PREDICTION OF SOIL SALINITY SPATIAL DISTRIBUTION AND ITS MANAGEMENT IMPLICATIONS FOR RICE PRODUCTION IN MAGOZI IRRIGATION SCHEME, IRINGA, TANZANIA

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EXTENDED ABSTRACT

Rice (*Oryza sativa* L.) plays an important role in improving household food security and national economies in Sub-Saharan Africa including Tanzania. There is an increase in annual per capita consumption of rice in Tanzania from 20.5 in 2001 to about 25 - 30 kg year^{-1} in 2011 coupled with an increase in population. Despite the increase in rice consumption, the current rice production in Tanzania is still as low as 2.3 t ha^{-1} while the potential rice yields are 4 to 10 t ha^{-1} in the country. Reasons for low rice production include poor agronomic practices and land degradation. Soil salinity which refers to the content of soluble salts in the soil is one of the main land degradation problems in many rice growing irrigation schemes in Tanzania.

Managing soil salinity in irrigated agriculture is crucial for minimizing its negative effects and for ensuring the long-term sustainability of irrigated agriculture. To achieve this, adequate and accurate information on the magnitude and spatial distribution of soil salinity is required. The knowledge on the nature and properties of soils from pedological characterization studies is also vital in planning the best use and management of soils in crop production. Magozi Irrigation Scheme is one of the rice producing irrigation schemes with an area of 1300 ha in Iringa, Tanzania. The farmers of Magozi depend on rice production from this scheme as their main economic activity. Despite the importance of rice production in this irrigation scheme, the production yields are generally low where the average rice yields have been reported to be 3.05 t ha^{-1} while the potential yield in the area is 4.06 t ha^{-1}. There is no detailed study that has focused on addressing soil salinity problem in this irrigation scheme to understand the magnitude and its spatial distribution. This research assessed soil salinity and used GIS-based approach to predict spatial distribution of soil salinity. The study further recommends the soil, crop and irrigation management options that will contribute enhancement of sustainable rice production at Magozi Irrigation Scheme.

In order to understand the nature and properties of soils in this irrigation scheme, the first specific objective was a study on pedological characterization whereby three (3) representative soil profiles namely MAG-P1, MAG-P2 and MAG-P3 were opened and characterized for their soil morphological, physical and chemical properties. The soils were then classified to the family level using USDA Soil Taxonomy and to the Tier 2 in the World Reference Base for Soil Resources (WRB). The second specific objective focused on a study to develop a linear regression model that can be used to predict electrical conductivity of the saturated paste extract (EC_e) from values of electrical conductivity measured in soil to water suspension ($EC_{1:2.5}$). The EC_e is a globally used soil salinity index for assessing plant response to salinity. A total of 60 soil samples (45 samples for model training and 15 samples for model validation) were collected and analyzed for soil $EC_{1:2.5}$, EC_e and soil texture. A linear regression model relating EC_e and $EC_{1:2.5}$ was developed and validated for use in the next study. Lastly, the study assessed soil salinity and used GIS-based approach to predict spatial distribution of soil salinity in Magozi Irrigation Scheme. A total of 81 geo-referenced soil samples at a depth of 0 - 30 cm collected from the scheme were analyzed for soil physical and chemical properties where EC_e was used as the main soil salinity index. The soil salinity spatial distribution map of the scheme based on EC_e was generated using Inverse Distance Weighting (IDW) interpolation method in Geographic Information System (GIS).

The results on pedological characterization showed that the soils were moderately deep to very deep with vertic characteristics varying in degree of expression. Based on silt/clay ratios, the soils of Magozi Irrigation Scheme are relatively young with high degree of weathering potential. According to the USDA Soil Taxonomy, the soils were classified as *Typic Haplusterts* (MAG-P1), *Vertic Endoaquepts* (MAG-P3) and *Vertic Epiaquepts* (MAG-P3) while in WRB for Soil Resources they were classified as *Haplic Vertisols*, *Eutric Vertic Cambisols* and *Eutric Vertic Stagnic Cambisols* for MAG-P1, MAG-P2 and MAG-P3 respectively. The information from this study is crucial in planning the best use and management options of the soils of Magozi Irrigation Scheme.

The linear regression model $\mathbf{EC_e = 3.4954{*}EC_{1:2.5}}$ (R^2 = 0.956) was developed from the study which focused on relating EC_e with $EC_{1:2.5}$ to facilitate accurate soil salinity assessment in this area through predicting EC_e from $EC_{1:2.5}$ values. The results on soil salinity assessment study indicated that soil salinity in terms of EC_e ranged from non-saline (0.24 dS m^{-1}) to extremely saline (33.3 dS m^{-1}) with an EC_e mean of 2.5 dS m^{-1} being slightly saline. The mean EC_e value of 2.5 dS m^{-1} recorded in this area is high enough to cause 10 to 25 % crop yield reduction from the total yield. In terms of rice response to salinity and effects in its production, the mean EC_e value of 2.5 dS m^{-1} is very close to 3 dS m^{-1} which is the EC_e threshold for rice crop. The EC_e showed positive significant correlation at $p \leq 0.05$ significance level with soil Cl^- (r = 0.459), exchangeable Na (r = 0.341), ESP (r = 0.302) and SAR (r = 0.320).

The soil salinity spatial distribution map indicated that out of 1300 ha of the cultivated land, about 622.21 ha (47.86%) were slightly saline to extremely saline soils. This research work found that soil salinity is a growing land degradation problem in Magozi Irrigation Scheme. This may be due to poor soil and irrigation management practices as well as poor drainage structures leading to waterlogging problems which promote salt accumulation in the soil. Therefore, suitable irrigation, crop and soil management practices must be adopted by the farmers to reduce soil salinity development for sustainable rice production in the scheme. It is recommended that the farmers should be encouraged to adopt efficient rice farming technologies such as the system of rice intensification (SRI), improve irrigation drainage channels and adopt growing of salt tolerant rice varieties such as SATO 1 as well as use of inorganic and organic fertilizers.

DECLARATION

I, Daniel Porkalpo Isdory, do hereby declare to the Senate of Sokoine University of Agriculture, that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

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The above declaration is confirmed by;

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Prof. Balthazar M. Msanya Date

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Dr. Boniface H. J. Massawe Date

(Supervisor)

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I wish to dedicate this work to my beloved parents Pastor Porkalpo Isdory Mbalamwezi (Father) and Afra Kituta (Mother) and to my family.

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LIST OF ABBREVIATION AND SYMBOLS

Al	Aluminium
BD	Bulk Density
BS	Base Saturation
C:N	Carbon to Nitrogen ratio
Ca	Calcium
Ca^{2+}	Calcium ion
CEC	Cation Exchange Capacity
CEC_{clay}	Cation Exchange Capacity of clay
CEC_{soil}	Cation Exchange Capacity of soil
Cl^-	Chloride ion
cm	centimetre
$cmolkg^{-1}$	centimole (+) per kilogram
CO_3^{2-}	Carbonate ion
$dS\ m^{-1}$	deciSiemens per meter
EC	Electrical conductivity
$EC_{1:2.5}$	Electrical conductivity of the soil to water suspension
EC_a	Electrical conductivity measured on the bulk soil
EC_e	Electrical conductivity of the saturated paste extract
EC_w	Electrical Conductivity of water
ESP	Exchangeable Sodium Percentage
et al.	and others
FAO	Food and Agriculture Organization
Fe	Iron
g	gram
GDP	Gross Domestic Product

GIS	Geographic Information System
GPS	Global Positioning System
ha	hectare
HCO_3^-	Bicarbonate ion
IDW	Inverse Distance Weighting
IUSS	International Union of Soil Sciences
K^+	Potassium ion
kg	kilogram
m.a.s.l.	metres above sea level
MAG-P1	Magozi Irrigation Scheme Soil Profile Number 1
MAG-P2	Magozi Irrigation Scheme Soil Profile Number 2
MAG-P3	Magozi Irrigation Scheme Soil Profile Number 3
Mg^{2+}	Magnesium ion
mm	millimetre
MPa	megaPascals
MSc	Master of Science
N	Nitrogen
Na^+	Sodium ion
NO_3^-	Nitrate ion
O	Oxygen
^oC	Celsius centigrade
OC	Organic carbon
OK	Ordinary Kriging
OM	Organic Matter
P	Phosphorous
pH	Potential hydrogen
PR	Penetrometer Resistance

PSA	Particle Size Analysis
PTEs	Potentially toxic elements
r	Correlation coefficient
R^2	Coefficient of determination
RMSE	Root Mean Square Error
S	Sulfur
SAR	Sodium Adsorption Ratio
Si	Silicon
SMR	Soil Moisture Regime
SO_4^{2-}	Sulphate ion
SRI	System of Rice Intensification
STR	Soil Temperature Regime
SUA	Sokoine University of Agriculture
t	tonne
TDS	Total Dissolved Solids
TEB	Total Exchangeable Bases
Ti	Titanium
TN	Total Nitrogen
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
WRB	World Reference Base for Soil Resources
XRF	X-Ray Fluorescence

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background Information

Rice (*Oryza sativa* L.) plays an important role in improving household food security and national economies in Sub-Saharan Africa including Tanzania (Nhamo *et al.,* 2014; Mtengeti *et al.,* 2015). However, rice production in the region, including Tanzania, is generally low due to production constraints such as poor agronomic practices, climate change and soil degradation among other factors (Nhamo *et al.,* 2014; Rugumamu, 2014). There has been an increase in annual per capita consumption of rice in Tanzania from 20.5 kg year^{-1} in 2001 to about 25 - 30 kg year^{-1} in 2011 coupled with an increase in human population (Mghase *et al.,* 2010; Katambara *et al.,* 2013). This increase in rice consumption has led to a growing gap between the demand and supply of rice which has to be filled by increasing rice production in the country or through imports (Mghase *et al.,* 2010).

The current rice production in Tanzania is still as low as 2.3 t ha^{-1} due to various production constraints such as land degradation while the potential rice yields are between 4 to 10 t ha^{-1} (Mtengeti *et al.,* 2015). Rice production can be improved by using existing production technologies such as irrigation farming (Mghase *et al.,* 2010; Nhamo *et al.,* 2014; Kashenge-Killenga *et al.,* 2016; Mdemu *et al.,* 2017) to avoid depending on rainfed agriculture which is associated with frequent crop failures.

Improving rice production in Tanzania will contribute significantly in enhancing food security, incomes of the farmers and the national economy by exporting the surplus (Katambara *et al.,* 2013; Kahimba *et al.,* 2013). However, increasing rice production in

Tanzania requires addressing a number of challenges including land degradation issues in the crop growing areas (Katambara *et al.,* 2013; Kashenge-Killenga *et al.,* 2014). Soil salinity which refers to the excess content of soluble salts in the soil is one of the land degradation problems in many rice irrigation schemes in Tanzania (Kashenge-Killenga *et al.,* 2013; Kashenge-Killenga *et al.,* 2014; Kashenge-Killenga *et al.,* 2016). The land degradation due to soil salinity has also been associated with low rice yields in Tanzania especially from the irrigated areas which are very prone to this problem (Kashenge-Killenga *et al.,* 2013).

Soil salinity, especially in arid and semi-arid regions of the world, is one of the most crucial environmental problems because of its adverse effects on agricultural productivity and sustainable development (Amezketa, 2006; Gorji and Sertel, 2015). Therefore, there is a need to address the problem of soil salinity in order to enhance and sustain rice productivity in Tanzania, hence improving food security and incomes of farmers. For effective management options development, adequate and accurate information on the magnitude and spatial distribution of soil salinity is required (Bannari *et al.,* 2008; Shahabi *et al.,* 2017).

However, conventional soil salinity risk identification and management methods have disadvantages and limitations in spatial data analysis and often provide an inadequate description of the problem, time consuming, costly since dense sampling is required to adequately characterize the spatial variability of an area and demanding when considering large areas (Shafiq *et al.,* 2001; Dinh *et al.,* 2018). The Geographical Information System (GIS) based approaches for predicting the spatial distribution of soil salinity is a promising method widely accepted in current literature with advantages over conventional methods in time saving, wide range of coverage as well as facilitation of faster and long term monitoring (Shahabi *et al.,* 2017; Zewdu *et al.,* 2017).

Magozi Irrigation Scheme is one of the rice producing schemes in Iringa Region (Mdemu *et al.,* 2017), currently as one of the major economic activities in Magozi area (Mziray *et al.*, 2015; Mdemu *et al.*, 2017). However, production levels are still low with the average rice yields reported by Mdemu *et al.* (2017) to be 3.05 t ha^{-1} as compared to the potential yield of 4.06 t ha^{-1}. Soil salinity development in some parts of the scheme has been reported by farmers and extensionists as one of the land degradation processes taking place in the area (Mziray *et al.,* 2015; Matimbwa, A. personal communication, 2017). However, there is no study on detailed soil salinity assessment in the scheme. Furthermore, although pedological characterization is a tool for understanding the soils and their best use and management (Msanya *et al.*, 2003), no such study on soil characterization ever done in this scheme.

Therefore the pedological characterization of the soils was carried out in order to generate soil information useful for sustainable soil use and management in Magozi Irrigation Scheme. The linear regression model was used to predict electrical conductivity of the saturated paste extract (EC_e) from values of electrical conductivity measured in soil to water suspension ($EC_{1:2.5}$) for facilitating accurate soil salinity assessment in the scheme. Finally, the study carried out soil salinity assessment and by using GIS software, the spatial distribution of soil salinity was predicted. This study recommended the soil, crop and water management strategies that will enhance and sustain rice production at Magozi Irrigation Scheme.

1.2 Problem Statement and Justification

Managing soil salinity in irrigated agriculture is crucial for minimizing its negative environmental effects and for ensuring the long-term sustainability of crop production (Abbas *et al.,* 2013). To achieve this, adequate and accurate information on the magnitude and spatial distribution of soil salinity is required (Bannari *et al.,* 2008; Shahabi *et al.,* 2017). Magozi Irrigation Scheme is one of the rice producing schemes with an area of 1300 ha in Iringa, Tanzania with about 578 farmers depending on rice production as their main economic activity (Mziray *et al.,* 2015; Mdemu *et al.,* 2017). Despite the importance of rice production in this irrigation scheme, the yields are low where the average rice yield reported by Mdemu *et al.* (2017) is 3.05 t ha^{-1}, while the potential yield as reported by Mdemu *et al.* (2017) is 4.06 t ha^{-1}.

Soil salinity development in some parts of the scheme following land use change from non-irrigated annual crop production to irrigated rice farming is currently a concern among farmers and agricultural extensionists (Mziray *et al.,* 2015; Matimbwa, A. personal communication, 2017). However, there is no detailed study on addressing soil salinity problem in this irrigation scheme. Therefore, a critical study on the extent and magnitude of this problem to sustain rice production is of paramount importance. Moreover, there is no study on understanding the nature and properties of soils in this area through pedological characterization. This research assessed soil salinity and used GIS software to predict spatial distribution of soil salinity and proposed the soil management options to enhance sustainable rice production at Magozi Irrigation Scheme, Iringa, Tanzania. Also, as part of this research work, pedological characterization has been conducted to understand and generate information on the nature and properties of soils of Magozi Irrigation Scheme.

1.3 Objectives

1.3.1 Overal objective

The overall objective of this research was to assess and predict spatial distribution of soil salinity at Magozi Irrigation Scheme and identify soil management options for sustainable rice production.

1.3.2 Specific objectives

The specific objectives of this work were:

i. To characterize soil morphological, physical and chemical properties and classify soils of Magozi Irrigation Scheme using USDA Soil Taxonomy and World Reference Base for Soil Resources.
ii. To develop a linear regression model that can be used to predict electrical conductivity of the saturated paste extract (EC_e) from values of electrical conductivity measured in soil to water suspension ($EC_{1:2.5}$).
iii. To assess and predict spatial distribution of soil salinity in Magozi Irrigation Scheme using GIS-based Inverse Distance Weighting (IDW) interpolation method.
iv. To recommend soil management options based on the results for rice production sustainability in the scheme.

1.4 Organization of the Dissertation

Chapter one is about general introduction, providing the study theoretical background information as well as introducing the problem statement and justification of the study. Also, this chapter has provided the general and specific objectives of the study. Chapter two covers general literature review on aspects related to rice production in Tanzania and a review of soil salinity and its effects in rice production.

Chapter three presents a pedological study that characterized soil morphological, physical and chemical properties and classification of soils of Magozi Irrigation Scheme using both USDA Soil Taxonomy and World Reference Base for Soil Resources classification systems. Chapter four addresses the study which developed a linear regression model that can be used to predict electrical conductivity of the saturated paste extract (EC_e) from values of electrical conductivity measured in soil to water suspension ($EC_{1:2.5}$). This model was used in Chapter five to predict EC_e from $EC_{1:2.5}$ values for accurate assessment of soil salinity.

Chapter five is about assessment and prediction of spatial distribution of soil salinity in Magozi Irrigation Scheme using GIS approach. Chapter six covers general conclusions and recommendations drawn from the entire study. The issues addressed in this part include the information on pedological characteristics of the soils of Magozi Irrigation Scheme, the linear regression model that can be used to predict EC_e from $EC_{1:2.5}$ values and soil salinity spatial distribution and its implications in soil, crop and irrigation management for enhancing rice production sustainability in the area.

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CHAPTER TWO

2.0 GENERAL LITERATURE REVIEW

2.1 Rice Production in Tanzania

2.1.1 Rice Plant

Rice (*Oryza sativa* L.) is a crop plant described as an annual grass with round, hollow, jointed culms; narrow, flat, sessile leaf blades joined to the leaf sheaths with collars; well-defined, sickle-shaped, hairy auricles; small acute to acuminate or two cleft ligules and terminal panicles (Moldenhauer and Slaton, 2001; Itoh *et al.,* 2005). The life cycle of rice cultivars ranges from 110 to 150 days from germination to maturity, depending on the variety and the environment (Moldenhauer and Slaton, 2001; Katambara *et al.,* 2013). The general rice growth phases are germination, vegetative, reproductive and ripening phases (Moldenhauer and Slaton, 2001; Itoh *et al.,* 2005; Gholizadeh and Navabpour, 2011). Fig. 2.1 adopted from Itoh *et al.* (2005) is a general schematic representation of a mature rice plant.

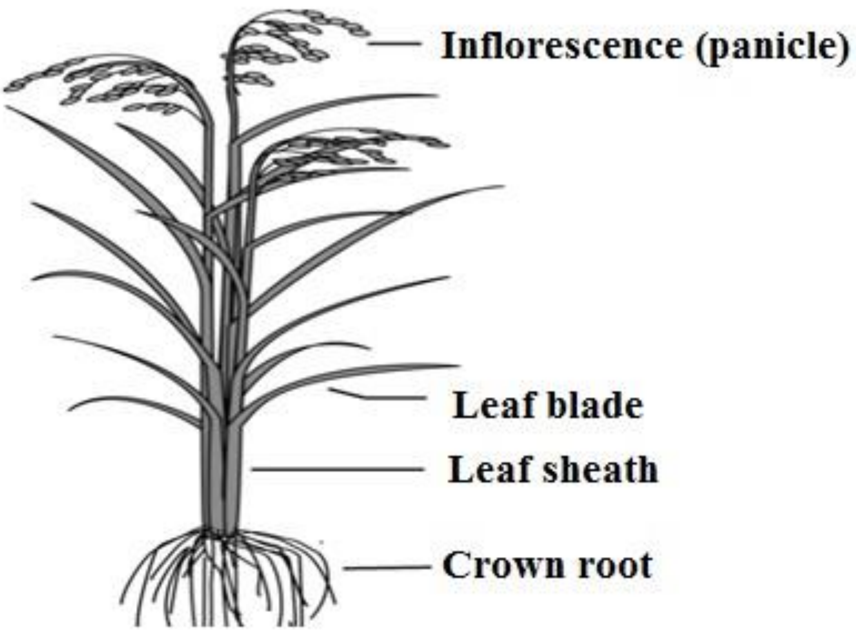

Figure 2.1: Schematic representation of a mature rice plant (Itoh *et al.,* 2005)

2.1.2 Status of Rice Production in Tanzania

Tanzania's economy continues to be dominated by agricultural production, which accounts for more than 50% of GDP (Michael *et al.,* 2014). Therefore, enhanced agricultural productivity is crucial in any national economic strategy to combat poverty (Leyaro and Morrissey, 2013; Michael *et al.,* 2014) by enhancing food security and incomes of farmers in the country. Rice is one of the major staple food and cash crops grown in Tanzania (Michael *et al.,* 2014; Massawe, 2015; Mtengeti *et al.,* 2015) and constitutes 13% of total food production in the country (Mtengeti *et al.,* 2015). According to the report by Barreiro-Hurle, (2012), rice production in Tanzania covers approximately 681 000 ha, representing 18 percent of cultivated land. Generally, about 90 % of all rice in the country is grown by smallholder farmers (Barreiro-Hurle, 2012).

Rice is grown in different areas in Tanzania mainly within three ecosystems; rain fed lowlands (68%), rain fed uplands (20%) and irrigated rice (12%) (Barreiro-Hurle, 2012). Mtengeti *et al.* (2015) reported that the current rice productivity in Tanzania is still as low as 2.3 t ha^{-1} while the potential rice yields are between 4 to 10 t ha^{-1}. This production level is not matching with the increasing demand for food due to population growth unless there is an expansion of cultivated land or intensification measures are imparted to smallholder farmers, who produce nearly 90% of most crops in the country (Mtengeti *et al.,* 2015). However, expansion of cropped areas is currently being limited by increased land pressure and human population increase (Mtengeti *et al.,* 2015).

The situation of rice production in Tanzania is largely similar to that of Africa as a whole where rice yield is stagnant while arable land per agricultural population is declining due to rapid population growth and accelerated land degradation (United Republic of Tanzania 2009; Kashenge-Killenga *et al.,* 2013; Massawe, 2015; Nakano and Kajisa, 2013). Soil salinity is one of the major global land degradation aspects limiting crop production such as rice in different parts of the world including Tanzania (Kashenge-Killenga *et al.,* 2013; Hoang *et al.,* 2016). Therefore, increasing rice yield per unit area by addressing some production challenges such as soil salinity is critical for increased production (Kashenge-Killenga *et al.,* 2013; Nakano and Kajisa, 2013).

2.2 Soil Salinity and its Effects in Crop Production

2.2.1 Meaning of Soil Salinity and Salt-affected Soils

Salinity is a general term used to describe the presence of excessive levels of different salts such as sodium chloride, magnesium and calcium sulphates and bicarbonates in soil and water (Hoang *et al.,* 2016). It refers to the total salt concentration in the soil solution (the aqueous liquid phase of the soil and its solutes) consisting of soluble and readily dissolvable salts including charged species such as Na^+, K^+, Mg^{2+}, Ca^{2+} cations; Cl^-, HCO_3^-, NO_3^-, SO_4^{2-} and CO_3^{2-} anions; non-ionic solutes and ions that combine to form ion pairs (Hardie and Doyle, 2012; Corwin and Lesch, 2013; Corwin and Yemoto, 2017).

Other literatures describe soil salinity as the presence or content of soluble salts in soil or soil water at levels that adversely affect plant growth (Rengasamy, 2006; Hardie and Doyle, 2012; Asfaw *et al.,* 2018). All soils contain some soluble salts, but when soil and environmental conditions allow the concentration of such salts in soil layers to rise to a level that negatively impact agricultural production, environmental health and economic welfare, then soil salinity becomes an issue of land degradation (Rengasamy, 2006; Naifer *et al.,* 2011; Allbed and Kumar, 2013; Salih *et al.,* 2014).

Generally, the main sources of soluble salts in the soil include mineral weathering, rainfall, poor irrigation and various surface waters, groundwater which redistributes accumulated salts during evaporation and anthropogenic activities (Rengasamy, 2006; Aguilar *et al.,* 2017; Corwin and Yemoto, 2017). According to Corwin and Yemoto (2017), geochemical weathering of rocks from the earth's upper strata is considered as the primary source of salts in soil and water while atmospheric deposition and anthropogenic activities such as poor irrigation serve as secondary sources. The types and relative importance of the different ions that contribute to soil salinity can be studied by determining the soluble anion and cation concentrations of soil water extracts by approaches such as flame-atomic absorption spectroscopy, colorimetric methods, ion chromatography and titrimetric methods (Hardie and Doyle, 2012; Corwin and Yemoto, 2017).

In many literatures, the term 'salinity' is used to describe salt-affected soils (Rengasamy, 2006). Soil salinization is the process of enrichment of soil with soluble salts that result in the formation of salt-affected soil (Rengasamy, 2006; Zinck and Metternicht, 2009; Li *et al.*, 2014; Asfaw *et al.*, 2018). This process results to the accumulation of water-soluble salts in the soil solum or regolith to a level that negatively impact agricultural production, environmental health and economic welfare (Rengasamy, 2006). Soil salinization is a serious environmental problem that can be caused by natural or human activities (Li *et al.,* 2014). Primary salinization is a natural phenomenon involving accumulation of salts through natural processes due to high salt contents in parent materials or ground water (Rengasamy, 2006; Yuan *et al.,* 2007; Li *et al.,* 2014). Secondary salinization occurs frequently mainly as a result of over irrigation caused by poor irrigation practices, improper management of irrigation facilities, poor soil internal drainage condition and unsuitable quality of irrigation water (Rengasamy, 2006; Yuan *et al.*, 2007; Li *et al.*, 2014).

The process of evapotranspiration causes accumulation of salts in the root zone of agricultural soils. This is because evapotranspiration selectively removes water, leaving salts behind (Corwin and Yemoto, 2017). Furthermore, soil salinity can accumulate as a consequence of poor irrigation water quality; poor drainage due to a high water table or low soil permeability; topographic effects where an upslope recharge results in a downslope discharge of salts (Corwin and Lesch, 2013; Corwin and Yemoto, 2017); saltwater spills associated with oil field activities; high rates of manure and sludge applications and seawater intrusion in coastal areas.

Although soil salinity can occur in almost all climatic conditions (Salih *et al.,* 2014), this problem is particularly more common in arid and semi-arid regions, where precipitation is too low to maintain a regular percolation of rainwater through the soil which causes accumulation of soluble salts in the soil (Qadir *et al.,* 2000; Eynard *et al.,* 2005). In arid and semi-arid regions, there is intense evaporation which tends to accumulate salts in the upper soil profile, especially when it is associated with an insufficient leaching or where soluble salts move upward in the soil profile from a water table instead of downward (Qadir *et al.,* 2000; Makoi and Ndakidemi, 2007). Therefore, soil salinity is a crucial soil chemical property for soil health and quality that is routinely measured and monitored due to its impact on agriculture (Corwin and Yemoto, 2017).

2.3 General Impacts of Soil Salinity in Agricultural Crop Production

Salt accumulation in the root zone (soil salinity) has a variety of negative effects in agricultural crop production (Arora, 2017; Corwin and Yemoto, 2017). It has been found that salts in the root zone can reduce plant growth, reduce yields and in severe cases, cause crop failure (Zhu, 2001; Allbed and Kumar, 2013; Aguilar *et al.,* 2017; Corwin and Yemoto, 2017). It has also been observed that increased soil salinity affects soil microbiological activities (Yuan *et al.,* 2007; Wong *et al.,* 2008; Egamberdieva *et al.,* 2010). Therefore, growth and yield reduction of crops is a serious issue in salinity prone areas of the world (Makoi and Ndakidemi, 2007; Ashraf, 2009; Haq *et al.,* 2009; Aguilar *et al.,* 2017).

2.3.1 Main effects of Salinity in Crops

Generally, there are two main effects of salinity on crops or the combination of these, where the first is the osmotic (total soluble salt) effect and the second is the specific ion effect (Hamza, 2008). The soluble salts change the osmotic potential of soil solution (Hamza, 2008; Kashenge-Killenga *et al.,* 2013; Corwin and Yemoto, 2017) and therefore, in the osmotic effect, the plant roots' ability to absorb water decreases with increasing soil salinity (Hamza *et al.,* 2007; Corwin and Yemoto, 2017) then stops altogether when the osmotic potential equals that inside the plant root (Hamza *et al.,* 2007; Hamza, 2008). If salinity of soil solution increases further, water moves along a water potential gradient from the root to the soil and roots start shrinking (Hamza *et al*., 2006; Hamza, 2008) which may lead to total crop failure due to lack of water.

Soil salinity may also cause specific ion effect or toxicity which upsets the nutritional balance of plants (Corwin and Yemoto, 2017) due to the increasing effect in the content of exchangeable ions from soluble salts (Hamza, 2008; Kashenge-Killenga *et al.,* 2013). Ions such as Na^+, Cl^-, $H_4BO_4^-$ and HCO_3^-, are quite toxic to many crops when they exist in high concentration (Brady and Weil, 2002; Hamza, 2008). Also, the composition of the salts in the soil solution influences the composition of cations on the exchange complex of soil particles, which subsequently influences soil permeability and tilth (Corwin and Yemoto, 2017). For example, Na^+ causes soil dispersion and during plant uptake, it competes with K^+ in the transport process across the cell membrane (Brady and Weil, 2002).

Furthermore, soil salinity impacts extend to the economy (Naifer *et al.*, 2011; Allbed and Kumar, 2013). According to Naifer *et al.* (2011), the economic losses due to crop loss in Batinah region in Oman due to secondary salinization have been estimated at US$ 1604 ha^{-1} (28%) when the salinity increases from low to medium level and US$ 4352 ha^{-1} (76%) if it jumps from low to high level.

2.3.2 Effects of soil salinity in rice plant growth and development

Soil salinity is an ever increasing problem that reduces rice yield in many fields around the world (Shereen *et al.,* 2005; Sankar *et al.,* 2011; Mohammadi-Nejad *et al.,* 2012; Dolo, 2018). Therefore, salinity is considered as one of important physical factors influencing rice (*Oryza sativa* L.) production (Haq *et al.,* 2009; Mohammadi-Nejad *et al.,* 2012). Knowledge of salinity effects on rice plant growth and yield components can improve management practices in fields as well as increase our understanding of salt tolerance mechanisms in rice (Zeng and Shannon, 2000; Shereen *et al.,* 2005; Mohammadi-Nejad *et al.,* 2012).

2.3.2.1 Rice sensitivity and response to salinity

Rice plant is highly susceptible to the rhizosphere salinity than other cereals (Grattan *et al.,* 2002; Gholizadeh and Navabpour, 2011; Hussain *et al.,* 2017). The rice plant has been rated as a salt sensitive plant (Shereen *et al.*, 2005; Mohammadi-Nejad *et al.,* 2012; Flowers *et al.,* 2014; Aguilar *et al.,* 2017; Dolo, 2018) and is the most salt sensitive cereal crop with an EC_e threshold of 3 dS m^{-1} for most cultivated varieties (Zeng *et al.,* 2001; Grattan *et al.,* 2002; Flowers *et al.,* 2014; Hoang *et al.,* 2016). Even at EC_e as low as 3.5 dS m^{-1}, rice loses about 10% of its yield (Hoang *et al.,* 2016). Rice yield loss of 50% was recorded at EC_e 7.2 dS m^{-1} as reported by Umali (1993).

Salinity affects all stages of the growth and development of rice plant but its response to salinity varies with growth stages, salt concentration and duration of exposure to salt (Grattan *et al.,* 2002; Hoang *et al.,* 2016). Many studies have reported that most commonly cultivated rice varieties are tolerant to salinity during germination, but become very sensitive during early seedling (Grattan *et al.,* 2002; Shereen *et al.,* 2005; Gholizadeh and Navabpour, 2011; Mohammadi-Nejad *et al.,* 2012; Hussain *et al.,* 2017). It again becomes more tolerant during vegetative growth with the sensitivity returning again during pollination and fertilization stages and finally it again becomes more tolerant at maturity (Grattan *et al.,* 2002; Gholizadeh and Navabpour, 2011; Hussain *et al.,* 2017). Symptoms of salt toxicity in rice include firing of leaves and reduced dry matter production (Zeng *et al.,* 2001; Grattan *et al.,* 2002).

It has been indicated that grain yield is adversely affected by salt than the vegetative growth (other than that of very young seedlings) (Zeng *et al.,* 2001). Rice yield comprises many components and these yield components are related to final grain yield which also have been reported to be severely affected by salinity (Zeng *et al.,* 2001). For example, panicle lengths, spikelets per panicle, number of tillers, grain weight and floret sterility are significantly affected by salinity hence reducing the final yield (Zeng *et al.,* 2001; Grattan *et al.,* 2002; Aguilar *et al.,* 2017).

2.4 Soil Salinity Measurements

Soil salinity problem in soil is commonly evaluated by laboratory testing of various soil salinity indices such as electrical conductivity (EC), total dissolved solids (TDS), soil pH, sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) (US Salinity Laboratory Staff, 1954; Rhoades and Chanduvi, 1999; Horneck *et al.,* 2007; Corwin and Yemoto, 2017). The following laboratory measurements are made on such indices in order to assess soil salinity problem:

2.4.1 Electrical Conductivity (EC)

This is the main global soil salinity index which measures the ability of the soil solution to conduct electricity and is commonly expressed in decisiemens per meter (dS m^{-1}) (Horneck *et al.,* 2007; Sonmez *et al.,* 2008; Corwin and Yemoto, 2017). Due to the fact that pure water is a poor conductor of electricity, increases in soluble salts result in proportional increases in the solution EC (US Salinity Laboratory Staff, 1954; Sonmez *et al.,* 2008; Corwin and Yemoto, 2017). The more salts in the soil solution, the greater the EC reading, and the greater the toxicity to plants (US Salinity Laboratory Staff, 1954; Kargas *et al.,* 2018; Corwin and Yemoto, 2017).

The standard procedure for soil salinity testing is to measure EC of a solution extracted from a soil wetted to a saturation paste (US Salinity Laboratory Staff, 1954; Rhoades and Chanduvi, 1999; Sonmez *et al.,* 2008). The EC measured by saturated paste extract standard method is known as electrical conductivity of the saturated paste extract (EC_e). Apart from the standard saturated paste extract method, an EC maybe measured on the bulk soil (EC_a), in various soil to water ratio suspensions of 1:1 to 1:5 such as 1:1, 1:2, 1:2.5 and 1:5 or directly on soil water extracted from the soil in the field (EC_w) (US Salinity Laboratory Staff, 1954; Sonmez *et al.,* 2008; Corwin and Yemoto, 2017; Kargas *et al.,* 2018).

According to U.S. Salinity Laboratory Staff (1954), a saline soil has an EC of the saturated paste extract (EC_e) of more than 4 dS m^{-1}, a value that corresponds to approximately 40 mmol salts per litre. Crops vary in their tolerance to salinity and some may be adversely affected at EC values less than 4 dS m^{-1}. For example, rice plant is rated as a salt sensitive crop with an EC_e threshold of 3 dS m^{-1} for most cultivated varieties (Shereen *et al.,* 2005; Mohammadi-Nejad *et al.,* 2012; Hoang *et al.,* 2016;

Aguilar *et al.,* 2017; Dolo, 2018). Soil salinity is most commonly classified based on electrical conductivity values of the saturated paste extract (EC_e) (Richard, 1954; Rhoades and Chanduvi, 1999; Bannari *et al.,* 2008) as described in Table 2.1. This classification is also known as agronomic soil salinity classification and it provides the potential salinity effects on crops (Richard, 1954; Rhoades and Chanduvi, 1999).

Table 2.1: Soil salinity classes based on EC_e (Richard, 1954; Rhoades and Chanduvi, 1999; Bannari *et al.,* 2008)

EC_e (dS m^{-1})	Salinity class	Salinity effects on crops
0 - 2	Non-saline	Salinity effects are negligible
2 - 4	Slightly saline	Yields of very sensitive crops may be restricted
4 - 8	Moderately saline	Yields of many crops restricted
8 - 16	Very saline	Only tolerant crops yield satisfactory
> 16	Extremely saline	Only a few very tolerant crops yield satisfactorily

2.4.2 Total Dissolved Solids (TDS)

This measurement provides similar information as EC, but it is based on an evaporative test (Rhoades and Chanduvi, 1999; Shirokova *et al.,* 2000). TDS results are expressed in milligrams per liter (mg L^{-1}) (Rhoades and Chanduvi, 1999; Shirokova *et al.,* 2000; Muyen *et al.,* 2011). However, this measurement has been largely replaced by the EC test partly due to higher costs associated with the laboratory TDS measurements (Rhoades and Chanduvi, 1999; Shirokova *et al.,* 2000; Muyen *et al.,* 2011).

The literatures show that linear relationship exists between TDS and EC within a certain range that can be useful to closely estimate soluble salts in a soil solution or extract (Rhoades and Chanduvi, 1999; Shirokova *et al.,* 2000). Therefore, it has been established that, TDS can be estimated by multiplying the EC_e (dS m^{-1}) of lesser saline samples by

640 (Rhoades and Chanduvi, 1999; Shirokova *et al.*, 2000; Grattan, 2002) or the EC_e of very saline samples by 800 (Grattan, 2002) as shown in the following equations respectively:

$$TDS\ (mg\ L^{-1}) = EC_e\ (dS\ m^{-1}) \times 640 \text{ for lesser saline soil samples} \quad (1)$$

$$TDS\ (mg\ L^{-1}) = EC_e\ (dS\ m^{-1}) \times 800 \text{ for very saline soil samples} \quad (2)$$

where TDS is the Total Dissolved Solids in mg L^{-1} and EC_e is the electrical conductivity of the saturated paste extract in dS m^{-1}.

2.4.3 Soil pH

Soil pH is a measure of the hydrogen ion concentration in soil solution (Brady and Weil, 2008). Soluble salts affect soil pH and vice versa, thus soil pH is often included in evaluations and discussions of soil salinity (US Salinity Laboratory Staff, 1954; Brady and Weil, 2008; Hardie and Doyle, 2012). Decreasing the soil pH increases the solubility of soluble bases and basic salts such as $CaCO_3$ while increasing the pH decreases their solubility which may lead to salt accumulation in soil (Brady and Weil, 2008; Hardie and Doyle, 2012). The main implication of changing the soil pH is its influence on plant nutrient availability and soil microbial activity (Brady and Weil, 2008).

2.4.4 Sodium Adsorption Ratio (SAR)

Sodicity is a measure of the excess sodium in a soil which imparts a poor physical condition to the soil (Eynard *et al.,* 2005; Valipour, 2014). The term ‘sodicity’ is connected to salinity but has a special feature of having high concentrations of sodium (Na^+) ions in the solution (Valipour, 2014; Abou-Baker and El-Dardiry, 2015). Sodium adsorption ratio (SAR) is an index used to express the proportion of Na^+ concentration relative to the proportions of Ca^{2+} and Mg^{2+} concentration in soil solution (Qadir and

Oster, 2004; Valipour, 2014; Abou-Baker and El-Dardiry, 2015). It is a widely accepted index for characterizing soil sodicity and therefore, it is used to assess sodium hazard in soil or irrigation water (Qadir and Oster, 2004; Eynard *et al.*, 2005; Abou-Baker and El-Dardiry, 2015). SAR is unitless because it is a ratio of two same concentration units (Qadir and Oster, 2004). It is computed using the following formula where concentrations of Na^+, Ca^{2+} and Mg^{2+} are expressed in $cmol_{(+)}kg^{-1}$) (Qadir and Oster, 2004):

$$SAR = Na^+ / [(Ca^{2+} + Mg^{2+})/2]^{0.5} \quad (3)$$

where SAR is the Sodium Adsorption Ratio.

According to the literatures, when SAR is greater than 13, the soil is called a sodic soil (US Salinity Laboratory Staff, 1954; Siyal *et al.*, 2002; Eynard *et al.*, 2005). Excess sodium in sodic soils causes soil particles to repel each other, preventing the formation of soil aggregates (Siyal *et al.*, 2002; Eynard *et al.*, 2005). This causes a tight soil structure with poor water infiltration, poor aeration and surface crusting, making tillage difficult and restricts seedling emergence and crop root growth (Shirokova *et al.*, 2000; Eynard *et al.*, 2005; Abou-Baker and El-Dardiry, 2015).

2.4.5 Exchangeable Sodium Percentage (ESP)

Exchangeable sodium percentage (ESP) refers to the percentage of soil exchange sites occupied by sodium ions (Na^+) (Ibrakhimov *et al.*, 2007; Eynard *et al.*, 2005). It is another soil salinity index used to measure soil sodicity and expressed in percentage (%) (US Salinity Laboratory Staff, 1954; Qadir and Oster, 2004; Eynard *et al.*, 2005; Valipour, 2014). ESP is calculated by dividing the concentration of Na^+ ($cmolkg^{-1}$) cations by the total cation exchange capacity (CEC) in $cmolkg^{-1}$ (Ibrakhimov *et al.*, 2007; Valipour, 2014) by using the following formula:

$$ESP (\%) = (Na^{+}/ CEC) \times 100 \quad (4)$$

where ESP is the Exchangeable Sodium Percentage.

According to US Salinity Laboratory Staff (1954), soil is characterized as sodic when it has an ESP greater than 15. The ESP can be used to determine gypsum requirement for management of sodium-affected soils (Abou-Baker and El-Dardiry, 2015). It has been established that ESP is used to characterize the sodicity of soils only, whereas SAR is applicable to both soil and soil solution or irrigation water (US Salinity Laboratory Staff, 1954; Qadir and Oster, 2004; Eynard *et al.*, 2005; Abou-Baker and El-Dardiry, 2015).

2.5 Formation of Salt-affected Soils

Salt-affected soils refers to soils with substantial enough salt concentrations that affect plant health, soil properties, water quality and other land and soil resource uses (Siyal *et al.*, 2002; Ali, 2011). It is also regarded by other scholars (Ali, 2011; Hardie and Doyle, 2012) as the general term used for soils which contain soluble salts or exchangeable sodium (sodicity) and or both, in such amounts that can retard plant growth and development. Driving forces for natural salt affected soils are climate, rock weathering, ion exchange, and mineral equilibria reactions that ultimately control the chemical composition of soil and water (Siyal *et al.*, 2002; Hardie and Doyle, 2012). Usually, where evapotranspiration is greater than precipitation, downward water movement is insufficient to leach solutes out of the soil profile leading to salts precipitation (Ali, 2011; Hardie and Doyle, 2012).

2.5.1 Types of salt-affected soils

The various sources of soluble salts in the soil, coupled with environmental modifications, lead to three different types of salt-affected soils that are grouped so for management purposes which are: saline soils, saline-sodic soils and sodic soils (Siyal *et* *al.*, 2002; Makoi and Ndakidemi, 2007). The general chemical properties of salt-affected soils according to the literature (Siyal *et al.*, 2002; Eynard *et al.*, 2005; Makoi and Ndakidemi, 2007) are as summarized in Table 2.2.

Table 2.2: General chemical properties of salt-affected soils (Siyal *et al.*, 2002; Eynard *et al.*, 2005; Makoi and Ndakidemi, 2007)

Type of salt-affected soil	EC_e (dS m^{-1})	ESP (%)	SAR	Soil pH
Saline	> 4.0	< 15	< 13	< 8.5
Sodic	< 4.0	> 15	> 13	> 8.5
Saline-Sodic	> 4.0	> 15	> 13	< 8.5

2.5.1.1 Saline soils

The predominant exchangeable cations in saline soils are calcium and magnesium (Siyal *et al.*, 2002; Waskom *et al.*, 2003; Ali, 2011; Arora, 2017). Commonly these soils have visible salt deposits on the surface and are sometimes called white alkali soils (Siyal *et al.*, 2002; Ali, 2011). Salts in soil solution have a positive effect on soil structure (flocculation) and water infiltration (Siyal *et al.*, 2002; Eynard *et al.*, 2005; Ali, 2011). Saline soils are further categorized as non-saline (0-2 dS m^{-1}), slightly saline (2-4 dS m^{-1}), weakly saline (4-8 dS m^{-1}), moderately saline (8-15 dS m^{-1}) and strongly saline (>15 dS m^{-1}) (Moore, 2001).

2.5.1.2 Sodic soils

Sodic soils contain sufficient exchangeable sodium as compared to calcium and magnesium to interfere with the growth of the majority of crop plants (Makoi and Ndakidemi, 2007; Ali, 2011). As the proportion of exchangeable Na^+ increases, the soil tends to become dispersed and less permeable to water (Siyal *et al.*, 2002; Eynard *et al.*, 2005). These soils are usually plastic and sticky when wet and form large clods on drying (Siyal *et al.*, 2002; Makoi and Ndakidemi, 2007) and they are difficult to manage for cropping (Waskom *et al.*, 2003).

The crusting tendency is a hazard to seedling emergence and accounts for a poor stand of crops hence reducing crop yield (Siyal *et al.*, 2002; Ali, 2011). They often have a black color due to dispersion of organic matter and a greasy or oily-looking surface with little or no vegetative growth. These soils have been called black alkali (Siyal *et al.*, 2002; Eynard *et al.*, 2005; Ali, 2011). Maintaining the productivity of sodic soils requires control of the flocculation-dispersion behavior of the soil (Makoi and Ndakidemi, 2007; Horneck *et al.*, 2007).

2.5.1.3 Saline-sodic soils

The saline-sodic soils are high in sodium and other salts (Rhoades and Chanduvi, 1999; Siyal *et al.*, 2002; Qadir and Oster, 2004). They can have the characteristics of either a saline or sodic soil, depending on whether sodium or calcium dominates (Rhoades and Chanduvi, 1999; Qadir and Oster, 2004; Horneck *et al.*, 2007). Generally, they have good soil structure and adequate water movement through the soil profile than sodic soils (Siyal *et al.*, 2002; Horneck *et al.*, 2007).

2.5.2 Pedological classification of salt-affected soils in the USDA Soil Taxonomy and World Reference Base for Soil Resources (WRB) Systems

2.5.2.1 Saline soils in USDA Soil Taxonomy and WRB soil classification systems

A salic horizon is used as a diagnostic horizon by both systems in pedological classification of saline soils (Msanya, 2003; Soil Survey Staff, 2014; IUSS Working Group WRB, 2015). A salic horizon is a surface horizon or a subsurface horizon at a shallow depth that contains high amounts of readily soluble salts, that is salts more soluble than gypsum ($CaSO_4 \cdot 2H_2O$ at 25 °C) (IUSS Working Group WRB, 2015). A salic horizon has at some time of the year an electrical conductivity of the saturation extract (EC_e) at 25 °C of $\geq$ 15 dS m^{-1} or $\geq$ 8 dS m^{-1} if the pH_{water} of the saturation extract is ≥ 8.5 and at some time of the year a product of thickness (in centimeters) and EC_e (dS m^{-1}) at 25 °C of ≥ 450; and a thickness of ≥ 15 cm (Msanya, 2003; IUSS Working Group WRB, 2015).

According to IUSS Working Group WRB (2015), Solonchaks is a name at a reference group level given to soils with high concentration of soluble salts at some time in the year. Solonchaks are largely confined to the arid and semi-arid climate zones and to coastal regions in all climates (IUSS Working Group WRB, 2015). The common international names for solonchaks are Saline soils and Salt-affected soils (IUSS Working Group WRB, 2015). Solonchaks corresponds to Salids at the suborder level of the USDA Soil Taxonomy (Soil Survey Staff, 2014; IUSS Working Group WRB, 2015).

2.5.2.2 Sodic soils in USDA Soil Taxonomy and WRB soil classification system

Both systems recognize natric horizon to be a diagnostic horizon for sodic soils. The features of this horizon are similar among the two systems and according to Soil Survey Staff (2014) a natric horizon is an illuvial horizon that is normally present in the subsurface and has a significantly higher percentage of silicate clay than the overlying horizons. It shows evidence of clay illuviation that has been accelerated by the dispersive properties of sodium (Soil Survey Staff, 2014) and meets the following requirements:

i. This horizon meets all the requirements of the argillic horizon.
ii. It has a prismatic or columnar structure and ESP = or > 15% (Msanya, 2003).

The natric horizon is used in classifying sodic soils at different levels in the two systems. Solonetz is a reference group name used in WRB (IUSS Working Group WRB, 2015) given to sodic soils in World Reference Base soil classification system. Solonetz have a dense, strongly structured, clayey subsurface horizon that has a high proportion of adsorbed Na^+ and in some cases also Mg^{2+} ions. Solonetz that contain free soda (Na_2CO_3) are strongly alkaline (with pH > 8.5). In the USDA Soil Taxonomy, Solonetz belong to the natric great groups of several orders such as Natraqualfs and Natrargids (Msanya, 2003; Soil Survey Staff, 2014).

2.6 Soil Salinity in Irrigated Lands

The continued dependence on rainfall in agriculture has proved incapable of sustaining the population increase (Mwakalila and Noe, 2004). Therefore, irrigation has been found to be a central key part in curbing food scarcity not only in Tanzania but also in many other developing countries (Mwakalila and Noe, 2004; Mwakalila, 2006; Thomas, 2008). The primary reason for irrigating land is to improve agricultural productivity in areas where surface soils are dry (Mwakalila and Noe, 2004), especially in areas where rainfall is low and unreliable. Unfortunately, agricultural productivity in many irrigation schemes is not always realized due to a number of challenges facing the irrigation sector especially in the developing countries (Farifteh *et al.,* 2006; Wu *et al.,* 2018). One of the challenges is land degradation in the irrigation schemes due to soil salinity (Farifteh *et al.,* 2006; Wu *et al.,* 2018).

Soil salinity development is one of the most active land degradations and environmental hazards in irrigated lands worldwide, especially in arid and semi-arid regions (Farifteh *et al.,* 2006; Wu *et al.,* 2018). According to Hoang *et al.* (2016), irrigation and extensive clearing of vegetation, which bring the groundwater with soluble salts to or close to the soil surface, are the two major human activities accelerating salinity. Since irrigated agriculture provides about one third of the world food supply, secondary salinity in irrigated lands is of major concern (Tanji, 2002). This requires careful monitoring of the quality of irrigation water, soil salinity status and variation to curb degradation trends and secure sustainable land use and management (Qureshi and Al-Falahi, 2015; Hoang *et al.*, 2016).

2.6.1 Irrigation water salinity

Irrigation water induced soil salinity is one of the factors leading to salt-affected soils in many irrigated lands (Grattan, 2002; Muyen *et al.*, 2011; Kashenge-Killenga *et al.*, 2013). Irrigation water quality has an impact on crop production (Ali, 2011; Grattan, 2002). It is well known that all irrigation water contains dissolved mineral salts in form of ions, but the concentration and composition of the dissolved salts vary depending on the source of the irrigation water (Grattan, 2002; Muyen *et al.*, 2011). For example, groundwater contains higher salt levels (Grattan, 2002). The most common salts in irrigation water are sodium chloride, calcium sulfate, magnesium sulfate and sodium bicarbonate. Irrigation can contribute a substantial amount of salt to a field over the season (Ali, 2011; Muyen *et al.*, 2011).

2.6.1.1 Characterizing salinity of irrigation water

An understanding of the quality of water used for irrigation is essential to avoid problems such as irrigation induced soil salinity and to optimize crop production (Makoi and Ndakidemi, 2007; Ali, 2011; Aguilar *et al.*, 2017). There are two common water quality assessments that characterize the salinity of irrigation water, which are total dissolved solids (TDS) and electrical conductivity (EC) (Grattan, 2002; Aguilar *et al.*, 2017). TDS measures the salinity of irrigation water by reporting the total salt concentration in water expressed in milligrams of salt per liter of water (mg L^{-1}) (Grattan, 2002). It is determined by evaporative method which aims to quantify the total number of milligrams of salt that would remain after 1 liter of water is evaporated to dryness. Generally, the higher the TDS, the higher the salinity of water (Grattan, 2002).

Electrical conductivity (EC) is the other and most commonly used measurement for assessing irrigation water salinity (Grattan, 2002; Aguilar *et al.*, 2017). EC is much more useful than TDS because it can be made instantaneously and easily by irrigators or farm managers in the field and laboratory (Grattan, 2002). Salts dissolved in water conduct electricity, and therefore, the salt content in the water is directly related to the EC. EC measured in the irrigation water is abbreviated as EC_w and expressed in dS m^{-1} (Grattan, 2002).

From literatures, conversions between EC_w and TDS are made using conversion factors which depend both on the salinity level and composition of the water. According to Grattan (2002), TDS can be estimated from EC_w using the following equations:

$$TDS\ (mg\ L^{-1}) = 640 \times EC_w\ (dS\ m^{-1})\ \text{when}\ EC_w < 5\ dS\ m^{-1} \quad (5)$$

$$TDS\ (mg\ L^{-1}) = 800 \times EC_w\ (dS\ m^{-1})\ \text{when}\ EC_w > 5\ dS\ m^{-1} \quad (6)$$

where EC_w is the electrical conductivity measured in irrigation water.

Sulfate salts do not conduct electricity in the same way as other types of salts (Grattan, 2002). Therefore, it has been recommended that if water contains large quantities of sulfate salts, the conversion factors are invalid and should be adjusted upward (Grattan, 2002).

2.7 Extent of Salt-affected Soils

2.7.1 Global extent of salt-affected soils

With the environmental deterioration caused by increasing climate change, the development of salt-affected soils is a serious and growing global problem (Wang *et al.*, 2011; Rengasamy, 2010; Li *et al.*, 2014; Aguilar *et al.*, 2017). It has also been highlighted in literature that in the future, stimulated by rapid growth of the human population, more wasteland will be reclaimed for use as cultivated land, mainly by means of irrigation, so the accompanying salinization problem will become more prominent (Wang *et al.*, 2011; Li *et al.*, 2014).

The record of global extent of soil salinity is varied in literature. For example, according to Rengasamy (2006), salt-affected soils occur in more than 100 countries of the world with a variety of extents, nature and properties. It has been reported by Li *et al.* (2014) that, about 7% of the world's land surface is currently threatened by salinization. Li *et al.* (2014) has reported that the soil salinity problem is worsening in countries like America, China, Hungary and Australia, and it will become even more severe in North Africa, East Africa, the Middle East, East Asia and South Asia. More than 800 million hectares of land in the world is salt-affected (Rengasamy, 2010). Hoang *et al.* (2016) reviewed the extent of global soil salinity and specified that a total of 835 million hectares of land in the world is salt-affected with different regional distribution as illustrated in Fig. 2.2.

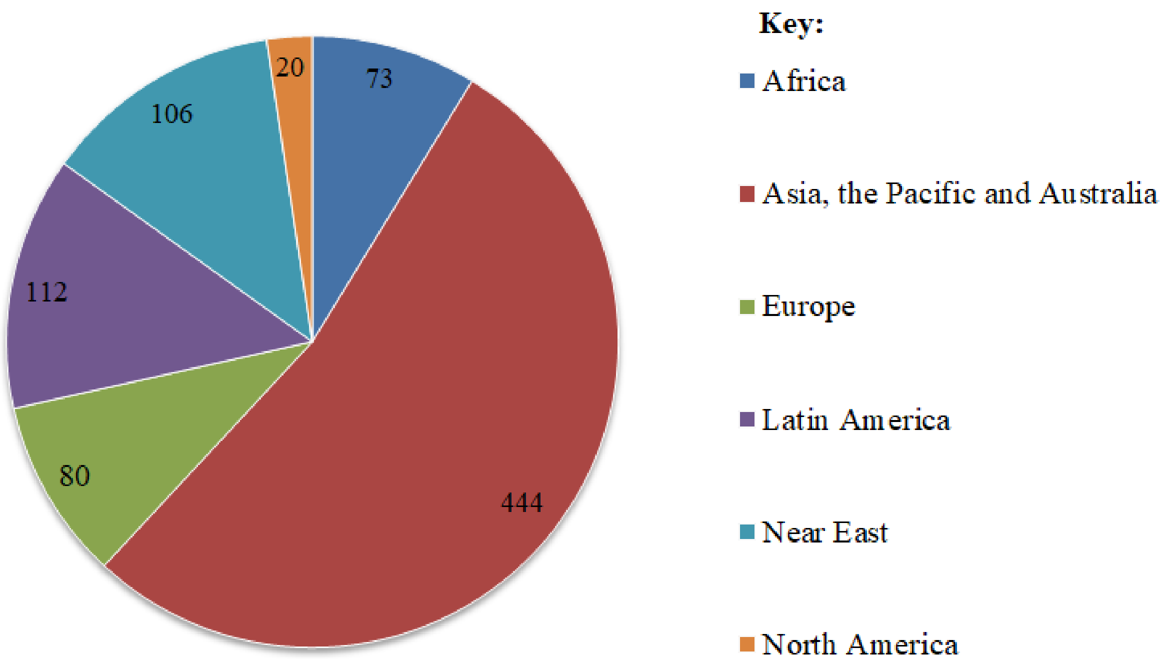

Figure 2.2: Global distribution of salt-affected soils in million hectares

Source: Hoang *et al.* (2016)

2.7.1.1 Extent of Soil Salinity in Irrigated Lands

Globally, it has been reported by Metternicht and Zinck (2003) that nearly 20% of all irrigated land is salt-affected, and this proportion tends to increase in spite of considerable efforts dedicated to land reclamation. According to Tanji (2002) the world has about 227 million ha of irrigated lands of which 20% are salt-affected. The most recent study by Hoang *et al.* (2016), provided similar record that, of the 230 million ha of the world's irrigated land, 45 million ha (20%) has been salt-affected. For example in Iraq, soil salinity problems has robbed the production potential of the 70% of the total irrigated area with up to 30% gone completely out of production (Qureshi and Al-Falahi, 2015).

2.7.2 Soil salinity in Tanzania irrigation schemes

The extent of salt affected soils in Tanzania has not been properly documented. But it has been reported that most of the irrigation schemes in Tanzania, which are especially located in the semiarid environments are already experiencing increased levels of salt-affected soils (Kashenge-Killenga *et al.,* 2013; Kashenge-Killenga *et al.,* 2016; Dolo, 2018). Kashenge-Killenga (2016) pointed out that this is largely due to mismanagement of the soils, the use of poor quality irrigation water, poor drainage systems, poorly designed and managed irrigation infrastructures, excessive use of irrigation water as well as climate change.

In their study, Kashenge-Killenga *et al.* (2016) used visual observation which showed that 100% of all the surveyed irrigation schemes in southwestern Tanzania which included Iringa region had symptoms of salt-affected soils. However, laboratory results from the same study by Kashenge-Killenga *et al.* (2016) showed that 67% of the schemes had salt problems. This study reported three types of salt-affected soils (saline, sodic, and saline-sodic) with extreme salinity (4-15 dS m^{-1}), sodicity (with 10-34 SAR) and high soil pH (up to 10) values from the surveyed irrigation schemes (Kashenge-Killenga *et al.,* 2016). Saline-sodic soil was the most common problem, followed by sodic soils (Kashenge-Killenga *et al.,* 2016). About 90% of the surveyed irrigation schemes had inadequate irrigation infrastructures, which seems to contribute to the problem (Kashenge-Killenga *et al.,* 2016). Additionally, Kashenge-Killenga *et al.* (2016) reported that land loss due to the effects of soil salinity in the surveyed irrigation schemes ranged from 5 to 25% while yield losses ranged from 5 to 100%.

2.8 Soil Salinity Prediction and Mapping

Generally, soil salinity development is a dynamic process with severe consequences for the soil, hydrological, agricultural, climatic, geochemical, social and economic aspects (Brunner *et al.,* 2007; Allbed and Kumar, 2013). Therefore, information on the spatial extent, nature and distribution of soil salinity is becoming very essential for development and implementation of effective soil reclamation programs for preventing or reducing any further salinization to sustain agricultural lands and natural ecosystems (Allbed and Kumar, 2013; Wu *et al.,* 2018). Thus, timely detection of soil salinity, monitoring and assessment of its severity level and extent have become very important both at local and regional scales (Allbed and Kumar, 2013; Wu *et al.,* 2018). Mapping spatial distribution and severity of salinity is essential for agricultural management and development (Wu *et al.,* 2018).

2.8.1 Soil salinity assessments and mapping methods

Conventionally, soil salinity is measured and assessed by collecting in situ soil samples and analyzing those samples in the laboratory to determine their solute concentrations or electrical conductivity (Brunner *et al.,* 2007; Allbed and Kumar, 2013). These methods are however, time consuming and costly since dense sampling is required to adequately characterize the spatial variability of an area (Brunner *et al.,* 2007; Iqbal, 2011). The other drawbacks of conventional soil salinity risk identification and management methods are that they have limitations in spatial data analysis and provide an inadequate description of the problem (Shafiq *et al.,* 2001; Dinh *et al.,* 2018). The Geographical Information System (GIS) based approach for predicting the spatial distribution of soil salinization is a promising method widely accepted in current literature with advantages over conventional methods in time saving, wide range of coverage as well as facilitation of faster and long term monitoring (Shahabi *et al.,* 2017; Zewdu *et al.,* 2017).

The process of soil salinity mapping has recently become more efficient through the applications of geostatistics and geographic information systems (GIS), which enable the prediction of soil salinity spatial distribution and its environmental hazards (Shahabi *et al.,* 2017; Hammam and Mohamed, 2018). Geostatistics analysis and GIS has been considered as efficient methods for studying, analyzing and evaluating spatial distribution of soil properties, their changes, reducing the error rate and increasing the output efficiency (Behera and Shukla, 2015; Hammam and Mohamed, 2018).

A number of GIS models including inverse distance weighting (IDW), spline, radial basis functions and the typical geostatistical models such as ordinary kriging, universal kriging, regression kriging and cokriging are already incorporated in GIS software packages (Meng *et al.,* 2013; Almasi *et al.,* 2014) like Quantum GIS software (QGIS). Ordinary kriging (OK) and inverse distance weighting (IDW) are among the most common GIS spatial interpolation methods used to predict and produce spatial distribution of soil characteristics such as soil salinity (Yao *et al.,* 2013; Almasi *et al.,* 2014; Emadi and Baghernejad, 2014).

2.8.1.1 Inverse Distance Weighting (IDW) and Ordinary Kriging (OK) spatial interpolation methods

Inverse Distance Weighting (IDW) and Ordinary Kriging (OK) spatial interpolation methods are based on the principle of spatial autocorrelation of samples by distance, where the closer the samples are from each other, the more similar would be their values (Li and Heap, 2008; Lu and Wong, 2008; Zarco-Perello and Simões, 2017; Hammam and Mohamed, 2018). Under this principle, the prediction of a value in an unsampled place is calculated by giving more weight to samples that are closer to the prediction point (Li and Heap, 2008; Lu and Wong, 2008; Almasi *et al.*, 2014; Zarco-Perello and Simões, 2017).

However, IDW uses arbitrary exponential weighting of the influence that each sample has according to distance, whereas OK involves a process of variography to model the spatial autocorrelation of the data to assign weights (Almasi *et al.*, 2014; Zarco-Perello and Simões, 2017). This can result in better interpolations under an appropriate sampling design; nonetheless OK is time consuming and it is still subjective since it involves many user decisions (Li and Heap, 2008). IDW is relatively fast and easy to compute and straight forward to interpret (Lu and Wong, 2008; Hammam and Mohamed, 2018). The IDW formula from Hammam and Mohamed (2018) is as follows:

$$\hat{z}(x_0) = \frac{\sum_{i=1}^{n} z\left(x_i d_{ij}^{-r}\right)}{\sum_{i=1}^{n} d_{ij}^{-r}} \tag{7}$$

where x_0 is the estimation point and x_i are the data points within a chosen neighborhood. The weights (r) are related to distance by d_{ij}, which is the distance between the estimation point and the data points.

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CHAPTER THREE

3.0 PEDOLOGICAL CHARACTERIZATION OF THE SOILS OF MAGOZI IRRIGATION SCHEME, IRINGA, TANZANIA

ABSTRACT

Pedological characterization study was carried out in Magozi Irrigation Scheme, Iringa, Tanzania. Three representative soil profiles namely MAG-P1, MAG-P2 and MAG-P3 were identified, excavated, described and sampled for laboratory soil physico-chemical analysis. The profiles were moderately to very deep with MAG-P2 and MAG-P3 profiles being dominated with mottles. The topsoil and subsoil bulk densities ranged from 1.21 to 1.69 g cm^{-3} and 1.34 to 1.72 g cm^{-3} respectively. Profile MAG-P1 was dominated with heavy clay and slickensides. The topsoil pH ranged from 7.0 (neutral) to 8.1 (moderate alkaline) and 7.4 (mildly alkaline) to 9.0 (strongly alkaline) for subsoils. The strongly alkaline pH values were dominant in profile MAG-P1, attributed to low leaching of bases in clay soils. The soils of MAG-P1 and MAG-P2 profiles may have limitations in availability of some plant nutrients like P because of pH values > 7.5. The topsoil organic carbon ranged from 1.13% (low) to 1.59% (medium). The topsoil total nitrogen ranged from 0.13% (low) to 0.23% (medium). All the topsoil available P were rated as high (14.59 to 22.87 mg kg^{-1}). The topsoil CEC_{soil} (17.6 to 26.6 $cmolkg^{-1}$) were higher than their subsoil (3.4 to 24 $cmolkg^{-1}$) due to higher topsoil organic matter. The topsoil BS was > 50% (high) in all profiles. The BS > 100% in some horizons of MAG-P2 can be due to free solution Ca, Mg, and/or Na from soil salts. In the USDA Soil Taxonomy, the soils were classified as *Typic Haplusterts* (MAG-P1), *Vertic Endoaquepts* (MAG-P3) and *Vertic Epiaquepts* (MAG-P3) and correlated as *Haplic Vertisols*, *Eutric Vertic Cambisols* and *Eutric Vertic Stagnic Cambisols* for MAG-P1, MAG-P2 and MAG-P3 respectively in WRB for Soil Resources. This information is crucial in planning the best soil use and management of this area.

Keywords: Pedological Characterization, Magozi Irrigation Scheme, Tanzania

3.0 INTRODUCTION

Agriculture has for a long time remained as an economic sector playing significant role in the economy and livelihoods of Tanzanians (Barakabitze *et al.,* 2015; Bergius *et al.,* 2018). It is well known that soil is a vital natural land resource which underpins human food and cash crops production (Sanchez, 2002; Pimentel, 2006; Sanchez *et al.*, 2009; Buol *et al.*, 2011; Msanya *et al.,* 2016) due to its role in plant growth and development (Tenga *et al.,* 2018). According to Hartemink (2016), the current pedological definition refers soil as a natural body comprised of solids (mineral and organic matter), liquid and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers and transformations of energy and matter or the ability to support rooted plants in a natural environment.

It has been frequently reported that, declining fertility of Tanzanian soils as it is the case for most parts of Africa, is because of soil nutrient mining and other forms of land degradation and is a major cause of decreased crop yields and per capita food production (Mowo *et al.,* 2006; Ndakidemi and Semoka, 2006; Funakawa *et al.,* 2012; Massawe, 2015). A good inventory on soil physical and chemical properties and associated site characteristics is essential for advice on both current and potential land users on how to best use soil resource (Msanya *et al.,* 2003; Abate *et al.,* 2014). Such inventory is achieved through soil surveys and pedological characterization.

Pedological characterization which provides an understanding of soil genesis, morphology and other key soil properties as well as classification of soils (Msanya *et al.,* 2003; Mukungurutse *et al.,* 2018) is a key for land resource planning and development of soil management interventions for improving and sustaining agricultural productivity (Msanya *et al.,* 2003; Kebeney *et al.,* 2014; Mukungurutse *et al.,* 2018; Tenga *et al.,* 2018). It has been emphasized by many soil scientists such as Msanya *et al.* (2003) that, soil information gathered by systematic identification, grouping and delineation into different soil types is required if sound interpretations towards land use potential are to be made. Furthermore, pedological information is important to land users especially farmers who use the data to make decisions on what crops and management practices are best for optimal and sustainable crop production (Msanya *et al.,* 2003; Msanya *et al.,* 2016; Mtama *et al.,* 2018; Mukungurutse *et al.,* 2018). Classification of soils is also useful to facilitate technology transfer and information exchange among soil scientists, decision makers, planners, researchers, agricultural extension advisors and guiding fertilizer industries to formulate soil and crop specific fertilizer blends (Assen and Yilma, 2010; Hailu *et al.,* 2015).

Although, soil characterizations in the form of soil surveys have been conducted in Tanzania, in the previous years (Msanya *et al.,* 1991; Msanya and Magoggo, 1993; Kilasara *et al.,* 1994), however, the concentration has been only in a few selected potential areas. It has also been observed that most of the existing soil resource inventories in this country were mostly of small scales which are not adequate for use at the large scale level by farmers and other stakeholders like researchers (Msanya *et al.,* 2016; Tenga *et al.,* 2018). Given the large size of Tanzania with its diverse soil and other land resources (Mtama *et al.,* 2018); it is evident that the available soil information remains inadequate. Moreover, it has been suggested that, there is still a need to concentrate soil characterizations at larger (detailed) scales in different parts of the country in Tanzania, for the aim of providing an up to date and more relevant soil and land information for various agricultural land users like farmers, agronomists and researchers for more appropriate fertilizer and soil management recommendations (Msanya *et al.,* 2003; Massawe, 2015; Msanya *et al.,* 2016; Tenga *et al.,* 2018).

The literature shows that detailed pedological characterizations for various purposes in Tanzania have been implemented in only some parts of the country regions including Iringa Region (Msanya *et al.,* 2003; Msanya *et al.,* 2016; Msanya *et al.,* 2018; Mtama *et al.,* 2018; Tenga *et al.,* 2018). But there are no detailed studies that have been done for soil pedological characterizations in Iringa Rural District.

Since 1980s to date, there had been a number of efforts in Tanzania to promote irrigation farming in order to increase food security and alleviate poverty among small holder farmers (Majule and Mwalyosi, 2005; Mdemu *et al.*, 2017). Evidences show that in most of these schemes there is poor agricultural productivity partly due to their poor management and land degradation such as salinization (Majule and Mwalyosi, 2005; Mdemu *et al.,* 2017). Soil information based on pedological characterization is also lacking in most of the Irrigation Schemes in Tanzania, hence management recommendations do not rely on the pedological information.

Although Magozi Irrigation Scheme appears to be very important for the livelihood of the surrounding communities for rice production (Mdemu *et al.,* 2017), there is no any scientific study carried out to characterize the soil resources of the irrigation scheme using pedological classification systems, in order to explore the potentials and limitations of the soils in this area. This may hinder the sustainable use of the soils for rice production in the future. Therefore, this study conducted a pedological characterization and classification of the soils of Magozi Irrigation Scheme with the aim of generating soil information necessary for sustainable rice production and land management options in the area.

3.1 MATERIALS AND METHODS

3.1.1 Description of study area

This research was conducted in Magozi Irrigation Scheme which has an area of 1300 ha. The scheme is located at about 65 km North West of Iringa town at Ilolompya Ward, in Iringa Rural District, Iringa Region and composed of three villages namely Magozi, Ilolompya and Mkombilenga. The scheme is located in zone 36 south, occupying the area lying between 9172000 to 9182000 m northings and 772000 to 774000 m eastings in the Universal Transverse Mercator (UTM) coordinate system. The irrigation water used in the scheme is drawn from Little Ruaha River through a system of irrigation canals as shown in Fig. 3.1. The average altitude is 700 m above mean sea level and the climate is semi-arid tropical with a monomodal rainy season between November and May.

The construction of Magozi Irrigation Scheme started in 2005 and was completed in 2007. This scheme is managed by the Mkombilenga Ilolo-Mpya and Magozi (MKILMA) farmers' organization, whose membership as of 2016 was 503 farmers (Mdemu *et al.*, 2017). Rice is the main crop produced by the farmers in Magozi scheme where the growing season starts from November to May each year. Fig. 3.1 shows the location Map of Magozi Irrigation Scheme.

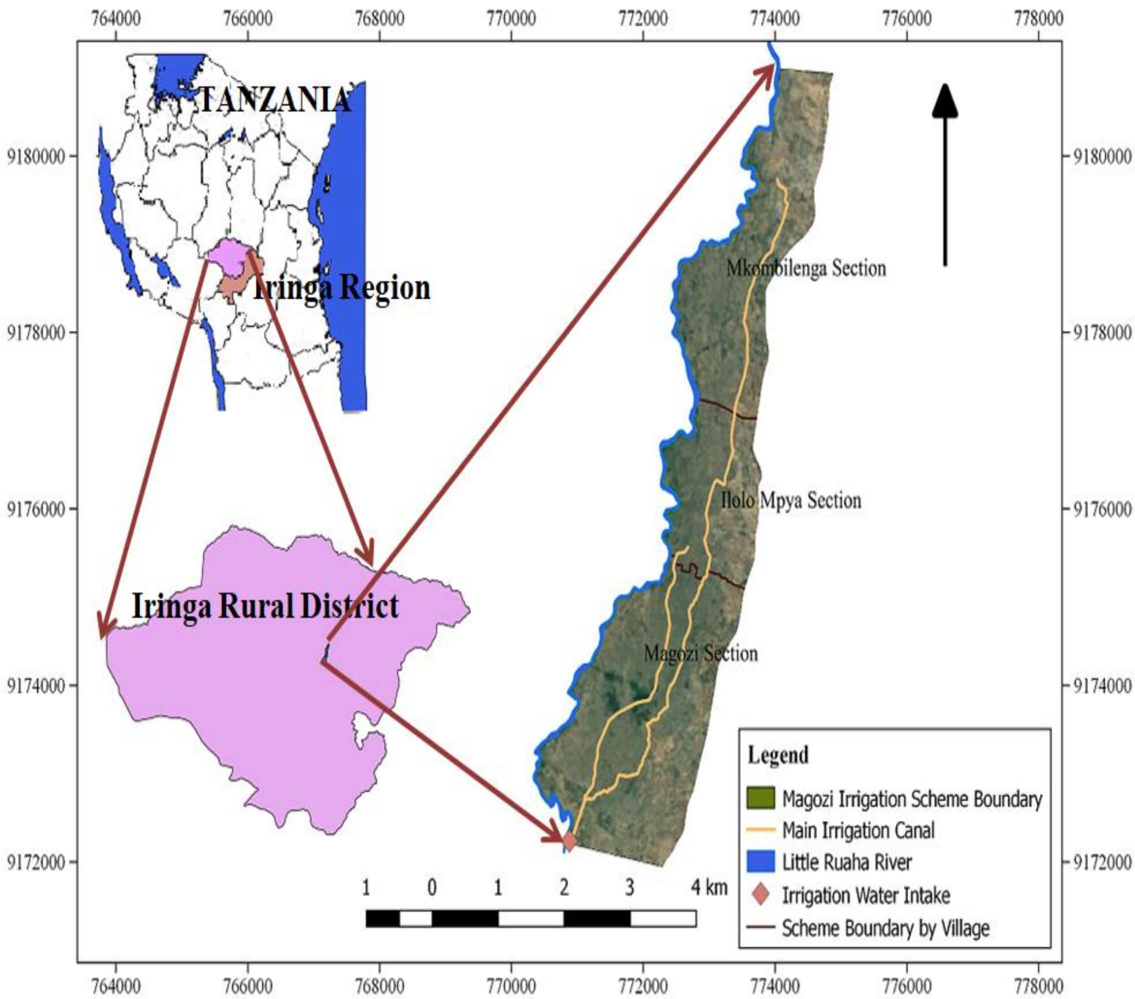


Figure 3.1: Location Map of Magozi Irrigation Scheme

3.1.2 Pedological characterization in Magozi Irrigation Scheme

3.1.2.1 Field methods

Reconnaissance survey was carried out in Magozi Irrigation Scheme using transect walks, auger observations and soil description in the field to identify major soil mapping units. Identification of mapping units was based on topography, soil depth, slope, soil morphological and physical characteristics, soil salinity surface features, parent material and vegetation as described by FAO (2006). Based on the information obtained from reconnaissance survey, three mapping units namely Mkombilenga, Ilolo Mpya and Magozi were identified. Therefore, at each mapping unit, one representative soil profile pit was dug to a depth of 2 m or to a limiting layer (FAO, 2006). The soil profiles were designated as MAG-P1, MAG-P2 and MAG-P3 for Mkombilenga, Ilolo Mpya and

Magozi units, respectively. Each soil profile pit was geo-referenced by international coordinates using Global Positioning System (GPS) device (GARMIN *etrex* 20), described and sampled according to the FAO guidelines (FAO, 2006) for laboratory physical and chemical analysis. The location of soil profiles is presented in Fig. 3.2. Nine undisturbed core samples were collected from selected genetic horizons of the studied soil profiles while ten composite soil samples representing all genetic horizons of the three profiles were collected.

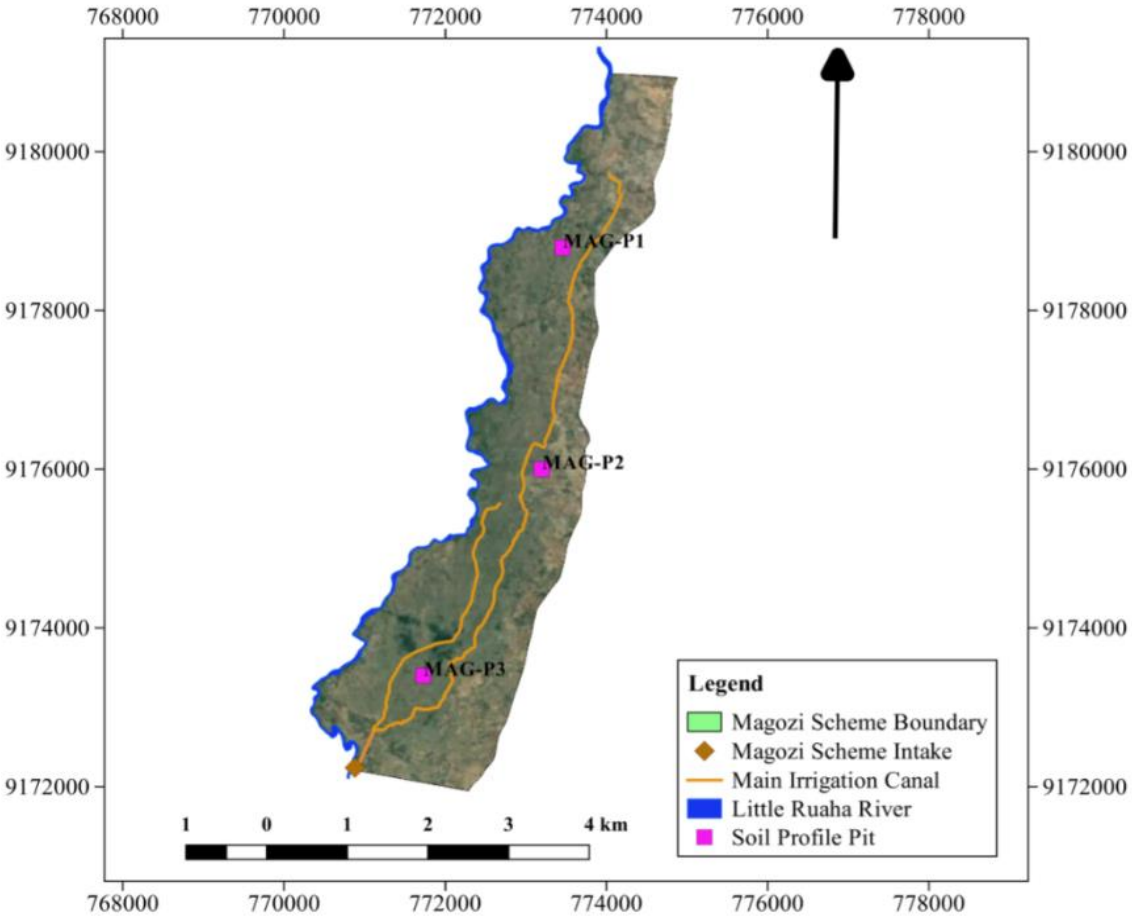


Figure 3.2: Location of soil profile pits in Magozi Irrigation Scheme

The information on geographic location, elevation, landform, land utilization, soil moisture regime and soil temperature regime for the identified soil profiles in Magozi Irrigation Scheme has been summarized in Table 3.1. Also, the characteristics on parent materials, weather condition, natural vegetation, slope and surface characteristics of the representative soil profiles at Magozi Irrigation Scheme have been reported in Table 3.2.

Table 3.1: Locations, elevation, landform and land use characterization of the three representative pedons at Magozi Irrigation Scheme, Iringa Region

Soil Unit	Profile no.	Location in the Scheme	Geographic Coordinates		Altitude (m) (m.a.s.l.)	Landform	Land use	SMR	STR
MKOMBILENGA	MAG-P1	Downslope	035° 28' 39.4" E	07° 25' 24.0" S	748	Alluvial plain	Rice cultivation	Ustic	Isohyperthermic
ILOLO MPYA	MAG-P2	Middle	035° 28' 26.6" E	07° 26' 57.0" S	751	Alluvial plain	Rice cultivation	Aquic	Isohyperthermic
MAGOZI	MAG-P3	Upslope	035° 27' 47.0" E	07° 28' 10.6" S	765	Alluvial plain	Rice cultivation	Aquic	Isohyperthermic

KEY:

SMR = Soil Moisture Regime; STR = Soil Temperature Regime; m.a.s.l. = metres above sea level

Table 3.2: Parent material, weather condition, vegetation, slope and surface characteristics of the representative pedons at Magozi Irrigation Scheme, Iringa Region

Soil Unit	Profile no.	Parent rock/material	Weather condition	Site Slope	Surface characteristics	Native Vegetation	Farming system
MKOMBILENGA	MAG-P1	Quarternary deposits predominantly sandy and silty alluvial and eluvial sediments originating from meta-igneous and meta-sedimentary rocks	Sunny, no rain for past five months	Slope: <1% Slope type: straight Position on slope: Lower quarter Slope length: 10km	Sealing: no Drainage class: moderately well drained Cracks: polygonal extensive deep wide cracks Run off: Slow Infiltration: Moderately slow Deposition: evident Erosion: water (slight interrill)	*Acacia spp, Ficus spp and Tamarindus indica*	Rice-rice rotation

Table 3.2 Continued

Soil Unit/Village	Profile no.	Parent rock/material	Weather condition	Site Slope	Surface characteristics	Native Vegetation	Farming system
ILOLO MPYA	MAG-P2	Quarternary deposits predominantly sandy and silty alluvial and eluvial sediments originating from meta-igneous and meta-sedimentary rocks	Sunny, no rain for past five months	Slope: <1% Slope type: straight Position on slope: middle Slope length: 10 km	Sealing: yes (salt crusts) Sealing thickness: 3mm Drainage class: moderately well drained Cracks: moderate deep cracks Run off: slow Infiltration: moderately slow Deposition: evident Erosion: water (slight interrill)	*Acacia spp.*, *Ficus spp.* and *Tamarindus indica*	Rice-rice rotation
MAGOZI	MAG-P3	Quarternary deposits predominantly sandy and silty alluvial and eluvial sediments originating from meta-igneous and meta-sedimentary rocks	Sunny, no rain for past five months	Slope type: straight Position on slope: upper quarter Slope length: 10 km	Drainage class: moderately well drained Cracks: deep wide cracks Infiltration: Moderately slow Deposition: evident Erosion: water (interrill)	*Acacia spp.*	Rice-rice rotation

3.1.2.2 Laboratory methods

Undisturbed core soil samples were used for determination of soil bulk density by the core method according to Okalebo *et al.* (2002). The 10 composite horizon soil samples were air-dried, ground and sieved through a 2-mm sieve as described by Tan (2005) and used for determination of selected physical and chemical soil properties. Particle size analysis was determined by hydrometer method after dispersion with 5% sodium hexametaphosphate (Moberg, 2001) whereby the soil textural classes were determined using USDA textural triangle (FAO, 2006). Soil pH was measured potentiometrically in water and 1 M KCl at a ratio of 1:2.5 soil-water and soil-KCl as described by Okalebo *et al.* (2002). Electrical conductivity was determined in 1:2.5 soil-water suspensions using an electrical conductivity meter as per the method described by Moberg (2001). Organic carbon was determined by Walkley and Black wet oxidation method (Okalebo *et al.*, 2002) where a factor of 1.724 was multiplied to the organic carbon obtained to convert it to organic matter according to Nelson and Sommers (1982).

Total N was determined using micro-Kjeldahl digestion-distillation method as described by Moberg (2001). Available phosphorus was determined using filtrates extracted by Olsen method as described by Okalebo *et al.* (2002) and determined by spectrophotometer at 884 nm following colour developed by Molybdenum blue method (Okalebo *et al.*, 2002). Cation exchange capacity of soil (CEC_{soil}) and exchangeable bases were determined by saturating soil with neutral 1M NH_4OAc (ammonium acetate) and the adsorbed NH_4^+ was displaced using 1M KCl and then determined by Kjeldahl distillation method for estimation of CEC of soil (Moberg, 2001; Okalebo *et al.*, 2002). Cation exchange capacity of clay (CECclay) was calculated using the formula outlined by Baize, (1993) which corrects for the CEC contributed by organic matter (OM) as follows:

$CEC_{clay} = (\{CEC_{soil} - (\% OM x 2)\} / \% clay) \times 100$ (8)

The exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+) were determined by atomic absorption spectrophotometer (Moberg, 2001). Total exchangeable bases (TEB) were calculated arithmetically as the sum of Ca^{2+}, Mg^{2+}, Na^+ and K^+ for a given soil sample (Moberg, 2001). Other parameters which were calculated included C/N ratio, percent base saturation (BS), exchangeable sodium percentage (ESP), nutrient ratios (Ca/Mg, Ca/TEB, K/Mg, and K/CEC %) and Silt/Clay ratio using the following formulas:

ESP (%) = Na^+ (cmolkg^{-1}) / CEC (cmolkg^{-1}) × 100 (4)

C/N = Organic C (%) / Total N (%) (9)

BS (%) = {Ca^{2+} + Mg^{2+} + Na^+ + K^+ (cmolkg^{-1})} / CEC (cmolkg^{-1}) × 100 (10)

Ca/Mg = Ca^{2+} (cmolkg^{-1}) / Mg^{2+} (cmolkg^{-1}) (11)

TEB (cmolkg^{-1}) = Ca^{2+} + Mg^{2+} + Na^+ + K^+ (cmolkg^{-1}) (12)

Ca/TEB = Ca^{2+} (cmolkg^{-1}) / TEB (cmolkg^{-1}) (13)

K/Mg = K^+ (cmolkg^{-1}) / Mg^{2+} (cmolkg^{-1}) (14)

K/CEC (%) = K^+ (cmolkg^{-1}) / CEC (cmolkg^{-1}) × 100 (15)

Silt/Clay Ratio = % Silt/% Clay (16)

3.1.2.2.1 Determination of Total Elemental Composition

The Total Elemental Composition in form of oxides as well as total concentrations of potentially toxic elements (PTEs) for each horizon soil sample was determined according to Krishna *et al.* (2007) as follows: Samples were ground to particle size ≤ 177 µm using swing mill pulverizer. Powdered samples were then pressed into XRF sample cups and mounted with PANalytical B.V. X-Ray film-polyester PETP (Polyethylene Terephthalate Polyester). Finally, the elemental oxides were measured by PANalytical, Minipal 4 Energy Dispersive X-Ray Fluorescence Spectrometer (ED-XRF) Model PW4030/45B.

3.1.2.3 Measurement of Soil Penetration Resistance (PR)

Penetrometers are widely used to measure the soil resistance to penetration, expressed as force per unit cross-sectional area of the cone-base (Bengough *et al.* 2000; Vanags *et al.*, 2004). In this study, Penetration Resistance (PR) in megaPascals (MPa) of each identified horizon for each soil profile (Hazeltonn and Murphy, 2016) was measured by using Japanese Penetrometer Model DKI-5551 of Daiki Rika Kogyo Company. The penetrometer readings in millimeters (mm) were first converted into kg cm^{-2} using the formula reported by Massawe *et al.* (2017) and then the PR values in kg cm^{-2} were converted into megaPascals (MPa) units using the factor of 1 kg cm^{-2} equals to 0.09807 MPa (Hazeltonn and Murphy, 2016).

$$\text{Penetration Resistance in MPa} = [(100*X)/0.7952(40 - X)^2]*0.09807 \qquad (17)$$

where X = penetrometer reading (mm).

3.1.2.4 Statistical data analysis

The obtained data were subjected to descriptive statistical analysis using Genstat Discovery Edition 4 (Wim *et al.*, 2007). Detection of functional relationships among key soil properties was determined by correlation analysis. Pearson correlations between selected soil physical and chemical properties were performed in Minitab Software and the significance of correlation coefficients was tested at $p \leq 0.05$.

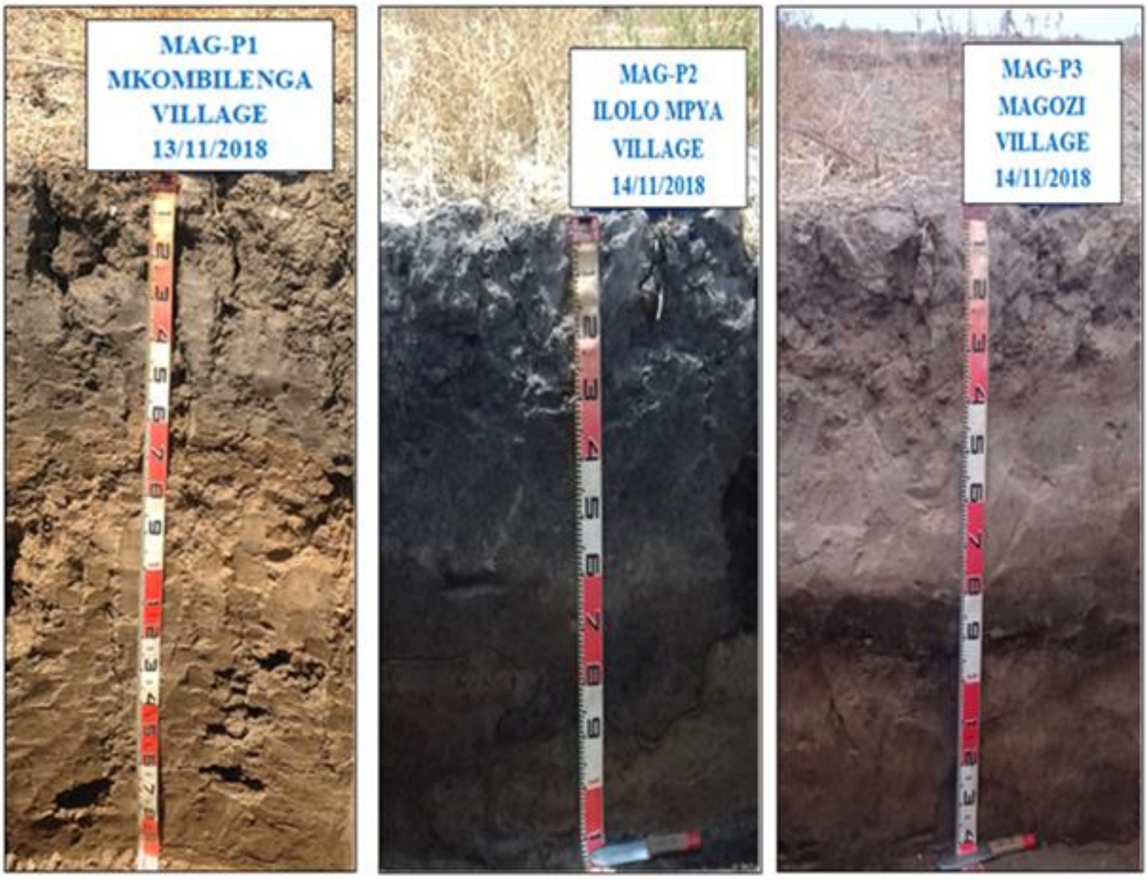
3.1.2.5 Soil Classification

The data on soil morphological, physical and chemical properties were used to define the diagnostic horizons and other features that were finally used to classify the soils up to the family level of the USDA Soil Taxonomy (Soil Survey Staff, 2014) and up to Tier-2 category of the World Reference Base for soil resources (IUSS Working Group WRB, 2015).

3.2 RESULTS AND DISCUSSIONS

3.2.1 Soil Morphological Characteristics

Plate 3.1 shows the three representative soil profiles designated as MAG-P1, MAG-P2 and MAG-P3 in Magozi Irrigation Scheme, Iringa Rural District, Tanzania. A summary of selected soil morphological properties for the studied representative soil profiles of Magozi Irrigation Scheme is presented in Table 3.3.



MAG-P1 MAG-P2 MAG-P3

Plate 3.1: Representative soil profiles in Magozi Irrigation Scheme, Iringa Rural District, Tanzania

Table 3.3: Selected morphological characteristics of soils of Magozi Irrigation Scheme in Iringa Region

Soil Unit/Village	Profile no.	Horizon	Depth (cm)	Munsell Soil Colour		Mottling	Consistence	Structure	Roots	Horizon boundary
				Dry Colour	Moist Colour					
MKOMBILENGA	MAG-P1	Ap	0 - 53/69	vdgb (10YR3/2)	vdg (10YR3/1)	_	vha, vfi, vst & vpl	mo co; pr	cm & mf	cw
		BAw	53/69 - 107/110	yb (10YR5/4)	dyb (10YR4/4)	_	vha, vfi, vst & vpl	mo co; pr	cf	cw
		Bss	107/110 - 200+	dyb (10YR3/6)	dyb (10YR3/4)	_	vha, vfi, vst & vpl	mo co; pr	cvf	_
ILOLO MPYA	MAG-P2	Ap	0 - 30	vdgb (10YR3/2)	bl (10YR2/1)	_	vha, vfi, vst & vpl	mo co; pr	fc & mfvf	ds
		BCg	30 - 52/92	dyb (10YR3/4)	vdgb (10YR3/2)	v&v, f, df, dyb (10YR4/6)	sha, fi, st & pl	we co; sb	cvf	cw
		Cg	52/92 - 110+	_	b (10YR4/3)	c, m, d, cl, yb (10YR5/8)	sst & spl	ma	cfvf	_
MAGOZI	MAG-P3	Apg	0 - 35/43	dg (10YR4/1)	vdb (10YR2/2)	c, fn, d, cl, yb (10YR5/6)	vha, vfi, st & pl	mo co; pr	mm & mf	cw
		Cg1	35/43 - 78	pb (10YR6/3)	dyb (10YR4/4)	c, fn, d, df, yb (10YR5/8)	so, vfr, nst & npl	sg	cf	as
		Cg2	78 - 92/97	_	vdgb (10YR3/2)	fw, fn, d, df, dyb (10YR3/6)	fr, sst & spl	we fi; sb	cf	cw
		Cg3	92/97 - 143+	_	b (10YR4/3)	v, fn, f, df, dyb (10YR3/4)	lo, nst & npl	sg	ff	_

KEY according to FAO (2006)

Soil Colour: vdgb = very dark grayish brown; vdg = very dark gray; yb = yellowish brown; dyb = dark yellowish brown; vdgb = very dark grayish brown; bl = black; b = brown; dg = dark gray; vdb = very dark brown; pb = pale brown.

Mottling: v&v = very few and very fine; f = faint; df = diffuse; dyb = dark yellowish brown; c = common; m = medium; d = distinct; cl = clear; yb = yellowish brown; fn = fine; fw = few.

Consistence: vha = very hard; vfi = very firm; vst = very sticky; vpl = very plastic; sha = slightly hard; fi = firm; st = sticky; pl = plastic; sst = slightly sticky; spl = slightly plastic; so = soft; vfr = very friable; nst = non-sticky; npl = non-plastic; fr = friable; lo = loose.

Structure: mo = moderate; co = coarse; pr = prismatic; we = weak; sb = subangular blocky; ma = massive; sg = single grain; fi = fine

Roots: cm = common medium; mf = many fine; cf = common fine; cvf = common very fine; fc = few coarse; mfvf = many fine and very fine; cfvf = common fine and very fine; mm = many medium; ff = few fine. **Horizon boundary:** c = clear; w = wavy; d = diffuse; s = smooth; as = abrupt smooth.

3.2.1.1 Soil Depth

The depths of the studied representative soil profiles ranged from 110 cm (moderately deep) to 200 cm (very deep) (FAO, 2006). The depth of MAG-P1 profile was not restricted by water table as compared to other profiles. Shallow water table was observed at a depth of 110 cm for MAG-P2 located at Ilolo Mpya Village as compared to MAG-P3 profile at Magozi village where the water table was observed at 143 cm (moderately deep). The presence of shallow water tables at Ilolo Mpya and Magozi villages may be associated with their closeness to the irrigation water intake leading to the oversupply of irrigation water to the land due to long-term intensive irrigation (Morway *et al.*, 2013) as compared to Mkombilenga Village section. This might also be attributed to poor irrigation infrastructures which do not facilitate uniform irrigation water distribution between the three village sections as well as poor drainage conditions. Shallow water tables have been identified as one of the factors limiting the sustainability of irrigated agriculture in the world as they lead to increased soil salinity and waterlogging problems (Schoups *et al.*, 2005).

3.2.1.2 Soil Colour

The topsoil dry colour was very dark grayish brown in MAG-P1 profile overlying yellowish brown and dark yellowish brown colour subsoil while the topsoil moist colour was very dark gray overlying dark yellowish brown colour. MAG-P2 profile had topsoil dry colour of very dark grayish brown overlying dark yellowish brown and the moist colour of black topsoil overlying very dark grayish brown subsoil. In profile MAG-P3, the topsoil dry colour was dark gray overlying pale brown subsoil while the topsoil moist colour was very dark brown overlying dark yellowish brown and very dark grayish brown subsoil. There was considerable variation in soil colour between topsoil and subsoil horizons in all the studied profiles. This may be due to differences in soil forming processes in such horizons as influenced by sedimentation and agricultural activities such as topsoil organic matter accumulations (Massawe, 2015; Kalala *et al.*, 2017; Mtama *et al.,* 2018; Mukungurutse *et al.,* 2018).

3.2.1.3 Mottling

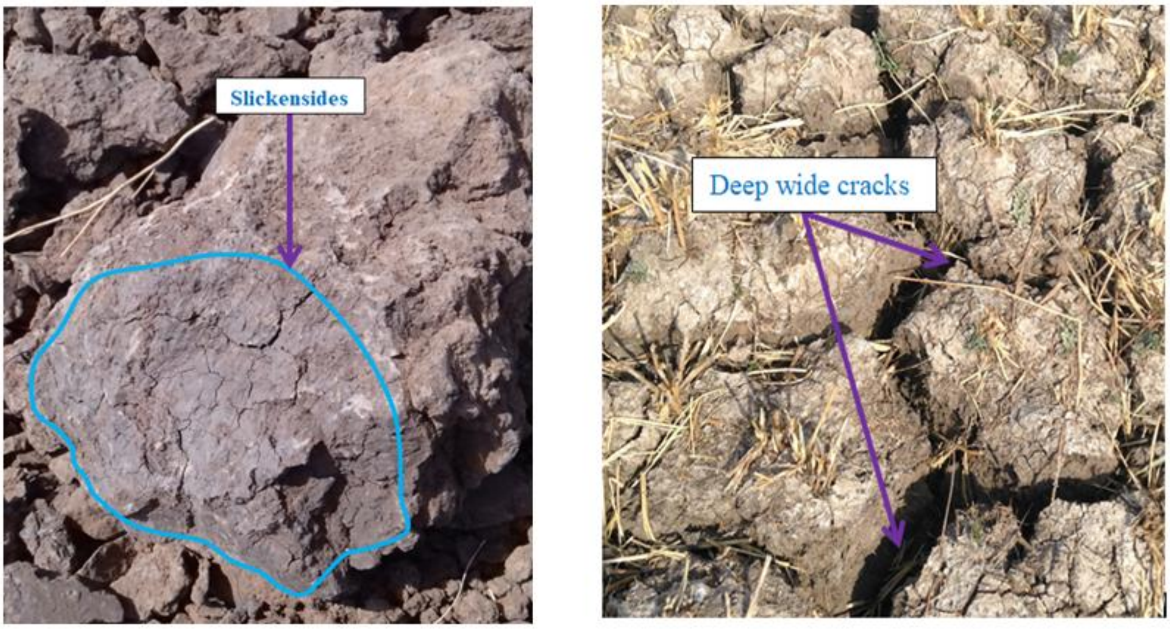
There were very few and very fine, faint, diffuse, dark yellowish brown mottles in horizon BCg and common, medium, distinct, clear, yellowish brown mottles in horizon Cg of profile MAG-P2. In MAG-P3 profile, there were common, fine, distinct, clear, yellowish brown mottles in horizon Apg. Horizon Cg1 had common, fine, distinct, diffuse, yellowish brown mottles while horizon Cg2 was characterized by few, fine, distinct, diffuse, dark yellowish brown mottles. Moreover, horizon Cg3 had very fine, faint, diffuse, dark yellowish brown mottles. The mottles have been recorded elsewhere in Tanzanian soils such as that of Dodoma Capital City District by Msanya *et al.* (2018) as well as beyond Tanzania (Mukungurutse *et al.*, 2018). The occurrence of redoximorphic features in form of mottles in MAG-P2 and MAG-P3 profiles are attributed to redox conditions in the profile resulting from fluctuating water table and poor drainage (Msanya *et al.*, 2018; Mukungurutse *et al.,* 2018). Hence, reduction and oxidation processes alternately take place in this profile (Msanya *et al.,* 2018).

3.2.1.4 Consistence

Topsoils of both profiles MAG-P1 and MAG-P2 topsoil had very hard dry, very firm moist, very sticky wet and very plastic wet consistence while MAG-P3 profile had very hard dry, very firm moist, sticky and plastic wet consistence. All the subsoil horizons in MAG-P1 had the same consistence as their topsoil. On the other hand, in MAG-P2 profile the BCg horizon had slightly hard dry, firm moist, sticky and plastic wet consistence while horizon Cg had slightly sticky and slightly plastic wet consistence. The subsoil of MAG-P3 profile was characterized by soft dry, very friable moist, non-sticky and non-plastic wet consistence for Cg3 horizon; friable moist, slightly sticky and slightly plastic wet consistence in Cg2 horizon as well as loose moist, non-sticky and non-plastic wet consistence in Cg3 horizon. These results showed that clay and sand contents in the horizons influenced the variation of soil consistence among and within profiles. The very hard consistence in topsoil of all the studied profiles in Magozi Irrigation Scheme is likely to restrict both root growth of most crop species and water flow as also observed elsewhere (Msanya *et al.*, 2018).

3.2.1.5 Soil Structure

The topsoil structures of all the three profiles in this study (Table 3.3) were moderate coarse prismatic. The topsoil structures of the studied soils may limit drainage, aeration and root penetration of most crops such as rice (Landon, 2014; Soil Survey Staff, 2014; Msanya *et al.*, 2018). The subsoil structures for MAG-P1 profile were the same as topsoil structures. On the other hand, there was variation in subsoil structures for MAG-P2 and MAG-P3 profiles. The MAG-P2 subsoil structures were weak coarse subangular blocks for horizon BCg and structure-less massive for Cg. In MAG-P3, the subsoils were structure-less single grained for Cg1 and Cg3 and weak fine subangular blocky for Cg2 horizons. Similar results of soil structures for some profiles were observed in Dodoma Capital City District soils by Msanya *et al.* (2018). Shiny slickensides in horizon Bss and deep wide cracks (Plate 3.2) were observed in MAG-P1 profile which are characteristic of many vertic soils (Msanya *et al.*, 2001; Assen *et al.*, 2010; Soil Survey Staff, 2014). These features together with the prominence of wedge-shaped structure in the subsoil indicate that *shrinking* and *swelling* and *argilli-pedoturbation* were typical pedogenic processes in this profile (Msanya *et al.*, 2018).



A B

Plate 3.2: Shiny slickensides (A) and deep wide cracks (B), a characteristic of vertic soils observed in MAG-P1 profile

3.2.1.6 Roots Abundance and Size

The roots abundance and size of the studied profiles (Table 3.3) showed that the topsoil (Ap horizon) of MAG-P1 profile was dominated by common medium and many fine roots while the subsoil was dominated by common fine roots and common very fine roots in BAw and Bss horizons respectively. In MAG-P2 profile, the topsoil was dominated by many fine and very fine roots in Ap horizon while the subsoil was dominated with common very fine roots and common fine and very fine roots in BCg and Cg horizons respectively. On the other hand, MAG-P3 profile topsoil (Apg) was dominated with many medium and many fine roots while its subsoil had common fine roots, common fine roots and few fine roots in Cg1, Cg2 and Cg3 horizons respectively. Generally, the abundance and size of roots from all the studied profiles decreased with increase in soil depth as also reported in other studies (Msanya *et al.*, 2001; Assen *et al.*, 2010).

3.2.1.7 Horizon Boundary Distinctness and Topography

In MAG-P1 profile, there was no difference in horizons boundary distinctness and topography between topsoil and subsoil as all were characterized by clear wavy boundary while MAG-P2 and MAG-P3 profiles showed slight variations within profiles. The MAG-P2 profile had diffuse smooth boundary between horizons Ap and BCg and clear wavy boundary between BCg and Cg horizons. The MAG-P3 was characterized by having clear wavy boundary between Apg and Cg1 horizons, abrupt smooth boundary between Cg1 and Cg2 horizons and clear wavy boundary between Cg2 and Cg3 horizons. Generally, horizon boundary characteristics of the studied profiles in Magozi Irrigation Scheme showed slight variations both among (for all profiles) and within (for MAG-P2 and MAG-P3) studied profiles. According to Assen *et al.* (2010), these differences seem to reflect variability in other soil characteristics such as weathering intensity, contents of organic matter and soil drainage conditions.

3.2.2 Soil Physical Properties

3.2.2.1 Particle Size Distribution and Textural Classes

The laboratory data on particle size distribution as well as soil textural classes of the studied soils of Magozi Irrigation Scheme are presented in Table 3.4. It is well known that soil texture is the most stable physical characteristic which influences several other soil properties such as soil structure, water and nutrient retention and nutrient leaching in the soil (Okalebo *et al.,* 2002; Msanya *et al.*, 2018; Mukungurutse *et al.,* 2018). The topsoil clay contents of the studied soils ranged from 34.48 to 50.48% while subsoil clay contents ranged from 10.48 to 52.48%. Generally, the clay content was higher in all soil genetic horizons of MAG-P1 than MAG-P2 and MAG-P3 profiles. Moreover, MAG-P3 had comparatively higher topsoil clay content than MAG-P2 while most subsoils of MAG-P2 had higher clay content than MAG-P3.

Table 3.4: Selected physical soil properties of three representative soil profiles of Magozi Irrigation Scheme in Iringa Region

Profile no.	Horizon	Depth (cm)	Particle Size Distribution (%) Clay	Silt	Sand	Textural Class	Silt/Clay Ratio	Bulk Density ($g\ cm^{-3}$)	Penetration Resistance (MPa)
MAG-P1	Ap	0 - 53/69	50.48	14	35.52	C	0.28	1.21	12.54
	BAw	53/69 - 107/110	48.48	17	34.52	C	0.35	1.72	10.12
	Bss	107/110 - 200+	52.48	18	29.52	C	0.34	1.54	5.83
MAG-P2	Ap	0 - 30	34.48	12	53.52	SC	0.35	1.69	5.24
	BCg	30 - 52/92	30.48	8	61.52	SC	0.26	1.34	1.08
	Cg	52/92 - 110+	22.48	3	74.52	SCL	0.13	1.59	0.16
MAG-P3	Apg	0 - 35/43	42.48	19	38.52	C	0.45	1.60	22.68
	Cg1	35/43 - 78	10.48	2	87.52	LS	0.19	1.39	0.38
	Cg2	78 - 92/97	21.48	5	73.52	SCL	0.23	1.37	0.38
	Cg3	92/97 - 143+	10.48	2	87.52	LS	0.19	nd	0.12

Key:

Textural class: C = clay; SC= sandy clay; SCL = sandy clay loam; LS = loamy sand; nd = not determined

The trend of clay content with depth was inconsistent in MAG-P1 and MAG-3 but it showed a decreasing trend with depth in MAG-2. This is different from the study by Msanya *et al.* (2018) for soils of Dodoma Capital City District in Tanzania where there was a general trend of clay increasing with depth.

The silt contents in topsoil of the studied profiles ranged from 12 to 19% while in subsoil it ranged from 2 to 18%. Generally, MAG-P1 had higher silt content in its all genetic horizons than other profiles with MAG-P3 having the lowest silt content in its all genetic horizons. The silt content increased with depth in MAG-P1 while it decreased with depth in MAG-P2 similar to the observation made by Assen *et al.* (2010) for some selected soil profiles of Gonde Micro-catchment, Arsi Highlands in Ethiopia. But the trend of silt content with depth was irregular in MAG-P3 profile which is similar to many recent pedological characterization studies (Assen *et al.*, 2010; Mtama *et al.*, 2018; Mukungurutse *et al.*, 2018).

The topsoil sand content from the studied profiles ranged from 38.52 to 53.52% while the subsoil ranged from 29.52 to 87.52% sand. Generally, MAG-P1 had lowest sand content throughout the profile depth as compared to other profiles with MAG-P3 having the highest sand content in its subsurface genetic horizons than MAG-P2 except for the topsoil sand content where the latter contains higher content. Generally, the sand content decreased with depth in MAG-P1, increased with depth in MAG-P2 and showed an irregular trend with depth in MAG-P3. Similar observations have been recorded for other soils in many pedological studies (Hailu *et al.*, 2015; Mbaga *et al.*, 2017; Mtama *et al.*, 2018).

In terms of soil textural classes, the MAG-P1 profile had clay topsoil overlying heavy clay subsoil similar to one of the pedons studied by Msanya *et al.* (2018) in Dodoma Capital

City District, Tanzania. The MAG-P2 had sandy clay topsoil overlying sandy clay and sandy clay loam subsoil while in MAG-P3 the topsoil was clay overlying loamy sand and sandy clay loam subsoil. The heavy clays observed in profile MAG-P1 as well as topsoil clay in MAG-P3 are likely to restrict root growth of most crop species (Msanya *et al.*, 2018; Soil Survey Staff, 2014) including rice crop which is commonly grown in the area. Also, these textures imply difficult workability and therefore, land preparation on this soil should be done when it is not very dry or wet as the workability is difficult in very dry and wet conditions for these soils (Assen *et al.*, 2010; Soil Survey Staff, 2014). The topsoil texture of profiles MAG-P2 is favourable and does not restrict root growth of most field crops such as rice (Mbaga *et al.*, 2017; Msanya *et al.*, 2018). The higher sand content in the subsoils of MAG-P2 and MAG-P3 may imply poor soil water holding capacity and higher risk of nutrient leaching.

3.2.2.2 Silt to clay (silt/clay) ratio

The results showed that topsoil silt/clay ratios of the studied soil profiles ranged from 0.28 to 0.45 while subsoil values ranged from 0.13 to 0.35. The silt/clay ratio showed a decreasing trend with increase in soil depth for soil profile MAG-P2 while profiles MAG-P1 and MAG-P3 showed an irregular trend with increasing soil depth similar to some selected studies for other soils (Sharu *et al.*, 2013; Kalala *et al.*, 2017; Tenga *et al.*, 2018). It has been reported that old parent materials usually have a silt/clay ratio below 0.15 while silt/clay ratios above 0.15 are indicative of young parent materials (Sharu *et al.*, 2013). The results of this study showed that, all the studied soils have silt/clay ratios above 0.15 except horizon Cg in profile MAG-P2 which had a silt/clay ratio of 0.13. Generally, these results indicate that the soils of Magozi Irrigation Scheme are relatively young with high degree of weathering potential. Similar results have been reported for other soils of similar ecological setting in Tanzania and beyond (Sharu *et al.*, 2013; Kebeney *et al.*, 2014; Kalala *et al.*, 2017).

3.2.2.3 Bulk Density

The soil bulk density values of the studied soils of Magozi Irrigation Scheme are as presented in Table 3.4. According to Msanya *et al.* (2018), bulk density (BD) is an important parameter for the description of soil quality and ecosystem function. Soil bulk density results are used as indicators of problems of root penetration and soil aeration in different soil horizons (Landon, 2014). For example, increases in soil bulk density can reduce the infiltration of water into the soil profile and increase runoff (Assen *et al.*, 2010; Landon, 2014; Msanya *et al.*, 2018).

The topsoil bulk densities of the studied soils ranged from 1.21 to 1.69 g cm^{-3} while subsoils ranged from 1.34 to 1.72 g cm^{-3}. The bulk density values in profiles MAG-P1 and MAG-P2 showed irregular trend with depth while they decreased with depth in MAG-P3. Generally, the bulk density values in MAG-P1 and topsoil in MAG-P3 were in the normal range of 1.00 to 1.6 g cm^{-3} for clay soils according to Landon (2014) except for horizon BAw in MAG-P1 which had a value of 1.72 g cm^{-3} that is beyond the normal range. All bulk density values for MAG-P2 and subsoils in MAG-P3 were in the normal range of 1.2 to 1.8 g cm^{-3} for soils with high sand content (Landon, 2014). According to Landon (2014), bulk densities above 1.75 g cm^{-3} for sands or 1.46 to 1.63 g cm^{-3} for silts and clays have been recorded to cause hindrance to root.

3.2.2.4 Penetration Resistance (PR)

Penetrometry or soil strength, measures the resistance of soil (penetration resistance) to vertical force by poking a rod or penetrometer into the soil (Leung and Meyer, 2003; Vanags *et al.*, 2004). Soil strength is an important characteristic affecting many aspects of agricultural soils, such as the performance of cultivation implements and root growth (Vanags *et al.*, 2004). The soil Penetration Resistance (PR) values in MPa of all the horizons of the studied soil profiles are presented in Table 3.4. These results showed that, the topsoil PR values ranged from 5.24 to 22.68 MPa. All the topsoil PR values of the studied profiles are greater than 3 MPa and therefore can be rated as extremely dense (compact) in terms of degree of soil consolidation according to Hazeltonn and Murphy (2016) where root growth virtually ceases. The subsoil PR values ranged from 0.12 to 10.12 MPa which can be rated as loose to extremely dense according (Hazeltonn and Murphy, 2016). The loose category of penetration resistance presents no effect to plant root growth (Hazeltonn and Murphy, 2016). In this study, generally, the PR values showed a decreasing trend with increasing soil depth in all the studied profiles with topsoil values being higher than subsoil values. This trend is contrary to other studies which reported lower topsoil PR values than subsoil values (Kebeney *et al.*, 2014; Massawe *et al.*, 2017). This variation may be due to the fact that soil penetration resistance mainly depends on soil type, bulk density and soil moisture content (Bengough *et al.*, 2000; Vanags *et al.*, 2004; Sudan, 2015; Hazeltonn and Murphy, 2016). In this study, the surface soils of all the profiles were relatively drier and more consolidated than most subsoil horizons, hence the observed higher PR values in topsoils than in subsoils.

3.2.3 Soil Chemical Properties

The selected chemical properties of the studied soil profiles in Magozi Irrigation Scheme are presented in Tables 3.5 and 3.6.

3.2.3.1 Soil pH

The soil pH values in water varied between and within soil profiles (Table 3.5). The soil pH in water (1:2.5 soil to water) ranged from 7.0 (neutral) to 8.1 (moderately alkaline) for topsoil while its subsoil pH ranged from 7.4 (mildly alkaline) to 9.0 (strongly alkaline) (Msanya *et al.*, 2001; Landon, 2014). The soil pH ranged from moderately alkaline to strongly alkaline in soil profile MAG-P1 (Msanya *et al.*, 2001) which can be attributed to low leaching of bases in clay soils (Landon, 2014; Mukungurutse *et al.*, 2018) typical in this profile. In MAG-P2, the soil reaction ranged from mildly alkaline to moderately alkaline while it ranged from neutral to mildly alkaline in MAG-P3. The soil pH values in

MAG-P2 and MAG-P3 were slightly lower than in MAG-P1 profile. This may be attributed to higher leaching of bases due to higher sand content in MAG-P2 and MAG-P3 profiles than in MAG-P1 (Landon, 2014; Mukungurutse *et al.,* 2018). The soil pH in KCl (pH_{KCl}) values of all the studied soil profiles were lower than soil pH in water (pH_{H2O}) values, indicating that the soils had net negative charge (Msanya *et al.,* 2018).

Generally, the soil pH showed irregular trend with depth in all the studied soil profiles except for MAG-P2 profile which showed a slight decreasing trend with depth. This is similar to some selected pedological studies in which the trend of soil pH showed irregular trend as well as regular trend with soil depth (Sharu *et al.*, 2013; Massawe, 2015; Mtama *et al.,* 2018). Most plants thrive well in soils of pH 6.5 to 7.5 (Baize, 1993; Massawe, 2015; Msanya *et al.,* 2018). Thus, MAG-P1 and MAG-P2 soils may present limitations to crop growth because of pH values > 7.5 in both topsoil and subsoil as compared to MAG-P3 by limiting availability of some plant nutrients such as phosphorus (Landon, 2014; Msanya *et al.*, 2018). However, flooding rice soils has been documented to moderate the pH towards a neutral pH condition (Massawe, 2015). Furthermore, the results of soil pH indicate a trend towards development of soil salinity in the scheme (Landon, 2014).

3.2.3.2 Electrical Conductivity (EC)

The electrical conductivity values in soil to water suspensions ($EC_{1:2.5}$) for the studied profiles are presented in Table 3.5. The topsoil $EC_{1:2.5}$ values ranged from 0.15 to 2.43 dS m^{-1} while the subsoil values ranged from 0.03 to 1.33 dS m^{-1}. Generally, there was irregular trend of $EC_{1:2.5}$ with soil depth similar to many other studies in different areas (Kalala *et al.,* 2017; Mtama *et al.,* 2018; Tenga *et al.*, 2018). According to Msanya *et al.* (2001), these values will cause no yield reduction because EC values are less than 1.7 dS m^{-1} while 10 to 25 percent (%) crop yield reduction occurs for values 1.7 to 2.5 dS m^{-1}. However, these ratings are based on electrical conductivity of the saturated paste extract EC_e which is a standard of assessing plant response to salinity. Since 1954 to date, the EC_e

has been considered as the best indicator of crop response to salinity compared with EC from other soil to water ratio suspension methods (US Salinity Laboratory Staff, 1954; He *et al.,* 2013; Matthees *et al.,* 2017; Kargas *et al.,* 2018).

3.2.3.3 Organic Carbon and Organic Matter Contents

The topsoil organic carbon (OC) in the studied soil profiles ranged from 1.13 to 1.59% while the organic matter (OM) ranged from 1.95 to 2.74% (Table 3.5) both rated as low to medium according to Msanya *et al.* (2001). On the other hand, subsoil organic carbon ranged from 0.09 to 1.97% and organic matter ranged from 0.16 to 3.40% rated as very low to medium (Msanya *et al.*, 2001). It has been documented that, the low accumulation of organic matter (OM) in cultivated soils could be due to the reduction in total organic inputs (litter, crop residues, and manure), increased mineralization rates of OM caused by tillage, increased soil temperatures due to exposure of the soil surface and increased wetting-and-drying cycles as well as the loss by soil erosion (Hailu *et al.,* 2015; Kalala *et al.,* 2017; Mbaga *et al.,* 2017).

The soil content of both OC and OM in MAG-P1 and MAG-P2 showed a clear decreasing trend with increase in soil depth while MAG-P3 profile showed an irregular trend of both OC and OM content with increase in depth. The OC and OM trends in the studied soil profiles are similar to many selected pedological studies (Assen and Yilma, 2010; Kebeney *et al.,* 2014; Mtama *et al.,* 2018).

3.2.3.4 Total Nitrogen (TN)

The results on Total Nitrogen (TN) of the studied soil profiles in Magozi Irrigation Scheme are presented in Table 3.5. The topsoil TN content ranged from 0.13% rated as low to 0.23% rated as medium while in subsoil content ranged from 0.04 to 0.1% corresponding to very low to low respectively (Msanya *et al.,* 2001; Landon, 2014).

Table 3.5: Selected chemical properties of soils of Magozi Irrigation Scheme in Iringa Region

Profile no.	Horizon	Depth (cm)	pH H_2O	pH KCl	EC ($dS\ m^{-1}$)	OC (%)	OM (%)	Total N (%)	C/N Ratio	Available P (Olsen) ($mg\ kg^{-1}$)
MAG-P1	Ap	0 - 53/69	8.1	6.8	0.42	1.13	1.95	0.13	8.69	22.87
	BAw	53/69 - 107/110	9.0	7.6	1.02	0.84	1.45	0.08	10.50	9.57
	Bss	107/110 - 200+	8.9	7.2	0.81	0.09	0.16	0.08	1.13	8.23
MAG-P2	Ap	0 - 30	7.9	7.4	2.43	1.59	2.74	0.23	6.91	14.59
	BCg	30 - 52/92	7.8	6.9	0.97	0.84	1.45	0.10	8.40	9.42
	Cg	52/92 - 110+	7.8	7.6	1.33	0.38	0.66	0.06	6.33	5.43
MAG-P3	Apg	0 - 35/43	7.0	5.7	0.15	1.13	1.95	0.14	8.07	19.18
	Cg1	35/43 - 78	7.4	6.2	0.03	0.19	0.33	0.05	3.80	4.98
	Cg2	78 - 92/97	7.5	6.0	0.07	0.56	0.97	0.06	9.33	12.97
	Cg3	92/97 - 143+	7.7	6.4	0.04	1.97	3.40	0.04	49.25	9.71

Table 3.6: Exchangeable bases and related chemical properties of the studied soil profiles in Magozi Irrigation Scheme

Profile no.	Horizon	Depth (cm)	Exchangeable Bases Ca ($cmolkg^{-1}$)	Mg ($cmolkg^{-1}$)	Na ($cmolkg^{-1}$)	K ($cmolkg^{-1}$)	TEB ($cmolkg^{-1}$)	CEC_{soil} ($cmolkg^{-1}$)	CEC_{clay} ($cmolkg^{-1}$)	BS (%)	ESP (%)
MAG-P1	Ap	0 - 53/69	12.51	2.83	0.49	1.61	17.44	26.6	44.98	65.56	1.84
	BAw	53/69 - 107/110	12.42	2.25	1.07	0.64	16.38	22.8	41.06	71.84	4.69
	Bss	107/110 - 200+	13.88	5.98	1.51	0.41	21.78	24	45.14	90.75	6.29
MAG-P2	Ap	0 - 30	15.80	4.20	0.91	0.69	21.60	17.6	35.14	122.73	5.17
	BCg	30 - 52/92	12.50	2.46	0.57	0.38	15.91	16	42.99	99.44	3.56
	Cg	52/92 - 110+	10.29	2.20	0.61	0.11	13.21	11.3	44.44	116.90	5.40
MAG-P3	Apg	0 - 35/43	12.85	3.03	0.68	0.51	17.07	19.8	37.44	86.21	3.43
	Cg1	35/43 - 78	0.43	0.54	0.29	0.09	1.35	3.4	26.19	39.71	8.53
	Cg2	78 - 92/97	5.66	0.40	0.32	0.26	6.64	8.4	30.12	79.05	3.81
	Cg3	92/97 - 143+	0.26	0.50	0.30	0.10	1.16	7.1	2.93	29.00	7.50

Key: TEB = Total Exchangeable Bases; CEC = Cation Exchange Capacity; BS= Base Saturation; ESP = Exchangeable Sodium Percentage

In MAG-P1 and MAG-P2 profiles, the total soil N showed a clear decreasing trend with increase in soil depth except for MAG-P3 profile which showed an irregular trend of total N with increase in depth. The trends of total N in these soil profiles are similar to some selected pedological studies in Tanzania and beyond (Assen and Yilma, 2010; Hailu *et al.*, 2015; Mbaga *et al.*, 2017; Msanya *et al.*, 2018). According to Hailu *et al.* (2015), the generally lower level of nitrogen in cultivated fields as observed in this study, implies that fertilizer and or organic matter additions have not replaced the total N lost due to harvest removal, leaching and humus losses associated with cultivation. Therefore, these results show that, the studied soils require nitrogen replenishment in order to sustain and improve rice productivity.

3.2.3.5 Carbon to Nitrogen (C:N) ratio

The soil C:N ratios give an indication of the quality of organic matter in terms of nitrogen mineralization (Msanya *et al.*, 2001; Landon, 2014). The results of C:N ratios of the studied soil profiles are as presented in Table 3.5. According to Msanya *et al.* (2001), the C:N ratios of 8-13, 14-20 and greater than 20 are classified as good quality, moderate quality and poor quality organic matter respectively. The topsoil C:N ratios in MAG-P1 and MAG-P3 with values 8.69 and 8.07 respectively were within the acceptable range of good quality organic matter, while the topsoil C:N ratio in MAG-P2 profile (6.91) was lower than 8 (Msanya *et al.*, 2001). The C:N ratios for subsoil horizons ranged from 1.13 to 49.25. The recorded C:N ratio of 49.25 rated according to Msanya *et al.* (2001) as of poor quality organic matter belongs to horizon Cg3 of MAG-P3 profile which had imperfect drainage, revealing that the variation in C:N ratio could be related to soil drainage condition as emphasized by Assen and Yilma (2010).

The small or narrow C:N ratio positively influences microbial activities to ensure rapid mineralization of organic matter with the consequent release of nutrient elements into the soil solution for crop plant assimilation (Kebeney *et al.,* 2014; Kalala *et al.,* 2017). The higher or wider C:N ratio indicates that a low level of mineralization exists in the soil (Assen and Yilma, 2010). Generally, there was inconsistent trend of C:N ratio with soil depth for all the studied soil profiles which has also been reported in many other studies (Assen and Yilma, 2010; Kalala *et al.,* 2017; Mtama *et al.,* 2018). This inconsistent trend may be attributed to the existence of different conditions of mineralization as suggested by Assen and Yilma (2010).

3.2.3.6 Available Phosphorus (P)

The data on available P from the studied soil profiles are as presented in Table 3.5. The topsoil available P ranged from 14.59 to 22.87 mg kg^{-1} which can be rated as high according to Msanya *et al.* (2001). Generally, the topsoil available P values correspond to high category (Msanya *et al.,* 2001). While this may mean adequate soil available P for crop production, on the other hand, the high soil pH values in the topsoil (7.0 to 8.1) may lead to unavailability of nutrients like P. This is because, according to Landon (2014), the soil pH ranges of 7.0 to 8.5 and higher decrease availability of P and cause deficiency in plants.

The subsoil horizons had available P values ranging from 4.98 to 12.97 mg kg^{-1} rated as low to high. The results showed that there was a decreasing trend of available P with increasing soil depth in MAG-P1 and MAG-P2 while an inconsistent trend was observed in MAG-P3 profile as similarly observed in other studies elsewhere (Kebeney *et al.,* 2014; Msanya *et al.,* 2018; Mtama *et al.,* 2018).

3.2.3.7 Exchangeable Bases

Exchangeable Ca

Exchangeable Ca in the surface soils (Table 3.6) ranged from 12.51 to 15.80 $cmolkg^{-1}$ both rated as high (Landon, 2014; Hazeltonn and Murphy, 2016). The topsoil exchangeable Ca content in the studied profiles was high according to the ratings by Hazeltonn and Murphy (2016). The subsurface exchangeable Ca ranged from 0.26 to 13.88 cmolkg^{-1} which is rated as very low to high (Landon, 2014; Hazeltonn and Murphy, 2016). According to Landon (2014), the high exchangeable Ca may cause less availability of P to plants. Generally, MAG-P3 had the lowest exchangeable Ca in its subsoil as compared to MAG-P1 and MAG-P2. The MAG-P2 profile showed a clear decreasing trend of exchangeable Ca with increasing soil depth while MAG-P1 and MAG-P3 profiles were characterized by an irregular trend with soil depth. Both trends have been reported in many pedological studies for other soils in Tanzania and beyond (Hailu *et al.,* 2015; Kalala *et al.,* 2017; Mtama *et al.,* 2018).

Exchangeable Mg

The results in Table 3.6 on exchangeable Mg indicated that, topsoil Mg values ranged from moderate (2.83 cmolkg^{-1}) to high (4.20 cmolkg^{-1}) according to the ratings by Hazeltonn and Murphy (2016). The subsoil exchangeable Mg ranged from 0.40 to 5.98 cmolkg^{-1} which is rated as low to high (Hazeltonn and Murphy, 2016). The exchangeable Mg was lowest in the subsoil horizons of MAG-P3 profiles. Generally, only MAG-P2 profile showed a clear decreasing trend of exchangeable Ca with increasing soil depth while irregular trend was observed in MAG-P1 and MAG-P3 profiles as also reported in many other studies (Hailu *et al.,* 2015; Mukungurutse *et al.,* 2018; Tenga *et al.,* 2018). It has been noted that Mg deficiency can be present in crops especially rice grown in the area which is associated with not only soil Mg deficiency but also the presence of large amounts of other cations, particularly Ca and K as discussed in nutrient ratios (Landon, 2014; Msanya *et al.,* 2016; Tenga *et al.,* 2018).

Exchangeable K

The exchangeable K as presented in Table 3.6 ranged from moderate (0.51 cmolkg^{-1}) to high (1.61 cmolkg^{-1}) for topsoil and very low (0.09 cmolkg^{-1}) to moderate (0.64 cmolkg^{-1})

in the subsoil according to the ratings of Hazeltonn and Murphy (2016). There was a clear variation in the content of exchangeable K both within and among the studied soil profiles. The MAG-P1 and MAG-P2 profiles showed a regular decreasing trend of exchangeable K with increasing soil depth while MAG-P3 was characterized by slight irregular trend. Such kinds of trends have also been reported in many studies (Hailu *et al.,* 2015; Kalala *et al.,* 2017; Mtama *et al.,* 2018). It has been reported by Landon (2014) that, in general terms a response to K fertilizer is likely when a soil has an exchangeable K value below 0.2 $cmolkg^{-1}$ and unlikely when it is above 0.4 $cmolkg^{-1}$. However, it has been noted according to Landon (2014) that, these limits should not be considered as definitive, since they are subject to variation dependent both on nature of the soil, the environment and the crop.

Exchangeable Na

The results on exchangeable Na of the studied soil profiles are presented in Table 3.6 where the topsoil values ranged from 0.49 to 0.91 $cmolkg^{-1}$ and 0.29 to 1.51 $cmolkg^{-1}$ in the subsoil. The topsoil exchangeable Na ranges from medium to high and low to high in subsoil (Msanya *et al.,* 2001; Hazeltonn and Murphy, 2016). More important than the absolute values of exchangeable Na is the exchangeable sodium percentage (ESP) which is a measure of soil sodicity (Landon, 2014; Hazeltonn and Murphy, 2016). The exchangeable K showed a regular increasing trend with increase in soil depth for profile MAG-P1 while profiles MAG-P2 and MAG-P3 were characterized by an irregular trend as also reported in other studies (Msanya *et al.,* 2016; Kalala *et al.,* 2017; Mukungurutse *et al.,* 2018). Although Na may, in particular circumstances, be utilized by some plants as a partial substitute for K, it is not an essential plant nutrient (Landon, 2014). When Na is present in the soils in significant quantities, particularly in proportion to other cations present, it can have an adverse effect both on crops and physical soil properties (Msanya *et al.,* 2001; Landon, 2014; Hazeltonn and Murphy, 2016).

3.2.3.8 Cation Exchange Capacity (CEC)

The soil Cation Exchange Capacity (CEC_{soil}) is the capacity of the soil to hold and exchange cations, which provides a buffering effect to changes in pH, available nutrients, calcium levels and soil structural changes (Landon, 2014; Hazeltonn and Murphy, 2016). The soil CEC values are presented in Table 3.6, showing values ranging from 17.6 $cmolkg^{-1}$ in MAG-P2 to 26.6 $cmolkg^{-1}$ in MAG-P1 rated according to Msanya *et al.* (2001) as medium to high, respectively. The subsoil CEC_{soil} ranged from 3.4 to 24 $cmolkg^{-1}$ rated as very low to medium (Landon, 2014; Hazeltonn and Murphy, 2016). Generally, the topsoil CEC_{soil} values were higher than most subsoil CEC_{soil} values probably due to the contribution of higher organic matter to CEC_{soil} from the topsoil compared to the subsoils, the observation which is in line with other studies (Assen and Yilma, 2010; Kebeney *et al.,* 2014; Mtama *et al.,* 2018). However, some studies have also reported lower topsoil CEC_{soil} values than subsoil CEC_{soil} values in some soil profiles (Msanya *et al.,* 2003; Hailu *et al.,* 2015; Mukungurutse *et al.,* 2018). The CEC_{soil} values showed a clear decreasing trend with increasing soil depth in profiles MAG-P1 and MAG-P2 except for MAG-P3 profile which had inconsistent trend. Both CEC_{soil} trends with increasing soil depth have been reported in many studies from other soils (Msanya *et al.,* 2003; Mtama *et al.,* 2018; Mukungurutse *et al.,* 2018).

The CEC of clay (CEC_{clay}) is an important indicator of both weathering stage and the type of clay minerals dominating the soil (Kebeney *et al.,* 2014). For example, soils with low both CEC and CEC_{clay} indicate advanced stage of weathering and vice versa (Kebeney *et al.,* 2014; Msanya *et al.,* 2018). The results on calculated CEC_{clay} are presented in Table 3.6, showing a range from 35.14 to 44.98 $cmolkg^{-1}$ while the subsoil CEC_{clay} ranged from 2.93 to 45.14 $cmolkg^{-1}$. The CEC_{clay} showed an inconsistent trend with increasing soil depth for profiles MAG-P1 and MAG-P3 while profile MAG-P2 showed an increasing trend of CEC_{clay} with increasing soil depth. Similar trends of CEC_{clay} have been observed in other pedological studies (Kebeney *et al.,* 2014; Msanya *et al.,* 2018; Tenga *et al.,* 2018). The MAG-P1 profile had the highest values of CEC_{clay} as compared to other soil profiles due to the higher clay content in all its horizons. Additionally, the results of CEC_{clay} indicated that the studied soils are more of mixed clay mineralogy with a high weathering potential (Kebeney *et al.,* 2014; Msanya *et al.,* 2018).

3.2.3.9 Base Saturation (BS)

Base saturation (BS) is an indicator of soil fertility (Landon, 2014) which refers to the percentage of cation exchange capacity that is saturated with total exchangeable bases (potassium, calcium, magnesium and sodium ions) (Hazeltonn and Murphy, 2016). The percent base saturation values of the studied soil profiles (Table 3.6) ranged from 65.56 to 122.73% which is rated as high to very high for topsoil and 29.00 to 116.90% for subsoils rated as low to very high (Hazeltonn and Murphy, 2016; Landon, 2014). When all the soil particle exchange sites are occupied with bases, the BS becomes 100% when the soil pH is well above 7 (alkaline) (Msanya *et al.,* 2018). However, in soil profile MAG-P2, the percent base saturation exceeded 100 % for horizons Ap with 122.73% and Cg with 116.90%. It has been reported that when the soil pH is above 7.2, there is free solution Ca, Mg, and/or Na (unattached to the soil exchange complex) in the soil that is unavoidably extracted (Msanya *et al.,* 2018). In this case the sum of the measured cation saturations could add up to more than 100% (Msanya *et al.,* 2018). Therefore, the high BS above 100% in some horizons of profile MAG-P2 can be due to their high soil pH values that are greater than 7.2. Generally, the topsoil percent base saturation was above 60% implying good soil fertility for crop production in the area (Hazeltonn and Murphy, 2016; Msanya *et al.,* 2018). In profile MAG-P1, the percent base saturation results showed an increasing trend with increasing in soil depth while soil profiles MAG-P2 and MAG-P3 exhibited an irregular trend as also reported in other studies (Kebeney *et al.,* 2014; Kalala *et al.,* 2017; Mukungurutse *et al.,* 2018).

3.2.4.0 Exchangeable Sodium Percentage (ESP)

Msanya *et al.* (2001) explained that exchangeable sodium percentage (ESP) is worthy reporting than the absolute level of exchangeable Na as it measures the soil sodicity. The results on ESP for the studied soil profiles in Table 3.6 indicated that the topsoil values ranged from 1.84 to 5.17% all being rated as non-sodic according to Msanya *et al.* (2001). The subsoil ESP ranged from 3.56 to 8.53% which can be rated as non-sodic to slightly sodic (Msanya *et al.,* 2001; Hazeltonn and Murphy, 2016). The ESP values showed a regular increasing trend with increasing soil depth for profile MAG-P1 while an irregular trend was observed for profiles MAG-P2 and MAG-P3.

3.2.4 Nutrient Balance

The availability of plant nutrients does not only depend on absolute concentrations of nutrients but also on nutrient balance (nutrient ratios) as well (Mtama *et al.,* 2018). The uptake of nutrients by crops is thus influenced by the relative concentrations of exchangeable bases (Mbaga *et al.,* 2017; Mtama *et al.,* 2018). The nutrient ratios of exchangeable bases for this study are presented in Table 3.7.

Ca/Mg ratio

There was irregular trend of Ca/Mg ratios with depth in all the studied soil profiles which is contrary to Landon (2014) that Ca/Mg ratios commonly decrease with depth. The Ca/Mg ratios of topsoil horizons of all soil profiles were in the optimal levels ranging from 3.76 to 4.42. The Ca/Mg ratios below 5:1 are considered favourable for most crops (Landon, 2014; Mbaga *et al.,* 2017). Some subsurface genetic horizons in all profiles were characterized by Ca/Mg ratios higher than 5:1 which are above the optimal level. Such values are 5.52, 5.08 and 14.15 in MAG-P1, MAG-P2 and MAG-P3 respectively. According to Landon (2014), when Ca/Mg ratios are higher than 5:1, Mg becomes unavailable with increasing Ca as well as reduced P availability when there is also high soil pH. The Ca/Mg ratios lower than 3:1 were also recorded in the subsurface genetic horizons of the studied profiles, ranging from 0.52 to 0.80 in MAG-P3 to 2.32 in MAG-P1. Landon (2014) reported that the Ca/Mg ratios below 3:1 may inhibit P uptake by plants as well as causing slight reduction of Ca availability.

K/Mg ratio

In this study, the K/Mg ratios of all the studied soil profiles of Magozi Irrigation Scheme ranged from 0.05 to 0.65 (Table 3.7) which are below 1.5. These are acceptable K/Mg ratios for field crops like rice because the acceptable K/Mg ratio should be less than 1.5 or 3:2 for the uptake of Mg^{2+} from soil by plants (Landon, 2014; Mtama *et al.*, 2018). Also, the K/Mg ratio greater than 2:1 may inhibit Mg uptake by plants, while the high K content in soils has an antagonistic effect on Mg uptake by plants because K^{+} competes for apoplast binding sites and transporters with Mg^{+} (Landon, 2014).

Table 3.7: Nutrient ratios for the representative soils of Magozi Irrigation Scheme

Profile no.	Horizon	Depth (cm)	Nutrient Ratio			
			Ca/Mg	Ca/TEB	K/Mg	K/CEC (%)
MAG-P1	Ap	0 - 53/69	4.42	0.72	0.57	6.05
	BAw	53/69 - 107/110	5.52	0.76	0.28	2.81
	Bss	107/110 - 200+	2.32	0.64	0.07	1.71
MAG-P2	Ap	0 - 30	3.76	0.73	0.16	3.92
	BCg	30 - 52/92	5.08	0.79	0.15	2.38
	Cg	52/92 - 110+	4.68	0.78	0.05	0.97
MAG-P3	Apg	0 - 35/43	4.24	0.75	0.17	2.58
	Cg1	35/43 - 78	0.80	0.32	0.17	2.65
	Cg2	78 - 92/97	14.15	0.85	0.65	3.10
	Cg3	92/97 - 143+	0.52	0.22	0.20	2.50

K/CEC ratio

The K/CEC ratios were generally decreasing with depth for MAG-P1 and MAG-P2 profiles contrary to MAG-P3 in which the K/CEC ratios increased with depth for the first three genetic horizons (Apg, Cg1 and Cg2) and then decreased for the deepest horizon (Cg3). According to Mtama *et al.* (2018), there were irregular trends with depth for K/CEC ratios in Seatondale, Mbimba and Inyala pedons while the Uyole pedon showed increasing K/CEC ratios with depth. In MAG-P1 and MAG-P2, the K/CEC ratios were greater than 2% except for their deeper horizons which had 1.71 in Bss and 0.97 in Cg for MAG-P1 and MAG-P2, respectively. The K/CEC ratios were greater than 2% in all soil genetic horizons for MAG-P3, implying favorable conditions for production of tropical crops (Mtama *et al.,* 2018) because 2% is a suggested minimum level of K/CEC ratio that avoid K deficiency in tropical soils (Landon, 2014).

3.2.5 Correlation between soil properties

Pearson's correlation matrix (Table 3.8) showed significant positive and negative correlations at $p \leq 0.05$ between some selected soil physical and chemical properties. Soil pH showed positive significant correlation with exchangeable Na (r = 0.752) similar to other studies (Worku and Bedadi, 2016; Mukungurutse *et al.,* 2018); clay content revealed positive signicant correlations with silt content (r = 0.940); CEC (r = 0.981); exchangeable bases (Ca, Mg, Na and K with r = 0.835, 0.770, 0.746 and 0.702 respectively); base saturation (r = 0.366) and a negative correlation with sand content (r = -0.995) as supported in other literatures (Hailu *et al.,* 2015; Mukungurutse *et al.,* 2018; Aderemi *et al.,* 2019). The silt content showed a negative correlation with sand content (r = -0.970) and positive correlations with CEC (r = 0.898), exchangeable Ca (r =0.772), Mg (r = 0.740) and Na (r =0.739). The sand content revealed strong negative correlations with CEC (r = -0.968) and exchangeable bases (Ca, Mg, Na and K with r = -0.826, -0.771,

-0.753 and -0.670 respectively) which is supported in other literatures (Iqbal *et al.,* 2005; Hailu *et al.,* 2015; Mukungurutse *et al.,* 2018).

Total N revealed a positive correlation with exchangeable Ca (r = 0.709). The available P showed positive correlation with exchangeable K (r = 0.807) and a negative correlation with ESP (r = -0.760). CEC indicated positive correlations with all the exchangeable bases (Ca, Mg, Na and K with r = 0.842, 0.757, 0.687 and 0.770 respectively) and a negative correlation with ESP (r = -0.634). Exchangeable Ca had positive correlations with exchangeable Mg (r =0.818), Na (r = 0.700) and base saturation (r = 0.790). Exchangeable Mg had positive correlation with exchangeable Na (r = 0.878) while exchangeable K revealed a negative correlation with ESP (r = -0.705). These results are in agreement with the reported correlations between similar properties in literatures (Papiernik *et al.,* 2005; Ufot *et al.,* 2016; Mukungurutse *et al.,* 2018; Aderemi *et al.,* 2019).

Table 3.8: Pearson correlation coefficients between selected soil properties for the studied soil profiles in Magozi Irrigation Scheme

	pH (H_2O)	% Clay	% Silt	% Sand	OC (%)	Total N (%)	Available P (mg kg^{-1})	CEC	Exch. Ca	Exch. Mg	Exch. Na	Exch. K	BS (%)	ESP (%)
								(cmolkg^{-1})						
pH	1													
% Clay	NS	1												
% Silt	NS	0.940*	1											
% Sand	NS	-0.995*	-0.970*	1										
OC (%)	NS	NS	NS	NS	1									
Total N (%)	NS	NS	NS	NS	NS	1								
Available P	NS	NS	NS	NS	NS	NS	1							
CEC	NS	0.981*	0.898*	-0.968*	NS	NS	NS	1						
Exch. Ca	NS	0.835*	0.772*	-0.826*	NS	0.709*	NS	0.842*	1					
Exch. Mg	NS	0.770*	0.740*	-0.771*	NS	NS	NS	0.757*	0.818*	1				
Exch. Na	0.752*	0.746*	0.739*	-0.753*	NS	NS	NS	0.687*	0.700*	0.878*	1			
Exch. K	NS	0.702*	NS	-0.670*	NS	NS	0.807*	0.770*	NS	NS	NS	1		
BS (%)	NS	0.366*	NS	NS	NS	NS	NS	NS	0.790*	NS	NS	NS	1	
ESP (%)	NS	NS	NS	NS	NS	NS	-0.760*	-0.634*	NS	NS	NS	-0.705*	NS	1

Key:

*Significant at $p \leq 0.05$; NS = Nonsignificant

3.2.6 Total Elemental Composition

3.2.6.1 Total Elemental Oxides

The concentrations of selected elemental oxides of the studied soil profiles in Magozi Irrigation Scheme are presented in Table 3.9. These results indicated that the most abundant oxide was SiO_2 which ranged from 47.1 to 51.9% for topsoils and 47.7 to 67.7% for subsoils. It has been reported that the high SiO_2 content in some soils is an indication of existence of amorphous silica (Msanya *et al.,* 2016; Kalala *et al.,* 2017). Generally, the content of SiO_2 was greatly influenced by sand content in which, MAG-P3 had the highest SiO_2 due to highest sand content followed by MAG-P2 with MAG-P1 having the lowest SiO_2 content as it was dominated by clay. Similar results were reported in other pedological studies in Tanzania (Msanya *et al.,* 2016; Kalala *et al.,* 2017). The Al_2O_3 was the second most abundant oxide with topsoil values ranging from 13 to 16% and subsoil values ranging from 9.3 to 16%.

The topsoil Fe_2O_3 ranged from 4.65 to 6.75% and 2.35 to 6.9% for subsoils. The content of Fe_2O_3 showed an increasing trend with increase in soil depth for profile MAG-P1, a decreasing trend with an increase in soil depth for profile MAG-P2 while showing an irregular trend with increase in soil depth for profile MAG-P3. Similar trends of Fe_2O_3 content have been reported in other pedological studies for soils of selected districts of Mbeya Region, Tanzania (Msanya *et al.,* 2016) and some typical alluvial soils of Kilombero District, Tanzania (Kalala *et al.,* 2017).

The K_2O content in the studied soils was low in topsoil and high in subsoils which is in agreement with the work by Kalala *et al.* (2017) for some typical alluvial soils of Kilombero District, Tanzania. The other reported oxides were CaO, TiO_2, MgO and SO_3 in which MgO content was the lowest.

Table 3.9: Total Elemental Oxides composition of soils of Magozi Irrigation Scheme

Profile no.	Horizon	Depth (cm)	Percentage Elemental Oxide Composition (%)								
			Al_2O_3	SiO_2	Fe_2O_3	K_2O	CaO	TiO_2	MgO	SO_3	TOTAL
MAG-P1	Ap	0 - 53/69	15	48.9	6.41	1.89	1.82	0.89	0.19	12.31	87.41
	BAw	53/69 - 107/110	15	48.5	6.53	1.9	1.95	0.92	0.19	8.47	83.46
	Bss	107/110 - 200+	16	47.7	6.9	1.86	1.74	0.96	0.16	14.16	89.48
MAG-P2	Ap	0 - 30	13	51.9	4.65	1.84	3.07	0.66	0.21	0.17	75.5
	BCg	30 - 52/92	12	55.2	4.38	2.01	1.85	0.67	0	15.93	92.04
	Cg	52/92 - 110+	14	55.4	4.03	2.08	2.48	0.56	0.23	6.42	85.2
MAG-P3	Apg	0 - 35/43	16	47.1	6.75	1.94	1.63	0.9	0.01	13.02	87.35
	Cg1	35/43 - 78	9.8	67.7	2.35	2.33	1.54	0.41	0.36	13.25	97.74
	Cg2	78 - 92/97	12	58	4.18	2.02	2.01	0.59	0.42	11.83	91.05
	Cg3	92/97 - 143+	9.3	67.1	2.61	2.31	1.16	0.33	0.16	0.21	83.18

The contents of K_2O, CaO, TiO_2 and MgO in the studied profiles were in low concentrations below 4.5% throughout the soil depth (Msanya *et al.*, 2016). According to Msanya *et al.* (2016) low levels of these elemental oxides in the studied soils may be associated with leaching during weathering process as well as due to low concentrations of these elements in the parent rocks or minerals.

3.2.6.2 Total concentrations of potentially toxic elements (PTEs)

Potentially toxic elements (PTEs) in soils are heavy metals and other trace elements that become toxic to living organisms when they reach higher concentrations than recommended (Antoniadis *et al.*, 2017). The PTEs include arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se), vanadium (V), strontium (Sr) and zinc (Zn) (Borůvka *et al.*, 2005; Hang *et al.*, 2009; Weindorf *et al.*, 2014; Antoniadis *et al.*, 2017). Soils are generally regarded as a sink of PTEs in terrestrial ecosystems (Antoniadis *et al.*, 2017). Therefore, soil pollution with PTEs has caused major concerns (Hang *et al.*, 2009; Weindorf *et al.*, 2014). This is because the PTEs above the background level in soils can be toxic to plants and may interfere with plant nutrient uptake as well as decreasing microbial biomass by killing or disabling soil organisms (He *et al.*, 2005; Hang *et al.*, 2009). Some PTEs such as Pb, Cr, Ni and Sr are carcinogenic and highly toxic to human beings and animals (Borůvka *et al.*, 2005; He *et al.*, 2005; Hang *et al.*, 2009).

The soils have natural levels of PTEs which vary due to the geology of the parent materials and exacerbated through repeated use of industrial fertilizers and/or pesticides containing the PTEs (He *et al.*, 2005; Weindorf *et al.*, 2014). The Total concentrations of PTEs measured by X-Ray Fluorescence Spectrometer in the studied soil profiles are Zn, Ni, Mn, Cu, Pb, V and Sr as indicated in Table 3.10. Although Zn, Ni, Mn and Cu are also considered as essential plant micronutrients, but when they occur in higher levels they are regarded as PTEs (Hang *et al.*, 2009; Zbíral, 2016).

Table 3.10: Total concentrations of potentially toxic elements (PTEs) for the studied soils of Magozi Irrigation Scheme

Profile no.	Horizon	Depth (cm)	Total concentrations of potentially toxic elements (mg kg^{-1})							
			Zn	Ni	Mn	Cu	Pb	V	Sr	Cr
MAG-P1	Ap	0 - 53/69	75	90	633	72	19	112	247	169
	BAw	53/69 - 107/110	75	106	660	102	21	128	264	152
	Bss	107/110 - 200+	66	88	788	90	19	135	262	161
MAG-P2	Ap	0 - 30	55	89	871	78	16	77	314	85
	BCg	30 - 52/92	44	86	552	75	19	70	284	123
	Cg	52/92 - 110+	41	68	365	66	14	73	342	98
MAG-P3	Apg	0 - 35/43	60	61	924	82	20	113	217	134
	Cg1	35/43 - 78	22	57	355	62	13	41	237	67
	Cg2	78 - 92/97	42	67	456	60	16	69	260	104
	Cg3	92/97 - 143+	28	64	281	57	14	40	217	56

The content of Zn in natural (unfertilized and uncontaminated) soil is related to the chemical composition of the parent rock and the extent of weathering processes (Nabulo *et al.,* 2006; Noulas *et al.,* 2018). Zn concentrations in the studied soils (Table 3.10) are within the acceptable range for uncontaminated soils (<100 mg kg^{-1}). Literatures indicate that typical total Zn contents in uncontaminated soils vary widely and can range from 10 to 100 mg kg^{-1} (Nabulo *et al.,* 2006; Alloway, 2012). Ni content in MAG-P1 profile and horizons Ap and BCg in profile MAG-P2 was above the critical concentrations of 70 mg kg^{-1} adopted in the UK and the Netherlands (Alloway, 2012) and 75 mg kg^{-1} set by the European Economic Community (EEC) (Pasquini, 2006). The content of Pb in the studied soils was below the critical concentrations of 70 mg kg^{-1} adopted in the UK and the Netherlands and 75 mg kg^{-1} set by the European Economic Community (EEC) as compared to Cr which was above these critical concentrations in all the profiles except in horizons Cg1 and Cg3 of MAG-P3 (Pasquini, 2006; Alloway, 2012). The maximum limit of 300 mg kg^{-1} for Pb and 600 - 800 mg kg^{-1} for Cr is permitted in agricultural soils in many countries (Li *et al*., 2006; Pasquini, 2006). Therefore, the concentrations of Pb and Cr in the studied soils of Magozi Irrigation Scheme were low hence not polluted or contaminated.

The Mn contents for the studied soils ranged from 281 to 924 mg kg^{-1}. The amount of Mn in rocks and soils varies greatly where as in soils they may range from 20 - 3000 mg kg^{-1}, yet most of this is unavailable for plant use (Lidon *et al.,* 2004; Millaleo *et al.,* 2010). Mn toxicity to plants is more common on very acidic soil (Millaleo *et al.,* 2010; Gałuszka *et al.*, 2015) which does not apply for soils of this study area because the soil pH values are mostly greater than 7.0. A background Cu level in soil (which refers to level in uncontaminated areas) result from weathering of Cu containing parent rock, and thus varies according to local geology and climate (Gałuszka *et al.*, 2015). In this study, soil Cu content ranged from 57 to 102 mg kg^{-1} which is within the typical concentrations of copper in soils that range from 14 to 109 mg kg^{-1} according to Gałuszka *et al.* (2015).

The earth's crust has an average vanadium (V) level of 100 mg kg^{-1} and in soils, V is released by either rock weathering and/or through anthropogenic emissions associated with the use of phosphate fertilizers (Carlon *et al.* 2007; Liu *et al.,* 2018; Shaheen *et al.,* 2019). The content of V in the studied soil profiles ranged from 40 to 135 mg kg^{-1}. According to Carlon *et al.* (2007), this range is within the safety limits for vanadium in soils that range between 90 and 500 mg kg^{-1} as set by European Union. Natural strontium (Sr) is the microelement that occurs in the earth's crust with an average concentration of 340 mg kg^{-1} (Dubchak, 2018; Gupta *et al.,* 2018). The levels of Sr found in the studied soils ranging from 217 to 342 mg kg^{-1} are within the normal range (Gupta *et al.,* 2018). The trend of Sr with soil depth showed similar trend as that of CaO in the studied profiles except for Apg and Cg1 horizons in MAG-P3, and the similarity could be due to Sr physical and chemical properties, which are analogous to those of calcium being its companion in geochemical processes (Dubchak, 2018).

3.2.7 Soil Classification

3.2.7.1 Classification of soils using USDA Soil Taxonomy

3.2.7.1.1 Diagnostic horizons and features

An inventory results on diagnostic surface and subsurface horizons and other features for each profile in Magozi Irrigation Scheme based on USDA Soil Taxonomy (Soil Survey Staff, 2014) have been summarized in Table 3.11.

Table 3.11: Diagnostic horizons and features or materials of the studied soil profiles in Magozi Irrigation Scheme (Soil Survey Staff, 2014)

Profile no.	Diagnostic epipedon	Diagnostic subsurface horizon	Other diagnostic features/materials
MAG-P1	Ochric Epipedon	Cambic horizon	Nearly level, very deep, clayey, moderate to strongly alkaline, ustic SMR, isohyperthermic STR, slickensides
MAG-P2	Ochric horizon	Cambic horizon	Nearly level, deep, sandy clay over sandy clay loam, mildly to moderate alkaline, aquic SMR, isohyperthermic STR
MAG-P3	Ochric horizon	Cambic horizon	Nearly level, deep, clayey over loamy sandy and sandy clay loam, neutral to mildly alkaline, aquic SMR, isohyperthermic STR

3.2.7.1.2 Soil Classification by the USDA Soil Taxonomy system

The information from Table 3.11 were used to classify the soils of Magozi Irrigation Scheme up to the family level using the USDA Soil Taxonomy system (Soil Survey Staff, 2014) and the results are as shown in Table 3.12. According to the Soil Survey Staff (2014), the soils of Magozi Irrigation Scheme were classified as *Nearly level, very deep, clayey, moderate to strongly alkaline, isohyperthermic, Typic Haplusterts*; *Nearly level,* *deep, sandy clay over sandy clay loam, mildly to moderate alkaline, isohyperthermic, Vertic Endoaquepts* and *Nearly level, deep, clayey over loamy sandy and sandy clay loam, neutral to mildly alkaline, isohyperthermic, Vertic Epiaquepts* for profiles MAG-P1, MAG-P2 and MAG-P3 respectively. These results showed that profiles MAG-P2 and MAG-P3 were both classified as Inceptisols at the order level and having vertic properties at the greatgroup level (Soil Survey Staff, 2014). On the other hand, MAG-P1 differed with other profiles and was classified as Vertisols at the order level.

Table 3.12: Classification of soils of Magozi Irrigation Scheme in the USDA Soil Taxonomy (Soil Survey Staff, 2014)

Profile no.	Order	Suborder	Great group	Subgroup	Family
MAG-P1	Vertisol	Ustert	Haplusterts	Typic Haplusterts	*Nearly level, very deep, clayey, moderate to strongly alkaline, isohyperthermic, Typic Haplusterts*
MAG-P2	Inceptisols	Aquepts	Endoaquepts	Vertic Endoaquepts	*Nearly level, deep, sandy clay over sandy clay loam, mildly to moderate alkaline, isohyperthermic, Vertic Endoaquepts*
MAG-P3	Inceptisols	Aquepts	Epiaquepts	Vertic Epiaquepts	*Nearly level, deep, clayey over loamy sandy and sandy clay loam, neutral to mildly alkaline, isohyperthermic, Vertic Epiaquepts*

3.2.7.2 Classification of soils using the World Reference Base for Soil Resources (WRB)

The inventory results of the studied soil profiles on their diagnostic horizons, principal and supplementary qualifiers as well as the final classification of soils to Tier 2 level in the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2015) have been presented in Table 3.13. The soils of profile MAG-P1 were classified as *Haplic*

Vertisols (Mazic, Ochric) while those of MAG-P2 and MAG-P3 profiles were classified as *Eutric Vertic Cambisols (Clayic, Ochric)* and *Eutric Vertic Stagnic Cambisols (Clayic, Ochric)* respectively; all according to IUSS Working Group WRB (2015).

Table 3.13: Diagnostic horizons, principle and supplementary qualifiers and classification of soils of Magozi Irrigation Scheme in the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015)

Profile no.	Diagnostic horizon(s)	Reference Soil group (Tier 1)	Principal Qualifier(s)	Supplementary Qualifier(s)	WRB Soil name (Tier 2)
MAG-P1	Cambic horizon Vertic horizon	Vertisols	Haplic	Mazic, Ochric	*Haplic Vertisols (Mazic, Ochric)*
MAG-P2	Cambic horizon	Cambisols	Vertic, Eutric	Clayic, Ochric	*Eutric Vertic Cambisols (Clayic, Ochric)*
MAG-P3	Cambic horizon	Cambisols	Stagnic, Vertic, Eutric	Clayic, Ochric	*Eutric Vertic Stagnic Cambisols (Clayic, Ochric)*

3.2.7.2 Correlation between World Reference Base for Soil Resources and USDA Soil Taxonomy systems taxa for the soils of Magozi Irrigation Scheme

In this study, the *Vertisols* reference soil group (RSG) in World Reference Base for Soil Resources correlated with *Vertisols* order in USDA Soil Taxonomy (IUSS Working Group WRB, 2015; Soil Survey Staff, 2014). Also, the *Cambisols* RSG in World Reference Base for Soil Resources correlated with *Inceptisols* order in the USDA Soil Taxonomy (IUSS Working Group WRB, 2015; Soil Survey Staff, 2014). This correlation will aid in better understanding of the soils among soil scientists and agronomists in terms of best use and management options for the soils in the study area.

Vertisols have been reported in many studies on soils of Tanzania and beyond (Assen and Yilma, 2010; Massawe *et al.*, 2017; Msanya *et al.*, 2018; Mukungurutse *et al.*, 2018).

Haplic Vertisols have also been reported in other areas of Tanzania such as by Massawe *et al.* (2017) for the soils of Mvumi Village, Kilosa District, Tanzania. Inceptisols (Cambisols in WRB) are soils of relatively young age and their occurence in Tanzania have been reported in many pedological studies (Msanya *et al.*, 2003; Msanya *et al.*, 2016; Kalala *et al.*, 2017; Msanya *et al.*, 2018; Tenga *et al.*, 2018).

3.3 CONCLUSIONS

The topsoils of the studied profiles showed slight variation in terms of their morphological, physical and chemical properties indicating their close similarity in ecological conditions and mode of formation. The soils were moderately deep to very deep, with vertic characteristics varying in the degree of expression. Based on silt/clay ratios, the soils of Magozi Irrigation Scheme are relatively young with high degree of weathering potential. Profiles MAG-P2 and MAG-P3 were dominated with mottles indicating the effects of waterlogging due to irrigation. The final classification in the USDA Soil Taxonomy for profile MAG-P1 is *Nearly level, very deep, clayey, moderate to strongly alkaline, isohyperthermic, Typic Haplusterts* while profiles MAG-P2 and MAG-P3 were named to the family level as *Nearly level, deep, sandy clay over sandy clay loam, mildly to moderate alkaline, isohyperthermic, Vertic Endoaquepts* and *Nearly level, deep, clayey over loamy sandy and sandy clay loam, neutral to mildly alkaline, isohyperthermic, Vertic Epiaquepts*, respectively. The soil names (taxa) were then correlated with the World Reference Base for Soil Resources (WRB) and the names at Tier 2 level were *Haplic Vertisols (Mazic, Ochric)*, *Eutric Vertic Cambisols (Clayic, Ochric)* and *Eutric Vertic Stagnic Cambisols (Clayic, Ochric)* for MAG-P1, MAG-P2 and MAG-P3, respectively. It is recommended that there should be good irrigation practices to avoid waterlogging in this scheme. Furthermore, there should be timing of land cultivation to avoid difficult in ploughing too wet or too dry vertic soils as well as managing soil fertility through application of appropriate inorganic and organic fertilizers to improve rice production.

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CHAPTER FOUR

4.0 PREDICTING SOIL EC_e BASED ON VALUES OF $EC_{1:2.5}$ AS AN INDICATOR OF SOIL SALINITY IN MAGOZI IRRIGATION SCHEME, IRINGA, TANZANIA

ABSTRACT

Soil salinity is one of the limitations to sustainable production of rice and other crops in many irrigation schemes of Tanzania. Soil salinity can be assessed from electrical conductivity (EC) measurements. Most soil laboratories in Tanzania appraise soil salinity from measurements of electrical conductivity of 1:2.5 soil:water suspensions ($EC_{1:2.5}$) by virtue of their simplicity. However, the influence of soil salinity on plant growth is mainly based on electrical conductivity of saturated paste extract (EC_e), so it is necessary to convert $EC_{1:2.5}$ to EC_e in order to assess plant response to salinity. This study was conducted at Magozi Irrigation Scheme, Iringa, Tanzania to establish regression model for predicting EC_e from $EC_{1:2.5}$ values. A total of 60 soil samples (45 samples for model training and 15 samples for model validation) were collected and analyzed for soil $EC_{1:2.5}$, EC_e and soil texture. $EC_{1:2.5}$ ranged from 0.1 to 9.2 dS m^{-1} with a mean value of 0.85 dS m^{-1}. EC_e ranged from 0.3 (non-saline) to 33.3 dS m^{-1} (strongly saline) with a mean of 2.9 dS m^{-1} (slightly saline). In order of dominance, soil textural classes were sandy clay loam, clay, sandy clay, sandy loam and clay loam. Strong linear relationships between EC_e and $EC_{1:2.5}$ were observed in the developed linear regression equations. After validation, the study selected equation $EC_e = 3.4954*EC_{1:2.5}$ with R^2 of 0.956 for combined soil textures to be used for prediction of EC_e from $EC_{1:2.5}$ at Magozi Irrigation Scheme. This model can be tested for its applicability to other similar soils in Tanzania in further studies.

Keywords: Soil salinity, EC_e, $EC_{1:2.5}$, Magozi Irrigation Scheme, soil salinity prediction

4.0 INTRODUCTION

The 21st century is marked by various global challenges to agricultural sustainability and food production to feed the growing population (Taddese, 2001; Shahbaz and Ashraf, 2013; Godfray and Garnett, 2014). Land degradation is considered as one of the main threats to sustainable agricultural development (Taddese, 2001; Bai *et al.*, 2008). Increasing pressure on land resources due to increased human population coupled with the effects of climate change lead to different types of agricultural land degradation including soil salinization, which is the process of salt accumulation in the soil profile (Biswas and Biswas, 2014; Shahbaz and Ashraf, 2013).

Irrigated agriculture has been viewed as one of the approaches in ensuring food security under the climate changing world (Rhoades and Chanduvi, 1999; Hanjra and Qureshi, 2010). Unfortunately, extensive areas of irrigated land have been and are increasingly becoming degraded by salinization and water logging resulting from poor irrigation practices and other forms of poor agricultural management (Rhoades and Chanduvi, 1999; Smedema and Shiati, 2002). Soil salinization leading to soil salinity is an important worldwide land degradation problem and poses a great threat to the development of sustainable agriculture, especially in arid and semi-arid regions (Bai *et al.*, 2008; Shrivastava and Kumar, 2015).

Soil salinity is one of the limiting factors of agricultural productivity (Sonmez *et al.*, 2008). It has been estimated that worldwide 20% of total cultivated and 33% of irrigated agricultural lands are afflicted by high soil salinity (Shrivastava and Kumar, 2015). Therefore, soil salinity has been considered as a basic factor which determines to a large extent, soil suitability for agricultural productivity (Sonmez *et al.*, 2008; Shrivastava and Kumar, 2015). Increased soluble salts in the root zone due to soil salinity reduce plant growth, crop yields and in severe cases, cause crop failure (Zhu, 2001; Datta and De Jong, 2002; Allbed and Kumar, 2013; Corwin and Yemoto, 2017). Therefore, soil salinity assessment has been viewed as an important component in agriculture management (Biswas and Biswas, 2014; Lesch *et al.,* 1995; Corwin and Yemoto, 2017). It is essential to assess soil salinity in a reliable and yet relatively cheap method (Sonmez *et al.,* 2008; Matthees *et al.,* 2017).

Soil salinity is generally measured by electrical conductivity (EC) (US Salinity Laboratory Staff, 1954; Sonmez *et al.,* 2008; Landon, 2014; Corwin and Yemoto, 2017). A soil is considered saline if the EC of a saturation extract exceeds 4 dS m^{-1} at 25^0C (Sonmez *et al.,* 2008; Kargas *et al.,* 2018). Soil salinity or EC maybe measured on the bulk soil (EC_a), in the saturation paste extract (EC_e), in soil: water ratio suspensions of 1:1 to 1:5 such as 1:1, 1:2, 1:2.5 and 1:5 or directly on soil water extracted from the soil in the field (EC_w) (US Salinity Laboratory Staff, 1954; Sonmez *et al.,* 2008; Corwin and Yemoto, 2017; Kargas *et al.,* 2018).

Since 1954 to date, the EC_e has been the best indicator of crop response to salinity compared with EC from other soil to water ratio suspension methods (US Salinity Laboratory Staff, 1954; Rhoades *et al.,* 1989; He *et al.,* 2013; Matthees *et al.,* 2017; Kargas *et al.,* 2018). Soil salinity assessment is therefore, based on measurements of the electrical conductivity of the saturated paste extract (EC_e), which has been established as the standard method (US Salinity Laboratory Staff, 1954; He *et al.,* 2013; Matthees *et al.,* 2017; Kargas *et al.,* 2018). However, the approach is expensive, cumbersome and tedious as it requires long time and skill on preparation of the soil paste (He *et al.,* 2013; Kargas *et al.,* 2018) than soil to water ratio methods.

Therefore, instead of measuring soil EC_e, a number of researches in various soil laboratories in the world have found it easier to measure the EC of soil: water ratios such as 1:1, 1:2, 1:2.5 and 1:5 which are more easily attainable (Sonmez *et al.,* 2008; He *et al.,* 2013; Landon, 2014; Kargas *et al.,* 2018) as they are easier to prepare, save time and less costly (He *et al.,* 2013). Therefore, it is likely that many laboratories, particularly commercial ones, will continue to appraise soil salinity from EC of soil to water suspensions like 1: 2.5 measurements because of their convenience and speed (He *et al.,* 2013; Matthees *et al.,* 2017; Kargas*et al.,* 2018). It has however been noted that the soil over water mass ratios are very poorly correlated with the actual soil moisture conditions (Sonmez *et al.,* 2008; Kargas *et al.,* 2018). Therefore, in order to assess plant response to salinity, it is necessary to convert EC from soil to water suspensions values to EC_e (Sonmez *et al.,* 2008; He *et al.,* 2013; Matthees *et al.,* 2017). Conversion factors obtained from model equations are used to estimate EC_e from EC values of soil to water suspensions (Khorsandi and Yazdi, 2011; He *et al.,* 2013).

Various studies have shown that highly significant linear correlation exists between EC values measured in saturated paste extracts and EC values from different soil to water ratios (Sonmez *et al.,* 2008). The study by Sonmez *et al.,* (2008) concluded that EC values from extracts of 1:1, 1:2.5 or 1:5 soil to water ratios can be used to estimate saturated paste electrical conductivity (EC_e). Recent study for Greece soils by Kargas *et al.,* (2018) reported that the methods providing $EC_{1:1}$ and $EC_{1:5}$ values are linearly correlated to the EC_e methodology with a high correlation coefficient (R^2> 0.93).

Most of the studies conducted in other countries were mainly based on relating EC_e with $EC_{1:1}$, $EC_{1:2}$ and $EC_{1:5}$ with very few on $EC_{1:2}$ (Sonmez *et al.,* 2008; Corwin and Yemoto, 2017). All equations have shown regional variability (Sonmez *et al.,* 2008; Corwin and Yemoto, 2017) suggesting that there is a need for regional specific equations. Soil testing laboratories in Tanzania run many thousands of samples each year for EC by using an easier method of $EC_{1:2.5}$. A specific benefit for measuring electrical conductivity using extracts of 1:2.5 soil to water ratio is that the measurements can be conducted for samples prepared for pH measurements and thus saving both time and resources for laboratory works (Sonmez *et al.,* 2008). However, there are no conversion factors developed for converting soil $EC_{1:2.5}$ to EC_e for Tanzanian soils. Furthermore, the soil EC interpretation guidelines used are based on EC_e (US Salinity Laboratory Staff, 1954; Sonmez *et al.*, 2008; Corwin and Yemoto, 2017). Literature has documented that the EC_e values are usually higher than the EC values determined by soil to water suspension methods like 1:2.5 (Sonmez *et al.,* 2008; Corwin and Yemoto, 2017). This means that the current approach of using EC_e based interpretation guidelines to interpret $EC_{1:2.5}$ values may lead to unrealistic soil salinity assessment.

Studies have shown that rice (*Oryza sativa* L.) production in Tanzania is threatened by salt affected soils among other factors (Kashenge-Killenga, 2010). Irrigated rice is one of the major sources of rice production in Tanzania as one of the efforts to ensure food security and incomes of farmers under the climate changing world (Kashenge-Killenga, 2010; Rugumamu, 2014; Mtengeti *et al.*, 2015). Magozi Irrigation Scheme is one of the rice producing schemes in Iringa region (Mdemu *et al.,* 2017) facing the problem of soil salinity. Assessment and monitoring of soil salinity in the scheme and other areas is important and require relevant salinity measurements (He *et al.,* 2013; Corwin and Yemoto, 2017; Matthees *et al.,* 2017). Although measurements of electrical conductivity (EC) in 1:2.5 soil to water suspension is possible, no linear model has been established to convert $EC_{1:2.5}$ to EC_e for accurate salinity assessments. This study developed a linear model that can be used to predict EC_e from $EC_{1:2.5}$ in this scheme with potential application in other soils of Tanzania.

4.1 MATERIALS AND METHODS

4.1.1 Description of the Study Area

This study was conducted in Magozi Irrigation Scheme with an area of 1300 ha. The scheme is located at about 65 km North West of Iringa town at Ilolompya Ward, in Iringa

Rural District of Iringa Region and composed of three villages namely Magozi, Ilolompya and Mkombilenga. The scheme is located in zone 36 south, occupying the area lying between 9172000 to 9182000 m northings and 772000 to 774000 m eastings in the Universal Transverse Mercator (UTM) coordinate system. The average altitude is 700 m above mean sea level and the climate is semi-arid tropical with a monomodal rainy season between November and May.

4.1.2 Pre-field work

A reconnaissance soil survey was conducted to understand and establish soil variation in terms of surface salinity features, soil texture and topography at Magozi Irrigation Scheme. The 500m x 500m sampling grid was prepared in QGIS (QGIS 2.6.1-Brighton) using the scheme boundary shape file and the sampling point UTM coordinates were captured by coordinate capturing tool in QGIS and later on transferred into the GPS device (GARMIN GPSmap 62) for navigation during soil sampling.

Plate 4.1: A part of Magozi Irrigation Scheme showing whitish surface a typical characteristic of salinity features

4.1.3 Field soil sampling

The pre field work established soil sampling points based on systematic 500m x 500m grids. However, additional points were included to take care of the observed soil variations in the area during soil sampling. Therefore, a total of sixty (60) surface composite soil samples at a depth of 0-30cm were collected from Magozi Irrigation Scheme and sent to Sokoine University of Agriculture Soil Science Laboratory for analysis of soil $EC_{1:2.5}$, EC_e and soil texture. Soil texture was included as an important parameter which affects soil electrical conductivity (US Salinity Laboratory Staff, 1954; Sonmez *et al.*, 2008).

4.1.4 Soil sample selection for studying EC_e prediction from $EC_{1:2.5}$

Out of 60 soil samples, 45 soil samples (75%) with combined soil textures were used as model training data set while 15 soil samples (25%) were used as model validation data set. The selection considered the location of sample point in the irrigation scheme area as well as the soil textural classes' variation in order to reduce sampling biasness. Fig. 4.1 is the map of Magozi Irrigation Scheme showing distribution of soil sampling points.

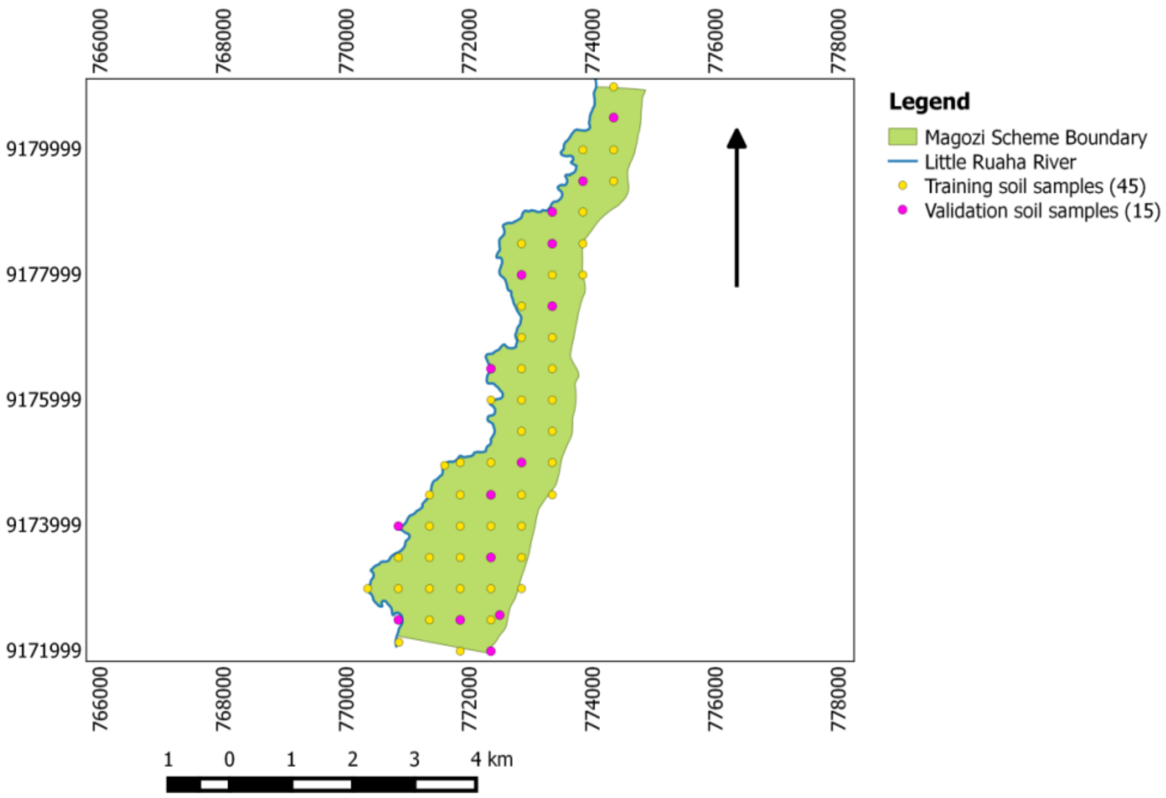

Figure 4.1: Soil sampling points distributions at Magozi Irrigation Scheme for ECe determination

4.1.5 Laboratory analysis for soil $EC_{1:2.5}$, EC_e and soil texture

Soil samples were air-dried, ground and passed through a 2-mm sieve for laboratory determination of soil $EC_{1:2.5}$, EC_e, particle size analysis (soil texture) at Soil Science Laboratory of the Sokoine University of Agriculture. Particle size analysis was determined by hydrometer method after dispersion with 5% sodium hexametaphosphate (Moberg, 2001) whereby the soil textural classes were determined using USDA textural triangle (Soil Survey Staff, 2014). Soil electrical conductivity ($EC_{1:2.5}$) in dS m^{-1} were measured potentiometrically in water at a ratio of 1:2.5 soil: water (Moberg, 2001; Okalebo *et al.*, 2002).

Soil EC_e was determined by saturated paste extract method (Rhoades, 1996; US Salinity Laboratory Staff, 1954) summarized as follows; 200g of air-dry soil was weighed for each soil sample. Distilled water was added to each sample while mixing to saturate the soil to the point where the soil paste glistens, flows slightly when the container is tipped and slides cleanly from the spatula. The soil paste samples were allowed to stand for 4 hours to check if saturation criteria are still met; where distilled water was added and thoroughly combined for samples which became stiffened or which did not glisten. The soil paste samples were left overnight to establish equilibrium. The wet soil was transferred to a Buchner funnel fitted with retentive filter paper, vacuum was applied and the filtrate was collected for measurement of electrical conductivity expressed in dS m^{1} by EC meter (Rhoades, 1996).

4.1.6 Linear relationship between electrical conductivity of the saturated paste extract (EC_e) and of the 1:2.5 soil to water suspension ($EC_{1:2.5}$)

4.1.6.1 Statistical Analysis

Linear regression analysis to relate EC_e and $EC_{1:2.5}$ for the training data set and the data set for each soil textural class were conducted using Genstat Software (Wim *et al.*, 2007) and

Microsoft Excel 2013 Analysis ToolPak. The linear relationships between EC_e and $EC_{1:2.5}$are presented by the following linear model equations respectively:

$EC_e = mEC_{1:2.5} \pm c$ with intercept (18)

$EC_e = mEC_{1:2.5}$ without intercept (19)

where EC_e is the dependent variable expressed in dS m^{-1}, $EC_{1:2.5}$ is an independent variable expressed in dS m^{-1}; m is an equation slope serving as the model estimate and c is an intercept constant expressed in dS m^{-1}. All statistical tests were performed at $p \leq 0.05$ significance level. The linear models were assessed by using coefficient of determination (R^2) according to Wim *et al.* (2007).

4.1.6.2 Model selection and validation

A linear regression model for use in this study was selected based on the number of samples used to develop it as compared to others and the size of validation data set available for testing it (Matthees *et al.*, 2017). Good R^2 (>0.8) was also considered while selecting the model. Further selection criteria for the final model was done by testing the prediction accuracy for the equation with intercept and without intercept when subjected to the validation data set (Matthees *et al.*, 2017; Kargas *et al.*, 2018). To further compare the prediction accuracy between model with intercept and without intercept, a scatter plot was established to relate linear relationship between measured EC_e and predicted EC_e by assessing R^2 and prediction error represented by root mean square error (RMSE) (Sonmez *et al.,* 2008; Kargas *et al.,* 2018). Therefore a model which predicted EC_e from $EC_{1:2.5}$ with smaller mean difference between measured and predicted EC_e, higher R^2 and smaller RMSE values as compared to other models was selected for use in this study (Sonmez *et al.,* 2008; Matthees *et al.,* 2017).

4.2 RESULTS AND DISCUSSION

4.2.1 Status of soil $EC_{1:2.5}$, EC_e and soil texture in the studied soils

The results for the selected 60 soil samples summarized in Table 4.1, showed that the soil electrical conductivity measured in 1:2.5 soil to water suspension ($EC_{1:2.5}$) ranged from 0.11 to 9.2 dS m^{-1} with the mean of 0.85 dS m^{-1}. The soil electrical conductivity (EC_e) determined by saturated paste extract method ranged from 0.3 to 33.3 dS m^{-1} with a mean of 2.9 dS m^{-1}. The studied soils showed variation in soil texture where the soil textural classes percentage composition per total soil samples were 42%, 28%, 10%, 10% and 10% for sandy clay loam, clay, sandy clay, sandy loam and clay loam, respectively.

Table 4.1: Descriptive statistics for selected physicochemical properties of the studied soils (n = 60)

Parameter	Minimum	Maximum	Mean	Standard deviation
Electrical conductivity (EC)				
Soil $EC_{1:2.5}$ (dS m^{-1})	0.11	9.2	0.85	1.33
Soil EC_e (dS m^{-1})	0.3	33.3	2.9	4.7
Particle size distribution				
% Clay	13.56	59.56	33.68	10.79
% Silt	4.28	33.92	17.27	7.35
% Sand	15.52	78.52	49.05	15.5
Soil textural classes	**Number of samples (n=60)**			**% Textural class**
Sandy clay loam	25			42
Clay	17			28
Sandy clay	6			10
Sandy loam	6			10
Clay loam	6			10

Significant differences between soil $EC_{1:2.5}$ and soil EC_e values at $p<0.05$ were observed (Sonmez *et al.,* 2008). The soil electrical conductivity (EC_e) of the saturated paste extract ranged from non-saline (0.3 dS m^{-1}) to strongly saline (33.3 dS m^{-1}) with a mean being slightly saline (2.9 dS m^{-1}) (Rhoades, 1996; Bannari *et al.*, 2008). The 33.3 dS m^{-1} EC_e which is rated as extremely saline (Rhoades, 1996) is an alarming result which indicates that some areas of Magozi Irrigation Scheme are at higher risk of developing more salinity. This might negatively affect rice production in this area.

4.2.2 Relationship between electrical conductivity of the saturated paste extract (EC_e) and $EC_{1:2.5}$

4.2.2.1 Linear regression equations relating EC_e and $EC_{1:2.5}$

Table 4.2 summarizes the mathematical equations indicating the linear relationships obtained between EC_e and $EC_{1:2.5}$ after linear regression analysis for the training data set with combined soil textural classes and the equations for individual soil textural classes.

Table 4.2: Linear regression models relating EC_e and $EC_{1:2.5}$

Soil sample type	Number of samples (n = 60)	Linear model with intercept		Linear model without intercept	
		Equation	**R^2**	**Equation**	**R^2**
Combined soil textures (Model training data)	45	$EC_e = 3.5381EC_{1:2.5} - 0.1337$	$R^2 = 0.9565$	$EC_e = 3.4954EC_{1:2.5}$	$R^2 = 0.956$
Sandy clay loam	25	$EC_e = 3.5326EC_{1:1.25} + 0.2106$	$R^2 = 0.9835$	$EC_e = 3.5811EC_{1:2.5}$	$R^2 = 0.9828$
Clay	17	$EC_e = 1.9719EC_{1:2.5} + 0.3779$	$R^2 = 0.9226$	$EC_e = 2.2413EC_{1:2.5}$	$R^2 = 0.8910$
Sandy clay	6	$EC_e = 3.403EC_{1:2.5} - 0.1125$	$R^2 = 0.9841$	$EC_e = 3.2919EC_{1:2.5}$	$R^2 = 0.9827$
Sandy loam	6	$EC_e = 5.0143EC_{1:2.5} - 0.1091$	$R^2 = 0.9915$	$EC_e = 4.926EC_{1:2.5}$	$R^2 = 0.9910$
Clay loam	6	$EC_e = 2.2794EC_{1:2.5} + 0.3171$	$R^2 = 0.9932$	$EC_e = 2.8622EC_{1:2.5}$	$R^2 = 0.9070$

The linear regression model estimates (m) ranged from 1.9719 in clay soils to 5.0143 in sandy loam soils and ranging from 2.2413 in clay soils to 4.926 sandy loam soils for equations with intercept and without intercept respectively. This indicates that clay textured soils showed smaller difference between EC_e and $EC_{1:2.5}$ as compared to other textural classes while sandy loam textured soils indicated higher difference between EC_e

and $EC_{1:2.5}$ by having the largest estimate. The R^2 ranged from 0.9226 for clay soils to 0.9932 for clay loam soils and 0.891 for clay soils to 0.991 for sandy loam soils for equations with intercept and without intercept respectively.

Good correlations (R^2>0.8) were observed in all linear regression models for combined soil textures and in individual soil textural classes. Generally the linear regression models slope estimates for $EC_{1:2.5}$ and coefficient of determination (R^2) varied with soils textural class. This variation may be due to the effects of soil texture in soil electrical conductivity as well as differences in number of samples for individual textural classes. The study conducted by Sonmez *et al.* (2008) at Akdeniz University in Turkey obtained a linear regression model $EC_e = 3.91EC_{1:2.5} + 0.27$ with R^2 of 0.99 for combined soil textures. The observed differences in slope and intercept from those obtained in this study may be due to the soil variability between the two countries.

4.2.2.2 Model selection and validation

The linear model for combined soil textures was selected for use in this study because it was developed using relatively adequate samples and it had validation data set of combined texture soil samples. But the small soil sample sizes for individual textures could not provide adequate samples to form training and validation data sets for each soil textural class and for estimates comparison purposes. The models to be selected in this category of combined soil textures (Fig. 4.2 and 4.3) were either $EC_e = 3.5381*EC_{1:2.5} - 0.1337$ with R^2 of 0.9565 and or $EC_e = 3.4954*EC_{1:2.5}$ with $R^2 = 0.956$ for equation with intercept and without intercept respectively. Moreover, the linear model for combined soil textures without intercept was preferred for use in this study to predict EC_e from $EC_{1:2.5}$ because the $EC_{1:2.5}$ cannot be absolute zero for the studied soils (Bannari *et al.*, 2008).

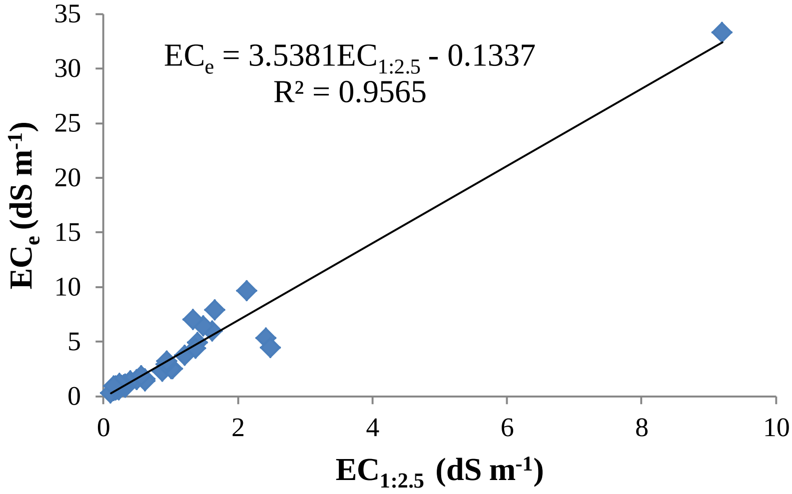

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Figure 4.2: Relationship between EC_e and $EC_{1:2.5}$ for training data set with combined soil textures (with intercept)

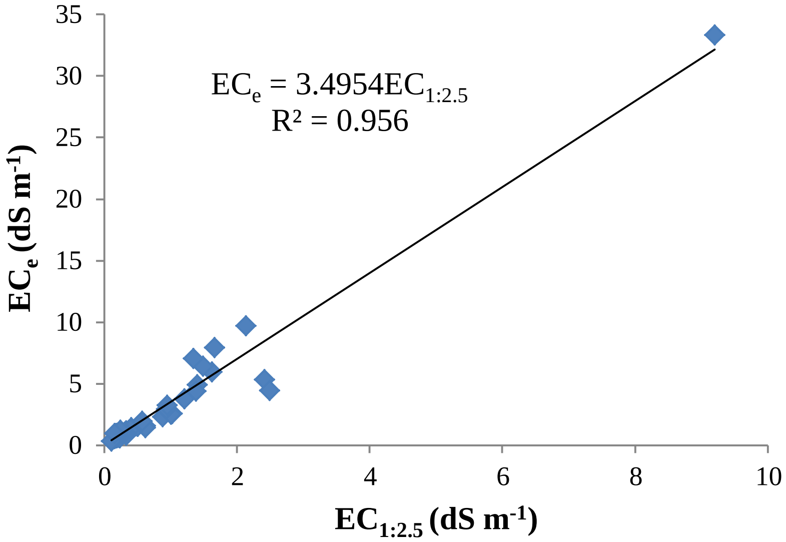

Figure 4.3: Relationship between ECe and EC1:2.5 for training data set with combined soil textures (without intercept)

4.2.3 EC_e prediction results on validation data set

The models $EC_e = 3.5381EC_{1:2.5} - 0.1337$ and $EC_e = 3.4954*EC_{1:2.5}$ were compared on their ability to predict EC_e from $EC_{1:2.5}$ by using validation data set (n = 15). A summary of predicted EC_e from measured values for both equations is presented in Table 4.3.

Table 4.3: EC_e prediction results for linear models with intercept and without intercept on the validation data set

Statistic	Measured EC_e (dS m^{-1})	Predicted EC_e (dS m^{-1})	
		$EC_e = 3.5381EC_{1:2.5} - 0.1337$	$EC_e = 3.4954{*}EC_{1:2.5}$
Minimum	0.65	0.33	0.45
Maximum	12.03	14.66	14.61
Mean	2.70	2.58	2.68
Standard deviation	3.15	3.64	3.60

Further comparison in EC_e prediction accuracy between $EC_e = 3.5381EC_{1:2.5} - 0.1337$ (with intercept) and $EC_e = 3.4954{*}EC_{1:2.5}$ (without intercept) models was performed by scatter plots (Fig. 4.4 and 4.5) to relate linear relationships between measured EC_e and predicted EC_e from both models.

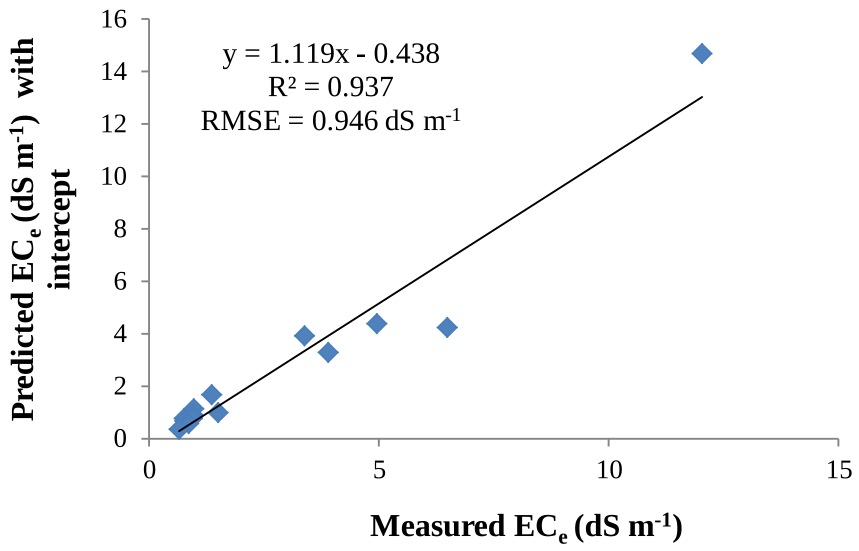

Figure 4.4: Relationship between measured EC_e and predicted EC_e from $EC_e = 3.5381EC_{1:2.5} - 0.1337$ (with intercept)

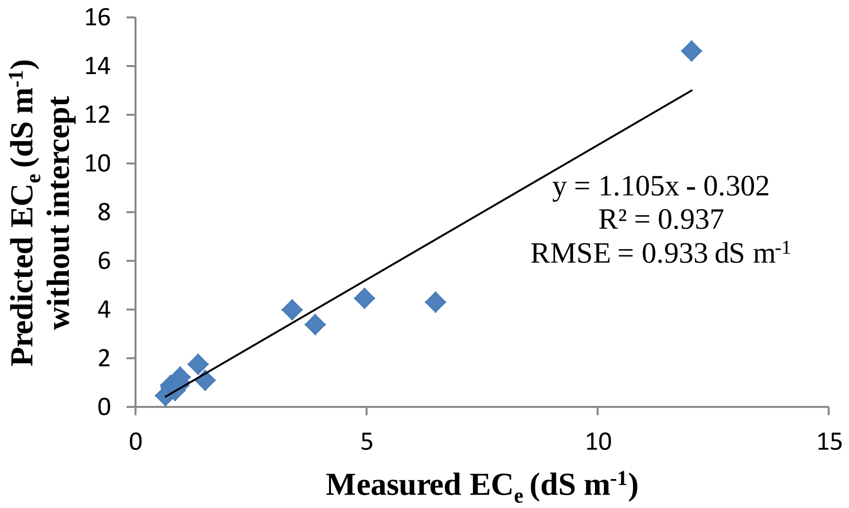

Figure 4.5: Relationship between measured EC_e and predicted EC_e from $EC_e = 3.4954EC_{1:2.5}$ (without intercept)

The R^2 and RMSE (prediction error) observed for the measured EC_e versus predicted EC_e from $EC_e = 3.5381EC_{1:2.5} - 0.1337$ (with intercept) scatter plot were 0.937 and 0.946 dS m^{-1} respectively. The R^2 and RMSE observed for the measured EC_e versus predicted EC_e from $EC_e = 3.4954EC_{1:2.5}$ (without intercept) scatter plot were 0.937 and 0.933 dS m^{-1} respectively.

While the mean value from the measured EC_e of validation data was 2.7 dS m^{-1}, the $EC_e = 3.5381EC_{1:2.5} - 0.1337$ model predicted mean EC_e of 2.58 dS m^{-1} while $EC_e = 3.4954*EC_{1:2.5}$ model predicted a mean of 2.68 dS m^{-1}. This indicated that the model without intercept ($EC_e = 3.4954*EC_{1:2.5}$) predicted mean EC_e more closely to the measured mean EC_e as compared to the model with intercept. All models showed the same R^2 while the prediction error (RMSE) was smaller for $EC_e = 3.4954*EC_{1:2.5}$ prediction results than $EC_e = 3.5381EC_{1:2.5} - 0.1337$. According to these results, the linear model without intercept ($EC_e = 3.4954*EC_{1:2.5}$) was selected for use in this study to predict EC_e from $EC_{1:2.5}$ in Magozi Irrigation Scheme due to its higher prediction accuracy as compared to $EC_e = 3.5381EC_{1:2.5} - 0.1337$.

4.3 CONCLUSIONS

This study showed that EC_e can be predicted from $EC_{1:2.5}$ for the soils of Magozi Irrigation Scheme. The linear regression model **$EC_e = 3.4954*EC_{1:2.5}$** for combined soil textures showed high EC_e prediction precision when tested with the validation data set, indicating that, this model can be used to predict EC_e for the soils of Magozi Irrigation Scheme. This model can also be tested for potential application in Tanzania for areas with similar soils to Magozi Irrigation Scheme. The other developed linear models according to textural classes in this study can be tested in further similar researches by using adequate validation soil samples of individual textural classes so as to test for their capability in predicting soil EC_e for particular soil textural classes.

Similar studies are suggested to be done in other soils of Tanzania in order to establish more regional specific linear models for comparison with the models in this study to be used for prediction of EC_e from the commonly measured $EC_{1:2.5}$. The soil laboratories in Tanzania can use such equation to serve time and labour for determination of EC_e. This will lead to more relevant soil salinity assessments in the country by providing EC_e values that are used to assess plant response to salinity as opposed to the current reliance on $EC_{1:2.5}$ for salinity assessment in Tanzania.

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CHAPTER FIVE

5.0 PREDICTION OF SOIL SALINITY SPATIAL DISTRIBUTION IN MAGOZI IRRIGATION SCHEME, IRINGA, TANZANIA

ABSTRACT

Soil salinity is a major global environmental constraint to crop production. It is one of the forms of land degradation especially in irrigated lands contributing to low rice productivity in Tanzania. Assessment of severity and spatial distribution of soil salinity are required for enhancing sustainable agricultural production. This study assessed soil salinity and used GIS-based approach to predict spatial distribution of soil salinity for enhancing sustainable rice production in Magozi Irrigation Scheme in Iringa, Tanzania. A total of eighty one (81) composite surface soil samples at a depth of 0 - 30 cm were collected from the scheme and each sampling point was geo-referenced using GPS device. The samples were analyzed for soil physical and chemical properties whereby electrical conductivity of the saturated paste extract (EC_e) was used as the main soil salinity index. The soil salinity spatial distribution map of the scheme based on EC_e was generated using Inverse Distance Weighting (IDW) interpolation method. The soil salinity in terms of EC_e ranged from non-saline (0.24 dS m^{-1}) to extremely saline (33.3 dS m^{-1}) with an EC_e mean of 2.5 dS m^{-1} being slightly saline. The EC_e showed positive significant correlation at $p \leq 0.05$ with soil Cl^- (r = 0.459), exchangeable Na (r = 0.341), ESP (r = 0.302) and SAR (r = 0.320). The soil salinity spatial distribution map indicated that out of 1300 ha cultivated land, a total of 622.21 ha (47.86%) were mapped as slightly saline to extremely saline soils. Therefore, suitable irrigation, crop and soil management practices must be adopted by the farmers to reduce soil salinity development for rice production sustainability in this scheme.

Keywords: Soil salinity, spatial distribution, EC_e, Magozi Irrigation Scheme

5.0 INTRODUCTION

Soil salinity is a major global environmental constraint to crop production (Shahid and ur Rahman, 2016; Hammam and Mohamed, 2018) and one of the forms of land degradation leading to low rice productivity in Tanzania (Kashenge-Killenga *et al.*, 2013; Kashenge-Killenga *et al.*, 2016; Dolo, 2018). It affects an estimated 45 million hectares of irrigated land worldwide (Roy *et al.*, 2014) and is expected to increase due to global climate changes and as a consequence of poor irrigation practices (Munns and Tester, 2008; Rengasamy, 2010; Roy *et al.*, 2014). Human-induced salinization leading to high levels of soil salinity occurs in irrigated agriculture farms due to poor management of soil and irrigation water, high water table, poor drainage conditions and the use of saline water for irrigation with less emphasis on leaching fraction (Ammari *et al.*, 2013; Shahid, 2013; Shahid and ur Rahman, 2016; Singh, 2018; Hammam and Mohamed, 2018).

There is a need to address the problem of soil salinity, especially in irrigated lands in order to enhance and sustain rice productivity among other crops in Tanzania (Kashenge-Killenga *et al.*, 2013). This will improve food security and incomes of farmers because rice is one of the major food and cash crops in the country (Mtengeti *et al.*, 2015). There is limited information on the extent of soil salinity in irrigated lands of Tanzania. However, it has been reported that most of the irrigation schemes (including rice growing irrigation schemes) in Tanzania, which are especially located in the semi-arid environments are already experiencing increased levels of salt affected soils (Kashenge-Killenga *et al.*, 2013; Kashenge-Killenga *et al.*, 2016; Dolo, 2018). Kashenge-Killenga *et al.* (2016) pointed out that this is largely due to mismanagement of the soils, the use of poor quality irrigation water, poor drainage systems, poorly designed and managed irrigation infrastructures, excessive use of irrigation water as well as climate change.

According to Kashenge-Killenga *et al.* (2016), visual observation showed that 100 % of all the surveyed rice growing irrigation schemes in southwestern Tanzania which included

Iringa Region had symptoms of salt affected soils. However, the laboratory results from the same study by Kashenge-Killenga *et al.* (2016) confirmed that 67 % of the surveyed schemes had salt problems. The study by Kashenge-Killenga *et al.* (2016) reported three types of salt-affected soils in the region (saline, sodic, and saline-sodic) with extreme salinity (4-15 dS m^{-1}), sodicity (with 10-34 SAR) and high soil pH (up to 10) values from the surveyed irrigation schemes.

Adequate and accurate information, assessment of the degree of severity and spatial distribution of soil salinity especially in its early stage is required to address soil degradation trends and is vital in terms of sustainable agricultural management (Bannari *et al.,* 2008; Shahabi *et al.,* 2017). Conventional soil salinity risk identification and management methods which involve dense soil sampling and laboratory analysis have disadvantages and limitations in spatial data analysis and often provide an inadequate description of the problem (Shafiq *et al.,* 2001; Nwer *et al.,* 2013; Shahid, 2013; Dinh *et al.,* 2018). This approach is also time consuming, costly since dense sampling is required to adequately characterize the spatial variability of an area and demanding when considering large areas (Shafiq *et al.,* 2001; Shahid, 2013; Dinh *et al.,* 2018).

There have been significant innovative advancements in technologies to assess, map and monitor soil salinity spatially and temporally, from regional, national to farm levels (Abdelfattah *et al.,* 2009; Nwer *et al.,* 2013). The use of Geographical Information System (GIS) approach is one of the advanced methods widely accepted in literature for better assessing and predicting spatial distribution of soil salinity with advantages over conventional methods in time saving, wide range of coverage as well as facilitation of faster and long term monitoring (Islam *et al.,* 2017; Shahabi *et al.,* 2017; Zewdu *et al.,* 2017).

Recently, the process of soil salinity mapping has become more efficient through the use of geostatistics and geographic information systems (GIS), which show the spatial distribution of salinity and its environmental hazards (Shahabi *et al.,* 2017; Hammam and Mohamed, 2018). Geostatistics analysis and GIS has been considered as efficient methods for studying, analyzing and evaluating spatial distribution of soil properties, their changes, reducing the error rate and increasing the output efficiency (Behera and Shukla, 2015; Hammam and Mohamed, 2018). Ordinary kriging (OK) and inverse distance weighting (IDW) are some of the common geostatistical interpolation methods used to predict and produce spatial distribution of soil characteristics such as soil salinity (Yao *et al.,* 2013; Emadi and Baghernejad, 2014; Islam *et al.*, 2017).

Although the soil salinity general assessment study by Kashenge-Killenga *et al.* (2016) provided very valuable information about the status of soil salinity in rice growing irrigation schemes in the southwestern Tanzania which included Iringa Region, it has got some shortcomings. The study was of exploratory scale and it involved many irrigation schemes in the region and therefore, it did not provide detailed information about soil salinity spatial distribution at the scheme level for practical farm management recommendations.

Magozi Irrigation Scheme is one of the rice producing irrigation schemes in Iringa Region, Tanzania with more than 578 farmers depending on rice production as their main economic activity (Mziray *et al.,* 2015; Mdemu *et al.,* 2017). Despite the importance of rice production in this irrigation scheme, the rice production yields are generally low where the average rice yield has been reported to be 3.05 t ha^{-1}, while the potential yield is 4.06 t ha^{-1} (Mdemu *et al.*, 2017). Soil salinization in some parts of the scheme following land use change from non-irrigated annual crop production to irrigated rice farming is currently a concern among local farmers and agricultural extensionists (Mziray *et al.*, 2015; Matimbwa, A. personal communication, 2017). However, there is no detailed study that has focused on addressing soil salinity problem by establishing its spatial variability in Magozi Irrigation Scheme for efficient management strategies. The aim of this research work was to assess soil salinity and use GIS to predict spatial distribution of soil salinity and propose the soil management options that contribute to enhance sustainable rice production at Magozi Irrigation Scheme, Iringa, Tanzania.

5.1 MATERIALS AND METHODS

5.1.1 Description of the Study Area

The research was conducted in Magozi Irrigation Scheme with an area of 1300 ha located at about 65 km North West of Iringa town at Ilolompya Ward, in Iringa Rural District, Iringa Region. This scheme is composed of three villages namely Magozi, Ilolompya and Mkombilenga. Magozi Irrigation Scheme is located in zone 36 south, occupying the area lying between 9172000 to 9182000 m northings and 772000 to 774000 m eastings in the Universal Transverse Mercator (UTM) coordinate system. The average altitude is 700 m above mean sea level and the climate is semi-arid tropical with a monomodal rainy season between November and May.

5.1.2 Field Work

Reconnaissance survey in the irrigation scheme was carried out using transect walks, auger observations and observation of surface soil salinity features to identify soil variability based on surface salinity features, landform, soil morphological characteristics, parent material and vegetation as described by FAO, (2006). Whitish salt precipitated on surface was used to differentiate affected and non-affected parts of the scheme and sites to locate soil sampling points.

5.1.2.1 Soil Sampling

A total of eighty one (81) topsoil composite samples collected at a depth of 0-30 cm using systematic grid of 500 m x 500 m spacing for laboratory determination of selected physical and chemical soil properties. Some soil sampling points were adjusted in order to accommodate the observed soil variation and avoid sampling obstacles such as irrigation canals in the area. Each soil sampling point was geo-referenced using GPS device (Shahabi *et al.*, 2017). The map showing sampling locations is shown in Fig. 5.1. The soil samples were taken to the Soil Science Laboratory of Sokoine University of Agriculture (SUA) for determination of electrical conductivity (EC), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), soil pH, soil texture, organic carbon, chlorides, carbonates, bicarbonates, exchangeable bases and cation exchange capacity (CEC).

5.1.2.2 Irrigation Water Sampling

The water from Little Ruaha River which is used for irrigation in the study area was sampled during the rice growing season in March, 2019 for laboratory water quality assessment. Three water sampling sections namely Magozi, Ilolo Mpya and Mkombilenga were identified (Fig. 5.1) where two subsamples at each section making a total of six (6) water samples (500 ml each) were collected using grab sampling technique (Danielson, 2004; Facchi *et al.*, 2007). Each water sample was analyzed for pH and water electrical conductivity (EC_w) at SUA Soil Science Laboratory using the standard methods (Rhoades *et al.*, 1992; Bauder *et al.*, 2011). The mean pH and EC_w values at each section were used to evaluate the quality of water for irrigation and any potential hazard for salinization (Rhoades *et al.*, 1992; Bauder *et al.*, 2011, Landon, 2014).

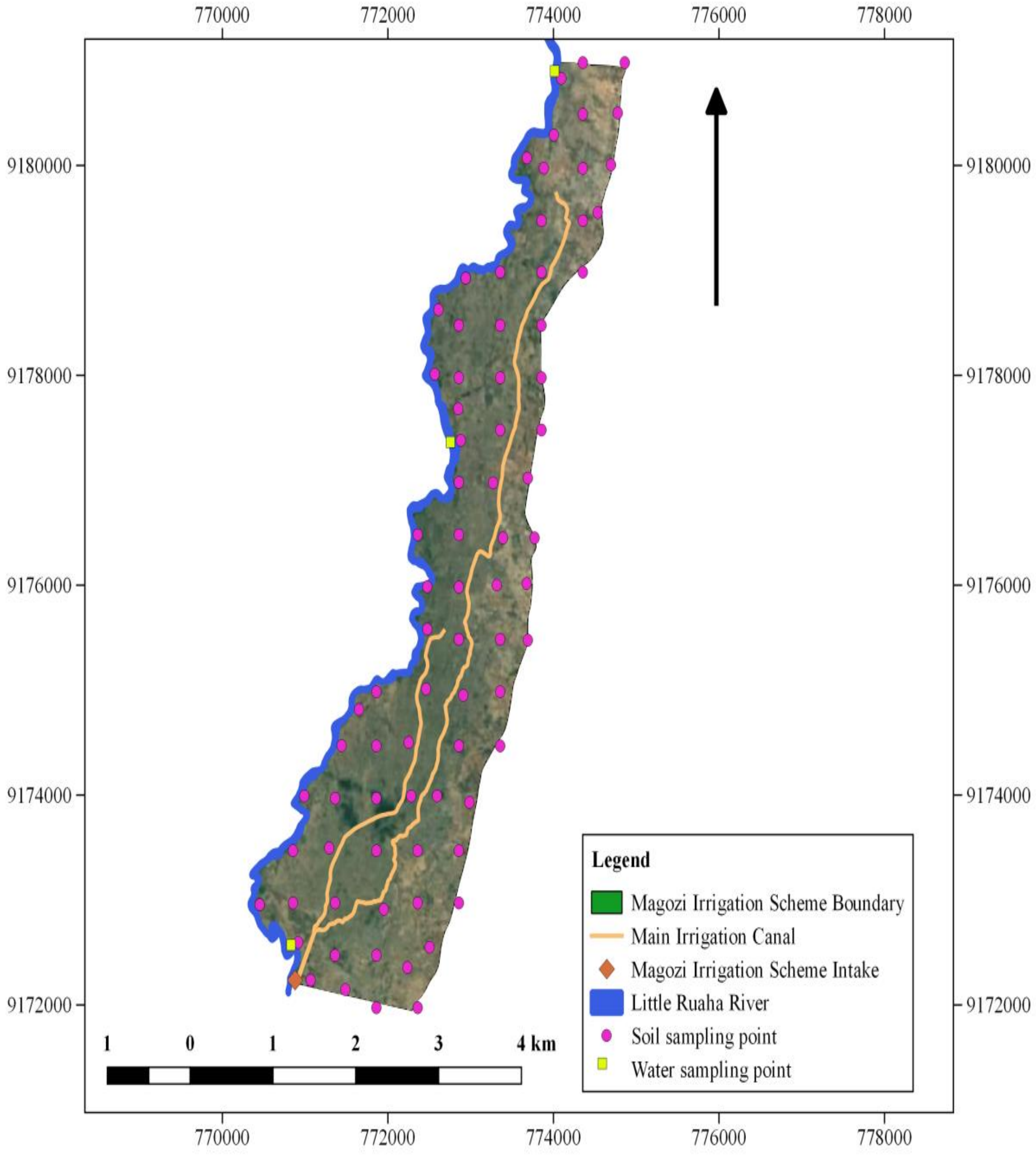

Figure 5.1: A map showing soil and water sampling locations in Magozi Irrigation Scheme

5.1.3 Laboratory Soil Analysis Methods

The composite soil samples were air-dried, ground and passed through a 2-mm sieve as described by Tan (2005) for laboratory determination of physical and chemical properties. Selection of physical and chemical soil properties to be analyzed, considered their importance in soil salinity and general soil characterization (Rengasamy, 2010; Shahid and ur Rahman, 2016). Particle size analysis was determined by hydrometer method after dispersion with 5% sodium hex metaphosphate (Moberg, 2001). The soil textural classes were determined using USDA textural triangle (FAO, 2006).

Soil pH was measured potentiometrically in water at a ratio of 1:2.5 soil to water as described by Okalebo *et al.* (2002). Electrical conductivity in 1:2.5 soil-water suspensions ($EC_{1:2.5}$) was determined for 81 samples using an electrical conductivity meter as per the method described by Moberg, (2001). The electrical conductivity of the saturated paste extract (EC_e) for selected 60 samples was determined in chapter 4 using the standard method (Rhoades, 1996; US Salinity Laboratory Staff, 1954). The electrical conductivity of the saturated paste extract (EC_e) of the remaining 21 soil samples was calculated using the following linear regression which was developed in chapter 4.

$$EC_e = 3.4954 * EC_{1:2.5} \quad (20)$$

where EC_e is the electrical conductivity of the saturated paste extract (dS m^{-1}) and $EC_{1:2.5}$ is the electrical conductivity determined in in 1:2.5 soil-water suspensions (dS m^{-1}).

Organic Carbon (OC) was determined by Walkley and Black wet oxidation method (Okalebo *et al.*, 2002). The soil chlorides, carbonates and bicarbonates concentrations were determined by titrimetric methods as described by Okalebo *et al.* (2002). Cation exchange capacity of soil (CEC_{soil}) and exchangeable bases were determined by saturating soil with neutral 1M NH_4OAc (ammonium acetate) and the adsorbed NH_4^+ was displaced by using 1M KCl and then determined by Kjeldahl distillation method for estimation of CEC of soil (Moberg, 2001; Okalebo *et al.*, 2002). The exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+) were determined by atomic absorption spectrophotometer (Moberg, 2001). Total exchangeable bases (TEB) were calculated arithmetically as the sum of Ca^{2+}, Mg^{2+}, Na^+ and K^+ for a given soil sample (Moberg, 2001). Other soil salinity indices which were calculated are sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) using the following formula:

$SAR = Na^+ / [(Ca^{2+} + Mg^{2+})/2]^{0.5}$ (3)

$ESP (\%) = (Na^+/ CEC) \times 100$ (4)

5.1.4 Assessment of Soil Salinity

Soil salinity at Magozi Irrigation Scheme was assessed using electrical conductivity of the saturated paste extract (EC_e), soil pH, sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) as main soil salinity indices (Bannari *et al.*, 2008). In order to determine the types and relative importance of the different ions that contribute to soil salinity in the area, the exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) as well as anions; chlorides (Cl^-), carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) were also assessed (Bannari *et al.*, 2008). Soil salinity was classified based on electrical conductivity values of the saturated paste extract (EC_e) (Richard, 1954; Rhoades and Chanduvi, 1999; Bannari *et al.*, 2008).

5.1.5 Statistical Analysis

Descriptive statistics including mean, minimum and maximum values of soil salinity indices and other soil properties related to soil salinity were computed using GENSTAT software. Pearson correlations between selected soil physical and chemical properties were performed in Minitab Software and the significance of correlation coefficients was tested at $p \leq 0.05$ (Wim *et al.*, 2007).

5.1.6 Soil Salinity Spatial Distribution Mapping

Inverse Distance Weighting (IDW) interpolation method in QGIS software (Version 2.18.25) was used for mapping of soil salinity spatial distribution based on electrical conductivity values of saturated paste (EC_e). The IDW method calculates the intermediate values by using the information of the nearby known points where the adjacent points have more weights than distant points and vice versa (Lu and Wong, 2008; Babak and Deutsch, 2009; Hammam and Mohamed, 2018). It is relatively fast and easy to compute and straightforward to interpret (Lu and Wong, 2008; Nezami and Alipour, 2012). The IDW formula from Hammam and Mohamed (2018) is as follows:

$$\hat{z}(x_0) = \frac{\sum_{i=1}^{n} z\left(x_i d_{ij}^{-r}\right)}{\sum_{i=1}^{n} d_{ij}^{-r}} \qquad (7)$$

where x_0 is the estimation point and x_i are the data points within a chosen neighborhood. The weights (r) are related to distance by d_{ij}, which is the distance between the estimation point and the data points.

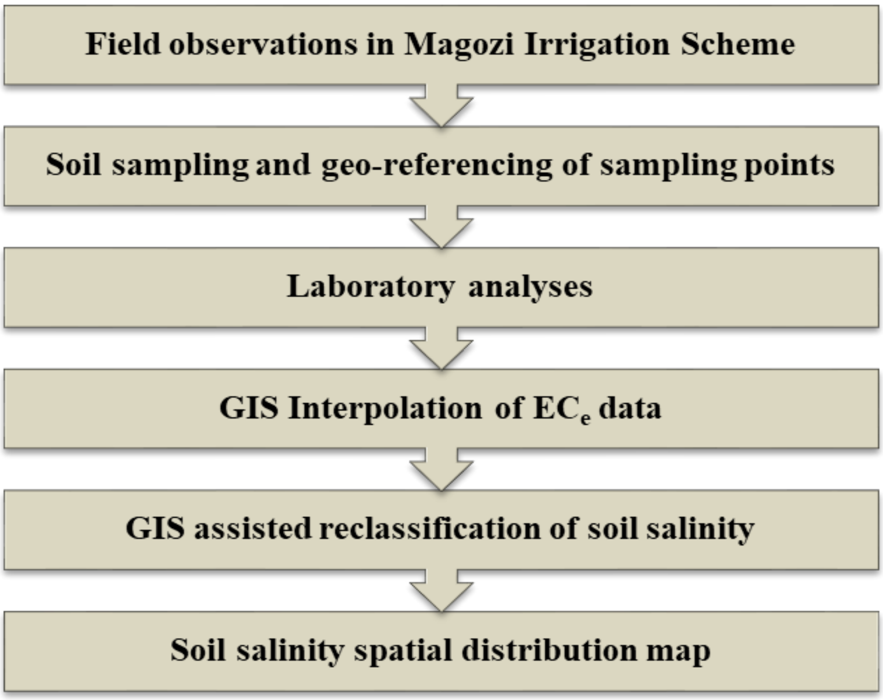

Figure 5.2: A general methodology workflow used in this study

The produced soil salinity map was reclassified using ArcGIS to obtain different salinity classes of the area based on EC_e (Richard, 1954; Rhoades and Chanduvi, 1999; Bannari *et al.*, 2008; Nezami and Alipour, 2012). Fig. 5.2 illustrates the methodology flow chart used in this study to assess and generate soil salinity spatial distribution map of Magozi Irrigation Scheme.

5.2 RESULTS AND DISCUSSION

5.2.1 Soil physical properties

5.2.1.1 Soil Texture

A summary of Particle Size Distribution and the Textural Classes of 81 soil samples has been given in Table 5.1. Comparatively, sand had the highest percentage of minimum, maximum and mean values followed by clay content. High sand content may be attributed to sand deposition in some areas of the scheme due to periodic floods during rainy season as well as sand brought in the field by irrigation water as supported in literatures (Mukhopadhyay, 2010; Schmitter *et al.*, 2010).

Table 5.1: Descriptive statistics on Particle Size Analysis of the studied soils of Magozi Irrigation Scheme

n = 81	Statistic			
	Minimum	**Maximum**	**Mean**	**Standard deviation**
Particle Size Distribution				
% Clay	13.56	59.56	33.01	10.37
% Silt	2.52	33.92	16.08	7.36
% Sand	15.52	79.52	50.91	15.38
Textural Classes	**Number of soil samples (n = 81)**		**Textural class percentage composition (%)**	
Sandy clay loam	36		44	
Clay	20		25	
Sandy clay	10		12	
Clay loam	7		9	
Sandy loam	8		10	
Total	**81**		**100**	

Sand depositions in the agricultural fields reduce soil fertility of the area (Schmitter *et al.*, 2010). Five (5) soil textural classes namely sandy clay loam, clay, sandy clay, clay loam and sandy loam were found in the study area. The dominant soil textural class was sandy clay loam (44%) followed by clay (25%) as indicated in Table 5.1. Sandy loam had the lowest percentage composition in the area with only 8%.

5.2.2 Soil chemical properties

The results of selected soil chemical properties from the studied area have been summarized in Table 5.2. The soil pH, electrical conductivity of the saturated paste extract (EC_e), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), chlorides, carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) have been largely discussed in relation to their estimation of salinity and sodicity hazards soil (Sonmez *et al.*, 2008; Zinck and Metternicht, 2009; Flowers *et al.,* 2014; Hazeltonn and Murphy, 2016; Corwin and Yemoto, 2017).

5.2.2.1 Soil pH

The soil pH as shown in Table 5.2 ranged from 5.2 which has been rated as strongly acid to 8.9 which is strongly alkaline with a mean of 7.3 being neutral (Msanya *et al.* 2001; Landon, 2014; Ideriah and Abere, 2017). The strongly alkaline soils may be attributed to low leaching of bases especially in clay soils (Landon, 2014; Mukungurutse *et al.*, 2018). It has been pointed out that most plants thrive well in soils with values between pH 6.5 and 7.5 being the optimal pH for plant nutrients uptake (Landon, 2014). Therefore, there can be limitations to crop growth because of some soils with pH values less than 6.5 or greater than 7.5 by limiting availability of some plant nutrients such as phosphorus and bases (Ca, Mg and K) (Landon, 2014). However, flooding rice soils have been documented to moderate the pH towards a neutral pH condition (Massawe, 2015).

5.2.2.2 Electrical Conductivity (EC)

It is well known that, electrical conductivity of the saturated paste extract (EC_e) is the main global soil salinity index which estimates correctly the ability of the soil solution to conduct electricity (Sonmez *et al.,* 2008; Corwin and Yemoto, 2017). In this study, the EC_e was used as the main measure and indicator of soil salinity in Magozi Irrigation scheme.

Table 5.2: Descriptive statistics of soil chemical properties in Magozi Irrigation Scheme

Statistic (n = 81)	pH	EC_e	OC	Exchangeable Bases				CEC	ESP	SAR	Cl^-	CO_3^{2-}	HCO_3^-
				Ca	Mg	Na	K						
	(H_2O)	(dS m^{-1})	(%)	(cmolkg^{-1})					(%)		(mg kg^{-1})		
Minimum	5.2	0.24	0.28	3.66	0.24	0.02	0.11	7.2	0.08	0.008	112.2	0.44	25.93
Maximum	8.9	33.3	5.7	17.77	3.51	7.37	10.7	39.2	68.06	3.62	11066	45	381.2
Mean	7.3	2.50	1.44	10.94	0.89	0.81	0.85	19.6	4.70	0.35	711.3	2.68	89.5
Standard deviation	0.74	4.28	0.85	3.03	0.45	1.20	1.17	6.87	9.02	0.55	1480	4.84	50.32

A summary of EC_e values for eighty one (81) soil samples has been given in Table 5.2. The EC_e values ranged from 0.24 dS m^{-1} to 33.3 dS m^{-1} interpreted as non-saline to extremely saline classes respectively with a mean value of 2.50 dS m^{-1} which is rated as slightly saline (Richard, 1954; Rhoades and Chanduvi, 1999; Bannari *et al.,* 2008). The EC_e results indicate that soil salinity development is vivid in many parts of the farms of Magozi Irrigation Scheme. According to Msanya *et al.* (2001), the mean EC_e value of 2.5 dS m^{-1} recorded in this area may cause 10 up to 25 % crop yield reduction.

In terms of rice response to salinity and effects in its production, the mean EC_e value of 2.5 dS m^{-1} from the studied area is generally close to 3 dS m^{-1} which is the EC_e threshold for rice crop (Zeng *et al.,* 2001; Grattan *et al.,* 2002; Landon, 2014; Hoang *et al.,* 2016).

Furthermore, an EC_e of 10 dS m^{-1} may lead to 50 % yield reduction of rice crop (Landon, 2014). Therefore, the recorded highest EC_e of 33.3 dS m^{-1} from the studied area is rather an alarming high salinity hazard which means some areas of this scheme are at higher risks of being salt-affected. This may adversely affect sustainability of rice production in the scheme and lead up to 100 % yield loss of this crop in the areas experiencing such extreme salinity levels.

The results in this study were in line with the general survey study on soil salinity in rice irrigation schemes in the southwestern Tanzania by Kashenge-Killenga *et al.* (2016). In this study, the laboratory results confirmed that 67 % of the surveyed schemes had salt problems. Kashenge-Killenga *et al.* (2016) reported that extreme salinity with EC_e of 4 to 15 dS m^{-1} was recorded from the surveyed irrigation schemes. The variability of soil EC_e in Magozi Irrigation Scheme may imply that some scheme areas currently experiencing lower salinity levels are at risks of developing higher salinity in the future if sound management strategies are not taken into consideration.

5.2.2.3 Organic Carbon (OC)

Soil organic carbon is a dynamic soil fraction that has many functions in soils including biological, physical and chemical (Funakawa *et al.,* 2012; Msanya *et al.,* 2016). The organic carbon (OC) content as summarized in Table 5.2 ranged from 0.28 to 5.7%, which correspond to very low to very high respectively (Msanya *et al.,* 2001; Landon, 2014; Ideriah and Abere, 2017). The mean value of organic carbon (OC) was 1.44% rated as medium (Msanya *et al.,* 2001). The very high soil organic carbon content recorded may be due to accumulation, incorporation and decomposition in the soil of plant residues including rice plant residues in the scheme area. In this irrigation scheme, the rice plant residues are mostly left in the field after harvest up to the next growing season. However, the observed low soil organic carbon content in some areas may be due to poor plant residues management by the farmers. This may include removal of rice plant residues from the field during land preparation which reduces the level of organic carbon in the soil.

5.2.2.4 Exchangeable Bases

The contents of exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) in the studied soils have been summarized in Table 5.2. These bases are components of many salt compounds in soils that lead to soil salinity. According to Msanya *et al.* (2001), the exchangeable calcium ranged from low (3.66 cmolkg^{-1} soil) to high (17.77 cmolkg^{-1} soil) with a mean of 10.94 cmolkg^{-1} soil which is rated as high. The areas with low soil calcium content in the scheme may induce its deficiency in rice crop as opposed to the soils having adequate calcium in the studied area. In soil salinity aspects on the other hand, high levels of calcium in some areas indicate that Ca^{2+} may be one of the salt cations in the area. The exchangeable magnesium ranged from very low to high (0.24 to 3.51 cmolkg^{-1} soil) with a mean of 0.89 cmolkg^{-1} soil rated as medium (Msanya *et al.*, 2001). The results showed that, exchangeable K ranged from 0.11 cmolkg^{-1} soil, which is rated to be very low to 10.7 cmolkg^{-1} soil which is very high with a mean of 0.85 cmolkg^{-1} soil which is medium (Msanya *et al.,* 2001). Generally, the soil potassium level in this area is not adequate for sustainable rice production. The exchangeable Na ranged from 0.02 to 7.37 cmolkg^{-1} soil, rated as low to very high respectively (Msanya *et al.*, 2001). The very high levels of Na may be toxic to rice plant and signifies presence of salts in the area.

5.2.2.5 Cation Exchange Capacity (CEC)

The soil cation exchange capacity (CEC) as presented in Table 5.2 ranged from 7.2 to 39.2 cmolkg^{-1} soil, which is rated as low to high, respectively according to Msanya *et al.* (2001). The mean CEC value was 19.6 cmolkg^{-1} soil. The high CEC values may be attributed to the high soil organic carbon content, hazardous cations such as Na^+ in salt affected soils as well as the dominance of 2:1 silicate clay minerals (Funakawa *et al.*, 2012; Hailu *et al.,* 2015; Msanya *et al.,* 2016).

5.2.2.6 Exchangeable Sodium Percentage (ESP)

According to Msanya *et al.* (2001), the exchangeable sodium percentage (ESP) is more important than the absolute level of exchangeable Na as it measures the sodicity of the soil. In the study, the results of ESP as summarized in Table 5.2 indicated that the area varied from non-sodic soil (0.08%) to extremely sodic soil (68.06%) with a mean of 4.7 % being non sodic (Msanya *et al.*, 2001). The higher ESP values in some areas of the irrigation scheme impose higher risk to rice production. It has been indicated that, ESP values of 16 to 25% may lead up to 50 percent (50%) yield reduction of most crops (Msanya *et al.,* 2001).

5.2.2.7 Sodium Adsorption Ratio (SAR)

SAR is the other soil salinity index which indicates sodium hazard (Joshi *et al.*, 2009; Landon, 2014; Hazeltonn and Murphy, 2016). The higher the SAR values mean the higher the Na hazard in the soil (Joshi *et al.,* 2009; Hazeltonn and Murphy, 2016). In this study, SAR values ranged from 0.008 to 3.62 with a mean value of 0.35. The SAR ratio of 1:5 is considered low and non-damaging, 6:10 is moderate and potentially damaging and greater than 11 is damaging (Joshi *et al.,* 2009; Hazeltonn and Murphy, 2016). In this case therefore, the SAR values from Magozi Irrigation Scheme were generally categorized as low. Therefore, the SAR results indicate that Magozi soils are largely not sodic but saline. However it has been observed that SAR values as low as three (3) can still cause soil dispersion and therefore cause soil structural problems (Hazeltonn and Murphy, 2016). The SAR reflects the Na: Ca + Mg ratio such that as sodium levels increase, the calcium and magnesium cations are replaced. This reduces soil structure and is often observed by crusting and low water permeability (Hazeltonn and Murphy, 2016).

5.2.2.8 Chlorides, Carbonates and Bicarbonates

Chlorides (Cl^-) are the main compounds responsible for the formation of soluble salts that make saline soils (Zinck and Metternicht, 2009; Flowers *et al.,* 2014). The content of soil Cl^- ranged from 112.2 to 11066 mg kg^{-1} with a mean value of 711.3 mg kg^{-1} (Table 5.2). Chlorides are highly soluble and may be highly toxic to plants (Zinck and Metternicht, 2009). Chlorides are more harmful to plants than carbonates or bicarbonates (Zinck and Metternicht, 2009; Flowers *et al.,* 2014). High levels of chloride with sodium in this study indicated that one of the dominant salts in the soils of Magozi Irrigation Scheme is that of sodium chloride (NaCl). It has been reported that, the highly soluble and toxic NaCl is the most common component of saline soils (Zinck and Metternicht, 2009; Flowers *et al.,* 2014).

Carbonates exert different effects on soils, depending on the cation the carbonate is bound to, the amount accumulated in the soil and the solubility (Zinck and Metternicht, 2009). The soil CO_3^{2-} ranged from 0.44 to 45 mg kg^{-1} with a mean of 2.68 mg kg^{-1} while the HCO_3^- ranged from 25.93 to 381.2 mg kg^{-1} with a mean value of 89.5 mg kg^{-1}.

5.2.2.9 Correlation between soil physical and chemical properties

In Table 5.3 the Pearson Correlation matrix was used to indicate the relationships between selected soil physical and chemical properties. The soil salinity indices have also been correlated with each other and with other soil properties. The electrical conductivity of the saturated paste extract (EC_e) had positive significant correlation at $p \leq 0.05$ with soil Cl^- (r = 0.459), exchangeable Na (r = 0.341), ESP (r = 0.302) and SAR (r = 0.320). The soil Cl^- showed positive significant correlation at $p \leq 0.05$ with exchangeable Mg (r = 0.443), Na (r = 0.492) as well as ESP (r = 0.789) and SAR (r = 0.458). The soil HCO_3^- indicated positive significant correlation at $p \leq 0.05$ with exchangeable Na (r = 0.416), K (r = 0.682) and SAR (r = 0.434). Exchangeable Ca showed non-significant correlations ($p \leq 0.05$) with Cl^- and HCO_3^-.

Generally, the correlation coefficients results between the selected soil physical and chemical properties were similar to the reported correlations between similar soil properties in literatures (Iqbal *et al.*, 2005; Papiernik *et al.*, 2005; Worku, 2015; Ufot *et al.*, 2016; Worku and Bedadi, 2016; Aderemi *et al.*, 2019).

Pearson correlation results together with a close view to other soil chemical parameters in this study indicated that the possible main soil salt anions in Magozi Irrigation Scheme may be Cl^- and HCO_3^-. On the other hand, the main salt cations in the area may be Na^+ and Mg^+ in relatively higher amounts than K^+ and Ca^+. Therefore, the main soil salts chemical compounds in this area may be NaCl, $MgCl_2$, $NaHCO_3$ and $KHCO_3$ in relatively higher concentrations as compared to $CaCl_2$ and $CaHCO_3$. However, a study on chemical salts speciation is required to derive full understanding of salt compounds in the area for more specific salinity management options.

Table 5.3: Pearson correlation coefficients between soil salinity chemical indices and other soil properties

	pH (H_2O)	EC_e ($dS\ m^{-1}$)	% Clay	% Silt	% Sand	OC (%)	Cl^-	CO_3^{2-}	HCO_3^-	CEC	Ca	Mg	Na	K	ESP (%)	SAR
							($mg\ kg^{-1}$)			($cmolkg^{-1}$)						
pH	1															
EC_e	NS	1														
% Clay	-0.341*	NS	1													
% Silt	NS	NS	0.490*	1												
% Sand	0.326*	NS	-0.909*	-0.809*	1											
OC (%)	NS	NS	0.226*	0.363*	-0.326*	1										
Cl^-	NS	0.459*	NS	NS	NS	NS	1									
CO_3^{2-}	NS	NS	NS	NS	NS	0.304*	NS	1								
HCO_3^-	0.595*	NS	NS	NS	NS	NS	NS	NS	1							
CEC	NS	NS	0.714*	0.400*	-0.673*	0.268*	NS	NS	NS	1						
Ca	NS	NS	0.583*	0.367*	-0.569*	0.217*	NS	NS	NS	0.555*	1					
Mg	NS	NS	0.366*	0.370*	-0.424*	NS	0.443*	NS	NS	0.329*	0.377*	1				
Na	NS	0.341*	NS	NS	NS	NS	0.492*	NS	0.416*	NS	NS	0.354*	1			
K	0.294*	NS	NS	NS	NS	NS	NS	NS	0.682*	NS	NS	NS	0.612*	1		
ESP	NS	0.302*	NS	NS	NS	NS	0.789*	NS	NS	NS	NS	0.334*	0.826*	0.270*	1	
SAR	NS	0.320*	NS	NS	NS	NS	0.458*	NS	0.434*	NS	NS	0.270*	0.991*	0.655*	0.816*	1

KEY:

*Significant correlation at $p \leq 0.05$

NS = Nonsignificant

5.2.3 Irrigation Water Quality Assessment

The results of pH and electrical conductivity in water (EC_w) of irrigation water from Little Ruaha River are presented in Table 5.4. The pH and EC_w have been selected in this study as among the chemical parameters used for assessing salinity hazard brought by irrigation water (Rhoades *et al*., 1992; Bauder *et al.,* 2011, Landon, 2014; Hazeltonn and Murphy, 2016).

Table 5.4: The pH and electrical conductivity values of irrigation water (EC_w) from Little Ruaha River at Magozi Irrigation Scheme and their interpretations

Statistic	pH (H_2O)	EC_w (dS m^{-1})	Water Salinity Class (Rhoades *et al*., 1992; Hazeltonn and Murphy, 2016)	Limitation for water use in irrigation based on EC_w (Bauder *et al*., 2011; Landon, 2014)
Minimum	6.6	0.13	None-saline	None
Maximum	6.7	0.16	None-saline	None
Mean	6.6	0.14	None-saline	None
Standard Deviation	0.02	0.01	-	-

The water pH values ranged from 6.6 to 6.7 with a mean of 6.6 which is rated as neutral according to Msanya *et al.* (2001). In general, water for irrigation is supposed to have a pH between 5.0 and 7.0 (Bauder *et al.,* 2011; Park *et al.,* 2014). Therefore, according to these results, the pH of water is suitable for irrigation purposes in this scheme. The EC_w values from the studied water samples ranged from 0.13 to 0.16 with a mean of 0.14 dS m^{-1}.

Generally, all the values of EC_w were non-saline (below 0.75 dS m^{-1}) and hence do not pose any limitation for irrigation use as documented in different literatures (Rhoades *et al*., 1992; Joshi *et al.,* 2009; Bauder *et al.,* 2011; Landon, 2014; Hazeltonn and Murphy, 2016). Therefore, the Little Ruaha River water is currently suitable for irrigation use in

Magozi Scheme. However, it has been shown that water quality alone cannot suffice to evaluate potential salinity hazard of irrigation water unless consideration is given to crop, soil, climate and existing agronomic and irrigation management practices (Smedema and Shiati, 2002; Bauder *et al.*, 2011). Hence, the observed soil salinity hazard in some parts of the scheme despite irrigation water being none-saline, may be due to poor irrigation, agronomic and soil management practices by farmers in Magozi Irrigation Scheme.

5.2.4 Spatial Distribution of Soil Salinity in Magozi Irrigation Scheme

5.2.4.1 Soil Salinity Spatial Distribution Map of Magozi Irrigation Scheme

Fig. 5.3 shows soil salinity spatial distribution map of Magozi Irrigation Scheme based on soil EC_e (dS m^{-1}).

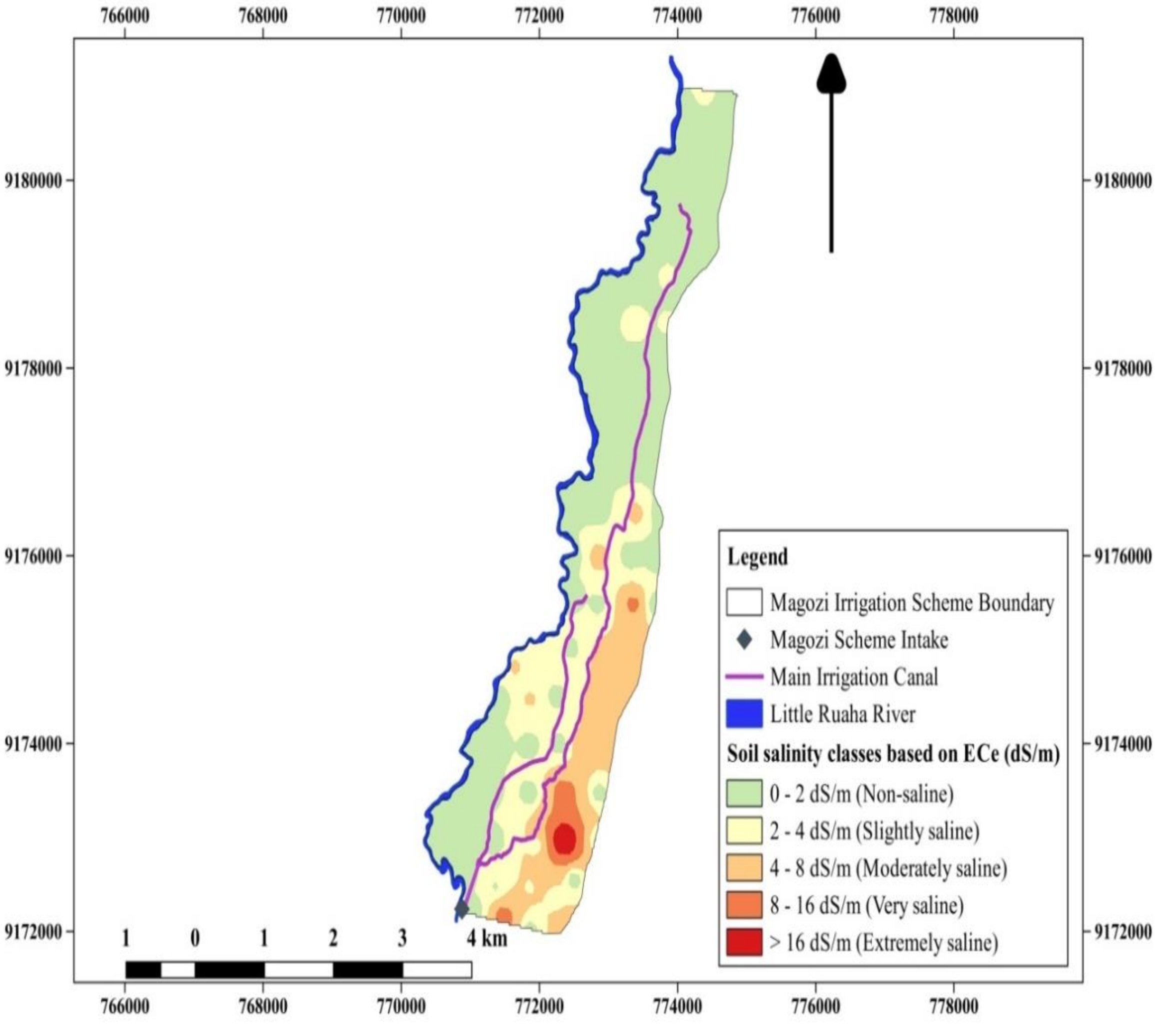

Figure 5.3: Spatial distribution of Soil Salinity in Magozi Irrigation Scheme

The information on spatial distribution of soil salinity especially in its early stage is also importantly required in addressing soil degradation trends and is vital in terms of sustainable agricultural management (Bannari *et al.*, 2008; Shahabi *et al.*, 2017). In their study, Abdelfattah *et al.* (2009) used Inverse Distance Weighting (IDW) interpolation technique in GIS to predict and produce soil salinity map with different classes varying in extent based on soil EC_e (dS m^{-1}) values in Abu Dhabi, United Arab Emirates.

The salinity map of Magozi Irrigation Scheme revealed the occurrence of five soil salinity classes based on soil EC_e (dS m^{-1}) namely 0 - 2, 2 - 4, 4 - 8, 8 - 16 and > 16 dS m^{-1} with varying extent in the area. These soil salinity classes have been interpreted as non-saline (0 - 2 dS m^{-1}), slightly saline (2 - 4 dS m^{-1}), moderately saline (4 - 8 dS m^{-1}), very saline (8 - 16 dS m^{-1}) and extremely saline (> 16 dS m^{-1}) (Richard, 1954; Rhoades and Chanduvi, 1999; Bannari *et al.*, 2008). This soil salinity classification system is also known as agronomic soil salinity classification and it provides the potential salinity effects on crops (Richard, 1954; Rhoades and Chanduvi, 1999).

The soil salinity spatial distribution map indicated that, the upper and middle sections of the scheme located at Magozi and Ilolo Mpya Villages, respectively, are more salt affected as they are more dominated by slightly saline to extremely saline classes than lower section located at Mkombilenga Village (Fig. 5.3). The eastern upper part of the scheme appeared to be most affected by soil salinity in the scheme, being dominated mostly by moderately saline to extremely saline classes. It has been reported in various studies (Mziray *et al.*, 2015; Manero, 2017; Mdemu *et al.*, 2017) that the upper and middle sections of Magozi Irrigation Scheme receive more irrigation water compared to other parts because they are closer to the water intake in the scheme (Fig. 5.3). Therefore, the higher soil salinity in the upper and middle sections of this scheme may mostly be attributed to higher waterlogging problems coupled with poor irrigation management practices by farmers as supported in literature (Konukcu *et al.,* 2006; Qureshi *et al.,* 2008; Ritzema *et al.,* 2008; Valipour, 2014). This information implies that, the trend of soil salinization in Magozi Irrigation Scheme is mainly from the upper section towards downstream. This means that, soil salinity has a potential to increase in this irrigation scheme and will extend to the currently less saline areas if sound management options are not addressed.

5.2.4.2 Extent of Soil Salinity Classes Spatial Distribution in Magozi Irrigation Scheme

Table 5.5 presents the data extracted from GIS environment on the area (ha) of each mapped soil salinity class in Magozi Irrigation Scheme. The results indicated that 52.14% of the total scheme land area (ha) was classified as non-saline whereby the salinity effect to crops is negligible (Richard, 1954; Rhoades and Chanduvi, 1999; Bannari *et al.,* 2008).

Table 5.5: Extent of Soil Salinity in Magozi Irrigation Scheme

Extent of Soil Salinity Classes in Magozi Irrigation Scheme					**Extent of slightly saline to extremely saline classes**	
S/N	**EC_e (dS m^{-1})**	**Soil Salinity Class**	**Area (ha)**	**Percent (%)**	**Area (ha)**	**Percent (%)**
1	0 - 2	Non-saline	677.79	52.14	622.21	47.86
2	2 - 4	Slightly saline	352.93	27.15		
3	4 - 8	Moderately saline	220.11	16.93		
4	8 - 16	Very saline	38.29	2.95		
5	> 16	Extremely saline	10.88	0.84		
Total			**1300.00**	**100.00**		

On the other hand, 27.15%, 16.93%, 2.95% and 0.84% of the total land were classified as slightly saline, moderately saline, very saline and extremely saline respectively. The presented salinity classes have different degrees of effects to crops where yields of very sensitive crops to salinity may be restricted for slightly saline soils while yields of many crops may be restricted for moderately saline soils, only tolerant crops yield satisfactory very saline soils and only few very tolerant crops yield satisfactorily for extremely saline soils.

5.2.4.3 Potential effects of soil salinity to sustainable rice production in Magozi Irrigation Scheme

The results presented in Table 5.5, showed that, the 622.21 ha of land which represents 47.86% of the total cultivated land area in Magozi Irrigation Scheme is already affected by soil salinity with classes ranging from slightly saline to extremely saline. This indicates that, rice production in the area is at higher risk of being greatly reduced by soil salinity effects, because the slightly to extremely saline soils have EC_e values that can affect rice growth and yield. The rice plant has been rated to be salt sensitive plant (Shereen *et al.*, 2005; Flowers *et al.*, 2014; Mohammadi-Nejad *et al.*, 2012; Aguilar *et al.*, 2017) and it is the most salt sensitive cereal crop with an EC_e threshold of 3 dS m^{-1} for most cultivated varieties (Zeng *et al.*, 2001; Grattan *et al.*, 2002; Flowers *et al.*, 2014; Hoang *et al.*, 2016). Even at EC_e as low as 3.5 dS m^{-1}, rice loses about 10% of its yield (Hoang *et al.*, 2016). Furthermore, rice losses yields of up to 50% at EC_e 7.2 dS m^{-1} as reported by Umali (1993). The information from the results as well as from literature suggest a strong need for addressing sound crop, soil and irrigation management strategies in order to avoid further salinity induced land degradation for enhancing sustainable rice production in Magozi Irrigation Scheme.

5.2.4.4 Visual symptoms of soil salinity in Magozi Irrigation Scheme

Plate 5.1 shows some selected photographs recorded during field work in Magozi Irrigation Scheme. The photographs showed that some areas of the scheme especially the upper eastern part were characterized with whitish surfaces and salt crusting that resulted to total plant failure. These features are known to be the visual symptoms of soil salinity (Matinfar *et al.*, 2013; Allbed *et al.*, 2014; Daliakopoulos *et al.*, 2016). The mentioned visual symptoms of soil salinity were mostly dominant in areas mapped indicating to be slightly saline to extremely saline (Fig. 5.3). The extremely saline areas are experiencing total crop failures. Such areas have been mostly abandoned from agricultural use in Magozi Irrigation Scheme.

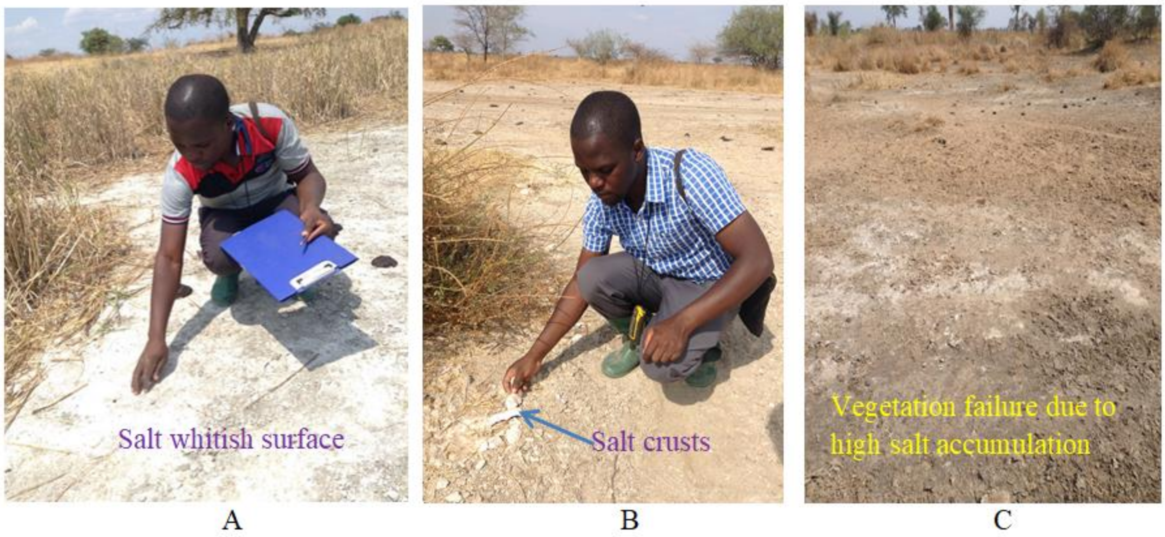

Plate 5.1: Whitish salt surface (A), salt crusts (B) and an area with total plant failure (C) in some parts of Magozi Irrigation Scheme

5.3 CONCLUSIONS

Based on electrical conductivity of the saturated paste extract (EC_e) results and its spatial distribution, it shows that soil salinity in Magozi Irrigation Scheme is developing. A total of 622.21 ha (47.86%) of the cultivated land in the scheme is already affected by soil salinity with classes varying from slightly saline to extremely saline. The soil salinity spatial distribution map indicated that this problem has a potential of expanding further in the scheme if appropriate irrigation, crop and soil management options are not taken into consideration to reduce salinization. The current extent and magnitude of soil salinity in the area may be one of the factors affecting rice productivity in Magozi Irrigation Scheme. This study suggests that suitable irrigation, crop and soil management practices have to be adopted by farmers in order to guarantee sustainable rice production in this scheme. Improving irrigation drainage structures will help to reduce waterlogging conditions which appear to be one of the factors causing soil salinity development in most parts of the scheme.

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CHAPTER SIX

6.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions can be drawn from the results of this study;

i. The soils of Magozi Irrigation Scheme were moderately deep to very deep and relatively young with high degree of weathering potential based on silt/clay ratios.

ii. The topsoil pH ranged from 7.0 (neutral) to 8.1 (moderate alkaline) and 7.4 (mildly alkaline) to 9.0 (strongly alkaline) for subsoils. The strongly alkaline pH values were dominant in profile MAG-P1, attributed to low leaching of bases in clay soils. The topsoil organic carbon ranged from 1.13% (low) to 1.59% (medium).

iii. The topsoil total nitrogen ranged from 0.13% (low) to 0.23% (medium). All the topsoil available P were rated as high (14.59 to 22.87 mg kg^{-1}). However, the soils of MAG-P1 and MAG-P2 profiles may have limitations in availability of some plant nutrients like P because of pH values > 7.5. The exchangeable K ranged from moderate (0.51 $cmolkg^{-1}$) to high (1.61 $cmolkg^{-1}$) for topsoil and very low (0.09 $cmolkg^{-1}$) to moderate (0.64 $cmolkg^{-1}$) in the subsoil.

iv. The soils were classified to the family level in the USDA Soil Taxonomy as *Nearly level, very deep, clayey, moderate to strongly alkaline, isohyperthermic, Typic Haplusterts* for profile MAG-P1 while profile MAG-P2 and MAG-P3 were classified as *Nearly level, deep, sandy clay over sandy clay loam, mildly to moderate alkaline, isohyperthermic, Vertic Endoaquepts* and *Nearly level, deep,* *clayey over loamy sandy and sandy clay loam, neutral to mildly alkaline, isohyperthermic, Vertic Epiaquepts* respectively. On the hand, in World Reference Base for Soil Resources (WRB) the soils were classified and named to Tier 2 level as *Haplic Vertisols (Mazic, Ochric), Eutric Vertic Cambisols (Clayic, Ochric)* and *Eutric Vertic Stagnic Cambisols (Clayic, Ochric)* for MAG-P1, MAG-P2 and MAG-P3 profiles respectively.

v. The study has found that soil salinity is a growing land degradation problem in Magozi Irrigation Scheme. This may be due to improper soil and irrigation management practices as well as poor scheme drainage structures leading to waterlogging problems which promote salinity development.

vi. The linear regression model $\mathbf{EC_e = 3.4954*EC_{1:2.5}}$ was developed to facilitate accurate soil salinity assessment in Magozi Irrigation Scheme and other areas with similar soils through predicting EC_e from $EC_{1:2.5}$ values.

vii. The spatial distribution of soil salinity map of Magozi Irrigation Scheme indicated that out of 1300 ha of the cultivated land, a total of 622.21 ha (47.86%) had slightly saline to extremely saline soils. This may negatively affect rice production in the scheme. However, the remaining non-saline area which is 677.79 ha (52.14%) is currently good for rice production under normal best agronomic practices.

viii. The spatial distribution of soil salinity map indicated that the problem of soil salinity has a potential of expanding further in the scheme area if appropriate irrigation practices, crop and soil management options are not taken into consideration to reduce or control soil salinity.

6.2 Recommendations

The following recommendations are suggested from this study:

i. The use of inorganic and organic fertilizers like manures is recommended to increase rice yields in Magozi Irrigation Scheme. Inorganic fertilizers such as UREA and NPK will supply adequate amounts of N, P and K nutrients as per rice requirements. It is recommended that Sulphur (S) fertilizers such as Sulphate of Ammonia (SA) should be applied as per recommendations to supply S nutrient as well as for lowering soil pH values in areas where it is strongly alkaline because they may lead to fixation of some nutrients such as P. However, a study on rice fertilizer response is required in order to establish sound fertilizer recommendations in this scheme.

ii. The land preparations in this scheme such as ploughing should be done timely when the soil is not very dry or very wet in order to avoid workability hardship of vertic soils.

iii. The linear regression model $\mathbf{EC_e = 3.4954*EC_{1:2.5}}$ developed in this study can be used for assessing and monitoring soil salinity in Magozi Irrigation Scheme based on EC_e. Furthermore, this equation can be tested for its applicability to other similar soils in Tanzania.

iv. More studies in other parts of Tanzania should focus on developing location and soil specific linear regression equations that can be used to predict electrical conductivity of the saturated paste extract (EC_e) from values of $EC_{1:2.5}$. Having these regression equations will facilitate accurate assessment and monitoring of soil salinity for sustainable crop production in the country.

v. The waterlogging problems observed in many areas of the scheme should be addressed by improving irrigation drainage channels which will enhance drainage of irrigation and rain water from the farmers' fields. This will help to reduce the risks of soil salinity development in the scheme.

vi. The problem of soil salinity in the scheme can also be reduced by encouraging and training farmers on the appropriate irrigation practices, adoption of water efficient rice farming technologies such as the system of rice intensification (SRI) and addition of adequate amounts of rice husks in the fields.

vii. The preparation of rice seedling nurseries should be done in areas having soils which are not salt-affected in order to avoid salt injury to the seedlings before transplanting.

viii. The farmers in this irrigation scheme should adopt growing of salt tolerant rice varieties such as SATO 1 in order to improve rice production in salt affected areas.

ix. Further soil salinity studies should focus on chemical speciation of salt compounds in order to understand the type of salts present in the soils of Magozi Irrigation Scheme for better management strategies.

x. Additionally, future research works should focus on generating spatial environmental correlates of soil salinity in order to improve future soil salinity modelling and prediction in GIS for enhancing sustainability of rice production in this area.