A MULTI-CRITERIA ANALYSIS FOR MAPPING SOYBEAN (*Glycine max* (L.) Merr.) LAND SUITABILITY IN KABWE DISTRICT OF CENTRAL ZAMBIA

BY

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A dissertation submitted to the University of Zambia in partial fulfilment of the requirements of the degree of Master of Science in Integrated Soil Fertility Management.

THE UNIVERSITY OF ZAMBIA
SCHOOL OF AGRICULTURAL SCIENCES
DEPARTMENT OF SOIL SCIENCE
LUSAKA

2017

DECLARATION

I, Prisca Munene, do hereby declare that this dissertation represents my own work and it has not previously been submitted for a degree, diploma or any other qualification to this or any other University.

Signature: ……………………………… Date: 17/01/2017

CERTIFICATE OF APPROVAL

This dissertation of Prisca Munene has been approved as partial fulfillment of the requirements for the award of Master of Science Degree in Integrated Soil Fertility Management by the University of Zambia.

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ABSTRACT

Land suitability is concerned with the process of estimating the fitness of land for alternative agricultural uses. Land suitability analysis for soybean (*Glycine max* (L.) Merr.) production culminates into suitability maps that can be used by farmers in decision making to enhance sustainable land use. Soybean is a high value crop with potential to generate income for households. Despite benefits associated with growing soybean, its production is limited by many factors that include decline in soil fertility, climate change and partly due to inadequate suitability information. It is against this background that this study was initiated. The objectives of the study were to (i) extract and map spatial attributes relevant to soybean production in Kabwe district (ii) apply a multi-criteria approach to generate a land suitability map for soybean and (iii) validate the quality of the suitability map generated for decision making. Spatial attributes relevant to soybean production including soil reaction, available phosphorus (P), soil organic carbon (SOC), soil texture, slope, drainage and climatic factors were assessed. Accessibility represented by distance to roads was also included since it affects suitability of an area. Data layers for slope and drainage (wetness) were extracted from the digital elevation model (DEM) using appropriate algorithms in ArcGIS. Elevation was used as a proxy for climate (rainfall and temperature) and was generated by reclassifying the elevation grid into elevation classes. The distance to roads dataset was generated using the euclidean distance tool. Data sets for soil parameters were generated by inverse distance weighting (IDW) based on soil samples collected from the field. A spatial process model based on multi-criteria evaluation was used to integrate selected spatial attributes in a weighted sum overlay to generate a soybean suitability map. The quality of the suitability map was assessed using an error matrix. Results showed that prediction maps were satisfactory for use in the suitability process model with prediction mean errors of -0.0101 for soil reaction, -0.1186 for P, 0.0012 for SOC and -0.0149 for texture. The suitability map show that 15.07 % of the area in Kabwe is highly suitable for soybean production, 26.53% is suitable and 25.18% is moderately suitable. The other 20.57 % is marginally suitable, whereas 10.74 % is currently not suitable and 1.92 % is permanently not suitable. Based on ground truth data, the suitability map was 65 % accurate, which is good enough for use as a guide in selecting suitable sites for soybean production.

ACKNOWLEDGEMNTS

I would like to acknowledge my supervisors Dr. L.M. Chabala and Dr. A. M. Mweetwa for their support and encouragement during the course of my study.

I am greatly indebted to the Agricultural Productivity Programme for Southern Africa (APPSA) for the financial support and the Zambia Agriculture Research Institute (ZARI) for granting me study leave.

Special thanks to the Lecturers and Support staff in the Department of Soil Science for their support during the course of my study.

Appreciation is extended to the Agricultural Camp Officers in Kabwe and all my colleagues for the help rendered during data collecting in the field.

I thank my family and friends for their continued support and encouragement.

Above all I give thanks to God for his divine guidance.

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LIST OF ABBREVIATIONS AND ACRONYMS

DEM……....Digital Elevation Model

FAO……….Food and Agriculture Organisation

GIS……......Geographical Information System

GDP……....Gross Domestic Product

GPS……….Geographical Positioning System

IDW……....Inverse Distance Weighting

LCCS……..Land Capability Classification System

LCM………Land Capability Map

LSA……....Land Suitability Assessment

LUT……….Land Utilization Type

MCDA…....Multi-Criteria Decision Analysis

MCE………Multi-Criteria Evaluation

MLNR…….Ministry of Lands and Natural Resources

MoA…........Ministry of Agriculture

MAL………Ministry of Agriculture and Livestock

SOC……….Soil Organic Carbon

TWI……….Topographic Wetness Index

USGS……..United States Geological Survey

ZMD……...Zambia Meteorological Department

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Soybean (*Glycine max.* (*L*) Merr), is a high value crop whose grain consists 40 percent protein, 20 percent oil and 34 percent carbohydrates. It is used in the production of oil, human food and stock-feed. Soybean was introduced in Zambia in the 1930s, cultivated by both commercial and small scale farmers (Muliokela, 1995). As a legume, soybean is usually incorporated in cropping systems to improve soil fertility. This leads to increased crop production, further resulting in increased food security and income generation.

There is potential for soybean production in Zambia, however productivity is usually limited by many factors that include decline in soil fertility, low availability of improved seed and climate change. To address these challenges, improved seed varieties, crop rotations and tillage practices, microbial inoculation, use of herbicides, pesticides, fungicides and fertilizers have been introduced at most farmers fields. While these technologies are intended to improve soybean productivity, the availability of soil suitability information when selecting production sites is also key for increased crop productivity. Soybean suitability information is relevant otherwise implementing new and improved technologies will have no positive impact on soybean production. There is however, limited information on land suitability for soybean production in Zambia, therefore a need for assessing the potential of land for soybean production.

Land suitability assessment (LSA) is key for generating land suitability information for various land use types. It classifies areas by assessing land qualities and matching them with requirements of specific land utilization types (FAO, 1976; FAO, 1983; FAO, 2007). Land suitability assessment is used as an agricultural planning tool for identification of suitable areas to growing crops. This allows farmers to make decisions on how best to manage land resources for crop production. The selection of agriculture crops based on suitability for a particular area is also becoming increasingly common among farmers, agriculture scientists and decision makers (Perveen *et al*., 2013).

Land suitability assessment for crop production is generally done by inventorizing the biophysical and ecological characteristics of a location such as soil, topography and vegetation, and then comparing them to crop requirements. The location where these conditions merge is identified as suitable (FAO, 1976; FAO, 1983; FAO, 2007; Olaniyi *et al*., 2015). Besides the general land characteristics, climatic factors, agro-ecological zones and social economic factors also influence land suitability for a particular crop in a given location.

In agricultural application, land suitability assessment involves several steps. The first step involves choosing a land utilization type (LUT). This means choosing a major kind of land use under rainfed agriculture, irrigated agriculture, forestry or grassland and then define it in as much detail as the purpose requires. The details of a particular land use are defined according to a set of technical descriptors in a given physical, economic and social setting (FAO, 1976). At this stage, the assessment of land qualities for a specific type of land use is based on land use requirements and constraints which are used as the basis for establishing an evaluation criteria. This includes a multi-criteria evaluation (MCE) which is used to describe a structured approach to determine overall preferences among alternative options where the options accomplish several objectives (Bolstad, 2005; Mendas and Delali, 2012; Perveen *et al*., 2013).

Integration of a MCE approach using geographic information system (GIS) is mostly used in identifying suitable localities for crop production. This further provides guidance for targeting research on crop production and soil fertility improvement (Delve *et al*., 2007). With reference to a multi-criteria evaluation, a set of algorithms at this stage are then employed to match the existing land qualities and the requirements of a particular land utilization type. This matching procedure then gives rise to a ranking of the potential of land for a given purpose. The final step in agriculture land suitability assessment results in a map showing the partitions of the area of interest into suitability classes for a selected land use. Additionally, validation of the resultant map is also considered as one of the main components of agriculture land suitability assessment.

In Zambia, due to limited studies on suitability mapping for soybean production, there is inadequate suitability information to assist farmers in the decision concerning areas for soybean production. This has contributed to fluctuations of soybean productivity at most farmers' fields. It was against this background that this study was undertaken to evaluate the suitability of land in Kabwe district of Central Zambia to soybean production.

1.2. Statement of the Problem

Land suitability assessment for soybean production provides best opportunities for farmers in making decision on best locations to grow the crop. In Zambia, there is inadequate detailed land suitability information for soybean production to assist farmers in the decision making concerning site selection. At times, land suitability information available does not effectively represent the conditions of most farmers' fields because the suitability assessments were done on a large scale. This has left most farmers with no choice but to plant the crop wherever there is available space without considering land suitability, hence contributing to fluctuations of soybean productivity. With inadequate information on soil suitability, adoption of improved technologies to enhance soybean productivity have also not resulted into better yields of soybean at most farmers' fields.

1.3. Rationale

Land suitability assessment for crops is an important prerequisite for sustainable agricultural development, and must be conducted to help decision makers as well as agricultural development planners (Halder, 2013). Information on the type of soil, climate, and topography occurring in an area is vital for the selection of crops to be grown and agronomic practices or technologies to be employed in a specific location. Previously, studies have been done focusing on the type of crops that can be grown in a specific agro ecological zone, delineated on the basis of rainfall. To increase productivity, there is further need to delineate areas within ecological zones based on different biophysical attributes to cover farmers' field where crops such as soybean can be grown.

In agriculture development, strategies such as diversification and specialization of crop production is key for farmers to improve productivity (Perveen, *et al*., 2013). Legume crops such as soybeans have long been recognized and valued as soil building crops, thus integrating them in cropping systems results in sustainable crop production, especially with changes in climate. Climate change results in fluctuating rainfall patterns and an increase in dry periods. It is therefore important that land suitability assessment is done periodically and often updated to act as mitigation and adaptation strategies to unpredicted climate change (Ayehu and Besufekad, 2015).

In Zambia, land suitability mapping that have been done for crop production are on a large scale, usually based on agro ecological zones. This does not represent well at most farmers' fields as detailed suitability information is lacking. Crop suitability maps are an important guide for farmers to help them make right decisions on what agronomic practices to employ with the prevailing weather conditions. Furthermore, unpredicted climate changes require implementation of fast and efficient ways of generating necessary information on land suitability. There is therefore need to integrate geographic information system to generate land suitability information for crop production (Halder, 2013; Chen, 2014). Detailed crop suitability analysis involving not only land characteristics, but the socio-economic factors also help farmers make decisions on managing the main limiting factors.

1.4. Objectives

The main objective of the study was to evaluate land suitability for soybean production in Kabwe district of central Zambia.

The specific objectives were:

(i) To extract and map spatial attributes relevant to soybean production in Kabwe district.

(ii) To apply a GIS based multi-criteria approach to generate a suitability map for soybean.

(iii) To validate the quality of the suitability map generated for decision making.

1.5. Research Hypotheses

The research hypotheses for the study were;

i. Spatial attributes relevant to soybean production can be extracted from different sources and mapped as guides for decision making.

ii. A GIS multi-criteria approach can generate an accurate land suitability map for soybean production.

1.6. Assumptions

There are a number of factors important in this study which were assumed or could not be considered.

1. The random method used to select the sampling sites was representative of the whole study area.
2. The use of elevation (altitude) as a proxy for climate (rainfall and temperature) was valid.
3. The selected crop requirements, land characteristics and land qualities were the most significant for optimum soybean growth.
4. Assessment of land suitability for soybean production assumed a low level of management of the farmers.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Agriculture and soybean production

Agriculture remains the key priority sector in economic diversification needed to reduce poverty and improve food security for the growing population in Zambia. Agriculture supports over 66 % of the Zambian population, making it an important source of livelihoods and employment (Tembo and Sitko, 2013). It is considered as the backbone of the economy despite its slow growth which has led to its declining share to the country's Gross Domestic Product (GDP). According to Tembo and Sitko (2013), the percent contribution of the agricultural sector to GDP declined from 16 % in 2001 to 12.6 % in 2012. The 2014 and 2015 estimates show that, the wholesale and retail trade industry had the highest contribution of 22 % to GDP in both years, followed by the mining and quarrying industry which was at 14.6 % in 2014 and 12.7 % in 2015. The share of agriculture, forestry and fishing reduced from 6.8 % in 2014 to 5.0 % in 2015 (CSO, 2016). There is therefore need to improve the growth conditions for agriculture in Zambia in order to improve both the overall GDP growth and the livelihoods conditions of the Zambian people.

Agriculture in Zambia comprises mainly of livestock, fisheries and crop production, including such crops as maize, tobacco, soybean, groundnut, cotton, sweet potato, sunflower, cassava and cowpea. Maize is a staple crop grown for food security and soybean is usually grown as a cash crop and for stock feed. Most small scale farmers in Zambia solely depend heavily on subsistence agriculture and hence have low income. Subsistence agriculture is faced with challenges that include poor harvest due to low soil fertility and climate change. This has seen some small scale farmers practice crop diversification, introducing legumes such as soybean in cropping systems to increase productivity. Like any other legume, soybean is usually grown in rotations or intercrops with cereal crops to improve soil fertility, leading to increased yields (Sullivan, 2003; Bationo *et al*., 2011). Increased soybean yield further lead to increased income generation for most households.

Soybean production in Zambia has increased by 29 %, from 203,038 metric tonnes in 2011/2012 farming season to 261,063 metric tonnes in 2012/2013 farming season. The total planted area also increased by 45 % from 2011/2012 to 2012/2013 farming seasons (MAL, 2013). In 2014/2015 farming season, production of soybean was projected to increase by 5.7 % to 226,323 metric tonnes from 214,179 metric tonnes in the 2013/2014 farming season. The area planted to soybean also increased by 11.2 %. However, despite an increase in the area planted, the national yield rate for soybean has declined by 5 %. The decline in soybean yields also applies to other agriculture crops whose yields are usually well below global averages (Tembo and Sitko, 2013; NAIS, 2015). Figure 1 and Figure 2 present soybean production and yield for the eleven year period from 2004 to 2015.

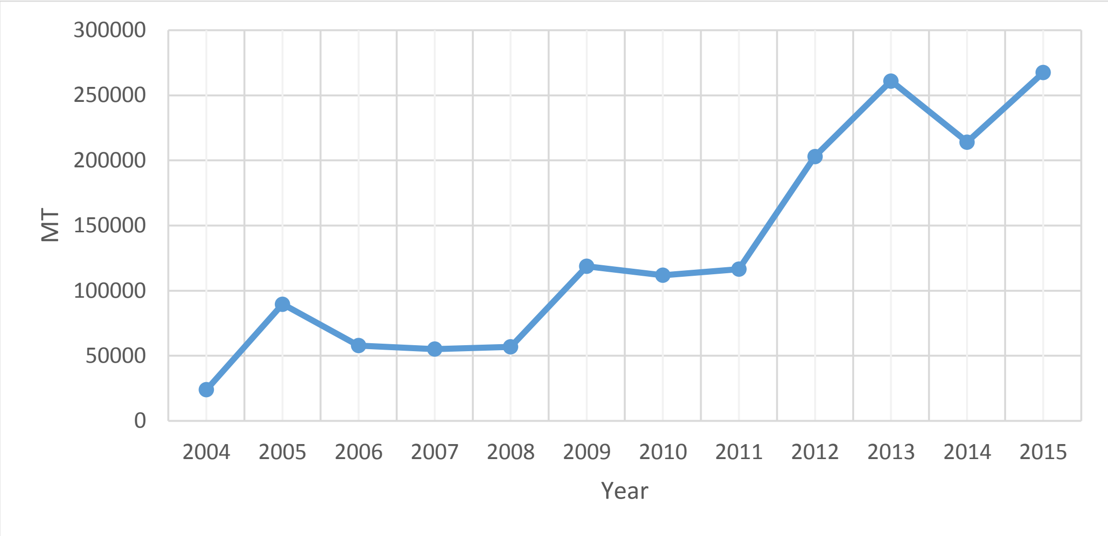

Figure 1: Soybean production in Zambia (Source: FAOSTAT 2015; MAL, 2016)

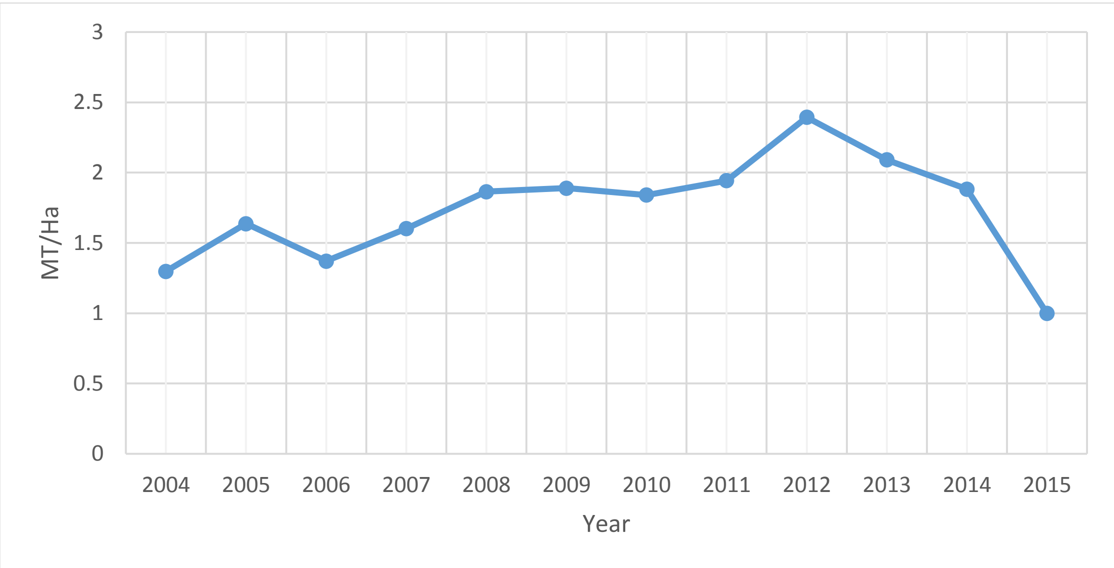

Figure 2: Soybean yield in Zambia (Source: FAOSTAT 2015; MAL, 2016)

The yields for soybean and other agriculture crops are affected by different factors such as low soil fertility, inappropriate cropping systems, low usage of improved seed varieties and climate change. Climate change has caused crop yields to vary from year to year, especially in the early 2000s when irrigation was less widely used by some farmers. It has been observed that crop yields have generally remained constant over time due to variations in weather (AGRA, 2014). It is further reported that, rapid and uncertain changes in rainfall and temperature patterns threaten food production, leading to food price shocks. This increases the vulnerability of small scale farmers, eventually leading to rural poverty (Lubungu *et al*., 2013; MAL, 2013).

Production of soybean by small scale farmers in Zambia is marginal due to limited availability of inputs, expertise and market opportunities. Other key constraints faced by small scale farmers producing soybean include the low usage of microbial inoculum, poor crop management practices such as late planting and poor disease management. These constraints lead to fluctuations in soybean yields on most farmers' fields. Despite these challenges, there is however potential to improve lives of the growing population especially the small scale farmers by improving the soybean value chain, taking advantage of the growing domestic market and export opportunities (MAL, 2013).

The use of improved seed varieties, microbial inoculum, phosphate fertilizer application, extension services and demonstration plots are some of the interventions that are known to improve soybean production (Bationo *et al*., 2011; Thierfelder *et al*., 2012). Public investment in feeder roads also improve the transportation of inputs and soybean produce to and from the market. Despite benefits associated with soybean and crop improvement strategies in Zambia, production levels remain fluctuating on farmers' fields partly due to inadequate land suitability information. Land suitability information guides farmers in selecting sites to grow crops and employ the appropriate technologies for increased and sustainable crop production.

The availability of arable land for soybean production in Zambia is not a constraint in itself. Information on suitable areas for growing soybean is the major constraint for most small scale farmers. These farmers therefore end up planting soybean crop anywhere without considering the suitability of the land. To ensure optimum production, selection of agriculture crops should be done according to their suitability to the area. Hence, this requires carrying out land suitability assessments to identify areas well suited for growing specific crops.

2.2 Land suitability assessment for crop production

Land suitability is the assessment and estimation of potential of land for various kinds of utilizations such as crop and livestock production. In LSA also referred to as land evaluation, the qualities of the land are assessed and matched with requirements of specific land utilization types. A land utilization type (LUT) is a kind of land use defined in more detail, according to a set of technical descriptors in a given physical, economic and social setting (FAO, 1983). Examples of LUTs include cropping system which can either be crops grown, cropping calendar or cropping intensity. Other examples are livestock, forestry, capital intensity, labour intensity, infrastructure, material inputs, yield and production, recreation and associated rainfed among others. Land qualities on the other hand are attributes of land which act in a distinct manner in their influence on the suitability of the land for a specific kind of use. These include temperature regime, nutrient availability, conditions affecting germination, soil workability, soil toxicities, location and soil degradation among others (FAO, 1976; FAO, 1983). In LSA, land suitability is considered either in its present condition or after improvement (FAO, 1976; FAO, 1983; FAO, 2007). Assessments of land suitability allows for the identification of the main limiting factors for agricultural production. Land suitability assessments also enable decision makers to develop crop management strategies for increasing land productivity (FAO, 1976, FAO, 1983; Olaniyi *et al*., 2015).

Land suitability assessments can be either qualitative or quantitative or both. Qualitative assessments give general information on the relative suitability of the land for different uses, and are mostly used in reconnaissance studies (FAO, 1976; Dent and Young, 1981). The suitability of the land in qualitative assessment is expressed in qualitative terms such as highly suitable, moderately suitable, marginally suitable or not suitable for a specified use. There are no quantitative expressions of the inputs used or outputs that are given in qualitative assessments. Quantitative assessments on the other hand determine land suitability using estimates of production of the land, such as inputs and crop yields. Chinene (1992) demonstrated the combination of qualitative and quantitative land suitability assessment in land evaluation of the University of

Zambia farm for selected crops. Land suitability is also classified in a structure that includes orders, classes, sub classes and units.

2.2.1 Suitability classification structure

According to the Food and Agriculture Organization (FAO) Framework for land evaluation, the suitability classification structure comprises orders, classes, sub classes and units. Land suitability orders reflect the kinds of suitability, indicating whether the land is assessed as suitable (S) or not suitable (N) for a specific utilization type. Land suitability classes reflect the degree of suitability within orders. The number of classes within the order suitable is not specific. However, the use of a minimum number of suitability classes is necessary to meet the interpretive aims (FAO, 1976; FAO, 1983; FAO, 2007). FAO therefore recognize three classes within the order suitable and two classes within the order not suitable as shown in Table 1.

Land suitability subclasses reflect the kinds of limitations, such as soil moisture deficiency or the kinds of improvement measures that are required within classes, except in class S1. The number of subclasses identified and the limitations indicated to distinguish them will differ in classifications for different uses. Land suitability units on the other hand are subdivisions of a subclass reflecting minor differences in required management within subclasses. These units usually have the same degree of suitability at class level and similar kinds of limitations at the subclass level (FAO, 1976; FAO, 1983; FAO, 2007). The classification structure of land suitability according to FAO is presented in Table 1.

Table1: Description of suitability classes according to FAO classification

Order	Class	Description
S-Suitable	S1-Highly Suitable	Land having no, or insignificant limitations to the given type of use, or land with minor limitations that cannot significantly reduce productivity.
	S2-Moderately Suitable	Land having limitations which are moderately severe for sustained application of a given type of use.
	S3-Marginally Suitable	Land having limitations which are severe for sustained application of a given use and can hence reduce productivity.
N-Not Suitable	N1-Currently Not Suitable	Land having severe limitations that preclude the given type of use. The limitations cannot be corrected with existing knowledge at currently acceptable cost but can be managed in time with specific management.
	N2-Permanently Not Suitable	Land with so severe limitations which preclude any possibilities of successful sustained use of the land for any given type of use.

Source: Adapted from FAO (1976).

2.2.2 Land suitability assessment in Zambia

Traditionally in Zambia, land suitability assessment for crop production is conducted through surveys. An area is usually surveyed to determine the potential of the available land resources in supporting plant growth. Survey reports produced from these assessments are intended to provide information to land users and land use planners. However, not all the intended parties get access to this information, yet land suitability still remains an important tool for decision making and has successfully been employed in farming ventures.

The Zambia Semi-Quantified Land Evaluation System for rain fed agriculture is used to assess land suitability, combining the Land Capability System and the Zambia Land Evaluation System. The Zambia Semi-Quantified Land Evaluation System incorporates physical and chemical properties of the soil, climatic conditions of the location and the farmer's ability to manage the land for crop production. It further predicts the potential yield of the crop cultivated (Kalima and Veldkamp, 1985; Veldkamp, 1987; Woode, 1988). According to Chinene, (1991) this system is very good for recognizing the limitations of land. Prior to this system, the Land Capability Classification System was used in land suitability assessments. This was followed by the Land Evaluation System developed by the Soil Survey Unit under Zambia Agriculture Research Institute (ZARI).

The Land Capability Classification System (LCCS) was designed to indicate the relative suitability of land for rainfed crops. This system emphasizes soil physical properties more than the chemical status of the soil. The LCCS system was applied in a number of land evaluation studies including that of Woode (1979) to assess the suitable area for the rural reconstruction center. Clayton (1974) also used the LCCS in a study to assess the extent of the soil suitable for Virginia tobacco and maize. The other works that applied a LCCS were by English (1982) and Sokotela (1982). Generally, the LCCS characterizes and evaluates land development units without taking into consideration the kind of land use. The system defines suitability classes considering that some soils or other land qualities can be suitable for specific crops and unsuitable for some crops. The main limiting factors for agricultural production are identified in this land capability evaluation. This enables decision makers, farmers, land use planners, and agricultural support services to develop crop management and be able to overcome such constraints and increase productivity (Rabia, 2012).

The Land Evaluation System developed by the Soil Survey Unit under ZARI, involves matching land use requirements with the actual properties of the land (Kalima and Veldkamp, 1985). The land use requirements include climatic factors, the physical and chemical conditions of the land and management levels of the farmers. This system involves qualitative assessments to indicate the relative suitability of the land for a specified land use, further indicating the limiting factors to that land use.

Despite the land evaluation studies that have been done using the developed land evaluation methods, the information in the final reports is not available to the intended land users such as the small scale farmers. The other suitability assessments done are more generalized as they are based on agro-ecological zones and not representing detailed suitability information at farm level (MTENR, 2007). The farmers are therefore left to plant crops anywhere without considering suitability issues, hence reduced crop yields.

2.3 Integrating multi-criteria analysis in land suitability assessments

The systems used in assessing land suitability allow for the integration of different factors that affect suitability. These factors include rainfall, temperature, topography, soil and ground water. Others are non- bio-physical factors such as social, economic and political governance aspects. Assessing land suitability is therefore a complex process involving the integration of different factors. Such complexities lead to the simultaneous use of several decision support tools such as Geographic Information Systems (GIS) and multi-criteria decision analysis (MCDA). These decision support tools are inevitable in determining suitable land for crop production (Mendas and Delali, 2012; Perveen *et al.*, 2013; Ayehu and Besufekad, 2015). Therefore, a number of data layers have to be handled in multi-criteria evaluation (MCE) in order to arrive at a decision for suitability.

A multi-criteria evaluation (MCE) is an evaluation system concerned with the allocation of land to suit a specific objective on the basis of a variety of attributes that the selected areas should possess (Malczewski, 2004; Malczewski, 2006; Mendas & Delali 2012). In a multi-criteria evaluation, there are multiple criteria which are considered in decision making environments. A criterion is simply a standard for evaluating something or a standard by which something can be decided upon. Hence it can be referred to the level of crop requirements, such as rainfall or temperature, at which they are said to be suitable or not suitable for growing a particular crop (Mendas and Delali 2012). These criteria which are usually conflicting are evaluated in making decisions such as the best land to grow a particular crop. In such instances crop requirements are considered including the social and economic factors such as cost of production and accessibility of an area. Therefore, different criteria in land suitability are evaluated in a multi-criteria approach to decide on which land is suited for a specified land use such as crop production. The integration of multi-criteria decision analysis approaches in GIS also provides a powerful spatial decision support system.

Integrating GIS based decision support system offers the opportunity to efficiently produce land suitability maps while providing better land use options to the farmers. GIS is one of the geospatial information technology tools which scientists from different fields including engineering, agriculture and social sciences incorporate in processing and presenting information to decision makers. GIS is said to be an efficient tool for collecting, storing, retrieving, transforming and displaying spatial and non-spatial data from the real world. This is done for a particular set of objectives such as conducting land suitability assessments prior to crop planting. Results from this system are usually reported in map, values in a table or as a chart (Forkuo and Nketia, 2011; Lupia, 2012). In agriculture studies, GIS has been used to generate information on soil and other environmental factors affecting crop production at specific sites thereby delineating land suitability with greater flexibility and accuracy (Halder 2013).

Productivity of land is determined by multiple environmental components such as climate, local topography, soil type and existing vegetation. GIS therefore combines information on these factors together with social-economic factors to provide a criteria for determining the area that is most likely suited to specific land use like crop production. Therefore, a GIS based multi-criteria evaluation (MCE) is integrated in assessing suitable agriculture land for crop production (Nwer, 2005; Mendas and Delali, 2012).

2.3.1 Performing multi-criteria analysis in land suitability assessment

Suitability analysis for crop using a multi-criteria approach involves selection of criteria relevant for growing a particular crop. Data layers are generated for each of the selected criteria and used as input in a weighted overlay analysis to generate a suitability map. An overlay analysis usually requires the analysis of many different factors or criteria which are usually in different scales of measurement and of different importance to the requirement of the crop. Therefore, these factors are usually reclassified into a common scale.

The attributes within each dataset are ranked on a scale based on their suitability for a specified land use. The highest values are assigned to more suitable attributes, and so, the higher the score, the more suitable the site for a defined use (Bolstad, 2005). It is also important to measure relative weights of each criterion used in the suitability evaluation since different criteria have varying degree of influence on a particular land use being assessed. Determination of relative importance of each criterion depends on individual preference and judgment supplemented by mathematical tool (Jankowski and Richard, 1994). Integrating such preferences, which are based on social, political and economic priorities, with the physical constraints addressed in land capability knowledge provide results that are not only environmentally suitable but also acceptable to decision makers (Jankowski and Richard, 1994; Perveen *et al*., 2013). Each criteria used in suitability analysis is therefore weighted according to importance resulting in datasets that have more influence in the suitability model. The data layers are then combined in an overlay analysis to generate a final suitability map.

2.4 Multi-criteria approach in land suitability assessment for different land uses

Literature shows different studies on land suitability assessment using multi-criteria approach. In a study by Delve *et al*., (2007), areas with actual and potential soil fertility management problems were investigated for targeting legume cover crops production using a multi-criteria approach. Adornado and Yoshida, (2008) also developed soil fertility map and determined crop suitability using the same approach. In their study, agro-environmental, soil information and crops biological requirements for growth were combined and analyzed to develop a crop suitability map. This map was used to correct the conventional practices of planting crops wherever the farmers or landowners preferred without taking into consideration the plants preferred ecological niche. In another study by Rabia (2012), a suitability map for each land use was developed illustrating the degree of suitability and displaying the spatial representation of soils suitable for agriculture. The map was developed to assist land managers and land use planners identify areas with physical constraints for a range of selected land uses. The map was also used as a guide in identifying management requirements to ensure sustainable land uses. Nurmiaty and Baja (2013) also employed a land evaluation method in a GIS based multi-criteria evaluation. The evaluation was based on the FAO framework for land evaluation. Their study was aimed at identifying suitability and availability of land for maize development to come up with recommendations for local government in devising agricultural land development in the study area.

The multi-criteria evaluation approach has been used in soybean land suitability analysis by Rota *et al*., (2006) who produced soil and climate characteristic maps from random sample point data, demonstrating their potential in land suitability evaluation for soybean production. Kamkar *et al*., (2014) also assessed the possibility and performance of crop rotation between canola (*Brassica napus L*.) and soybean using a multi-criteria evaluation approach. In this study, the uniformity of results from the final overlaid maps showed that GIS as a systemic approach plays a vital role in saving time and reducing research costs. Suitability maps for the two crops were developed to help policy makers design proper cropping patterns, particularly rotation systems. In another study, AbdelRahman *et al*., (2016) developed land suitability and capability maps in a GIS environment for different land uses including production of soybean. A multi-criteria approach was used in this study to evaluate factors that affect crop production. The factors evaluated include soil texture, depth, erosion, slope, flooding and coarse fragments as these were known to affect crop production such as in soybean production. The suitability maps that were generated from these studies were mostly used as guides for farmers and other land users in decision making. These suitability maps were validated to check for their accuracy before applying them to different uses that include decision making. Validation was also applied to the models that were used in these studies.

2.5 Validation of suitability maps

Validation of the models and the suitability maps allows decision makers use the generated suitability map or extend the use of the model to other studies. Several methodologies have been used to validate suitability maps and models. In Mbilinyi *et al*., (2007), the validation of the model developed in their suitability study was done by using information from a different location. Chabala *et al*., (2013) also validated the model used in their study by undertaking a physical study. Geographic Positioning System (GPS) points were located, noting the accompanying landform types and elevation. In another study by Perveen *et al*., (2013), the decision support system developed was validated using the already existing cropping zone map. The existing cropping patterns on the cropping zone map were compared with what was generated using the model in their study. Therefore, different methods are used in validating the maps and models before they can be used for decision making.

2.6 Land suitability assessment for soybean production in Zambia

In Zambia, like many other developing countries, current land use practices are not based on land suitability analysis, therefore an urgent need to use land in more sustainable ways. The pressure on land is ever increasing in many countries today leading to a decrease in the area of agricultural land. According to the World Bank (2006), many developing countries, especially in Africa, need to increase their agricultural production in order to feed the growing population. These countries also need to produce raw materials for local industry and export in sufficient quantities to support a healthy economy. Land suitability assessment therefore becomes key to increased sustainable agriculture production (De la Rosa *et al*., 2004).

Apart from the notable factors affecting soybean production in Zambia, inadequate land suitability information also contribute to fluctuations in soybean yields. Land suitability information is important in decision making for small scale farmers if soybean production is to be sustained. Crop suitability maps gives an indication to farmers of the suitable land as well as land that may require special management. On the other hand, successful production of soybean is known to be a function of many factors. These factors include soil, rainfall and temperature, and social economic factors. Therefore, a multi-criteria approach in assessing land suitability for soybean production in Zambia becomes imperative. The use of fast methods to map land suitability for crop production is also important considering the effects of climate change on some land qualities. A GIS based multi-criteria approach in assessing land suitability for soybean production therefore becomes key. Kalima and Veldkamp, (1985) also recommended a computerized system in land evaluation to reduce on the number of calculations which were done manually.

There are few studies that have been done in Zambia involving GIS multi-criteria approach in mapping land suitability for crop production, including soybean production. The use of geo-spatial mapping make it easy for land users and decision makers to utilize land resources at maximum, guided by the spatial map that are developed from such mappings (Mapedza *et al.* 2003). A number of studies that have been done in other developing countries have shown that geo-spatial technologies are capable of delineating land suitability for crop production. The geo-spatial technologies are also time saving and usually yields good data (Ceballos-Silva and

Lopez-Blanco, 2003). A few studies that have been done in Zambia include Chabala *et al* (2013) who applied digital soil mapping to classify landform using the digital elevation model. In another study, Chabala *et al*., (2014) employed geo-spatial methods to map soil acidity in which ordinary kriging was used to interpolate point data and create spatial maps.

A study was therefore undertaken to delineate suitable areas for soybean production in Kabwe district by applying a GIS based multi-criteria approach using relevant variables of soil, climate and topography. In addition, accessibility was also included as it affect the ease of transportation of inputs and the produce.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1 Location

The study was conducted in Kabwe district of Central Zambia. Kabwe district is located approximately 130 km north of Lusaka (Kabwe Municipal Council, 2010). It is connected to Lusaka and other surrounding districts by rail line and the Great North Road. Kabwe lies between Latitude 14°28′0″ S and Longitude 028°25′5″ E, covering an area of about 1565 km^2 (156,500 ha). The location of the study area is shown in Figure 3.

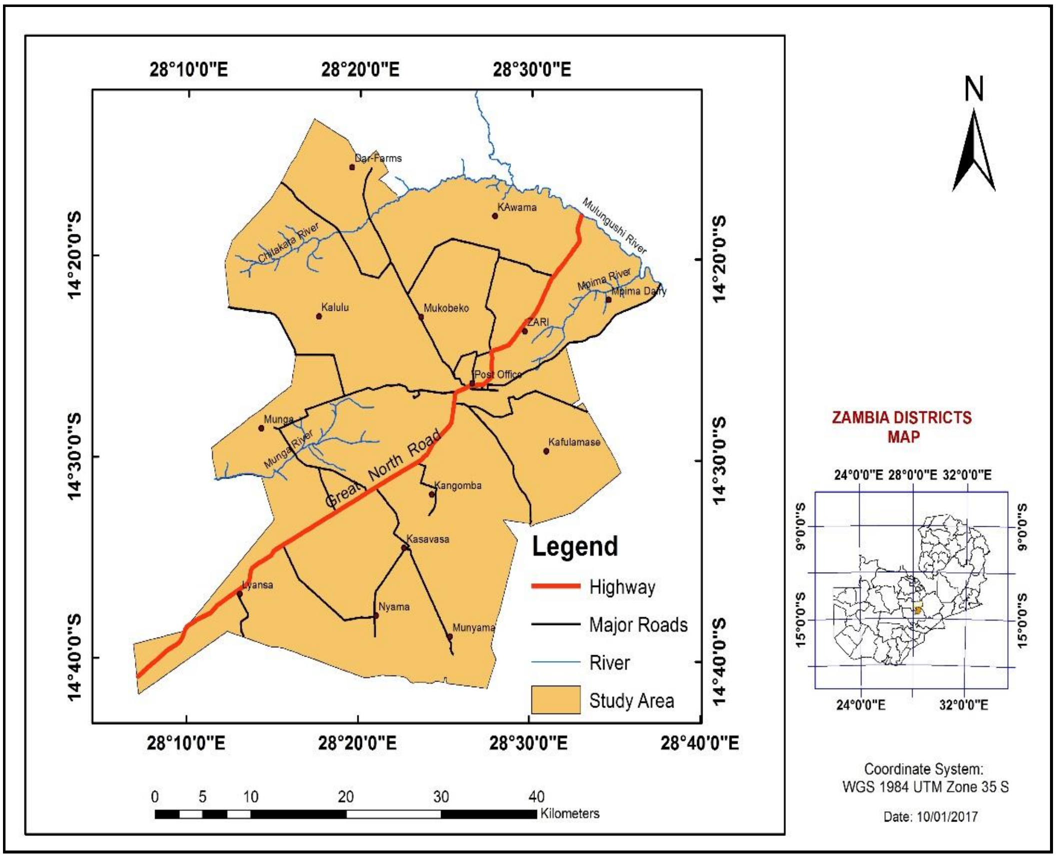

Figure 3: Study Area

3.1.2. Population and ethnic groups

According to CSO (2011), Kabwe district has an estimated population of 202,914 inhabitants. They comprise five main ethnic groupings locally known as the Lalas, Bisas, Ilas, Kundas and Bembas.

3.1.3. The Economy

During the early years of independence, Kabwe district was characterized by mining activities that included extraction and processing of zinc and lead. This led to the recognition of the district as one of the prosperous towns in Zambia with a vibrant economy. There were also industrial activities in the district that provided goods and services to the mines. These activities also led to an increase in employment for the locals. Following the closure of the mines in 1994 and other industries in the district, most of the inhabitants have now resorted to agricultural activities. The district has some commercial farming areas around that supply agricultural produce to the central market. Small scale farmers also supply the market with their produce mainly comprising maize, soybeans, groundnuts, vegetables and sweet potatoes. The road and rail line links in the district provide ready access to the markets within and outside the district. Other crops grown in the district include cowpeas, sorghum and cassava (Kabwe Municipal Council, 2010; CSO, 2011). Electricity is supplied by the Zambia Electricity Supply Company (ZESCO) but some parts of the district are supplied by the hydro-electric power stations of Mulungushi Dam and Lunsemfwa falls.

3.1.4 Agriculture and soybean production

Majority of the farmers in the area are small scale farmers who are mostly growing maize. There is less crop diversity due to factors such as limited land area, lack of seed and market opportunities. Some farmers practice intercropping on the available small piece of land. This however does not result in good yields. Soybean is one crop that is usually used in intercrop because of its ability to improve soil fertility. When grown as a mono-crop, it is usually grown on a small piece of land compared to maize. This is so because most small scale farmers in the area receive subsidies for maize and only a few receive for soybean. Other crops grown in the area include common beans, cassava, sweet potatoes, cowpeas, sorghum and groundnuts. These crops are usually grown on a scale without chemical fertilizers.

It is common practice for some small scale farmers to plant large portions of crops like maize or soybean and not apply the recommended fertilizer rate. This contributes to poor crop yields. Most small scale farmers growing soybean do not consider suitability conditions. They grow the crop on marginal land assuming that it is more tolerant to poor soil fertility than other crops. Lack of improved technologies, lack of inputs and information on the know-how inhibit the expansion of soybean production. Climate change and linkages to markets are some of the constraints to soybean production and marketing in the area.

3.1.5 Climate, soils and geographic features

Kabwe has a sub-tropical climate that is modified with altitude. The average altitude in the district is 1207 m above sea level. The weather pattern is determined largely by the movement of the inter-tropical convergence zone (ITCZ), resulting in three seasons. There is a cool dry season from April to August, a hot season from September to October and a rainy season from November to April. The average annual temperature is 31°C with mean monthly maximum of 36°C and a mean monthly minimum of 7°C (Kabwe Municipal Council, 2010; Zambia Meteorological Department, 2015).

Kabwe falls within agro ecological region IIa receiving between 800 mm and 1000 mm of rainfall (Figure 4). The average total rainfall received in the district is 966 mm, which occur during the rainy season. Due to the high temperatures, evapotranspiration is higher in the district and it usually exceeds precipitation.

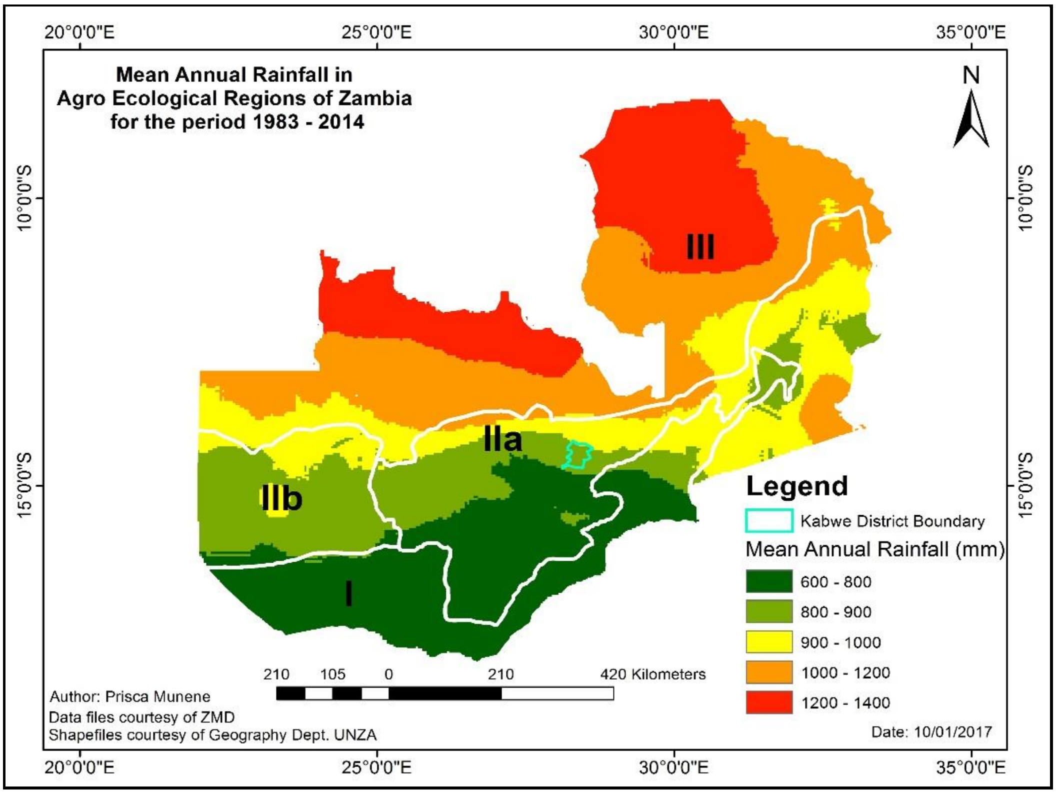

Figure 4: Map of Zambia showing the amount of rainfall received in the agro ecological zones

The soils in the district are comprised of Acrisols and Luvisols (FAO. 1988). Acrisols form on old landscapes that have an undulating topography and a humid tropical climate. According to the Zambian soil description, these are moderately leached reddish to brownish clayey to loamy soils, derived from acid rocks and mostly occurring in Miombo woodland. The Luvisols form on flat or gently sloping landscapes under climatic regimes that range from cool temperate to warm Mediterranean. These are moderately leached red to reddish clayey soils derived from basic rock, often in admixture with acid rocks. The soils in the district largely influence the drainage system of the area and they range from strongly to slightly acid.

The major river draining Kabwe district is Mulungushi River which borders with Kapiri Mposhi district in the eastern part. Other rivers are Chankwankwa, Chapya, Chitakata, Kalonga, Mpima, Munga,and Natuseko. These are the main tributaries to Mulungushi River (Topographic map sheets, 1428A2, 1428A4, 1428B3, 1428C1, 1428C2 and 1428D1). The area has open woodlands type of vegetation which is mainly miombo woodland. The other types of vegetation found in the area are chipya, munga, termitaria and grassland. The other feature characterizing the area is relief which is gently undulating plateau with gently sloping interfluve crests that are usually flat. The shoulders and middle slope are convex with moderate slope ranging between 1 to 3 percent (Kabwe Municipal Council, 2010).

3.2 Identification of spatial attributes relevant to soybean production

The land characteristics relevant for soybean production were identified from the literature search and reviews (Dugje *et al*., 2009; Rutherford 2010; Kanangi *et al*., 2013). In addition the soybean crop production guides available from the Ministry of Agriculture (MoA) were also reviewed (MoA, 2002). According to FAO, (1983), a land characteristic is an attribute of the land which can be measured or estimated and can influence suitability in several ways. A land characteristic is usually employed in suitability analysis as a means of describing land qualities. Based on these reviews, eight land characteristics were identified. These include soil texture, soil reaction, soil organic carbon (SOC), available phosphorus (P), rainfall, temperature, slope, and soil drainage. In addition, accessibility represented by roads was included as a layer since it determines the ease of crop movement and market access. The land qualities which were related to the eight identified land characteristics include, erosion hazard, soil degradation hazard, nutrient availability, nutrient retention capacity, soil toxicities, potential for mechanization, moisture availability and location.

3.2.1 Drainage

Drainage is relevant in soybean production, giving an indication of the stream networks and soil moisture conditions of an area. Drainage maps guide land users in developmental works such as irrigation which require a knowledge of surface drainage. The surface area where water falls and the network through which it travels to an outlet are shown on drainage maps. These indicate hydrological topographic variables including flow direction, flow accumulation, slope position, slope steepness and topographic wetness index (TWI). These variables are usually extracted from digital elevation models (DEMs). Therefore, topography as presented by the DEM can be used to represent soil moisture conditions (Zhao *et al*., 2013).

Soil drainage is one of the soil properties that is related to hydrological topographic variable giving an indication of soil moisture. It describes the duration and frequency when soils are free from water saturation and it is affected by soil properties including soil texture, subsurface stoniness and slope position (Bell *et al*., 1994; Ritung *et al*., 2007; Brandy and Weil, 2008). TWI is mostly usually used to represent soil drainage. This is a steady state wetness index that reflects soil moisture and drainage conditions. It is defined as a function of the natural algorithm of the ratio of local upslope contribution area to slope angle (Beven and Kirby, 1979; Wilson and Gallant 2000). Soil drainage is therefore important in land suitability mapping because it indicates water logging condition necessary to facilitate availability of oxygen required for soybean growth.

3.2.2 Slope

Slope is an important topographic factor in land suitability mapping, a guide to land management and risk of erosion. It is described as a measure that indicates the change in steepness or inclination of a given surface over the horizontal plane and can be expressed in degree or percentage (Chabala *et al*., 2013). Slope is calculated from the arctangent of the ratio of the change in height (dz) to the change in horizontal distance (dx) as shown in equation 1.

$$\text{Slope (degrees)} = \arctan (dz/dx) \qquad \text{Equation 1}$$

Percent slope on the other hand is calculated by multiplying the ratio of the change in height (dz) to the change in horizontal distance (dx) by 100 as shown in equation 2.

Slope (percent) = (dz/dx0)*100 Equation 2

Knowledge of slope guides in selecting farming practices taking into consideration the slope direction. This minimizes risk of erosion that usually occurs in sloping areas, and consequently minimal loss of soil nutrients due to water flow. A map showing slope variation of an area is therefore a useful guide to land users including farmers practicing contour farming and rain water harvesting.

3.2.3 Climate (rainfall and temperature)

Climate is another attribute relevant to soybean production. Climate affects the growth, development and yields of soybean, and can have positive or negative impacts on crop production. Rainfall and temperature are the two climatic factors which were selected in this study. Rainfall provides moisture to the soil media for non-irrigated crops and for the other plant physiological processes. Rainfall data observed for a time period helps to predict extreme precipitation events including droughts and floods. It enables one to estimate the quantity and quality of surface and groundwater, and to some extent soil moisture conditions. Temperature on the other hand is important for effective plant growth. It plays a major role in processes that enable plant growth, hence important in crop management. Soybean requires a range of temperatures between 20^{o}C and 30^{o}C with an optimum of 22^{o}C and about 500 mm to1000 mm of rainfall for its production.

3.2.4 Soil attributes

Soil was another factor considered relevant to soybean production. Soil is an important raw material acting as a growth medium for soybean and other agricultural crops. It provides anchorage and nutrients to crops. A knowledge of the chemical and physical characteristics of soil is therefore important in suitability mapping of soybean production. Four soil parameters were identified for mapping in this study. These were soil reaction, soil organic carbon (SOC), available phosphorus (P) and texture.

3.2.4.1 Soil reaction (pH)

Soil reaction indicates the measure of the soil reaction which refers to the acidity and alkalinity of the soil. It provides various indicators about the status of soil properties. It is therefore an essential soil property that needs to be monitored to ensure that nutrients are available to the crop in the right proportions (Bowen and Hollinger, 2002; Chabala *et al*., 2014). Soil reaction provides information about the solubility and potential availability of elements such as phosphorus which is critical to soybean production. An understanding of spatial variation of soil reaction within an area is therefore important in site specific management (Shi *et al*., 2009; Mustafa *et al.*, 2011; Chabala *et al*., 2014).

3.2.4.2 Soil Organic Carbon

Soil organic carbon (SOC) indicates the organic matter in the soil. Organic matter improves soil properties and the supply of mineral fertilizer needed for plant growth. The combination of organic matter and mineral fertilizers provides the suitable environmental conditions for the crop. Carbon stored in soil is as a result of its balance from that entering the soil through organic matter (OM) and that leaving the soil through processes of decomposition and mineralization. Erosion and leaching of dissolved carbon also contributes to carbon leaving the soil. (Hilinski, 2001). It is therefore necessary to do soil inventories to maintain the balance of SOC.

Assessing reserves of organic carbon in the soil through continuous soil inventories is somehow time consuming and mostly showing slight changes in its content in the soil and the spatial trend (Johnson *et al*., 2007; Kiser *et al*, 2009). Since the long term measurements of SOC is associated with some difficulties, quick methods are also preferred to understand the spatial distribution as can be presented in maps (McClean *et al.*, 2015). Spatial maps guide farmers identify areas where additional organic matter is required to improve soil fertility and crop yields.

3.2.4.3 Available phosphorus

Phosphorus is an important nutrient for legume crop production, stimulating growth and initiating nodule development. Phosphorus also influences the rate of interaction between rhizobium and legumes and hence needs to be monitored to check its abundance for crop growth. However, the balanced nitrogen (N), phosphorus and potassium (K) ratio is also an important parameter for crop production. The balanced NPK ratio contributes to soil health and crop yields by improving physical, chemical and biological environment of the soil. In tropical soils, phosphorus tends to be less available mainly due to soil reaction, as phosphorus availability depends on the pH

(Osodeke, 2005; Haruna, 2011). It is therefore of great importance to check the balance of phosphorus and pH in soybean production.

3.2.4.4 Soil texture

Soil texture is the relative quantities of mineral matter. It determines the effective growth of a plant and all the physical, biological and chemical processes affecting plant growth including nutrient retention. Water holding capacity and infiltration rate all depend on soil type influenced by textural components. Soil texture also has an effect on fertility of a soil, ease of cultivation, susceptibility to erosion and the ability to crack on drying. These eventually influence the soil's suitability for agriculture (Mzuku, 2005; Gozdowski, 2014).

Soil mapping provides information of the spatial distribution of the soil type in an area. The textural components are quantified in a textural analysis with clay fractions mostly considered in soil classification and mapping. The amount and kind of clay in a soil affect the fertility and physical condition of the soil and the ability of the soil to adsorb cations (Mzuku, 2005; Darwish, *et al*., 2015). According to Darwish *et al*., (2015), soil texture maps are sometimes difficult to derive with most of the existing soil maps, neither intensive nor specific enough, often describing soil types rather than texture. It was therefore imperative to use dataset for clay fractions in the mapping to represent texture. Generally, the best agriculture soils are those containing 10 to 20 percent clay, 5 to 10 percent organic carbon and equal amounts of silt and sand. Soybean requires deep and well drained soils varying in texture from sandy, sandy loams to clay loams.

3.2.5 Accessibility

In addition to the selected physical attributes, accessibility to the area, represented by a distance to roads layer was also included since it determines the ease of crop movement and market access. Roads have an influence on the suitability of an area in terms of transporting inputs and accessing the market. The closer the area is to the access road, the more suitable it is for a particular use such as soybean production.

The selected land characteristics relevant to soybean production (Table 2) were integrated in the process model for mapping soybean land suitability as shown in (Figure 5). The subsequent section describes in detail what was involved at each stage in the process model to generate a soybean suitability map.

Table 2: Land characteristics relevant to soybean production

Land characteristic	**Soybean growth requirement**
Soil reaction	A pH range of 6 and above or between the range of 5.6 – 7 depending on variety
Soil texture	Sandy, Sandy Loams to Clay Loams
Soil organic carbon (%)	Best grows in soil with 3% to 10% organic matter
Available phosphorus (ppm)	P value above 10ppm. Phosphorus is critical to soybean growth and at low pH, phosphorus is found in amounts not available to the plant.
Rainfall (mm) and soil moisture content	Rainfall range suitable for soybean is between 500–1000 mm. The crop requires enough moisture to effect rapid and uniform germination.
Temperature (^{o}C)	Optimum temperature for soybean is 22^{o}C. Suitable range is between 20 – 30 ^{o}C. Very high or very low temperatures stunt soybean growth.
Drainage (soil drainage)	Well drained soils
Slope (%)	Soybean can be planted on ridges or on flat seedbeds. Slope range from 0 to 4% is suitable for soybean.
Accessibility (km)	Area located close to access roads are more preferable

Source: Information retrieved from MoA, 2002; Dugje *et al*., 2009; Rutherford 2010; Kanangi *et al*., 2013;

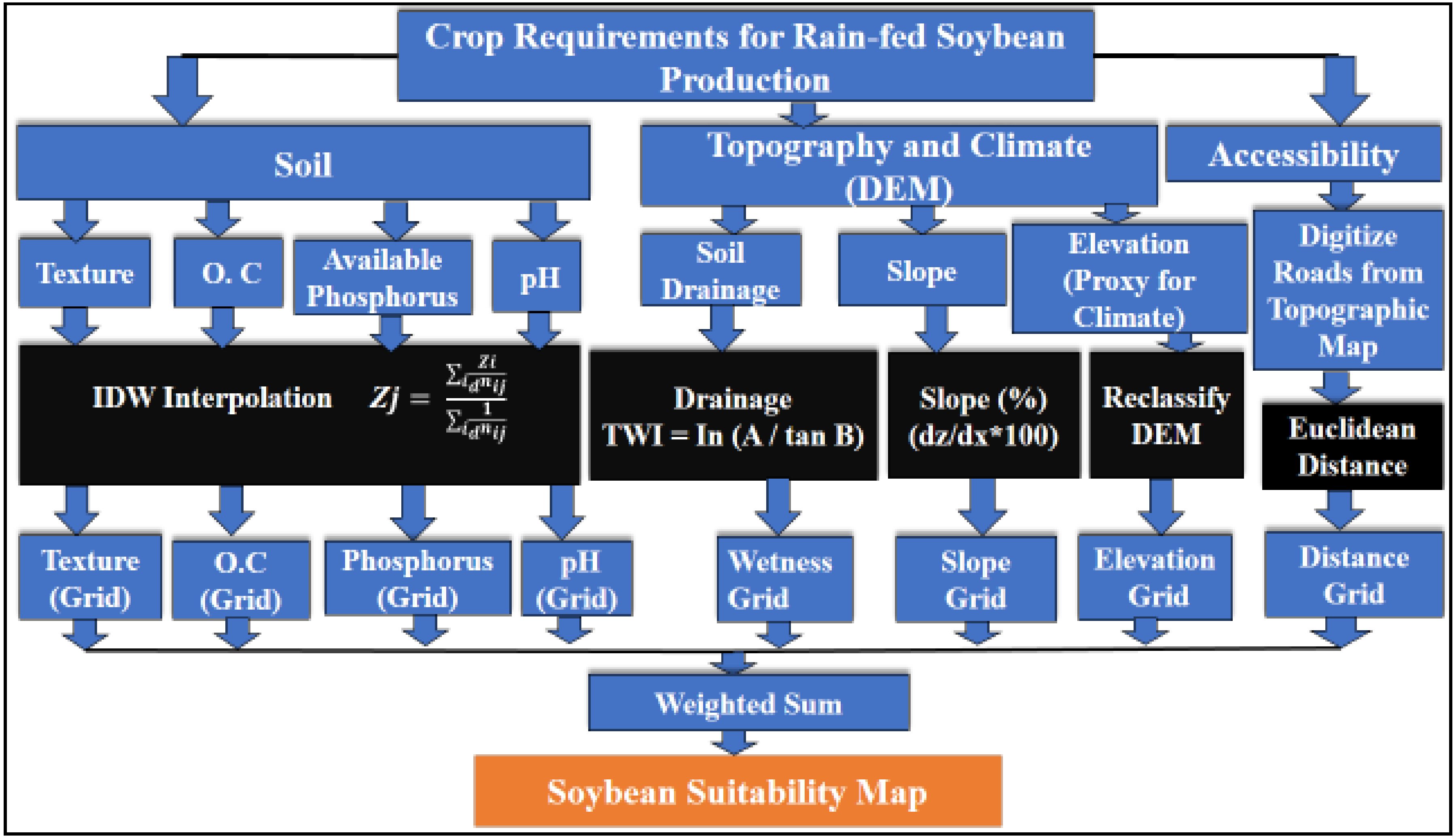

Figure 5: Flow chart of the methodology for the multi-criteria evaluation

3.3. Data sources

Data layers for the selected attributes were prepared from secondary and primary data sources. Sources of data sets included topographic maps obtained from Ministry of Lands and Natural Resources (MLNR), a 90 m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) and the national soil map of Zambia obtained from the soil survey unit of the Zambia Agriculture Research Institute. The SRTM DEM was downloaded from the United States Geological Survey (USGS) website (http://earthexplorer.usgs.gov) and was covering an area between Latitude and 14º25′42″ S and Longitude 028º27′05″ E. Technical reports and other publications reviewed were obtained from the Ministry of Agriculture (MoA). Climatic (rainfall and temperature) data sets were obtained from the Zambia Meteorological Department (ZMD), however elevation (DEM) was used as a proxy for climate. Soil samples were collected as primary data in order to generate data layers for identified soil attributes relevant to soybean production.

3.4 Preprocessing of the digital elevation model

The DEM was loaded into ArcMap which was projected to World Geodetic System 1984 (WGS 1984) UTM Zone 35S coordinates. It was then preprocessed to remove sinks related to imperfections in the data. A sink is also referred to an area of internal drainage which is an area surrounded by high elevation values. The highest point value in the DEM was 1348 m and the lowest 493 m.

In order to remove sinks in the DEM, a method by Chabala *et al*., (2013) was followed where the flow direction was first extracted using the flow direction tool. A raster of sinks was then created by enabling the sink tool with flow direction used as the input flow direction raster in the table. This was followed by the creation of a sink area raster by enabling the watershed tool. At this stage, the extracted flow direction was the input flow direction raster and the sinks as the feature pour point data or input raster. The zonal statistics tool was then used to create a raster of the minimum elevation in the watershed of each sink, with sink area as the input raster or feature zone data. The DEM was used as the input value raster and sink minimum as the output raster. When creating the sink minimum, statistics type was set to minimum and value as the zone field. The zonal fill tool was then used to create a raster of the maximum elevation with sink area as the input zone raster and the DEM as the input weight raster. Further, the minus tool was then used to subtract the minimum value from the maximum value to find the sink depth, with sink maximum as the first input raster and the sink minimum as second input raster. Finally, the fill tool was applied to the DEM with the Z value set to the sink depth to generate a DEM with all the sinks filled and a colour ramp assigned to it. The filled DEM was thereafter projected using the project raster too in order to define the linear units to meters.

Figure 6 shows the filled DEM from which the spatial attributes of slope and drainage (wetness index) were extracted. Elevation served as a proxy for climate to represent rainfall and temperature, and this was generated by reclassifying the DEM in to elevation classes.

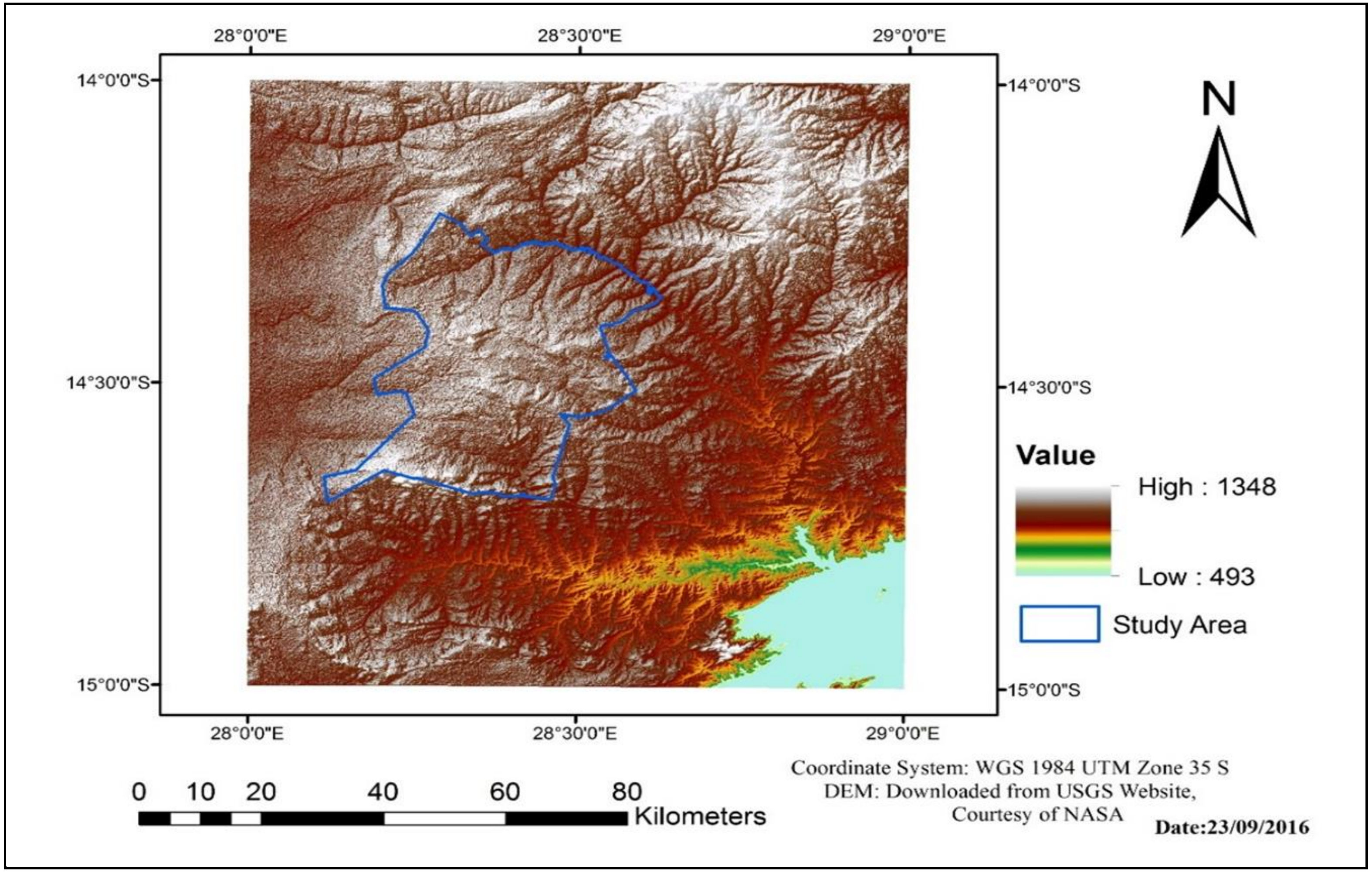

Figure 6: Digital Elevation Model

The processing of data layers was done in ArcGIS with the processing extent set to Kabwe district boundary. This was complimented by Global Mapper and Microsoft Windows software. The raster data layers generated were set to WGS 1984 UTM Zone 35 S coordinate system. The suitability levels assigned to each classified datasets were defined based on literature, expert knowledge, observation and practical experiences in soybean production. An extract of Kabwe district boundary area for each classified dataset was generated using the extract by mask tool. These extracts were used as inputs in the weighted sum overlay. The methods used to generate each of the datasets is explained in respective sections below.

3.5 Extracting slope, drainage (wetness) and elevation datasets from the DEM

3.5.1 Slope

Slope was extracted from the filled digital elevation model by enabling the slope tool in spatial analyst tools. The output measurement was in percentage with the Z value set to one. The extracted slope dataset was reclassified into six classes according to suitability for soybean production.

3.5.2. Drainage (wetness index)

Topographic wetness index (TWI) is said to be valid for areas where there are substantial amounts of lateral water movement and vertical flow (Schmidt and Persson, 2003). This was the case in Kabwe and therefore the appropriateness of using TWI to represent drainage. Equation 3 was used to calculate TWI where A is the area of flow accumulation in square meters, and B is the slope in radians.

$$TWI = \text{In} (A / \tan B) \qquad \text{Equation 3}$$

In order to extract the area of flow accumulation (A), flow direction was first extracted from the DEM using the flow direction tool. This tool is used to indicate the flow direction of water out of each cell in the DEM. Flow accumulation was then calculated by enabling the flow accumulation tool with flow direction dataset as the input. The final value of A was calculated by multiplying the generated flow accumulation grid within the area. Slope was converted from degrees to radians using the raster calculator based on equation 4.

$$\text{Slope in Radians} = \text{Slope in degrees} \times Pi / 180, \text{ where } Pi = 3.1415 \qquad \text{Equation 4}$$

The cells which had no data values in the wetness index grid were reclassed to zero using the raster calculator as indicated by the expression below:

Con (IsNull("WetnessIndex"),0,"WetnessIndex")

The generated wetness index grid was thereafter classified into five according to suitability for soybean production.

3.5.3 Elevation as a proxy for climate (rainfall and temperature)

The available datasets for rainfall and temperature for Kabwe district were more generalized and not showing much variations. Elevation was therefore used as a proxy for climate (rainfall and temperature), because of the well-known principle that the micro-climate of an area can be related to elevation (Subarna *et al.*, 2014). The void filled DEM was therefore reclassified into four elevation classes representing levels of suitability for soybean production related to the prevailing weather conditions.

3.6. Generating prediction maps for selected soil attributes

3.6.1. Soil sampling

Due to limited soil information data from secondary sources, a field survey of the study area was undertaken. Soil sampling was conducted using the random sampling method but meant to cover the whole study so as to incorporate different soil types and the relief (Figure 7). The study comprised of 92 sampling sites from which soil samples were collected at the depth of 0-20 cm. The distance between sampling locations ranged from 1 to about 10 kilometers. Sampling points were randomly selected with the help of a topographic map. Sampling locations were pre-marked on a topographic sheet before going to the field. The land use classes on the topographic map and contours aided the selection of sampling points. The Geographical Positioning System (GPS) was used to locate the preselected sampling points in the field. The GPS was also used to record the coordinates at sampling points. At each sampling point, five sub samples were collected within a radius of 10-20 m making a composite sample which was labelled and taken to the laboratory for analysis. The sampling points are shown in Figure 7.

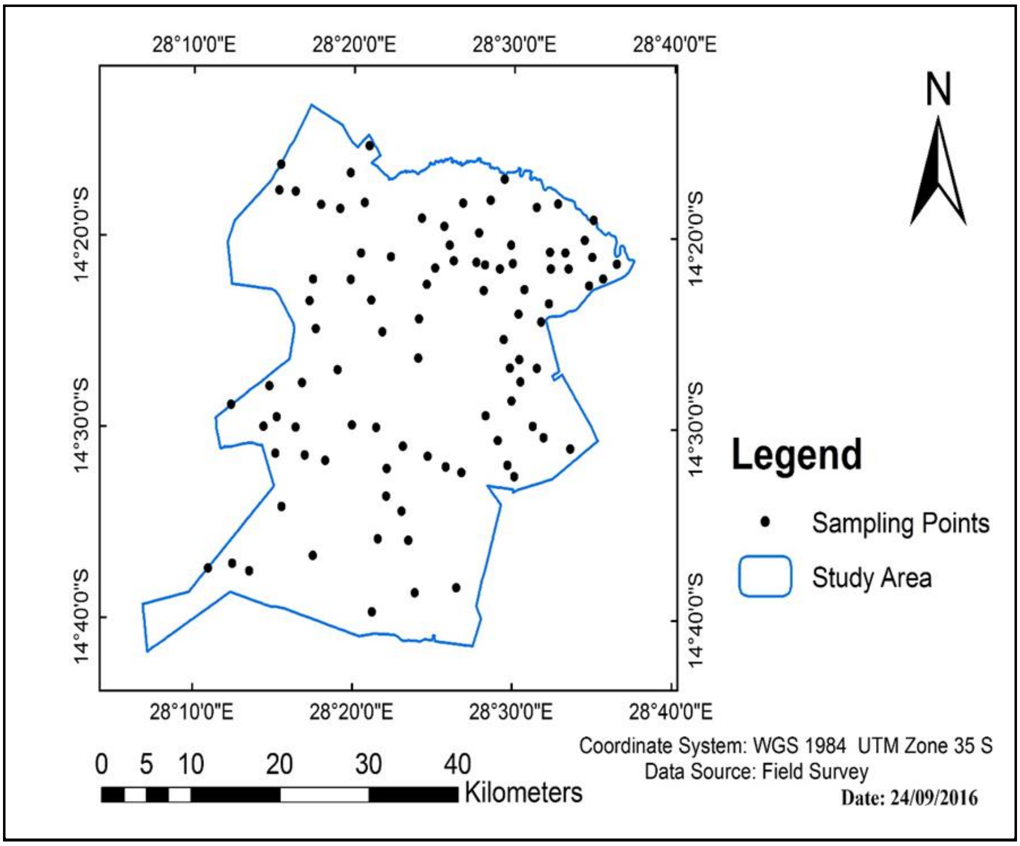

Figure 7: Map showing sampling points in the study area.

3.6.2. Laboratory analysis

The soil samples were first air dried and passed through a 2 mm sieve before being analyzed for pH, available phosphorus, organic carbon and texture at the Zambia Agriculture Research Institute (ZARI) laboratory. Soil reaction was measured in a 1:2.5 soil to solution ratio of 0.01 M $CaCl_2$ using electrometric method as described by Pearson and Adams (1967). This method allowed for the determination of hydrogen ions (H^+) extracted from the soil particles by displacing them with calcium cations (Ca^{2+}). SOC was analyzed using the Walkley-Black method (Walkley and Black, 1934) and phosphorus by the Bray 1 method as described by Bray and Kurtz (1945). Soil texture was analyzed using the pipette method as described by Hillel (2004).

3.6.3. Exploring data for the measured soil parameters

The values obtained for measured soil parameters together with the associated X and Y coordinates were recorded in excel sheet and added to ArcMap as a layer. The soil data was explored by checking for errors and its distribution on the histogram to identify trends before creating surfaces. The histogram and the normal quantile-quantile (QQ) plot were used to measure the normality of the data as interpolation methods used to generate a surface gives the best results when the data is normally distributed. The QQ plot was used to compare the distribution of the data to a standard normal distribution. The coefficient of skewness and kurtosis were also used to measure normality of data in this study. For normally distributed data, sample points in the QQ plot are located close to the standard line, whereas the mean and median values are similar and skewness is equal or near to zero. Kurtosis is also equal or near to three for normally distributed data. The data which was not normally distributed or highly skewed, was transformed so it could conform to a normal distribution before subjecting it to any interpolation. Data transformation was done for phosphorus using log transformation because it was highly skewed to the right.

A trend analysis was also performed to help identify the order of polynomial that could fit the trend best if a non-random trend was present in the data. There was no trend observed in the data and hence appropriateness of using inverse distance weighting (IDW) interpolation method to create spatial maps. After exploring the soil data for errors, interpolation was then proceeded to generate spatial maps for soil reaction, SOC, phosphorus and texture.

3.6.4. Generating prediction maps for soil attributes

The IDW interpolation method was used to create surfaces for soil reaction, SOC, phosphorus and texture by predicting values at unsampled locations. This method allowed for the prediction of values for cells in a raster from a limited number of sample data points. The points closer to the center of the cell, had more influence in the averaging processes of the values of the sampled data (Bolstad, 2005). The default of 15 maximum and 10 minimum neighboring points was used with the processing extent set to Kabwe district boundary for each of the prediction map. Equation 5 was used to predict values at unsampled location using measured values surrounding the prediction location. In this equation, Z_j is the estimate value for the unknown point at location j, d_{ij} is the distance from a known point i and n is the user defined exponent.

$$Zj = \frac{\sum_i \frac{Zi}{d^n{}_{ij}}}{\sum_i \frac{1}{d^n{}_{ij}}} \qquad \text{Equation 5}$$

The datasets for each of the soil variables were thereafter reclassified based on suitability for soybean production.

3.7 Generating the distance layer

A distance to roads raster was created by first digitizing the major accessible roads from the 1:50,000 topographic sheets covering Kabwe area. A shapefile for the roads was then created and used as an input feature source data to create the distance dataset using the euclidean distance. The euclidean distance is one of the tools that describes the relationship of each cell in a raster to a source or a set of sources based on the straight line distance. In particular, euclidean distance gives the distance from each cell in the raster to the closest source. In this study, it was used to calculate the distance from the cells in the roads raster to the closest suitability class. Hence, the area close to the road was classified as most suitable based on distance factor. The generated euclidean distance raster was classified into three classes based on soybean suitability.

3.8 Reclassifying and weighting of the datasets

Before performing an overlay, all the datasets generated were reclassified to a common scale. The generated raster datasets had different numbering systems such as parts per million for phosphorus, percentage for SOC and meters for elevation and they could therefore not be added or combined successfully in an overlay analysis. The datasets were thereafter ranked and assigned weights according to soybean suitability. The attributes within each dataset were first ranked based on their suitability for soybean production. The highest value was assigned to high suitability and the lowest value was assigned to not suitable. The higher the score, the more suitable the site for a defined use (Bolstad, 2005).

After ranking within criteria, relative weights were then assigned to each attribute depending on their importance in land suitability for soybean production. This was based on knowledge of the effects of the criteria to soybean production, as different criteria used had varying degree of influence on soybean production. Determination of relative importance of each criterion also depends on an individual preference or judgment supplemented by mathematical tool (Hbib, *et al.*, 1996; Bolstad, 2005). The weights for each of the processed datasets were calculated using equation 6.

$$W_i = (n - ri + 1)/\sum(n - rk + 1) \qquad \text{Equation 6}$$

In the equation, W_i is the weighting for criterion i, n is the number of criterion, ri is the rank for the ith criterion and k is a counter for summing across all criteria (Bolstad, 2005). Table 3 shows the weights calculated for each criterion used in the study.

Table 3: Weighting criteria

CRITERION	**RANK**	**NUMERATOR $(n-r_i+1)$**	**WEIGHT $(n-r_i+1)/\sum(n-r_k+1)$**
Slope	1	8-1+1=8	8/58=0.14
Drainage (Wetness)	1	8-1+1=8	8/58=0.14
Elevation (Proxy for Climate)	1	8-1+1=8	8/58=0.14
Phosphorus	2	8-2+1=7	7/58=0.12
Soil reaction	2	8-2+1=7	7/58=0.12
Soil organic carbon	2	8-2+1=7	7/58=0.12
Texture	2	8-2+1=7	7/58=0.12
Accessibility	3	8-3+1=6	6/58=0.10
SUM TOTAL		**58**	1

3.9. Generating the land capability map

A land capability evaluation was performed to generate a land capability map (LCM) of Kabwe before generating the land suitability map for soybean production. This was done by combining all the reclassified dataset except for the roads layer using the cell statistics tool. The overlay statistic was set at maximum to allow for the determination of the largest value in the input raster data being combined. The expression below summarizes the combination of the datasets in cell statistic to produce a land capability map:

LCM = Cell Statistics (["Slope", "Wetness", "Elevation"," SOC", "pH", "Phosphorus"," Texture"], "Maximum").

The generated land capability map was classified into capability classes indicating the different levels of limitations.

3.10. Generating the land suitability map for soybean production

Land suitability for soybean production was analyzed based on selected attributes including slope, elevation (rainfall and temperature), drainage (wetness), soil reaction, texture, SOC, phosphorus and accessibility. Each of these datasets was first standardized to a scale of 0 - 1 using the raster calculator according to the expression below:

Output raster = (Old grid-Min) /Max,

The old grid in the expression refer to the criterion or dataset to standardize, whereas the min and max refer to the minimum and maximum values in the dataset, respectively. The criteria were standardized in order to bring them to a common scale so as to effectively overlay them using the overlay analysis. After standardizing the datasets, a multi-criteria evaluation was performed using the weighted sum tool which combined all the weighted and standardized datasets. The tool summed up the datasets to generate a land suitability map according to the expression below:

MCE raster output = ((Slope *0.14) + (Elevation * 0.14) + (Wetness * 0.14) + (SOC * 0.12) + (Phosphorus *0.12) + (pH * 0.12) + (Texture * 0.12) + (distance * 0.1))

The output raster generated in this overlay analysis was reclassified into six classes to generate a suitability map for soybean production.

3.11. Validation of the land suitability map

The land suitability map developed in this study was validated by undertaking, a field visit to 135 farms where soybean production is practiced. Information on land suitability for soybean production was gathered by interviewing the farmers in the area while taking note of the physical attributes of each farm visited. The data collected was used to construct an error matrix by comparing field data with the generated land suitability map to calculate the accuracy of the map. An error matrix was constructed by comparing the number of correctly verified points out of the farm points that were visited with the predicted suitability map.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Extracting and mapping spatial attributes relevant to soybean production

The extracted and mapped spatial attributes were slope, drainage (wetness index), elevation (proxy for climate), soil reaction, SOC, phosphorus and texture (clay percent). Accessibility to the area was represented by a road network as another factor in soybean production. The sections below discuss each of the attributes and their spatial variations.

4.1.1. Slope

The results showed that 92.62 % of the land in Kabwe is almost flat with slope less than 3% as indicated in table 5. The other 7.09 % was moderately steep to very steep with slope ranging from 3.01 % to 12 %. Very steep slope greater than 8 % was recorded around hilly areas covering less than 0.55 % of the area (Table 4: Figure 8). The highest slope percent recorded was 39.45 % in areas near the hill. Results showed that slope is not a limiting factor for soybena production in Kabwe except for a few places characterzed by hills. Most of the area is almost flat, good for soybean production.

Chabala *et al.,* (2013) and Agidew (2015) employed the same method that was used in this study to extract slope from the DEM which was found to be effective. The generated slope map in Agidew (2015) was found to be essential for land suitability analysis as it had great influence on work efficiency, erosion control practices and crop adaptability.

Table 4: Slope classes and their suitability rating for soybean production

Slope range (%)	Description	Suitability rating	Rank (Suitability)	Area (%)	Area (km^2)	Area (ha)
0 - 1	Almost flat	Suitable	2	44.35	693.98	69398
1– 3	Almost flat	Suitable	2	48.27	755.44	75544
3 – 5	Moderately steep	Moderately Suitable	3	5.93	92.79	9279
5 – 8	Steep	Marginally Suitable	4	0.90	14.10	1410
8 – 12	Very steep	Currently not Suitable	5	0.26	4.11	411
12 – 40	Very steep (Hills)	Permanently not suitable	6	0.29	4.52	452
TOTAL				100	1565	156,500

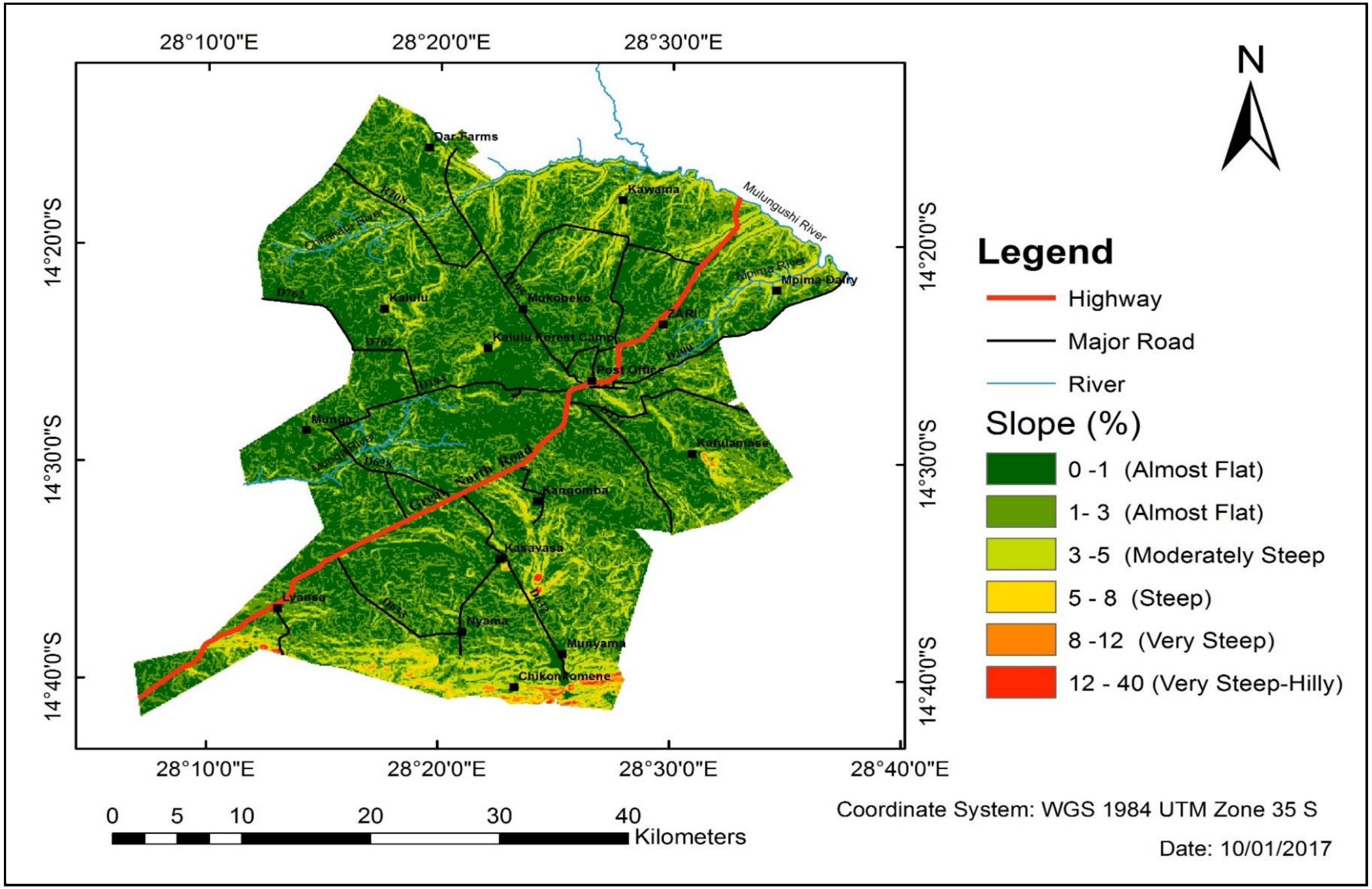

Figure 8: Extracted slope of Kabwe

4.1.2 Drainage (wetness index)

Results showed that five classes in terms of soil drainage as represented by wetness index existed in Kabwe. Three of these classes were classified as suitable, moderately suitable and marginally suitable with wetness indices of 14.56 – 16.73, 16.74 – 19.64 and 0.01 – 14.55 respectively (Table 5; Figure 9). TWI was developed by Beven and Kirkby (1979) and has widely been used in a number of studies to estimate soil moisture, its spatial distribution, and water flow in the subsurface at a given landscape (Zinko *et al*., 2005; Grabs *et al*., 2009). TWI correlates well with the measured soil moisture from the field as shown by Silva *et al*., (2014), and can therefore be used as a quickest method for estimating soil moisture.

In this study, the high accumulation area with wetness index greater than 19.64 was classified as rivers and streams covering 3.40 % of the total area. This correlated well as was verified by comparing the classified rivers and streams with the ones on the topographic map of the area. According to soybean suitability, these areas were classified as permanently not suitable for soybean production. The other area covering 51.83% of the investigated area lies on high land with no accumulation. These are areas where water usually flow out to other points. Results further showed that 44.76 % of the total area was classified as suitable, moderately suitable and marginally suitable with enough soil moisture to affect soybean growth (Table 5). Areas with high accumulation or with no accumulation were classified as not suitable for soybean production. These areas may get flooded or extremely dry respectively and hinder soybean growth unless soil moisture management is employed.

Table 5: Wetness index classes and their suitability rating for soybean production

Wetness Index	**Description**	**Suitability rating**	**Rank (Suitability)**	**Area (%)**	**Area (km^2)**	**Area (ha)**
0	No Accumulation	Currently Not Suitable	5	51.83	811.22	81122
0.01 – 14.55	Low Accumulation	Marginally Suitable	4	17.59	275.22	27522
14.56 – 16.73	Medium Accumulation	Suitable	2	17.03	266.48	26648
16.74 – 19.64	High Accumulation	Moderately Suitable	3	10.15	158.79	15879
19.65 – 26.5	Very High Accumulation	Permanently Not Suitable	6	3.40	53.24	5324
TOTAL				100	1565	156500

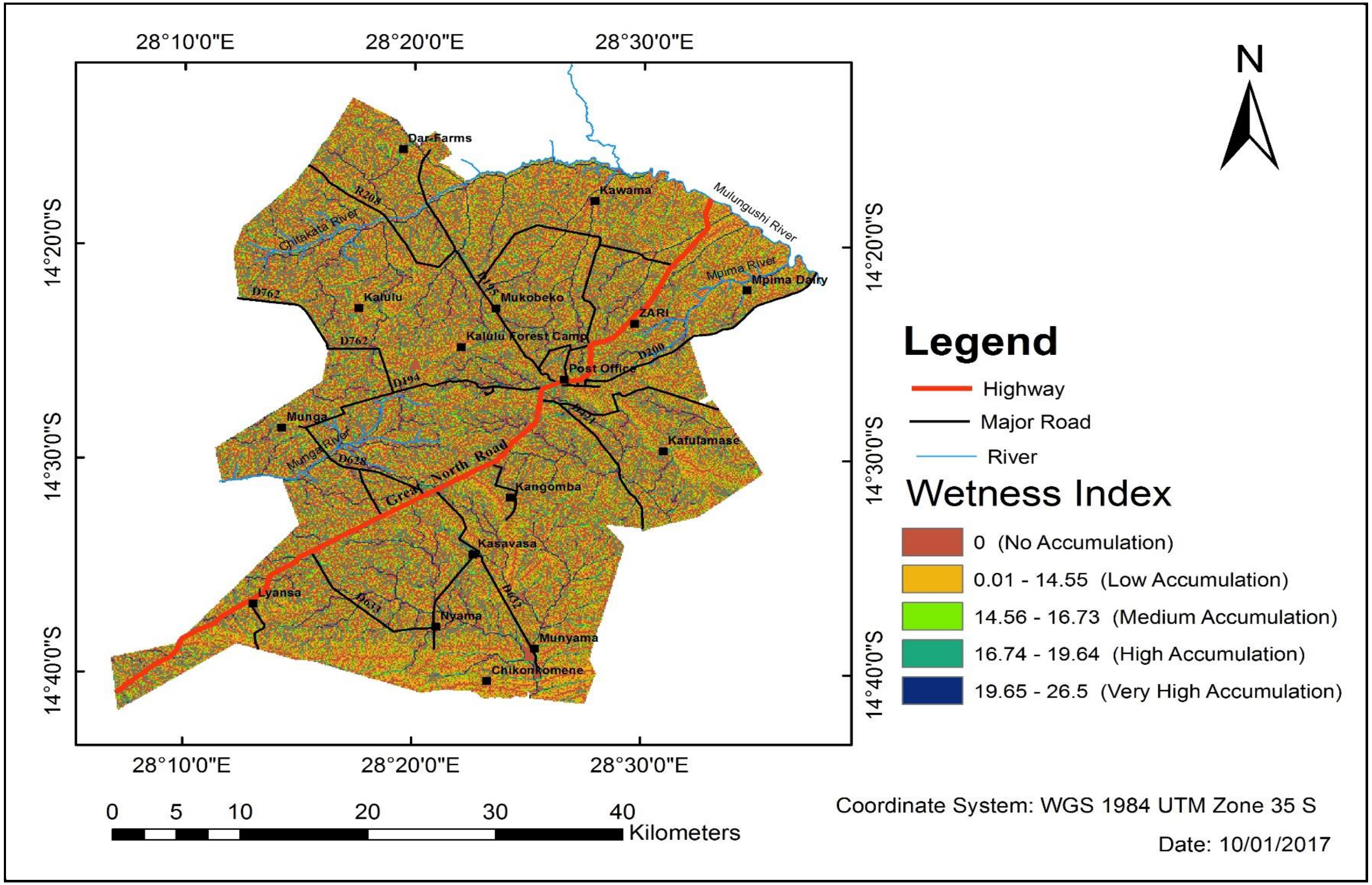

Figure 9: Generated wetness index representing soil drainage in Kabwe

4.1.3 Elevation as a proxy for climate (rainfall and temperature)

From the results, four elevation classes were generated according to soybean suitability with 50.99 % of the area rated as suitable and 33.66 % as moderately suitable for soybean production (Table 6; Figure 10). Relating elevation to climate (rainfall and temperature), results showed that the area with elevation between 1195 m and 1337 m was associated with severe weather conditions as indicated in Table 6 and Figure 10. This area covered 15.34 % of the total area and was lying on higher altitude characterized by hills and cooler temperatures, creating unsuitable conditions for soybean production. Thus this area was therefore rated as currently not suitable for soybean production.

The rest of the area covering 84.66 % of the total area was characterized by favorable to moderate weather conditions with elevation ranging between 1110 m and 1195 m. According Qing *et al*., (2011), elevation strongly governs the spatial distribution of the rainfall. This was also observed by Subarna *et al*., (2014) who showed a strong relationship between monthly rainfall and elevation.

Table 6: Elevation (a proxy for climate) classes and their suitability rating for soybean production

Elevation Range (m)	**Description**	**Suitability rating**	**Rank (Suitability)**	**Area (%)**	**Area (km^2)**	**Area (ha)**
1110 – 1154	Favorable weather conditions	Suitable	2	13.87	217.02	21 702
1154 – 1175	Favorable weather conditions	Suitable	2	37.13	581.00	58 100
1175 – 1195	Moderate weather conditions	Moderately suitable	3	33.66	526.81	52 681
1195 – 1337	Severe weather conditions	Currently Not Suitable	5	15.34	240.12	24 012
TOTAL				100	1565	156 500

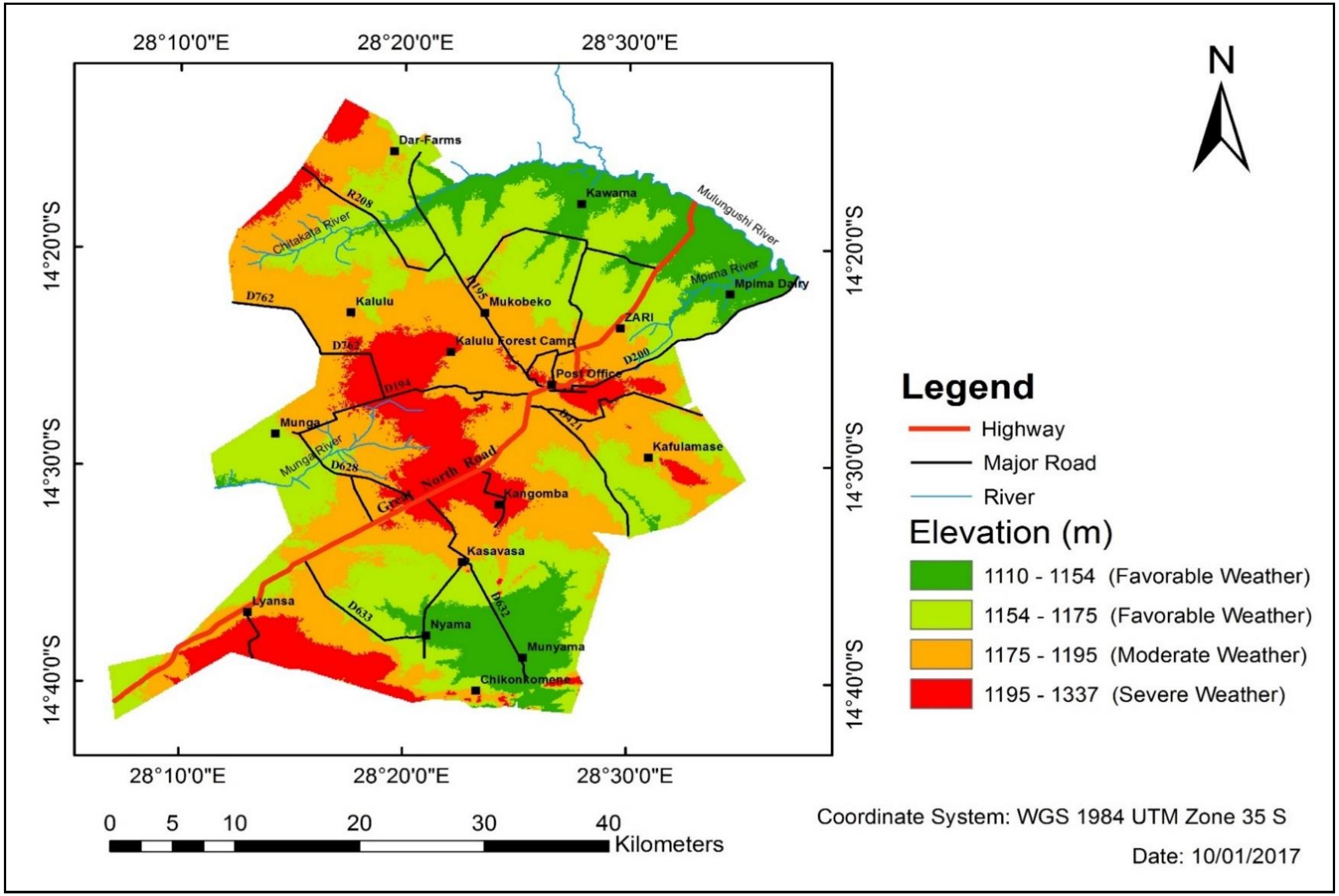

Figure 10: Elevation a proxy for climate (rainfall and temperature)

4.1.4. Soil measured parameters

Results of this study show that the prediction maps for soil pH, SOC, phosphorus and texture were satisfactory for use in the suitability process model having prediction mean errors of -0.0101 for pH, 0.0012 for organic carbon, -0.1186 for phosphorus and -0.0149 for clay proportions (Table 7).

Table 7: Table showing summary statistics from histogram for soil parameter data

Soil Parameter (measured and predicted)		**Mean**	**Median**	**Skewness**	**Kurtosis**	**Std.Dev**	**Prediction Mean Error**
Soil reaction	Measured	4.72	4.68	0.596	3.83	0.41	-0.0101
	Predicted	4.71	4.72	0.077	2.84	0.19	-0.0101
Soil organic carbon	Measured	0.71	0.61	1.664	6.49	0.39	0.0012
	Predicted	0.71	0.66	0.631	2.24	0.26	0.0012
Phosphorus	Measured	7.92	5.0	3.73	21.51	8.09	-0.1186
Phosphorus (Log Transformed)	Measured	1.78	1.61	0.529	3.96	0.71	-0.1186
	Predicted	1.96	1.92	0.366	5.19	0.42	-0.1186
Clay Proportions	Measured	20.69	18.7	1.172	4.77	7.59	-0.0149
	Predicted	20.67	19.88	0.607	2.59	3.35	-0.0149

4.1.5 Soil Reaction (pH)

Results show that the prediction map for soil reaction with the prediction mean error of -0.0101 was satisfactory for use in the process model for mapping soybean suitability. Results for soil analysis indicated soil reaction values ranging between 4.02 and 6.04. This showed slight differences with the national soil acidity mapped by Mambo and Phiri (2004), and this could have been attributed to the different mapping scales used. The Zambian national soil reaction map indicate the pH values in the range between 4.8 and 5.4 for Kabwe district.

From this study, four soil reaction classes were identified for the purpose of soybean production (Table 8; Figure 11). Results showed that 73.88 % of the area is characterized by strongly acidic soils with pH values ranging from 4.51 to 5.0. This area was rated as marginally suitable for soybean production in terms of soil reaction, and might require application of agricultural lime to improve soybean yields. The other 18.43 % of the area is characterized by very strongly acidic soils having pH values ranging from 4.02 to 4.5. This area was rated as currently not suitable for soybean production.

An understanding of spatial variation of soil reaction within an area is important in site specific management (Shi *et al*., 2009; Mustafa *et al.,* 2011). Geostatistics was used in this study to map the spatial variability of soil reaction which resulted into a spatial soil reaction map. The method used in this study showed similarities with a study by Chabala *et al., (*2014) in which interpolation method was used to create a soil reaction surface from point data. The spatial variation of soil reaction in Kabwe indicates that soil pH is a limiting factor to soybean production and therefore a need for specific management. Soybean growth requires a pH range of 5.6 to 7, and results shows that only 0.62 % of the investigated area is characterized by soils in this pH range indicating slightly acidic soil (Table 8; Figure 11).

Table 8: Soil reaction (pH) classes and their suitability rating for soybean production

Soil pH Range	Description	Suitability rating	Rank (Suitability)	Area (%)	Area (km^2)	Area (ha)
4.02 – 4.50	Very Strongly Acidic	Currently Not Suitable	5	18.43	288.50	28 850
4.51 – 5.00	Strongly Acidic	Marginally Suitable	4	73.88	1156.38	115 638
5.01 – 5.50	Moderately Acidic	Moderately Suitable	3	7.06	110.55	11 055
5.51 – 6.04	Slightly Acidic	Suitable	2	0.62	9.75	975
TOTAL				100	1565	156 500

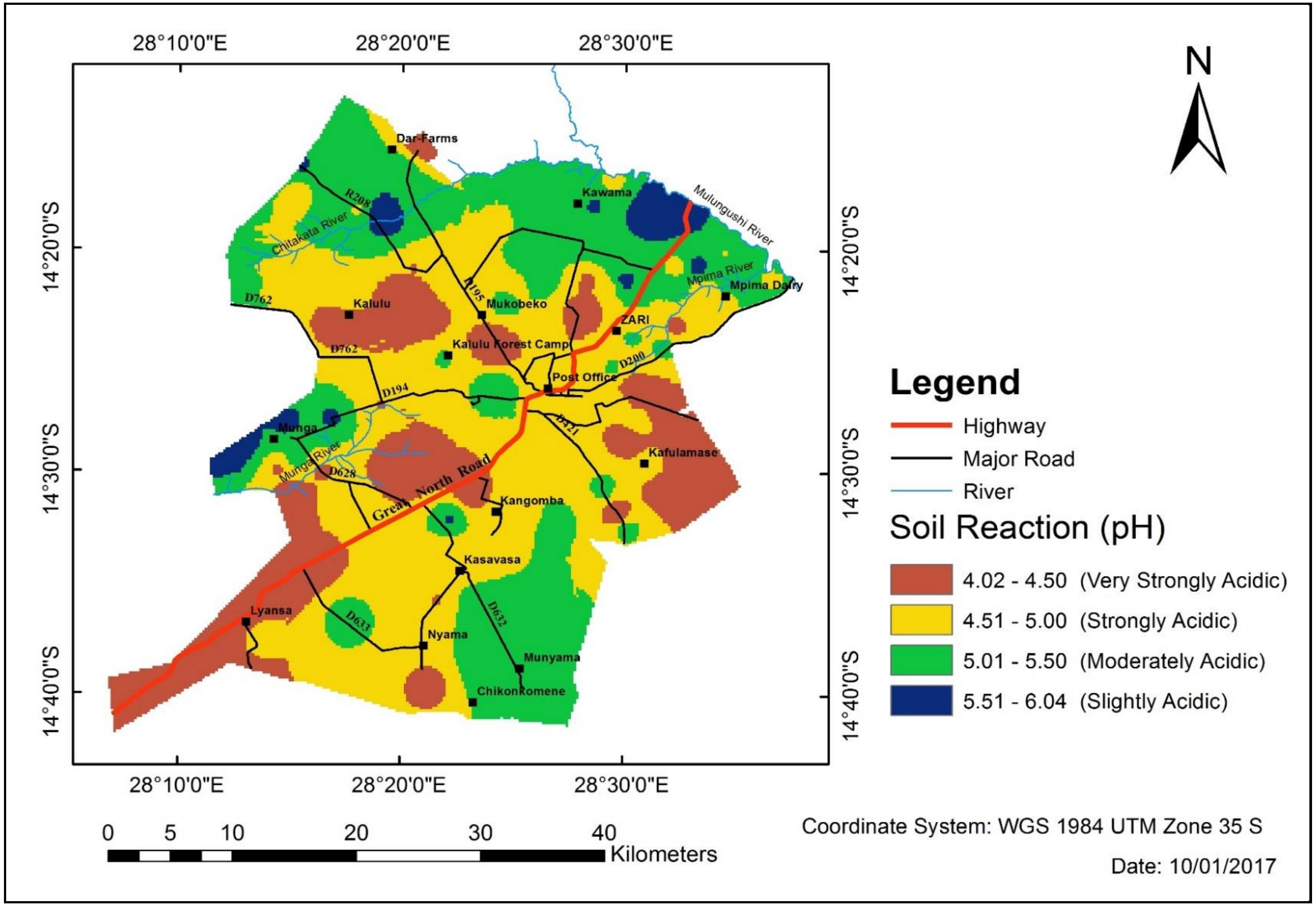

Figure 11: Spatial variability of soil reaction (pH) in Kabwe

4.1.6. Soil Organic Carbon (SOC)

The SOC prediction map had a mean prediction error of 0.0012. With this prediction mean error, the prediction map was satisfactory for use in the process model to develop a land suitability map. Spatial variability of SOC is vital in assessing soil quality and guide in precision agriculture and natural resources management (Zhang *et al*., 2012; McClean *et al.*, 2015). This study applied interpolation method to map spatial variability of SOC in the area. Similar interpolation method was applied in a study by Bhunia *et al*., (2016) in which several interpolation methods to map spatial variability of SOC were assessed.

Results of the spatial variability of SOC showed that, 19.55 % of the total area was characterized by soils containing moderate to high amounts of organic carbon which was greater than 1 % (Table 9; Figure 12). These soils were mostly concentrated in the southern part of Kabwe and were rated as suitable in terms of SOC. Soils containing moderate amounts of organic carbon ranging from 0.68 % to 0.99 % covered 37.73 % of the area. The rest of the area covering much of the northern part of Kabwe was characterized by soils containing less amounts of organic carbon ranging from 0.14 % to 0.67 % (Table 9; Figure 12). This class of soils was rated as marginally suitable for soybean production. Results in this study showed that SOC is not much of a limiting factor to soybean production in Kabwe. However it is important to employ management practices that improve organic matter in the soil mostly in areas characterized by soils having less than 1 % of organic carbon.

Table 9: SOC classes and their suitability rating for soybean production

SOC Range (%)	**Description**	**Suitability rating**	**Rank (Suitability)**	**Area (%)**	**Area (km^2)**	**Area (ha)**
0.14 – 0.67	Low availability	Marginally Suitable	4	42.71	668.55	66855
0.68 – 0.99	Moderate availability	Moderately Suitable	3	37.73	590.59	59059
1 – 2.38	Moderate to high availability	Suitable	2	19.55	306.05	30605
TOTAL				100	1565	156500

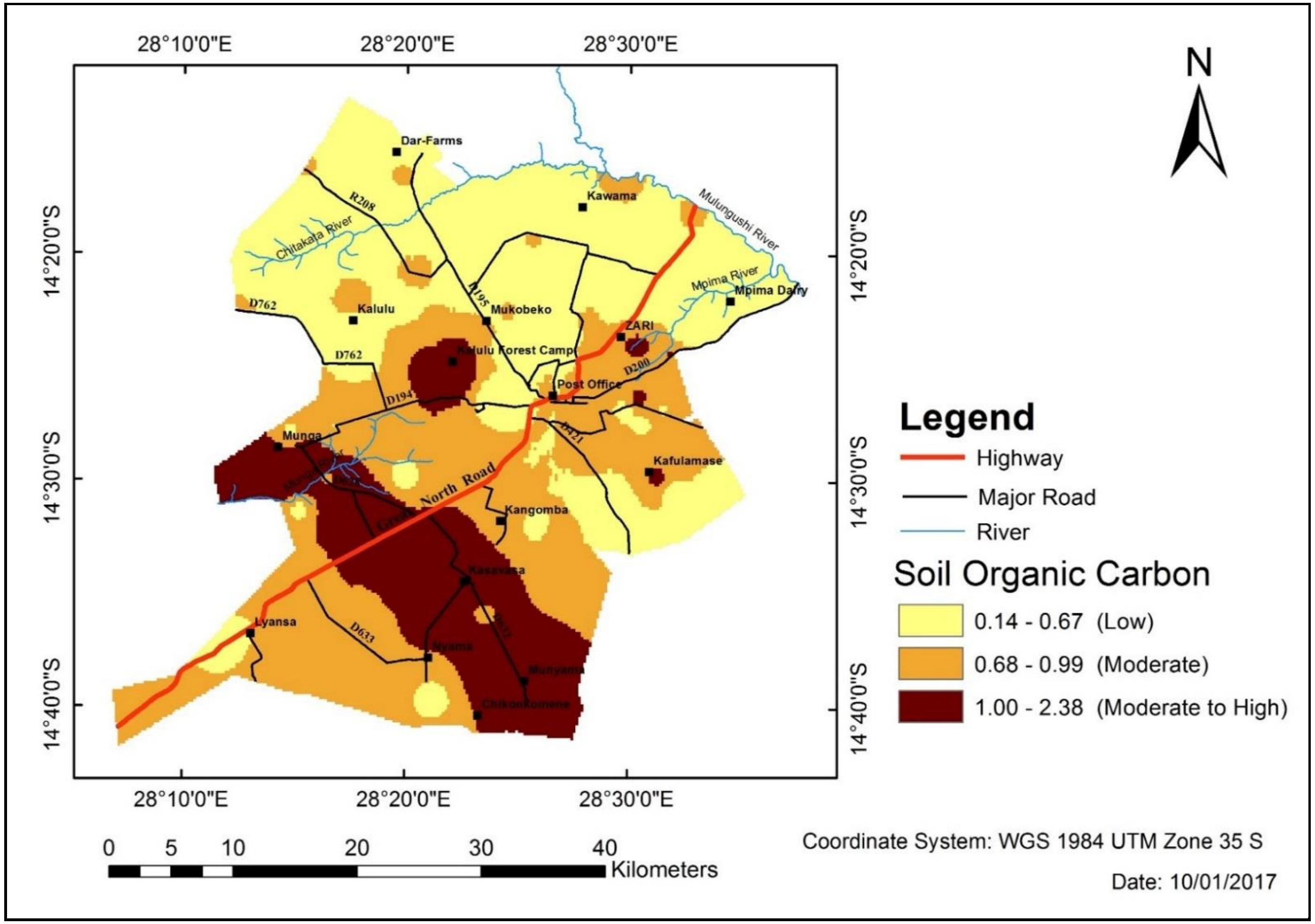

Figure 12: Spatial variability of SOC in Kabwe

4.1.7 Phosphorus

The prediction map for available phosphorus was successfully used in the process model having a prediction mean error of -0.1186. Five suitability classes in terms of available soil phosphorus existed in the area (Table 10; Figure 13). Results showed that, 86.15 % of the total area was characterized by soils having less than 10.86 ppm of available phosphorus. This could have been attributed to the low soil pH values recorded in most parts of the area as phosphorus availability depends on the pH of the soil according to Osodeke (2005). The other 13.85 % of the area was characterized by soils having more than 10.85 ppm of available phosphorus. The highest recorded value of phosphorus in the soil was 59.43 ppm (Table 10; Figure 13).

The area characterized by soils having more than 10.85 ppm of available phosphorus was rated suitable for soybean production in terms of available phosphorus. The other area with low to moderate amount of phosphorus covering 34.48 % of the total area was rated moderately suitable. This area was characterized by soils with available phosphorus ranging from 6.28 ppm to 10.85 ppm. The rest of the area covering 51.67 % of the investigated area was rated as marginally suitable with less than 6.28 ppm of available phosphorus in soil. These results indicated that phosphorus is another limiting factor in Kabwe for soybean production. It has been reported by Bekunda *et al* (1997) that most soils in sub-Saharan Africa are generally deficient in available phosphorus which is the main limiting factor for agriculture production. The results from the surveys conducted by Sokotela (1982) and Banda *et al*., (1986) in some parts of Kabwe also showed that phosphorus was less available in the soils of the area.

Soybean like most crops requires more than 10 ppm of phosphorus for effective growth. This is the critical limit at which phosphorus can be added to the soil to improve crop growth. Addition of phosphate fertilizers is therefore required in most parts of Kabwe to improve soybean yields.

Table 10: Phosphorus classes and their suitability ratings for soybean production

Available Phosphorus (ppm)	**Description**	**Suitability Rating**	**Rank (Suitability)**	**Area (%)**	**Area (km^2)**	**Area (ha)**
1.00 – 6.27	Low	Marginally Suitable	4	51.67	808.66	80866
6.28 – 10.85	Low to Moderate	Moderately Suitable	3	34.48	539.70	53970
10.86 – 19.10	Moderate	Suitable	2	9.98	156.18	15618
19.11 – 33.31	Moderate	Suitable	2	3.27	51.25	5125
33.32 – 59.43	Moderate to high	Suitable	2	0.60	9.39	939
TOTAL				100	1565	156500

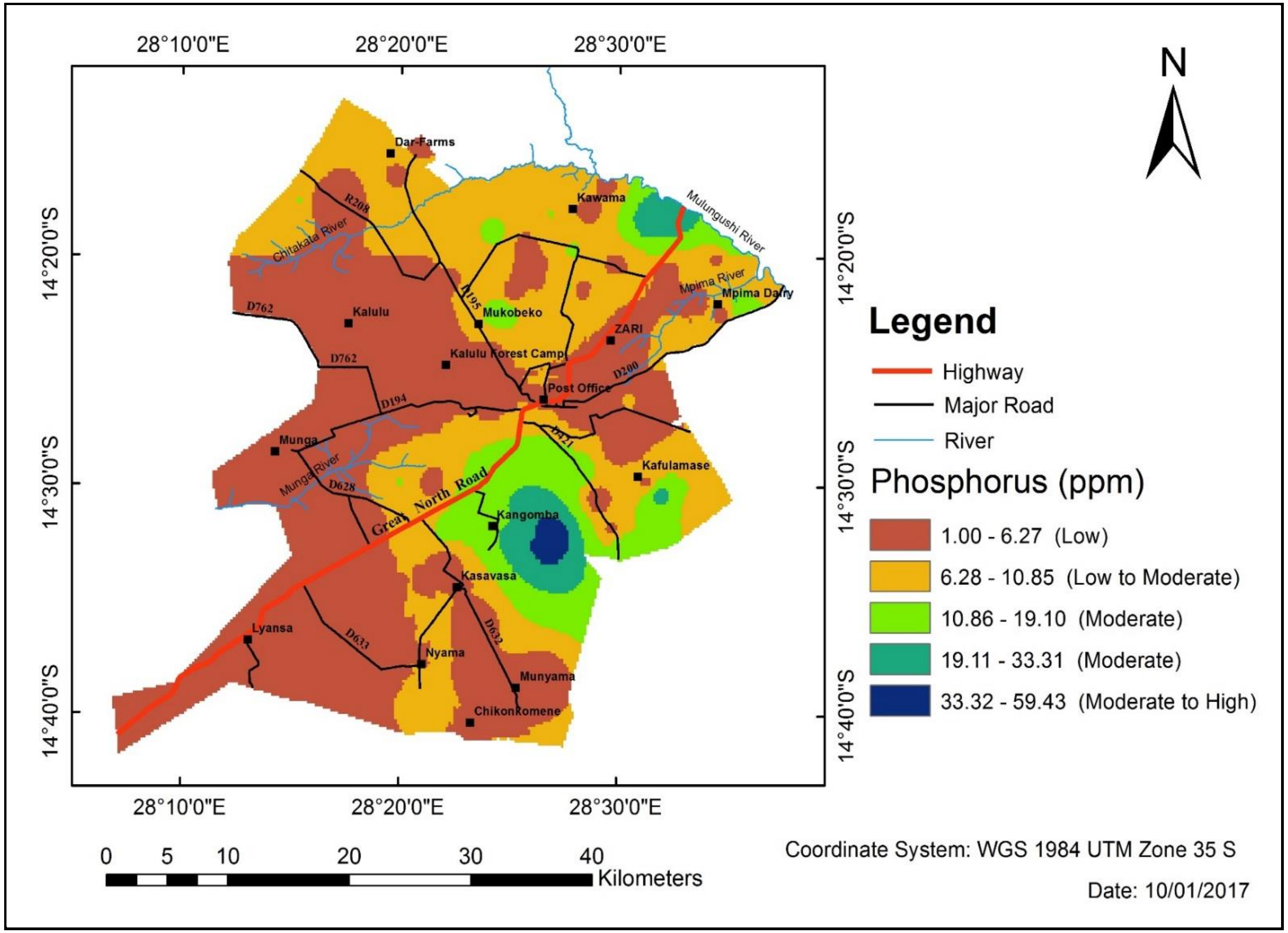

Figure 13: Spatial variability of available phosphorus in Kabwe

4.1.8 Clay proportions in soil

The clay percent prediction map having a prediction mean error of -0.0149 was successfully used in the process model for mapping soybean suitability. From the results four classes representing clay proportion were identified. Results showed that 72.07 % of the area in Kabwe was rated suitable for soybean production characterized by coarse and moderately coarse to medium coarse textural soils. These soils comprise sandy (S), loam (L), sandy loam (SL), and silt loam (SiL) soils with clay proportions ranging between 9.16 % and 23.17 %. It is known that the best soil for optimum soybean production is a loose, well-drained loam with less clay fractions (Dugje *et al.*, 2009).

The rest of the area covering 28.03 % of the total area was characterized by soils containing clay proportions ranging between 23.18% and 51.67 %. These were medium textured soils, moderately fine textured to fine textured soils and clayey soils, comprising of clay loam (CL), sandy clay loam (SCL), silt loam (SiL) and silt clay (SiC) soils (Table 11; Figure 14). This area characterized by these soils was rated moderately suitable for soybean production. The soils with high clay content are not suitable for soybean production as they become waterlogged when it rains and they usually form a hard crust surface on drying which becomes a barrier to emerging seedlings (Mzuku, 2005). The spatial distribution of clay proportions on the map shows that soils with more clay content were mostly distributed in areas associated with water.

Table 11: Classes of clay proportions and their suitability rating for soybean production

Clay Proportions (%)	**Description**	**Suitability rating**	**Rank (Suitability)**	**Area (%)**	**Area (km^2)**	**Area (ha)**
9.16 – 18.83	Coarse /Moderately coarse texture (Sandy Soils or Loamy Soils: S, LS, SL)	Suitable	2	39.91	624.74	62474
18.84 – 23.17	Moderately coarse/medium coarse texture(Loamy Soils: SL, L, SiL)	Suitable	2	32.07	501.90	50190
23.18 – 28.83	Medium texture/Moderately fine texture (Loamy Soils: L, SiL,CL,SCL)	Moderately Suitable	3	23.21	363.21	36321
28.84 – 51.67	Moderately fine texture/Fine texture (Loamy/Clayey soils: SiCL, SC,SiC)	Moderately Suitable	3	4.81	75.33	7533
TOTAL				100	1565	156500

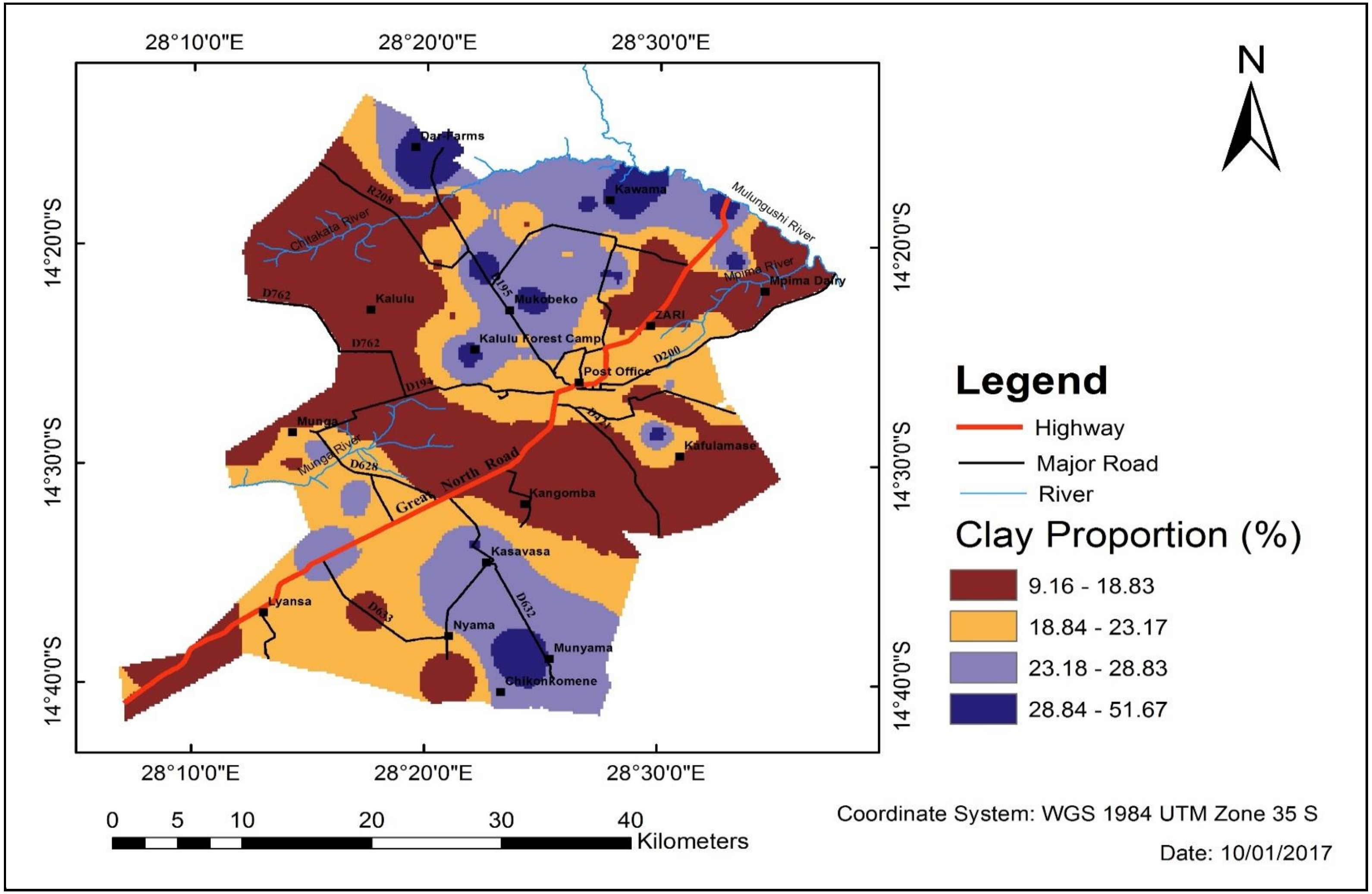

Figure 14: Map showing spatial variability of clay proportions in the soils in Kabwe

4.1.9 Accessibility

A distance to roads raster showed that 50.52 % of the area in Kabwe is close to the access roads within a distance of 1.53 km (Table 12; Figure 15). The area within this distance was rated suitable for soybean production characterized by ease of access to farm and market places. The area lying between 1.54 km and 3.42 km was rated moderately suitable and covered 32.84 % of the total area. The rest of the area covering16.64 % of the total area falls at a distance greater than 3.42 km and was rated as marginally suitable for soybean production in terms of distance to roads (Table 12; Figure 15).

Table 12: Distance to roads classes and their suitability rating for soybean production

Distance to Roads (km)	**Description**	**Suitability rating**	**Rank (Suitability)**	**Area (%)**	**Area (km^2)**	**Area (ha)**
0 – 1.53	Close to roads	Suitable	2	50.52	790.67	79067
1.54 – 3.42	Moderately close to roads	Moderately Suitable	3	32.84	514.05	51405
3.43 – 7.51	Further from roads	Marginally Suitable	4	16.64	260.46	26046
TOTAL				100	1565	156500

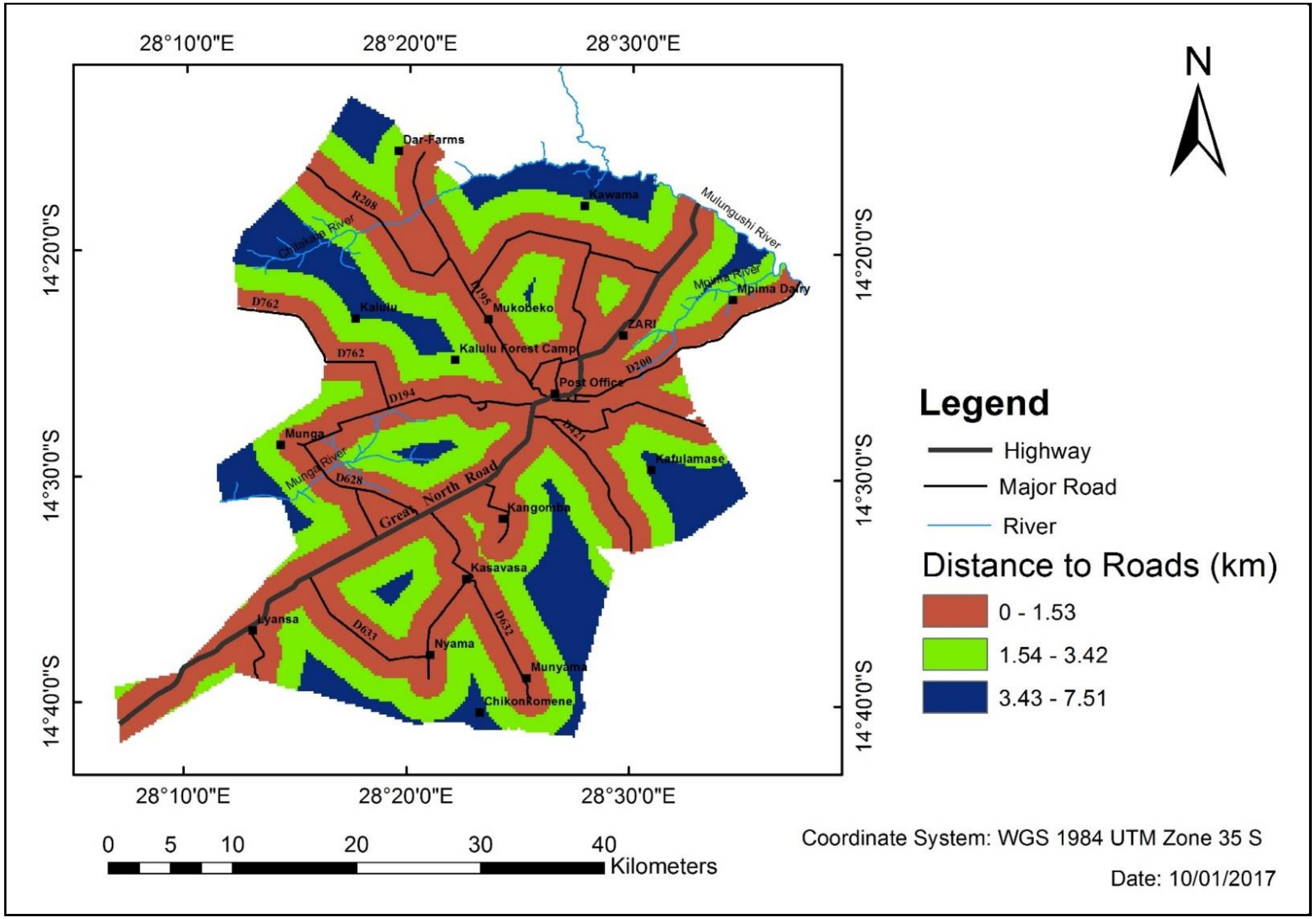

Figure 15: Distance to the roads raster

4.2 Generated land capability map

A land capability classification was carried out to assess the land for its ability to support agricultural practices on a long term sustainable basis. The assessment was based on the degree of limitations imposed on the land by the biophysical features of the land including climate. The land capability map generated in this study was classified into five classes all having different levels of limitations to soybean production. The limitations that would affect the long term use of the land for crop production including drainage, erosion or fertility were taken into account. Accessibility was not included in the capability assessment as land capability assessment does not take into account the economics of agricultural production, distance from markets, social or political factors (Grose, 1999; FAO, 1976).

Results show that, 53.13 % of the area has severe limitations due to available phosphorus soil reaction. In this area, phosphorus was less available mainly due to soil reaction, as phosphorus availability depends on the pH (Osodeke, 2005; Haruna, 2011). Soils in this area were characterized by low pH values indicating strongly to very strongly acid soils. Results further show that, 37.13 % of the area has moderately severe limitation due to soil reaction and SOC, whereas 9.34 % has moderate limitations due to slope (Table 13; Figure 16). Area with extremely severe limitations covered 0.31 % of the total area. This area was characterized by hills and sustained use of the land in this area is not possible. A small percent of the area covering 0.01 % of the total area has minor limitations to soybean production, requiring less resource inputs.

Generally, the capability map indicated that each location in the area has limitations but with varying severity. Production of soybean in the area may therefore require an input of crop management at different levels such as application of phosphate fertilizer. Results from the land capability assessment showed that available phosphorus and soil pH are the main limiting factors for soybean production in Kabwe, and therefore, there is need to manage these limiting factors to enhance soybean yields.

Table 13: Land capability classes and their level of limitations to soybean production

Capability Class	Description and Limitations	Area (%)	Area (km^2)	Area (ha)
2	Minor Limitations due to slope	0.01	0.16	16
3	Moderate Limitations due to slope	9.34	146.19	14619
4	Moderately Severe Limitations due to soil reaction and SOC (low fertility)	37.13	581.15	58115
5	Severe limitations due to available phosphorus and soil reaction	53.13	831.58	83158
6	Extremely severe limitations due to the rock out-crop and steep slope	0.31	4.85	485
TOTAL		100	1565	156500

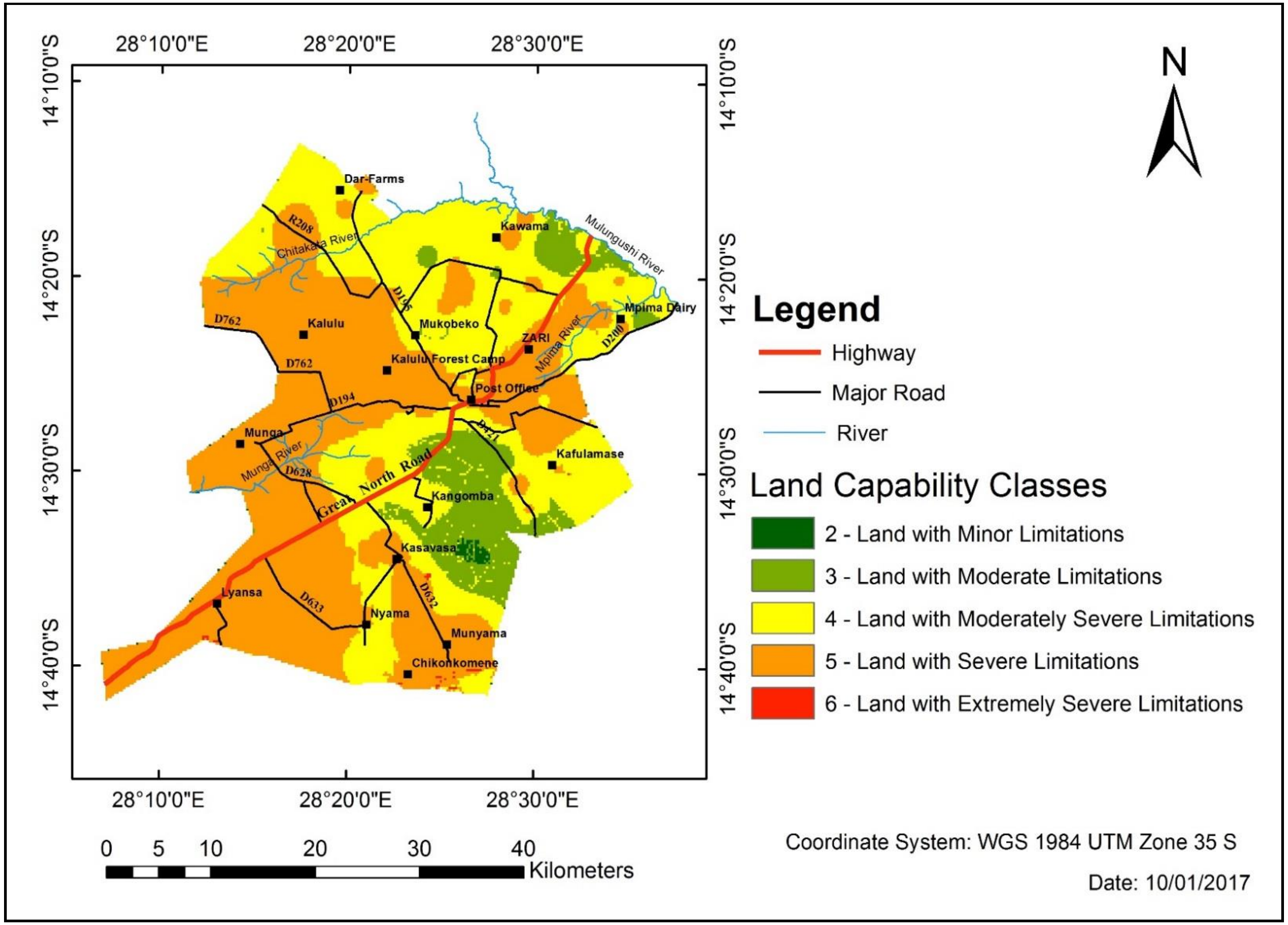

Figure 16: Land capability map of Kabwe

4.3 Generated land suitability map for soybean production in Kabwe

Results from suitability analysis showed that 87.35 % of the area in Kabwe was rated suitable for soybean production, out of which 15.07 % was rated highly suitable, 26.53 % was rated suitable and 25.18 % was rated moderately suitable. The other 20.57 % of the area was rated marginally suitable (Table14; Figure 17).

Land suitability mapping that has been done in the area show that Kabwe district is suitable for soybean production as shown in the agro ecological map and suitability ratings for Zambia in Ministry of Tourism and Natural Resources (MTENR) (2007). However, the crop suitability rating were based on land qualities in agro-ecological zones. Land suitability mapping in such works are therefore more generalized and do not represent much details of the land suitability at most farmers' fields. This study however showed that, land suitability in some parts of Kabwe is marginal for soybean production, and completely not suitable in other parts owing to some physical constraints. Soybean production in areas rated marginally and moderately suitable can however be improved by taking into consideration the main limiting factors associated with each of these classes such as soil reaction, low availability of phosphorus and steep slope in a few places. Woode and Mwenda. (1988) also showed that the area in the extreme north of Kabwe is steep and recommended land levelling.

The remaining 12.66 % of the total area investigated was rated not suitable for soybean production, of which 10.74 % was rated as currently not suitable and 1.92% as permanently not suitable (Table 14; Figure 17). Based on ground truth data and topographic maps, the area which was rated as permanently not suitable was owing to wetness and rocks as this area was identified as rivers, streams and hills. A survey by Banda *et al*., (1986) found similar results in which part of their survey area was rated as poor arable area due to wetness and depth limitations. The spatial extent of the different suitability classes for soybean production is shown in Figure 17.

Table 14: Table showing suitability classes for soybean production in Kabwe

Suitability Class	**Description**	**Area (%)**	**Area (km^2)**	**Area (ha)**
1- Highly Suitable	Land with optimum conditions for soybean growth with insignificant limitations.	15.07	235.87	23,587
2- Suitable	Slope range from 1% to 3 %, moderate water accumulation, favorable weather conditions, slightly acid soils with moderate to high amount of SOC and phosphorus. Well drained sandy (S), loamy sand (LS) and sandy loam (SL) soils. Area close to access roads within a distance of 0 to 1.52 km.	26.53	415.24	41,524
3- Moderately Suitable	Moderate weather conditions, moderately steep slope ranging from 3% to 5%, and high water accumulation. Moderately acid soils with moderate percent SOC and low to moderate amount of phosphorus. Moderately well drained loam (L), silt loam (SiL), clay loam (CL), sandy clay (SC), sandy clay loam (SCL) and silt clay loam (SiCL) soils. Area moderately close to roads within a distance of 1.54 km 3.42 km.	25.18	394.11	39,411
4- Marginally Suitable	Steep slope, low water accumulation, strongly acid soils, low SOC and phosphorus. Area within a distance of 3.43 km and 7.51 km.	20.57	321.96	32,196
5- Currently Not Suitable	Severe weather conditions, steep slope ranging between 5 % and 8 % and no water accumulation. Very strongly acid soils.	10.74	168.10	16,810
6- Permanently Not Suitable	Hilly with steep slope greater than 12 % and area with very high water accumulation.	1.92	30.05	3,005
TOTAL		100	1565	156,500

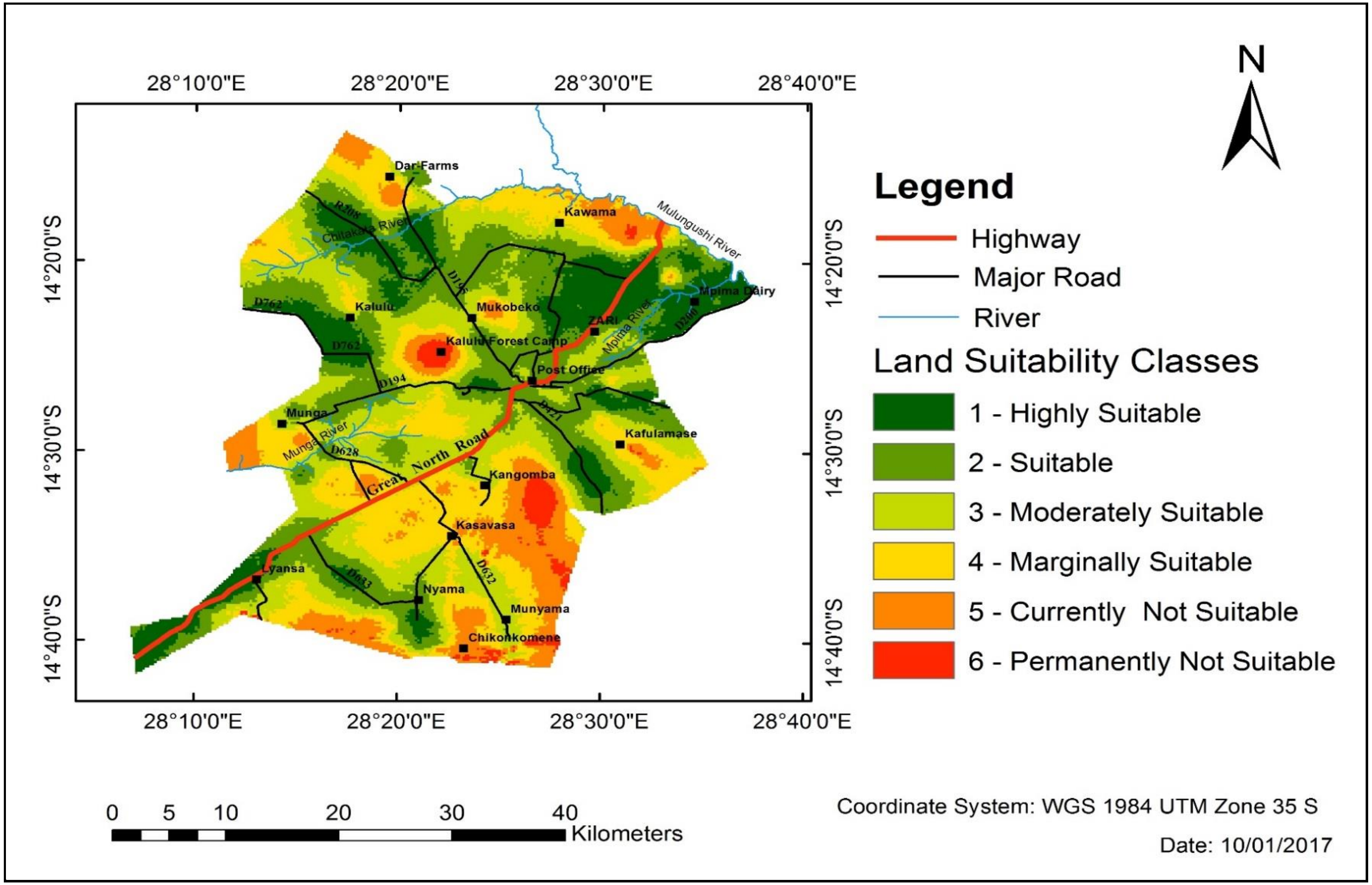

Figure 17: Land suitability map for soybean production in Kabwe

4.4 Comparison of the capability and suitability classified maps

Results from land capability assessment showed that Kabwe area has some limitations owing to different factors including low phosphorus levels in the soil, low SOC, low pH values and climate (rainfall and temperature). This indicated that there was no area that could be classified as highly suitable without limitations or with insignificant limitations. However, results from land suitability assessment showed that 15.07 % of the area was highly suitable contrary to the results obtained in a land capability assessment (Table 15). This was attributed to the fact that only the physical factors were considered in land capability assessment while suitability analysis included distance to roads as a non-biophysical factor contributing to land suitability for soybean (Grose, 1999; FAO, 1976).

Results from land capability assessment further showed that 53.13 % of the total area has severe limitations and suitability analysis showed that an area covering 10.74 % of the total area having severe limitations was rated currently not suitable (Table 15). The area with extremely severe limitations where soybean production is not possible only covered 0.31 % of the total area. Generally, 87.35 % of the area was rated as suitable for soybean production with 15.07 % having no limitation, 26.53 % having minor limitations, 25.18 % having moderate limitation and 20.57 % having moderately severe limitations (Table 15). The rest of the area was rated as not suitable, of which, 10.74 % was rated currently not suitable with severe limitations and 1.92 % as permanently not suitable with extremely severe limitations which were owing to rock outcrops and slope.

Table 15: Area covered in each suitability and capability classified maps

Suitability class and the degree of limitations	Area covered in land Suitability Map			Area covered in land Capability Map		
	%	km^2	ha	%	km^2	ha
Highly suitable / No Limitations	15.07	235.85	23,585	0	0	0
Suitable / Minor Limitations	26.53	415.19	41,519	0.01	0.16	16
Moderately Suitable / Moderate Limitations	25.18	394.07	39,407	9.34	146.17	14,617
Marginally Suitable / Moderately Severe Limitations	20.57	321.92	32,192	37.13	581.09	58,109
Currently Not Suitable / Severe limitations	10.74	168.08	16,808	53.13	831.49	83,149
Permanently Not Suitable / Extremely Severe Limitations	1.92	30.05	3,005	0.31	4.85	485
TOTAL	100	1,565	156,500	100	1,565	156,500

4.5. Validation of the generated land suitability map for soybean

Based on ground truth data, the overall classification accuracy of the suitability map was 65 % (Table 16). At this percent accuracy, this map (Figure 17) can rightly be used by small scale farmers growing soybean and other land users for decision making. The validation and accuracy of physical land evaluation that use a qualitative method may not be possible (FAO, 1976; Rossiter, 1996). However, this study used the validation method by investigating the production of soybean in the area, thereby making a comparison with results from the predicted suitability map. This method was also used by Chabala *et al.,* (2013) and Elsheikh (2013) to compare the models used in their respective studies.

The accuracy for each suitability class in this study was 70 % for highly suitable, 60 % for suitable, 77 % for moderately suitable and 57 % for marginally suitable (Table 16) Results further showed that the accuracy for currently not suitable and permanently not suitable classes was 60 % for each. These two classes had a few farms around which were visited during validation.

Table 16: Error matrix showing classification accuracy of the suitability map

Suitability Class	**Points Verified**	**Correctly Classified Points**	**Percent Correctly Classified Points (%)**
Highly Suitable	30	21	70
Suitable	30	18	60
Moderately Suitable	30	23	77
Marginally Suitable	30	17	57
Currently Not Suitable	10	6	60
Permanently Not Suitable	5	3	60
TOTAL	135	88	65

The resultant maps from suitability assessments serve as guides in decision making once they have been validated or once the models used have been validated. The validation results in this study revealed that the delineated suitability classes were in close agreement with what is expected of the land in the area. This map can therefore be used as guide in decision making on site selection for soybean production.

There are several studies that applied a similar approach used in this study to map land suitability with the resultant maps validated and used in decision making. One such study is by Abdelrahman *et al*., (2016) who integrated different land quality parameters in a GIS based multi-criteria analysis to generate land suitability and capability maps. These maps were developed to illustrate the suitability degrees and display the spatial representation of soils suitable for agricultural crops including soybean. However, the study by Abdelrahman *et al*., (2016) was only limited to the physical land parameters. Another similar study was by Joshua *et al*., (2013) who developed a model to determine land suitability for agricultural production. The attributes used in the model were soils, slope, water bodies and other environmental factors. A suitability map was generated in this study and it was used to support decisions making for sustainable agricultural production. Other studies were by Ayehu and Besufekad, (2015), Rabia (2012) and Rota *et al*., (2006) who used a GIS-based MCE to integrate parameters of soil, climatic conditions and topography to develop suitability maps. These maps were used in agriculture planning for the production of crops including rice and soybean crops.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The spatial attributes relevant for soybean production including slope, drainage (wetness), climate (rainfall and temperature), soil reaction, SOC, available phosphorus and clay proportions were extracted and mapped. In addition, accessibility was included as a non-biophysical factor affecting land suitability.

The spatial variation showed that 92.62 % of the land in Kabwe was almost flat with slope less than 3 %. Steep slope greater than 5 % were also recorded near hilly areas covering 1.45 % of the total area. This areas was characterized by severe weather conditions as shown in the elevation classified map. The soil drainage as represented by the wetness index was also less in areas lying on high slope. There is less accumulation in these areas as water will not usually percolate but instead flow to other parts.

Spatial variation of soil reaction showed that only 0.62 % of the total area was characterized by soils with a pH range between 5.51 and 6.04. This area was rated as suitable for soybean production in terms of soil pH because soybean requires soils with a pH value between 5.6 and 7 for effective growth as was identified in literature. Spatial variability of available phosphorus showed that 13.85 % of the area was characterized by soils having more than 10.85 ppm of available phosphorus. This area was rated as suitable for soybean production in terms of available phosphorus. SOC was found to be in less amounts with 80.45 % of the area recording less than 1 % of organic carbon. SOC was however not a major limiting factor to soybean production, however management practices that add organic matter to the soil can be employed to improve productivity. The soil texture in the area as represented by clay proportion layer was rated as suitable and moderately suitable for soybean production.

Based on the findings of this study, it can be concluded that Kabwe has great potential for soybean production. From the generated land suitability map, results showed that 87.35 % of the total area was rated suitable for soybean production, of which 15.07 % was rated highly suitable, 26.53 % was rated suitable and 25.18 % was rated moderately suitable. The other 20.57 % was rated marginally suitable. The findings further showed that only 12.66 % of the area was not suitable for soybean production of which 10.74 % was rated as currently not suitable and 1.92 % as permanently not suitable. Spatial variation of soil parameters showed that available phosphorus and soil pH were the main limiting factors for growing soybean in Kabwe as identified in the land capability analysis. Therefore, a supplement of these limiting factor is necessary through the application of phosphate fertilizers to address low available phosphorus and agriculture lime to correct soil acidity.

Map validation results showed that the suitability map was 65 % accurate. It can further be concluded that the map can be used as a guide in decision making on soya bean production. The study therefore demonstrated that GIS based multi-criteria analysis can be considered as an important tool for delineating land suitability for soybean production.

5.2 Recommendations

It is recommended that, the method used in this study be applied in future studies to map land suitability for the production of soybean or other crop, with addition of other parameters that were not included in this study such as the social-economic factors. The fact that this study was restricted to only one crop, it is recommended that future studies apply the analysis method used in this study to develop land suitability maps for other crops such as cereals. It is further recommended that field trials can be set up in the various suitability classes as identified in the study. This will allow for testing of the various management options for sustainable soybean production in each of the suitability classes. The management options may include the application of agricultural lime and phosphate fertilizers to improve on soil reaction conditions and available phosphorus respectively as these were the most limiting factors to soybean production in Kabwe.

REFERENCES

AbdelRahman, M. A. E., A. Natarajan and R. Hedge. 2016. Assessment of Land Suitability and Capability by Integrating Remote Sensing and GIS for Agriculture in Chamarajanagar District, Karnataka, India. *The Egyptian Journal of Remote Sensing and Space Sciences.* (Article in Press)

Adornado, H. A. and M. Yoshida. 2008. Crop Suitability and Soil Fertility Mapping using Geographic Information System (GIS). Agricultural Information Research 17(2), 60–68. Available online at www.jstage.jst.go.jp/ Accessed on 15/10/2016.

Agidew, A. A. 2015. Land Suitability Evaluation for Sorghum and Barley Crops in South Wollo Zone of Ethiopia. *Journal of Economics and Sustainable Development,* 6(1), 14-25.

Alliance for a Green Revolution in Africa (AGRA). 2014. Africa Agriculture Status Report: Climate Change and Smallholder Agriculture in Sub-Saharan Africa. Nairobi, Kenya.

Ayehu, G. T. and S. A. Besufekad. 2015. Land Suitability Analysis for Rice production: A GIS Based Multi-Criteria Decision Approach. *American Journal of Geographic Information System*. 4(3), 95-104.

Banda, D. J., G. Chongo and C. V. D. Meeren. 1986. Semi-Detailed Soil Survey of Ronwell Farm: (Farm Nos. 797 and 3255, Kabwe, Central province. Soil Survey Report No. 135. Soil Survey Unit, Department of Agriculture, Zambia.

Bationo, A., B. Waswa., J. Okeyo., F. Maina., J. Kihara and U. Mokwunye. 2011. Fighting Poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management. Springer, Netherlands.

Bekunda M.A., A. Bationo and H. Ssali. 1997. Soil fertility management in Africa. In Buresh R. J, P. A. Sanchez and F. Calhoun (editors). Replenishing soil fertility in Africa. *Soil Sci. Soc. of America*. Special Publication (51). Madison Wisconsin. USA, 63-79.

Bell, J.C., R. L. Cunningham and M. W. Havens. 1994. Soil drainage class probability mapping using a soil-landscape model. *Soil Sci. Soc. Am. J*. 58, 464-470.

Beven, K. J. and M. J. Kirby. 1979. A physically based variable contributing area model of basin hydrology. Hydrological Science Bulletin. 24, 43-69.

Bhunia, G. S., P. K. Shit and R. Maiti., 2016. Comparison of GIS-based interpolation methods for spatial distribution of soil organic carbon (SOC). *Journal of the Saudi Society of Agricultural Sciences.* (ARTICLE IN PRESS)

Bolstad, P., 2005. GIS Fundamentals: A First Text on Geographic Information System, 2nd ed. Eider Press, USA.

Bowen, C. R. and S. E. Hollinger. 2002. Alternative Crop-Suitability Maps. Illinois State Water Survey, Champaign, Illinois. http://www.sws.uiuc.edu/data/altcrops/ Accessed on 11/04/2016.

Brady, N. C. and R. R. Weil, 2008. The nature and properties of soils. 14th ed. Pearson Education, Inc., Upper Saddle River, New Jersey.

Bray, R. H. and L.T. Kurtz. 1945. Determination of total organic and available forms of phosphorus in soils. *Soil Science*, 59, 39-45.

Ceballos-Silva, A. and J. Lopez-Blanco. 2003. Delineation of suitable areas for crops using a Multi-Criteria Evaluation approach and land use/cover mapping: a case study in Central Mexico. *Agric. Sys.* 77(2), 117-136.

Central Statistical Office (CSO), 2011. Zambia 2010 Census of Population and Housing: Preliminary Population Figures. Lusaka.

Central Statistics Office. 2016. The Monthly Bulletin, Vol.162. Lusaka, Republic of Zambia: Accessed on 01/01/2017 from http://www.zamstats.gov.zm/gen/monthly.php

Chabala, L. M., A. Mulolwa and O. Lungu. 2013. Landform classification for digital soil mapping in the Chongwe-Rufunsa area, Zambia. *Agriculture, Forestry and Fisheries*, 2 (4), 156-160.

Chabala, L.M., A. Mulolwa and O. Lungu. 2014. Mapping the Spatial Variability of Soil Acidity in Zambia. *Agronomy Journal*, 4, 452-461.

Chen, J. 2014. GIS-based multi-criteria analysis for land use suitability assessment in City of Regina. Chen Environmental Systems Research, 3, 1-13. http://www.environmentalsystemsresearch.com/content/3/1/13 Accessed on 26/11/2016

Chinene, V. R. N. 1991. The Zambian Land Evaluation System. Soil Use and Management, 7(1), 21-29.

Chinene, V. R. N. 1992. Land evaluation using the FAO Framework: An example from Zambia. Soil Use and Management, 8(3), 130-139.

Clayton, D. B. 1974. Reconnaissance Soil Survey: Mukonchi East Block (Western Half). Soil Survey Report No. 21. Soil Survey Unit, Land Use Branch, Department of Agriculture, Zambia.

Darwish, K. M., M. Rashad., S. Z. Mohamed and A. Gad. 2015. Spatial distribution analysis of soil variables for agronomic development in El-Omayed Area, North-Coastal of Egypt, *Environ Earth Sci*., 74 (1), 889-901. doi:10.1007/s12665-015-4095-2.

De la Rosa, D., F. Mayol., E. Diaz-Pereira., M. Fernandez and D. de la Rosa Jr., 2004. A land evaluation decision support system (MicroLEIS DSS) for agricultural soil protection with special reference to the Mediterranean region. *Environmental Modelling and Software*, 19, 929–942.

Delve, J., J. E. Huising and P. Bagenze. 2007. Target area identification using a GIS approach for the introduction of legume cover crops for soil productivity improvement: a case study eastern Uganda. *African Journal of Agricultural Research*, 2(10), 512-520.

Dent, D. and A.Young. 1981. Soil Survey and Land Evaluation. George Allen and Unwin Publishers. London, U.K.

Dugje, I. Y., L. O. Omoigui., F. Ekeleme., R. Bandyopadhyay., P. L. Kumar and A. Y. Kamara. 2009. Farmers' Guide to Soybean Production in Northern Nigeria. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

Elsheikh, R., A. R. B. M. Sharrif., F. Amiri., N. B. Ahmad., S. K. Balasundram and M. A. M. Soom. 2013. Agriculture Land Suitability Evaluator (ALSE): A decision and planning support tool for tropical and subtropical crops. *Computer and Electronics in Agriculture*, 93, 98-110. http://dx.doi.org/10.1016/j.compag.2013.02.003 Accessed on 15/12/2016.

English, C. 1982. Semi-Detailed Soil and Land Capability Survey of Liteta Leprosarium, Central Province. Soil Survey Report No. 101. Soil Survey Unit, Land Use Branch, Department of Agriculture, Zambia.

FAO, 1976. A Framework for Land Evaluation: Food and Agriculture Organization, Soils Bulletin. No. 32, Rome, Italy.

FAO. 1983. Guidelines: Land Evaluation for Rain fed Agriculture, Food and Agriculture Organization, Soils Bulletin. No. 52, Rome, Italy.

FAO. 1988. FAO-UNESCO, Soil Map of the World-Revised Legend. World Soil Resources Report No.60. Food and Agricultural Organization of the United Nations, Rome, Italy.

FAO, 2007. Land Evaluation: Towards a revised framework. Land and Water Discussion Paper 6, Rome, Italy.

Forkuo, E. K. and A. K. Nketia. 2011. Digital soil mapping in GIS environment for crop-land suitability analysis. *International Journal of Geomatics and Geosciences*. 2(1), 133-146. (Research Article)

Gozdowski, D., M. Stepien., S. Samborski., E.S. Dobers., J. Szatylowicz and J. Chormanski. 2014. Determination of the most relevant soil properties for delineation of management zones in production fields. *Commun Soil Sci Plan*, 45 (17), 2289-2304.

Grabs, T., J. Seibert., K. Bishop and H. Laudon. 2009. Modeling spatial patterns of saturated areas: A comparison of the topographic wetness index and a dynamic distributed model, *Journal of Hydrology*, 373, 15–23.

Grose, C. J., 1999. Land Capability Handbook: Guidelines for the Classification of Agricultural Land in Tasmania, 2nd ed. Foot and Playsted, Launceston, Tasmania.

Halder, J. C. 2013. Land Suitability Assessment for Crop Cultivation by Using Remote Sensing and GIS. *Journal of Geography and Geology*, 5(3), 65-74. Available on http://dx.doi.org/10.5539/jgg.v5n3p65 Accessed on 21/10/2016

Haruna, I. M. 2011. Dry matter partitioning and grain yield potential in Sesame (Sesamum indicum L.) as influenced by poultry manure, nitrogen and phosphorus at Samaru. *Nigeria.J.Agric.Technol*., 7, 1571–1577.

Hbib, M., Alshuwaikhat and K. Nasef. 1996. A GIS-based Spatial Decision Support System for Suitability Assessment and Land Use Allocation. *Arabian Journal for Science*, 21(4A), 525-543.

Hilinski, T. E., 2001. Century 5: Implementation of Exponential Depth Distribution of Organic Carbon in the CENTURY Model 1. Department of Soil and Crop Sciences, Colorado State University.

Hillel, D., 2004. Introduction to Environmental Soil Physics. Elsevier Academic Press, USA.

Jankowski, P. and L. Richard. 1994. Integration of GIS-based suitability analysis and multicriteria evaluation in a spatial decision support system for route selection. *Environment and Planning B*, 21, 326–339.

Johnson, D. W., D. E. Todd., C. F. Trettin and J. S. Sedinger. 2007. Soil Carbon and Nitrogen changes in forests of Walker Branch watershed, 1972 to 2004. *Soil Sci. Soc. Am. J*., 71(5), 1639 - 1646.

Joshua, K. J., C. Nneoma and A. A. Jajere, 2013. Land suitability analysis for agricultural planning using GIS and multi criteria decision analysis approach in

Greater Karu Urban Area, Nasarawa State, Nigeria. *African Journal of Agricultural Science and Technology (AJAST)*, 1(1), 14-23.

Kabwe Municipal Council, 2010. Kabwe District State of Environmental Outlook Report Kabwe, Zambia.
https://issuu.com/di-novista/docs/kabwe_district_state_of_environment

Kalima, C. and W. J. Veldkamp. 1985. Land Evaluation Methodology of the Zambia Soil Survey Unit. In: Woode. P. R. (editor). Proceedings of the XI th International Forum on Soil Taxonomy and Agro-technological Transfer. Zambia, July15th to August 1st, 1985. 148-157.

Kamkar, B., A. M. Dorri and A. J. Teixeira da Silva. 2014. Assessment of land suitability and the possibility and performance of a canola (Brassica napus L.) – soybean (Glycine max L.) rotation in four basins of Golestan province, Iran. *The Egyptian Journal of Remote Sensing and Space Sciences*, 17, 95–104. (Research Paper)

Kanangi, G. A. D., E.Yohane., D. Siyeni., L. Kachulu., L. Mtambo., B. F. Chisama., H. Malaidza., F. Tchuwa and O Mulekano. 2013. A Guide to Soybean Production in Malawi, Department of Agricultural Research Services (DARS), Lilongwe. Malawi.

Kiser, L. C., J .M. Kelly and P. A. Mays. 2009. Changes in Forest Soil Carbon and Nitrogen after a thirty-year interval. *Soil Sci. Soc. Am. J.*, 73(2), 647-653.

Lubungu. M., W. J. Burke and N. J. Sitko. 2013. Analysis of the Soya Bean Value Chain in Zambia's Eastern Province. Working Paper 74. Indaba Agricultural Policy Research Institute (IAPRI), Lusaka, Zambia. http://www.iapri.org.zm Accessed on 10/07/2016.

Lupia, F., 2012. Crop/Land Suitability Analysis by ArcGIS Tools. Technical Report. Research Gates.

Malczewski, J. 2004. GIS-based land-use suitability analysis: a critical overview. *Progress in planning*, 62 (1), 3–65.

Malczewski, J. 2006. Ordered weighted averaging with fuzzy quantifiers: GIS-based multi criteria evaluation for land-use suitability analysis. *International Journal of Applied Earth Observation and Geoinformation*, 8(4), 270–277.

Mambo, A and L. K. Phiri. 2004. Soil Acidity Map of Zambia; Zambia Agriculture Research Institute, Lusaka, Zambia.

Mapedza, E., J. Wright and R. Fawcett. 2003. An investigation of land cover change in Mafungautsi Forest, Zimbabwe, using GIS and participatory mapping. *App. Geog.* 23(1), 1-21.

Mbilinyi, B.P., S. D. Tumbo., H. F. Mahoo and F. O. Mkiramwinyi. 2007. GIS-based decision support system for identifying potential sites for rainwater harvesting. *Physics and chemistry of the earth*, 32, 1074–1081 http:/www.sciencedirect.com Accessed on 21/10/2016

McClean, G. J., R. L. Rowe., K.V. Heal., A. Cross., G. D. Bending and S. P. Sohi. 2015. An empirical model approach for assessing soil organic carbon stock changes following biomass crop establishment in Britain. *Biomass and Bioenergy*, 83, 141-15. (Research paper)
http://www.elsevier.com/locate/biombioe

Mendas, A. and A. Delali. 2012. Integration of Multi-Criteria Decision Analysis in GIS to develop land suitability for agriculture: Application to durum wheat cultivation in the region of Mleta in Algeria. *Computers and Electronics in Agriculture*, 83,117–126.

Ministry of Agriculture (MoA), 2002. Soybean Production Guide. Soils and Research Branch of the Ministry of Agriculture, Republic of Zambia.

Ministry of Agriculture and Livestock (MAL), 2013. The Crop Forecasting Survey Report for the 2012/2013 Agriculture Season. Republic of Zambia.

Ministry of Agriculture and Livestock (MAL), 2016. The Crop Forecasting Survey Report for the 2015/2016 Agriculture Season. Republic of Zambia.

Ministry of Tourism, Environment and Natural Resources (MTENR), 2007. Formulation of the National Adaptation Programme of Action on Climate Change

(Final Report). Lusaka, Republic of Zambia. Available at: http://unfccc.int/resource/docs/napa/zmb01.pdf. Date accessed 8/01/2017.

Muliokela, S. W., 1995. Zambia Seed Technology Handbook. Ministry of Agriculture, Food and Fisheries, Zambia.

Mustafa, A. A., S. Man., R. N Sahoo., A. Nayan., K. Manoj., A. Sarangi and A. K. Mishra. 2011. Land suitability analysis for different crops. A multi criteria decision making approach using remote sensing and GIS. Indian Agricultural Research Institute, New Delhi-110 012.

Mzuku, M., R. Khosla., R. Reich., D. Inman., F. Smith and L. MacDonald. 2005. Spatial variability of measured soil properties across site-specific management zones. Soil Sci. Soc. Am. J. 69, 1572-1579.

National Agriculture Information Service (NAIS), 2015. The Crop Forecasting Survey for the 2014/2015 Agricultural Season and the Food Balance Status for the 2015/2016 Marketing Season. Agriculture Minister's Speech, Republic of Zambia.

Nurmiaty and S. Baja., 2013. Spatial Based Assessment of Land Suitability and Availability for Maize (Zea mays L.) Development in Maros Region, South Sulawesi, Indonesia. *Open Journal of Soil Science*, 3, 244-251 http://dx.doi.org/10.4236/ojss.2013.35029 Accessed on 21/10/2015

Nwer, B. A. B., 2005. The Application of Land Evaluation Technique in the North-East of Libya. PhD Thesis, Faculty of Environment, Cranfield University, Silsoe.

Olaniyi, A. O., A. J. Ajiboye., A. M. Abdullah., M. F. Ramli and A. M. Sood. 2015. Agricultural Land Use Suitability Assessment in Malaysia. *Bulg. J. Agric. Sci*., 21, 560–572.

Osodeke, V. E. 2005. Determination of Phosphorus requirements of Cowpea (Vigna unguiculata (L.) Walp) in the Acid Soils of South Eastern Nigeria using Sorption Isotherms. *Global J. of Agric.Sci*., 4 (2), 135–138.

Pearson, R. W. and F. Adams, 1967. Soil acidity and liming. Agronomy 12, 1-41. Am. Soc. of Agron. Inc., Madison, Wis.

Perveen, S., M. H. Arsalan., M. H. Siddiqui., I. A. Khan., S. Anjum and M. Abid. 2013. GIS Based Multi-Criteria Model for Cotton Crop Land Suitability: A Perspective from Sindh Province of Pakistan. *FUUAST J. BIOL*., 3(1), 31 -37.

Qing, Y., M. Zhu-Guo and C. Liang. 2011. A Preliminary analysis of the relationship between precipitation variation trends and altitude in China. *Atmospheric and Oceanic Science Letters*, 4(1), 41-46.

Rabia, A. H. 2012. A GIS Based land suitability assessment for agricultural planning in Kilte Awulaeo district, Ethopia. The 4th International Congress of ECSSS, EUROSOIL, Bari, Italy, 2012. Available on http://works.bepress.com/ahmed_rabia/5 Accessed on 21/10/2015

Ritung, S., F. Wahyunto Agus and H. Hidayat. 2007. Land suitability evaluation with a case map of Aceh Barat district. Indonesian Soil Research Institute and World Agro forestry Centre, Bogor, Indonesia.

Rossiter, D.G., 1996. A theoretical framework for land evaluation. Geoderma 72, 165–202.

Rota, J. A., P. Wandahwa and D. O. Sigunga. 2006. Land evaluation for soybean (Glycine max L. Merrill) production based on kriging soil and climate parameters for the Kakamega district, Kenya. *Journal of Agronomy* 5(1), 142-150.

Rutherford, R. J. 2010. An Assessment of Rain-fed Crop Production Potential in South Africa's Neighboring Countries. Report No. P RSA 000/00/12510, Department of Water Affairs, Republic of South Africa.

Schmidt, F. and A. Persson. 2003. Comparison of DEM Data Capture and Topographic Wetness Indices. *Precision Agriculture*, 4, 179–192.

Shi, W., J. Liu., Z. Du., Y. Song., C. Chen and T. Yue. 2009. Surface Modelling of Soil pH. *Geoderma* 150, 113-119.

Silva, B. M., S. H. G. Silva., G. Cesár *de* Oliveira., P. H. C. R. Peters., W. J. Reis dos Santos and N. Curi. 2014. Soil Moisture Assessed by Digital Mapping Techniques and its Field Validation. *Ciênc. Agrotec. Lavras*, 38(2), 140-148.

Sokotela, S. B. 1982. Detailed Soil and Land Capability Survey of Chief Liteta Proposed Multi-Purpose CO-OPR. Farm, Central Province. Soil Survey Report No. 92. Soil Survey Unit, Land Use Branch, Department of Agriculture, Zambia.

Subarna, D., M. Y. J. Purwanto., K. M. Murtilaksono and Wiweka. 2014. The relationship between monthly rainfall and Elevation in the Cisangkuy watershed Bandung Regency. *International Journal of Latest Research in Science and Technology*, 3 (2), 55-60.

Sullivan, P., 2003. Intercropping principles and production practices. Agronomy System Guide, Appropriate Technology Transfer for Rural Areas (ATTRA), Fayetteville. http://attra.ncat.org/attra-pub/intercrop.html Accessed 14/09/2016

The World Bank, 2006 Annual Report.

Thierfelder, C., S. Cheesman and L. Rusinamhodzi. 2012. A Comparative Analysis of Conservation Agriculture Systems: Benefits and Challenges of Rotations and Intercropping in Zimbabwe. Field Crops Research, 137, 327–250. http://www.sciencedirect.com/science/article/pii/s0378429012002845 Accessed on 12/05/2016.

Tembo, S. and N. J. Sitko. 2013. Technical Compendium: Descriptive Agricultural Statistical Analysis for Zambia. Working Paper. Lusaka: IAPRI.

Veldkamp W. J., 1987. Reconnaissance/ Semi- detailed Semi- Quantified Land Evaluation System for Non- Irrigated Agriculture. Technical Guide No .19. Soil Survey Unit Research Branch, Department of Agriculture. Lusaka, Zambia.

Walkley, A. and I. A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* 37:29-38.

Wilson, J. P. and J. C. Gallant. 2000. Terrain Analysis: Principles and Applications. John Wiley and Sons, Inc. New York.

Woode P., 1979. Reconnaissance Soil Survey of Muswishi Rural Reconstruction Centre, Soil Survey Technical Report No. 60. Soil Survey Unit, Land Use Branch, Department of Agriculture, Zambia.

Woode P., 1988. Field guide for soil surveyors. Technical Guide No. 18. Soil Survey Unit, Department of Agriculture, Zambia.

Woode P. and R. Mwenda. 1980. Semi-Detailed Soil Survey of Chibote Farms LTD: Farm Numbers 3571 and 3189, Kabwe District, Central Province. Soil Survey Report No. 61. Soil Survey Unit, Land Use Branch, Department of Agriculture, Zambia.

Zambia Meteorological Department. 2015. Weather and Climate Reports. Lusaka, Zambia.

Zhang, W., K. L. Wang., H. S. Chen., X. Y. He and J. G. Zhang. 2012. Ancillary information improves kriging on soil organic carbon data for a typical karst peak cluster depression landscape. *J. Sci. Food Agric*. 92 (5), 1094–1102.

Zhao, Z., D. A. MacLean., C. P. A. Bourque., D. E. Swift and F. R. Meng. 2013. Generation of Soil Drainage Equations from an Artificial Neural Network-Analysis Approach. *Can. J. Soil Sci*, 93, 329–342.

Zinko, U., J. Seibert., M. Dynesius and C. Nilsson. 2005. Plant species numbers predicted by a topography based groundwater-flow index. *Ecosystems,* 8, 430–441.