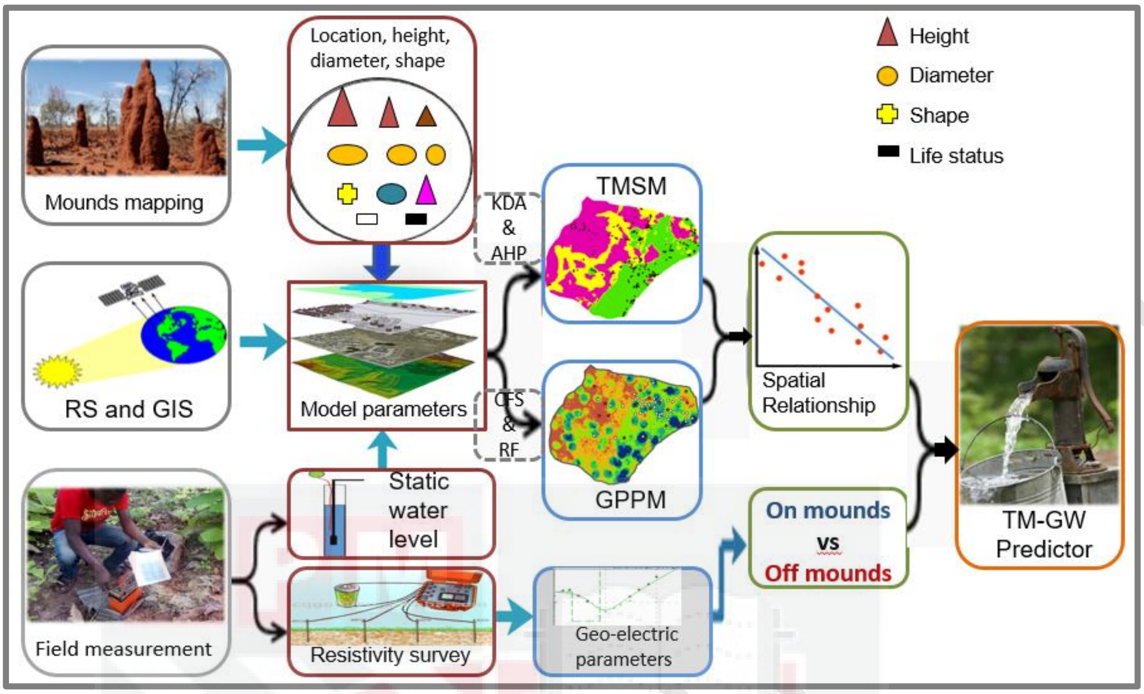

Figure 1.2 : General methodology flow chart

1.7 Thesis organisation

This thesis is based on research chapters (objective based). There are six chapters in it with chapter one containing an introduction to termites and termite mounds, followed by problem statement and objectives of the research. The chapter further highlights the research questions, scope of the research and concluded by providing the structure of the thesis. Chapter two presents detailed description of the biology of termites, features of termite mounds and factors affecting their distribution and diversity. It also highlights the techniques in mapping mounds distribution together with their limitations and stressed the economic importance of termites and termite mounds. It further discusses groundwater potential and looked at the parameters needed in the spatial modelling, the types of models available and gave a detailed discussion on Multi-criteria Decision Analysis (MCDA) and Random Forest models. Chapter three contains the first research chapter in which detailed description of the study area, field mapping campaign and data collection procedures were presented. Further, knowledge-based analysis of termite mounds site preference and MCDA analysis to assign relevant weights to criteria and achieve a site suitability model for termite mounds construction was discussed. Chapter four presented results of the spatial distribution of groundwater in the study area and revealed the spatial relationship between termite mounds and groundwater conditioning parameters. Chapter five contains the last research chapter. In it, the assessment of aquifer potential around termite mounds using geo-electric resistivity measurement was put forward. Further comparisons between on-mound and off-mounds aquifer potential was also achieved. Chapter six finalises the thesis with summary, conclusions and suggestions for future research.

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LIST OF PUBLICATIONS

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