ESTIMATION OF IRRIGATION WATER ABSTRACTION IN THE UPPER REACHES OF LUNSEMFWA, MULUNGUSHI, MWOMBOSHI AND MKUSHI SUB-BASINS

By

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Dissertation submitted in partial fulfillment for the degree of Master of Engineering in Agricultural Engineering

The University of Zambia

August, 2018

DECLARATION

I, **LAMONG TSHENYEGO** do hereby declare that the contents in this dissertation are my original work and have not been previously submitted to any University for the award of a degree or any other qualification. The collaborative contributions have been indicated clearly and acknowledged. Due references have been provided on all supporting literatures and resources used in the dissertation.

Signature…………………………………… Date……………………………

CERTIFICATE OF APPROVAL

This dissertation submitted by **LAMONG TSHENYEGO** is approved as fulfilling the requirements for the award of the degree of Master of Engineering in Agricultural Engineering at the University of Zambia.

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ABSTRACT

Water abstraction is achieved by many means, and for many purposes. Abstraction depends on many variables that include the purpose for the abstraction, the location, the type of laws in place regarding the procedure, and the type of resources available for the abstraction process. The overall objective of the study was to estimate the abstraction for irrigation water from the upper reaches of Mkushi, Mulungushi, Mwomboshi and Lunsemfwa sub-Basins. For the years 2013–2017 Landsat (L8OLI/TIRS), QGIS and AquaCrop packages were used to generate water abstraction estimates. Field and climate data was obtained from the internet and literature as well as weather stations under Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSACAL) project closer to the sub-catchments.

Reference evapotranspiration was determined using FAO ETo calculator and ranged from 6.84 mm/day to 7.02mm/day. The QGIS software was used to delineate the catchments areas. Mwomboshi had a smallest catchment area of 3043 km^2, while Lunsemfwa had largest area of 7794 km^2. Classified estimates of irrigated areas within each sub basin under the study were for the period 2013 to 2017. The least recorded irrigated area was in Mkushi in 2016 (12 km^2) while highest being 167 km^2 in Lunsemfwa in 2013. For the five years period (2013 to 2017) Mkushi has irrigated a sum of 103.83 km^2, Lunsemfwa 692.00 km^2, Mulungushi 136.00 km^2 and Mwomboshi with the sum of 115.17 km^2. For this study the soils were set as described by in the soil map of Zambia and put into the soil Characteristic calculator to estimate their physical properties.

The results show that maximum volume of water abstracted in all the catchment was estimated at 120,203,800 m^3 in 2013, while the minimum was in 2014 estimated at 73,366,400 m^3. The results show that for maximum volume abstracted for irrigation had a significant difference when comparing Lunsemfwa catchment to Mkushi. Mulungushi and Mwomboshi show no chances of being the same at alpha of 0.05 level.

DEDICATION

I dedicate this research to my late mother, Maatla Tshenyego and family for their prayers, love and unending support throughout my postgraduate studies at the University of Zambia.

AKNOWLEDGEMENTS

I am highly obliged to my sponsors, Mobility to Enhance Training of Engineering Graduates in Africa (METEGA), first, for awarding me the scholarship to pursue a MEng-Agricultural Engineering at the University of Zambia and secondly, covering the tuition fees and the other necessary support such as medical insurance and a monthly stipend. Without these, this study would not have been possible.

Honest appreciation goes to my supervisors Mr K. Mulonda and Dr. Isaac N. Simate for their insightful contribution that helped me stay on track and to finish this project within the time frame allocated to the study. May the almighty God bless your endeavors.

I would also like to acknowledge the head of Department Agricultural Engineering, University of Zambia Dr. J.M Chileshe together with his entire members of staff, technical and support staff for their generous input. The progress presentations that were held at the Department enabled me to share the milestones from the study and in return received insightful comments that were relevant to the study.

Last but not least, to my colleagues Mogomotsi Jason Molefhe, Pauline Katjodumbo, Luqman (from Ghana) and Lt. Col. Mukuwa (from Zambia); thank you for providing such a good atmosphere where knowledge, culture and issues pertaining to life were shared.

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LIST OF ABBREVIATION

DEM	- Digital Elevation Model
EPSG	- European Petroleum Survey Group
GEOTiff	- Geostationary Earth Orbit Tagged Image File Format.
LSD	- Least Significant Difference
NASA	- National Aeronautics and Space Administration
NOAA	- National Oceanic and Atmospheric Administration
OLI/TIRS	- Landsat 8 Operational Land Imager/Thermal Infrared Sensor
POWER	- Performance Optimized With Enhanced Risk
QGIS	- Quantum Geographic Information Systems
RAW	- Readily Available Water
SAGA	- System for Automated Geo-scientific Analyses
SASSCAL	-Southern African Science Service Centre for Climate Change and Adaptive Land Management.
SPSS	- Statistical Package for the Social Sciences
USGS	- United States Geological Survey
UTM	- Urchin Tracking Module
WARMA	- Water Resources Management Authority
ZEMA	- Zambia Environmental Management Agency

NOMENCLATURE

CCo - Canopy size of the average seedling at 90% emergence

CCx - Maximum canopy cover (fraction soil cover)

ETc -Crop Evapotranspiration

ETo - Reference Evapotranspiration

K_s - Soil Stress coefficient

K_{sat} - Saturated hydraulic conductivity

θ_{FC} - Soil water content at Field Capacity

θ_{PWP} - Soil water content at Permanent Wilting Point

θ_{sat} - Soil water content at soil saturation

ρ_{b-} - Soil bulk Density

ρ_s -Soil density

CHAPTER 1 INTRODUCTION

The rise in water demand for agriculture, industries, domestic, and environmental needs requires knowledgeable use of this limited resource. Since agriculture (mainly irrigation) is the major user of water, estimation of irrigation water abstraction from the basin is of high importance. Zambia has put in measures and policies to encourage private sector to provide electricity to its general public in most case by the use of hydro electricity. This has brought competition in water demand. This chapter presents a background to the study, the statement of the problem, the significance of the study, the study objectives, and the scope of the study. The chapter also presents the research structure and then a brief conclusion.

1.1. BACKGROUND INFORMATION

Lunsemfwa Hydro Power Company (LHPC) is a company that generates electricity using water. It was initially meant to produce and supply power to Kabwe mine. The mine was closed and LHPC was sold. The company is 51 % Norwegian owned by a company called SN power and 49 % Zambian owned by individuals mostly former Kabwe miners. Mulungushi Dam (capacity of 2.60×10^{8} m^{3}) and Mitta hills dam (capacity of 6.79×10^{8} m^{3}) provides water for generating its hydro power (Brett Lawson, 2013) through its two power stations. The Mulungushi Dam power plant has the capacity of producing 31 MW and the Mitta hills power plant has the capacity of producing 54 MW (Brett Lawson, 2013). The company produces power and sells to ZESCO which then distributes across the country (Mike Everett, 2013).

The company faces major challenges with regards to water which is needed for power generation. The lack of sufficient rains in the past years has led to the dams failing to fill up which in turn has caused reduced power generation. In some cases even shutting down of generation to allow for the dams to fill up was done. The change in climate which is causing unpredictable weather patterns is just one of the major problems. The Lunsemfwa basin, in which both the Mitta hills Dam and the Mulungushi Dam lie faces high levels of water abstraction for irrigation. This is due to the large number of commercial farms which are situated in the upper reaches of the Lunsemfwa basin.. This is causing the company not to generate power to its capacity.

This research was carried in the Republic of Zambia in the central Lunsemfwa basins which is the major region for commercial agriculture and other economics activities such as energy production. Figure 1.1 shows the map of the Republic of Zambia and the location of the LHPC site.

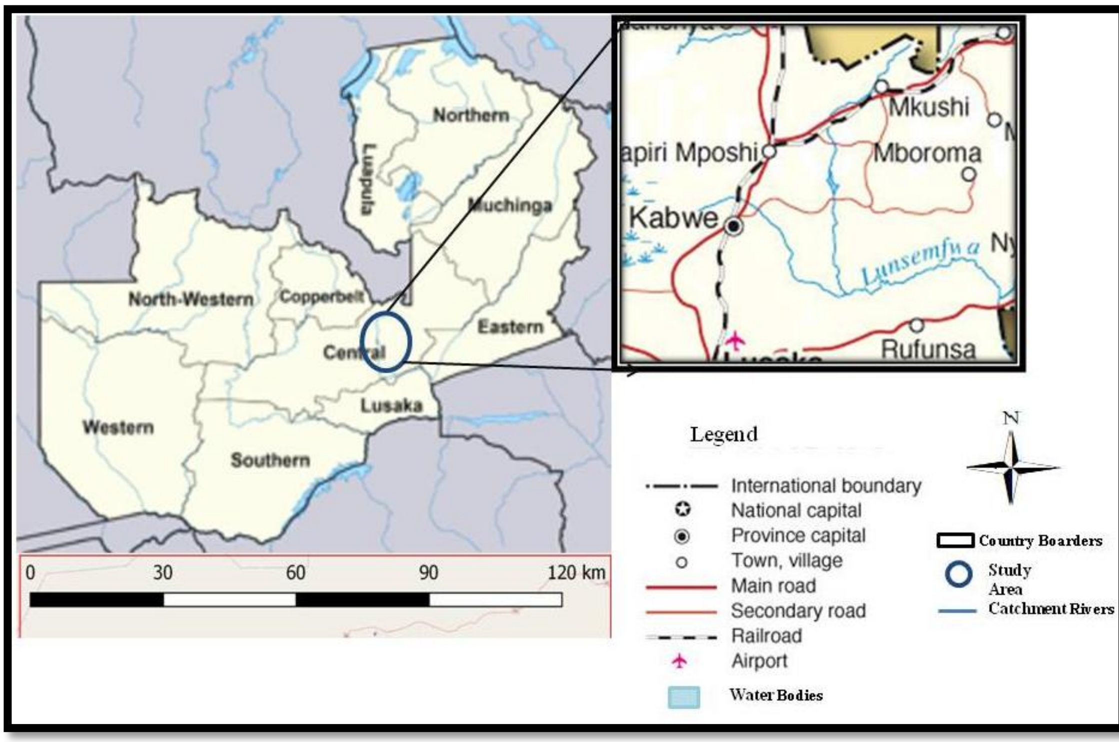

Figure 1.1 Map of Zambia showing location and study area with reference to the roads and the whole country

The Lunsemfwa River enters the Luangwa Rift valley about 40 km from its western end, where the valley is about 45 km wide. It flows to the middle of the valley and turns east as a meandering river with oxbow lakes and a 1-2 km wide floodplain. 100 km further on it merges with the Lukusashi coming from the north-east, and the combined river turns south towards the Luangwa River.

The Mulungushi River in central Zambia is a tributary of the Lunsemfwa River and the Luangwa River, and are part of the Zambezi River basin. It rises on the plateau north-west of Kabwe and flows south-east into the Luangwa Rift Valley where it joins the Lunsemfwa River. Zambia like many other countries has existing water use from the basins, however there is lack of information and more accurate strategies to calculate the amount of water abstraction for each use.

Irrigation water use is one of the major uses of water from the basins. Irrigation water can be estimated by the use of plant water requirements grown in the given area. In upper Ewaso Ng'iro river basin Kenya the amount of water use has increased in a period of ten years and account to 64 percent of water being used in irrigation over the last 5 years (Gichuki, 2008). Moreover Gichuki (2008) have mentioned that the proportion of unauthorized water use have increased over years and recently at about 80% and 95% during high and low flows respectively which lead to conflict among water users.

1.1.1 General River Basin Water Uses

Basin's climatic condition and soil characteristic influence agriculture productivity and can be a driving force of local economy. As a result of irrigation crop yields of up to six times higher than in rain fed are attained as the problem of water stress prevail. This makes it important to estimate the volume of water abstracted from the basin by irrigation as accurately as possible (Emilio *et al.*, 2014).

The result from this study can be useful for assessment in hydrology and or the operational and maintenances of storage structures downstream. During dry season basin flow are used mainly for irrigation which may affect power generation and other water uses (Gichuki, 2008). In this study the amount of water abstracted from the four basins needs to be estimated in order to account for the part used in irrigation. Such information is needed for operation and management of the hydroelectric power station.

The irrigation water abstraction from the basin can be estimated through evapotranspiration of the grown crops in the four sub- catchment. The knowledge of the soil characteristics, weather conditions together with the use of computer softwares like AquaCrop, ETo calculator and Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions (Saxton & Rawls, 2006). Daily weather data (rainfall, minimum and maximum temperature, solar radiation, relative humidity, and wind speed) were obtained from the meteorological station of SASSCAL located adjacent to the basins and used as inputs into the software to estimate water abstraction.

1.1.2 Basin water use in Zambia

Although Zambia is considered to have abundant water resources, development in the sectors of irrigated agriculture and hydropower generation coupled with a rising population, is exerting heavy pressure on the available water resources base especially in the Kafue River basin (Casarotto, 2013).

Water in Zambia is mostly used for agriculture and hydropower which plays the major key role in the development of the country (Thomas *et al.*, 2016) and are recognised by the country to be the priority sector after mining. Currently almost 70,000 hectares are improved in commercial irrigation for some basins along Kafue river and it is expected to increase with time thus making irrigation the second most water user after power production (Thomas *et al.*, 2016). River basin water across the country is abstracted mainly for municipal supplies, mining activities and the other being the survival of the dense fishery activities, which serve as a livelihood for people living along the basin (Alaerts, 2015).

The country water allocation has faced number of challenges between private and state owned areas as well as contradictory interests for water resource in place. This is moreover caused by lack of information on basin use and accurate hydrological information as well as unreliable water allocation among users (Brett Lawson, 2013). The issue lead to the government prioritising specific sectors which earn valuable foreign exchange such as hydropower export and irrigation in agriculture (Thomas et al., 2016). These lead to the low income left behind in livestock development. This makes it necessary to know the amount of the water being used by the two sectors, although it undermines other sectors to develop within the basin.

Knowledge of the amount of the water used in agricultural can make it easy to allocate the basin water among user and giving priorities to the local low income farmers who normally represent the lager population within the basin and provide two-third of the annual staple food harvest (Malasha, 2007). The inter-ministerial contest for control of important water resources affects the planning and implementation of policies in the water sector. Yet and often small-scale farmers still do not get the share of water they need as a result of overlapping competences (Thomas *et al.*, 2016).

Water used in irrigation is one of the priories of allocation to basin users, therefore it is important to know irrigation and crop water demand in order to cater for any other major sectors of the basin and to undertake the feasibility study of proposed projects (Brett Lawson, 2013); and easement of water demand which serves as baseline input for hydrological model and storage structures (Yamba *et al*., 2011). In Zambia alone the irrigation water is only accessible to some farmers for mechanized irrigation depending on the land ownership. This affects indirectly to the low income and strategies to fight poverty and majority of subsistence farmers in Zambia (Thomas *et al.*, 2016).

The government of Zambia have aimed to provide irrigation water to additional agricultural areas in order to maximise agricultural net benefits (Casarotto, 2013). Commercial irrigation plays a role in maize production through irrigation to ensure higher yield in the dry years. Typical commercial crops are coffee, cereal, horticulture and floriculture which are mainly intended for export markets together with crops like soya beans and surgacane (Casarotto, 2013).

Irrigation impact in Zambia depends on factors such as the level of demand and importantly on the prioritisation given to irrigation over hydropower production (Stricevic et al., 2011). This is mostly the case in dry areas (Yamba et al., 2014). Agricultural irrigation is one of the global abstractor of water for approximately 70% of water in the world (Gichuki, 2008). It is projected that irrigated land in developing countries will increase by 27% in the next 20 years (Jonah *et al.*, 2015). Water for irrigation is the one of option to improve food production in low rainfall regions through supplementation of the crop water requirement. This also has posed some uncertainty about quantity and reliability of the water supply (Jonah *et al.*, 2015). Therefore irrigation can also result in the reduction of both the upstream and downstream flows. The requirement of irrigation basically represents the difference in crop water requirement, while crop water requirement together with effective rainfall also include additional water for leaching of salts and compensate for other water loss (Gichuki, 2008).

1.1.3 Evapotranspiration [ET]

The quantity of water required to compensate for the evapotranspiration loss from agricultural land is referred to as crop water requirement. Crop water requirement is the amount of water needed to support crop growth on the other hand, crop evapotranspiration refers to the amount of water that is lost through evaporation and transpiration. Due to high cost for field measurement, ET is normally calculated from using field weather data. Empirical equations are available for estimating evapotranspiration from weather data and may be valid under specific condition.

The FAO Penman-Monteith method is considered as the standard method for calculation of reference evapotranspiration, (ETo). The reference evapotranspiration is the evapotranspiration rate from a reference surface, well supplied with water. A large uniform grass (or alfalfa) field is considered worldwide as the reference surface. The reference crop completely covers the soil, is kept short, well-watered and is actively growing under optimal agronomic conditions.. It is influenced by crop coefficients (Kc) that relates it to potential evapotranspiration (ETc). The ETo from crop surfaces under non-standard conditions is adjusted by a water stress coefficient (Ks) and by the crop coefficient (Allen, 1998) to give ETc not adjusted. Therefore this makes ETo the key driver to any water supplied to the crops by irrigation to compensate the loss due to evapotranspiration.

1.2. PROBLEM STATEMENT

The rise in water demand for agriculture, industry, domestic, and environmental needs requires knowledgeable use of this limited resource. Since agriculture is the major user of water, estimating of water abstraction by irrigation from the basin is very important. Meanwhile due to lack of information of more accurate strategies to calculate the amount of water abstraction for each use, it is difficult to know the exact amount used for irrigation.

Efficient agricultural water management requires reliable estimation of crop water requirement and evapotranspiration. Evapotranspiration (ET) is the transfer of water from the soil surface (evaporation) and plants (transpiration) to the atmosphere. ET is a critical component of water estimation at plot, field, farm, catchment, basin or global level. From an Agricultural point of view, ET is also used to estimate the amount of water required for irrigation. Information on ET is important to help determine canal size, pumps, and dams for irrigation water abstraction (Zeleke & Wade, 2009).

Therefore, the study estimates the amount of water used in irrigation for the period 2013 to 2017 within the upper reaches of Lunsemfwa, Mulungushi, Mwomboshi and Mkushi basins.

1.3. SIGNIFICANCE OF STUDY

The amount of water that is abstracted for irrigation when known make it easier to manage water resources for the purposes:

- Management and operation of dams for hydroelectric production.
- The monitoring of the basin environmental flows.
- Help in conservation of water for other purpose such as drought mitigation.

1.4. OBJECTIVE OF THE RESEARCH

The main objective is to estimate the amount of irrigation water abstraction from the upper reaches of the Lunsemfwa, Mulungushi, Mwomboshi and Mkushi sub-basins of Zambia.

1.4.1 Specific objectives

i. To evaluate the evapotranspiration in each catchment sub-basin.
ii. To determine soil water characteristic in the four sub-catchments.
iii. To estimate the area irrigated in the basins from 2013 to 2017.
iv. To estimate the net and gross irrigation water requirement for wheat and soybean crops within the sub basins.

1.5. SCOPE OF THE STUDY

The study was conducted in the upper Lunsemfwa, Mulungushi, Mwomboshi and Mkushi sub basins. The study involved identifying crops, collection of soil data, weather data, estimating irrigated area and water consumption from each sub basin.

1.6 RESEARCH STRUCTURE

The dissertation estimates the amount of water used for irrigation from year 2013 to 2017 in the basin of upper reaches of Lunsemfwa, Mulungushi, Mwomboshi and Mkushi. . The dissertation structure follows largely the stages of irrigation water abstraction and analysis outlined as follows:

Chapter one – The chapter introduces the topic under discussion including the problem statement that underpins the study, background statement, objectives and the scope of the study.

Chapter two – Chapter two focuses on a discussion of the literature review on the irrigation water abstraction. Also the chapter presents methods and tools used to estimate irrigation water abstraction, factors affecting irrigation, crop requirements, and evapotranspiration procedure and calculation. A summary of the literature reviewed in the study is presented in the later part of chapter two.

Chapter Three – This chapter discusses the research methodology. Research methodology is the blueprint which outlines the steps or procedures of how the entire study was conducted and includes aspects such as observation and sampling, methods and data collection, research ethics and analysis of the gathered samples and reporting format.

Chapter Four – This chapter present the results or findings of the study. The chapter also discussed the results and presents an outline of the water used in each basin and the findings on the evapotranspiration of each basin.

Chapter five – chapter five gives the conclusions and recommendations based on the findings from Chapter four, the chapter gives guidance and direction to all stakeholders based on the findings of the study. The chapter also proposes areas of further studies based on gray areas which were not clearly investigated or explained by the study.

CHAPTER 2 LITERATURE REVIEW

2.1. OVERVIEW

This chapter looks at literature related to irrigation water abstraction. Also the chapter discusses methods and tools of crop modeling; catchment delineation and evapotranspiration estimation. A summary of the literature reviewed in the study is presented in the later part of the chapter.

2.2. IRRIGATION WATER ABSTRACTION

Water abstraction is a term that is used to define the process by which water in its natural environment is artificially moved. This process of water abstraction is ancient one that goes back many centuries. Water abstraction depends on a lot of variables that include the purpose for the abstraction, the location, governing laws and regulations, and resources available for extraction. Water abstraction may have existed for millennia and can be achieved through open wells boreholes, to access ground water and directly from rivers, dams to access surface water.

Regulation is necessary in order to guide the abstraction of water through various sources due to the negative consequences that are associated with the rampant removal or diversion of water. Some of these negative factors include the overdrawing of the water in that area until the water table falls to a level that will not be easily accessible, or the manner in which such abstraction affects the level of other natural bodies of water, such as rivers and streams. To this end, many countries have laws and regulations specifically to manage water resources sustainably.

Demand to water resources is increasing with the increase in population and demands for energy and food in developing regions of the world, leading to a strong competition of water resources. The River Basins in Southern Africa are relatively undeveloped for hydropower generation as well as food production through irrigated agriculture. Zambia alone have about 60 million ha of arable land of which only 15 % is currently cultivated (Chapman et al, 2014). The country's economy is increasing rapidly with the population growth of 3% annually. The need for electricity already exceeds supply thus posing a real competition in water use.

Gichuki, (2008) observed that river flow showed a progressive decline due to water abstraction especially in irrigation during dry seasons..

2.3 CROP WATER REQUIREMENT

Water for crop irrigation is normally predicted by the use of evapotranspiration. Evapotranspiration is combination of evaporation from the surface where crops are grown and transpiration from the plants(Allen et al 2000). Evapotranspiration combines both evaporation and plant transpiration to the atmosphere. Evaporation accounts for movement of water from surfaces to the air while transpiration accounts for movement of water within a plant and subsequent loss of water as vapour through leaf stomata(Allen et al 2000).

In the view of Allen (2000) the water consumed by irrigated crops is predicted by the use of crop coefficient (Kc) and reference evapotranspiration (ETo) guidelines. Reference evapotranspiration (ETo) is calculated for a grass or alfalfa reference crop and then multiplied by the empirical crop coefficient (Kc) to produce prediction of the actual crop evapotranspiration (ETc), this is also supported by earlier findings by Allen (Allen et al 1998). Reference evapotranspiration represents the climatic demand for water and defined over an extensive surface of referenced vegetation free of diseases and pest, not water stressed and covering the soil surface completely (Allen et al 1998). The reference crop is hypothetical crop with an assumed height of 0.123m with a fixed surface resistance, an albedo of 0.23, closely representing and extensive surface of green grass of uniform height, actively growing and adequately watered (Allen et al 1998).

Allen (2000) furthermore explains that evapotranspiration is the combination of the two separate processes whereby water is lost from the soil surface by evaporation and from crops by transpiration. Evaporation is the process whereby liquid water is converted to water vapour and removed from the evaporating surface (Davis & Dukes, 2010). Water evaporates from different surfaces such as lakes, river, and pavements while in the content of this study it is from soil surface and wet vegetation. Transpiration is vaporization of water from the plant tissues into the atmosphere (Allen, 2000). Crops normally lose their water through the stomata which are the small opening on the leaf of the plant through which gases and water vapour passes. Accurate quantification of ET is crucial in water allocation, irrigation management, and evaluating effects of land use changes on water yield (Allen et al., 1998)

2.4 FACTORS AFFECTING EVAPOTRANSPIRATION (ET)

Evapotranspiration (ET) as the key factor in computing the crop water evapotranspiration (ETc) is affected by number of parameter such as; weather parameter, crop characteristics, management and environmental aspects. The following sub section explains the factor that affect ET.

2.4.1 Weather

Weather is one of the key factors that affect how plant abstracts water from the soil. The major weather parameters affecting evapotranspiration are radiation, air temperature, humidity and wind speed (Raes, 2008). The atmospheric demand for water through plants is measured by the reference crop evapotranspiration (ETo) (Davis & Dukes, 2010).

2.4.2 Crop factors

The type of crop, variety and development stage must be considered when assessing the ET for crops grown in large, well-managed fields. The variability in transpiration, crop roughness, reflection, root system and ground cover result in discrepancy in ET level in dissimilar crops at different environmental conditions (Allen et al., 1998).

2.4.3 Management and Environmental Conditions Factor

Furthermore (Allen et al., 2000) stated that salinity, poor land fertility, the presence of hard or impenetrable soil horizons, the absence of control of disease and pest and poor soil management among others may limit the crop develop leading to low evapotranspiration, too much water may also result in water logging which damages root thus limiting root water uptake by inhibiting respiration.

In this research, the maximum water that can be used at no limiting factor will be estimated. For optimal irrigation water estimations, the assumption is that there are no limiting management and environmental factors . Irrigation efficiency depents on the system used to irrigate the land. Drip irrigation is on method that have high irrigation effeciency. For this study the irrigation effecince for sprintler will be used in order to estimate gross irrigation requirements.

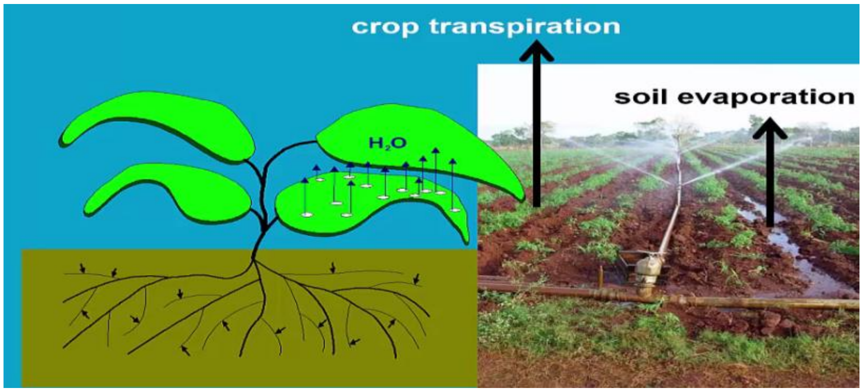

Figure 2.1 Evapotranspiration; Transpiration from the crop and Evaporation from the soil surface (Raes, Steduto, Hsiao, & Fereres, 2012a)

Figure 2.1, shows both effect of water loss from the plant and soil surface contribution to gross irrigation requirement. This is influenced by the weather conditions.

2.5 REFERENCE EVAPOTRANSPIRATION (ETo)

This sub section explains the methods to calculate the ETo from meteorological data. The FAO Penman- Monteith method is recommended to compute the ETo, the method is derived from meteorological data (Raes, 2008). According to (Raes, 2008) and (Allen et al., 2000) the Penman-Monteith method for predicting ETo is applied on the 24 hours basis calculation time steps has the form;

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \textbf{(2.1)}$$

Where ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],

u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
e_s-e_a saturation vapour pressure deficit [kPa],
Δ Slope vapour pressure curve [kPa °C^{-1}],
γ Constant [kPa °C^{-1}].

Allen (2000) stated that from Equation (2.1) factors that affect the ETo are climatic parameter. Radiation and air temperature quantifies the evaporation of liquids while air humidity and wind speed quantifies the vapour removal. Consequently the reference evapotranspiration can be calculated from weather data. ETo is the evaporating power of the atmosphere at the specific location and time and it does not consider the soil characteristics and soil factors.

2.5.1 The Evapotranspiration calculator

Generally it is difficult to estimate all the weather parameter mentioned in the Penman-Monteith equation. In view of this, the program develop by the FAO called the ETo calculator estimates the evapotranspiration of the area given some meteorological measurements and location (Raes *et al.,* 2012). In their view (Raes *et al.,* 2008) the ETo Calculator uses a build in Penman-Monteith procedure to come up with nearly accurate estimations of the ETo. Raes (2008) also have stated that the program was developed by the Land and Water division of FAO.

Furthermore Raes (2008) explain that the ETo calculator assesses the ETo from the metrological information closely to the location and elevation, and it includes both physiological and aerodynamic parameters. The program can handle daily, ten day and monthly climatic parameters. The ETo calculator program can also be used in case of missing climatic data, this is possible because it has a procedure for estimating missing climatic data.

Even the information from the meteorology contains only the maximum and minimum air temperature; it is still possible to obtain acceptable estimation of ETo for ten-day or monthly by selecting the appropriate range of lower and upper limits for the dataset Raes (2008). The calculator is applicable to a quality check when the specification of information is done and the outcomes can be imported to other programs for analysis or plotter for discussion in various way specified by the user. As for this study the research used the methodology of the program to compute and estimate ETo. ETo calculator was meant as a practical tool to help agro-meteorologists, agronomists and irrigation engineers to carry out standards calculations for ETo, to be later used in crop water use studies (Raes, 2008).

2.6 THE CROP COEFFICIENT (KC)

In the growing stage of the crop, water up take is influenced by the type of the crop grown. The single mean crop coefficient (Kc) is used to compute both soil evaporation and plant transpiration over the growing period of the plant. According to FAO -56 the crop stages are divided into four phenological stages of growth. Initial stage starts from planting to 10% growth of the crop cover, development stage from 10% to maximum cover. The midseason stage is from full cover to start of senescence while the late stage start from senescence to full senescence.

The crop coefficient during these stages is summarized in Figure 2.2 and is dependent on the type of the crop (Zeleke & Wade, 2009). The three coefficients are given for the seasons being $K_{c\ ini}$, K_c mid and $K_{c\ end}$. During the initial stage the Kc ini it is assumed to be constant and relatively small (less than 0.4).

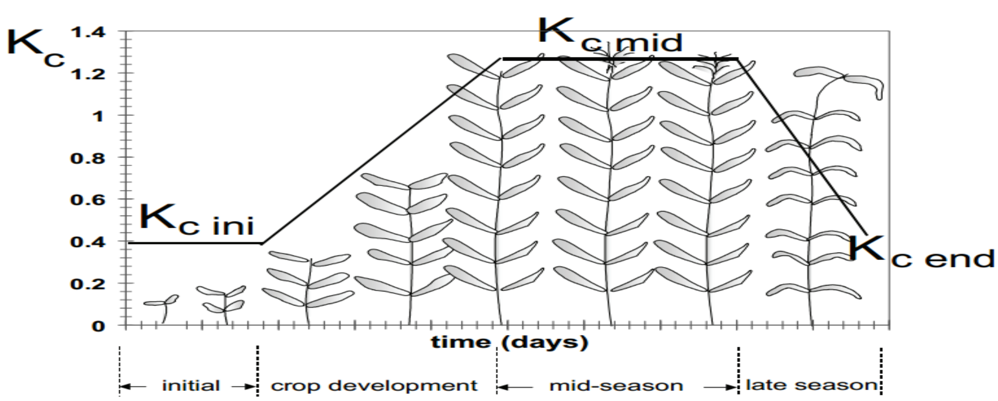

Figure 2.2 Summaries of the crop coefficients from FAO-56

The Kc increases linearly in crop development stage and reaches maximum value and Kc mid of which is relatively constant for most crops and varieties. As crop leaves dies off during the late period of senescence the Kc decreases to the lower value at the end. Linear interpolation is normally used to estimate the Kc at development from the value of the initial and midseason Kc, moreover the same procedure is used for the Kc at the late stage by using interpolation of the mid Kc and the end. The initial Kc and end Kc can varies on daily basis, depending on the frequency of water application to the crop either by irrigation and or rainfall (De et al., 2009).

The Kc average can be used for irrigation planning and scheduling and is more accurate in sprinkler and surface irrigation system and can be used in hydrology for Basin water balancing studies (Allen et al., 2000). The average crop coefficient is then multiplied with the ETo to give the actual or the potential crop evapotranspiration ETc. In case where field practical is cumbersome and not readily available, researches have shown that Kc can be calculated with some empirical formulae as;

$$Kc = Kc_{FAOtable} + [0.04(u_2 - 2) - 0.04(RH_{\min} - 45)](\frac{h}{3})^{0.3} \qquad \textbf{(2. 2)}$$

Where	Kc_{FAO}	is the Kc at the stages in Figure 2.2 [mm/day
	u_2	is the mean daily wind speed [m/s]
	RH_{min}	is the minimum relative humidity [%] and
	h	is the average crop height [m]

The adjustments to K_c for climate are generally made using mean values for U_2 and RH_{min}, for the entire midseason period (Payero *et al.*, 2009). Since localized Kc values are not always available in many parts of the world, the values of Kc as suggested by FAO (Allen et al., 2000) are being widely used to estimate evapotranspiration.

2.7 CROP EVAPOTRANSPIRATION UNDER STANDARD CONDITIONS (ETc)

The crop evaporation under a standard condition is denoted by the ETc which means the evapotranspiration from well grown crop free from any limiting factors and well fertilized and achieving full production under a given climatic conditions. ETc can be on the range of 1 to 9 mm/day from warm to cool average temperatures (Allen et al., 1998). The ETc is the same as the amount of water needed by the crop to compensate for evapotranspiration. In this study, the sprinkler irrigation efficiency was considered to be 0.75. The crop evapotranspiration can be calculated from the equations and it provides the potential maximum evapotranspiration of the crop when soil moisture is not limiting.

$$ETc = KcETo \quad \textbf{(2.3)}$$

Where ETc is the crop evapotranspiration [mm]
Kc is the crop Coefficient [mm/day]
ETo is the Reference Evapotranspiration [mm/day]

Ray and Dadhwal (2001) stated that when water application from either rainfall or irrigation are not enough to keep the soil moisture content, the root zone moisture is also reduced to low level and cannot sustain the potential crop evapotranspiration ETc. The plant in this state are said to be under water stress. Furthermore Ray and Dadhwal (2001) elaborated that the evapotranspiration when crop is under water stress is called actual evapotranspiration ETa which in general varies from plant varieties as in ETc. This is because the actual evapotranspiration (ETa) is the fraction of the potential evapotranspiration (ETc) depending on soil water availability. Actual evapotranspiration ETa is calculated from a combination of Kc and the soil water stress coefficient Ks as shown in Equation 2.4 (Zeleke & Wade, 2009).

$$ETa = KsKcETo \quad \textbf{(2.4)}$$

Where ETa is the actual evapotranspiration [mm]
Kc is the crop Coefficient [mm/day]
ETo is the Reference Evapotranspiration [mm/day]
Ks is the soil water stress

Zeleke and wade (2009) stated that the soil water stress coefficient can be calculated from the soil water hydraulics and it reduces from one to zero which leads to reduction in Kc where there is lower water in the roots zone to sustain the crop transpiration. This stress due to water can be calculated from the amount of moisture the crop depletes from the root zone.. The amount of water depleted from the root zone is expressed as root zone depletion (Dr), which is water storage relative to the field capacity (FC) (Zeleke & Wade, 2009). The stress is supposed to initiate when Dr exceeds the readily available water (RAW). When the RAW is extracted from the root zone and root zone depletion is greater than RAW the soil water stress Ks is expressed as (Allen et al., 1998) in Equation 2.5;

$$Ks = \frac{TAW - Dr}{TAW - RAW} = \frac{TAW - Dr}{(1-p)TAW} \qquad \textbf{(2.5)}$$

Where	Ks	is the water stress coefficient
	TAW	is the total available water in the root zone [mm]
	Dr	is root zone depletion [mm]
	RAW	is readily available water to the crop in the root zone [mm]
	P	is fraction of TAW that a crop can extract from the root zone without suffering water stress

The amount of water that crop can extract without stress is called readily available water RAW and is expressed as (Allen et al., 2000) in Equation 2.6.

Figure 2.3 shows how Raes *et al* (2012a) described the soil stress Ks in relation with total available water

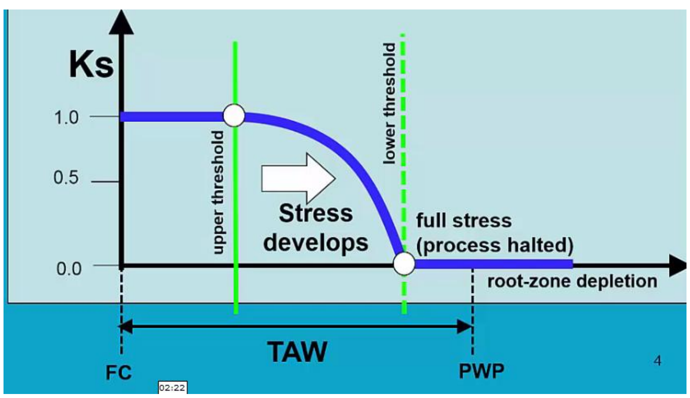

Figure 2.3 The Soil water stress coefficient Ks graphs(Raes et al., 2012a)

The soil depletion fraction (p) is the fraction of soil water in the root zone that can be depleted before stress occurrs. FAO (Allen et al., 1998) When Dr ≤ RAW, Ks =1 indicating no water stress.

$$RAW = pTAW \qquad \textbf{(2.6)}$$

The soil depletion fraction (p) is the fraction of soil water in the root zone that can be depleted before stress occurred.The total available water in the root zone (TAW, mm) is estimated as the difference between the water content at the field capacity and wilting point (Allen et al., 1998) given as Equation 2.7

$$TAW = 1000(\theta_{FC} - \theta_{PWP})Zr \quad \textbf{(2. 7)}$$

Where TWA is the total available water to the root zone (mm)

θ_{FC} Is water at field capacity [mm]

θ_{PWP} Is water at permanent wilting point [mm].

Zr is effective rooting depth (m)

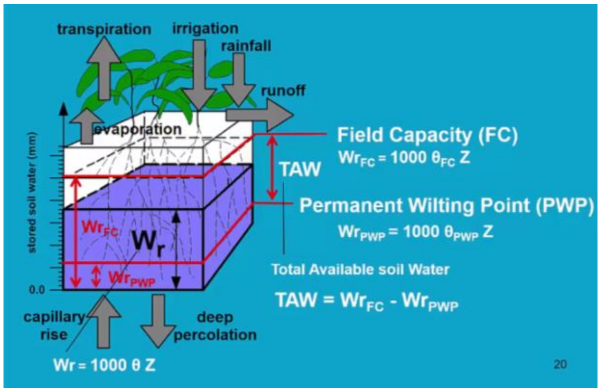

Figure 2.4 Total available water in the soil (Raes et al., 2012a)

The K_s component is the water stress coefficient used to reduce K_c under conditions of water stress or salinity stress. The average water content of the root zone is expressed as root zone depletion, D_r, defined as water shortage relative to field capacity. At field capacity, $D_r = 0$. The degree of stress progressively increases as D_r passes the depth of readily available water (RAW) in the root zone.

Rainfall, irrigation, and capillary rise of groundwater add water to the root zone and decrease the root zone depletion. Soil evaporation, crop transpiration, and deep percolation losses remove water from the root zone and increase the depletion. In this research the water for irrigation will be assumed to be the water that is abstracted. The next sub section look at the soil characteristic and how it influences the total amount of water that is to be used by a crop in a field.

2.8 THE SOIL CHARACTERISTIC

The soil consists of the particles which describe the texture of the soil; normally the mineral particles are classified according their size in three fraction which are sand, silt and clay. The relative proportion of the mass of sand, silt and clay defines the textural class of the soil. Usually the textural triangle is used to find the soil texture classification.

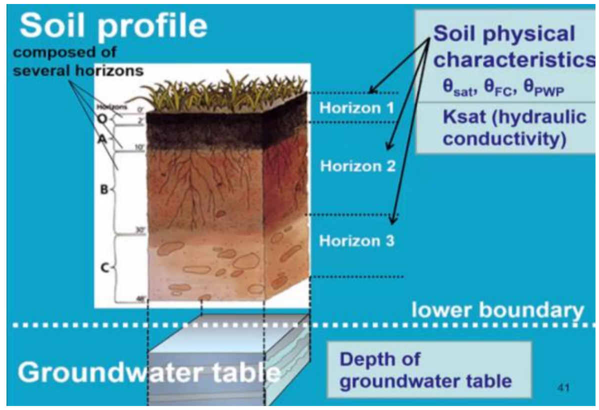

Figure 2.5 The soil profile (Raes et al., 2012a)

Saxton & Rawls, (2006) summarises hydraulic equations to estimate available water in the soil using physical parameter. As water is removed from the soil by plants the pressure potential is decreased Adding water to the soil increases the matric potential. In this case soil water can be represented with the soil water characteristic or retention curve that shows the matric potential and soil water content relationship.

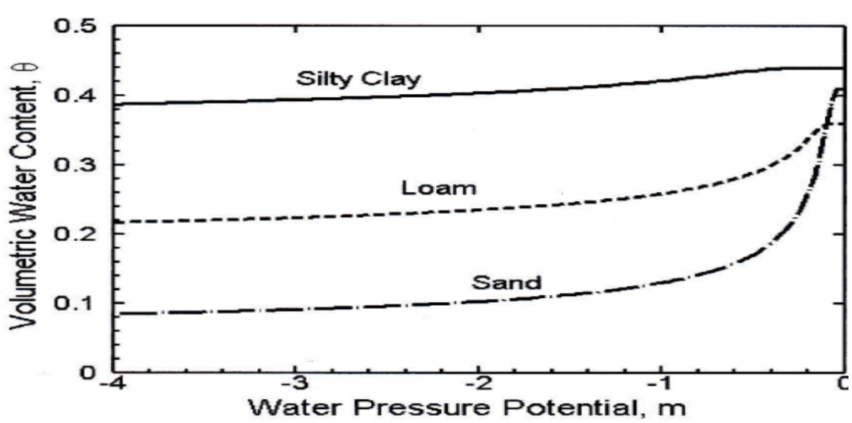

Figure 2.6 Soil water potential and matric potential relationship (Raes et al., 2012b)

In their view Saxton & Rawls, (2006) defined soil water capacity to refers to the slope (dΘ/dh) of the soil water characteristic at any point on the curve. The capacity represents the change in water content per unit change in matric potential and is important for water storage and release in the soil. As for this study it will be used to represent the storage of different soils found in the four (4) basins. The knowledge of water in the soil at the potential above a critical level, along with crop water requirements allows estimating irrigation requirements in a growing season. According to (Raes et al., 2012b) the amount of water that is left in the soil at saturation differs with soil texture, organic matter content and structure.

2.8.1 Methods of determining the soil water characteristics

The use of soil is preferred where by a sample of soil is placed in a pressure chamber on a retaining ring and saturated overnight, the desired pressure is then applied until outflow ceases and the soil considered being in equilibrium with the applied pressure. Then the amount of water in the soil is determined, usually by oven drying. The procedure is then followed at a different pressure with the second sample and finally the resulting soil water content is plotted against applied pressure or vacuum, expressed as potential in millibars or cm to for the soil water characteristic (Saxton & Rawls, 2006).

2.8.2 Estimating soil water parameters

Field capacity and permanent wilting point were very import in the past in soil water estimating, field capacity (FC) refers to the soil water content in the soil after drainage has ceased. It estimates the amount of water stored in the soil profile for plant use (Er-raki et al., 2007). The permanent wilting point (PWP) on the other hand is the amount of water below which plants growing in the soil remain wilted even when transpiration is nearly eliminated. The soil water content at PWP correspond to the average water content of the bulk soil and not to the soil in the root surfaces while the soil next to the root surface will be usually drier than the bulk soil because water cannot move toward the root surface fast enough to supply plant needs developing into a water content gradient near the roots. These make plant water withdraw zero at PWP and it is function of demand and soil condition.

Furthermore the amount of water released between FC and PWP is called available water. Many farmers irrigate when the available water is depleted and it depend on the crop grown as irrigation may be set at different percentage of available water remaining in the soil depending in the crop.

2.8.3 Methods for Characterizing Soil water

The soil water characteristic at a location in the field may be obtained by water potential measuring devices in combination with soil measurement. The following sub sections explain the method of characterising soil water on the basis of agriculture.

Measuring water content

The use of Gravimeter is an accepted standard for soil water measurement. Gravimeter measurements involves weighing a sample of moist soil, drying it to a constant weight at a temperature of 105° to 110°C, and reweighing to determine the amount of water lost on drying the results expressed as the ratio of mass of water lost to mass of dry soil. Usually 24 hours is sufficient for drying but the required time is obtained by repeatedly weighing a sample after various periods of drying. The bulk density of soil is measured by drying and weighing a known volume of soil.

Other method that can be used to measure soil water content is the use of Neutron scatting method where by a source of high energy or fast neutrons is lowered to the desired soil depth into a previously installed access tube. The fast neutrons are emitted into the soil and gradually lose energy by collision with hydrogen, present almost entirely in soil water. The degree of the slowing down of neutrons is an indirect measure of the soil water content. The rate of pulsation is measured with a rate meter. Count rate is almost linearly related to the water content.

Measuring soil water potential

The tensiometers are usually commonly used for measuring the higher ranges of soil water potential in the field. Porous Ceramics Blocks can also be used.

Soil Water Characteristics Hydraulic Properties Calculator

According to (Saxton & Rawls, 2006) the hydraulic properties calculator estimates the soil water tension, conductivity and water holding property based on the soil texture, organic matter, gravel content, salinity and compaction. The information from the field sample of soil physical characteristic are input in the program to estimate the soil water characteristic (Saxton and Willey, 2006). The procedure in this model or program is that the soil data profile is explained by order of horizon and water characteristic for each horizon.

Further, for pressure and conductivity relationship as a faction of the amount of water in the soil are very difficult to compute into the program. Measured values of the two are not commonly available for hydrological locations, to estimate the water holding capacity may require field data laboratory analysis (Saxton and Rawls, 2006;Saxton, Willey, 2006). Therefore the estimating method for soil water characteristic has been developed and included. The technique is a set of generalized equations which describe soil tension and conductivity relationships versus moisture content as a function of sand, clay and organic matter (Rawls *et al.*, 1982; 1992; 1998; Saxton and Rawls, 2006). The soil water characteristic equations are available within the range of soil texture of 0% to 60% clay content and 0% to 95% sand content. There have been improvements to the solution by adding the effects of bulk density and salinity to the program. The model also has a programmed texture triangle as an input command screen and is incorporated in the model and as a standalone program which provides ready solutions to the equations and values for the layer definitions of the soil profile (K E Saxton & Rawls, 2006) as shown in Figure 2.7.

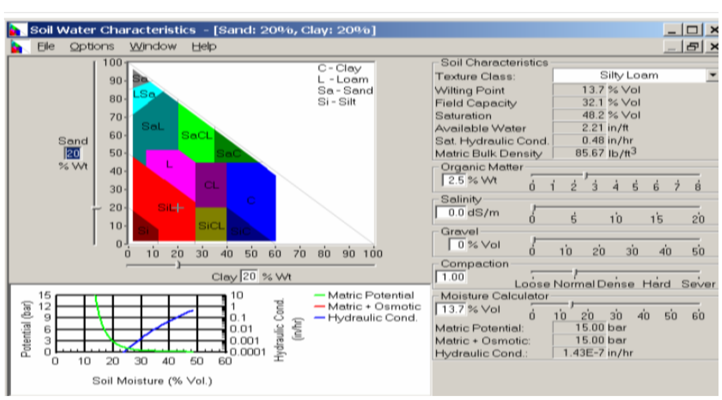

Figure 2.7 texture triangle data screen to estimate soil water characteristics

2.9 ELEMENTS OF SOIL VOLUME

Many soil-water properties can be defined relative to the elemental soil volume. The volume of soil has been separated into its air, water, and solid constituents. The mass of air (M_a,) is assumed negligible. The mass of water and solids are indicated as (M_w) and (M_s) respectively. The total mass is shown as M_t. V_a is the volume of air which can be a significant percentage of the soil volume under field conditions. V_w represents the volume of water, and V_s the volume of solids. The volume of pores, V_p, is the sum of the volume of air and water. The total volume V_b is normally termed the bulk volume in agricultural applications.

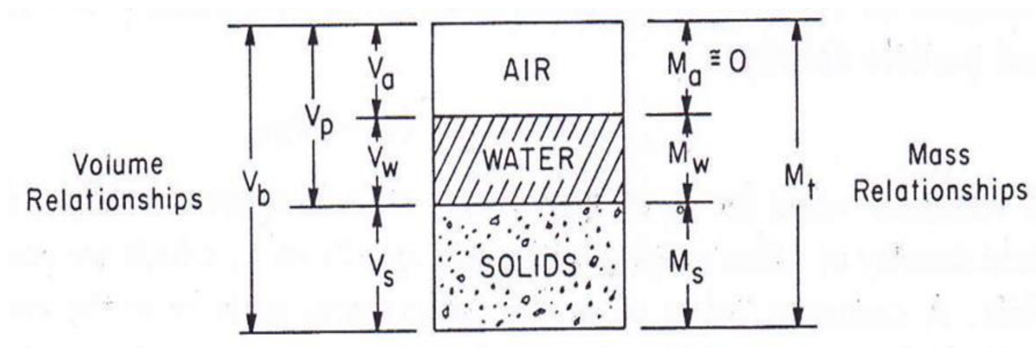

Figure 2.8 Element of soil volume (Raes et al., 2012a)

The bulk density may be derived as a function of the soil porosity and density of the soil particles. A common value for particle density (ρ_s) in agricultural soils is approximately 2.65 g/cm^3, the particle density of silica sand, granite, and quartz rock, which are common parent materials. A common value of bulk density (ρ_b) for agricultural soils is in the range of 1.3 g/cm^3, indicating that porosities of agricultural soils are typically around 0.5 or 50 percent air plus water. Another relationship which may be derived is that between water content on a mass basis, which is relatively easy to measure, and water content on a volume basis, which is more useful in irrigation system design.

2.10 CATCHMENT DELINEATION

Catchment delineation is an important step of irrigation water abstraction to represent hydrologic drainage boundaries. Catchments are scale independent delineations to capture surface water drained in an area (Wagner, S. Kumar, 2013). There are two types of delineation; manual and automatic, the manual is the traditional method for large scale watersheds and it takes time while automatic use raster or digital elevation model (DEM) as an input (Akram et al, 2012).

The DEM can be defined as numeric or a digital representation of terrain elevation specified in a location. DEM is fundamental data for automatic delineation of catchments for spatially distributed hydrological model (Amir et al, 2014). They are usually used to divide the watershed into set elements, run-off producing sub-catchment which drain in one channel. Quality DEM is the precondition of successful and accurate catchment delineation.

Akram *et al* (2012) mentioned that with the computer and information technology development, automatic catchment delineation is widely used and common. The advocate also elaborated that for accurate the quality of the grid based DEM is important. The quality of the DEM depends on the horizontal resolution and vertical accuracy. In their view Amir *et al.*, (2014) mentioned that it is expensive and labour intensive to get the measured cross-section manually, therefore automatic cross-sectional digital elevation model (DEM) is the easiest and cheapest option. In this study, watershed delineation and cross-section extraction from DEM for upper Lunsemfwa, Mkushi, Mulungushi and Mwomboshi river basin are presented.

2.11 LITERATURE REVIEW SUMMARY

From the reviewed literature, it can be seen that irrigation water abstraction can be estimated from knowledge on the crop water use calculations. This is because different crops need different volumes of water in a season and also farmers irrigate different areas of field from time to time. The use of DEM and Landsat images helps in coming up with the estimation of irrigated areas at watershed level and AquaCrop to simulate crop water use for given crop parameters, climate and soil characteristics.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 OVERVIEW

This chapter presents the methods and materials specific to each objective. The study site and the period in which the analysis were done have also been indicated. The analysis was carried out from the upper reaches of Lunsemfwa, Mulungushi, Mwomboshi and Mkushi in Zambia. Studies on the abstraction of water from the catchments were assessed to give an insight of the whole water abstraction estimation using AquaCrop. Intensive literature review on the use of AquaCrop, ETo Calculator and Soil Water Balance in agricultural crop water estimation was done using internet and textbooks, journals and other materials.

3.2 DESCRIPTION OF THE STUDY AREA

This research is carried in the republic of Zambia in the Lunsemfwa basins located within the following coordinates 14° 55′ 50″ S, 29° 43′ 53″ E, 13° 35′ 01″ S, 29° 48′ 114″ E, 13° 39′ 30″ S, 28° 37′ 56″ E and 14° 58′ 04″ S, 28°29′ 22″ E. It is the major region for commercial agriculture and other economic activities such as energy production. Lunsemfwa river rises on the South-Central African Plateau at an elevation of about 1250 m to the north of Mkushi town, and flows south. It is used to generate hydroelectric power for the Kabwe mines through the Mita Hills Dam, built in the 1950s with a reservoir of about 30 km long by 3-5 km wide, and another power station at Lunsemfwa Falls. About 30 km below the dam it enters a remote and inaccessible gorge which it has cut back into the plateau from the edge of the Luangwa Rift Valley into which it flows. Known as the Lunsemfwa Wonder Gorge it is 20 km long, up to 500 m deep and about 1 km wide at the top. A viewpoint called Bell Point overlooks the confluence of the Lunsemfwa and its tributary the Mkushi River, about 15 km along the gorge, and can be reached on a gravel road. The Lunsemfwa enters the Luangwa Rift valley about 40 km from its western end, where the valley is about 45 km wide. It flows to the middle of the valley and turns east as a meandering river with oxbow lakes and a floodplain 1 to 2 km wide. 100 km further on it merges with the Lukusashi coming from the north-east, and the combined river turns south towards the Luangwa river. The Mulungushi river in central Zambia is a tributary of the Lunsemfwa river . It rises on the plateau north-west of Kabwe town and flows south-east into the Luangwa Rift Valley where it joins the Lunsemfwa River. The area under the study is mainly the upper reaches of Lunsemfwa river basin, Mulungushi, Mwomboshi and Mkushi. The study area is show in Figure 3.1.

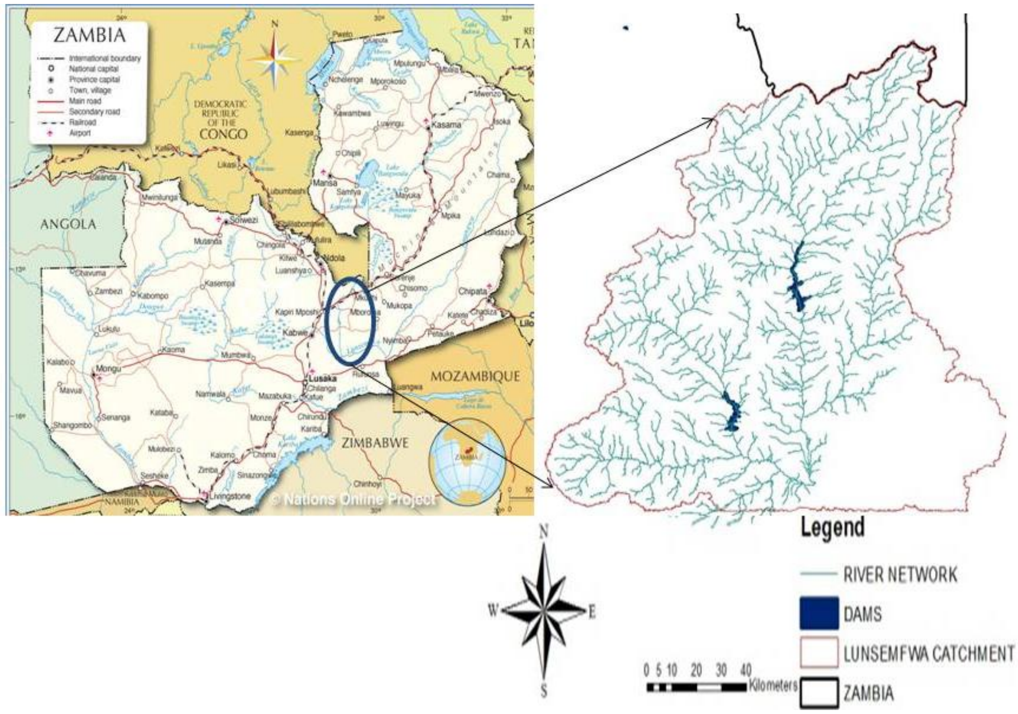

Figure 3.1 Location of Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchments in Zambia ('Zambia-political-map', 2000)

The basin lies at an elevation of about 1,010 meters above the sea level. The river basins contribute to the Lunsemfwa power project. The four basins has average summer maximum temperature of 37 °C and minimum temperature of 14 °C while winter has maximum of 27 °C and minimum 7 °C.

3.3 IRRIGATION AREA CLASSIFICATION

This section covers how the areas of irrigated farms were estimated from 2013 to 2017. It first covers how the areas of study catchments were obtained and also how the irrigated areas in the catchments were estimated. Using landsat8 images from 2013 to 2017 the sequential steps followed in this study for delineation of catchment and stream network using Digital Elevation Model (DEM) data are presented in sub-section 3.3.1

3.3.1 Catchments Delineation

The catchment area for the upper Lunsemfwa basin and the shape file of the area was defined using the United States Geological Survey (USGS) earth explorer. For this study, the 3 sec DEM (30m x 30m) data of USGS HydroSHEDS were collected and used for the derivation of catchment and drainage flow direction.

The map that cover the area under the study was obtained from Short Topography Mission and provided the Geotiff file that was downloaded (Akram et al., 2012).

The downloaded geotiff files were collected through the Quantum Geography Information System (QGIS) software version 2.18.19 (Tara *et al*., 2018). The tiles that form the area under the study were collected using the Zambia authority ID of European Petroleum Search Group EPSG: (32535) and of World Geographical System (WGS) 72BE/ UTM zone 35S coordinate referencing systems. This was achieved by the use of the spatial reference online to find the right EPSG code, which covers the study area. The raster map were build into a mosaic after re-projection. The following procedures were used to come up with channels and basin shapes:

Fill Sinks: It is the first step of DEM pre-processing. The Geo-processing plug-in was used to fill the sink using Wang & Liu method (Rüdiger *et al*., 2018). The objective of this step is to make a depression less elevation model. Sinks in the original DEM were identified using the Sink tool. A sink is usually an incorrect value lower than the values of its surroundings. These depressions points create problem as any water that flows into them cannot flow out. To ensure proper drainage mapping, these depressions were filled using the Fill (Akram et al., 2012).

Flow Direction: In this step, the direction in which water would flow out of each cell was determined. Calculations were made to come up with the strahler order which were also corrected by loading strahler order minimum and maximum value. Strahler organizes run-off of water. Based on the strahler order the rivers were decided upon where by the streahler greater than eight (D8) was set to be a river. The fill DEM found in the previous step was treated as input here and the Flow Direction tool is used. The output is an integer raster whose values range from 1 to 255. Flow directions were calculated using the eight-direction (D8) flow model which assigns flow from each grid cell to one of its eight adjacent cells, in the direction with a steepest downward slope. The D8 method which was introduced by (Akram et al., 2012), is currently being widely used.

The river calculation set was done under raster calculator, which after calculation the legend was change to single band pseudocolour and classified to two classes 1 and 0. In the transparency under properties the 0 class was made invisible. The channel network and drainage basins were calculated from SAGA tool by the use of a threshold. The strahler 8 were the input and the channels..

Flow Accumulation: It is the initial stage of defining the stream network system. Using the Flow Accumulation tool, the numbers of upslope cells flowing to a location were calculated here. The output flow direction raster created in the previous step was used as input.

To get the catchment area, rivers were used. By the use of the SAGA tool of upslope and the coordinate capture tool together with geo-cording tool which help to find the place on the map near the delineated channel; the coordinate capture tool was used to capture the points on the delineated river (streahler greater than 8) and X and Y coordinates were copied to the area algorithm of the filled DEM.

The raster was converted to a polygon shape file using the raster convection polygonizer command with upslope area as an input, then categorized and classified under style menu. The streams were clipped to the catchment area using the vector clipper tool. The DEM was also clipped to the catchments using the mask layer clipper tool.

Catchment Polygon Processing: Finally catchment polygons have been found. Among them the polygon on which the study area is situated as seen from the Figure 3.2.

All other catchments were delineated using the procedure mentioned in the sub section 3.3.1 and divide into four as seen in Figure 3.2. They were clipped to the landsat images to determine the area of the irrigated farms from each catchment. The procedure of the clipping and calculating of the irrigated farm is described in the sub-section 3.3.2. Mkushi, Lunsemfwa, Mulungushi and Mwomboshi sub-catchments are shown in Figure 3.2.

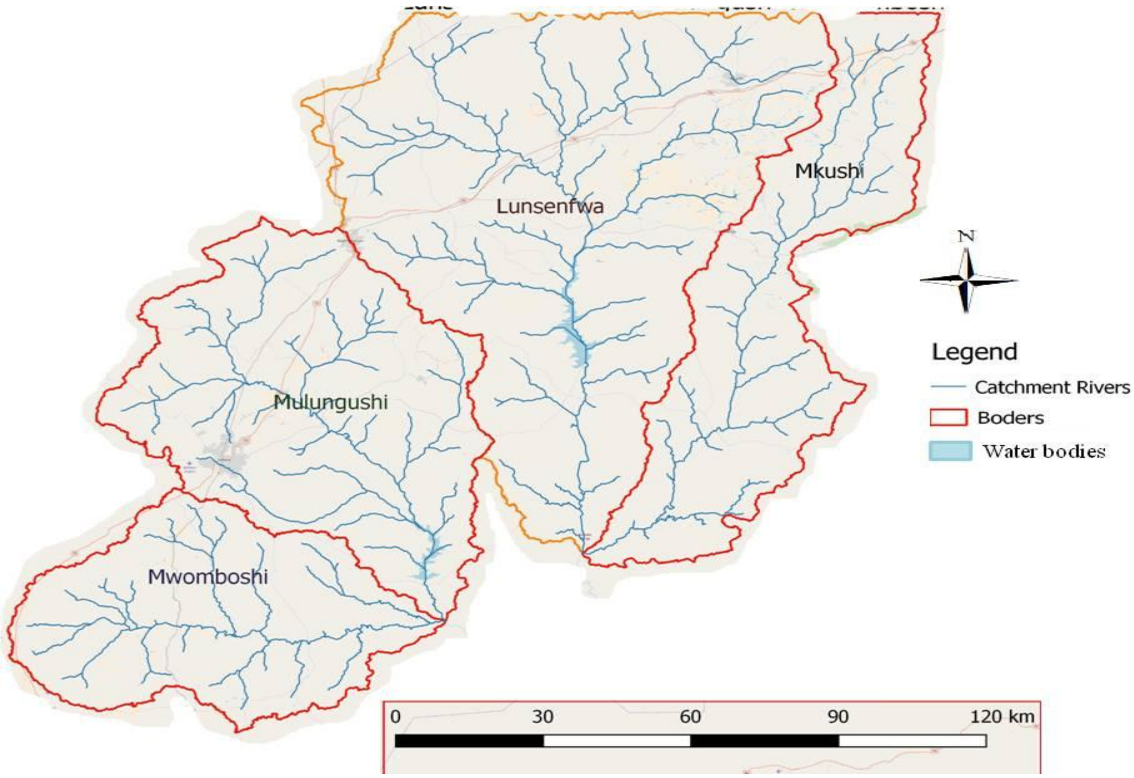

Figure 3.2 Full catchment location and Rivers using (30m x 30m) data from QGIS with reference to Southern Africa

3.3.2 Landsat8 OLI/TIRS image analysis

For this study, the USGS earth explorer website was used to obtain the satellite images. The procedures for downloading the free images included registering for USGS accounts and searching the desired area of study then download the Geotiff image from landsat 8 OLI/TIRS archives.

Figure 3.3 shows the procedure that was used to download the Landsat imagery (L8OLI/TIRS path 171-171and 172-172 row 70-70, and 69 to 69).

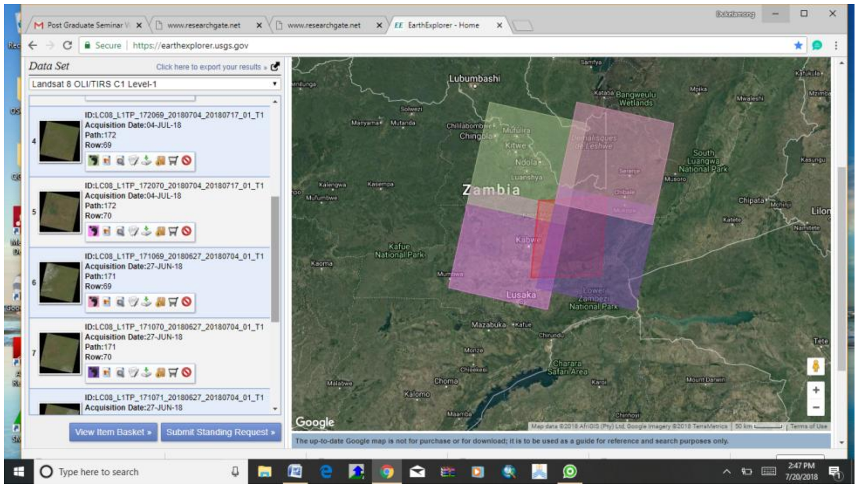

Figure 3.3 Footprints of landsat8 image passing on the study area

The Landsat 8 Images were set to the date of early May to August of each year from 2013 to 2017 to cover the period when irrigation is carried out. Landsat imagery (L8OLI/TIRS) was then clipped to the shape files of the delineated catchments in order to classify irrigated farms. Clipped landsat imagery files were classified as seen from Landsat imagery (L8OLI/TIRS) distinguished by different colours and spatial geographical features. Area of irrigated farm was calculated with the aid of field calculator in the attribute table of the shape of every catchment file in QGIS.

For each year; four Landsat imagery (L8OLI/TIRS) for each month of May, July and August was used, and combined into one image to be clipped to the shape files obtained by delineation process. This process was repeated from 2013 to 2017 for the same area under the study. An average irrigated area was classified for the months of May, July and August each year for all the four catchments The catchment area was obtained from the attribution table calculated in QGIS software (Rüdiger et al., 2018).. The areas were used to calculate the volume of water used after simulation of the crop net irrigation in the AquaCrop software.

3.3.3 Simulation of Net Irrigation Requirements using AquaCrop

The growth engine of AquaCrop is water-driven, in that transpiration is calculated first and translated into biomass using a conservative, crop-specific parameter: the biomass water productivity, is normalized for atmospheric evaporative demand and air CO_2 concentration. The normalization is to make AquaCrop applicable to diverse locations and seasons (Raes *et al*, 2011). Simulations are performed on thermal time, but can be on calendar time, in daily time-steps. The model uses canopy ground cover instead of leaf area index (LAI) as the basis to calculate transpiration and to separate soil evaporation from transpiration (Steduto *et al*., 2009).

The main model (AquaCrop) was used to simulate water abstraction in the basins,. AquaCrop is a menu-driven program with a well developed user interface. Multiple graphs and schematic displays in the menus help the user to discern the consequences of input changes and to analyze the simulation results. From the main menu, the user has access to a whole set of menus where input data is displayed and can be updated. Input consists of weather data, crop, irrigation and field management, soil and groundwater characteristics that define the environment in which the crop will develop. Also the sowing or planting day, the simulation period and conditions at the start of the simulation period are inserted. Before running a simulation; the following were specified in the main menu; the sowing date, the simulation period and the appropriate environmental, initial and off-season conditions.

Figure 3.4 shows the major input data required for the model to run. The ETo calculator was used to calculate ETo while the Soil Water Characteristics Hydraulic Properties Calculator, was used to obtain soil hydraulic parameters for the study area. This information was then fed into the AquaCrop model. By creating a data file from the ETo calculator for each basin and importing them into the AquaCrop model, crop grown were simulated in each basin. This gave seasonal crop water requirement estimation.

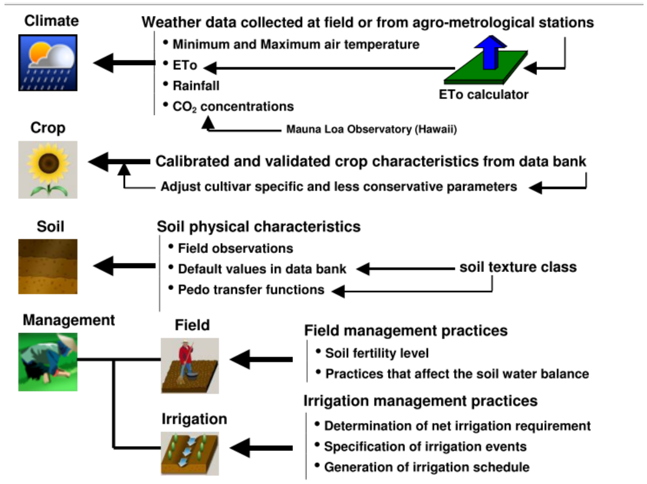

Figure 3.4 Major input data for AquaCrop (Raes *et al.*, 2012a;)

3.3.4 Climate data collection (ETo, rainfall and temperature)

The obligatory weather data input of AquaCrop program consists of reference evapotranspiration ETo, maximum and minimum temperature, rainfall and mean annual CO_2. From meteorological data recorded in the local weather station adjacent to the basins, reference evapotranspiration (ETo) was computed.

Minimum and maximum temperatures were also collected which AquaCrop uses to determine the growing degree day and model the speed of crop development while catering for cold and heat stress. The ETo, minimum and maximum temperatures can be entered as daily, 10-day or monthly data. For this research monthly data was used in the ETo calculator, since the period of simulation was based on months when there was no or less rainfall.

Figure 3.5 shows the rainfall data collected from all stations adjacent to the catchments under study.

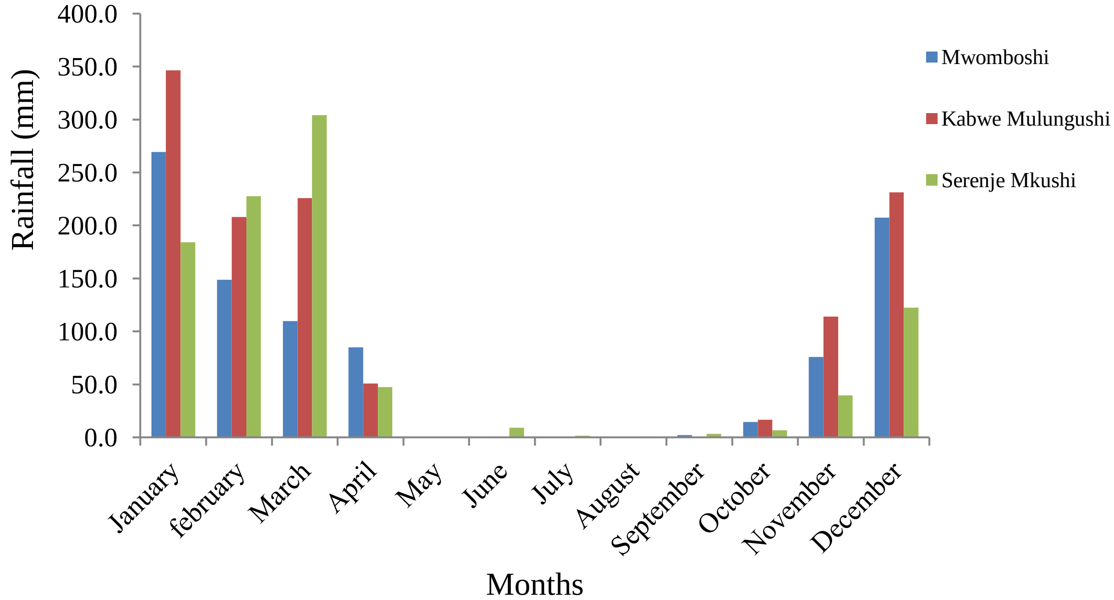

Figure 3.5 Lusaka Airport, Kabwe Mulungushi, & Serenje (zambia) - Monthly Average Rainfall data: January 2013 - December 2017

From Figure 3.5 average monthly rainfall in mm for five year period in Mwomboshi catchment decreases from month of January to April. Mwomboshi shows that have little or no rainfall from May to September. Kabwe catchment received highest rainfall in January of all catchments and the trend is alternating until April. There was no rain from the month of May to September and rain starts in October. Mkushi received increasing rainfall from October until highest in March. It also has little or no rainfall in May to September.

AquaCrop also requires the rainfall data to update daily soil water balance and simulate soil water stresses. Rainfall data can be entered 10-daily or monthly but in this study the data was entered monthly. The software will convert it to daily data to accurately simulate the crop response to water stresses. For this study rainfall was not used for simulation as the period of growth was the dry season. Finally the mean CO_2 is required as it affects the biomass production and crop transpiration; this data was obtained from past records.

3.3.5 Crop data collection

AquaCrop can use conservative parameters, where by parameter of crops in use are specific and do not change with time, management practices, geographical location, climate or cultivar which means they are valid for all cultivar in all environments. The use of non conservative parameters, accounts for parameters affected by; field management, planting mode, condition in the soil profile and climate. They need to be tuned to the cultivar or the environment. The conservative crop parameters are not tuned or changed parameters affected by planting and management;

- Type of planting methods, which was sowing
- plants density which is dependent on the initial canopy cover (CCo) which determine the maximum canopy cover (CCx)
- The time to 90% seeding emergence for wheat and soybean

The type of planting method can be direct sowing or transplanting. Direct sowing is conservative crop parameter hence no adjustment will be made to the model while the transplanted seedling size depends on the time it spends in the nursery so the size of the seedling is specified during transplanting. Secondly the plant density is specified which determines the initial canopy cover (CCo) AquaCrop needs that to describe the canopy development as a function of time. For this study the growing stages of soybean and wheat were used according to FAO, (Allen, 1998) and described in sub-section 3.3.6.

CCo = plant density * size of the cover per seedling

The final parameter affected by planting and management is the time to 90% seedling emergence; it should be specified as affected by the field preparation, soil temperature, and soil water content.

After tuning the parameter affected by planting and management the following parameters were tuned as indicated;

- Time to reach maximum canopy (CCx) wheat - 50 days and soybean - 40 days
- Time to beginning of canopy senescence, wheat - 80 days and soybean - 70 days
- Time to physiological maturity, wheat - 120 days and soybean - 85 days
- Time to start of the following or the start of yield formation, wheat - 50 days and soybean - 50 days
- Duration of flowering, wheat - 15 days and soybean - 10 days

The green canopy parameter as affected by the crop and the growth stage are described in Figure 3.6;

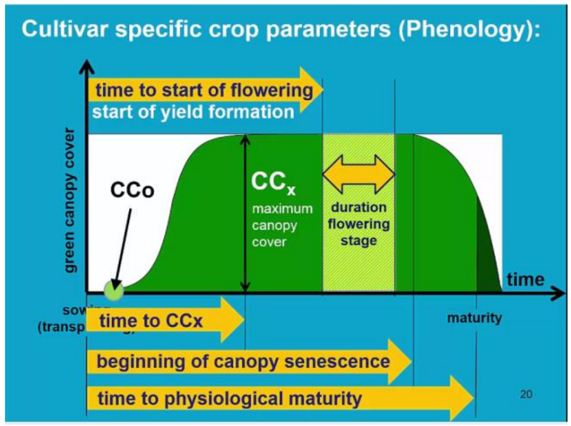

Figure 3.6 Graphical representation of Cultivar specific crop parameter (Raes et al., 2012b)

The next step is the tuning of the crop parameters affected by soil conditions as indicated;

- Maximum effective rooting depth, wheat - 0.9 m and soybean – 0.7 m
- Time to reach maximum effective rooting depth or root zone expansion rate, wheat - 65 days and soybean - 40 days

The model uses the concept of the effective rooting depth which is the depth where major water uptake takes place. This is given in the root tab sheet of AquaCrop. Expansion rate are used where by the growing root per day is specified. Figure 3.7 shows effective root depth.

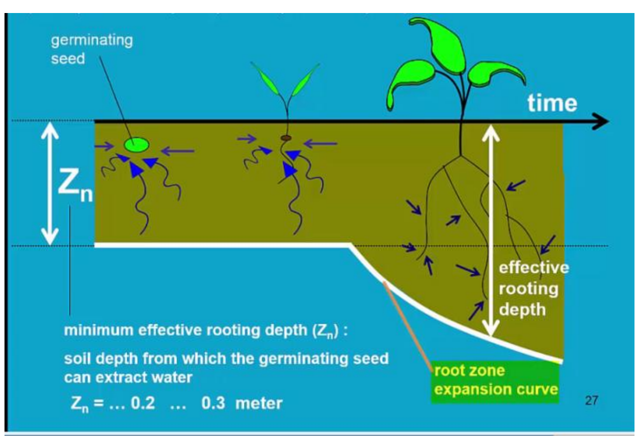

Figure 3.7 Effective root depth (Raes et al., 2012b)

3.3.6 Crops Used for Irrigation Water Estimation

Crop selection was based on the minimum water user being Soybeans (*Glycine max L. Merril*) and wheat (*Triticum aestivum)* which was assumed to be using most irrigation water.

3.3.6.1 **Wheat** *(Triticum aestivum)*

Climate: The crop is grown as rain-fed crop in temperate climates, in sub tropics with winter rainfall, in the tropics close to the equator, in highlands with winter rainfall, in tropics near the equator, in highlands with altitudes of more than 1500 m and in the tropics away from the Equator where the rainy season is long and where the crop is grown as a winter crop. It is grown in lowlands away from Equator (Yang *et al*, 2011)

Sowing rate: Under good conditions of water supply from irrigation and good fertility measures row spacing is 0.12 to 0.15 m (450,000 to 700,000 plants / ha) but increases to 0.25 m or more under poor rainfall conditions (less than 200000 plant/ha). Sowing rates under irrigation are 100 to 120kg/ha (drilled) to 110 to 140 kg/ha (broadcast) (Allen *et al.*, 1998).

Crop Development stage: Higher yield water requirements are up to 650 mm which is mostly depending on climate and length of growing period. During the initial stage the Kc is 0.3-0.4 (15-20 days), the development stage 0.7-0.8 (25 to 30 days), the mid season stage 1.05-1.2 (50 to 65 days), the late stage 0.65-0.7 (30 to 40 days) and harvest 0.2-0.25. Figure 3.8 shows growth development stages of winter and spring wheat (Yang *et al*, 2011).

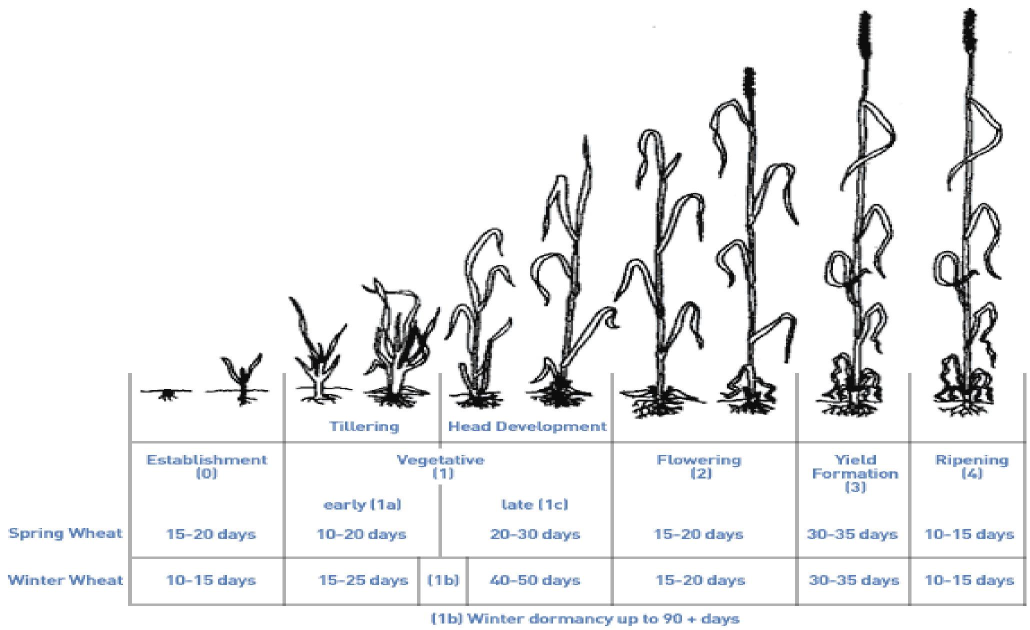

Figure 3.8 FAO crop development of wheat (Delphine *et al*., 2014;Allen, *et al*., 1998)

Length of growing: The length of growing ranges from 100 to 130 days for spring wheat while winter wheat require 180 to 250 days to mature in temperate climate. Day length and temperature are most important in selecting the variety. For this study 120 days was used as maximum growing length from May to August each year from 2013 to 2017.

Root Development: Wheat crop has lateral roots formed from nodes which are normally near the ground surface. Depth and density of rooting are affected by water, nutrient and oxygen in the soils. In deep soils, the active rooting depth for winter wheat ranges from 0.9 to 1.5m. The root ratio increases with crop development and double during the vegetative period in winter. Wheat primary root system is developed in autumn and full rooting depth is reached earlier than in spring. It requires 50 to 75 days after emergence to reach full depth (Allen, *et al*., 1998).

3.3.6.2* Soybean *(Glycine max)

This section presents information on soybeans and provides links to other sources of information based on soybean. Soybeans crops may have vaporization (when liquid is converted to a gas) value below 15 g/m^2 due to their biological nitrogen fixation process meaning they use less water (Allen, *et al*., 1998).

Climate: soybean is grown in warm conditions in tropics, sub-tropics and temperate climates. Soybean is relatively resistance to low and very high temperature but growth rates above 35°C and below 18 °C. In some varieties flowering can happen at above 24 °C and minimum temperature of growth is 10 °C and the crop production about 15 °C . Soybean is basically a short-day plant but respond to day length varies with different temperature (Allen, *et al*., 1998).

Growing length and Sowing rate: Short days hasten flowering, particularly for early maturity varieties. Vegetative growth normally ceases during yield formation. The length of total growing period is 100 to 130 days or more. Soybean is often growing rows spacing from 0.4 to 0.6m with 30 to 40 seeds per metre of row (Allen, *et al*., 1998).

Crop Development stage: Water requirements (ET) of soybean vary from 450 to 700 mm/season depending on the climate and the length of growing period (Allen, *et al*., 1998). The water is given by the Kc in relation to the reference evapotranspiration (ETo) and Kc is as follows: initial stage 0.3 to 0.4 (20 to 25 days), the development stage 0.7 to 0.8 (25 to 35 days), the mid season development stage 1.0 to1.15 (45 to 65 days), the late stage 0.7 to 0.8 (20 to 30 days) and at harvest 0.4 to 0.5. Figure 3.9 shows growth periods of soybean, for this study the length of growing was 85 days (Allen, *et al*., 1998).

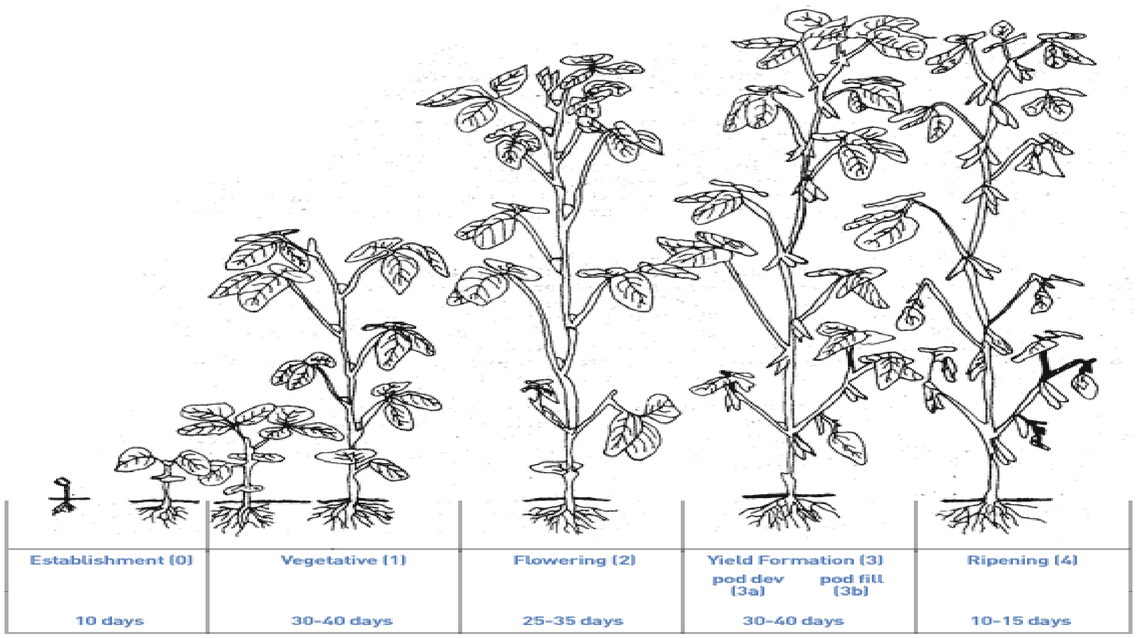

Figure 3.9 FAO crop development of soybean crop (Allen, *et al.*, 1998)

Root Development: Depending on the availability of water in the soil, early root development in deep soils is relatively rapid and vigorous. Most root growth is often noted after start of flowering (Allen, *et al.*, 1998). The tap root may extend to over 1.5 m. Roots are generally concentrated in the first 0.6 m or even sometimes in the first 0.3 m but 100% of the water uptake occurs from the first 0.6 to 1.3 m (Yang *et al*, 2011; Allen, *et al.*, 1998).

The crop parameters were used to create crop file and the conservative crop parameter were entered as described in this sub-section. Both soybean and wheat were used to simulate the net irrigation water abstraction used in each catchment (Allen, *et al.*, 1998).

3.3.7 Soil characteristics data

In AquaCrop the soil profile can be composed of up to five different horizons of variable depths, each with its own physical characteristics. The main soil characteristics are the hydraulic conductivity at saturation (K_{sat}) and soil water content at saturation (θ_{sat}), field capacity (θ_{FC}), and permanent wilting point (θ_{PWP}) (Raes *et al.*, 2012a).

The user can make use of the indicative values provided by AquaCrop for various soil texture classes, or import locally determined values or derived data from soil texture with the help of pedo-transfer functions. If an impermeable layer blocks the root zone expansion, its depth in the soil profile has to be specified as well. Soil characteristic from each basin should be known. To describe soil water balance and soil water retention in the root zone there's need to know soil water content at;

- Saturation (θ_{sat})
- Field Capacity (θ_{FC})
- Permanent Wilting Point (θ_{PWP})

To describe soil water movement AquaCrop needs the following;

- Saturated hydraulic conductivity (K_{sat})
- Soil type which is known from the Saturation (θ_{sat}) Field Capacity (θ_{FC}) and Permanent Wilting Point (θ_{PWP}).

Soil physical characteristics are required for each soil horizon. From this information the software derived other soil characteristics which are total available water (TAW) which determines the size of the soil reservoir, readily available water (RAW), readily evaporative water which determines the soil evaporation, soil type, capillary rise drainage and surface runoff.

The Soil Water Characteristic Software was used and requires soil data input as percentage by mass of clay and sand particles (Dr. Keith E. Saxton, 2007). This identifies the type of soil and gives indicative values for wilting point, Field Capacity, Saturation, Saturated Hydraulic conductivity and Matric Bulk Density.

The physical characteristics are also determined by the amount of organic matter in the soil and compaction. The soil profile is imported to AquaCrop and specified. For this study the soils were set as described by the soil map of Zambia (appendix IIIa) which was used to obtain the soil characteristics for the four catchments. For this study crop management in the area was not considered.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 OVERVIEW

This chapter presents the results and discussions of the findings. The chapter covers; the soil characteristics in all the four catchments; the overall catchment area covered, area under irrigation from 2013 to 2017, the evapotranspiration rates values for each catchment from 2013 to 2017 and lastly the crop net requirements. Gross irrigation requirements were used to determine the total volume of water in each catchment from 2013 to 2017.

4.2 CLIMATIC CONDITIONS

Reference evapotranspiration ETo was determined by using FAO ETo calculator (Raes,2012) for each catchment. The inputs for calculating ETo were maximum temperature, minimum temperature, relative humidity, wind speed and net solar radiation shown in (APPENDIX I). Monthly average ETo for five years were plotted as shown in Figure 4.1. In this study the climate data was collected from the following weather stations: Lusaka Airport to be use for Mwomboshi Catchment, Mulungushi in Kabwe to be used for Mulungushi and Lunsemfwa Catchment and Serenje to be used for Mkushi Catchment. All the weather stations have digital data recording system and the information is available on line. They are operating under Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) program in Zambia. The ETo was then calculated by the use of ETo calculator version 3.2 September 2012 which is free for non commercial use.

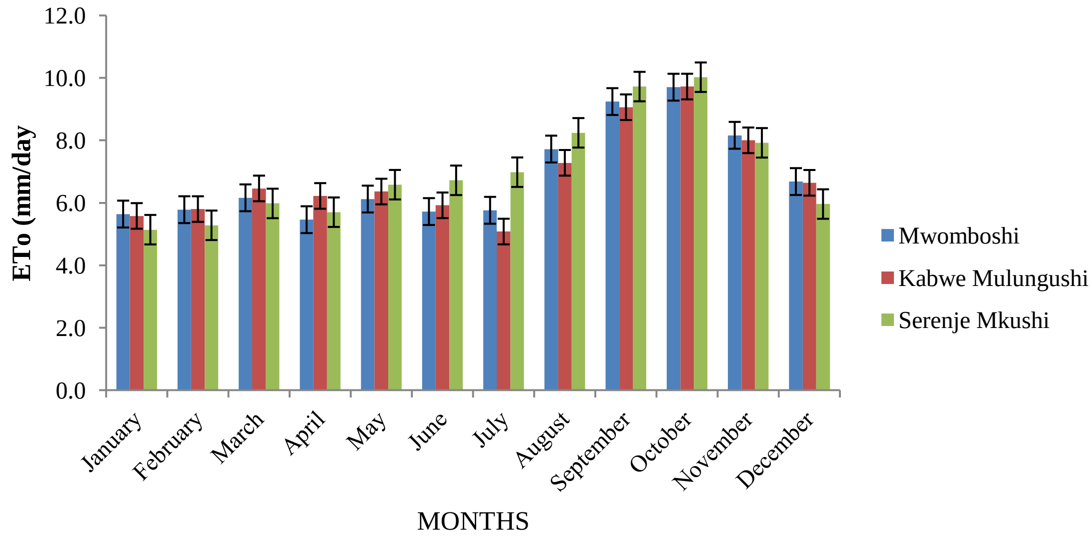

Figure 4.1 Average daily ETo (for the five (5) year period

The results show that for period May-June, ETo is highest at an average of 7.02 mm/day in Serenje and Mkushi while the least was in the Mulungushi at 6.84 mm/day. The variation of monthly ETo of the three weather stations from 2013 to 2017 are presented in Table 4.1.

Table 4.1 Monthly analysis of variance from Serenje, Kabwe and Lusaka airport weather station 2013 to 2017

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Months	0.2473	2	0.123	0.0537	0.947	3.284
Within Months	75.908	33	2.300			
Total	76.156	35				

Table 4.1 shows that for all months from the three weather stations can be said to have the same ETo. Hence it can be said that the average ETo is the same from 2013 to 2017 in all weather stations with a probability of 0.947 or at 95% confident level.

Rainfall data was also plotted and analysed from Serenje, Kabwe and Lusaka airport weather stations. The results of average five year rainfall and monthly rainfall are presented. Figure 4.2 shows the average monthly rainfall for a five year period from the Serenje, Kabwe and Lusaka weather stations. The rainfall was represented in the yearly sums as shown in Figure 4.2

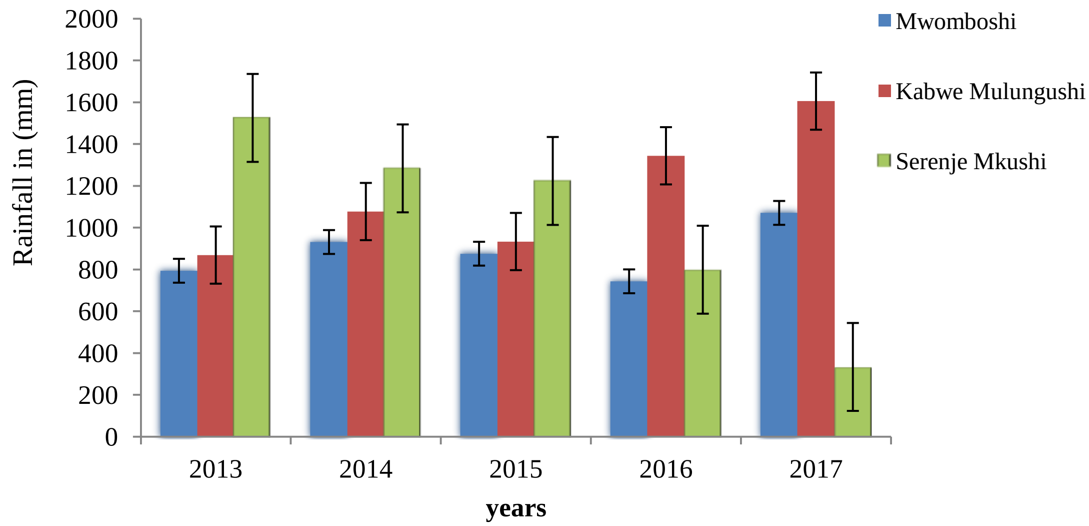

Figure 4.2 Annual Rainfall of Lusaka Airport, Kabwe, Mulungushi, and Serenje: January 2013 - December 2017

The rainfall data was summarized in Microsoft excels to test for similarities between mean and variance. Table 4.2 shows the data that was used to test for the means.

Table 4.2 summary of parameters used to analyze average rainfall variance from 2013 to 2017 in Serenje, Kabwe and Lusaka airport weather stations

Weather Stations	*Count*	*Sum*	*Average*	*Variance*
Mwomboshi	5	4413.2	882.64	16275.7
Kabwe Mulungushi	5	5827.733	1165.547	93726.47
Serenje Mkushi	5	5163.4	1032.68	221281.6

Table 4.2 shows summary of rainfall recorded in the catchments obtained from SASSACAL weather stations. The table also shows that rainfall varies more in Serenje or in Mkushi catchments which recoded highest variation of rainfall from 2013 to 2017. The results were used to test the difference between the means of rainfall. The analysis of variance for rainfall of the three weather stations is presented in Table 4.3.

Table 4.3 Yearly analysis of rainfall variance from Serenje, Kabwe and Mwomboshi weather station 2013 to 2017

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Catchments	200336.2	2	100168.1	0.907	0.429	3.885
Within Catchments	1325135	12	110427.9			
Total	1525471	14				

From the three weather stations there is no significant difference in rainfall mean from 2013 to 2017. There was a 0.429 probability of rain from the three weather stations being the same. The mean average of rainfall was the same statistically because the calculated *F* (F value > 0.05.) is less than the tabulated F critical (3.885) at alpha of 0.05 or 95% confident level.

4.3 SOIL TYPE USED FOR IRRIGATION WATER ESTIMATION

The soil types of the study area were chosen based on the soil map of Zambia shown in the (APPENDIX IIIa).

The soil map on (APPENDIX IIIa) shows that the catchments of Mkushi, Mulungushi and Lunsemfwa recline on loamy sandy soils rather course grained, the clay content increasing with depth. Yellowish –red to light yellowish brown are well drained and grey brown are poorly drained. Soil was analyzed using the soil water characteristic software and result were shown in Table 4.4.

Table 4.4 Mkushi, Mulungushi, and Lunsemfwa (Loamy sands) analyzed soil results

Soil Parameter	Catchments			
	Mkushi	Lunsemfwa	Mulungushi	Mwomboshi
Wilting Point [%]	7.3	7.3	7.3	18.3
Field Capacity [%]	14.4	14.4	14.4	28.3
Saturation [%]	49.4	49.4	49.4	43.2
Organic Matter [%]	4.0	4.0	4.0	2.5
Hydraulic Conductivity [mm/Hr]	72.78	72.78	72.78	52.7
Soil Type	Loamy sand	Loamy sand	Loamy sand	Sandy Clay Loam

Table 4.4 shows the parameter of loamy sands soil found in the Lunsemfwa, Mulungushi and Mkushi catchment area. The results showed that the soil contains 20% of gravel (not in the table), the soil wilting point at 7.3 % by volume, field capacity at 14.4 % and saturation at 49.4% . The soil also contains 4% organic matter and the saturation hydraulic conductivity of the soil is 72.78mm/hr.

The Red brown clay loam covers the part of Mwomboshi catchment area. These are soils with a topsoil texture of clay to sandy clay loam. Dark red are well drained and brown to dark gray brown are poorly drained.

From Table 4.4 sandy clay loam of Mwomboshi had a wilting point of 18.3%, field capacity of 28.3% and saturation of 43.2% by volume. The results also show that the soil contains 25% of organic matter and have a saturated hydraulic conductivity of 5.70 mm/hr.

4.4 AQUACROP NET IRRIGATION ESTIMATION

The results from sub-section 4.2 to subsection 4.3 being, climate of the catchments; crop characteristics and soil characteristics, were used to set the AquaCrop model and run the simulation of net irrigation requirement for wheat and soybean. Both crops were planted by direct sowing method in the month of May. Wheat gives higher net irrigation requirements than Soybean. This helps in estimating the minimum and maximum water that could be abstracted due to irrigation. The results from each catchment are presented in Table 4.5.

Table 4.5 Net and Gross irrigation of both wheat and soybean from the four catchments as estimated from AquaCrop

		Net irrigation [mm]					Gross irrigation [mm]				
		2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
Mkushi	Soybean	481.2	453	504.8	406.3	408.6	641.6	604.0	673.1	541.7	544.8
	Wheat	678.0	639.6	710.0	577.3	592.6	904.0	852.8	946.7	769.7	790.1
Lunsemfwa	Soybean	407.9	423.0	438.8	409.8	341.4	543.9	564.0	585.1	546.4	455.2
	Wheat	473.3	566.9	403.3	558.5	462.2	631.1	755.9	537.7	744.7	616.3
Mulungushi	Soybean	407.6	423	438.8	409.8	341.4	543.5	564.0	585.1	546.4	455.2
	Wheat	473.3	566.9	403.3	558.5	462.2	631.1	755.9	537.7	744.7	616.3
Mwamboshi	Soybean	314.4	395.4	458.4	294.7	306.6	419.2	527.2	611.2	392.9	408.8
	Wheat	603.3	639.7	646.0	610.0	447.3	804.4	852.9	861.3	813.3	596.4

The net irrigation from Table 4.5 was obtained from simulation of crop net irrigation requirements in AquaCrop. The net irrigation was then divided by the sprinkler efficiency of 0.75 to obtain the gross irrigation. The Gross and the net irrigation of Lunsemfwa and Mulungushi have the same value because the weather data and the soil type were found to be the same from Kabwe weather station and Zambia soil map in (APPENDIX IIIa) respectively.

The analysis of variance was done to distinguish if the water used to irrigate wheat crop in all catchment was the same and is represented in Table 4.6.

Table 4.6 Summary of yearly analysis of variance of wheat crop from Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchments from 2013 to 2017

Groups	*Count*	*Sum*	*Average*	*Variance*
Mkushi Wheat	5	3197.5	639.5	3130.24
Lunsemfwa Wheat	5	2464.2	492.84	4783.538
Mwomboshi Wheat	5	2946.3	589.26	6635.883

The summary in Table 4.6 was used to test whether water across the catchments were the same statistically. The results are shown in Table 4.7.

Table 4.7 Yearly analysis of Net irrigation variance of wheat crop from Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchments 2013 to 2017

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	55550.05	2	27775.02	5.726943	0.0179	3.885
Within Groups	58198.64	12	4849.887			
Total	113748.7	14				

Table 4.7 shows that for wheat crops grown in three catchments net irrigation water from 2013 to 2017 used is different, therefore crop water demand was statistically different across the catchments. This is proved by the calculated F (5.7) being greater than the *F*-critical (3.885). The least significant difference (LSD) comparison of estimated Net irrigation was carried out in SPSS software to identify where such differences exists for wheat in the four catchments. The results were presented in (APPENDIX IV).

Mulungushi net irrigated water compared to that of Mkushi and Mwomboshi shows that there is significant difference giving probability of 0.006 and 0.049 chances of being the same to Mulungushi net irrigated water respectively at alpha of 0.05 level.

Mkushi net irrigated water compared to that of Mwomboshi shows that there is no significant difference giving probability of 0.276 chance of being the same at alpha of 0.05 level. Hence conclude that the difference exist between Mulungushi and both

Mkushi and Mwomboshi. This may be the fact that there are more farming activity in Mkushi than in Mwomboshi. Hence more water is used. It can be concluded that water requirement in Mkushi and Mwomboshi are of the same average.

The results for soybean crop are also shown in the Table 4.8

Table 4.8 Summary of five year analysis of variance of soybeans crop from Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchments from 2013 to 2017

Soybean catchment	*Count*	*Sum*	*Average*	*Variance*
Mkushi Soybean	5	2253.9	450.78	1901.522
Lunsemfwa Soybean	5	2020.9	404.18	1384.872
Mwomboshi Soybean	5	1769.5	353.9	4986.17

The summary in Table 4.8 was the output of Single factor analysis of variance of soybean net irrigations in Mkushi, Lunsemfwa and Mwomboshi catchments. The variation and *F* test of means are shown in Table 4.9.

Table 4.9 Five year analysis of Net irrigation variance of soybean crop from Mkushi, Lunsemfwa, and Mwomboshi catchments 2013 to 2017

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between catchment	23475.621	2	11737.81	4.257	0.040	3.885
Within catchment	33090.256	12	2757.521			
Total	56565.87733	14				

Table 4.9 shows that the average net irrigation water requirement in Mkushi and Mwomboshi was different for the soybean crops giving the calculated *F* at 4.257 more than the tabulated *F* critical at 3.88 with the probability of 0.04. This shows that soybean grown in three catchments used different amount of water. The least significant difference (LSD) comparison of estimated net irrigation was carried out in the SPSS software to identify where such differences exist from the soybean crop in the four catchments. The results were presented in the (APPENDIX IV).

Mulungushi net irrigated water requirement compared to that of Mkushi and Mwomboshi showed that there was no significant difference giving probability of 0.186

and 0.156 chances of being the same to Mulungushi net irrigated water respectively at alpha of 0.05 level.

Mkushi net irrigated water compared to that of Mwomboshi showed that there was significant difference giving probability of 0.013 chance of being the same at alpha of 0.05 level. Hence the difference exists between Mkushi and Mwomboshi net irrigation water requirement. The net irrigations water was represented in the Figure 4.3 as shown.

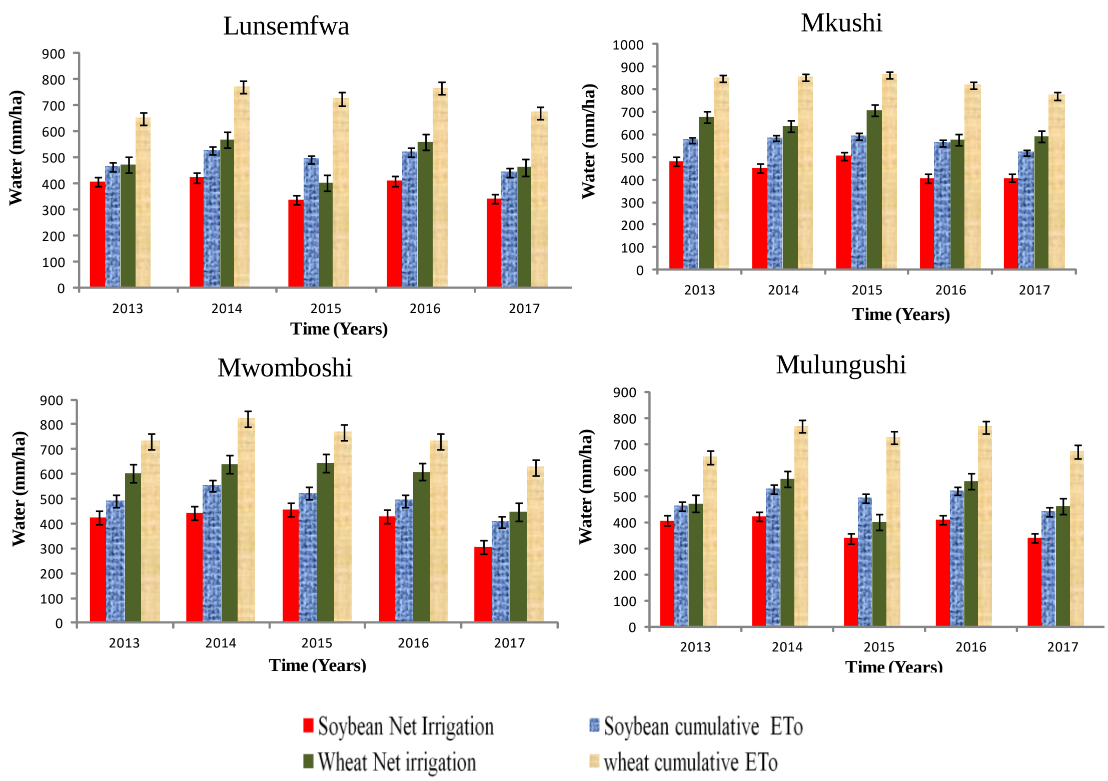

Figure 4.3 Yearly analysis of Net irrigation per hectare and Evapotranspiration of soybean and wheat crop from Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchments for the period 2013 to 2017

From Figure 4.3 the net irrigation and cumulative ETo of the two crops in the four catchments are from 2013 to 2017. In general, water demand decreased from 2013 to 2017 in Mwomboshi catchment and Mkushi. The higher water user (wheat in this study) had alternating water demand from 2013 and to 2017 in Mwomboshi, Mulungushi and Lunsemfwa; Any slight change in cumulative ETo from 2013 to 2017 causes change in net irrigation water as shown in Figure 4.3. Climate change is likely to cause these changes (Chami *et al.*, 2015). Although the same crop and soil was simulated the difference in cumulative ETo influenced the net irrigation water, more over this may be due to alternating solar radiation, humidity and wind speeds recorded from weather station resulting in alternating ETo.. The detail values are shown in (APPENDIX IIa)

The water used for soybean estimates the minimum water that can be used and also had a decreasing trend due to decreasing temperature from 2013 to 2017 in Mwomboshi catchment. The ETo of the crop varies as simulated by the AquaCrop software giving alternating values of net irrigation from 2013 to 2017. Mulungushi and Lunsemfwa showed similar values as same weather and soil were used for simulations in AquaCrop. From Figure 4.3 cumulative ETo for wheat and soybean are different as the crop had different growing period. Wheat recorded higher values for cumulative ETo as it was simulated for longer period (120 days) while soybean was simulated for shorter periods (85 days). More detail shown in (APPENDIX IIa).

4.5 CATCHMENTS AND IRRIGATION AREA CLASSIFICATION

Catchment areas were delineated from the Earth explorer; shape files of the areas were determinate and used to clip the landsat8 images for the three months (May, July and August) of the year. The procedure used to estimate the area of irrigated farms was described in chapter 3. This sub-section further gives results of the areas of irrigated farms after classification of the landsat8 images for the three months from the year 2013 to 2017, this helped in coming up with the estimations of volumes of water used per catchment and per year.. The catchment elevation models and shape files are as shown in Figure 4.4.

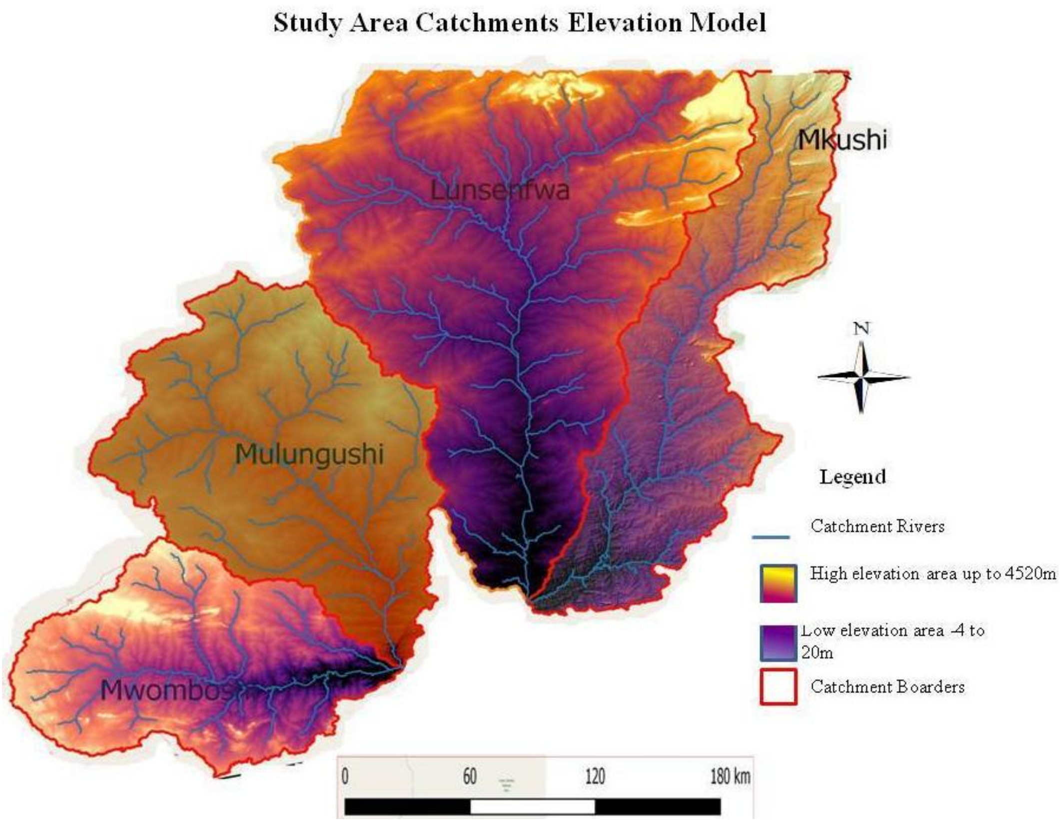

Figure 4.4 Mkushi, Lunsemfwa, Mulungushi and Mwomboshi Catchments area elevation models

4.5.1 Catchment Area

In Figure 4.4 Mkushi catchment area consists of the Mkushi River, and covers a land of about 3479.93 km^2. The darker area in Figure 4.4 shows low land and the lighter shows the high altitude areas of the catchment.

In Figure 4.4 the shape and elevation model of Lunsemfwa catchment is displayed. The catchment covers an area of about 7794.5 km^2.

The Mulungushi catchment area is about 4445 km^2 and is made up of Mulungushi River. The catchment shares boundaries with the Mwomboshi which is the smallest of the four catchments under the study. Mwomboshi catchment covers area of about 3043 km^2. It comprises of Mwomboshi River which meets with Mulungushi River at the lower end of the catchment.

4.5.2 Classification of Irrigated Area

Irrigated areas were obtained from the clipped landsat8 with the shape files in sub-section 4.5.1. An average of three months classified irrigated area was estimated after classification was done for each catchment. Figure 4.5 shows the clipped landsat8 to the shape file. Most of the clipped catchment landsat8 image can be reviewed in (APPENDIX IIIb).

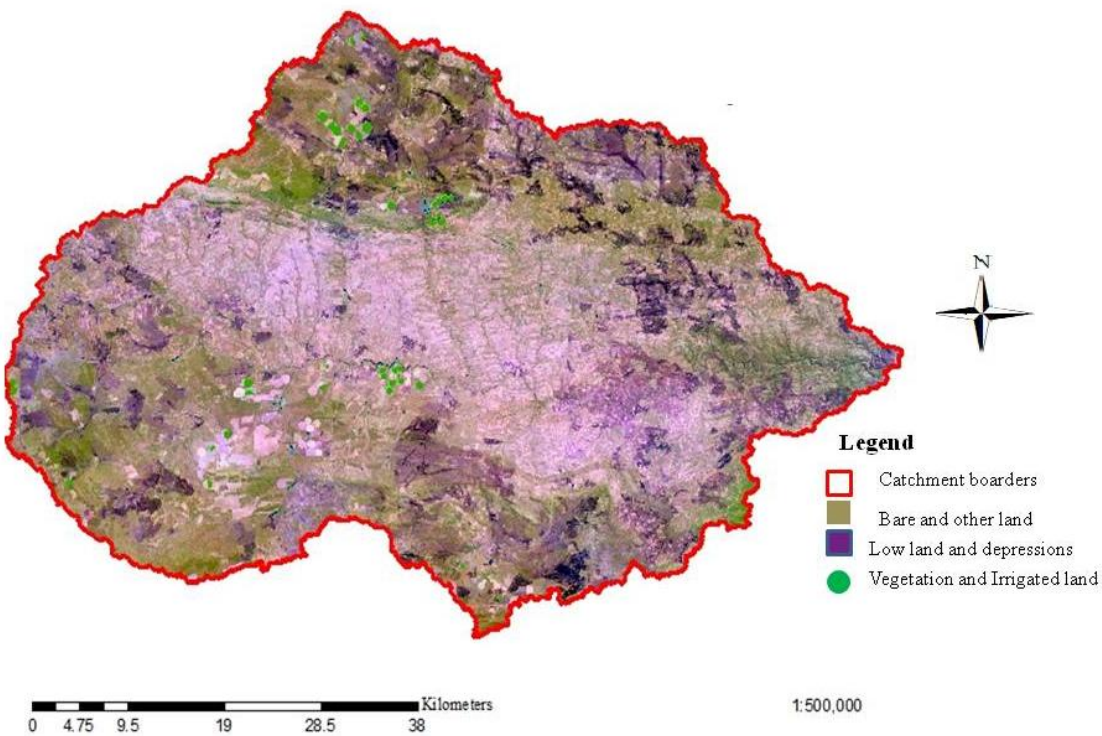

Figure 4.5 A clipped landsat8 image for Mwomboshi Catchment

2013 to 2017; Figure 4.6 shows the classified clipped Mwomboshi catchment.

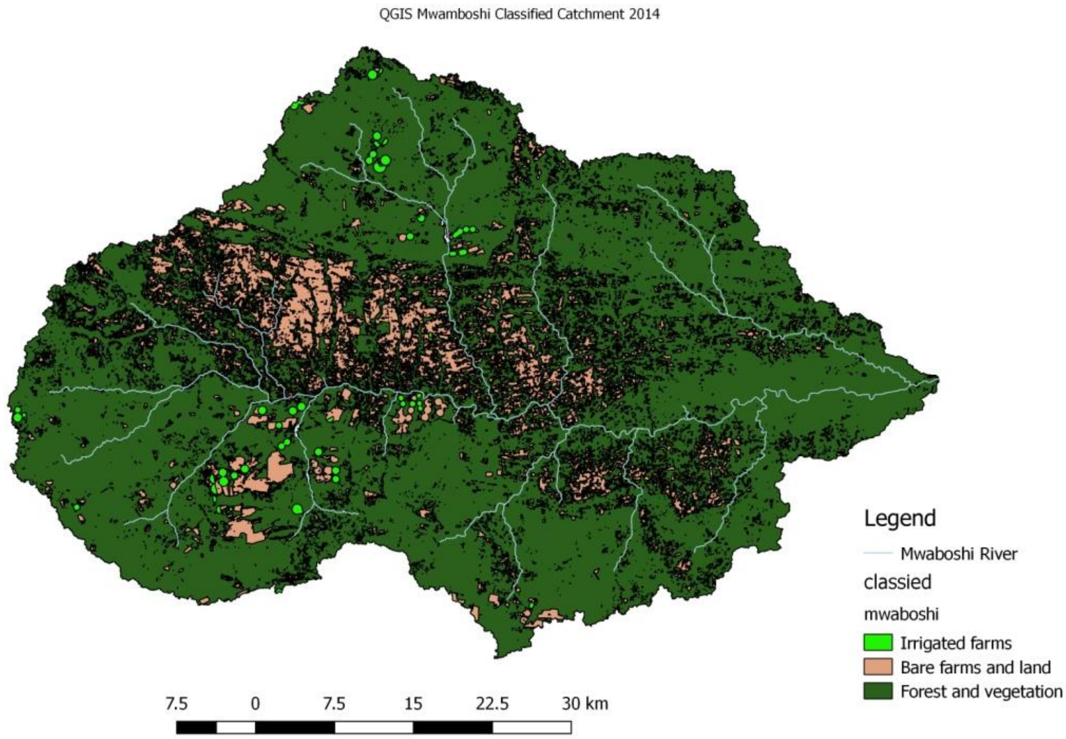

Figure 4.6 A classified landsat8 for Mwomboshi catchment

Figure 4.6 shows classified irrigated areas for Mwomboshi catchment. Classified results all catchments are shown by Figure 4.7.

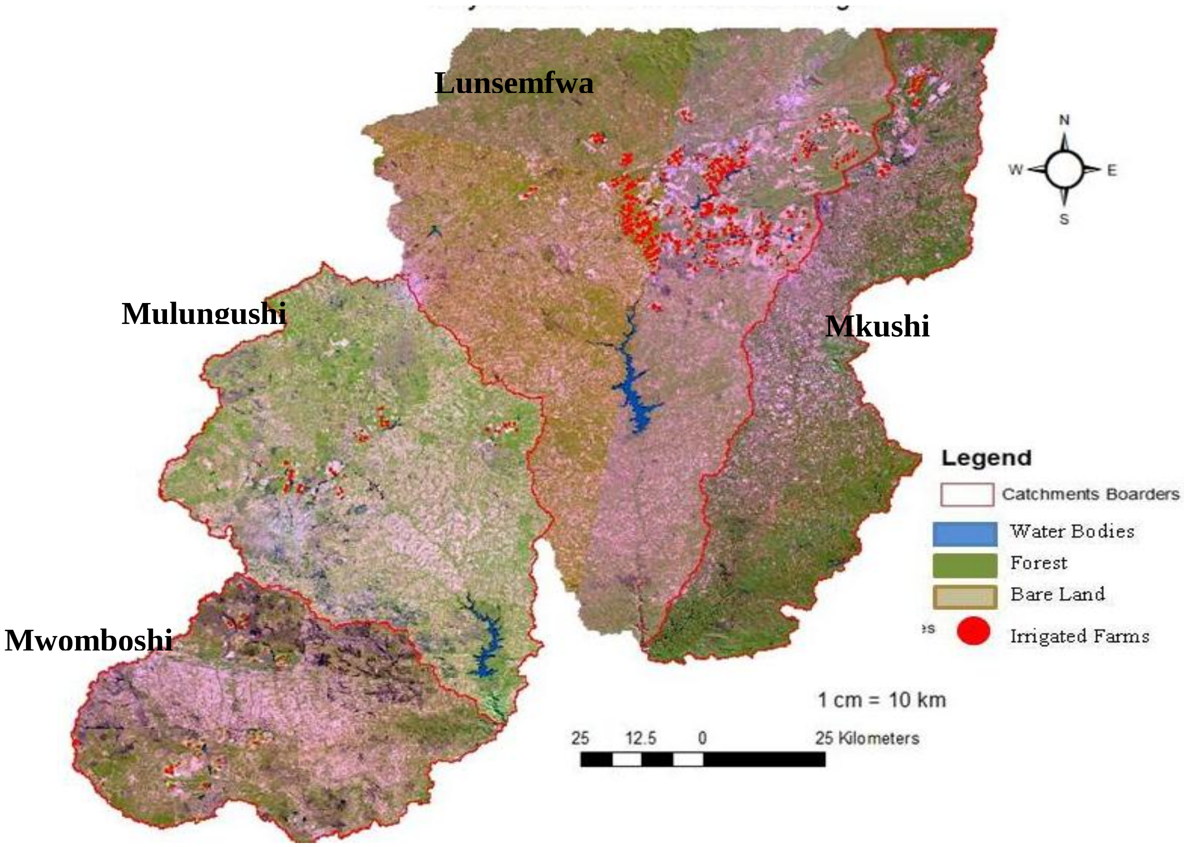

Figure 4.7 classified Sub-catchments

In Figure 4.7 Lunsemfwa catchment shows more irrigated farms than the Mkushi catchment. These gives more irrigated farms in the catchment than any other catchment. The results of the average irrigated areas from 2013 to 2017 estimated of the catchment are shown in the Figure 4.8

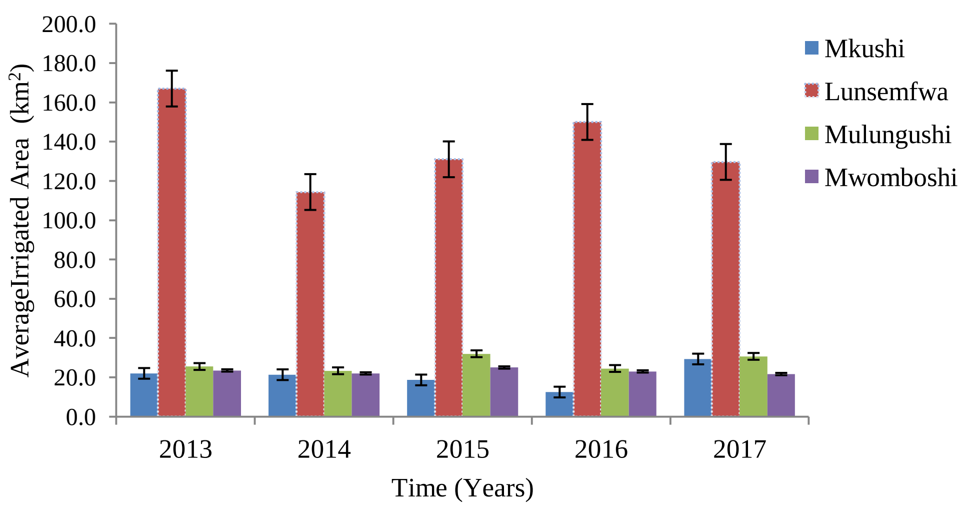

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Figure 4.8 Relationship of irrigated areas from four catchments

Figure 4.8 shows the estimated irrigated areas from 2013 to 2017 from the four catchments, the Lunsemfwa catchment shows largest area irrigated with Mkushi catchment showing low irrigated areas. The summary of irrigated areas is described in Table 4.10.

Table 4.10 shows the descriptive statistic with respect to irrigated areas estimated from 2013 to 2017.

Table 4.10 Descriptive statistics of Mkushi, Mulungushi, Lunsemfwa and Mwomboshi of irrigated area 2013 to 2017 in m^3

Descriptive Statistic	*Mkushi*	*Lunsemfwa*	*Mulungushi*	*Mwomboshi*
Mean	20.77	138.40	27.20	23.03
Kurtosis	1.20	-0.54	-2.70	-0.04
Skewness	0.10	0.49	0.50	0.73
Minimum	12.50	114.33	23.33	21.67
Maximum	29.33	167.00	32.00	25.00
Sum	103.83	692.00	136.00	115.17
Confidence Level (95.0%)	7.55	25.32	4.82	1.65

Table 4.10 shows the descriptive statistic of the estimated areas at alpha 0.05 areas irrigated. The least was recorded in Mkushi in 2016 (12 km^2) while highest being 167 km^2 in Lunsemfwa in 2013. For the five years period (2013 to 2017) Mkushi has irrigated a sum of 103.83 km^2, Lunsemfwa 692.00 km^2, Mulungushi 136.00 km^2 and Mwomboshi with the sum of 115.17 km^2.The estimated area averages are used to calculate the volume of water that was used to irrigate wheat and soybean crops in all catchments. Detailed volumes of water abstracted from each catchment in the five years are described in sub-section 4.6 based on sprinkler irrigation efficiency of 75 %.

4.6 VOLUME OF WATER ABSTRACTION

This sub-section gives results of the main objective of this study. The volume of water was estimated from irrigated areas and gross irrigation water requirements for wheat and soybean. Table 4.11 shows the summary of the calculation of the volumes. Can be reviewed in (APPENDIX II)

4.6.1 Volume of Water Abstracted from Mkushi

The volume of water abstracted was mostly influenced by the area planted as estimated from the classified images. Maximum volume was represented by the water demand from wheat crop and minimum was represented by soybeans. Water abstracted from Mkushi catchment are represented in Figure 4.9:

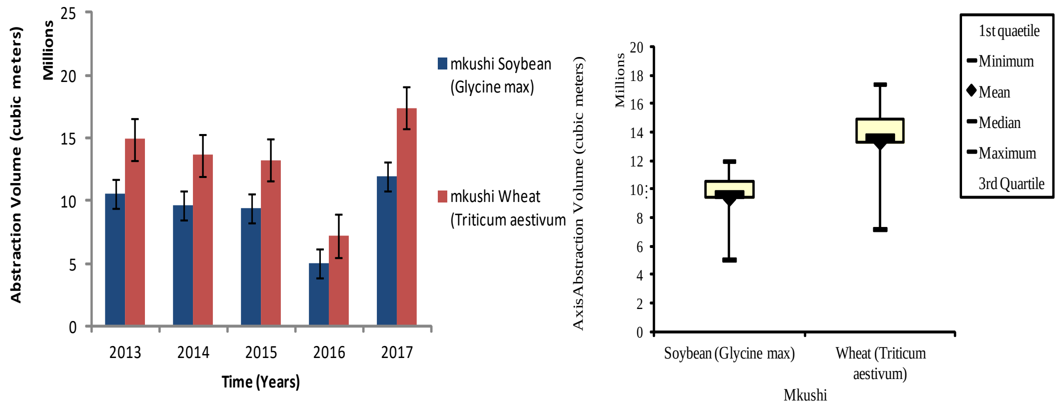

Figure 4.9 Maximum =wheat and minimum= soybean Mkushi (2013-2017)

The maximum volume recoded in Mkushi catchment was in 2017 at 83,775,000 m^3 and the minimum of 5,078,750 m^3 in 2016. The mean maximum water that was abstracted from Mkushi catchment was estimated to be 68,079,180 m^3 while the mean minimum volume of water that was used for irrigation in the five year period was 9,347,536.667 m^3. Table 4.11 summaries the estimated statistical relationship of maximum (wheat) and minimum (soybean) irrigation water volume abstracted in Mkushi catchment from 2013 to 2017.

Table 4.11 Summary of descriptive statistics of volume of irrigated water from Lunsemfwa catchment from 2013 to 2017 in m^3

Descriptive Statistics	*Wheat (Triticum aestivum)*	*Soybean (Glycine max)*
Mean	68,079,180	9,347,536.66
Standard Error	5813856.74	1158070.24
Sample Variance	1.690E+14	6.706E+12
Kurtosis	-2.149	2.643
Skewness	0.202	-1.379
Minimum	52,832,300	5,078,750
Maximum	83,775,000	11,985,600
Sum	340,395,900	46,737,683.33
Confidence Level (95.0%)	1,6141,854.11	3,215,318.461

Table 4.11 describes the statistical relationships of the minimum and maximum volume of irrigation water that was estimated to have been used in Mkushi catchment from

2013 to 2017. The data are positively skewed or skewed right, meaning that the right tail of the distribution is longer than the left for wheat. Skewness is negative, for soybean meaning the data are negatively skewed or skewed left. Positive Kurtosis for soybean data meaning lot of data in the ends of the distribution or tails while negative Kurtosis shows there is little data on the tails of wheat data. The Kurtosis and skewness shows whether the data is normally distributed and may need transformation, when the skweness is more than 1 the data may need transformation. The table gives all the parameter at alpha is 0.05 or 95% confidence level.

4.6.2 Volume of Water Abstracted from Lunsemfwa

Lunsemfwa catchment is the largest sub-catchment in this study and have the largest irrigated areas compared to other sub-catchments. The maximum and minimum volumes of water abstracted from the catchment were also estimated and the results are represented in Figure 4.10.

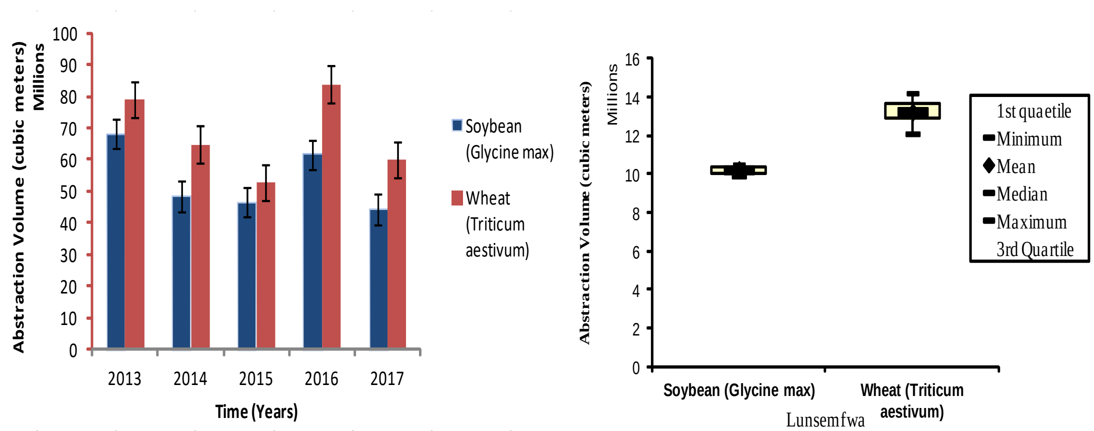

Figure 4.10 Abstracted Volumes Maximum =wheat and minimum= soybean Lunsemfwa (2013-2017)

From Figure 4.10 maximum water abstraction was decreasing from 2013 of about 80 million m^3 to 52 million m^3 2015, then increase to 84 million m^3 in 2016. The volume of water abstracted was estimated to be less in 2015. The alternating pattern may be the result of crop rotation and farmer preferences of growing rain fed crops than irrigated ones. The other cause of the alternating volume may be the rainfall pattern which was changing in the region resulting in low irrigation field when there is insufficient water. Synopsis of relationship of minimum and the maximum water that was abstracted from the Lunsemfwa catchment area is shown in the Table 4.12.

Table 4.12 Summary of descriptive statistics of volume of irrigated water from Mkushi catchment from 2013 to 2017 in m^3

Descriptive statistics	*Wheat*	*Soybean*
Mean	13,282,663.33	9,347,536.667
Standard Error	1679484.693	1,158,070.244
Standard Deviation	3755441.941	2589523.789
Kurtosis	2.332390918	2.64314148
Skewness	-1.17935472	-1.37962716
Minimum	7216250	5078750
Maximum	17382933.33	11985600
Sum	66413316.67	46737683.33
Confidence Level (95.0%)	4662997.055	3215318.461

Table 4.12 shows that the mean maximum (wheat) volume abstracted from 2013 to 2017 was 13,282,663.33 m^3 while the mean minimum of soybean was 9,347,536.67 m^3. The Table is numerical description of Figure 4.10.

4.6.3 Volume of Water Abstracted from Mulungushi

Mulungushi catchment is in the middle of the Lunsemfwa and Mwomboshi, for period of five years from 2013 to 2017 there were few numbers of irrigated farms as seen from the estimation of irrigated areas in section 4.5. Volumes of irrigation water abstracted from Mulungushi catchment were plotted in a bar chart against the year of abstraction and are presented in the Figure 4.11.

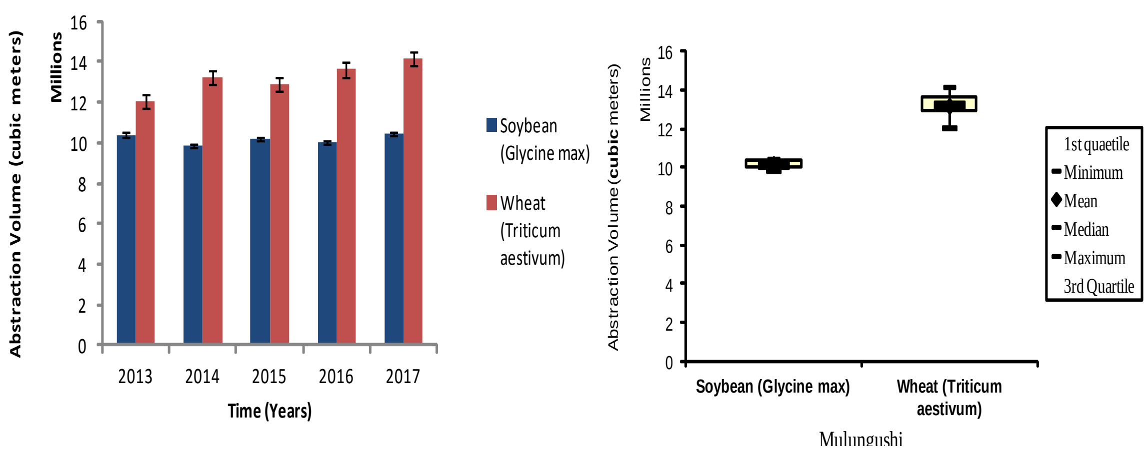

Figure 4.11 Abstracted volumes Maximum =wheat and minimum= soybean Mulungushi (2013-2017)

Figure 4.11 shows the estimated volume of irrigation abstraction in Mulungushi with the maximum abstraction in the catchment increasing from million 12 m^3 in 2013 to 14 million m^3 in 2017. Summarized relationship of the estimated irrigation water abstraction is numerically represented in Table 4.13

Table 4.13 Summary of descriptive statistics of volume of irrigated water from Mulungushi catchment from 2013 to 2017 in m^3

Descriptive Statistics	*Wheat*	*Soybean*
Mean	13,203,440	10,193,375
Standard Error	353,552.034	110,574.647
Standard Deviation	790,566.381	247252.425
Kurtosis	0.272	-1.671
Skewness	-0.413	-0.229
Minimum	12,069,150	9,870,000
Maximum	14,174,133.33	10,469,600
Sum	66,017,200	50,966,875
Confidence Level (95.0%)	981,617.8137	307,004.4351

Table 4.13 shows that the mean maximum of water that was abstracted from Mulungushi catchment was 13,203,440 m^3 from 2013 to 2017. For the five year period the minimum water abstraction was estimated at 9,870,000 m^3 for Mulungushi catchment.

4.6.4 Volume of Water Abstracted from Mwomboshi

Mwomboshi catchment is the smallest of the four catchments hence have less number of irrigation farm area recoded. Water abstracted from this catchment was displayed in a form of combination bar chart for minimum abstraction for soybean and box plot for maximum abstraction for wheat. The results are shown in Figure 4.12.

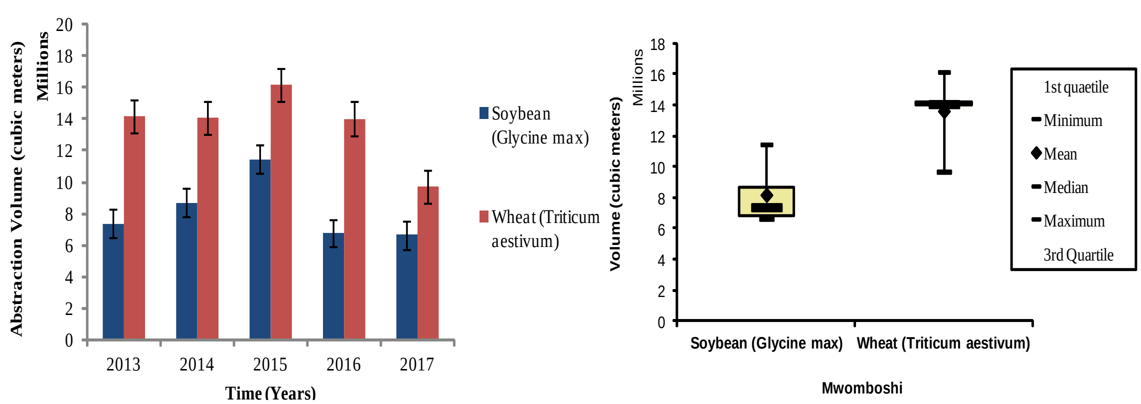

Figure 4.12 Abstracted volumes Maximum =wheat and minimum= soybean Mwomboshi (2013-2017)

Figure 4.12 shows that there is increasing maximum water use in Mwomboshi catchment from year 2013 to 2015 and then the abstraction declined from 2015 until 2017. It was also observed that the range in maximum and minimum water abstraction is estimated to 14 million m^3 and the mean minimum estimated at about 8 million m^3.

Sub-section 4.6 has elaborated the volume of abstracted irrigation water estimated from all the four catchments. The total volume of irrigation abstraction water was plotted against and represented in the box plot in Figure 4.13 from 2013 to 2017.

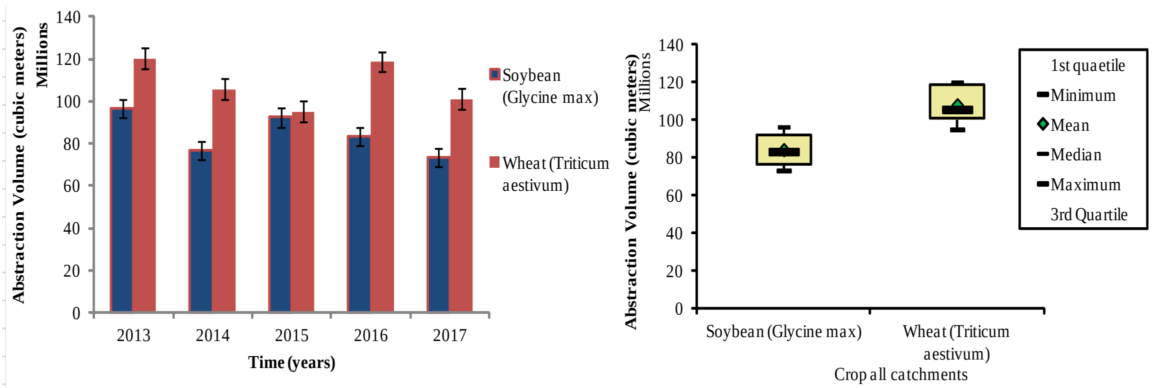

Figure 4.13 Abstracted overall volumes (maximum =wheat and minimum= soybean) for Mkushi, Lunsemfwa, Mwomboshi and Mulungushi (2013-2017)

Figure 4.13 shows that all irrigation water abstracted from the study area would increase depending on the crop irrigated. It have also been estimated that the maximum water that was abstracted in all the catchments had mean volume of 108,189,773 m^3 with maximum volume of 120,203,800 m^3 overall in 2013, while the minimum was estimated in 2014 at 73,366,400 m^3. In simple terms the maximum irrigation water abstraction decreased from 2013 (120,203,800 m^3) to 2015 (95,147,633.33m^3), increased to 118,655,500 m^3 in 2016 and reduced in 2017 to 101,180,500 m^3. The minimum irrigated water abstraction drop from 96,487,900 m^3 in 2013 to 76,595,800 m^3 in 2014 then increased to 92,407,333.33 m^3 in 2015 and lastly dropped in 2016 and 2017 to 73,366,400 m^3.

The variation of mean maximum volume were analyzed in Microsoft excel to determine the similarity between irrigation abstracted volume means for wheat throughout all catchments. The summary of result are shown in the Table 4.14

Table 4.14 Summary of five year analysis of abstracted irrigated water variance of wheat crop from Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchments 2013 to 2017 in m^3

Catchments	*Count*	*Sum*	*Average*	*Variance*
Mkushi	5	66413317	13282663	1.41E+13
Lunsemfwa	5	3.4E+08	68079180	1.69E+14
Mulungushi	5	66017200	13203440	6.25E+11
Mwomboshi	5	68122450	13624490	5.63E+12

Summary in Table 4.14 was used to analyze the abstraction of water for wheat in Table 4.15. The variation were highest in Lunsemfwa and least in Mulungushi as seen from last column of Table 4.14

Table 4.15 Five year analysis of irrigated abstracted volume of water variance of wheat crop from Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchment s2013 to 2017 in m^3

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Catchments	1.12E+16	3	3.74E+15	79.033	8.27E-10	3.238
Within Catchments	7.57E+14	16	4.73E+13			
Total	1.2E+16	19				

Table 4.15 shows that one can conclude that the maximum estimations of irrigation abstraction from four catchments have different mean from 2013 to 2017 as the *F* (79.033), calculated is higher than the *F* critical (3.23) at alpha is 0.05 or 95 %Hence, it can be conclude that there is significant difference in the means of irrigation volume abstraction from all catchments. The least significant difference (LSD) comparison of estimated abstracted volumes was carried out in the SPSS software to identify where the differences exist for wheat in the four catchments. Results in the form of a table are presented in (APPENDIX IV).

The results shows that for wheat , the volumes abstracted had a significant difference when comparing Lunsemfwa catchment to Mkushi Mulungushi and Mwomboshi.

Mkushi irrigated water abstracted volume compared to that of Mulungushi and Mwomboshi shows that there is no significant difference giving probability of 0.99 and 0.94 changes of being the same to Mkushi volume respectively at alpha of 0.05 level.

Mulungushi irrigated water abstracted volumes compared to that of Mwomboshi shows that there is no significant difference giving probability of 0.92 chance of being the same at alpha of 0.05 level. Hence conclude that volumes of abstracted irrigation water are different between Lunsemfwa and Mkushi; Lunsemfwa and Mulungushi and Lunsemfwa and Mwomboshi.

The results for the minimum abstraction volumes of soybean crop were tested with single factor analysis of variance in Microsoft excel software and shown in Table 4.16

Table 4.16 Summary of five year analysis of abstracted irrigated water variance of soybean crop from Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchments from 2013 to 2017 in m^3.

Groups	*Count*	*Sum*	*Average*	*Variance*
Mkushi	5	46737683	9347537	6.71E+12
Lunsemfwa	5	2.8E+08	55940660	9.37E+13
Mulungushi	5	54815100	10963020	3.02E+12
Mwomboshi	5	40968300	8193660	4E+12

Summary in Table 4.16 was used to analyze the abstraction of water volumes for soybean. The variation were highest in Lunsemfwa and least in Mulungushi as seen from last column of Table 4.16

Table 4.17 Five year analysis of irrigated abstracted volume of water variance of wheat crop from Mkushi, Lunsemfwa, Mulungushi and Mwomboshi catchments from 2013 to 2017

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Catchments	8.11E+15	3	2.7E+15	100.5862	1.35E-10	3.238872
Within Catchments	4.3E+14	16	2.69E+13			
Total	8.54E+15	19				

Table 4.17 shows that one can conclude that the minimum estimations of irrigation water abstraction volumes in all four catchments have different means from 2013 to 2017 as the F (100.5862) calculated, is higher than the F critical (3.238) at alpha is 0.05 or 95 %. The least significant difference (LSD) comparison of estimated irrigation volumes was carried out in the SPSS software to identify were the differences exist for soybean in the four catchments. The results are presented in the (APPENDIX IV).

The results shows that for soybean crop volume of abstracted irrigation water had significant difference when comparing Lunsemfwa catchment to Mkushi, Mulungushi and Mwomboshi.

Mkushi irrigated water abstracted volume compared to that of Mulungushi and Mwomboshi shows that there is no significant difference giving probability of 0.62 and 0.729 changes of being the same at alpha of 0.05 level. Mulungushi irrigated water abstracted volumes compared to that of Mwomboshi shows that there is no significant difference giving probability of 0.411 chance of being the same at alpha of 0.05 level.

Results and discussions of the study were covered in this chapter. Relevant literatures to back up the findings of the study have been provided as much as possible. In general, the specific objectives were met as the volume of water abstracted from the four sub-catchments are estimated, analyzed and presented based on the parameters that were defined in the study.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATION

5.1 OVERVIEW

This chapter presents the conclusions and recommendations drawn from the study. The conclusions have been presented to reflect the achievement of each specific objective and for clarity purposes.

5.2 CONCLUSIONS AND SUMMARY OF FINDINGS

The average ETo of Serenje for five year period was 7.22 mm/day followed by Mwomboshi catchment at 6.85 mm/day and lowest in both Mulungushi and Lunsemfwa catchments at 6.84 mm/day.

Loamy sands soils are found in the Lunsemfwa, Mulungushi and Mkushi catchment area. The results shows that the soil contains 20 % of gravel, the soil has a wilting point of 7.3 % by volume, field capacity of 14.4 % and saturation at 49.4% by volume. Sandy clay loam of Mwomboshi was found to have crop wilting point of 18.3 %, field capacity of 28.3% and saturation of 43.2 % by volume. The results also show that the soil contains 2.5 % of organic matter and have saturated hydraulic conductivity of 52.70 mm/hr.

The net irrigation water was determined from AquaCrop software were simulation of net irrigation for wheat and soybean was done to find the range between the maximum and minimum net irrigation water requirements. Mkushi catchment uses the highest gross irrigation water in five year period due to high ETo found in the region as recorded from the close weather station of Serenje. The highest net irrigation of 710 mm per ha was recorded in 2014 for the wheat crop and total of 3197.5 mm/ha while a minimum of 2253.9 mm/ha for soybean from 2013 to 2017.

The Mwomboshi catchment had maximum net irrigation recorded in 2013 with a total of 2946.3 mm/ha and minimum of 1769.5mm/ha for the five year period.

Mulungushi and Lunsemfwa catchments had the same net irrigation water as they record same climate obtained from the Kabwe Mulungushi weather station with the total maximum of 2464.2 mm/ha (Lunsemfwa), 2462.4 mm/ha (Mulungushi) and minimum total of 2020.9 mm/ha (Lunsemfwa), 2020.6 mm/ha Mulungushi for a five year period (2013 to 2017).

Lunsemfwa catchment shows highest irrigated area in 2013 of about 167 km^2 and the total estimated irrigated area of 692 km^2 for five year period cumulatively, it was followed by Mulungushi with a maximum of 30.67 km^2 in 2017 and a total irrigated area of 136 km^2 from 2013 to 2017. Mwomboshi have an irrigated area, recording a maximum of 23.05 km^2 in 2013 and having the total irrigated area of 115.17 km^2 irrigated from 2013 to 2017 and lastly Mkushi had recorded a maximum of 29.33 km^2 in 2017 and a total of 103.83 km^2 irrigated area from 2013 to 2017.

The volumes of irrigation abstraction from the catchments are estimated to be highest in the Lunsemfwa catchment at average of $6.81* 10^7$ m^3 in the five year period followed by averages of $1.36 *10^7$ m^3 in Mwomboshi catchment and Mkushi at $1.33 * 10^7$ m^3 and lowest average in Mulungushi at $1.32 * 10^7$ m^3. The large abstraction is due to large number of farming area in the catchment. On average $6.81* 10^7$ m^3 of water is abstracted from the Lunsemfwa catchment for irrigation each year.

5.3 RECOMMENDATIONS

The following recommendations were made;

1. Doing bathymetric studies on the dams upstream to ascertain the amount of water farmers are capable of storing.
2. For online improved estimates, field observations need to be carried out to validate the software results.
3. Better high resolution images could help in better precision leading to better estimate than the landsat8 which gives 30m by 30m resolution these could be archived with finding finances which provide the expensive images with better resolutions.
4. For accuracy of weather data in farming areas, farmers must be encourage to record their own physical weather data instead of taking data from distance weather station thus lead to high errors.

5.4 CLOSING REMARKS

This chapter provides the conclusions and the recommendations from the study. The conclusions have been linked to the set specific objectives in order to enhance clarity while the recommendations section has attempted to point out some gaps that need to be investigated by subsequent researches.

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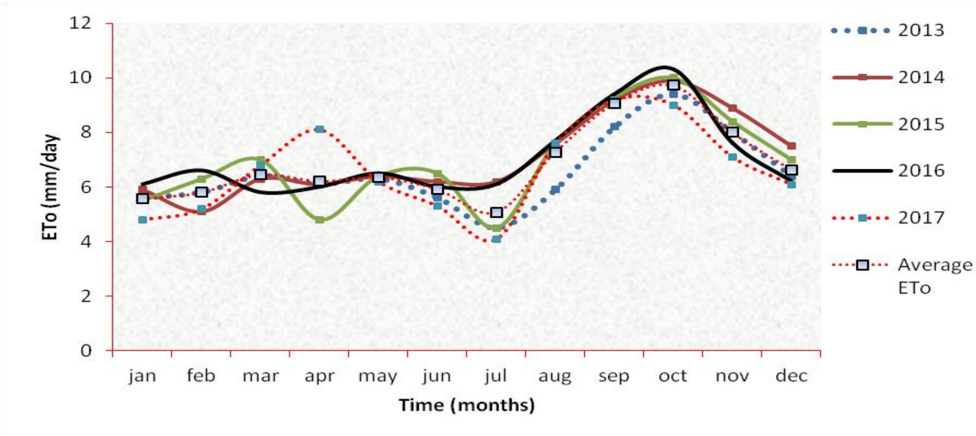
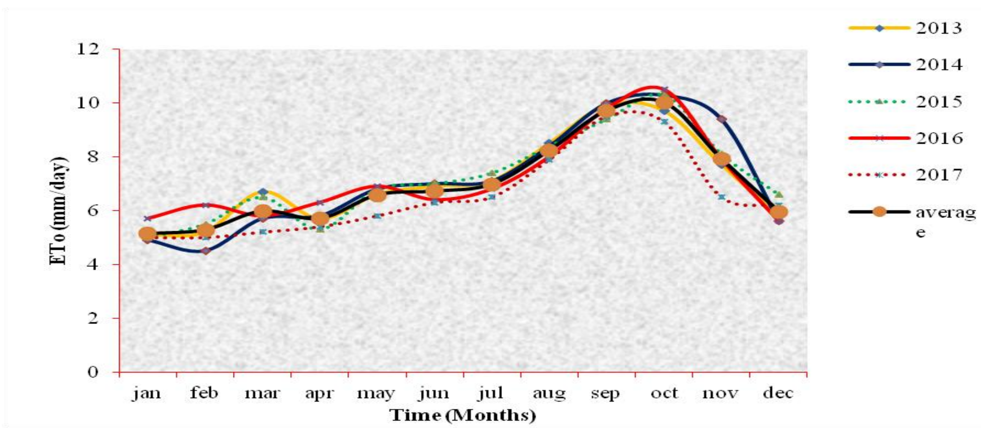
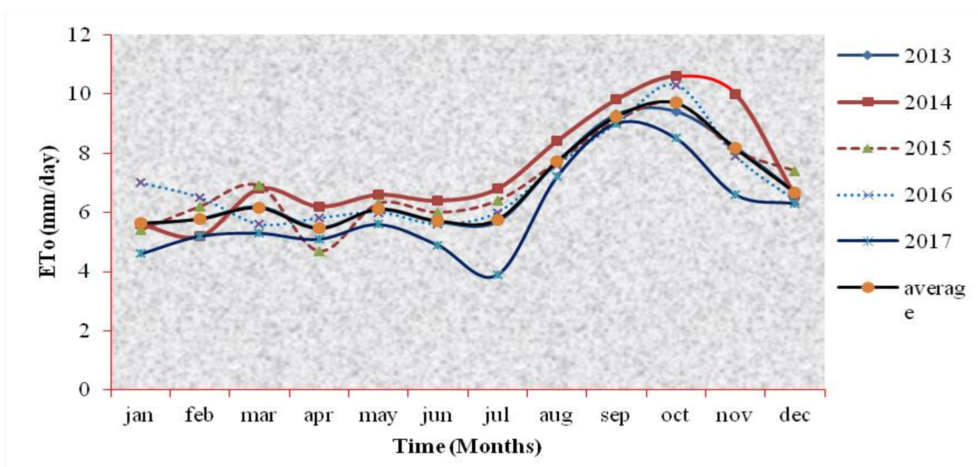
APPENDIX I; CLIMATE DATA FOR ETo CALCULATIONS AND RAINFALL DATA



Kabwe mulungush (zambia) - monthly data: January 2013 - December 2017



Serenje (zambia) - monthly data: January 2013 - December 2017



Lusaka Airport (zambia) - monthly data: January 2013 - December 2017

WEATHER DATA

kabwe Mulungushi weathe data																				
rainfall	2013	2014	2015	2016	2017	average	min tem	2013	2014	2015	2016	2017	average	max tem	2013	2014	2015	2016	2017	average
Jan-13		300.1	292.4	365.6	427.8	346.5	**Jan-13**		16.4	15.1	15.3	17	16.0	**Jan-13**		31.1	30.7	35.1	29.4	31.6
Feb-13		169.2	138.0	177.4	346.8	207.9	**Feb-13**		16	15.6	17.3	17.3	16.6	**Feb-13**		29.7	31	33.4	30.6	31.2
Mar-13		223.8	90.0	275.6	314.0	225.9	**Mar-13**		13.7	12.4	16.1	11.7	13.5	**Mar-13**		30.6	32.7	32.1	45.5	35.2
Apr-13		20.4	113.6	39.8	29.0	50.7	**Apr-13**		11.1	8.7	9.2	12	10.3	**Apr-13**		31.3	28.6	30.3	48	34.6
May-13		0.0	0.0	0.0	0.0	0.0	**May-13**		5.4	5.5	4.5	11.4	6.7	**May-13**		30	29.1	29.6	29.9	29.7
Jun-13		0.0	0.0	0.0	0.0	0.0	**Jun-13**		2.6	2.4	2.8	4	3.0	**Jun-13**		30.6	29.6	27.4	27.4	28.8
Jul-13		0.0	0.0	0.0	0.0	0.0	**Jul-13**		2.3	13	2.3	3	5.2	**Jul-13**		28.8	32.1	31	27.8	29.9
Aug-13		0.0	1.2	0.0	0.0	0.3	**Aug-13**		4.4	10	4.2	4.6	5.8	**Aug-13**		33.4	29	32.1	31.9	31.6
Sep-13		0.2	0.0	0.4	0.0	0.2	**Sep-13**		4.8	12	8.5	4.8	7.5	**Sep-13**		35.7	34.7	35.4	35.3	35.3
Oct-13	46.2	5.2	0.0	0.0	31.0	16.5	**Oct-13**	13.8	10.8	11.8	11.8	10.2	11.7	**Oct-13**	36.8	36.9	37.4	37.2	38.4	37.3
Nov-13	55.9	10.4	81.0	243.0	180.0	114.1	**Nov-13**	16.3	12.8	11.5	15.5	14.2	14.1	**Nov-13**	36.4	36.8	37	36.4	35.8	36.5
Dec-13	73.4	347.6	217.2	241.8	276.6	231.3	**Dec-13**	16.5	15.9	16.4	16.9	14.2	16.0	**Dec-13**	35.0	35	35.4	32.9	31.4	33.9
humidiy %	2013	2014	2015	2016	2017	average	**wind mm/s**	2013	2014	2015	2016	2017	average	**rn solar**	2013	2014	2015	2016	2017	average
Jan-13		83.8	85.8	78.8	88.7	84.3	**Jan-13**		0.5	0.3	0.8	0.8	0.6	**Jan-13**		19.19177	18.24627	18.82541	15.99585	18.1
Feb-13		87.4	84.3	82.6	88.9	85.8	**Feb-13**		0.4	0.3	0.6	0.4	0.4	**Feb-13**		16.94507	20.86311	20.98886	16.94075	18.9
Mar-13		83.4	80.3	87.0	87.8	84.6	**Mar-13**		1.5	1.9	0.9	1.4	1.4	**Mar-13**		20.87547	22.03424	18.63587	17.39847	19.7
Apr-13		79.2	86.3	80.3	79.8	81.4	**Apr-13**		2.1	1.7	2.2		2.0	**Apr-13**		19.08924	16.22578	19.25117	16.9711	17.9
May-13		70.6	74.7	71.0	64.7	70.3	**May-13**		2.0	1.8	2.2		2.0	**May-13**		19.85948	21.16008	20.19616	17.94845	19.8
Jun-13		66.6	71.0	68.6	71.7	69.5	**Jun-13**		2.0	1.7	2.0		1.9	**Jun-13**		18.02697	14.7073	19.54648	16.76539	17.3
Jul-13		63.9	47.1	65.4	66.0	60.6	**Jul-13**		1.8	0.1	1.9		1.3	**Jul-13**		19.25007	1.089	17.4376	10.49552	12.1
Aug-13		54.1	46.8	55.2	60.9	54.2	**Aug-13**		2.1	0.2	2.6		1.6	**Aug-13**		19.92906	1.637527	20.13721	20.81012	15.6
Sep-13		45.3	38.1	40.5	46.8	42.7	**Sep-13**		2.4	2.1	2.5		2.3	**Sep-13**		22.69639	6.777564	22.31879	22.62672	18.6
Oct-13	46.8	42.3	38.4	36.8	50.4	42.9	**Oct-13**	1.8	2.1	2.5	2.5		2.2	**Oct-13**	18.66	24.93129	24.16651	23.83979	20.53104	22.4
Nov-13	56.3	49.4	55.7	61.3	72.0	58.9	**Nov-13**	1.5	1.7	1.1	1.6		1.5	**Nov-13**	24.89	23.55325	21.72694	20.65534	20.32272	22.2
Dec-13	75.4	73.9	75.5	81.7	85.4	78.4	**Dec-13**	0.9	0.4	0.6	0.7		0.7	**Dec-13**	20.52	18.40336	21.749	19.76769	18.73747	19.8

Serenje weather station																				
rainfall	2013	2014	2015	2016	2017	average	min tem	2013	2014	2015	2016	2017	average	max tem	2013	2014	2015	2016	2017	average
Jan-13		146.5	399.4	178.4	12.2	184.1	41275.0		14.9	14.8	15.2	16.0	15.2	41275.0		28.6	28.7	30.5	29.6	29.4
Feb-13		273.7	265.0	212.4	159.8	227.7	41306.0		15.5	14.7	15.8	15.2	15.3	41306.0		28.5	30.4	31.1	30.2	30.1
Mar-13		787.6	117.4	307.0	4.6	304.2	41334.0		15.0	12.8	13.4	13.3	13.6	41334.0		29.5	30.4	30.7	28.1	29.7
Apr-13		40.2	90.8	11.4	47.8	47.6	41365.0		10.2	9.8	10.8	13.3	11.0	41365.0		29.3	28.6	29.3	29.4	29.2
May-13		0.0	0.4	0.0	0.0	0.1	41395.0		7.0	6.8	6.4	9.9	7.5	41395.0		27.6	27.2	28.2	27.5	27.6
Jun-13		0.0	0.0	36.6	0.0	9.2	41426.0		4.0	4.4	4.7	6.7	5.0	41426.0		28.3	28.1	25.3	26.6	27.1
Jul-13		0.0	0.0	0.0	6.0	1.5	41456.0		4.8	5.5	5.4	5.2	5.2	41456.0		28.5	28.8	28.5	25.8	27.9
Aug-13		0.0	0.0	0.0	3.2	0.8	41487.0		7.9	6.1	7.4	9.4	7.7	41487.0		31.7	29.5	29.5	30.1	30.2
Sep-13		0.0	12.8	0.0	0.0	3.2	41518.0		10.8	9.8	10.1	11.5	10.6	41518.0		33.3	32.8	32.9	33.5	33.1
Oct-13	0.2	0.0	15.0	9.8	8.2	6.6	41548.0	13.8	13.4	14.6	13.4	12.5	13.5	41548.0	35.1	35.2	34.9	34.3	36.3	35.2
Nov-13	51.4	0.6	61.2	16.6	67.6	39.5	41579.0	16.3	14.8	12.8	14.3	14.6	14.6	41579.0	36.4	34.9	35.9	34.8	33.5	35.1
Dec-13	265.4	34.8	261.2	26.4	24.0	122.4	41609.0	16.5	14.7	16.1	14.7	13.5	15.1	41609.0	32.2	31.8	33.4	30.9	31.3	31.9
humidity %	2013	2014.0	2015.0	2016.0	2017.0	average	wind m/s	2013.0	2014.0	2015.0	2016.0	2017.0	average	rn solar	2013.0	2014.0	2015.0	2016.0	2017.0	average
Jan-13		86.4	87.6	82.4	88.8	86.3	41275.0		0.6	0.3	0.8	0.3	0.5	41275.0		16.5	16.8	18.4	16.6	17.1
Feb-13		89.4	86.4	85.6	89.5	87.7	41306.0		0.2	0.4	0.8	0.4	0.5	41306.0		15.0	18.2	20.1	16.3	17.4
Mar-13		83.2	79.2	86.4	87.8	84.2	41334.0		2.3	2.7	1.5	2.3	2.2	41334.0		19.7	21.9	19.0	17.8	19.6
Apr-13		79.8	82.9	76.4	85.0	81.0	41365.0		3.3	2.9	3.6	3.6	3.4	41365.0		17.9	17.1	19.2	17.8	18.0
May-13		66.6	67.7	67.3	78.2	70.0	41395.0		3.6	3.4	3.6	3.6	3.5	41395.0		20.7	21.6	20.7	18.7	20.4
Jun-13		59.3	62.7	63.1	69.1	63.6	41426.0		3.6	3.4	3.5	3.7	3.5	41426.0		19.3	20.3	20.2	19.5	19.8
Jul-13		57.4	56.5	58.7	62.4	58.7	41456.0		3.3	3.2	3.3	3.6	3.3	41456.0		19.6	20.9	18.3	20.1	19.7
Aug-13		48.3	48.2	51.6	55.1	50.8	41487.0		3.6	3.7	4.0	3.7	3.7	41487.0		20.1	21.9	20.1	20.8	20.7
Sep-13		42.9	43.0	39.4	42.4	41.9	41518.0		3.9	3.6	3.4	3.9	3.7	41518.0		23.5	22.0	23.3	23.4	23.0
Oct-13	44.2	42.0	40.4	37.0	47.3	42.2	41548.0	3.0	3.1	3.4	3.3	2.9	3.2	41548.0	14.7	24.5	23.8	24.4	21.6	21.8
Nov-13	54.3	48.9	59.9	59.7	73.1	59.2	41579.0	2.7	2.6	1.8	2.3	2.0	2.3	41579.0	14.3	24.0	22.1	20.6	18.8	20.0
Dec-13	77.5	72.9	78.9	85.4	85.0	80.0	41609.0	1.1	0.4	0.6	1.0	1.2	0.8	41609.0	15.3	18.0	20.8	18.3	20.2	18.5

Lutaka international airpory																				
rain fall	2013	2014	2015	2016	2017	average	solar[W/m²]	2013	2014	2015	2016	2017	average	max tem	2013	2014	2015	2016	2017	average
Jan-13		262.5	243.6	146.0	425.0	269.275	Jan-13		18.5	17.9	21.2	15.1	18.2	**Jan-13**		31.1	30.7	35.1	29.4	31.6
Feb-13		123.4	140.0	83.8	247.6	148.7	Feb-13		17.3	20.1	20.6	16.8	18.7	**Feb-13**		29.7	31	33.4	30.6	31.2
Mar-13		81.0	56.4	191.2	110.0	109.65	Mar-13		22.8	22.0	17.8	17.9	20.1	**Mar-13**		30.6	32.7	32.1	45.5	35.2
Apr-13		60.8	188.0	61.0	29.4	84.8	Apr-13		19.5	15.5	18.3	16.6	17.5	**Apr-13**		31.3	28.6	30.3	48	34.6
May-13		0.0	0.4	0.2	0.0	0.15	May-13		21.0	20.4	18.5	17.4	19.3	**May-13**		30	29.1	29.6	29.9	29.7
Jun-13		0.0	0.0	0.0	0.0	0	Jun-13		18.6	18.4	17.5	15.0	17.4	**Jun-13**		30.6	29.6	27.4	27.4	28.8
Jul-13		0.0	0.0	0.0	0.0	0	Jul-13		20.5	18.5	16.4	8.6	16.0	**Jul-13**		28.8	32.1	31	27.8	29.9
Aug-13		0.8	0.0	0.0	0.0	0.2	Aug-13		22.3	20.9	19.8	19.7	20.7	**Aug-13**		33.4	29	32.1	31.9	31.6
Sep-13		0.0	7.8	0.0	0.0	1.95	Sep-13		24.4	22.4	22.3	22.0	22.8	**Sep-13**		35.7	34.7	35.4	35.3	35.3
Oct-13	51.8	0.0	0.0	7.4	12.8	14.4	Oct-13	18.7	27.1	23.7	25.2	20.9	23.1	**Oct-13**	36.8	36.9	37.4	37.2	38.4	37.3
Nov-13	55.0	76.0	44.8	112.2	91.2	75.84	Nov-13	25.4	26.5	22.2	21.7	18.6	22.9	**Nov-13**	36.4	36.8	37	36.4	35.8	36.5
Dec-13	219.8	326.6	194.2	141.2	154.4	207.24	Dec-13	20.3	20.6	22.5	20.0	20.1	20.7	**Dec-13**	35.0	35	35.4	32.9	31.4	33.9
min temp	2013	2014	2015	2016	2017	average	Humidity	2013	2014	2015	2016	2017	average	wind m/s]	2013	2014	2015	2016	2017	average
Jan-13		16.3	15.1	16.7	17.2	16.325	Jan-13		85.8	86.5	76.4	91.0	84.9	Jan-13		0.3	0.5	1.0	0.3	0.5
Feb-13		17	15.8	17.6	17.3	16.925	Feb-13		87.8	85.8	83.8	89.5	86.7	Feb-13		1.5	0.4	0.8	0.6	0.8
Mar-13		14.3	13.8	16.6	13.2	14.475	Mar-13		82.4	79.1	86.5	86.8	83.7	Mar-13		1.6	1.7	1.0	1.6	1.5
Apr-13		12.5	11.9	11.8	11.4	11.9	Apr-13		77.6	85.7	79.4	84.5	81.8	Apr-13		1.8	1.6	1.7	2.0	1.8
May-13		8.4	8.4	6.8	10.9	8.625	May-13		68.3	71.0	69.0	78.3	71.6	May-13		1.9	1.7	1.8	1.6	1.7
Jun-13		7.4	5.9	6.3	6.3	6.475	Jun-13		62.0	65.9	65.1	71.2	66.1	Jun-13		1.9	1.7	1.7	1.8	1.8
Jul-13		5	6.4	5.3	6.7	5.85	Jul-13		57.4	61.1	59.4	60.4	59.6	Jul-13		1.9	1.7	1.8	2.0	1.8
Aug-13		6.8	5.6	6	8	6.6	Aug-13		46.1	48.0	49.9	54.2	49.5	Aug-13		2.1	2.1	2.3	2.0	2.1
Sep-13		9.3	10.1	11.5	10.9	10.45	Sep-13		41.0	41.3	37.6	43.7	40.9	Sep-13		2.4	2.2	2.1	2.3	2.3
Oct-13	16.0	13.2	16.2	14.1	13.8	14.66	Oct-13	46.2	39.6	38.4	35.5	48.2	41.6	Oct-13	1.9	2.0	2.0	2.1	1.7	1.9
Nov-13	16.0	15.5	11.9	16.8	2.4	12.52	Nov-13	55.9	46.3	53.1	58.8	71.5	57.1	Nov-13	1.6	1.9	1.2	1.4	1.2	1.4
Dec-13	17.0	16.7	17.8	16.9	16.5	16.98	Dec-13	73.4	74.3	71.5	79.9	82.0	76.2	Dec-13	1.0	0.5	0.6	0.7	1.1	0.8

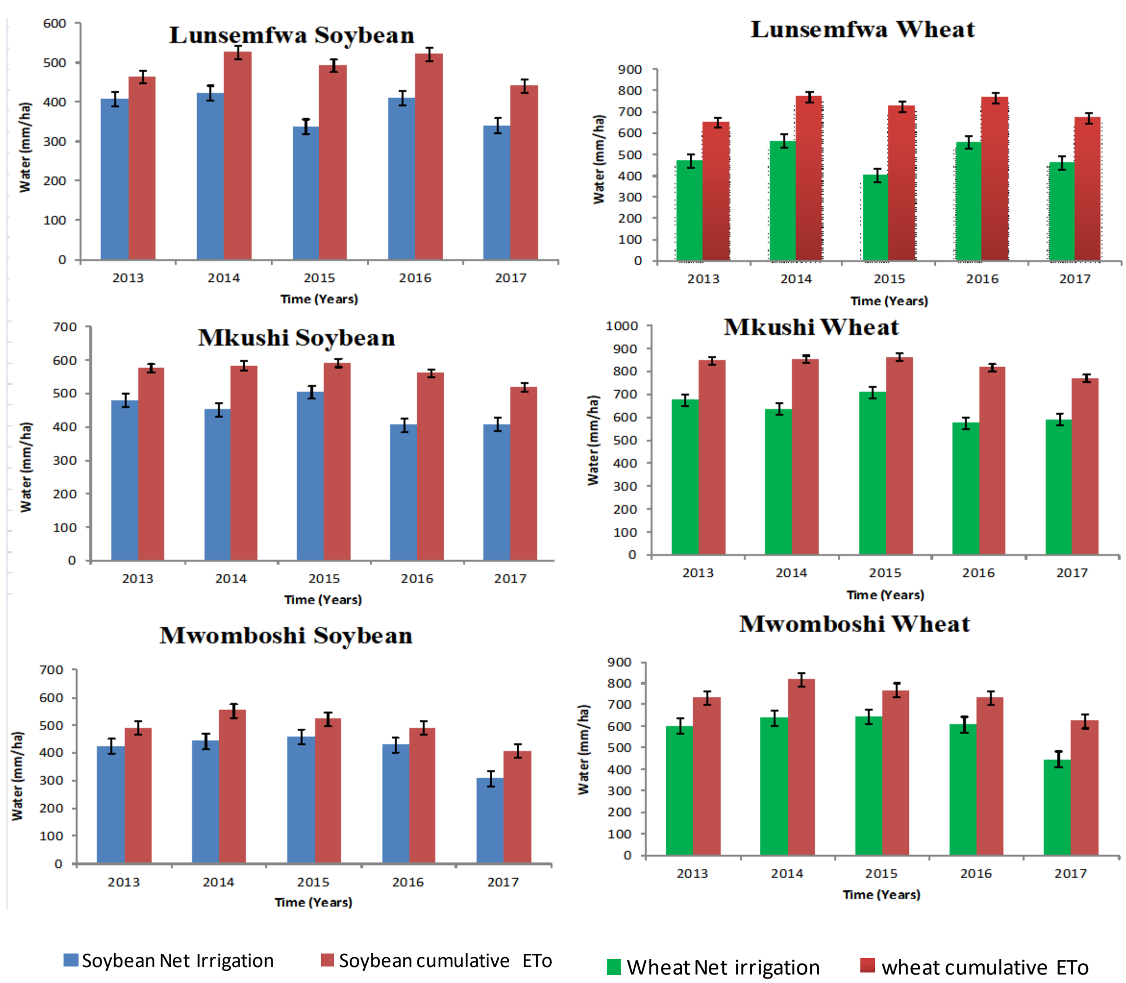
APPENDIX II; CALCULATION OF VOLUME ABSTRACTED

Wheat Gross Volume Calculations															
	2013			2014			2015			2016			2017		
catchments	irr mm/ha	area [ha]	VOL [m3]	irr mm/ha	area [ha]	VOL [m3]	irr mm/ha	area [ha]	VOL [m3]	irr mm/ha	area [ha]	VOL	irr mm/ha	area [ha]	VOL [m3]
mkushi	678	2200	14916000	639.6	2133.333	13644800	710	1866.667	13253333.33	577.3	1250	7216250	592.6	2933.3333	17382933
lunsemfwa	473.3	16700	79041100	566.9	11433.33	64815567	403.3	13100	52832300	558.5	15000	83775000	462.2	12966.667	59931933
mulungushi	473.3	2550	12069150	566.9	2333.333	13227667	403.5	3200	12912000	556.5	2450	13634250	462.2	3066.6667	14174133
mwamboshi	603.3	2350	14177550	639.7	2200	14073400	646	2500	16150000	610	2300	14030000	447.3	2166.6667	9691500

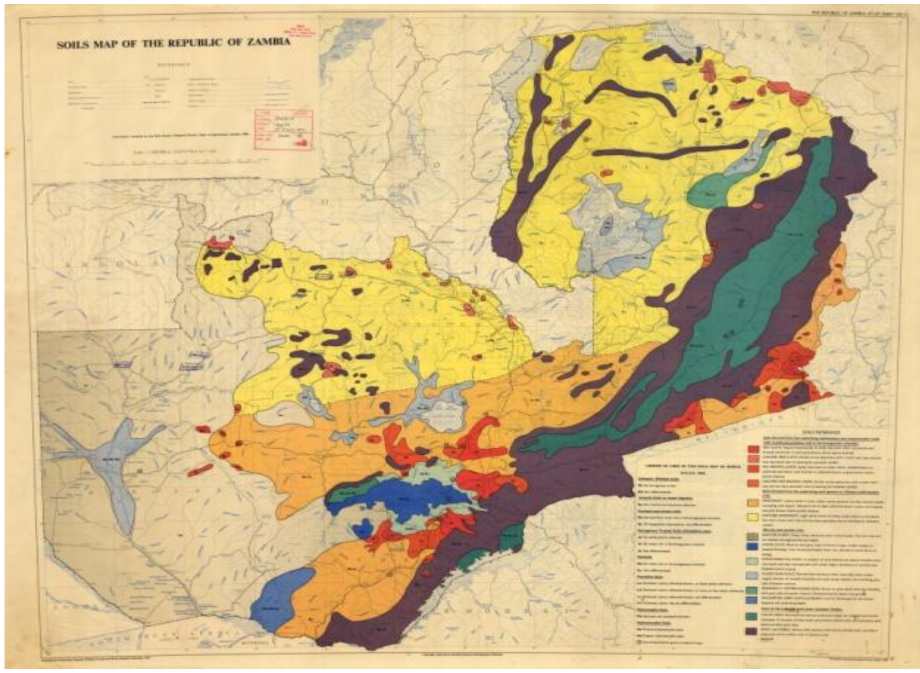
	Soybean Gross Volume Calculations														
	2013			2014			2015			2016			2017		
Catchments	irr mm/ha	area [ha]	VOL [m3]	irr mm/ha	area [ha]	VOL [m3]	irr mm/ha	area [ha]	VOL [m3]	irr mm/ha	area [ha]	VOL	irr mm/ha	area [ha]	VOL [m3]
mkushi	481.2	2200	10586400	453	2133.333	9664000	504.8	1866.667	9422933.333	406.3	1250	5078750	408.6	2933.3333	11985600
lunsemfwa	407.9	16700	68119300	423	11433.33	48363000	438.8	13100	57482800	409.8	15000	61470000	341.4	12966.667	44268200
mulungushi	407.6	2550	10393800	423	2333.333	9870000	438.8	3200	14041600	409.8	2450	10040100	341.4	3066.6667	10469600
mwamboshi	314.4	2350	7388400	395.4	2200	8698800	458.4	2500	11460000	294.7	2300	6778100	306.6	2166.6667	6643000

APPENDIX IIa; SUMMURY OF RELATIONSHIP OF ETo AND NET IRRIGATION

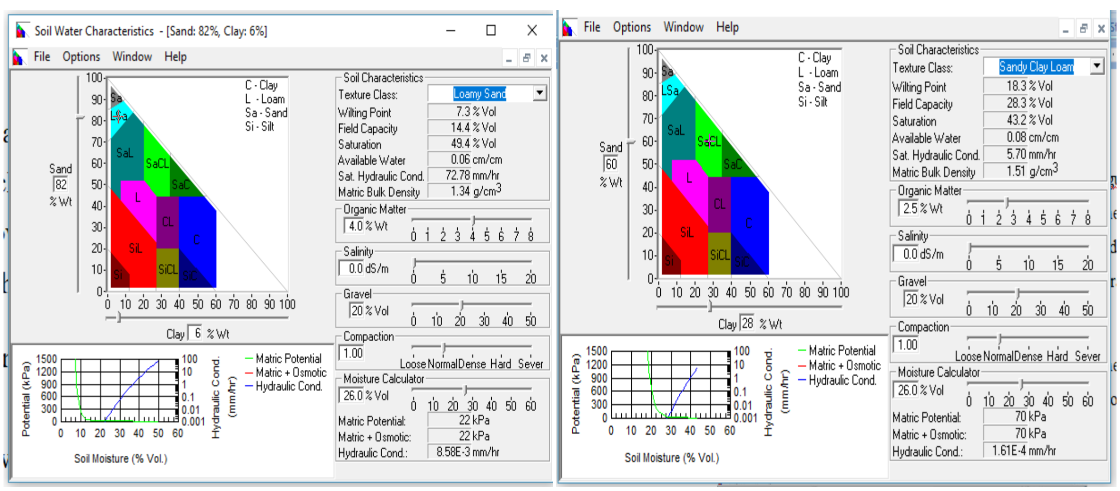
The relationship between ETo and Net irrigation per catchment from 2013 to 2017						
	Years	**2013**	**2014**	**2015**	**2016**	**2017**
Lunsemfwa	Soybean Net Irrigation	407.9	423	338.8	409.8	341.4
	Soybean cumulative ETo	463.2	526.6	493.1	521	441.3
	Wheat Net irrigation	473.3	566.9	403.3	558.5	462.2
	wheat cumulative ETo	649.5	769	725.3	765.5	671.1
	rain	4.5	0	10.3	3.6	0
Mkushi	Soybean Net Irrigation	481.2	453	504.8	406.3	408.6
	Soybean cumulative ETo	575.9	584.7	592.2	562.1	519.7
	Wheat Net irrigation	678	639.6	710	577.3	592.6
	wheat cumulative ETo	848	854.1	863.4	818.9	772
	rain	12.7	0	5.2	37	9.1
Mwamboshi	Soybean Net Irrigation	426	442.8	458.4	428	306.6
	Soybean cumulative ETo	490.4	553.4	522.7	492	406.9
	Wheat Net irrigation	603.3	639.7	646	610	447.3
	wheat cumulative ETo	732.5	821	769	733.2	624.7
	rain (mm)	4.5	0	10.8	3.6	0



APPENDIX IIIa; SOIL MAP FOR ZAMBIA AND SOIL ANALYSIS RESULTS

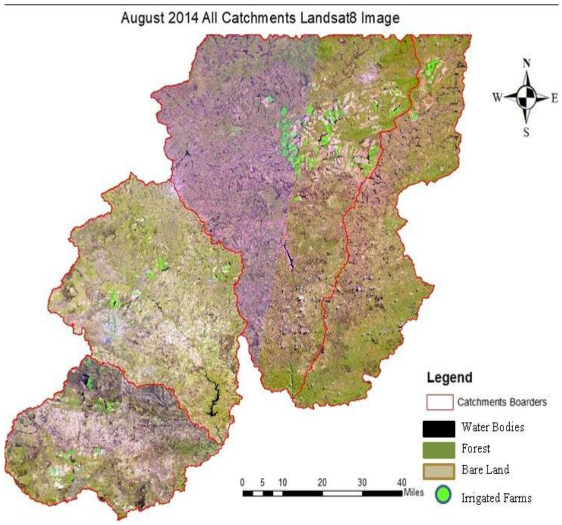


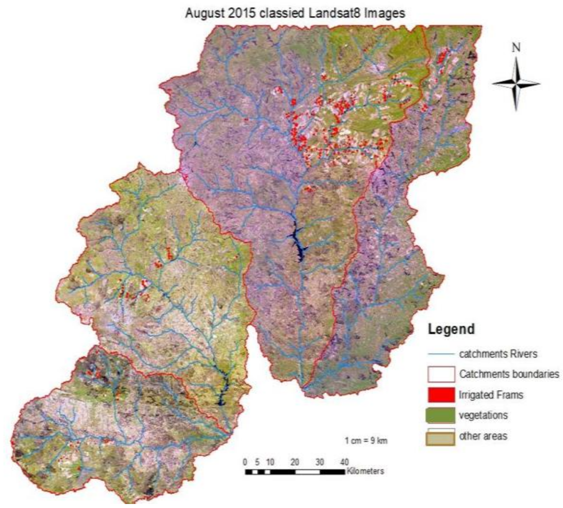
Soil map of Zambia which was used to obtain the soil characteristics of the four catchments under study

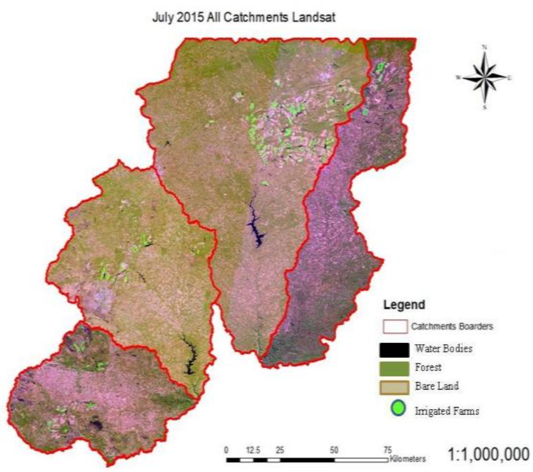


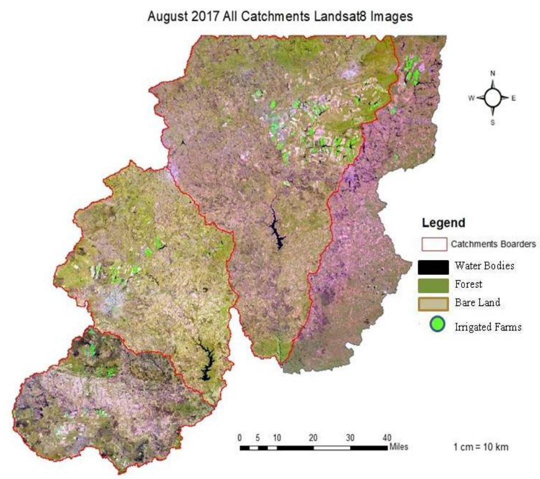
Mkushi, Mulungushi, and Lunsemfwa (Loamy sands) right Mwomboshi Sandy Clay Loams analyzed soil results (left)

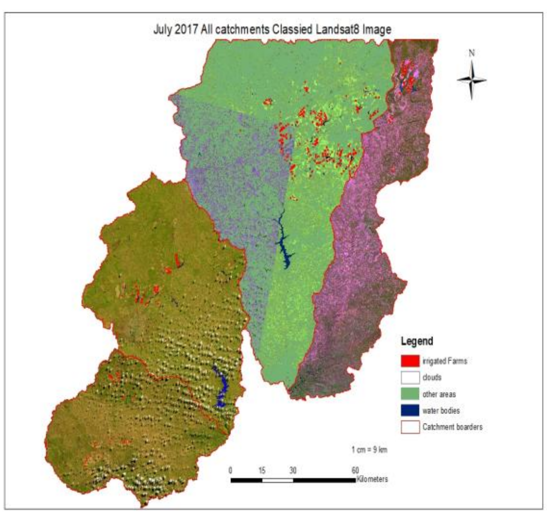
APPENDIX IIIb; CLASSIFIED CATCHMENTS

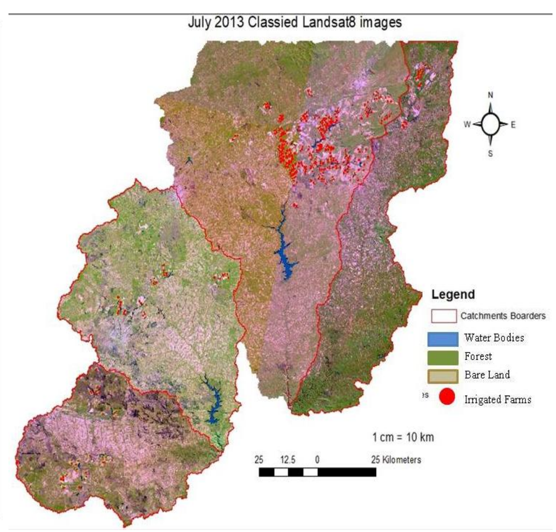


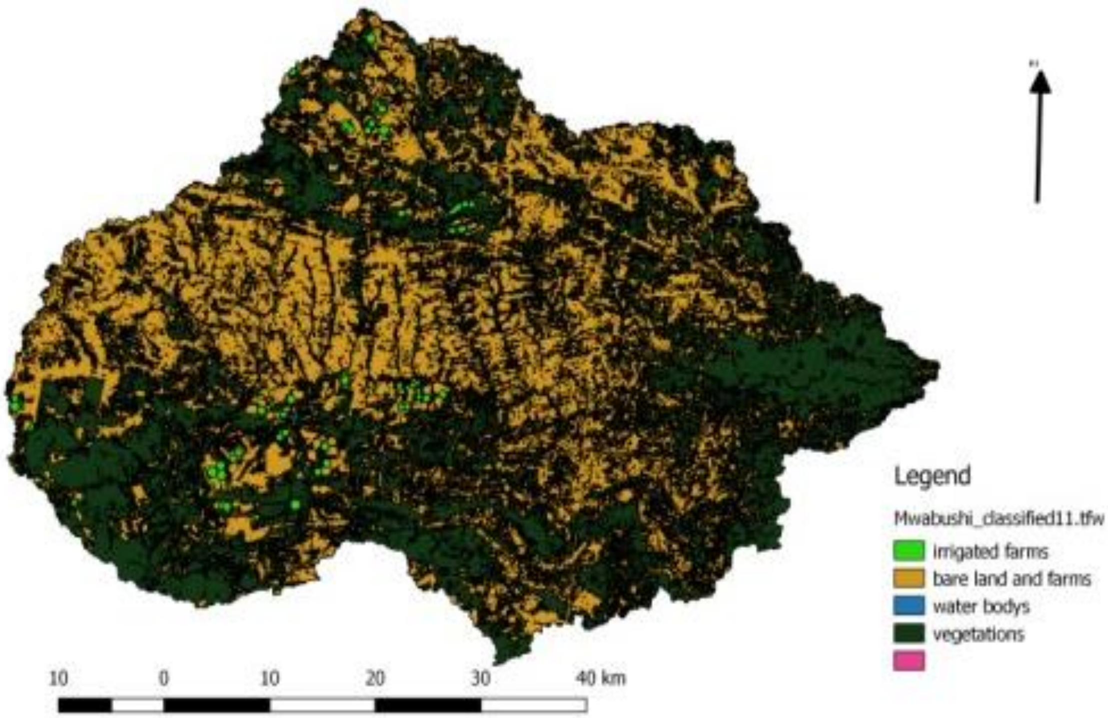


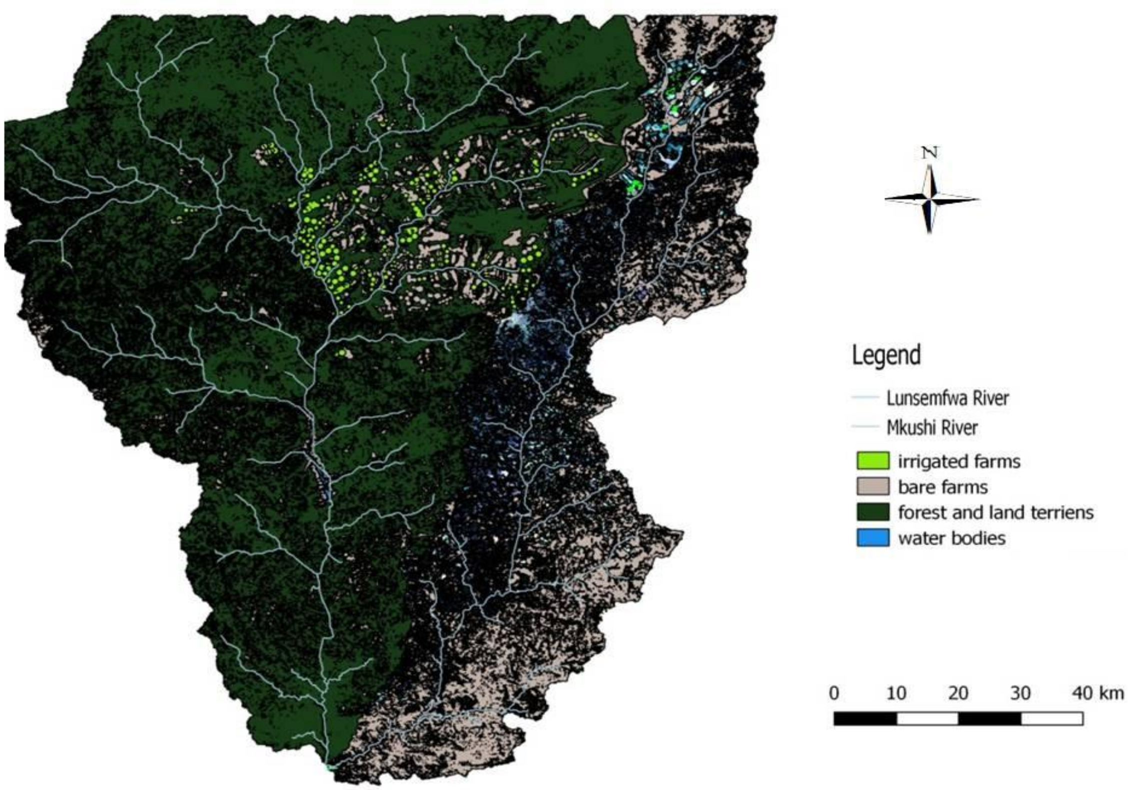


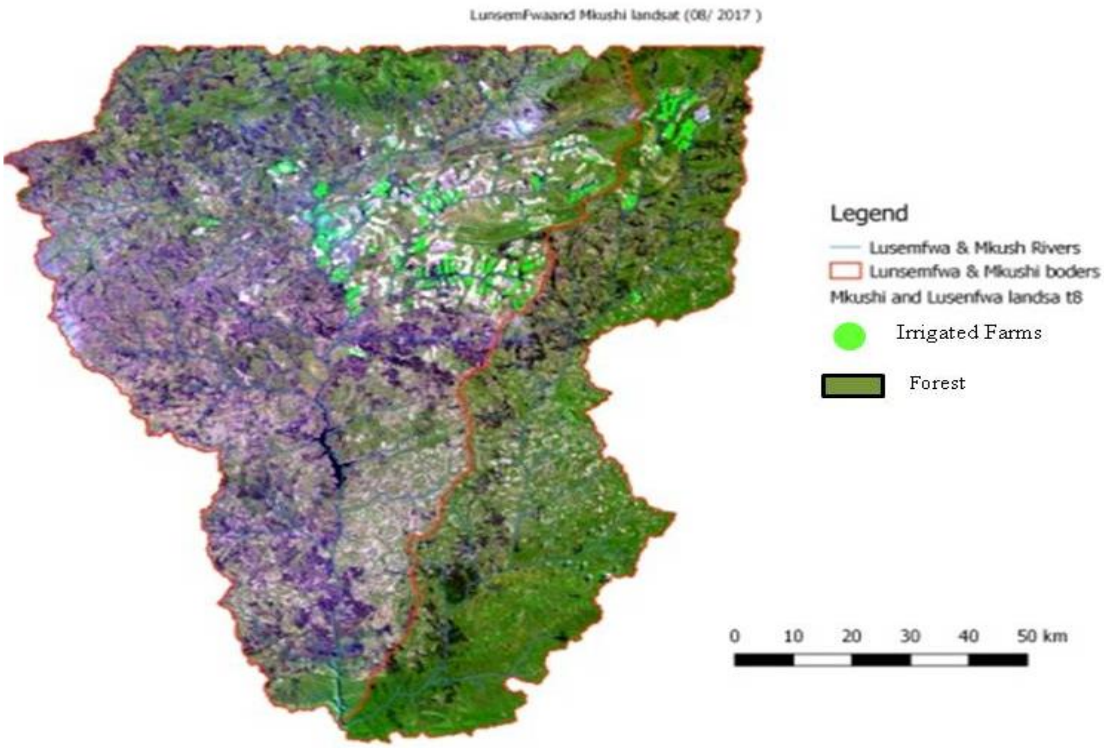


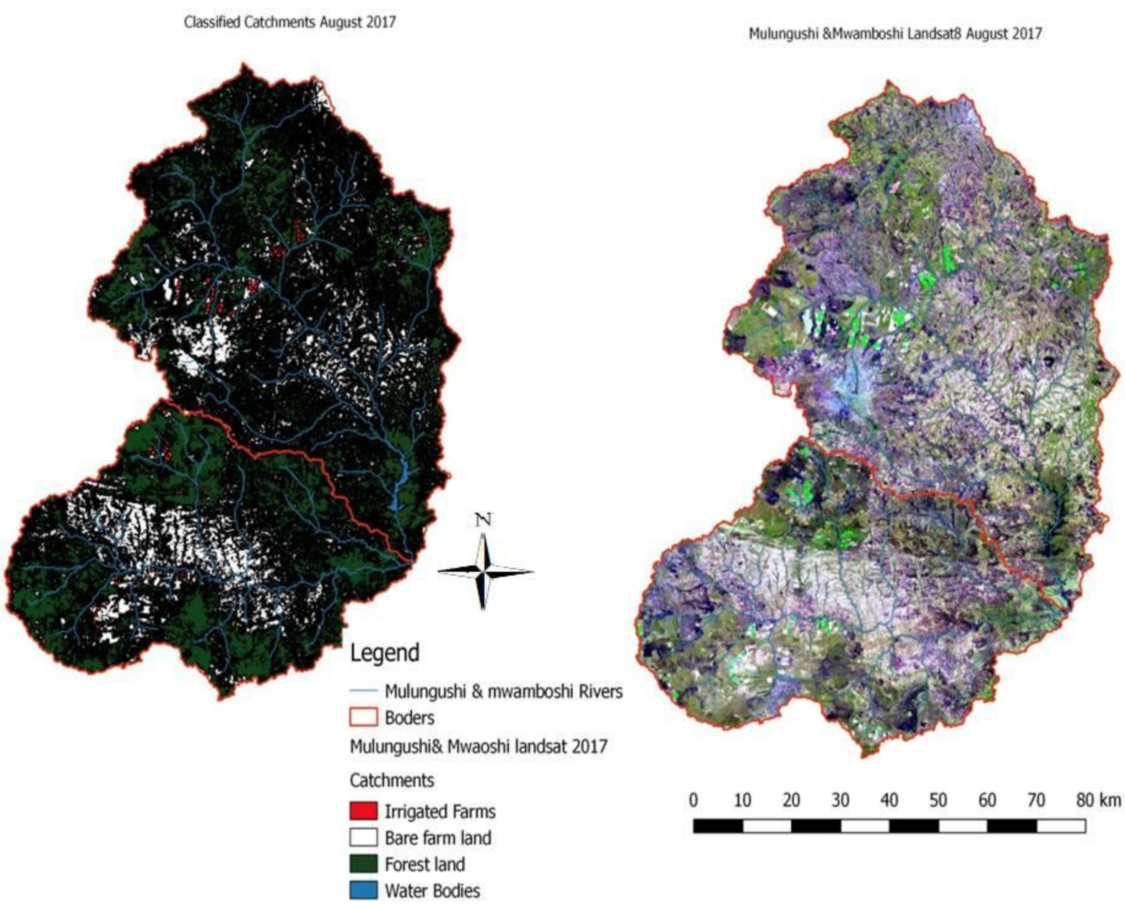





Legend
Mwabushi_classified11.tfw
irrigated farms
bare land and farms
water bodys
vegetations
10
0
10
20
30
40 km


N
Legend
Lunsemfwa River
Mkushi River
irrigated farms
bare farms
forest and land terriens
water bodies
0
10
20
30
40 km


LunsemFwaand Mkushi landsat (08/ 2017)
Legend
Lusemfwa & Mkush Rivers
Lunsemfwa & Mkushi boders
Mkushi and Lusenfwa landsa t8
Irrigated Farms
Forest
0 10 20 30 40 50 km


Classified Catchments August 2017
Mulungushi &Mwamboshi Landsat8 August 2017
N
Legend
Mulungushi & mwamboshi Rivers
Boders
Mulungushi& Mwaoshi landsat 2017
Catchments
Irrigated Farms
Bare farm land
Forest land
Water Bodies
0 10 20 30 40 50 60 70 80 km

APPENDIX IV; SPSS LEAST SIGNIFICANT DIFFERENT COMPARISONS RESULTS

Multiple Comparisons of wheat abstracted Irrigation Volume [m^3] 2013 to 2017 LSD

(I) Catchment	(J) Catchment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Lunsemfwa	Mkushi	54796516.67	4351581.345	0.000	45571576.31	64021457.02
	Mulungushi	54875740	4351581.345	0.00	45650799.65	64100680.35
	Mwomboshi	54454690	4351581.345	0.00	45229749.65	63679630.35
Mkushi	Lunsemfwa	-54796516.67	4351581.345	0.00	-64021457.02	-45571576.31
	Mulungushi	79223.33333	4351581.345	0.99	-9145717.02	9304163.686
	Mwomboshi	-341826.6667	4351581.345	0.94	-9566767.02	8883113.686
Mulungushi	Lunsemfwa	-54875740	4351581.345	0.00	-64100680.35	-45650799.65
	Mkushi	-79223.33333	4351581.345	0.99	-9304163.686	9145717.02
	Mwomboshi	-421050	4351581.345	0.92	-9645990.353	8803890.353
Mwamboshi	Lunsemfwa	-54454690	4351581.345	0.00	-63679630.35	-45229749.65
	Mkushi	341826.6667	4351581.345	0.94	-8883113.686	9566767.02
	Mulungushi	421050	4351581.345	0.92	-8803890.353	9645990.353

Based on observed means: The error term is Mean Square(Error) = 47340650502465.200."
*The mean difference is significant at the 0.05 level.

Multiple Comparisons of wheat Net irrigation water [mm/ha] 2013 to 2017 LSD

(I) Catchment	(J) Catchment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Lunsemfwa	Mkushi	-146.66	44.045	0.01	-242.625	-50.694
	Mwomboshi	-96.42	44.045	0.05	-192.385	-0.454
Mkushi	Lunsemfwa	146.66	44.044	0.01	50.694	242.625
	Mwomboshi	50.24	44.044	0.28	-45.725	146.205
Mwomboshi	Lunsemfwa	96.42	44.044	0.05	0.454	192.385
	Mkushi	-50.24	44.044	0.28	-146.205	45.725

"Based on observed means: The error term is Mean Square (Error) = 4849.887."
*. The mean difference is significant at the 0.05 level.

Multiple Comparisons of soybean abstracted Irrigation Volume [m3] 2013 to 2017 LSD

(I) Catchment	(J) Catchment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Lunsemfwa	Mkushi	46593123.33	3278084.057	0.00	39643895.57	53542351.1
	Mulungushi	44977640	3278084.057	0.00	38028412.24	51926867.76
	Mwomboshi	47747000	3278084.057	0.00	40797772.24	54696227.76
Mkushi	Lunsemfwa	-46593123.33	3278084.057	0.00	-53542351.1	-39643895.57
	Mulungushi	-1615483.333	3278084.057	0.63	-8564711.097	5333744.431
	Mwomboshi	1153876.667	3278084.057	0.73	-5795351.097	8103104.431
Mulungushi	Lunsemfwa	-44977640	3278084.057	0.00	-51926867.76	-38028412.24
	Mkushi	1615483.333	3278084.057	0.63	-5333744.431	8564711.097
	Mwomboshi	2769360	3278084.057	0.41	-4179867.764	9718587.764
Mwomboshi	Lunsemfwa	-47747000	3278084.057	0.00	-54696227.76	-40797772.24
	Mkushi	-1153876.667	3278084.057	0.73	-8103104.431	5795351.097
	Mulungushi	-2769360	3278084.057	0.41	-9718587.764	4179867.764

Based on observed means: The error term is Mean Square (Error) = 26864587712847.240.

*. The mean difference is significant at the 0.05 level.

Multiple Comparisons of soybean Net irrigation water [mm/ha] 2013 to 2017 LSD

(I) Catchment	(J) Catchment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Lunsemfwa	Mkushi	-46.6	33.211	0.19	-118.962	25.762
	Mwomboshi	50.28	33.211	0.16	-22.082	122.642
Mkushi soy	Lunsemfwa	46.6	33.211	0.19	-25.762	118.962
	Mwomboshi	96.88	33.211	0.01	24.518	169.242
Mwomboshi	Lunsemfwa	-50.28	33.211	0.16	-122.641	22.082
	Mkushi	-96.88	33.211	0.01	-169.242	-24.518

Based on observed means;The error term is Mean Square(Error) = 2757.521.

*. The mean difference is significant at the 0.05 level.